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Klystron Modulator Design for the Los Alamos Neutron Science Center Accelerator

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***Abstract* – This paper will describe the design of the 44 modulator systems that will be installed to upgrade the Los Alamos Neutron Science Center (LANSCE) accelerator RF system. The klystrons can operate up to 86 kV with a nominal 32 Amp beam current with a 120 Hz repetition rate and 15% duty cycle. The klystrons are a mod-anode design. The modulator is designed with analog feedback control to ensure the klystron beam current is flat-top regulated. To achieve fast switching whilst maintaining linear feedback control, a grid-clamp, totem-pole modulator configuration is used with an "on" deck and an "off" deck. The on and off deck modulators are of identical design and utilize a cascode connected planar triode, cathode driven with a high speed MOSFET. The derived feedback is connected to the planar triode grid to enable the flat-top control. Although modern design approaches suggest solid state designs may be considered, the planar triode (Eimac Y-847B) is very cost effective, is easy to integrate with the existing hardware, and provides a simplified linear feedback control mechanism. The design is very compact and fault tolerant. This paper will review the complete electrical design, operational performance, and system characterization as applied to the LANSCE installation.**

EXISTING SYSTEM

The forty four modulator systems used at the LANSCE accelerator are the original equipment installations and have been in service for over 40 years (Photo 1). These systems can operate up to 2.75 MW peak power with the average power limited by the available -86 kV power supply system. The nominal RF output rating of each klystron is 1.25 MW at 850 MHz. The existing modulator design derives the klystron mod-anode voltage from a triode tube operated as a saturated switch, as noted in Figure 1, with a tapped high power voltage divider. Multiple taps on the high voltage divider provide the means to adjust the required mod-anode voltage. The ohm-weave resistor assembly dissipates almost 10 kW and gives a 60 µs (beam current) rise time and an 80 µs fall time. The triode switch tube is grid pulsed via an isolation transformer with a 300V, 1.2 kW driver. The klystron mod-anode / grid drive circuitry also has the undesired characteristic of a 50 µs turn-off delay that results in wasted klystron collector power at the end of the RF drive beam gate. The electrical efficiency of the modulator systems are such that the klystron oil tank requires an internal oil to water heat exchanger and an auxiliary (3Ø) oil pump. As the klystrons and modulators are grouped together with 6 or 7 tubes operating from a common capacitor bank and power supply system, one "sector" of the LANSCE accelerator, the common bank voltage must be

Photo 1. LANSCE 2.75 MW Klystron and Modulator System

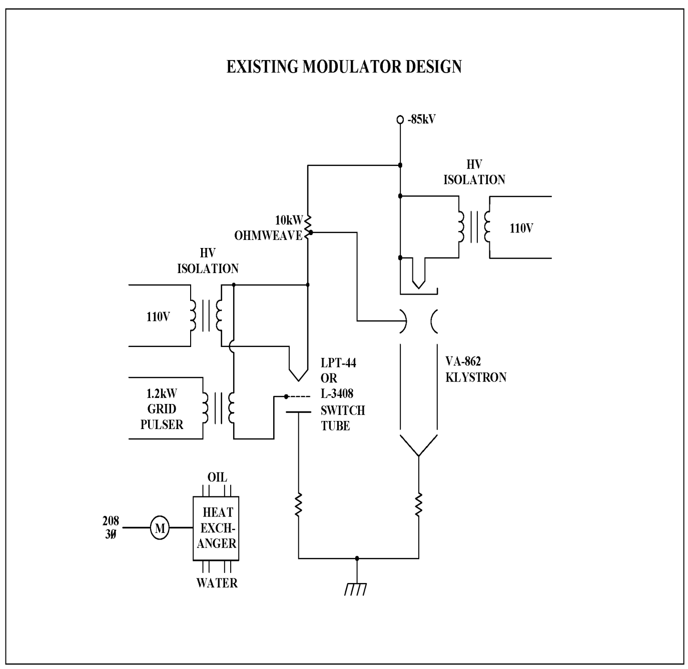

Figure 1. Saturated Switch Klystron Modulator

increased to accommodate the klystron with the weakest cathode emission. Individual control of the klystron mod-anode voltage is difficult and time consuming and is not utilized. Operating a sector at the parameters of the weakest tube creates an additional loss to the overall electrical system efficiency. With the saturated switching, the klystron beam current, RF gain, and RF phase all "droop" as the capacitor bank voltage droops and sufficient control margin must be available to achieve appropriate drive linearity and control.

I. LANSCE-RM DESIGN UPGRADE

The LANSCE-RM modulator upgrade provides a higher performance and electrical efficiency parameter as the new system has a regulating "on" deck with a tail-biter "off" deck which only switches the associated mod-anode capacitances. The mod-anode capacitance is less than 100 pF with an additional 250 pf for the modulator deck and isolation transformer assembly. The performance parameters of this system as presently operated is given in Table 1.

Nominal operational voltage	**86 kV**
Klystron beam rise (Tr) and fall (Tf) time	**20 µs**
Minimum pulse width	**60 µs**
Mod-anode voltage range	**5% - 50%**
Klystron beam current regulation	**1 %**
Maximum duty factor	**15%**
Maximum pulse width	**1.475 ms**
Nominal pulse width	**825 µs**
Maximum repetition rate	**120 Hz**

Table 1. LANSCE-RM modulator performance parameters

This modulator design can be described as a grid-clamp, totem-pole, mod-anode modul**ator as seen in Figure 2.**

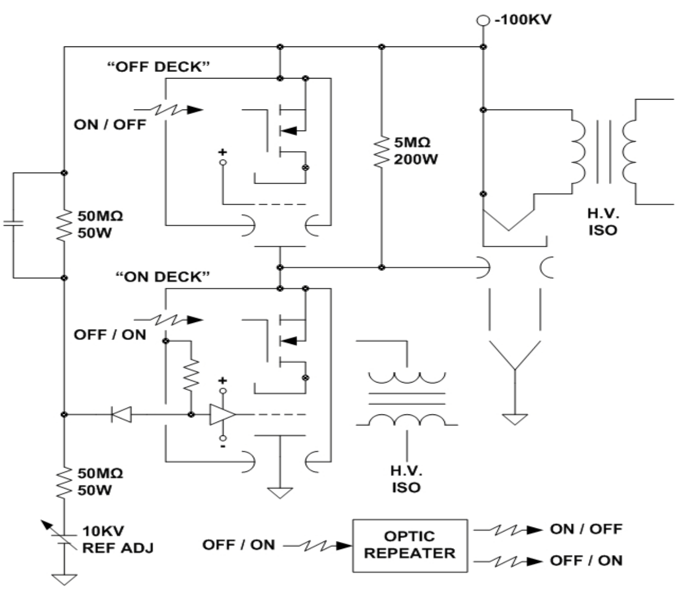

Figure 2. Grid-Clamp Totem-Pole Mod-Anode Modulator

The switch decks are of identical design and are completely interchangeable. This system is controlled via fiber optics and the older 1.2 kW grid pulser is not required. The fiber optic signal is buffered with an optic repeater and re-transmitted (in phase) to the on deck. At the end of the gate pulse, the optic repeater sends a 300 us pulse to the off deck to discharge the mod-anode capacitance. The mod-anode is then held at cathode potential via the 5 Meg "pull-up" resistor, maintaining the off condition. To regulate the klystron mod-anode voltage, a reference voltage is determined by a high impedance voltage divider, the 50 MΩ resistors in Figure 2. The node voltage between the reference resistors can be altered with a (HV) power supply as part of that network. This provides individual adjustment to the mod-anode voltage and klystron cathode current. Regulation is provided by dis-continuous feedback. When the on deck is off, the "clamp" diode is reverse biased and the feedback loop is open circuited. When the on deck is pulsed on, it switches quickly until the potential is reached when the clamp diode is forward biased and then the feedback loop closes. The bypass capacitor across the upper 50 MΩ reference resistor couples the bank voltage droop into the mod-anode reference and flat-tops the beam current. A view of the completed modulator assembly can be noted in Photo 2.

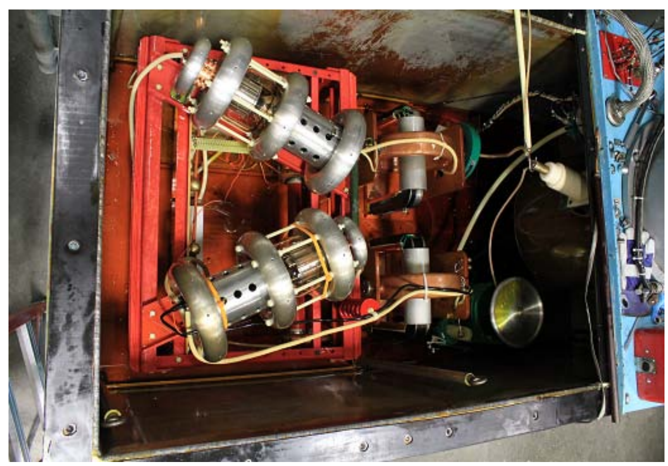

Photo 2. Grid-Clamp Totem-Pole Modulator Assembly

Switching waveforms of the new modulator show rise and fall times better than 20 µs and a well regulated beam current flat top as noted in Photos 3 and 4.

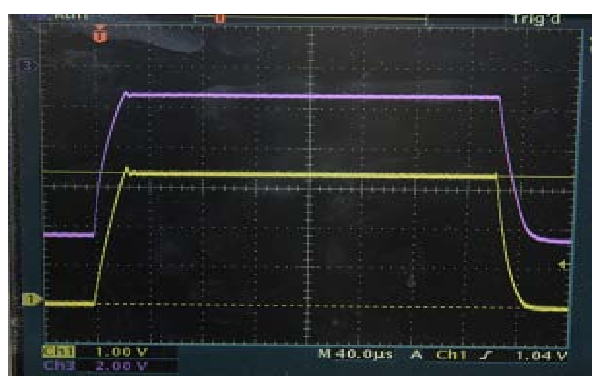

Photo 3. Detail of Klystron Beam Current and Mod-anode Voltage
Yellow: Beam Current (33.4 A) Purple: Mod-Anode Voltage (-85 kV)

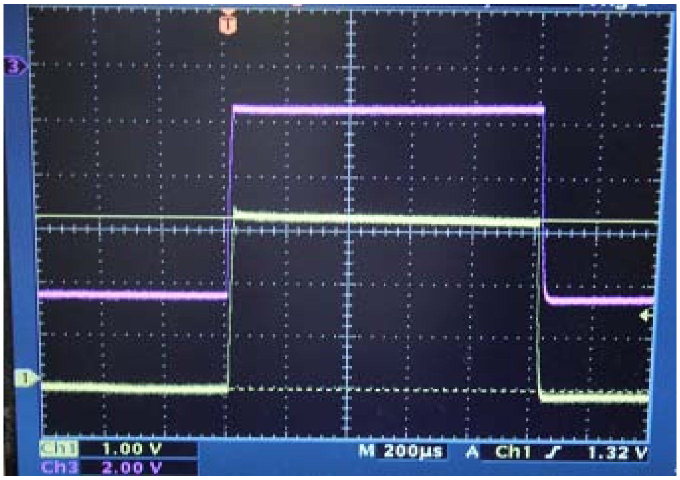

Photo 4. Long Pulse Klystron Beam Current and Mod-anode Voltage
Yellow: Beam Current (33.4 A) Purple: Mod-Anode Voltage (-85 kV)

The current viewing transformer droop and related end of pulse undershoot, when corrected, indicate an excellent beam current flat-top as the capacitor bank droops.

II. MODULATOR DECK DESIGN

Fast switching of the LANSCE klystrons is easily achieved with a cascode connected MOSFET and planar triode. The on/off control is independent from the feedback circuit and the system is self-biasing as noted in Figure 3. The on/off control is via a fiber optic receiver, buffered with a gate driver that connects to power MOSFET. When the MOSFET is off, so is the tube. The cathode self biases to the desired cut-off voltage and the zener diode accommodates any cut-off leakage current. When on, the cathode is grounded and the slightly positive grid turns the tube on quickly.

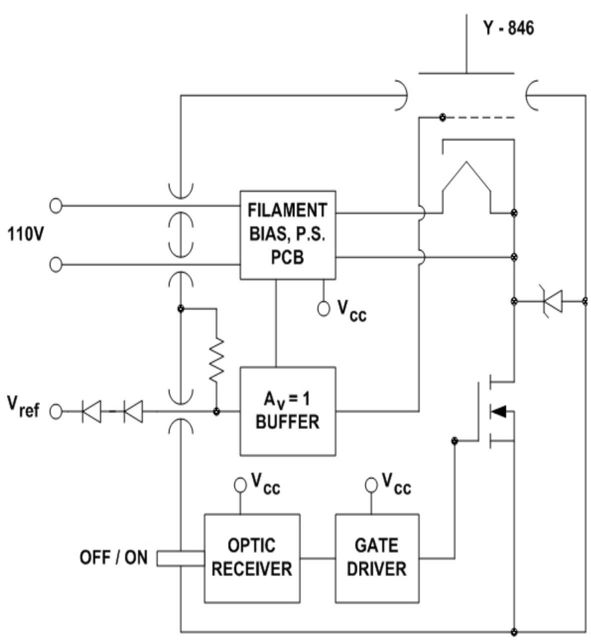

Fig. 3 Diagram of Fast Switching, Regulating Hot Deck

For the "on-deck", the clamp diode string is simply plugged into the feedback input. The buffer circuit is a bipolar transistor emitter follower that connects to the tube grid, and the overall design is very compact. A detail of the individual modulator deck assembly and drive card can be noted in Photo 5 and Photo 6.

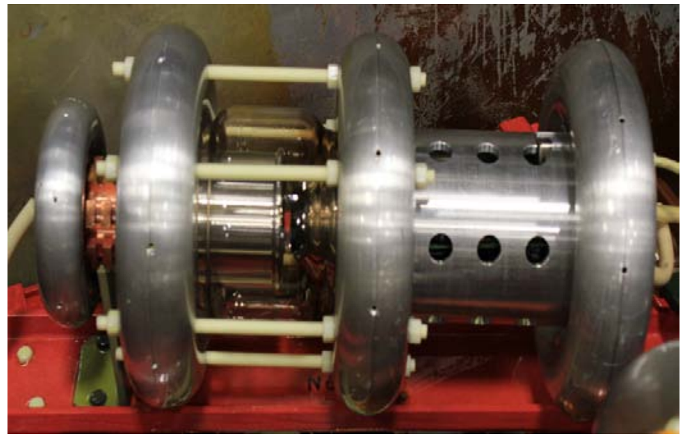

Photo 5. Modulator Deck Assembly

Photo 6. Y-847B Planar Triode Cascode Driver and Feedback Controller

As the planar triode has a gain of 2500, the full range of control, assuming 100,000 volts on the plate, would require a grid swing between "0" and "-40" volts. However, to enhance turn-on switching speed, a slight positive grid voltage is used, but once flat-top is achieved, the grid operates in a slightly negative range (~-10V). To ensure this complete control range, the emitter follower circuit operates between +15 volts and -80 volts and many transistors are suitable for this application. To facilitate reliable operation during klystron arcing and crowbar events, the solid state circuitry is well protected with clamp diodes, de-Qing resistors, and movistors.

III. Y-847B PLANAR TRIODE

The Y-847B planar triode shown in Photo 7 is a modern glass design with a very high gain, a mu of 2500, and is easily driven with low voltage solid state devices. The dispenser cathode requires only 50 watts and provides a DC pulsed current rating of 4 Amperes. The plate assembly has been optimized to minimize field stresses between the plate (cylindrical structure) and grid assembly (conical structure). Table 2 provides a summary of the electrical characteristics of the Y-847B planar triode.

Photo 7. Y-847B 100 kV, 4 Amp Planar Triode

Plate Voltage Rating	**100 kV**
Filament Voltage	**6.3 V**
Filament Current	**8.4 A**
Input Capacitance (Cgf)	**25 pF**
Feedback Capacitance (Cgp)	**6 pF**
Plate Dissipation	**2 kW**
Cut-off Bias at 100 kV (.1 ma leakage)	**-40V**

Table 2. Performance Characteristics of the Y-847B Planar Triode

The glass envelope tube is preferred over older ceramic designs as the tube internals can be examined, the glass is easier to clean, and has better vacuum / sealing characteristics. With this tube, switching and linear feedback is obtained in a very small system package, about .75 cu foot, with a weight of less than 10 pounds for each tube and deck assembly. Commercial off the shelf aluminum toroids (Ross Engineering) are used for the field grading structures and standard aluminum pipe for the electronic assembly enclosure. When integrated together, with the single control card, the system is easy to transport and maintain.

CONCLUSION

The LANSCE-RM upgrade has leveraged robust and proven evolutionary electrostatic mod-anode switching technology which provides an excellent platform for high fidelity long pulse klystron operations. These designs show that modern planar vacuum tubes can be utilized to perform fast feedback and dynamic regulation of klystron beam parameters that help achieve a more stable RF drive characteristic. With this system design, both the on-deck and off-deck are of identical design and completely interchangeable. The planar triodes are driven with solid state components in a simple configuration. The overall assemblies are very small, about .75 cu foot for the complete deck assembly. These tubes are inexpensive and perform functions that cannot be accommodated by series strings of semiconductor switching arrays. These systems will fit in the existing klystron modulator tank with minimum interface requirements and provide a significantly higher efficiency while also regulating klystron beam current. In the LANSCE-RM upgrade, oil tank losses are reduced by ~12 kW which obviates the need of the oil to water heat exchanger and related oil pumping system. The oil pump and heat exchanger system will be removed from the oil tank providing additional reliability improvements. With the faster klystron rise and fall times, coupled with the lack of any switching delays, additional electrical efficiencies are also realized. The ability to adjust the individual klystron cathode current will minimize the head room required of the sector capacitor banks as the weakest klystron can be adjusted for more mod-anode voltage drive at a given bank voltage. A calculation of the utility savings indicates that once the LANSCE remediation is complete, a utility savings of ~ 2.5M$ per year can be realized. There are many klystron types that are switched via the mod-anode, this grid-clamp totem pole modulator topology offers many benefits and performance capabilities that still cannot be easily or economically achieved with solid state devices.