

# SOLID-STATE SWITCH MODULATOR DECK FOR THE MIT-BATES S BAND TRANSMITTER

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## *Abstract*

This paper describes how to modernize and simplify the design of a pulse amplitude modulator for klystron power amplifiers. The existing modulator design uses two parallel-connected Litton Injectron™ Beam Switch Tubes (BSTs) in series with the cathode of an RF amplifier klystron. A vacuum-tube based modulator sends high-voltage pulses to the modulating anodes of the BSTs to produce a current pulse through the klystron. In recent years, the vacuum-tube circuitry that drives the BSTs and klystron has become difficult and expensive to maintain. The new design replaces this circuitry with a single switch, comprising multiple series-connected, high-voltage, high-current Insulated-Gate-Bipolar Transistors (IGBTs). Figure 1 illustrates the basic design of the solid-state modulator deck.

The prototype of this system along with its control and feedback circuitry has been built at the Bates Linear Accelerator Center and has been successfully tested in one of the Bates accelerator RF transmitters. The new cathode switching design will not only replace obsolete and failing technology but will also significantly improve the reliability and performance of the accelerator and the RF transmitters.

## 1. INTRODUCTION

The MIT-Bates linear electron accelerator uses the output of six S-Band RF transmitters to produce the high-level electric fields that accelerate the beam. Each of these transmitters contains two klystron power amplifiers. The modulator in use today uses two parallel-connected Litton Injectron™ Beam Switch Tubes (BSTs) in series with the cathode of each klystron. A vacuum-tube based modulator sends high-voltage pulses to the modulating anodes of the BSTs to produce a current pulse through the klystron. In recent years, the vacuum-tube circuitry used in the present system to drive the BSTs and the klystron has proven difficult and expensive to maintain. As part of the MIT-Bates upgrade project, a new design has been created to replace this old and obsolete technology.

## 2. SOLID-STATE SWITCH

At the heart of the new modulator design is the 17.5 kV 100 Amp Solid-State Switch (SSS). In the spring of 1997, MIT Bates Linear Accelerator Center awarded a contract for a prototype 20 kV, 100-Ampere solid state switch to Diversified Technologies Inc. of Bedford MA.

This switch utilized the core elements of their commercial unit, the HVPM 20-150.

The switch itself consists of 8 Insulated Gate Bipolar Transistor (IGBT) modules, connected in series, and a high-frequency inverter power source for the gate drive circuitry, designed to be compatible with immersion in insulating oil. Each switch module contains four series-connected IGBTs (actually two dual-IGBT assemblies), and their associated control, over-voltage protection and diagnostic circuitry. Each IGBT is rated at 1200 V and 100 A continuous. The overall switch comprises 32 IGBTs in series, with a total voltage rating of 38 kV, shunted by over-voltage clamping which begins to conduct at a voltage of 22 kV, utilizing DTI's patented design. The eight switch modules and the associated switch power supply were each mounted on aluminum heat sinks, approximately 7" x 15". These nine component modules were integrated into an insulating framework, and installed in the solid-state switch deck.

## 3. SOLID STATE DECK

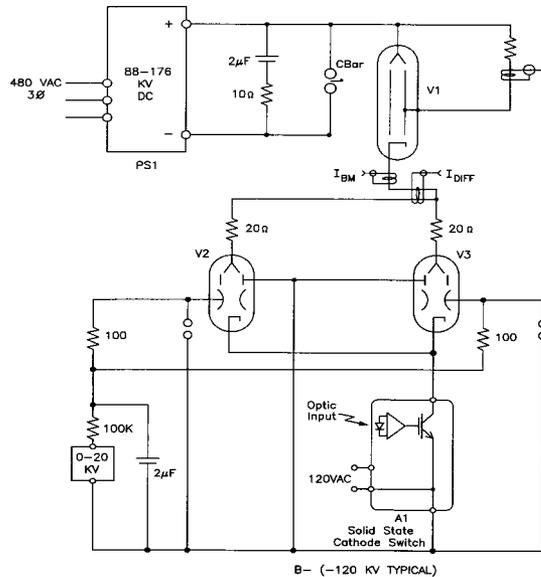


Figure 1: Basic Diagram of the Solid-State Deck

The purpose of the modulator is to send pulses of regulated current, up to 100 Amps, through the klystron power amplifier. When timed correctly, the klystron input RF power is amplified and injected into the beam line to accelerate the beam. The current pulses must have very quick rise and fall times (less than 1 µs) and must be very stable during the flattop portion of the pulse. The present design accomplishes this by sending pulses of high-voltage

(up to 15kV) to the mod-anode of the BSTs. The new design accomplishes the same thing with a constant precision DC high voltage (.001% ripple, .001% regulation) applied to the mod-anodes and by the use of the SSS in series with the cathodes of the BSTs (see Fig. 1). With the switch in the "open" condition, and with the mod-anode power supply at a nominal level, high voltage (up to 170kV) is applied across the klystron, BSTs, and the SSS connected in series. The only current flowing through the klystron in these conditions is the SSS leakage current (less than 1mA). In this situation, the cathodes of the BSTs assume the voltage, relative to the mod-anode, necessary to regulate this small current. Depending on the individual BST, this voltage could even be a small amount more positive than the mod-anode. The solid-state cathode switch is closed in response to fiber-optically-coupled pulses of light. When the switch closes, the current through the klystron rises (in less than 1 $\mu$ s) to the level set by the mod-anode power supply. The switch stays closed for a time that is set by the trigger control circuitry (from 1-50 $\mu$ s) and then opens again. When the switch opens, the current falls back to the leakage level in less than 1 $\mu$ s. This process can take place at various pulse current levels (up to 100 Amps), various widths (up to 50 $\mu$ s) and at various pulse repetition rates (up to 600 Hz.). The klystron current can be increased or decreased by increasing or decreasing the mod-anode power supply output voltage.

The peripheral equipment on the solid-state deck includes the mod-anode power supply, the dual filament power supply, and the dual solenoid supply. These power supplies are all necessary to run the BSTs.

The mod-anode power supply is a positive-output 300-Watt high-voltage power supply that is adjustable to 20 kV. This power supply, manufactured by Bertan Associates, is an extremely precise supply. The ripple and regulation specifications are both 0.001%. This amount of precision is necessary to regulate the klystron current without any noticeable pulse to pulse, phase, or amplitude jitter (the phase-pushing factor of the klystron is approximately 10 degrees per 1 percent beam voltage change, or per 1.5 percent current change). Shunting the output of the power supply is a 100,000 $\Omega$  resistor and a 30 kV, 2 $\mu$ F capacitor that together form a low-pass filter to further attenuate any ripple on the mod-anode voltage.

The dual-filament power supply provides AC power to the filaments of each BST. Each BST filament requires 10 Amps at 12 volts to ensure that the tubes are never temperature limited. The dual-filament supply consists of two transformers. The first transformer is a SOLA AC regulator. This device takes the AC power that is floating at high voltage and converts it to a regulated 120 VAC. The second transformer is a 500 VA multi-tapped, step-down, isolation transformer. This transformer provides isolation for up to 30kV, which is necessary because when the SSS opens, the cathodes of the BSTs float at a voltage near the mod-anode power supply output. The secondary of the isolation transformer is tapped at 10.5, 11, 12 (nominal),

13, 14, 16, and 18 VAC. The taps below the 12V nominal tap are provided to run the filaments cooler in order to prolong the tube's lifetime. The taps above 12V are provided for when the tube begins to deteriorate and the filaments have to be run hotter to produce the desired klystron current. The filaments are connected to the supply in parallel and can be switched to a different tap by the use of a rotary switch.

The dual solenoid power supply provides regulated DC current (8 Amps nominal) to the solenoids of each BST.

## 4. PROTECTION

Along with the basic building blocks that make up the solid-state switch deck, there are many devices that are integral to the reliability, susceptibility, and durability of the design. First, all AC power circuits are protected with correctly rated circuit breakers and varistors to provide short circuit and transient protection. The SOLA AC regulator of the filament power supply also provides transient and inrush current protection. The mod-anode power supply is protected from arcs that conceivably could occur from the BST collectors to a mod-anode of one of the BSTs. The first line of defense is a 17kV arc-gap connected between the mod-anode of each BST and the negative high-voltage rail. These gaps ensure that the mod-anode power supply will never be destroyed by such a destructive occurrence. However, these arc-gaps take a small amount of time before they fire. They also work more reliably when the voltage across them ramps up slowly. The 2• F capacitor across the output of the mod-anode power supply provides the means to slow down the voltage transient and allows the arc-gaps to work more effectively. The capacitor is rated for 30kV and 5,000 Amps of transient current for this purpose. The arc-gaps also provide protection to the mod-anode of the BSTs, the filament power supply, and the SSS. If the mod-anode power supply output rises too high, all these circuits could be over-voltaged if not for the arc-gaps.

Another arc protection strategy uses the shield of the BSTs themselves. The inner geometry of the BST is such that the collector of the BST is most likely to arc to the shield electrode. On the solid-state switch deck, the shield is tied directly to B-, the reference of the deck. In this way, nearly every arc will go straight to the reference. The cathodes of the BSTs and the SSS are also protected from arcs by two components. A wire wrapped tube is connected between the cathodes of the BSTs and the SSS. In the event of an arc to the cathode, which would damage the SSS, this small inductance will limit the current and hold a portion of the voltage during the arc. The second stage of this arc protection is a very large metal-oxide varistor (MOV) across the entire SSS, which provides a great deal of transient protection. The third stage is the protection circuitry in the SSS itself. With all these safeguard

strategies, the BSTs, the peripheral supplies, and the SSS are all protected.

## 5. INSTRUMENTATION

Signals from the SSS, the mod-anode power supply, the solenoid power supply, and the filament power supply are all transmitted from the deck, which is floating at high voltage, to the ground level instrumentation via fiber optic links.

The SSS sends a fiber optic signal from each IGBT module that indicates whether or not the IGBT module is open or closed. The mod-anode power supply sends back a 20kHz to 100kHz frequency signal that indicates the level of the power supply output. This signal is converted to a voltage and fed to a digital meter that displays the mod-anode power supply output in kilovolts. The solenoid power supply sends back a 0Hz to 100kHz frequency signal that indicates the current through the solenoids. This signal is converted to a voltage and fed to another digital meter that displays the solenoid current in Amps. The AC current to each BST filament runs through a small transformer. Across the secondary of the transformer is a resistor that is sized so that the output voltage of the transformer, when rectified, is 9 VDC when 10 Amps AC is flowing through the filament. This voltage is converted to a frequency that is sent to ground via a fiber optic cable. This frequency is converted back to a voltage and the current through each filament, in Amps, is displayed on a digital meter. In this way, all the necessary information from the solid-state deck is conveyed to ground level and displayed in the correct units.

## 5. CONTROL

The SSS is turned on and off by a gate signal that is converted to a fiber optic pulse. This pulse is transmitted to the SSS via a fiber optic cable and the switch is closed as long as there is light at the end of the cable. The width and frequency of the gating signal determines the width and frequency of the current pulses through the klystron. Pulse current transformers are used to monitor the collector, cathode, and body current of the klystron. The collector and cathode current can be viewed with an oscilloscope. In the event of a klystron arc, the body current transformer will produce a pulse and the SSS will be latched open. There is also a ground current pulse transformer that monitors all currents through ground. This transformer will also produce a pulse during a klystron arc but this pulse will fire the crowbar of the transmitter, thereby de-energizing the main high-voltage power supply and the energy-storing capacitor banks. It is undesirable to fire the crowbar in the event of a klystron arc. Therefore, any signal from the ground current transformer is integrated so that it does not reach its crowbar trigger level for 10  $\mu$ s. In this way a klystron arc may be extinguished without firing the crowbar, but any other fault through the ground path will fire the crowbar after 10 $\mu$ s.

There is also a pulse current transformer that monitors the amount of current difference between the two BSTs. If this current becomes too large, as in a BST arc, the crowbar is fired. With any of these crowbar events, the switch is latched in the open position. A 0-5 VDC voltage that is converted to a 20kHz to 100 kHz fiber optic signal controls the mod-anode power supply. This control signal must be as stable as the power supply in order to keep the ripple and stability percentages low.

## 6. PROTOTYPE PERFORMANCE

During the week of December 1, 1997 the prototype solid-state-switch-deck was installed into the oil tank of one of the Bates transmitters after having been extensively tested in air. On December 3, the deck was turned on and began to pulse. That day the transmitter was processed to a klystron current of 60 Amps with a pulse width of 20 $\mu$ s at 60 Hz. The system ran for 3 hours and experienced 3 major crowbars as part of processing and remained undamaged. The next day the system was processed to 80 Amps with a width of 22  $\mu$ s and with a pulse repetition rate of 600 Hz. The system ran at this level for 24 hours with no major failures. Figure 2 shows an oscilloscope picture of the klystron pulse current at 74 Amps at a pulse repetition rate of 600 Hz. Trace #1 is the trigger input to the control circuitry and trace #2 is the signal from the klystron collector current transformer, which has an output ratio of 0.1 volts per Amp.

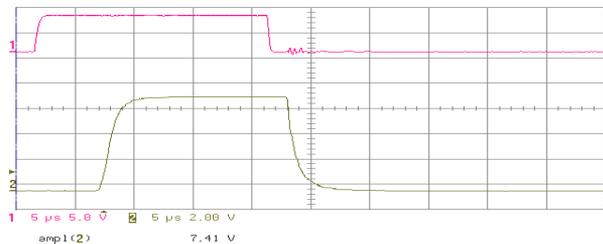


Figure 2: Klystron Current Pulse

This very successful test proved the functionality of the solid-state switch deck. The full-power 24 hour heat run did not reveal any weaknesses and there were no reliability problems associated with this test.

## 8. CONCLUSION

The new solid-state deck at the Bates Linear Accelerator is a vast improvement over the old modulator designs of the past. The new design uses less power, is much smaller, uses fewer components, is much more reliable, and is easier to control. The system has been thoroughly tested in the air and in the transmitters at Bates and has been proven to work successfully. This new modulator design will greatly increase not only the efficiency of the accelerator overall, but will improve the performance as well.