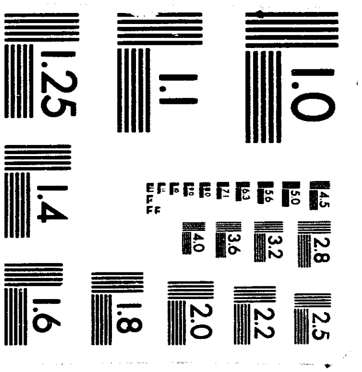
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LA-SUB--93-233

A 200 kV FAST RISE TIME, LOW JITTER, TRIGGER SYSTEM WITH MAGNETIC PULSE SHARPENER *

N.C. Jaitly, M.D. Coleman†, and A. Ramrus
Balboa Division, Maxwell Laboratories, Inc.
8888 Balboa Ave.
San Diego, CA 92123

AND

L.M. Earley, J.N. Downing, H.H. Reisch, L.D. Caudill, and S.A. Eversol
Los Alamos National Laboratory, Group M-4, MS P942
P.O. Box 1663
Los Alamos, NM 87545

ABSTRACT

The DARHT Facility is being designed at Los Alamos National Laboratory to produce high resolution flash radiographs of hydrodynamic experiments. Two linear induction accelerators (LIA), each in the range of 16 to 20 MeV, will be used to produce intense bremsstrahlung X-ray pulses of short duration (60 ns flat top). Each LIA will produce a 3 kA, high brightness, electron beam using a 4 MeV injector and a series of 250 kV induction cells. Technology demonstration of key accelerator subsystems is under progress at the DARHT Integrated Test Stand (ITS). The eight inductions cells present in the ITS are driven by a Maxwell prototype Induction Cell Pulsed Power Supply (ICPPS) which provides 250 kV, 70 ns pulses via four Blumleins. Each Blumlein drives two cells and is triggered using independently controlled trigger units. This turnkey DARHT Trigger System, consisting of four separate trigger units, provides 200 kV trigger pulses with low jitter and fast rise time to each of the four Blumlein coaxial spark gaps. Details of the trigger system design and results obtained during extensive testing at Maxwell are described

INTRODUCTION

The turnkey DARHT Trigger System consists of a single control console which controls four independent trigger units. The console is 6 feet high and made up of two 19 inch rack mount cabinets bolted side-by-side. The trigger unit enclosures, each 33 inch wide by 39 inch long by 46 inch high, are located 100 feet from the control console. The Trigger System performance specifications, as demonstrated during the acceptance testing, are summarized in Table 1.

The key components of the trigger system are described below.

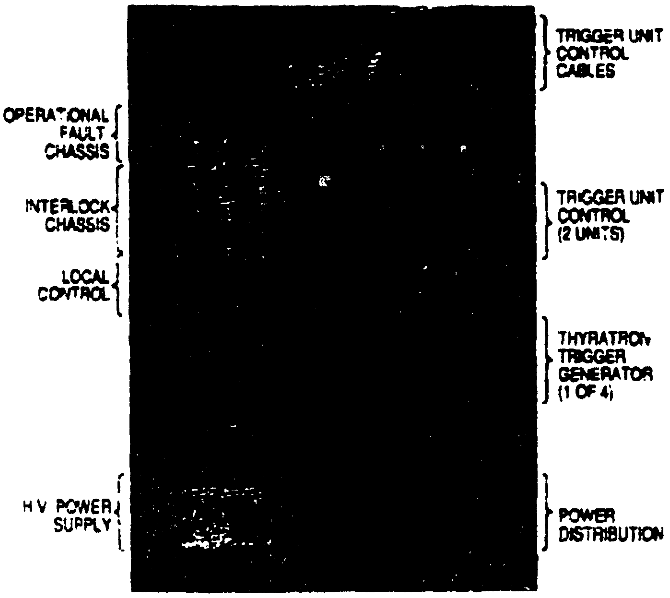


Fig. 1 DARHT Trigger System Control Console

Table 1. DARHT Trigger System Test Results

Peak Output Voltage	70 to 220 kV adjustable
Pulse Polarity	Negative
Operating Voltage	200 kV max. (into matched load)
Pulse Rep-Rate	Single shot to 0.2 Hz
Major Component Life	> 10^7 charge/discharge cycles
Pulse Fall time (10% to 90%)	< 14 ns for output above 150 kV (measured at 67 Ω cable input)
Trigger System Jitter (measured from control room low voltage trigger to HV output)	< 275 ps (1σ), and < 1.5 ns peak-to-peak (based on any 100 consecutive test shots)
Drift in Output Pulse Timing	~ 4 ns in 2000 consecutive shots at 0.2 Hz
Trigger System Pre-fire and No-Fire Rate	No pre-fires or no-fires in 5000 consecutive shots
Pulse Shot-to-Shot Reproducibility (3σ)	≤ ±2.5% of mean peak amplitude
Load	67 Ω cable (30 feet) connected to coaxial spark gap via matching termination
Input Power:	
Thyratron Dual-Pulse Generator and Supplies	120 V, 1φ, 15 A, regulation ±1%
HVPS	208 V, 3φ, 15 A, unregulated

TRIGGER SYSTEM CONTROL CONSOLE

The control system design allows independent operation of one, all, or any combination of the four independent trigger units. Trigger system controls are based on 24 V relay logic. Operation in the LOCAL MODE is carried out from the control console front panels as shown in Figure 1. In the REMOTE MODE trigger units are operated and monitored via a MODICON programmable logic controller through isolated relay contacts.

The system controls incorporate protection circuits which monitor out-of-range thyratron cathode and reservoir heater dc voltages. Digital panel meters display all heater voltages and currents along with charge voltage for each trigger unit. Also monitored are thyratron discharge over-current and condition of pre-fire/no-fire. Protection circuits also monitor the dc reset current and pulse sharpener output overvoltage. A number of other system and safety interlocks are provided for safe operation. Under a fault condition the Trigger System high voltage is automatically inhibited and the type of fault displayed via indicators on the front panels. Isolated relay contacts provide various operational/fault status conditions of the system to REMOTE. All safety and operation fault interlocks are latching in nature, and must be manually reset (after fault conditions are cleared) before operation can be resumed.

DISCLAIMER

High Voltage Power Supply

The console houses a compact 2 kJ/s Maxwell switching power supply. This is a nonstandard, 70 kV (four outputs), version of Maxwell's CCDS power supply product line. This power supply, specifically designed for the DARHT Trigger System, charges a single trigger unit in 56 ms (4 units in 224 ms) to 56 kV; the maximum primary capacitor charge voltage required for delivering the 200 kV output pulse. Each of the four high voltage output cables is 100 feet long and runs along with the control cable bundle within an electrical steel conduit to the individual unit. This power supply is chosen because of its high reliability, compactness and a single unit 19 inch rack mount construction. Since a single power supply with four outputs is employed, the charge voltage can not be independently adjusted for the four units in the system. The power supply regulates the primary capacitor charge voltage to ≤ ± 0.05%. This regulation is essential for meeting the ± 2.5% (3σ) pulse amplitude variation specification.

Thyratron Dual-Pulse Trigger Generator

Also located in the control console are four independent thyratron trigger generators (model MA2165M) manufactured by EEV. Each of these generators provide all the pulsed and dc voltages required for grid biasing and triggering of the EEV CX1725X thyratrons employed in the trigger units. A dual-pulse thyratron triggering scheme is used to minimize thyratron conduction jitter. This generator contains 2 line type pulsers. The PFN providing the pre-ionization grid (G1) current pulse is charged to ~1.5 kV. The control grid (G2) voltage pulse is generated by a second PFN charged to ~3 kV. To minimize the G1 and G2 pulse jitter each PFN is switched via a CX1848 glass thyratron switch. No bias voltage is used for thyratron grid G1 and the positive polarity pulse output is applied via a 100 ft RG-58 cable. The connection to the grid is made via a suitable series resistor at the end of the cable. The grid G2 pulse is again positive and is superimposed on a negative 130 V bias which the trigger generator provides. Again a 100 ft of RG-58 cable with a resistor at the end of the cable applies the pulse to the thyratron grid G2. An external trimpot controls the delay between the grid G1 and grid G2 pulse output. This delay adjustment is necessary for optimizing the thyratron jitter characteristics.

Thyratron Trigger Jitter Measurement: The four thyratron trigger generators are triggered manually for single shot operation. Rep-rate operation up to 1 pps is either via an external 15 V (< 30 ns rise time) pulse or a fiber optic pulse. A universal time interval counter (HP model 5370) was employed for all jitter measurements reported here. The timing jitter associated with G2 pulse in relation to the fast external electrical trigger input pulse is < 75 ps (1σ) based on any 10 consecutive shot series. When triggered manually the above jitter increased to 0.5 ns (1σ). Fiber optic triggering resulted in this jitter being somewhat higher than that observed for the electrical trigger mode. A positive drift on the order of 0.55 ns in G2 pulse timing over a 100 consecutive shot sequence is observed for electrical triggering. Jitter between G1 and G2 pulses is < 0.66 ns peak-to-peak based on a 100 shot test sequence. For lowest jitter and drift a 30 min warm-up and regulation of 120 V ac power to within ±1% is necessary.

TRIGGER UNIT HIGH VOLTAGE SECTION

Each of the four trigger units is self contained within a steel enclosure. Figure 2 shows the layout of the trigger unit high voltage section. Each unit utilizes two Maxwell, type-S plastic case, 30 nF capacitors connected in parallel. As shown in Figure 3, a resistor diode network is provided at the input charge feedthrough to protect the switching power supply from capacitor voltage reversals. The primary capacitors charge a Maxwell high voltage 0.5 nF capacitor via a pulse transformer. The primary capacitors are switched by a 70 kV thyratron. The voltage across the 0.5 nF capacitor on the transformer secondary is input to a pulse sharpener via a low inductance connection. The output end of the sharpener is connected to the 67 Ω output cable via a low inductance coaxial feedthrough. Performance of the key high voltage components in the trigger unit are described below.

High Voltage Thyratron

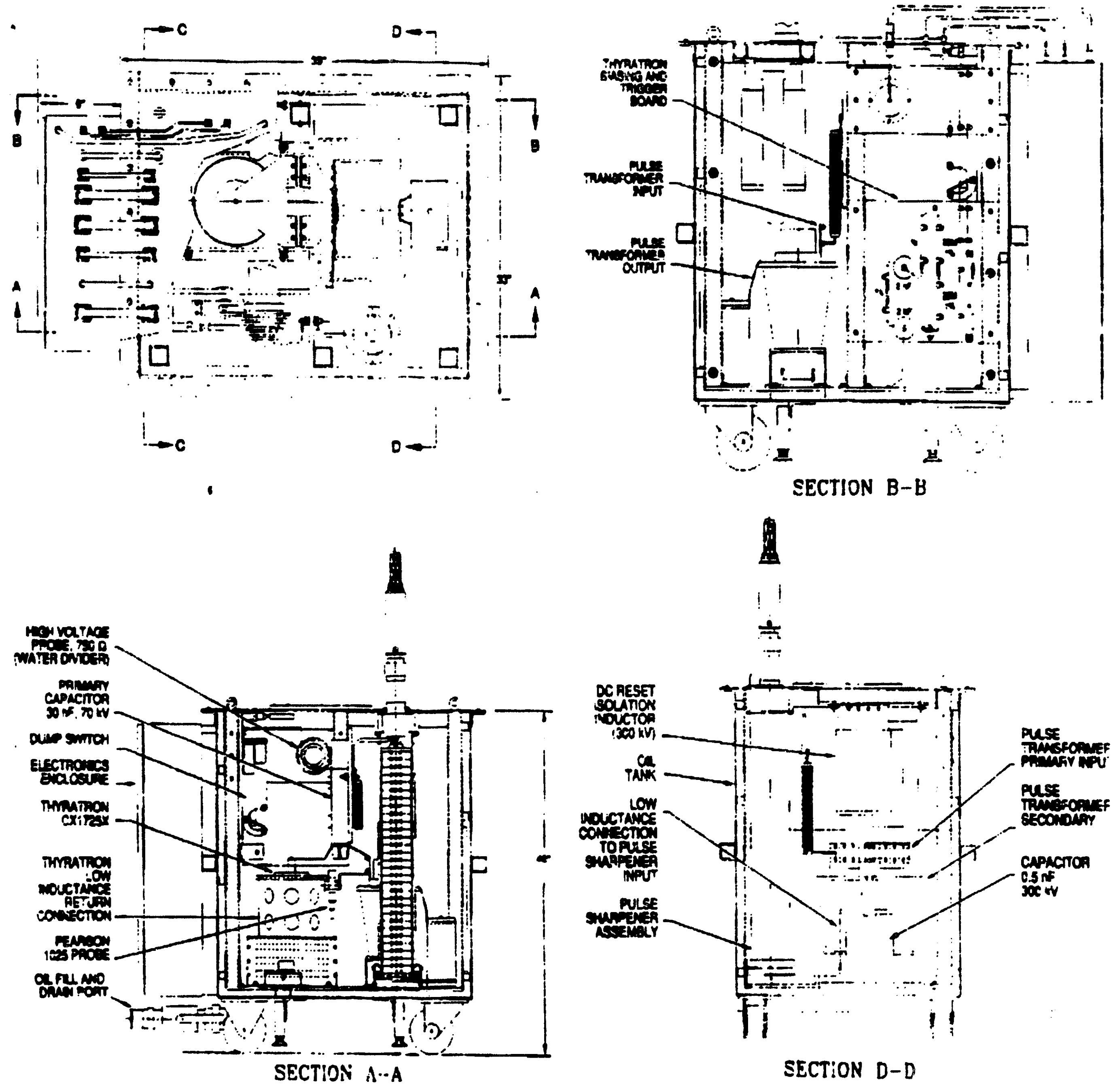
The DARHT Trigger system specifications require major component life of 10^7 charge/discharge cycles, a total system jitter (3 σ) of ≤ 3 ns, and a pre-fire/no-fire rate of 1 in 5000 shots each. This specification could be met only by using a thyratron as the primary switch. The CX1725X thyratron manufactured by EEV is chosen due to its high anode voltage rating and the availability of well documented life and performance data. The CX1725X is a rugged 2 gap, hollow anode, thyratron with a metal-ceramic envelope. It is supplied with an external decade box to precisely control the heating of the reservoir filament which controls the gas pressure inside the tube. This version of the thyratron makes the optimization of the tube performance easy; especially as the tube ages.

Thyratron heater dc power supplies: To minimize thyratron conduction jitter, separate linear dc power supplies (< ±0.1% voltage regulation) are used for the cathode and reservoir heater filaments. The cathode heater is operated at 6.6 V with the reservoir voltage maintained at 6.3 V. The currents drawn by the cathode and reservoir filaments are 45 A and 7 A respectively. A considerable effort had to be expended to protect the low voltage dc supplies (including the dc reset supply) from the fast voltage transients associated with thyratron switching (very high dI/dt). Protection as shown in Figure 3 is provided in the form of LC filters and bypass capacitors. Each dc supply, in addition, is provided with a fast protection circuit consisting of various capacitors, MOV, and transorb directly across the output terminals.

Thyratron voltage hold-off: Thyratron anode voltage hold-off and gas pressure is optimized using the thyratron external decade box. Different settings allow the reservoir filament heater current to be controlled in fine discrete steps. Lowering the current through the reservoir heater (by lowering the shunt resistance value applied across the heater by the decade box) reduces gas pressure. This increases the anode hold-off voltage since the tube operates on the left hand portion of the Paschen's curve. The CX1725X reliably holds-off a maximum anode voltage of 63 kV under the charging conditions associated with the trigger units. This voltage exceeds the maximum 56 kV charge required for delivering the 200 kV output pulse. Even with the lowest gas pressure setting allowed by the external decade box (tube practically starved of gas) the thyratron pre-fired after a few seconds above 63 kV charge. In an effort to improve the dc hold-off voltage performance, the thyratron gradient grid biasing, shown in Figure 3, was changed from its recommended 50%/50% value. The voltage biasing ratio of the anode to gradient grid and gradient grid to cathode was changed to 40%/60% and subsequently to 60%/40%, respectively by appropriately changing the resistor values in the gradient grid biasing resistor chain. Both these voltage grading significantly deteriorated the thyratron hold-off voltage compared to the 50%/50% gradient grid biasing. The 40%/60% biasing, being the worst, reduces the hold-off to < 60 kV even at very low gas pressures. The gradient grid is thus carefully biased at half the anode voltage using 1% precision high voltage metal oxide resistors.

New thyratrons exhibit a conditioning effect. All tubes are conditioned by reducing the gas tube pressure to the minimum allowed by the external decade box settings and applying a few hundred shots at 63 kV. The tube is considered conditioned if it withstands a 1 minute dc high-pot test and no more conditioning shots are applied. This conditioning ensures that the tube reliably holds the maximum required charge voltage of 56 kV. As shown in Table 1, no pre-fires or no-fires were present in the 5000 consecutive shot test sequence at 0.2 Hz. This clearly demonstrates the inherent reliability of the trigger units.

Thyratron discharge current: The hollow anode configuration successfully conducts large reverse currents. Figure 4 shows the thyratron discharge current when a 3 μH output inductor located from the pulse sharpener output to ground is used for determining the effect of dc reset on pulse sharpening. This inductor provides a convenient way to reset the pulse sharpener ferrites using the same



SECTION B-B

SECTION A-A

SECTION D-D

Fig. 2 Section views of trigger unit showing component layout

constant current reset supply (~60 A) used for re-setting the pulse transformer. Reset in this case is applied on the transformer secondary winding and requires a reset power supply isolation choke (2 mH, 300 kV) as shown in Figure 3. The 3 μH inductor (not shown in Figure 3) provides a parallel path for the reset current. The net reset current resistively divides between transformer secondary resistance and the 3 μH inductor resistance. The resistance of the 3 μH inductor was tailored so as to allow at least 20 A of reset current to flow in the pulse transformer winding. The reset current for the pulse sharpener in this case is ~35 A. The thyratron peak discharge current in the forward direction is 16 kA with a current reversal peak of 12 kA. Several thousand of such 75% reversal ringing current pulses have been applied to the thyratron during the testing of the first trigger unit. The hollow-anode CX1725X has been subjected to a maximum forward peak current of 20 kA with 75% current reversal for few hundred shots. The thyratron successfully survives these current discharges with no deterioration observed in its performance.

<u>Primary and Secondary Capacitors</u>

Two 30 nF capacitors are used in the primary circuit to minimize the total primary circuit inductance. The capacitors (model 35158), rated at 70 kV and 20% voltage reversal, have been specifically designed by Maxwell capacitor department to provide life $>10^7$ charge/discharge cycles. The single extended foil capacitor is 2.3 inch x 5.9 inch x 15.5 inch high.

A 0.5 nF Maxwell double-ended capacitor is used on the pulse transformer secondary. The capacitor (model 35147), rated at 300 kV and 20% voltage reversal, is again designed for a life $>10^7$ charge/discharge cycles. This capacitor is 4 inch x 6 inch x 8 inch high in overall dimensions and assists in yielding a higher voltage at the pulse sharpener input. The input voltage peak amplitudes are ~10% higher with 0.5 nF capacitor at the transformer secondary compared to the case when it is absent. Higher input voltage of the

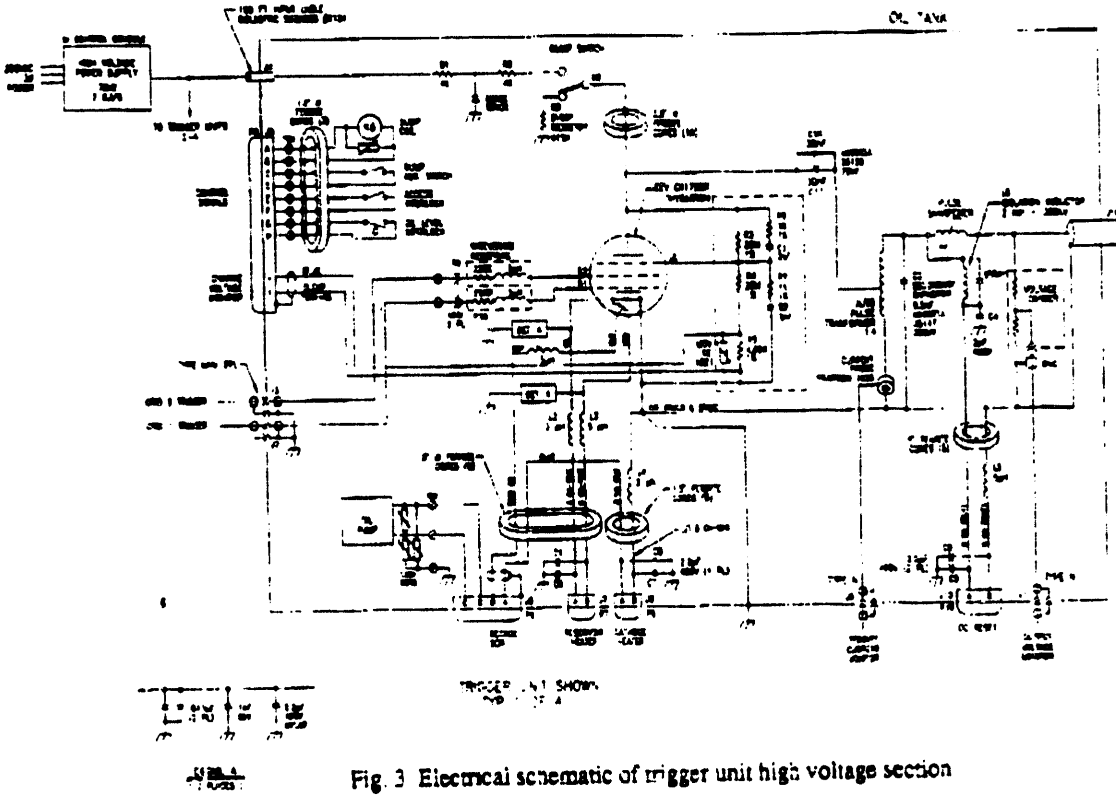


Fig. 3 Electrical schematic of trigger unit high voltage section

pulse sharpener increases reliability since lower charge voltage is required for generating the same 200 kV pulse. At charge voltages of 30 kV, the output pulse voltage is ~17% higher while at 63 kV the output pulse voltage is ~13% higher with the 0.5 nF capacitor present on the transformer secondary. Addition of this capacitor on the pulse transformer secondary, however, slows the fall time (10% to 90%) of the pulse sharpener input from 52 ns to 100 ns. This slowing of the pulse, however, does not have a noticeable effect on the fall time of the pulse sharpener output pulse as shown later.

Pulse Transformer

A Stangenes iron-core pulse auto-transformer (model SI 7638) designed for DARHT steps-up the primary capacitor voltage. The leakage inductance of this transformer, with a 2 turn primary and 8 turn secondary, measures 195.5 nH at 1 MHz referred to the primary winding. The magnetizing (self) inductance at 1 MHz is 252 μH referred to the secondary winding. The transformer secondary is rated for 300 kV. The overall dimensions of this pulse transformer are 15 inch x 9 inch x 18 inch high. A single 2 mH, 300 kV choke (60 A dc rating) is used to reset the transformer. Reset on the secondary winding (instead of the primary) enables the use of a single dc reset supply for both the transformer and the pulse sharpener. The transformer requires at least 15 A of reset current when the core is being reset from the secondary winding. Larger number of secondary (8 instead of 2) turns help in using a lower wattage power supply whose size is also small. This, however, comes at the expense of a large isolation inductor rated for transformer secondary voltage.

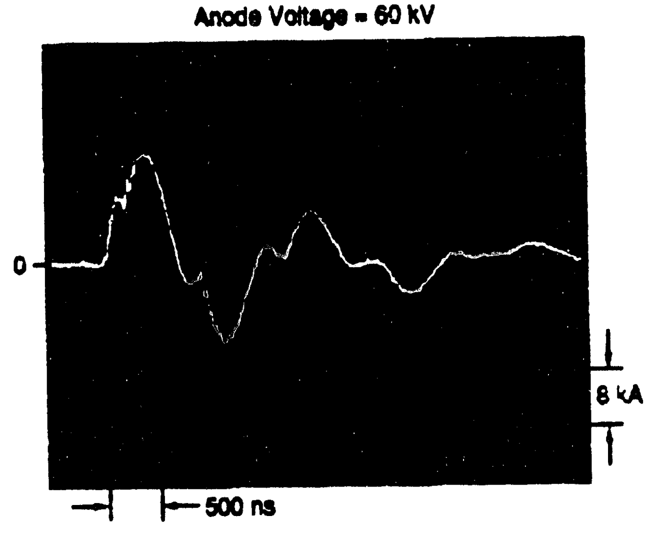


Fig. 4 Thyratron current waveshape with 75% reversal

The presence of the pulse sharpener influences the net voltage step-up ratio depending on the charge voltage. For a charge voltage of 30 kV the total voltage ring-up factor determined from the measured transformer secondary voltage is 4.26. This factor drops to 3.38 at charge voltage of 60 kV. These factors are for the case with the 0.5 nF capacitor present at the transformer secondary and the pulse sharpener being reset (current ~35 A) using the 3 μH output inductor. Ring-up factors are lower when the 0.5 nF capacitor is not used. Pulse sharpener output voltage is higher in the absence of the 3 μH output inductor.

Pulse Sharpener

The voltage appearing at the 0.5 nF capacitor on the transformer secondary has a fall time (10% to 90%) of ~100 ns. The fall time of this pulse is sharpened using the pulse sharpener prior to being delivered to the load via the 67 Ω coaxial output cable.

The pulse sharpener is a ferrite filled coaxial transmission line as shown in Figure 5. The inner 1.5 inch O.D. aluminum conductor is surrounded by 29 high frequency nickel-zinc ferrite toroids (Ceramic Magnetics C2010) with a 1.51 inch I.D., 3.98 inch O.D., and 1 inch thickness. The outer aluminum conductor of the transmission line surrounding the ferrites has a 4.25 inch I.D. This ferrite filled transmission line is supported vertically by a Lexan plate attached at the bottom of the outer conductor. The line is transformer oil insulated and adapts to a 67 Ω high voltage cable at

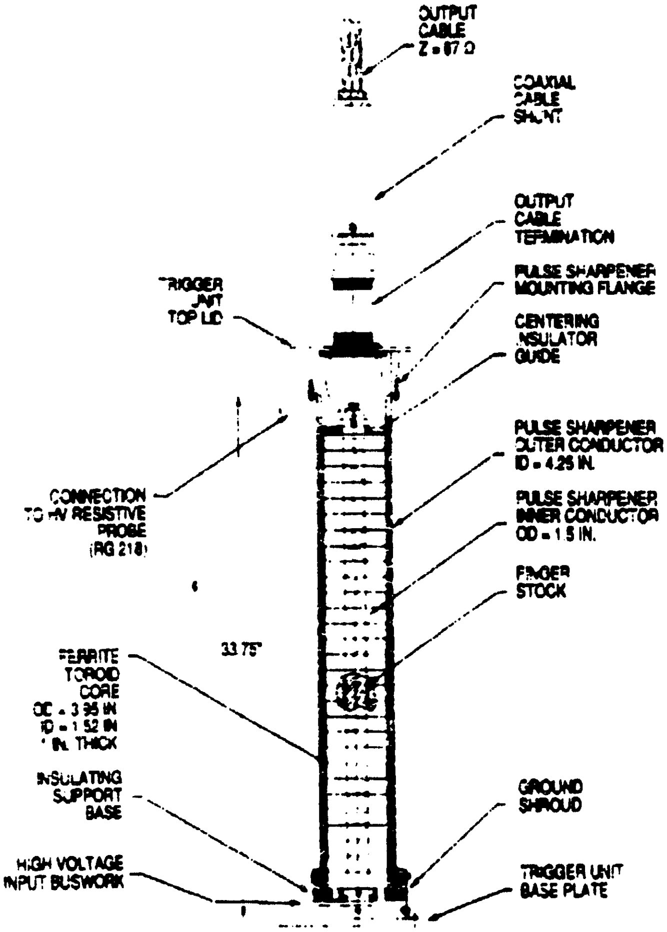


Fig. 5 Pulse sharpener details

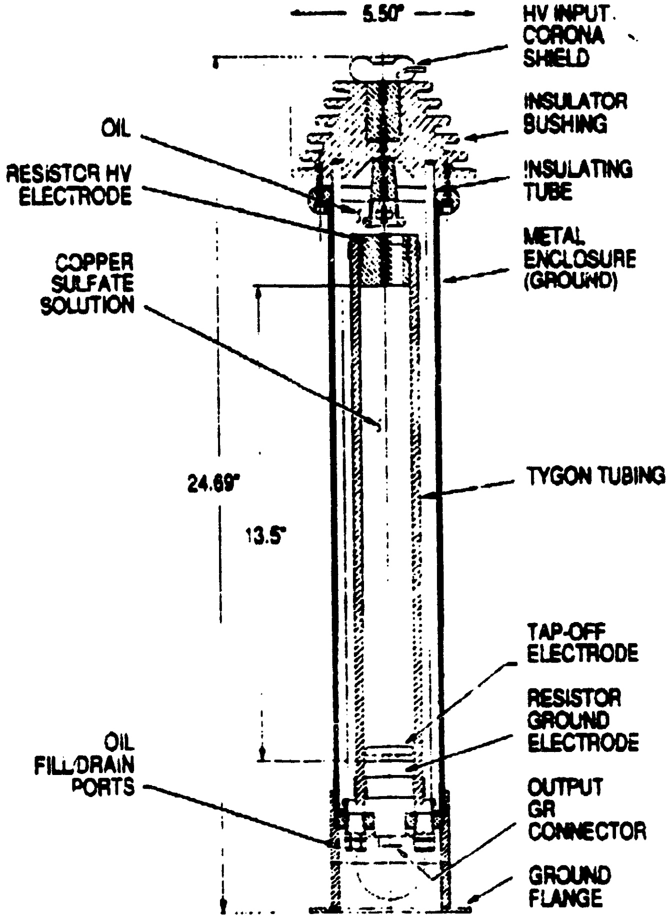


Fig. 6 Fast response resistive water probe

its output via a specially designed (Isolation Design model D-108-MS) low inductance coaxial feedthrough. A cable (resistive) current shunt (T&M Research model LF-500-2-MAX/N) located at the feedthrough output monitors the output pulse current. A fast response water divider probe, shown on Figure 6, connected at the junction of the pulse sharpener and the cable feedthrough measures the fall time and amplitude of the pulse injected into the 67 Ω cable.

The material composition of the ferrites used in the line is a key parameter in producing pulse sharpening. Earlier experiments at Maxwell demonstrated that ferrites with Mn-Zn composition perform very poorly compared to Ni-Zn composition.

DARHT TRIGGER SYSTEM TEST RESULTS

Trigger System Jitter Performance

Time Interval Counter (HP model 5370) is used to measure the total system jitter. A fast low voltage (zero-time trigger with < 30 ps peak-to-peak jitter) signal from LANL REMOTE console starts this counter. The counter is stopped using the output pulse signal from the high voltage resistive (750 Ω) probe. The counter START and STOP levels are set at 50% of the respective signal peaks.

Dual-pulse triggering of the thyratron grids is the key to obtaining the lowest system jitter. The pre-ionization (G1) current peak, control grid (G2) pulse delay, and rate-of-rise of G2 pulse have to be optimized for obtaining low jitter. The optimization involves adjusting the grid G2 pulse delay and reducing the peak current of the grid G1 pulse to < 5 A, as shown in Figure 7. The peak current is reduced by proper selection of the resistor at the output end of G1 pulse cable. A 220 Ω wire wound (3 μH inductance) resistor proved suitable. With G1 pulse current peak exceeding 5 A, the CX1725X always fires on the grid G1 pulse when the anode voltage exceeds 45 kV. Thyratron firing from G1 pulse increases the system peak-to-peak jitter very significantly compared to the case when it fires from the delayed (~800 ns) grid G2 pulse as shown in Figure 7. The measurements also reveal that the jitter is higher at lower thyratron gas pressures. For a fully optimized thyratron and its dual-pulse trigger, DARHT Trigger System jitter of < 275 ps (1σ) based on 100 consecutive shots at full output voltage has been achieved. The corresponding peak-to-peak Trigger System jitter is < 1.5 ns. System jitter at lower output voltage range are no different from those at the highest level. To achieve the 1.5 ns peak-to-peak trigger system jitter it is extremely important to regulate the 120 V ac input to the dc supplies and the thyratron trigger generators to ±1%.

With the grid G1 pulse current peak > 5 A, the jitter above 45 kV anode voltage is >2 ns (1σ). The waveforms recorded for grid G1 and G2 pulses for this case clearly indicate that the thyratron fires from the grid G1 pulse soon after the pre-ionization current exceeds 5 A. For anode voltage < 45 kV and pre-ionization current peak as high as 18 A the thyratron fires correctly from the grid G2 pulse and the jitter is similar to those reported above for the optimized system. With no input voltage regulation the system jitter is > 3 ns (1σ).

Pulse Sharpener Performance

Electrical failure of the pulse sharpener occurs in form of surface tracking initiating at the ferrite-oil edge on the I.D. of the core. The track runs radially outward between adjacent ferrite surfaces towards the outer conductor. Tracking has been observed when electric fields at the ferrite-oil interface exceed 500 kV/cm. This value is very similar to breakdown strength of transformer oil calculated from the well known J.C. Martin's breakdown equation:

$$E_b = 500\, t^{-1/3} A^{-0.1}\ \text{kV/cm}$$

for positively charged surface. Here t is the effective time in μs for

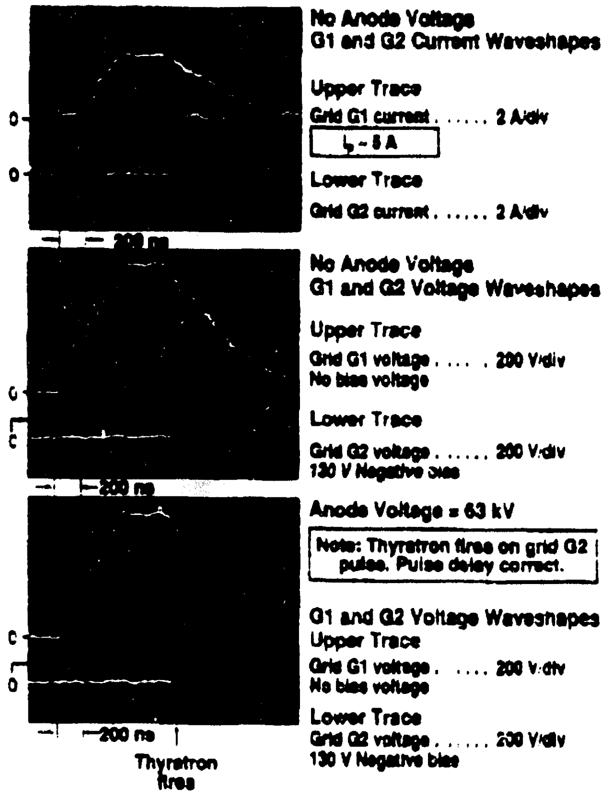


Fig. 7 Optimized dual-pulse triggers for CX1725X thyratron

which the voltage exceeds 63% and A is the stressed area in cm^2. The use of finger stock between the pulse sharpener inner conductor and the edges where the adjacent ferrite core surfaces are in contact led to a superior performance. Presence of air bubbles, as with any other high voltage system, is very detrimental to the voltage hold-off of the pulse sharpener. All output pulse waveshapes reported below are recorded using the water probe shown in Figure 6.

Figure 8 shows the input and output waveshapes recorded for the pulse sharpener at a charge voltage of 60 kV. In this case the pulse sharpener has a 30 A dc reset applied via the 3 μH inductor connected at the output. The pulse sharpening effect is clearly evident. Voltage reversals at the input are also evident which are a result of the inductor present at the pulse sharpener output. As seen in the waveforms, reverse input voltages swings are also pulse sharpened. The input pulse fall time (10% to 90%) of 100 ns is sharpened to ~12.5 ns. Pre-pulse on the output pulse is negligible.

Figure 9 shows the output pulse waveshapes recorded when the input pulse fall time is reduced from 100 ns to 52 ns by removing the 0.5 nF capacitor. The sharpener has a 35 A reset. It is evident that the pulse output fall time at 63 kV is similar to that of the earlier case where the input pulse fall time is 100 ns. Two things to be noted from this figure are that the output pulse arrives earlier in time and pulse sharpening improves as the charge voltage increases. Pulse sharpening in this pulse sharpener design was very poor very poor below 25 kV charge.

Finally the the effect of no reset applied to pulse sharpener is shown in Figure 10. For this case the 3 μH inductor at the output of the pulse sharpener is removed. The 0.5 nF capacitor is present on the transformer secondary and the pulse transformer reset current is 16 A. As shown in this figure the output pulse fall times are not very different from the case where the pulse sharpener has a 30 A reset. Not only does the pulse sharpening remain unaffected, but also the output voltages are the highest of any case. This is due to the fact that the output inductor loads the pulse sharpener output. Maximum output voltage of 232 kV with a fall time of ~13 ns is measured at charge voltage of 63 kV. As shown in Figure 11 no current or output voltage reversals are present with the 3 μH inductor removed. This figure also shows the output pulse waveshape as recorded by the cable shunt. It is clearly evident that the shunt has a very noisy response.

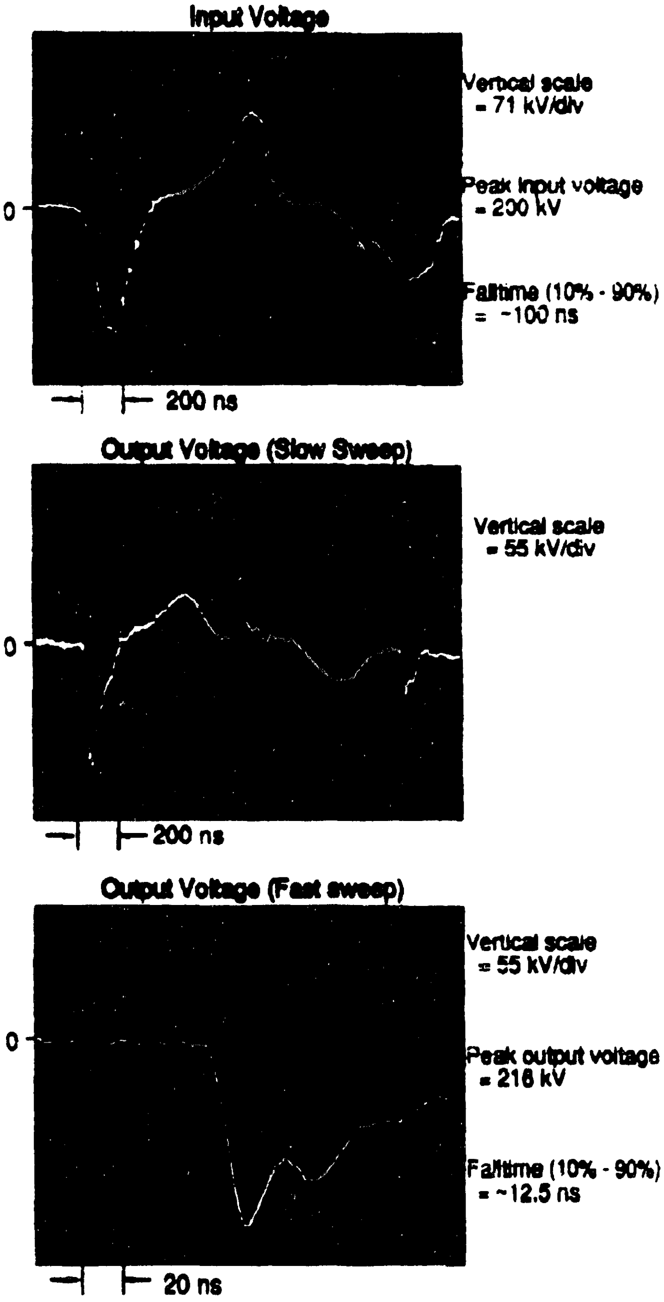


Fig. 8 Pulse sharpener input/output waveforms (30 A reset)

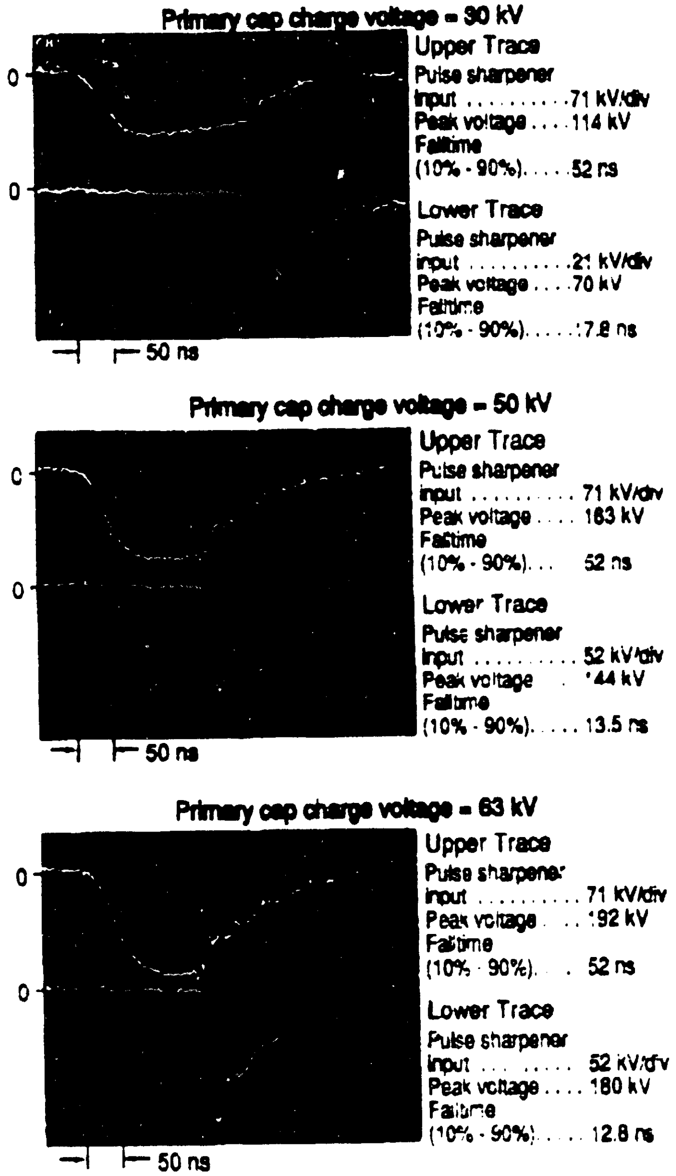


Fig. 9 Pulse sharpener input/output waveforms without 0.5 nF capacitor. Input pulse fall times now 52 ns.

CONCLUSIONS

The prototype DARHT Trigger System exceeds all design goals and specifications. As demonstrated by extensive acceptance testing of four units at Maxwell, this type of trigger system is capable of providing 200 kV voltage pulses with dV/dt > 15 kV/ns into 67 Ω coaxial cable load. The extreme reliability of this design is demonstrated by very low pre-fire/no-fire probability of << 0.02%. Extremely low system peak-to-peak jitter of < 1.5 ns and long maintenance free life makes these thyratron-transformer-sharpener based high voltage fast rise time pulsers very attractive.

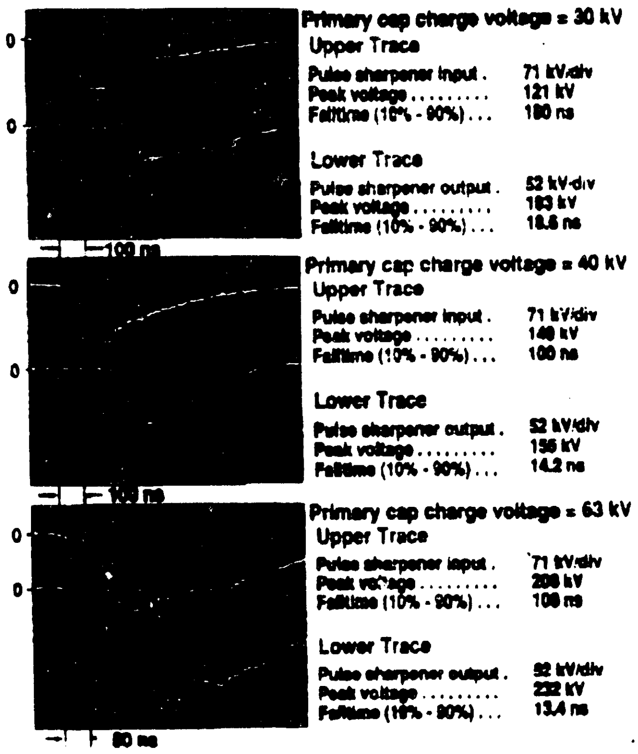


Fig. 10 Pulse sharpener input/output waveforms without 3 μH inductor (no reset). 0.5 nF capacitor present.

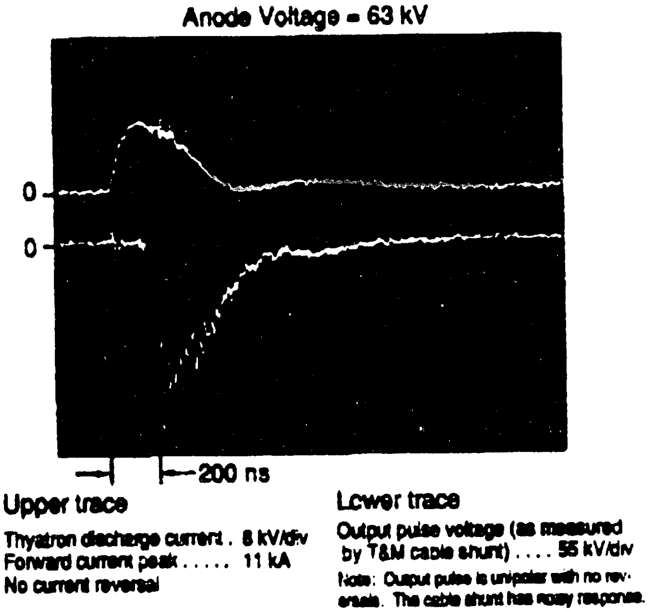


Fig. 11 Thyratron current without 3 μH inductor and output pulse voltage as recorded by T& M cable shunt.

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† Presently at Directed Technologies, Inc., San Diego, CA 92121

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