STATUS OF THE SOLID-STATE SWITCH PULSE MODULATOR FOR THE MIT-BATES S-BAND TRANSMITTER

A. Zolfaghari, R. Campbell, A. Hawkins, W. North, L. Solheim, Defa Wang, C. Wolcott,
MIT-Bates Laboratory, Middleton, MA 01949, USA

Abstract

This paper describes the status of the solid-state cathode-switching pulse modulator upgrade project at the MIT Bates Linear Accelerator. First, a prototype modulator system was built and tested successfully in one of the Bates RF transmitters. Then, last year, the emphasis was on a full-scale implementation of the concept that would eventually extend to all twelve of the high-power klystron RF power amplifiers. A new modulator design has been completed, including replacing the water-cooling of the Litton Beam Switch Tubes (BSTs) with oil-cooling; a compact, current-regulated power supply for the BST focus solenoids; a highly-precise, low-ripple power supply for the BST modulating anodes; an adjustable, inrush-current-limited DC filament supply for the BSTs; and an upgraded solid-state switch that uses Insulated-Gate Bipolar Transistors (IGBTs) rated at 1700V instead of 1200V (reducing the switch-module count from seven to five) with improved (third-generation) gate-drive circuitry. Fourteen full sets of the solid-state switches have been manufactured and delivered, and construction of six switch-tube decks has been completed.

Two transmitters have been upgraded with the new system, which includes the modulators, instrumentation, control circuitry, and oil cooling. A large improvement of the RF system output has been observed, and the reliability of the RF transmitters is expected to be greatly enhanced.

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 older modulator 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 current pulses through the klystron. In recent years, the vacuum-tube circuitry used in the old system to drive the BSTs has proven difficult and expensive to maintain. As part of the upgrade project, a new design has been created to replace this 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 20kV, 100A solid state switch to Diversified Technologies Inc.(DTI) of Bedford MA. After extensive testing of the prototype, a final 17.5kV, 100A design was engineered and built for all six transmitters. The switch consists of 4 Insulated Gate Bipolar Transistor (IGBT) modules, connected in series, and a high-frequency inverter power source for the gate drive circuitry, all designed to be compatible with immersion in insulating oil. Each switch module contains four series-connected IGBTs (two dual-IGBT assemblies), control, over-voltage protection, and diagnostic circuitry. Each IGBT is rated at 1700V and 100A continuous. The overall switch comprises 20 IGBTs in series, with a total voltage rating of 34kV, shunted by over-voltage clamping which begins to conduct at a voltage of 20kV, utilizing DTI's patented design. The four switch modules and the associated switch power supply are each mounted on aluminium heat sinks, approximately 7" x 15". These five component modules are integrated into an insulating framework, and installed in the solid-state switch deck.

3 MODULATOR DECK

The purpose of the modulator is to gate pulses of regulated current, up to 100A, through the klystron power amplifier. Synchronized pulses of klystron input RF power are amplified and injected into the beam line to accelerate the beam. The current pulses must have rapid rise and fall times (less than 1μs) and must be non-variant during the flattop portion of the pulse. The old modulator accomplishes this by sending pulses of high-voltage (up to 15kV) to the mod-anodes of the BSTs. The new design achieves the same result with a constant precision DC high voltage (0.001% ripple, 0.001% 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.

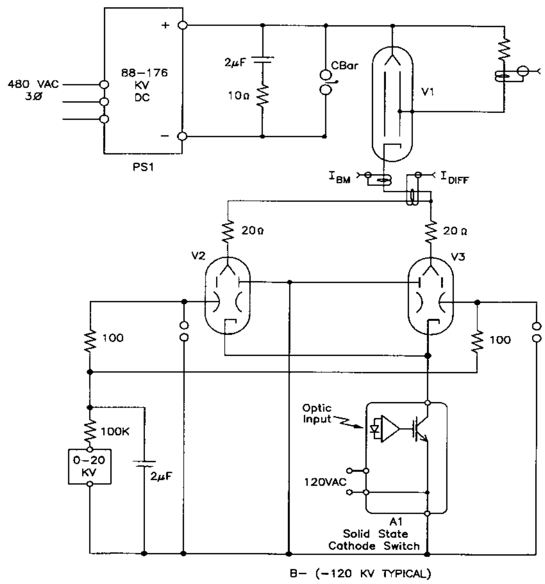

Figure 1: Basic Diagram of the Solid-State Deck

Depending on the individual BST, this voltage could even be somewhat more positive than the mod-anode. The solid-state cathode switch is closed in response to a photonic gate signal. When the switch closes, the current through the klystron rises (in less than 1μs) to the regulation level of the BSTs, which is set by the mod-anode power supply. The switch stays closed for the duration of the photonic gate signal (from 1-50μs) and then opens. When the switch opens, the current falls back to the leakage level in less than 1μs. This process can take place at various pulse current levels (up to 100As), various widths (up to 50μs) and at various pulse repetition rates (up to 2000Hz.). 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 for the two BSTs. The mod-anode power supply is a positive-output 300-Watt high-voltage power supply that is adjustable to 20 kV, manufactured by Bertan Associates. The ripple and regulation specifications are both 0.001%. The unit is powered by a 500VA SOLA ferro-resonant AC regulator that regulates the input AC voltage to 1%. This precision is necessary to regulate the klystron current without any noticeable pulse-to-pulse, RF output phase, or amplitude jitter (the phase-pushing factor of the klystron is approximately 10° per 1% beam voltage change, or per 1.5 % current change). Shunting the output of the power supply is a 100,000Ω resistor and a 30kV, 2μF capacitor in series to form a low-pass filter, further attenuating ripple on the mod-anode voltage.

Experiments with AC filament excitation of the BSTs showed that it produced excessive phase modulation of the klystron RF output signal at a 60Hz rate. Accordingly, a dual-output DC filament supply was designed and built, producing nominal 12V, 10A outputs, individually adjustable from 11.25 to 14.25VDC, in 0.25V increments, allowing optimization of filament input power. AC input to the supply is from a 500 VA step-down transformer with 30kV isolation between secondary and primary/core, to accommodate the 17kV pulse voltage on the BST cathodes. Primary power to the transformer is from a 500VA SOLA ferr-resonant regulator, which maintains 1% output voltage stability and limits cold-filament inrush current.

The dual-solenoid DC power supply, designed and built by MODPower, Inc. of Taunton, MA, uses a high-frequency boost-type regulator to produce 8A nominal current to two series-connected BST focus solenoids.

4 PROTECTION

In addition to the solid-state switch deck, there are many features that are integral to the reliability, 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 that provides power to the filament power supply and the Mod-anode 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. 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 2μF capacitor across the output of the mod-anode power supply, rated for 30 kV and 5000A transient current slows down the voltage transient and allows the arc-gaps to work more effectively. The arc-gaps also provide protection to the mod-anode of the BSTs, the filament power supply, and the SSS by limiting the voltage to these components.

Another arc protection strategy uses the shield of the BSTs themselves. The inner geometry of the BST is such that the collector 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, diverting arc current directly to the reference. The SSS is also protected by a center-tapped inductor connected between BST cathodes and the SSS with a high-current 18kV metal-oxide varistor (MOV) connected between center-tap and B^-. The SSS contains its own inherent protection circuitry as well. With these safeguard strategies, the BSTs, the peripheral supplies, and the SSS are all well protected.

5 INSTRUMENTATION

Signals from the SSS and the mod-anode power supply are transmitted from the deck, which is floating at high voltage, to the ground level circuitry via fiber optic cables. The SSS sends two photonic signals from each IGBT module. One signal indicates whether or not the IGBT module is open or closed and the other indicates the status of the module's power supply. The mod-anode power supply sends back two 20kHz to 100kHz photonic frequency signals that indicate the voltage and current outputs of the power supply. These signals are converted to voltages and fed to digital meters that display the mod-anode power supply voltage and current outputs in kV and mA.

6 CONTROL

The SSS is turned on and off by gate signals that are converted to photonic pulses. There, pulses are transmitted to the SSS via fiber optic cables. The switch closes when 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 and body current of the klystron, which are inputs to the control circuitry and can also be viewed with an oscilloscope. If collector current is detected when the modulator is not being gated-on (a wide or spurious pulse), the transmitter crowbar is fired, which de-energizes the system. In the event of a klystron arc, the body current transformer will produce a pulse and the SSS will be opened within 2μs, thereby extinguishing the arc. The switch will only be opened for that particular pulse so that only one pulse will be lost and the transmitter may keep operating without interrupting the accelerator beam. This feature is also helpful if a klystron needs processing. There is also a ground current pulse transformer that monitors all currents through ground. This transformer will produce a pulse during a klystron arc which will fire the crowbar of the transmitter. Because it is undesirable to fire the crowbar in the event of a klystron arc, any signal from the ground current transformer is integrated so that it does not reach its crowbar trigger level for 10μs. 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 10μs.

There is also a pulse current transformer that monitors the amount of current difference between the two BST outputs. If this current becomes too large, as in a BST arc, the crowbar is fired. For any of these crowbar events, the switch is latched in the open position. A 20kHz to 100kHz photonic frequency signal controls the mod-anode power supply. This control signal must be as stable as the power supply in order to keep the voltage fluctuations low.

7 MODULATOR 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. After months of testing in the transmitter, a new design was engineered and two new decks were built and installed into a transmitter. After the new design was proven, Transmitters #3 and #4 were fully upgraded with new modulators and control systems and began to deliver real accelerator beam in January of 2000. Since then the new transmitter systems have proven to be very reliable and have shown enhanced RF performance. The RF output phase deviation is less than 0.2^o. The transmitters have delivered beam for the commissioning of the Bates South Hall Storage Ring but their greatest achievement to date is contributing to the first 1GeV beam run in the Laboratory's history. Transmitter #3 ran the highest power of all the transmitters while sending 20μs, 98A peak current pulses through each klystron at a PRF of 600Hz.

8 CONCLUSION

The new solid-state pulse modulator 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 and two transmitters at Bates are successfully accelerating beam using the new modulators and control systems. During the year 2000 two more transmitters will be upgraded and by the end of 2001 all six RF transmitters will have been upgraded with the new systems. The modulator design greatly increases not only the efficiency and reliability of the accelerator, but improves the performance as well, allowing the Laboratory to run experiments at higher energies.