

## THYRATRON REPLACEMENT

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### Abstract

Semiconductor thyristors have long been used as a replacement for thyratrons in low power or long pulse RF systems. To date, however, such thyristor assemblies have not demonstrated the reliability needed for installation in short pulse, high peak power RF stations used with many pulsed electron accelerators. The fast rising current in a thyristor tends to be carried in a small region, rather than across the whole device, and this localized current concentration can cause a short circuit failure. An alternate solid-state device, the insulated-gate bipolar transistor (IGBT), can readily operate at the speed needed for the accelerator, but commercial IGBTs cannot handle the voltage and current required. It is, however, possible to assemble these devices in arrays to reach the required performance levels without sacrificing their inherent speed. Diversified Technologies, Inc. (DTI) has patented and refined the technology required to build these arrays of series-parallel connected switches. DTI is currently developing an affordable, reliable, form-fit-function replacement for the klystron modulator thyratrons at SLAC capable of pulsing at 360 kV, 420 A, 6μs, and 120 Hz.

### BACKGROUND

The Stanford Linear Collider (SLC) has used thyratrons in its klystron modulators since its inception in 1963. While the thyratrons function, they need replacement every 10,000 hours at a cost of \$13,000 each, plus labor. Furthermore, periodic maintenance is required to adjust their reservoir heater voltage over the thyatron lifetime. As the Stanford Linear Accelerator Center (SLAC) continues to run its accelerator over the next two decades, replacing the thyratrons with a solid-state switch that would last 25 years or more, and does not need maintenance, would provide significant savings – both in the avoided cost of thyratrons as well as the labor in replacing and adjusting them.

SLAC is presently funding the development of a solid-state switch, based on thyristor technology to replace the thyratrons (Figure 1), meeting the requirements of existing klystron modulators (Table 1). The difficulty is that a fast rising current in a thyristor tends to be carried in a small region, rather than across the whole device, and this localized current concentration can cause a short circuit failure.

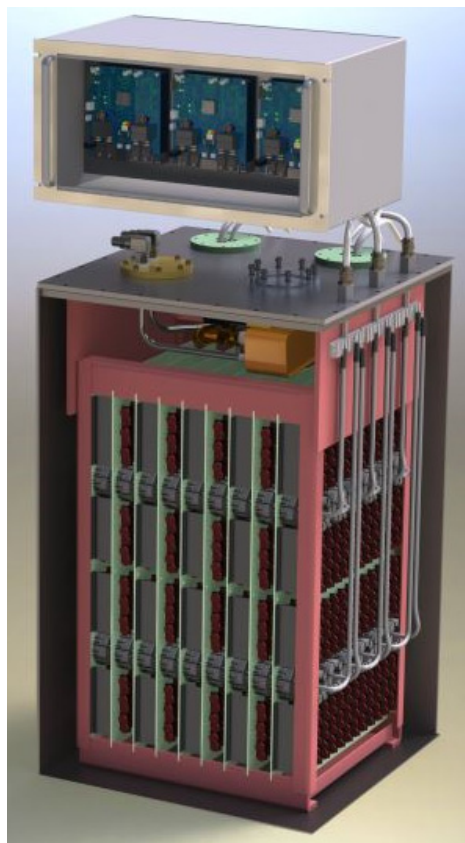


Figure 1: DTI solid-state replacement for the L-4888 thyatron used at SLAC. The switch, which operates at 48 kV and 6.3 kA, fits in the same location as the legacy thyatron assembly.

Table 1: ESS Klystron Modulator Requirements

Specification	
Voltage	48 kV
Current	6.3 kA
Pulse Width	6 μs
Risetime	1 μs, 10 A/μs
Frequency	120 Hz

### DESIGN

An alternate solid-state device, the insulated-gate bipolar transistor (IGBT), can readily operate at the speed needed for the accelerator, but commercial IGBTs cannot handle the voltage and current required. It is, however, possible to assemble these devices in arrays to reach the required performance levels without sacrificing their inherent speed. Diversified Technologies, Inc. (DTI) has patented and refined the technology required to build these arrays of series-parallel connected switches. DTI has shipped more than 500 systems leveraging this tech-

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nology, which have been operating in facilities around the world for many years.

In the initial phase of this project, DTI evaluated a number of IGBT switching devices, and selected the one with high current capability, short-circuit tolerance, and lowest cost. We verified that the temperature of this IGBT in operation will be low, giving high reliability. We also tested a series array of 60 devices with the number of faults that they would see in 20 years of operation; there was no sign of damage. We built and tested a  $10 \times 10$  array of IGBTs (Figure 2), which demonstrated operation in both series and parallel, with peak-to-peak jitter less than 1.5 ns. DTI performed an initial design of the switch assembly, showing that it fits in the modulator cabinet at SLAC. These switches will be delivered to SLAC, and their performance and reliability will be demonstrated in a SLC modulator.

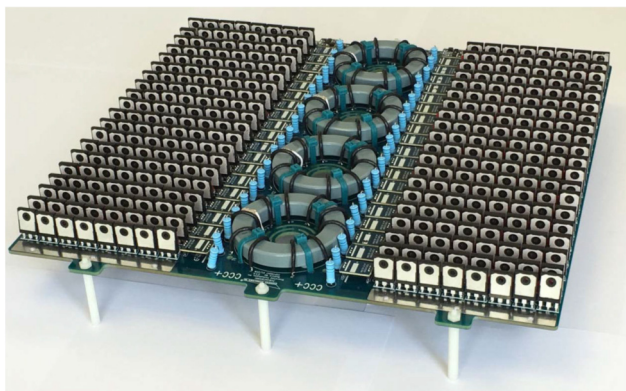


Figure 2: 8 kV, 3.2 kA switch plate. Each plate uses 20 devices in series by 16 devices in parallel.

## MOTIVATION

The market for thyratrons is in decline. As newer solid-state modulators are deployed, and older thyatron systems are taken out of service, the demand for thyratrons has diminished significantly. In response, several vendors have either gone out of business or stopped manufacturing thyratrons, further diminishing their availability. It is not clear how long the supply of thyratrons for these legacy systems will continue, making a solid-state thyatron replacement critical for their continued operation and support.

For this and other reasons, the thyratrons in many klystron modulators represent a major expense in operation – not only from the increasing cost of replacement, but from the labor involved both in such annual replacement and in the need to adjust them for proper operation during their relatively short life.

Most of these systems, including commercial medical accelerators, were designed decades ago, before solid-state switches were available. Even today, the cost of transitioning from thyratrons and pulse-forming networks to solid-state modulators remains prohibitive for many of these systems, despite the declining availability of thyratrons. Consequently, DTI anticipates a wide range of benefits from the development of a cost-effective, drop-in

replacement for the thyratrons in operation in commercial and scientific systems around the world.

## MECHANICAL DESIGN

For this effort to be practical and cost-effective, the thyatron replacement switch must readily fit in the existing cabinet with minimum modifications required for its installation. The volume available for the new switch is that of the existing thyatron chassis which includes the thyatron and heater supplies. Applying this 17" x 17" x 37" volume to the new switch with 2080 devices, the volume per device would be 5.1 in<sup>3</sup>. This means that the switch will need to be very tightly packed. There is certainly room for the devices themselves, but providing the required cooling and voltage standoff (preferably with air) presents a challenge.

## CURRENT LIMITS

The peak current requirement is large, which is not an issue for a thyatron, but does represent a challenge for semiconductor devices. To minimize the size and cost of the modulator, each IGBT should carry the maximum current possible. The IGBT chosen will have the highest current possible consistent with the risetime. The trade-off is that higher current devices have a longer risetimes.

Another limit to the current is the gate voltage; this should be as high as possible, consistent with reliability. The gate voltage also needs to have a fast risetime to minimize the switching losses.

The current rate-of-rise in an IGBT is limited mainly by the inductance in the emitter lead of the device. As  $dI/dt$  is increased, the inductive voltage drop on the emitter lead increases, reducing the gate voltage on the device itself. This raises the conduction voltage drop, increasing the power dissipated in the device. Higher power dissipation raises the device temperature, which in turn limits device reliability. Therefore, low inductance in the emitter lead is required for both speed and reliability.

Once the device was selected, 60 devices were connected in series and tested to demonstrate series operation and ruggedness to arcs at a current of 250 A. The switch has more devices in series than the minimum required, so multiple devices can fail short without affecting the switch operation. The switch has monitors that measure the number of devices that have failed, so that maintenance can be scheduled as necessary. These monitors are voltage dividers, made with the blue resistors next to the toroids.

To determine the current sharing, it is not feasible to make direct measurements, since there are 320 devices in a plate. Instead, we took thermal pictures of the switch after operation (Figure 3).

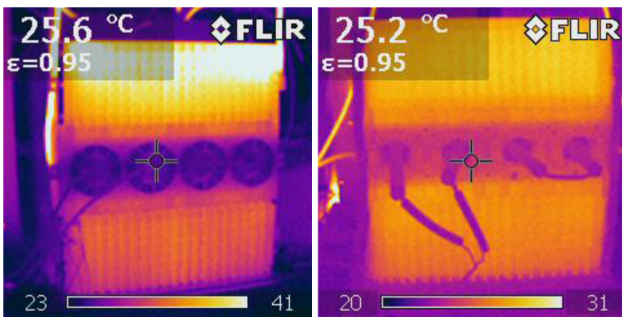


Figure 3: Thermal image of switch plate operating for 10 minutes. Left shows poor current sharing; right shows improved sharing (note scale).

### TEST RESULTS

DTI built and checked the twelve circuit boards needed for a modulator. The tests were:

- Resistive load, inductance corresponding to normal operation. This test demonstrated that the voltages share evenly in a series stack. It also showed that the current rises to its peak value in under 2  $\mu\text{s}$  (Figure 4).
- Arc, inductance corresponding to a klystron arc. We performed 300 tests with the switch stack, which corresponds to the number of klystron arcs the switch would experience in 20 years of operation. Based on other DTI work, the IGBTs are expected to survive many more arcs; our IGBT switches are routinely used for klystron conditioning.
- Arc, inductance corresponding to a cable short. There were 10 tests for the switch stack. This is more than the number of cable shorts the switch would see in 20 years of operation.

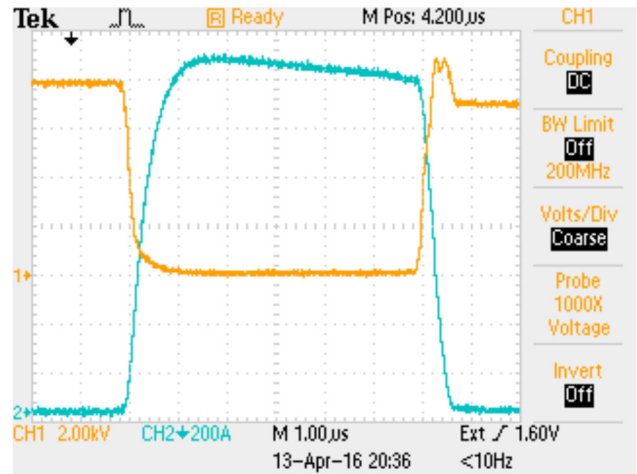


Figure 4: Plate test at 8 kV (yellow, 2 kV/div), 1.8 kA (blue, 200 A/div).

### FUTURE PLANS

DTI will continue testing candidate devices and drives while being mindful of final cost. We estimate that the DTI switch (as presently designed) will provide more than 20X the lifetime of a thyatron, for approximately three times the price, resulting in greatly reduced lifecycle costs – especially after the hours required for thyatron adjustment and replacement are included.

Following successful development, fabrication, and demonstration of the thyatron replacement switches for SLAC, DTI plans to make the switch assembly commercially available, targeting other legacy systems still using thyatron pulse-forming network pulse modulators.

### ACKNOWLEDGEMENTS

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