# A NEW CROWBAR DRIVER FOR THE MIT BATES LINEAR ACCELERATOR HIGH-POWER RF SOURCES

A. Zolfaghari, R. Campbell, A. Hawkins, P. MacGibbon, W. North, L. Solheim, Defa Wang,
MIT-Bates

## *Abstract*

The high-power S-band klystron power amplifiers used in the MIT-Bates linear accelerator derive their pulsed beam-current input from a 150 kVDC power supply and a shunt-connected energy storage capacitor bank. The klystrons are protected from damage which could result from capacitor discharge and power-supply short-circuit current into an internal electron gun arc by a combination of series current-limiting resistance and a shunt-connected Electronic Crowbar, an air-insulated triggered spark-gap. A trigger pulse of 200 kV is derived from the secondary of a step-up pulse-transformer, requiring a 15 kV-peak primary voltage. The existing driver employs an obsolescent dual-triode as a blocking oscillator and an equally obsolescent hydrogen thyratron as the capacitor-discharge switch to produce the 15 kV pulse. The newly developed driver circuit uses an SCR input stage and a triggered vacuum gap output discharge switch. The input is connectivity fail-safe. If the input coaxial cable is severed or removed the crowbar will either fire or the SCR charging voltage will not recover, opening the transmitter interlock. Successful testing of the new driver with the crowbar has been completed, and it has been installed in one of the transmitters.

## 1 INTRODUCTION

The MIT-Bates accelerator obtains its RF power from six transmitters, each with two 6-MW peak-power klystrons. Recent modernization of the klystron pulse modulators replaced obsolescent vacuum tube drive circuitry with high-voltage, solid-state electronic switches using series-connected IGBTs (Insulated Gate Bipolar Transistors). Not all vacuum tubes or VEDs (Vacuum Electron Devices) have been eliminated. The operating high-voltage DC can be greater than 150 kV. The original design uses two parallel-connected Litton L-5097 Injectron Beam Switch tubes in series with the cathode of each klystron, capable of producing a 130 kV peak pulse voltage at 100 Amperes peak beam current, for pulse durations exceeding 20 uS at pulse rates of up to 1000 Hz. The DC input is buffered by a shunt-connected 2 uF capacitor bank which stores the electrical charge from which the total of 200 Amperes peak pulse current is obtained. This capacitor bank also stores sufficient energy to be potentially damaging to both the klystron and the beam switch tube in the event of simultaneous internal arcs, often referred to as "shoot-through" conditions. Such events result in short-circuits on the high voltage system. The fault current is limited, by a total of 30 Ohms resistance, in series with the capacitor bank, to 6000 Amperes maximum. Attempts to quantify the internal tube damage caused by discharges of such magnitude have been inconclusive at best, Nevertheless, it is traditional to mitigate such effects by the use of an Electronic Crowbar, and these transmitters are no exception.

## 2 THE MIT/BATES ELECTRONIC CROWBAR

An Electronic Crowbar requires a two-state device or subsystem. In its "normal" state, it must hold off the entire system voltage with negligible current flow through it. In its "fault-response" mode, it must change, within microseconds, to a highly conductive state comparable to that of the vacuum-tube arcs in response to an electrical triggering signal. An Electronic Crowbar is, unfortunately, an active system. It has no fail-safe properties like those of a fuse. It must function as intended or it will afford no protection. All that it can do is divert charge from a load arc into its own arc. All but a small fraction of the total stored energy is dissipated in the surge resistance that is an essential part of the discharge loop. The surge resistance is divided into two segments: 10 Ohms on the capacitor-bank side and 20 Ohms on the switch-tube cathode side. The Crowbar switch is connected between the junction of these two resistance components and the low-voltage return to the capacitor bank from the klystron collectors. The 10 Ohm resistance limits the current through the Crowbar switch, in this case to a maximum of 15,000 Amperes, and dissipates most of the stored energy. The 20-Ohm segment isolates the faulty vacuum tubes from the current source effectively extinguishing the arc current.

Not many devices can hold off 150 kVDC and then transition, in microseconds, to 15,000 Ampere conduction. The device that does this in the Bates Accelerator transmitters is an "infinite voltage-ratio" Crowbar, invented by Energy Systems Inc., the designers of the original transmitters, over 30 years ago. It is a three-electrode air-insulated spark gap, supported by a large plastic enclosure or "bug-shield". It comprises two large-diameter (11") spherical main electrodes and a transverse "mid-plane" needle-shaped trigger electrode, that is maintained at the mid-point of the voltage between the main electrodes, by a resistive divider. This electrode lies along the equipotential line between the two main electrodes and therefore, in the "normal" state, produces no field distortion in spite of its intentionally low radius of curvature. To trigger the gap into conduction, a shortduration but high-voltage (200 kV open-circuit) pulse is applied to the trigger electrode through a 100 kV series “sharpening “ air gap. Depending upon the polarity of the system voltage applied to the main electrodes, the initial breakdown is from trigger electrode to either main electrode. In a conventional design, the other half of the gap will not ionize unless sufficient system high voltage is present. In this design, a small value of inductance in the form of flat-spirals is inserted in series with each main electrode. This prevents the initial breakdown from short-circuiting the trigger source. The trigger voltage, therefore, is still present between the trigger electrode and the other main electrode causing that gap to almost instantaneously break down as well, producing ionization of complete channel between main electrodes with no system voltage applied. This is why the operating voltage ratio is infinite. But the requirement for a high-amplitude trigger input is why the Crowbar Driver is a crucial subassembly.

The collectors of the klystrons are isolated from ground. In the original system design, the low-level triggering signal for the Crowbar is derived from the total ground current made up almost entirely of the body current of both klystrons which is normally a small fraction of the total pulse current. An internal klystron arc produces fault-current that is entirely ground current. If neither modulator switch tube arcs, the klystron fault-current is limited to only slightly more than the normal peak beam current by the high incremental collector impedance of the switch tubes but the Crowbar is caused to fire anyway. A feature of the modulator upgrade is that the pulse modulators for the klystrons in each transmitter are now independently controlled. In addition, the body currents of the two klystrons are independently monitored by algebraically subtracting the cathode and collector currents in individual current-monitor transformers. If the klystron body current exceeds a threshold, the photonic drive to the solid-state switch modules associated with that klystron is interrupted terminating the remainder of that pulse and the arc current in the klystron. For somewhere between 95% and 99% of such instances, successive pulses are automatically re-enabled and the consequence of a klystron gun arc is one missing pulse. For the remaining 1% to 5% of such instances, one of the beam switch-tubes internally arcs as well between collector and a “shield” electrode adjacent to it that is connected to the negative high-voltage input causing a complete “shoot-through” with fault current limited by the 30 Ohm surge resistance. This current is integrated for a 10-uS interval. If it hasn’t been terminated by then, the Electronic Crowbar is signalled to fire.

## 3 THE NEW CROWBAR DRIVER

The function of the Crowbar driver is to discharge a capacitor charged to approximately 15 kV into the primary winding of a step-up pulse transformer, the secondary of which produces the greater-than-100 kV peak-pulse trigger voltage to the Crowbar switch. The existing crowbar driver uses a type 5C22 hydrogen thyratron as the discharge device. The device is obsolescent, prone to self-firing and it depends upon thermionic emission for its electron charge carriers, and low-pressure hydrogen gas for its breakdown characteristics both of which are subject to depletion over time. Its continued availability is also not assured. The grid pulse for the thyratron is derived from a dual-triode vacuum tube which is also obsolete.

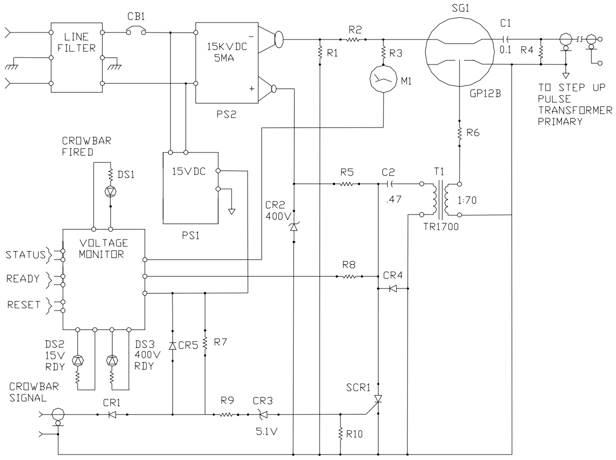

Figure 1: Basic Diagram of the new Crowbar Driver

The new design is shown in simplified form in figure 1. It has two stages of pulse generation. The output stage shown as SG1 is a triggered spark gap, type GP12B, rated for operation from 10 kV to 24 kV with a peak discharge current of 50 kA and charge transport of 0.5 Coulomb. The self-breakdown rating is 30 kV. The output capacitor, C1, is charged to 15 kV storing 1.5 milliCoulombs. Even though the actual gap charge transport may be a multiple of the charge storage, if the discharge is oscillatory in nature, tests indicate life expectancies between ten million and one hundred million shots. The operating mode of the spark gap is with the “adjacent” electrode (associated with the trigger electrode) grounded and with the “opposite” electrode at negative potential which is its optimum firing mode. Gap ionization occurs when a trigger pulse exceeding 20 kV in peak amplitude is applied between trigger and adjacent electrodes obtained from the secondary of a 70:1 step-up pulse transformer. A 400 V primary pulse results from the discharge of a storage capacitor, C2, when the silicon-controlled-rectifier, SCR1, is gated on.. The gate drive is obtained from the 15 VDC source, PS1, through R7, R8, and a noise-threshold device, CR2. The Crowbar-fire signal from the Control Unit is reverse-logic. In its normal state , the output is a current sink to ground which lowers the SCR1 gate signal through CR1. This current sink opens to fire the Crowbar. The cable between Control Unit and Crowbar driver must be connected to prevent SCR1 conduction.

The charging current for both discharge capacitors comes from a 15 kVDC power supply, PS2. The voltage across C2 is clamped to 400 V by the series string of 100-Volt Zener diodes in the positive return of PS2. The voltage at the output gap is indicated by the front panel meter M1. The current through the meter produces a voltage at the input of a voltage comparator in the voltage monitor. The voltage at the anode of SCR1 is also applied to a voltage comparator. When these voltages have exceeded their thresholds (14 kV and 330 V), both indicator LEDs are illuminated and an output relay is energized, whose normally-open contacts are in series with the HV interlock chain. When the Crowbar is fired, the internal voltages momentarily collapse opening the interlock and illuminating the “Crowbar-fired” LED indicator. Even though the discharge capacitors are automatically recharged following a Crowbar event, the interlock must be externally reset.

## 4 CONCLUSIONS

Although Electronic Crowbar systems typically engender love/hate relationships and, in all likelihood, will eventually be replaced by solid-state fast-acting opening switches (the electronic, re-closable fuse), the Bates Accelerator Transmitter Electronic Crowbar is generally considered to be more of a benefit than a hindrance to system operation. With the successful driver upgrade having virtually no wear-out mechanisms, self-firing proclivities, or long-term procurement uncertainties, the Crowbar is expected to fill the protection gap for years to come.