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PULSED KLYSTRONS WITH FEEDBACK CONTROLLED MOD-ANODE MODULATORS

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***Abstract*— This paper describes a fast rise and fall, totem-pole mod-anode modulators for klystron application. Details of these systems as recently installed [1] utilizing a beam switch tube "on-deck" and a planar triode "off-deck" in a grid-catch feedback regulated configuration will be provided. The grid-catch configuration regulates the klystron mod-anode voltage at a specified set-point during switching as well as providing a control mechanism that flat-top regulates the klystron beam current during the pulse. This flat-topped klystron beam current is maintained while the capacitor bank droops. In addition, we will review more modern on-deck designs using a high gain, high voltage planar triode as a regulating and switching element. These designs are being developed, tested, and implemented for the Los Alamos Neutron Science Center (LANSCE) accelerator refurbishment project, "LANSCE-R". An advantage of the planar triode is that the tube can be directly operated with solid state linear components and provides for a very compact design. The tubes are inexpensive compared to stacked semiconductor switching assemblies and also provide a linear control capability. Details of these designs are provided as well as operational and developmental results.**

INTRODUCTION

The design of the grid-catch, totem-pole klystron modulator system for the Indiana University Low Energy Neutron Source (LENS) accelerator and the Los Alamos LANSCE-R accelerator project are based on the initial designs from the Los Alamos Strategic Defense Initiative (SDI) Ground Test Accelerator (GTA) [2] program. The GTA design requirement was a low rep-rate modulator typically operating below a 6% duty with a 2 ms pulse width. However, the GTA design did not utilize a tailbiter or significant mod-anode voltage drive of the beam switch tube (BST). Therefore, the GTA system had a relatively slow risetime and an even longer fall time due the use of a 1 MΩ pull-down resistor to discharge the klystron mod-anode and deck capacitances at the end of the pulse. A GTA style modulator was initially implemented for the LENS accelerator [3] and the modulator switching characteristics can be noted in Figure 1. The klystron cathode current pulses are shown in channels 1 and 3 and have a 300 us rise time and an 800 us fall. The Indiana system was then upgraded in various stages to its' final design as shown in Figure 2. The mod-anode reference voltage for the klystron is determined by a high impedance voltage divider. When the on-deck is pulsed via fiber optics, it switches to the potential where the diode stack becomes forward biased. The diodes connect directly to a tetrode buffer amplifier assembly, which

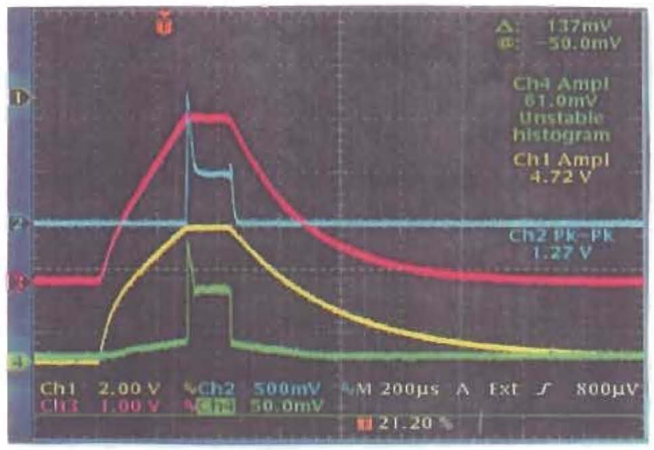

Fig. 1 Switching of a single ended modulator deck, Tr ~300 uS, TF ~800us

then drives the BST. The overall network acts like a cathode follower that regulates the klystron mod-anode to cathode voltage. To adjust the klystron beam current a low current (< 10 mA), 10 kV power supply is used to alter the reference potential of the divider. To provide a flat klystron beam current pulse as the cathode bank voltage droops, a capacitor (not shown) connected across the upper divider resistor provides passive compensation to the buffer tetrode amplifier.

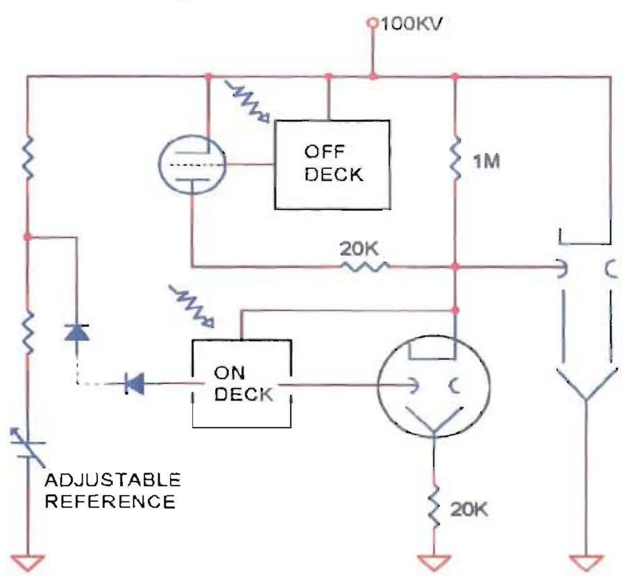

Fig. 2 Simplified block diagram of a totem-pole grid-catch modulator

I. INDIANA DESIGN CHANGES

To provide a faster system rise and fall time, changes were needed to the modulator deck assemblies. To improve the risetime, a higher voltage tetrode buffer amplifier plate supply was needed. Differences in tetrode plate voltage are also desired as one modulator drives 2 klystrons and another modulator drives a single klystron. For the same tetrode plate voltage, the 2 klystron modulator assembly would be slower due to the higher load capacitance to ground. To provide a faster fall time, a "tail-biter" was added to quickly discharge the klystron mod-anode and drive deck capacitances. A view of the tail-biter off-deck during assembly can is shown in Figure 3. The Y-810 planar triode is rated for 95 kV at 10 Amps and the off-deck is connected in a cascode configuration, a MOSFET in the cathode of the tube is utilized as the control switching element. The planar triode control grid is DC grounded. The zero bias minimizes grid dissipation but does not fully optimize overall switching performance. A view of the completed klystron modulator deck assembly showing the BST "on-deck" and the planar triode tail-biter (off-deck) can be noted in Figure 4.

Fig. 3 95 kV tail-biter assemblies with a Y-810 planar triode

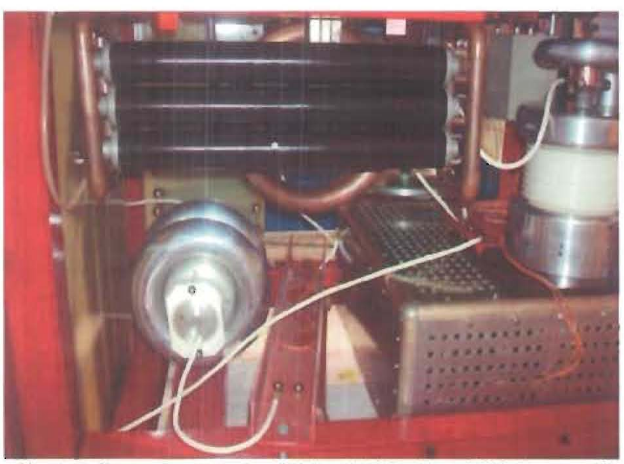

Fig. 4 Indiana planar triode tail-biter "off-deck" and BST "on-deck"

Other operational design improvements for the LENS accelerator include the installation of 100 kV self-healing capacitors for the klystron system capacitor bank. These capacitors have a good energy density, very long design life, and can be safely paralleled in direct subsets. An additional capacitor safety feature is the inclusion of multiple internal bleed resistors to self-discharge in an off-normal event. The LENS 24 uF, 100 kV self healing capacitor bank installation, in Figure 5, is the first installation of this type. These capacitors were developed and manufactured by General Atomics Electronics Systems (formerly Maxwell) in San Diego, California.

Fig. 5 LENS 24 uF, 100 kV self healing capacitor bank (~2 M width)

II. LENS OPERATIONAL RESULTS

The LENS upgrades provide improvements in rise time to ~30us with one klystron, ~70us with 2 klystrons and a fall time of ~100us. The flat-topped klystron cathode current (upper most trace) results from the increased slope of the mod-anode to cathode voltage, second trace. The flat-topped cathode current produces a more stable klystron amplifier RF gain characteristic. The klystron mod-anode current (bottom trace) is 20 mA peak during the pulse rise and fall, well within the capability of any mod-anode controlled klystron.

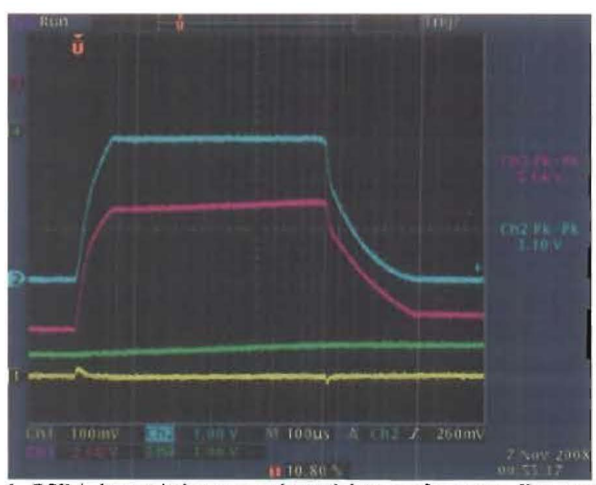

Fig. 6. BST / planar triode totem-pole modulator performance. Traces, top to bottom are the cathode current (10A/div), mod-anode voltage, cathode voltage (-90kV), and klystron mod-anode current (100 mA/div).

Klystron long pulse performance, shown in Figure 7, depicts 1 ms flat-top characteristics with good rise and fall. The single klystron modulator system (lowest trace) has a 30 us rise operating with a 32 A beam current at 90 kV.

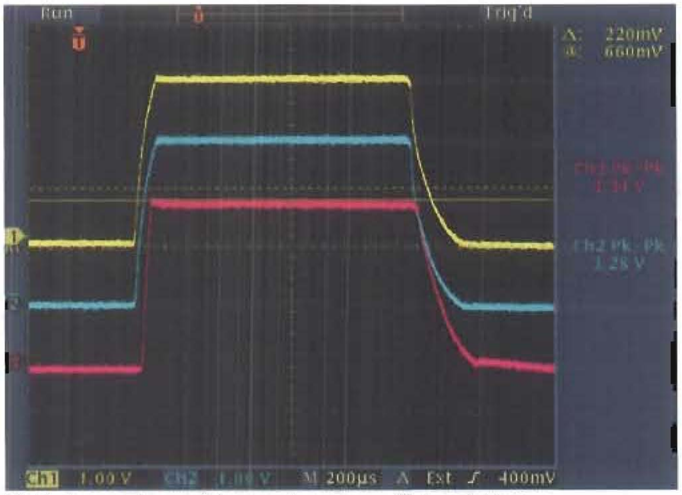

Fig 7. Long pulse modulator performance, ~32 A each klystron

III. LANSCE-R ACCELERATOR UPGRADE

Even faster klystron switching may be achieved with a slightly more aggressive klystron mod-anode drive parameter. This can be accommodated by the use of modern HV planar triodes. The LANSCE-R klystron modulator system, being jointly developed by LANL and Indiana, will use a higher current 20 A planar triode, the CPI / Eimac (Palo Alto, California) YU-847A shown in Figures 8 and 9.


Fig. 8 CPI / Eimac YU-847 cathode and grid connections

This planar triode has a very high gain, a mu of 1500, and is easily driven with low voltage solid state devices. In addition, linear feedback is obtained within a very small package, about .75 cu foot for the tube and complete deck assembly. A preliminary design and set-up of the LANSCE-R / Indiana system has been assembled as shown in Figure 10 using an older ceramic planar tube, the Y-846. However, the newer glass envelope tube is preferred as the tube internals can be examined, the glass is easier to clean, and has better vacuum / sealing characteristics.


Fig. 9 CPI / Eimac Y-847A plate connection


Fig. 10 On-deck preliminary assembly

The totem-pole grid catch modulator block diagram is shown in Figure 11. Both the on-deck and off-deck are configured nearly identically and will share a common MOSFET switching assembly. A slight positive grid bias will be used on these designs to enhance the triodes peak current switching capability. Modeling suggests klystron beam current rise and fall times of 40 us can be achieved. A fiber optic repeater accepts a single fiber optic command on / off signal to control both the on-deck and off-deck. The on-deck control signal is a pass-through where the off-deck is delayed slightly to prevent "shoot-through" at the end of the klystron beam pulse. The off-deck receives a short pulse of sufficient duration to discharge the deck and mod-anode capacitances. In the inter-pulse time, the 5 MΩ pull-down resistor ensures the klystron remains off. Power to the off-deck is derived from the klystron filament circuit and the on-deck requires a separate, but low power HV isolation transformer. Changes in the klystron beam current set point is accommodated via an adjustable power supply used to alter the voltage divider set point. The klystron mod-anode voltage and resulting beam current is clamped at the desired reference voltage where the diode string becomes forward biased. Bank voltage droop is capacitively coupled into the amplifier circuits maintaining a flat-topped klystron beam current for pulse widths exceeding 2 ms, as demonstrated on the GTA.

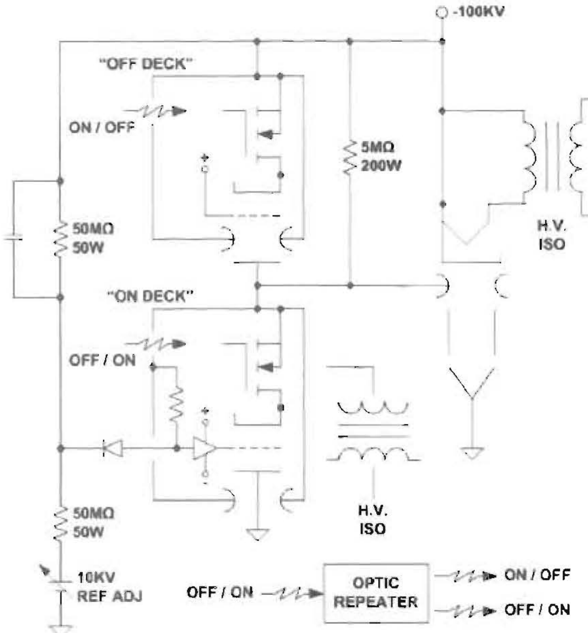

Fig. 11 Simplified diagram fast switching totem-pole grid-catch modulator

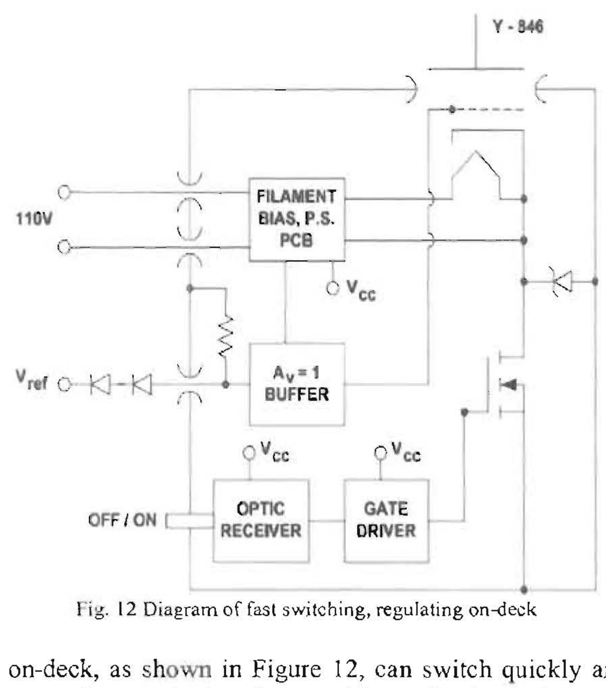

Fig. 12 Diagram of fast switching, regulating on-deck

The on-deck, as shown in Figure 12, can switch quickly and clamp at the required voltage with a simple, unity gain amplifier circuit. The high-z input buffer amplifier is required only to swing between the required positive grid drive voltage (~15V) and that required for tube cut-off (-150V). A zener diode across the MOSFET assures the cathode voltage, when cut-off, will not exceed that dictated by the rated grid to cathode voltage (200V). In the cut-off condition, the tube will self-bias to that required to maintain "0" current. In the event of a klystron with slight current leakage across the ceramic, the zener clamps that leakage current.

CONCLUSION

The LANSCE-R upgrade and Indiana designs have leveraged robust and proven evolutionary technology to provide 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. In addition, modern high voltage, high gain, planar triodes can be used for both the on-deck and off-deck switching and regulating functions. For linear regulation in the on-deck, planar triodes can be driven directly with solid state components. With the modern high gain planar triode, 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. Control is simple with proven results. 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-R upgrade, oil tank losses are reduced by 10 kW which obviates the need of the oil to water heat exchanger and related oil pumping system. This compact and fast feedback topology is extremely cost effective and energy efficient.

ACKNOWLEDGEMENTS

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