A THYRATRON TRIGGER WITH LOW JITTER

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Abstract

A very low jitter trigger is required for the Main Injector Proton Injection kicker. The trigger is also designed to be reliable against thyratron arc down to the trigger grid. The trigger uses a wide band coaxial cable transformer that operates at 1500 V with a 500 ns pulse width and a 10% – 90% rise time of 20 ns. An FET is used as the switch and a very low inductance capacitor is used to store the trigger energy. Typical total jitter between TTL trigger pulse and the 50% load current value has been measured at < 2 ns over a period of 8 hours and 10^5 pulses. About half this jitter is attributed to the trigger system, and the other half to the thyratron. The trigger has been subjected to several thyratron sparks without problem. The paper will present the trigger schematic, waveforms, components and the thyratron connections.

1. TRIGGER CIRCUIT

The trigger circuit uses several minor variations on a standard pulse generator. Most of the design effort was in component selection, circuit board layout and transient immunity. The schematic is shown in Fig. 1. This is not a capacitor full discharge circuit. Capacitors C29 and C30 discharge only about 6% during a pulse.

The 750 V power supply that charges C29 and C30 is not shown in Fig. 1 and neither are the thyratron trigger negative bias voltage and the thyratron DC priming current. These thyratron support supplies are derived from the thyratron filament supply. Detailed discussions of all the major components follow.

1.1 FET Switch

One novel component is the FET switch. This switch, from DEI Inc., has a ceramic low inductance package so that it may be used for high power amplifiers up to 15 MHz. The package has coplanar line connections. There are two source leads on either side of the gate and two source leads on either side of the drain. The DE375-X2 102N20 has a voltage breakdown rating of 1000 V, an average current rating of 20 A, drain–source voltage fall and rise times of approximately 7 ns and a price of approximately $200. This device has a measured voltage fall time (90%–10%) in our circuit of ~ 10 ns.

It was experimentally determined that the peak FET drain current should be limited to two or three times the average current rating to achieve the fast rise and fall times. In initial prototyping, the DE375-102N10, a smaller FET with an average current rating of 10 A, was used. In the prototype circuit the peak drain current was ~ 60 A and the drain–source voltage was 850 V. The measured drain–source voltage fall time with this FET was 50 ns. Using the same gate circuit with the higher average current DE375–X2 FET, the drain–source voltage fall time was reduced to 10 ns. Subsequent modifications to the circuit have reduced the peak drain current to 30 A.

The operating voltage of the FET is 750 V in the final design. This level is relatively close to the FET breakdown voltage, however the inverse diode across the transformer primary and the very low inductance of the primary capacitor limit the normal transient voltages to 900 V. The inverse diode and primary load resistor also reset the pulse transformer. Thyratron arc down transients are somewhat clamped by the MOV and current limited by the 49 Ω resistor. The body diode of the FET protects it from overvoltage and R8-R11 limit the body diode current.

The drive circuit for the high voltage FET was also a substantial design effort. A very fast FET driver from Unitrode, the UC1711JE, was chosen as the first power stage. The two drivers in this package are paralleled to drive peak currents of ~ 3 A into the next stage, a voltage follower. This discrete complimentary FET driver has an $R_{DS(ON)}$ resistance of 150/300 mΩ for the N/P channel devices. These devices have a silicon gate to increase switching speed and all the driver components are surface mount parts to reduce lead inductance. The zener diode voltage drop of 5.1V is slightly less than twice the gate source threshold voltage of the drive FETs. This biases both FETs slightly on to reduce delay times. Finally, the power supply bypass capacitors consist of three 0.1μF surface mount capacitors each for the +15 V and -5 V supplies. In addition, a 33 μF Aluminum electrolytic capacitor and 1 μF leaded ceramic capacitor were used on each supply. The layout of all the drive components was done to minimize inductance. Because of the electrical and mechanical design of the DE375-X2, the drain current flows primarily through the source leads next to the drain and the gate current flows primarily through the source leads next to the gate. This further decreases the fall time since the gate circuit does not have to overcome the drain source leads L dI/dt drop.

1.2 Pulse Transformers

There are two high voltage pulse transformers used in this circuit and each had it own unique problems. X1 is used to allow the FET to be source grounded. This avoids further complications on an already difficult gate drive circuit. X2 is used to isolate the thyratron high voltage, nominally 30 kV during the pulse, from the trigger circuit. The use of two transformers also allows some effective clamping components to be used. The first transformer is a coaxial cable transformer. In the prototype, this transformer provided a 1:2 step up ratio in addition to isolation. The advantage of that construction was a reduction in the leakage inductance of the second pulse transformer. Unfortunately, the required core size for the second transformer was already substantial because of the required volt seconds and use of only a single turn on the primary.

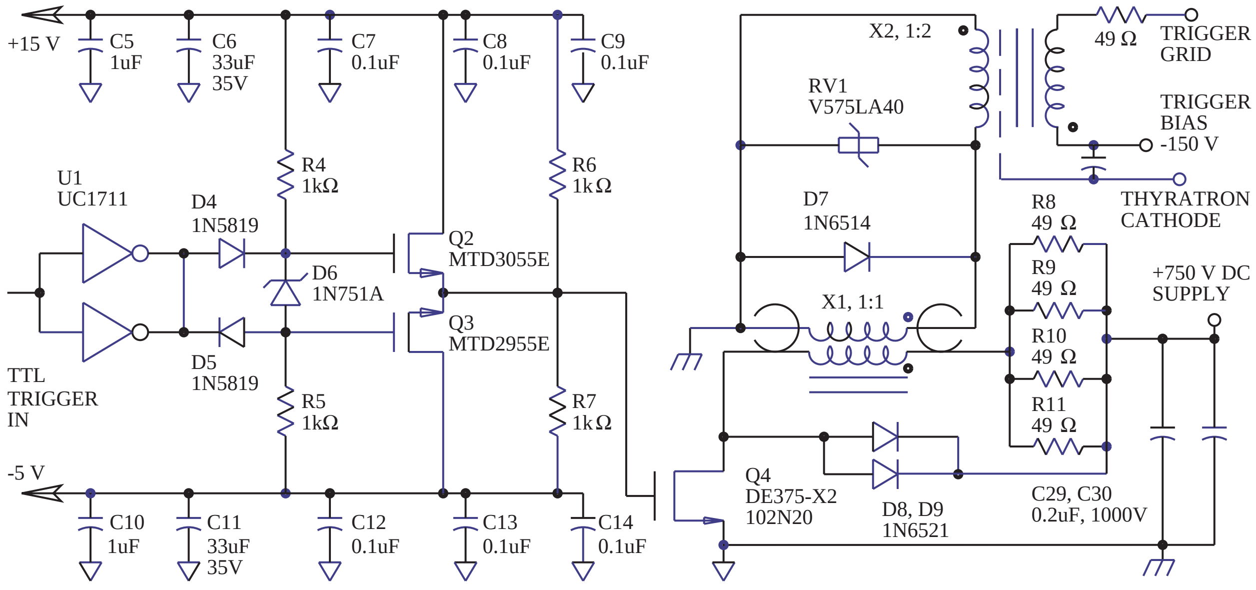

Figure 1, Thyratron Trigger Schematic

X1 is constructed of two parallel 1.5 m lengths of 0.047 inch outer diameter 25 Ω coaxial cable, Precision Tube # 25DA047. The core used is 4 pieces of a Ceramic Magnetics 3000–4 two hole balun core made from CMD5005 ferrite. There are 4 turns through each hole and the total cross sectional area is approximately 9 cm^2. In order to shield the 750 V DC voltage on the cable, for personnel safety, the center conductor is the primary and the outer conductor is the secondary. The total leakage inductance of the transformer is less than 100 nH. The transformer has adequate core area for a volt second rating of approximately 0.5 mV•s without any bias. The corona extinction voltage of the coaxial cable is approximately 850 V_{rms} at 60 Hz which is sufficient for very long lifetime.

The polarity of the transformer is particularly important in this application to achieve fast rise times. Since the cable is charged between pulses, a traveling wave is launched down the coaxial cable of the pulse transformer when the FET is closed. The current in the secondary is in the correct direction to provide full voltage into a matched load when the wave exits the other end of the transformer. In this respect, the rise time of the output pulse is limited mainly by the FET switching time when driving into a matched load. This is strictly true only if the 12.5 Ω resistor in series with the energy storage capacitor is not present. In practice this resistor increases the rise time by less than 30%.

X2 has a single turn primary and a two turn secondary. To achieve high isolation voltage, the center conductor and polyethylene of a piece of RG220/U is used as the primary. An electric field screen with a gap in the middle is place over this piece of cable and then the secondary is wound with 10 parallel pieces of AWG #22 wire. The cores used for this transformer have a total cross sectional area of 14.5 cm^2 and are made of Ceramic Magnetics CMD5005 material. Even with this substantial core and because of the single turn primary, a bias drive of 15 A/m is required to achieve a 0.2 mV•s rating. The bias current (2 A turns) is provided by a third winding and blocking inductor on the high voltage side (not shown in the diagram). The X2 transformer bias supply is derived from the thyratron filament supply on the high voltage side.

1.3 Other Components

One component that was specially ordered for the circuit was a very low inductance 0.2µF, 1000V capacitor from Electronic Concepts. This capacitor, #5PT-11635K, was designed to have a 10 year life at 1000 VDC and has an internal inductance of approximately 10 nH. The construction is an extended foil / polypropylene capacitor with 2" wide leads for each connection. The capacitor is packaged in an IC style dual inline pin package with 40 pins per side.

The trigger circuit also provides a closed relay contact back to the control system when all the DC voltages on the trigger board are within ±5% of the nominal values.

2 THYRATRON CIRCUIT

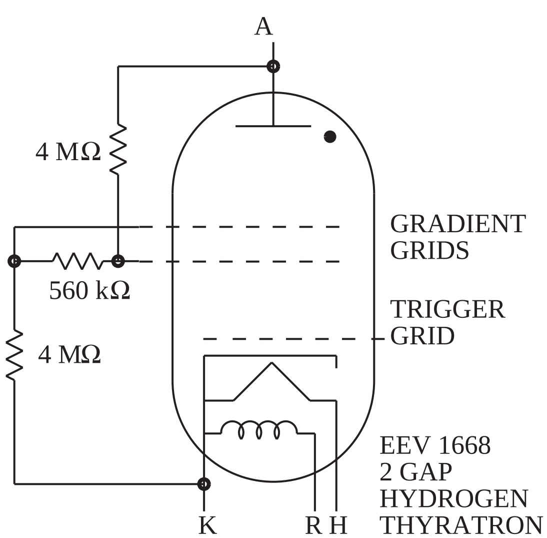

Figure 2, Thyratron Cross Connection Scheme for Proton Injection Kicker

The thyratron connection is also different from standard practice. EEV Inc. suggested using a "cross connection" at the gradient grids, Fig 2. This applies a reverse bias, in reference to the anode – cathode voltage, across the drift space between each pair of gradient grids. The voltage must be substantial enough to start a glow discharge in the drift space. The main benefit of this connection is a dramatic reduction in the delay time between successive gap breakdown in the thyratron.

The filament and reservoir supplies are 20 kHz switching supplies. They are not rectified on the high voltage side. The high voltage isolation required for these transformers is the same as the trigger and the same design is used. These isolation transformers have the same single turn primary, but the secondary has 15 to 20 turns. As previously mentioned, the filament transformer has further auxiliary windings to provide power for thyratron trigger and priming biasing.

3 SYSTEM RESULTS

The measured rise time (10% - 90%) on the thyratron trigger grid is approximately 20 ns as shown in Fig. 3 The data was captured with a HP54540 scope and Tektronix P5100 probe. Fig. 4 shows the measured jitter on the actual proton injection kicker system, measured from the TTL trigger signal to the measured current in the magnet load resistor. This is the envelope of the measured current. The peak to peak difference at the 50% current level after 4 hours and 50,000 pulses is 1 ns. The oscilloscope contributes approximately 200ps of jitter.

REFERENCES AND ACKNOWLEDGMENTS

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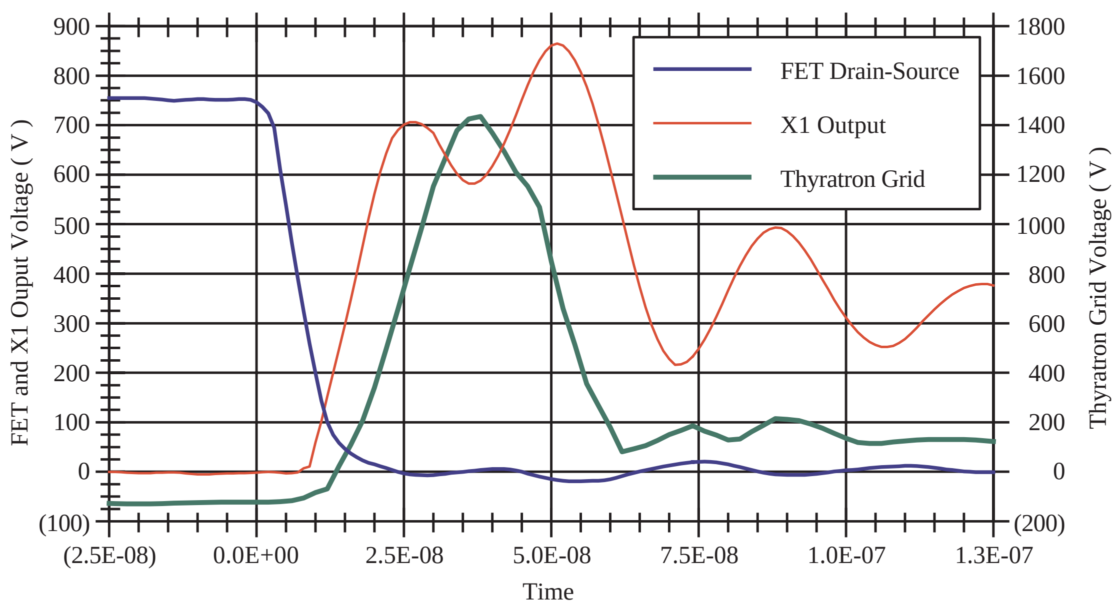

Figure 3: Measured Trigger Circuit Waveforms at Main Switch FET, Output of X1 and Trigger Grid of Thyratron

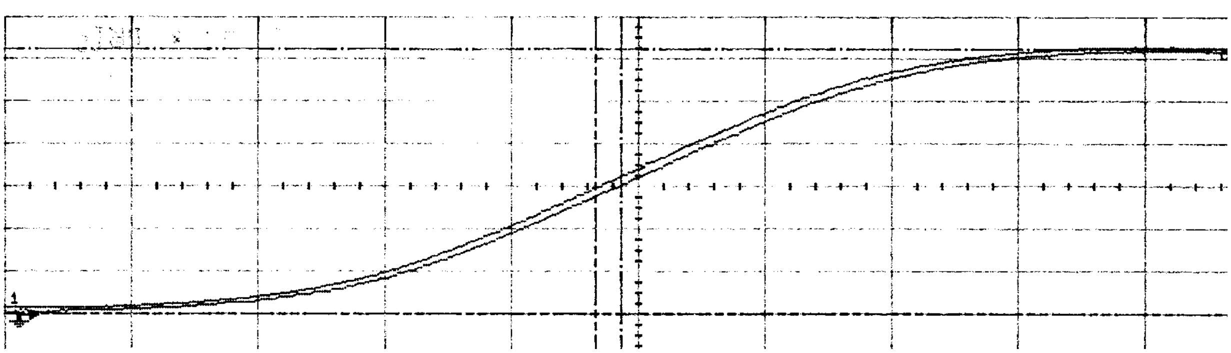

Figure 4: Proton Injection Kicker System Jitter for 50,000 Pulses over 4 Hours, 5 ns/div, 1 ns peak-peak jitter From TTL Trigger to 50% Current Level