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Ernest O. Lawrence Radiation Laboratory

DEVELOPMENT OF 36-MEGAWATT MODULATORS FOR THE ASTRON 1000-MEGAWATT ELECTRON ACCELERATOR

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Vernon L. Smith

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Summary

A 1000-megawatt peak-power linear electron accelerator is required for the injection of electrons into a thermonuclear fusion experimental device, called the Astron, which is now under construction at the Lawrence Radiation Laboratory in Livermore, California. The Astron will determine the feasibility of an actual power-producing fusion reactor utilizing the principles of confinement and heating of a plasma by establishing a long rotating layer of relativistic electrons.

The linear electron accelerator under construction is designed to produce a pulsed electron beam with an energy of 5 Mev ±0.5%, a pulse current of 200 amperes, with a pulse duration of 0.25 μsec and at 60 pulses per second. The accelerator will be of the induction type utilizing large magnetic cores. Approximately 400 cores will be used and each one will contribute a minimum acceleration of 12,000 volts.

The details of the design and development of a line-type modulator used for pulsing cores and capable of an output peak power of 36 megawatts will be discussed in detail. A type 6587 and type 5949A thyratron were life-tested at 32 kv, 2000 amperes, and 60 pps. Useful life in excess of 1000 hours was obtained. In addition, it was necessary to develop corona-resistant connectors for this application. Life data and final design for a small connector suitable for operation at 16-kv, 0.4-μsec (70% amplitude points) pulses with 60-nanosecond rise time, and at 60 pps are presented.

Introduction

A possible method to attain the long-sought goal of a controlled thermonuclear reaction is to utilize high-energy electrons to produce magnetic confinement and, simultaneously, heat the plasma by transfer of some of the electron energy to the plasma particles.

The Astron[1] thermonuclear fusion experimental device, which is now under construction at the Lawrence Radiation Laboratory in Livermore, California, will be used to determine if these principles can be utilized to make a power-producing fusion reactor. A 1000-megawatt, linear electron accelerator[2-4] capable of producing a relativistic beam of electrons of high intensity and quality is required to perform these experiments. Table I lists the specifications for the accelerator.

Development of Core Pulsing Requirements

After considerable study by the Physics Staff of the Lawrence Radiation Laboratory, it was decided to build an accelerator utilizing a basic induction principle,[5-7] known for many years, but never before employed in a practical linear accelerator. This basic principle is to use an accelerating induction electric field generated by changing the magnetic flux in a ferromagnetic material. This method is inefficient with low beam currents because of the extremely high exciting currents of known magnetic materials. An efficiency approaching 10% may be realized in the Astron accelerator when operating at beam currents of 200 amperes. An increase in the number of primary turns affects the input impedance, as in a pulse transformer, but results in a corresponding stepdown of accelerating potential.

TABLE I

Accelerator Specifications

Electron energy	5 Mev
Peak beam current	200 amperes
Peak beam power	1000 megawatts
Pulse length of ±0.5% flat portion	0.25 μsec
Repetition rate, variable	0 to 60 pps
Energy spread (during the pulse and/or from pulse to pulse, and at a variable repetition rate)	±0.5%
Beam diameter	~1 cm
Beam quality	< 10^{-2} radian - cm

The Astron accelerator is designed[8] to utilize tape-wound, toroidal, doughnut-shaped, magnetic cores with the electrons accelerated through the center of the core. A one-turn primary is used

*Work performed under the auspices of the U. S. Atomic Energy Commission.

in order to keep the system voltage as low as possible.

The choice of magnetic material vastly affects the core modulator requirements because the pulse permeability[9] (at 0.4 μsec) can easily vary orders of magnitude depending on material composition, thickness of lamination, and annealing methods.

Many different materials were tested[10] and optimization studies were made comparing the combined costs of magnetic materials and pulse modulator systems. One-mil, 50% nickel-iron, tape-wound cores were found to represent a reasonable compromise. The final design uses two sizes of cores: The electron gun section uses forty-five 18-inch ID × 33-inch OD × 1/2-inch-thick cores; the eight accelerator sections (forty-eight cores each) use 384 8-inch ID × 24-inch OD × 1/2-inch-thick cores.

The large cores will be pulsed to 16,000 volts and the small ones to 12,000 volts. Under optimum conditions this would yield an output of 5.32 Mev, however, beam loading effects and variations of the magnetic properties between cores (as much as ± 30%) will reduce the output.

The electron injection requirements of the Astron dictate that a square-wave pulse voltage be developed across the secondary plates[8] of the accelerator. The waveforms of Fig. 1 show test results for gun and accelerator cores. The apparent core input impedance, (primary voltage/input current), is shown in Fig. 2. These data reveal the need for a modulator that can deliver a constant voltage across a load impedance that varies approximately 4 to 1 during a 0.4-μsec pulse.

The core pulsing requirements for each type of core are summarized in Table II.

system (500 kw now) would be excessive.

(c) The size and close linear stacking of the cores creates a density packaging proglem for the high-power pulse equipment needed.

(d) The requirements of 50 nsec rise time and a low jitter of ± 5 nsec are formidable tasks for a pulsing system of this peak power and impedance level.

The initial development work centered around hard-tube modulators developed for performing acceptance tests on the large cores. This equipment[11] utilized a Westinghouse Type WX-4366 in the final stage and was capable of an output of 64 kv, 600 amp, for 0.3 μsec. The required ampere-turns excitation was obtained by using a 4-turn primary winding. For details refer to the basic schematic, Fig. 3 and for the test setup, Fig. 4.

This type of modulator performed very successfully. Consequently, considerable effort was expended in the hope that a design applicable to the accelerator could be evolved. The principal advantages of hard tubes are low jitter, pulse shape control, low source impedance relative to the load impedance, and possibly high efficiency. The latter two items are most significant when the load varies as in the case of magnetic cores. Various tubes were tested and several hard-tube modulator designs accomplished.[12] However, it was apparent that available modulator tubes would not be satisfactory, primarily because of cost and size per megawatt of switch power.

Therefore, it became necessary to consider the application of a line-type modulator. This type of modulator can be used to drive a low impedance

TABLE II

Typical Core Pulsing Requirements

	Item	Gun Core	Accelerator Core
1.	Peak primary voltage*	16,000 volts	12,000 volts
2.	Peak input current*	4,500 amp	1,800 amp
3.	Peak power input*	70 Mw	21.6 Mw
4.	Maximum input impedance	12.5 Ω	17.5 Ω
5.	Minimum input impedance	2.9 Ω	6.0 Ω
6.	Primary voltage rise time	40 nsec	40 nsec
7.	Secondary voltage rise time	40 nsec	40 nsec
8.	Primary voltage fall time	60 nsec	60 nsec
9.	Secondary voltage fall time	60 nsec	60 nsec
10.	Pulse duration over ±0.50% portion	0.25 μsec	0.25 μsec

*Measured at the end of the 0.25-μsec flat region of pulse

Modulator Development

The core pulsing requirements and the required gradient of 20 to 30 kv/inch in the magnetic material created several critical design dilemmas. These were:

(a) To be able to switch very high currents into an impedance which varies during the pulse by 4 to 1 and at the same time maintain at least ± 1/2% voltage regulation across this impedance.

(b) A reasonable efficiency is required or the power demands for the complete

and by the use of conventional coaxial transmission line (RG-213/U) it was possible to locate the equipment any desirable distance from the cores. Thus, it was possible to evolve a system design which allowed the positioning of the pulse equipment outside the shield walls for the accelerator. This is obviously a strong maintenance and trouble-shooting advantage because observations can be made during the accelerator operation. The use of coaxial transmission lines allows the design of low inductance and shielded connections to each core strap. The main disadvantages of the line-type modulator for this application are a relatively high fixed source impedance, jitter, and loss of efficiency caused by mismatches. The choice of a thyratron was made because:

(a) The ionization time requirements are shorter than 0.03 μsec. Size A ignitrons were tested[13] and the shortest ionization time recorded was 0.5 μsec.
(b) Spark gaps were eliminated because it was believed the failure rate of 500 in service would be excessive.
(c) Magnetic switches[9] were considered, but due to insufficient design information it was felt a long development program would ensue.
(d) Hard tubes would be too costly and bulky.

A summary of test results and comments about various thyratron tubes is given in Table III. This work concluded with the choice of the type 5949A tube.

The voltage droop at the core (load impedance) due to the mismatch between the coaxial transmission line characteristic impedance and the core is eliminated by a pulse shaper located in the output circuit of the modulator. However, the flatness is obtained with a sacrifice in efficiency. The pulse shaper can be adjusted to produce an approximate ramp voltage to be transmitted to the core (see block diagram Fig. 5). Secondary voltages from the core have been observed with a ripple less than ± 1/4% when the pulse shaper is properly adjusted (see Fig. 5).

The output pulse is positive and is taken from the cathode of the thyratron. This technique improves the life of the RG-213/U transmission lines to the cores by at least an order of magnitude. The peak pulse voltage on the output cables can be 18 kv under maximum output conditions and pulse shaper adjustment. The cable can withstand many times (100 kv or more) this voltage under dc or long rise time pulse conditions. However, under fast pulse conditions, corona bursts occur during the rise and fall of voltage and holes are bored through from the braid to the inner conductor.[14]

The minimum electrical length of the transmission lines to the cores is set at one-half the pulse width (130 feet) in order to prevent reflections from arriving back during the pulse. The maximum length is limited by cable attenuation and will not exceed 200 feet. The pulse-forming network consists of three 260-foot reels of RG-218/U and one 130-foot length of RG-218/U to an isolating resistor which is connected to the high-voltage charging power supply.

The gun core, at an output of 16 kv, requires three times the peak power of the accelerator core. Three modulators in parallel will be used to power the gun core instead of using a different design modulator. Refer to Fig. 5 for the block diagram of the modulator and a simplified equivalent circuit.

Design Features of the Modulator

The final design of the modulator system consists of the pulse-forming network (PFN) charging power supplies, PFN's in the form of reels of RG-218/U, a switch chassis, trigger system, pulse shaper, load cables, and connections to the core straps. The switch chassis, which houses the type 5949A thyratron in a low inductance enclosure, (see Fig. 6) is designed to plug into the PFN and load cables. The PFN cables are charged to 32 kv by external power supplies. External units supply trigger and core reset bias pulses to the switch chassis. The trigger pulse is fed through an adjustable delay and suitable grid isolation. The core reset bias pulse is used to drive the cores into reverse saturation in order to obtain the maximum possible flux change. This pulse is fed to the output cables through suitable isolation and is transmitted to the cores by the load cables. The switch chassis has a high frequency response resistive attenuator which is used to monitor the cathode.

TABLE III

Test Results of Thyratron Tube Testing (0.4-μsec Pulse)

Tube*	Rating				Tested At:				Circuit Impedance Load + Source ohms	Rise Time 10 - 90% nsec	Approx. Cost in Large Quantity $	Comments
	Volts kv	Peak Current amp	Peak Power Mw	P_B Factor $\times 10^{-9}$	Volts kv	Peak Current amp	Peak Power Mw	P_B Factor $\times 10^{-9}$				
A	16	325	2.6	3.2	16	1600	12.8	1.5	10	60	21	Did not attempt higher voltage
B	16	325	2.6	3.2	32	2240	36.	4.3	14.3	40	40	Used a low inductance version & pre-aged at 35 kv
C	33	2000	33	20	32	3850	61	7.4	8.3	100	600	Rise time long
D	33	2000	33	30	32	3850	61	7.4	8.3	25	1200	High cost/amp
E	33	2000	33	40	32	3850	61	7.4	8.3	25	1200	High cost/amp
F	25	500	6.25	6.25	32	2240	36	4.3	14.3	45	60	Prefire good, Low cost/amp

* A - Kuthe 5C22; B - Kuthe 6587; C - Kuthe 1257; D - GE GL7390; E - Kuthe KU-74; F - Kuthe and Tung-Sol 5949A

The circuit details will be discussed below.

Switch Chassis (Fig. 7)

Switch and Housing. The 5949A is mounted in an inexpensive cast aluminum housing with features to minimize the insertion inductance. The housing also reduces the x-ray radiation from the grid-to-anode region that occurs primarily during the PFN charging cycle.[15] The rise time of the switch chassis into a termination consisting of seven RG-213/U cables in parallel has been measured at 0.05 μsec from the 10 to 90% amplitude points, see Fig. 8. Neglecting the ionization time, the insertion inductance is 0.325 μh calculated as follows:

$$T_r = 2.2\ L/2Z_0 ,$$

$$L = \frac{T_r\ 2\ Z_0}{2.2} ,$$

where

T_r = rise time in seconds, 10 to 90% of amplitude
= 0.05 μsec,

Z_0 = characteristic impedance of charge line

$= \frac{50}{7}$ ohms,

$$L = \frac{0.05 \times 10^{-6} \times 2 \times 50}{2.2 \times 7}$$
= 0.325 μh.

Grid and Cathode Isolation. An unusual isolation design is necessary in order to accomplish the following:

(1) Allow a low-frequency reset pulse (200 μsec long) to pass to the cathode, but keep the fast cathode pulse from being deteriorated by the reset circuit.
(2) Allow the fast trigger (0.3-μsec square pulse) to appear from the grid to cathode, but not affect the cathode pulse.
(3) In addition, supply heater and reservoir current via circuits that are isolated from the cathode sufficiently so as not to cause excessive ripple on the cathode pulse.

The heater and reservoir isolation were solved by the use of a special filament transformer (T-1) designed for low secondary-to-primary capacitance (80 μμf maximum) and the ability to withstand the cathode high-voltage pulse from secondary to primary. This combination of requirements results in a somewhat bulky, inefficient transformer, however, this is of little importance to this application. The addition of isolating inductors in series with each filament lead could be used to improve the response, if needed.

The choke L-2 was made by winding approximately 100 turns of RG-58/AU on a 1-inch × 3-inch mandrel. The trigger pulse is applied between the inner conductor and the braid. It is coupled to the braid with a small 0.1-μf capacitor, C-2. This capacitor is a high impedance to the reset pulse, which is applied between the braid and ground. The output of the choke L-2 is connected as follows: inner conductor to the grid (via choke L-1, which isolates the input trigger line from a 30-kv spike that occurs at the grid when the anode-to-grid region fires); and the braid to the cathode. Thus, the trigger pulse appears satisfactorily from grid to cathode and the reset bias pulse current passes through the braid to the cathode. The inductance of the braid is sufficient to isolate the cathode from ground for a pulse width of 0.4 μsec. The inductance of the braid is about 200 μh. The time constant, L_1/R-25 was set at 60×10^{-9} which limited L_1 to 3.3 μh.

A voltage develops between the grid and the cathode due to transformer coupling through L-2 from the reset bias. This causes some variations in anode firing or intermittent firing. In the final system, the PFN's will be pulse charged in 1 millisecond and held at high voltage for 2 milliseconds before firing the switch chassis. The reset bias can be applied during the anode off time, which eliminates any difficulty from the reset bias feed-through to the trigger circuit.

Adjustable Trigger Delay. The specifications for a trigger delay are:

Delay time pulse voltage	0 to 105 nsec
Peak pulse voltage	2500 volts
Pulse duration	0.3 μsec
Response	20 nsec
Repetition rate, maximum	60 pps
Input impedance	50 ohms
Output impedance	50 ohms
Resolution	5 nsec

We were unable to procure a commercial unit to meet our specifications. We adopted a design using toggle switches and short sections of RG-58A/U cable for delay. Standard toggle switches were life tested and operated satisfactorily at the high pulse voltages.

Cathode Monitor. The cathode monitor is a simple, high-resistive network designed for 100-to-1 attenuation into 50 ohms. In order to obtain the required response with minimum ringing, it was necessary to put the divider string inside the thyratron housing. In the final design the resistors were molded into the cathode support in order to save space and minimize possible breakdown to ground planes.

Pulse-Forming Network

The network requirements for each switch chassis are:

Peak voltage	32 kv
Pulse width, 70% amplitude	0.330 μsec
Rise time, 0 to 100%	0.050 μsec
Fall time, 0 to 100%	0.050 μsec
Impedance	7.14 ohms
Repetition rate, maximum	60 pps
Flat portion, constant amplitude	to ±0.25%
Flat portion, minimum length	0.3 μsec
Life at 32 kv, 60 pps, minimum	10,000 hours

Various types of pulse-forming networks were considered and an early decision resulted in the use of RG-218/U transmission lines. This decision was made because of the following:

(a) No known lumped-constant PFN would do the job and it would be time consuming to procure and test a new design.
(b) The pulse characteristics of RG-218/U are very satisfactory and result in low ripple and fast rise time.
(c) Limited life tests at 32 kv had been performed with no failures.
(d) Short delivery.
(e) Low Cost.

An early decision was required in order to complete the basic modulator design. The drawbacks to the use of 218/U were the unknown life at 32 kv, 60 pps, and the difficulty of handling the 500,000 feet needed. Subsequent life tests have shown reasonably long duration, however, it is apparent that a life less than 7,000 hours will be attained. This is less than expected and a new design will be needed for reliable operation at a sustained repetition rate of 60 pps.

The physical handling of the cable has been solved by winding the cable on reels and connecting the ends to fixed plugs which are mounted in racks. The cable reels are mounted on two platforms as shown in Fig. 9. Ample room has been allowed so that defective reels can be replaced.

Connector Design

Several varieties of coaxial connectors were designed for use with RG-213/U and RG-218/U at high pulse voltages. We felt it was very desirable to avoid the use of oil, however, the small spacings allowable created a severe corona problem. The corona eventually deteriorates the polyethylene by boring through it and causing catastrophic breakdown. In all of the RG-213/U connectors a cylindrical sleeve of isomica (silicone bonded mica) insulation was used to protect the cable dielectric from corona bombardment. This has worked satisfactorily and the connectors have been life tested at 32 kv (actual use will be at 16 kv) for over 1,000 hours at 60 pps. This design protects the polyethylene from corona, however, after long use at 60 pps the corona causes deterioration of surrounding metal surfaces and ultimately the connector must be serviced by cleaning.

Performance Characteristics of the Modulator

The performance specifications required of each modulator channel incorporating one switch chassis and terminated in a resistive load of 7.14 (50/7) ohms are listed in Table IV

Peak Current

The maximum current demanded by the circuit (see Fig. 5) is

$$I_m = \frac{V_c}{Z_0 + Z_1} = \frac{32{,}000}{\frac{50}{7} + \frac{50}{6}} = \frac{32{,}000}{\frac{650}{42}} = \frac{42}{650} \times 32{,}000$$

$$= 2070 \text{ amp.}$$

The modulator performs satisfactorily and does not appear to be approaching a maximum pulse current limitation.

Hold-Off Voltage

The anode voltage rises in about 2 msec (see Fig. 10) and the switch chassis are fired about 1 msec after the peak voltage is reached. The modulator has worked well up to 32 kv under such conditions. In order to obtain such performance on 25-kv tubes we have pre-aged the tubes. The aging process is a run-in time of 12 hours at 33 kv. The optimum reservoir setting is determined during the aging process. A 5 to 10% reduction of the manufacturer's recommended reservoir setting aids in voltage holding. However, too much reduction reduces the maximum rate of rise of anode current (see Fig. 11).

Peak Power

The output is approximately 36 Mw and the modulator operates satisfactorily. We have not attempted to make higher peak power runs.

TABLE IV

Peak power	36 Mw
Output voltage	8 to 16 kv
Output current	1120 to 2240 amp
Average power	680 watts
Load impedance	50/7 ohms ±2%
Anode current (average)	0.054 amp
Anode current (rms)	11 amp
Pulse length (flat region)	0.3 μsec
Rise time (10 to 90%)	50 nsec
Fall time (10 to 90%)	50 nsec
Pulse repetition rate	0 to 60 pps
Time jitter	±5 nsec
Pulse-to-pulse amplitude jitter	±0.25%
Pulse ripple	±0.25%

Average Power

Twelve test modulators have been run at an average power of 680 watts each, with a combined running time of over 10,000 unit hours. The highest component failure rate was due to connectors.

Anode Delay

The anode delay is a function of repetition rate, peak current, anode voltage, trigger voltage, and possibly other things such as the ambient temperature. We have experienced variations up to a maximum of 40 nsec during a 15-minute period after changing the repetition rate from 10 pps to 60 pps. (See Fig. 12.) Similar variations occur when the anode voltage is changed from 20 kv to 30 kv. The exact cause of this effect has not been determined although it is felt that it is related to gas pressure that may be changing due to increased tube dissipation (heating) at higher currents or repetition rates. The anode delay vs trigger voltage is shown in Fig. 13 and clearly indicates excellent performance above 1700 volts.

Jitter

The jitter is less than ±2 nsec with the exception of the long-term drifts discussed above.

Prefire Characteristics

The life tests on the 6587 tube revealed a prefire rate of up to two per hour at 32 kv, 60 pps. This would mean an average of nearly three per second in a system involving 500 tubes. The larger size thyratron (Type 5949A) was chosen in hopes of reducing the prefire rate. Subsequent testing showed that the type 5949A has an insignificant prefire rate at 32 kv, using pulse charging of the PFN's per Fig. 10.

Output Pulse Characteristics

Rise times of 50 nsec (10 to 90%) have been realized into a load impedance consisting of seven RG-213/U cables (7.07 ohms). This rise time could be improved slightly by a lower inductance coaxial structure, however, the tube inductance will ultimately be the major limitation. This rise time was adequate for our purposes.

Effects of Load Shorts

The peak current rises to nearly 5,000 amperes if a short or an arc develops from cathode to ground. The tubes will operate under conditions of random faults and do not appear to be damaged. Under conditions of a continuous fault, our experience has been that other components fail before the tube (insulator, or cables burning). However, in some cases the tubes have been damaged by running several seconds at the increased current conditions.

Life Tests at 28 kv, 60 pps

Switch Tube. One type 5949A thyratron has been life tested continuously at 28 kv, 0.4 μsec, 60 pps, for over 5,000 hours. This particular tube has outlasted several designs of connectors and mounting hardware. Several other type 5949A's have been used in excess of 1,000 hours without failure. Numerous tubes have been aged satisfactorily up to 100 hours of life.

PFN. Tests on the PFN cable reels reveal an approximate MTBF of 5,000 to 10,000 hours. In a system of about 2,000 cable reels, the failure rate may be excessive at both high repetition rate and high PFN voltage. Fortunately, a number of experiments can be carried out at lower repetition rates. A program has been initiated to design an improved PFN.

Anode and Cathode Connectors. Various connectors have been tested at a peak voltage of 30 kv, 0.4 μsec, 60 pps, and satisfactory operation has been attained in excess of 2,000 hours. In actual practice, the maximum pulse will be 16 kv, therefore it is hoped this design will be sufficiently reliable to operate nearly 3,000 connectors in the system. It is expected that a preventive maintenance program may be required to clean parts corroded from ozone.

Conclusions

As a result of extensive testing and development, we believe the type 5949A hydrogen thyratron can be successfully used as the switching component of a 36-Mw modulator and operate at

(a) four times rated peak current (2240 amp),
(b) five times rated peak power (36 Mw),
(c) twenty times rated maximum amp/μsec (50,000 amp/μsec)

and yield reasonable life of three to five thousand hours at 60 pps, 0.4 μsec pulse width.

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Initial testing of 6587 tubes: D. O. Kippenhan
Hard-tube modulators: K. Aaland, G. A. Reeser, and B. M. Loth
Life testing: H. M. Graham
Final design of the switch chassis: C. D. Nail, K. A. Saunders, and L. L. Steinmetz.

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FIGURE CAPTIONS

Fig. 1. Compensated core waveforms. Sweep speed 100 nsec/cm.

Fig. 2. Input core impedance (primary voltage/primary current) vs time during voltage pulse.

Fig. 3. Simplified schematic of hard-tube modulator used for core testing.

Fig. 4. Core testing setup with hard-tube modulator.

Fig. 5. Block diagram of modulator system.

Fig. 6. Switch chassis.

Fig. 7. Schematic of switch chassis.

Fig. 8. Waveforms of output of switch chassis terminated in a 7.14-Ω load.

Fig. 9. Installation of PFN reels and racks for switch chassis. (Showing about 40% of the final system.)

Fig. 10. Waveform of pulse charging of PFN of modulator. Sweep speed 500 μsec/cm, vertical sensitivity 10,000 volts/cm.

Fig. 11. Waveforms of core output showing effects of low reservoir settings. Sweep speed 100 nsec/cm, vertical sensitivity 7000 volts/cm.

Fig. 12. Waveforms from eight switch chassis fired simultaneously showing variations in anode delay caused by increasing repetition rate from 10 to 60 pps. Sweep speed 20 nsec/cm.

Fig. 13. Anode delay vs trigger voltage.

/wa

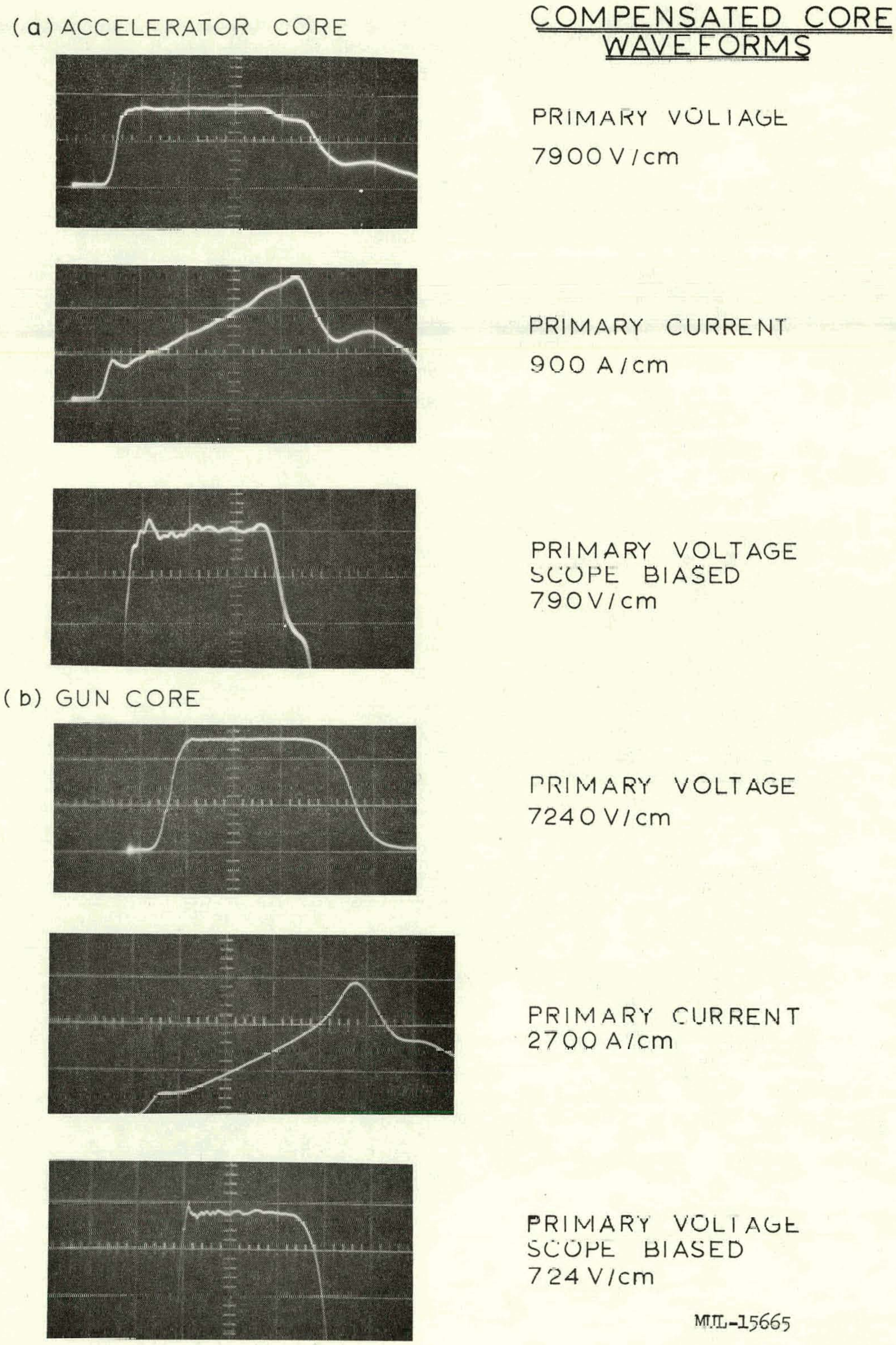
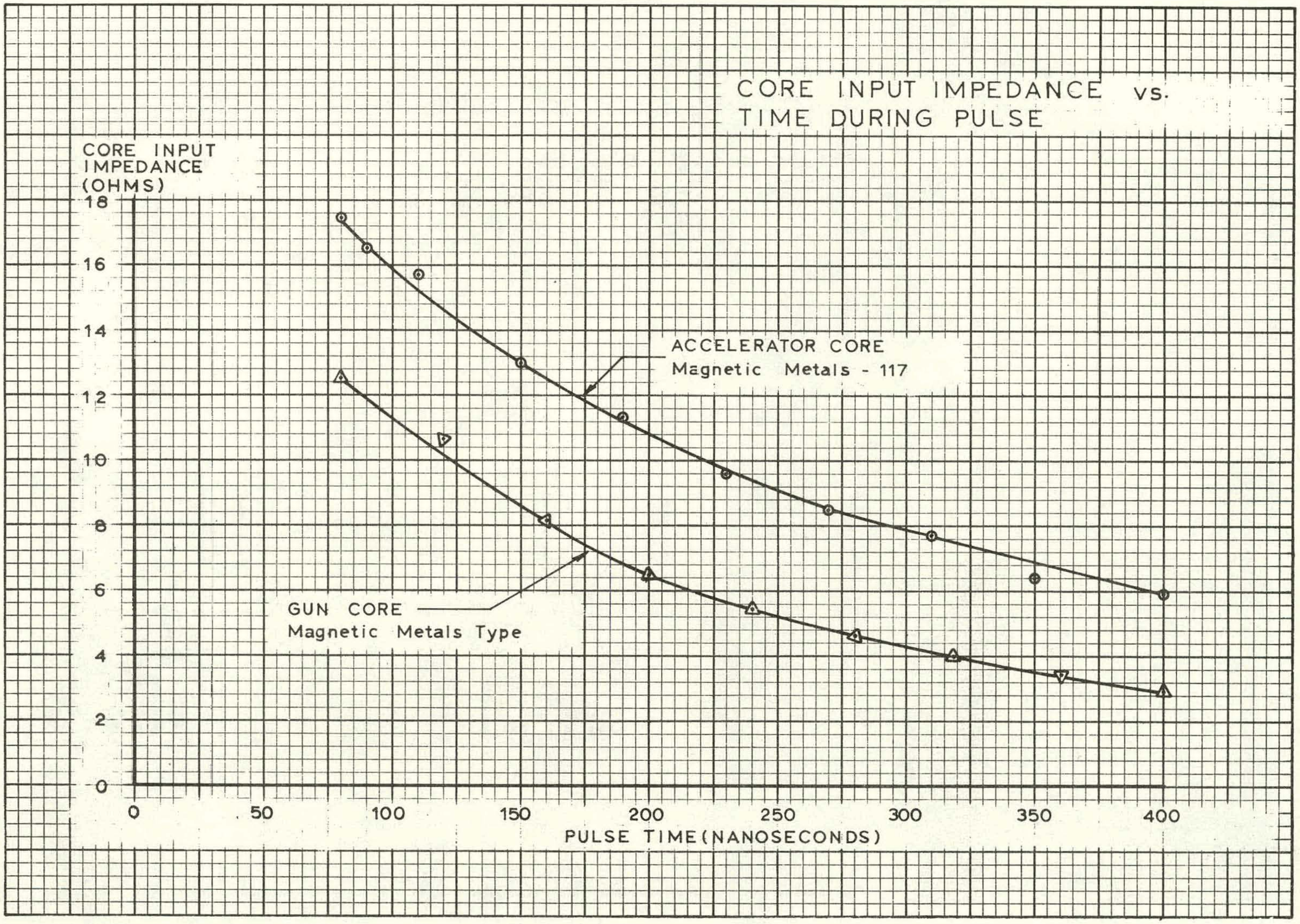
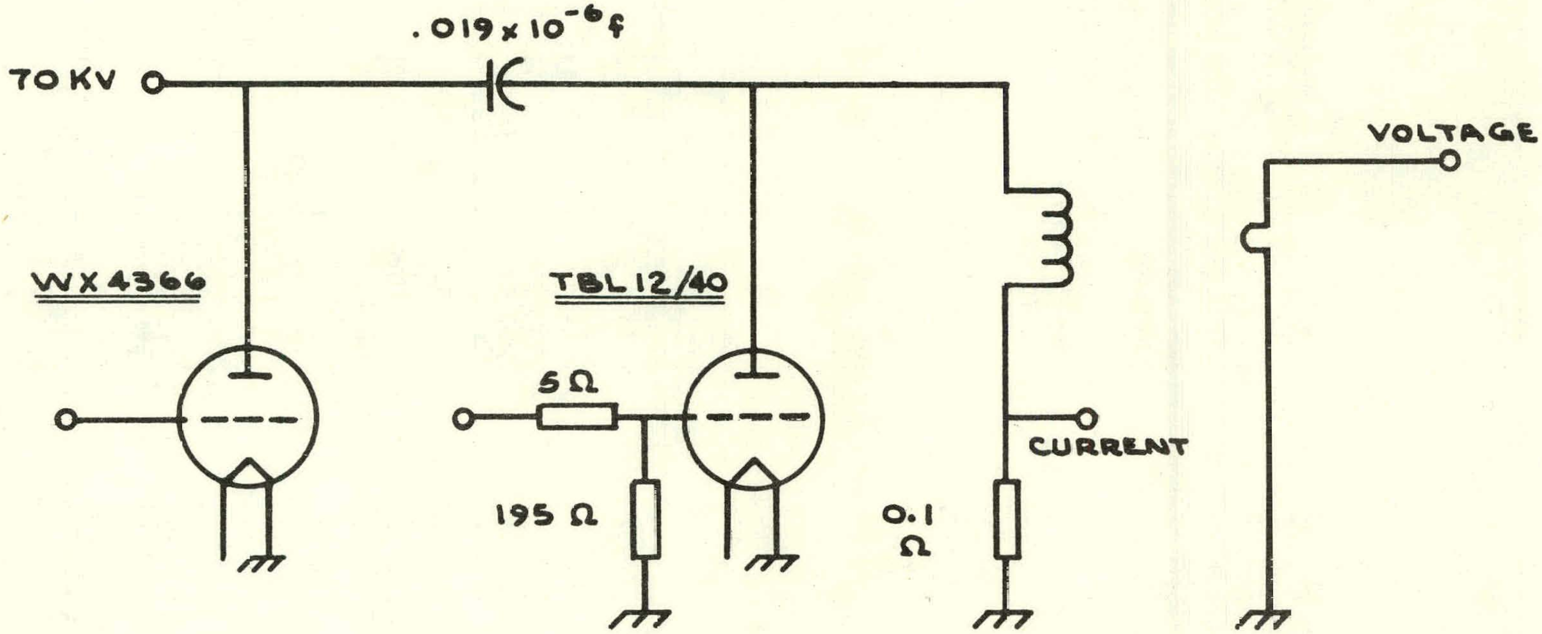


Fig. 1. Compensated core waveforms. Sweep speed 100 nsec/cm.



MUL-15668

Fig. 2. Input core impedance (primary voltage/primary current) vs time during voltage pulse.



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30 MW CORE PULSER
(SIMPLIFIED SCHEMATIC)

Fig. 3. Simplified schematic of hard-tube modulator used for core testing.

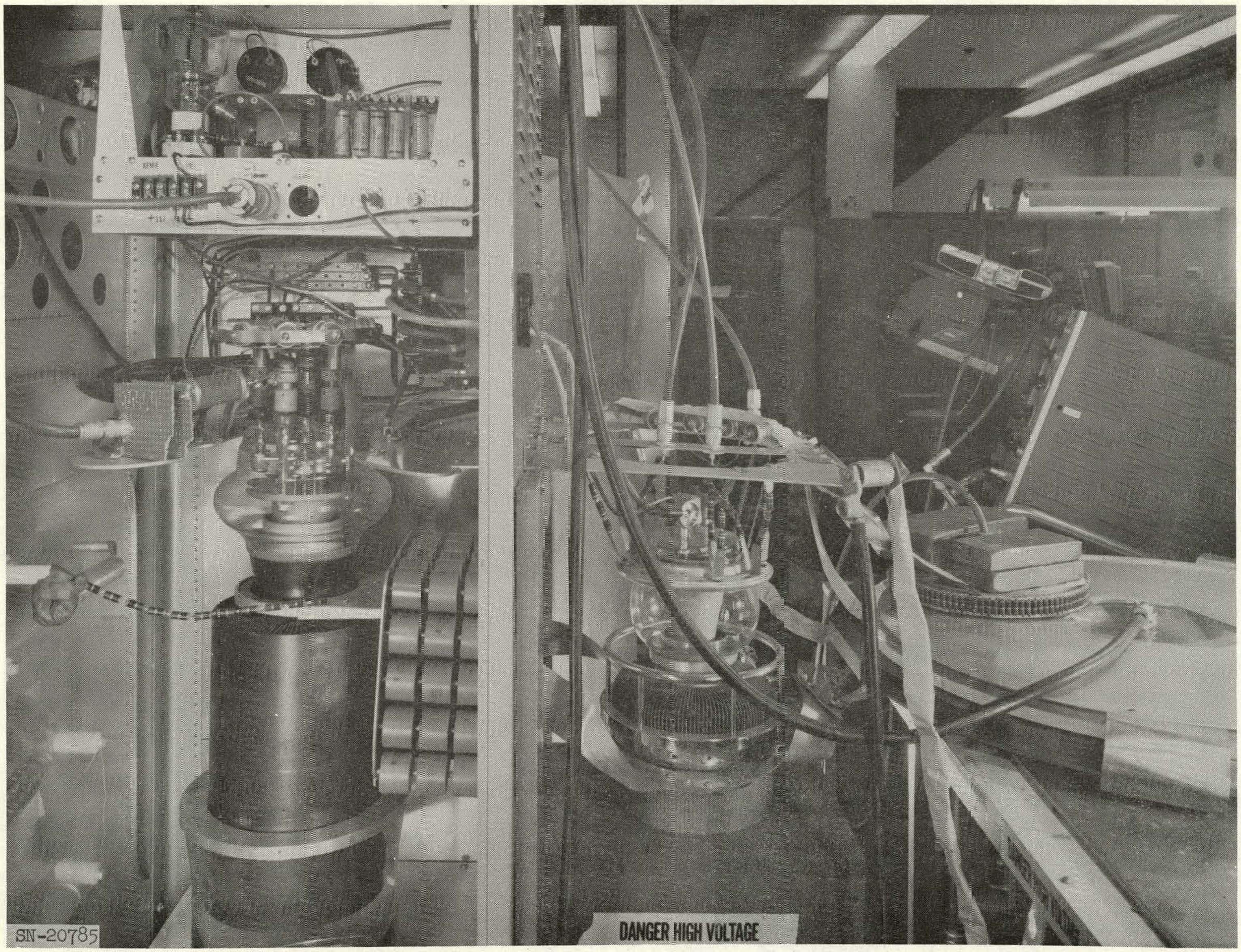

Fig. 4. Core testing setup with hard-tube modulator.

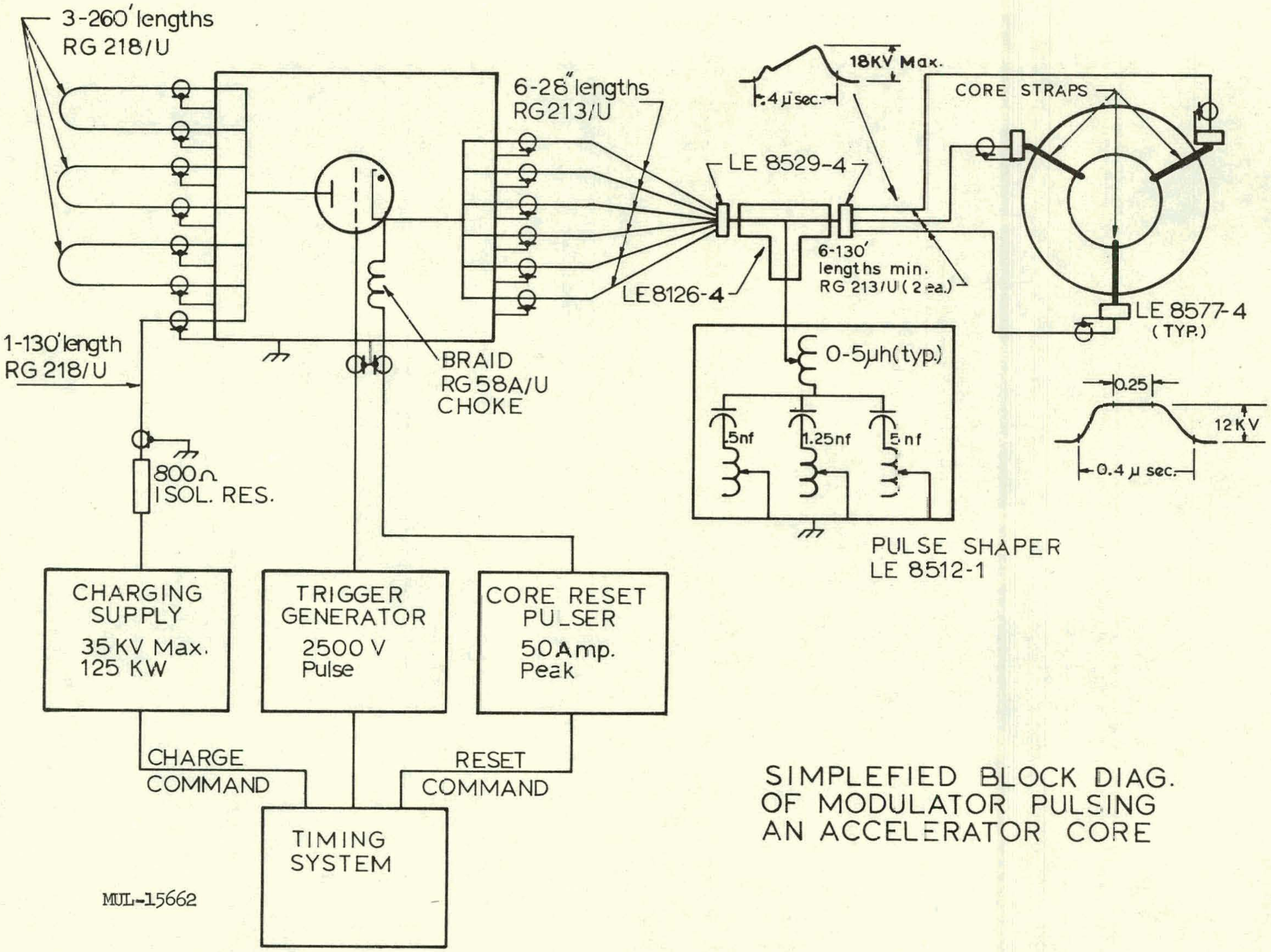

Fig. 5. Block diagram of modulator system.

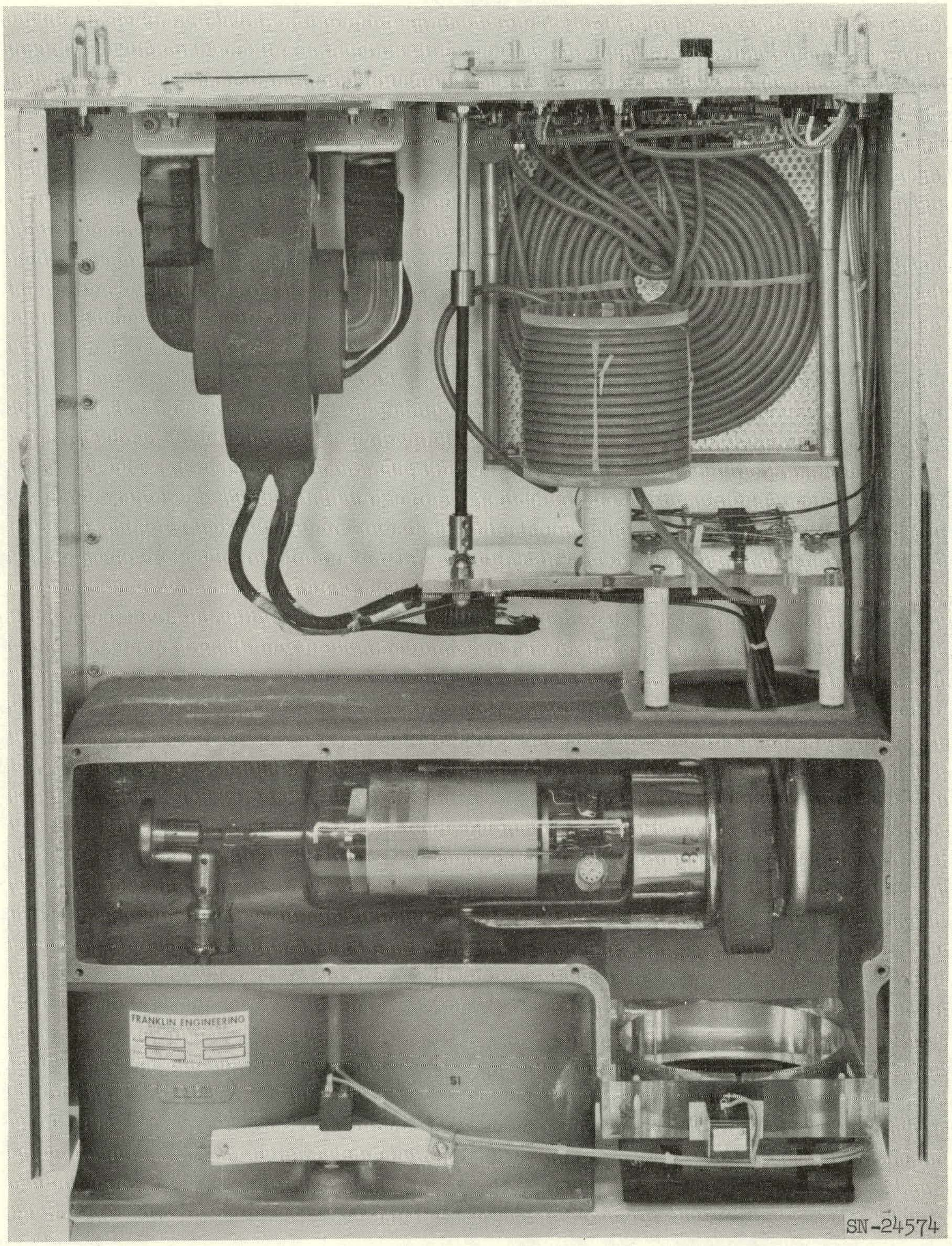

Fig. 6. Switch chassis.

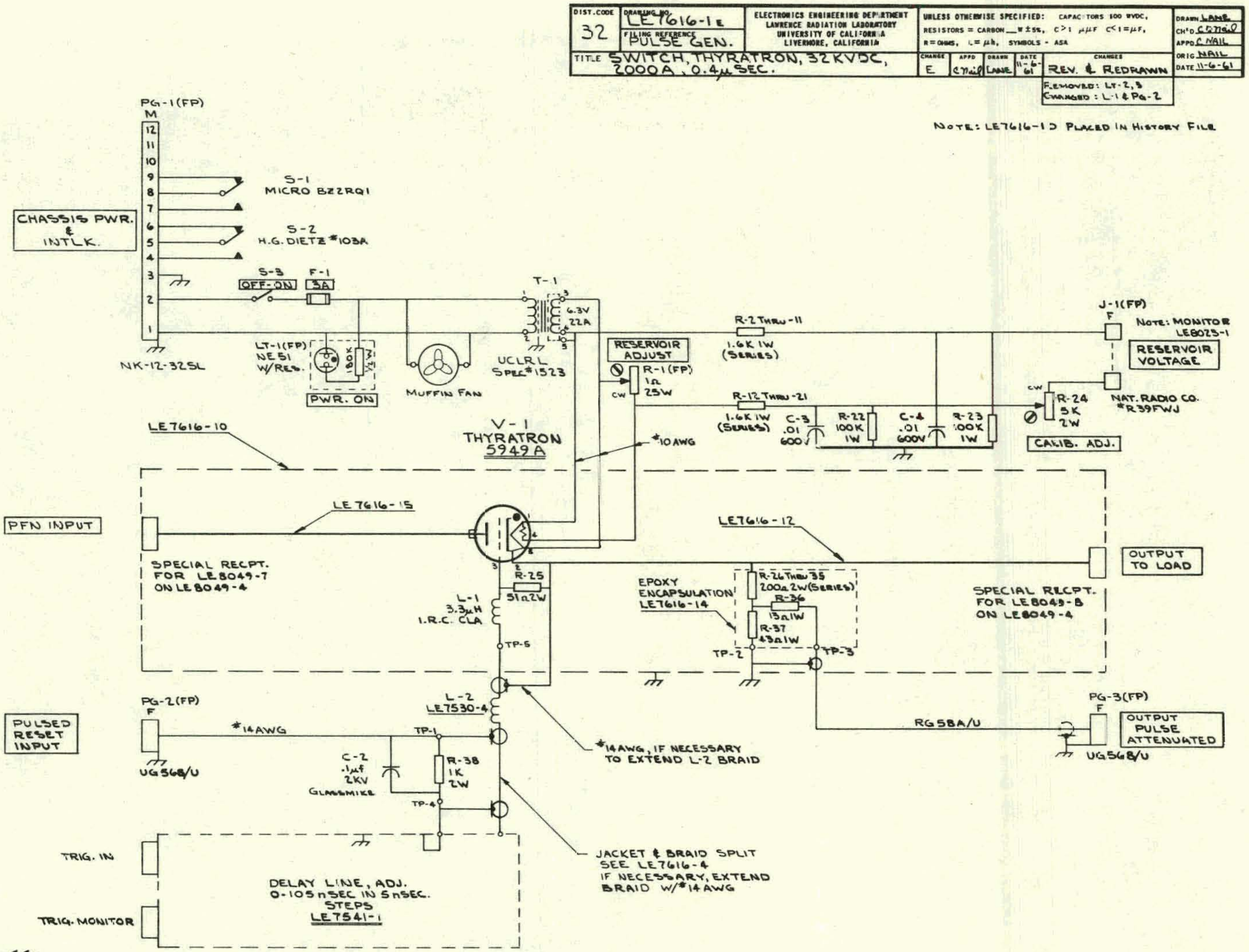

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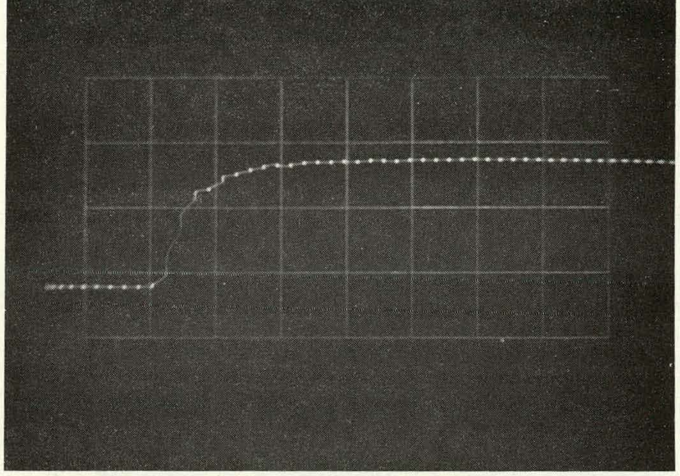
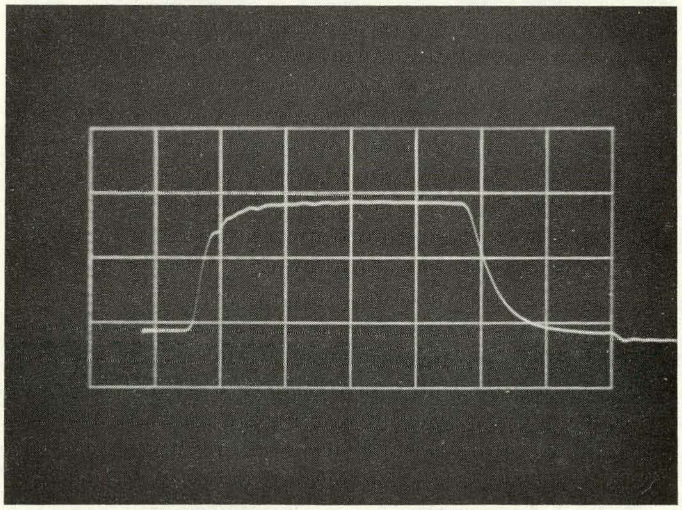
Fig. 7. Schematic of switch chassis.



SWEEP SPEED: 50ns/cm
TIMING FREQ: 100mc
applied to Horizontal
Deflection Plates
("DOT ROSSI" Technique)



SWEEP SPEED: 100ns/cm

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Fig. 8. Waveforms of output of switch chassis terminated in a 7.14-Ω load.

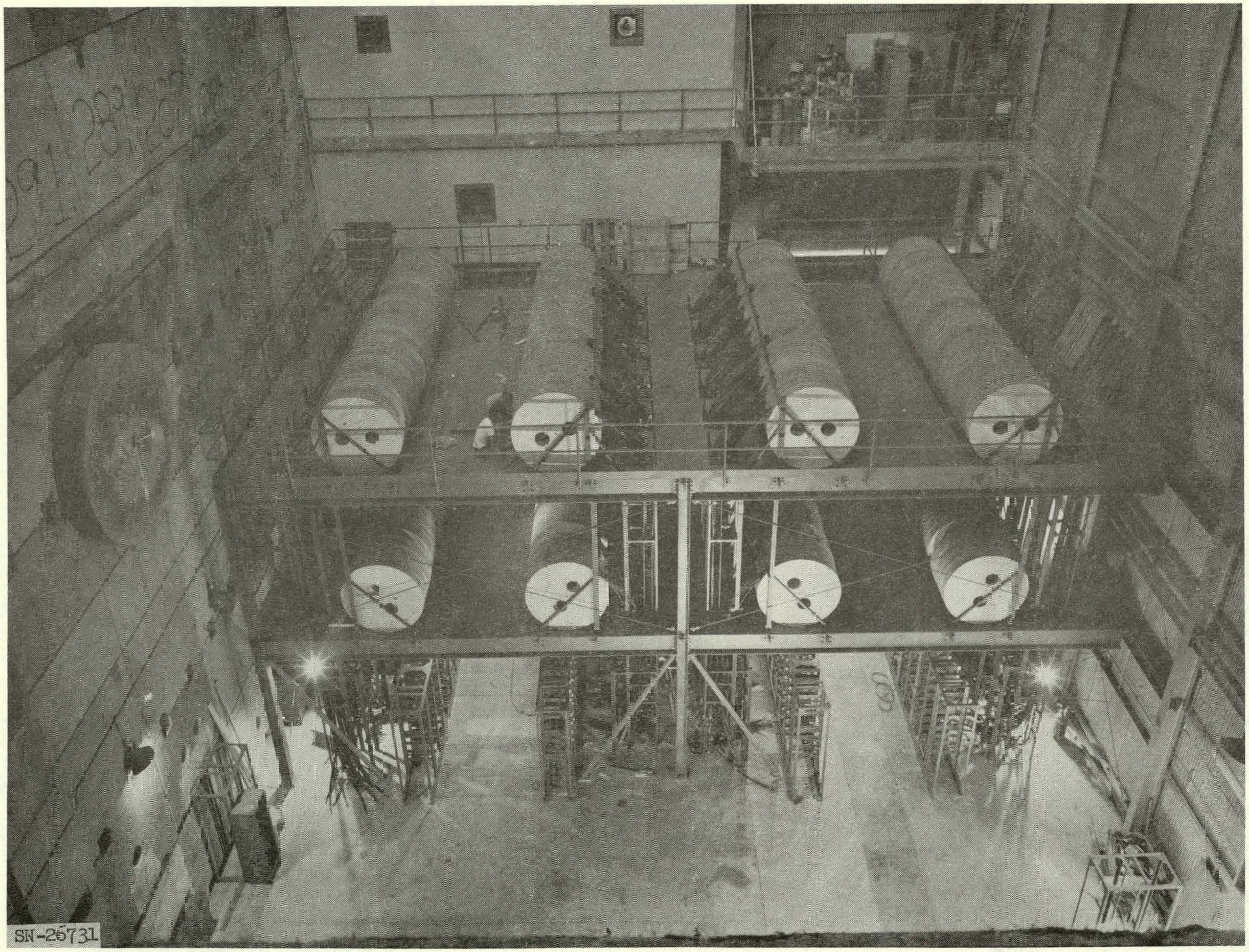
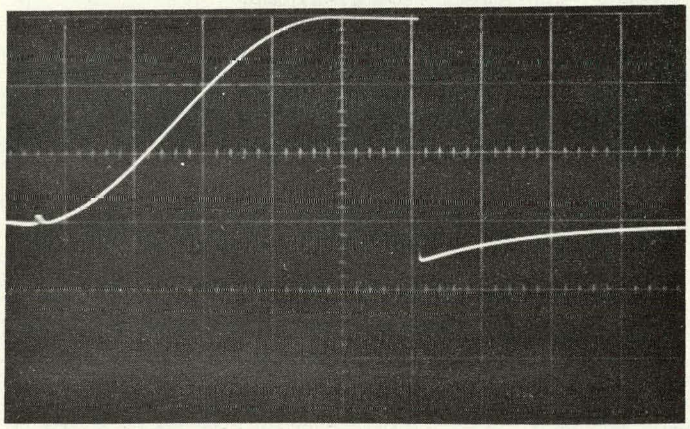
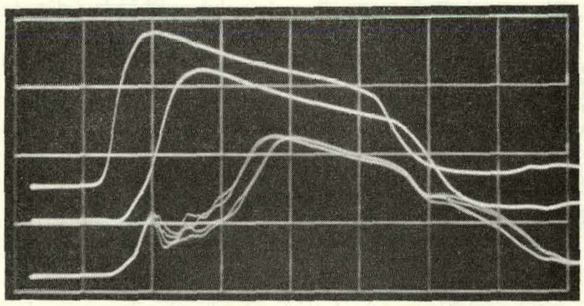


Fig. 9. Installation of PFN reels and racks for switch chassis. (Showing about 40% of the final system.)



MUL-15667

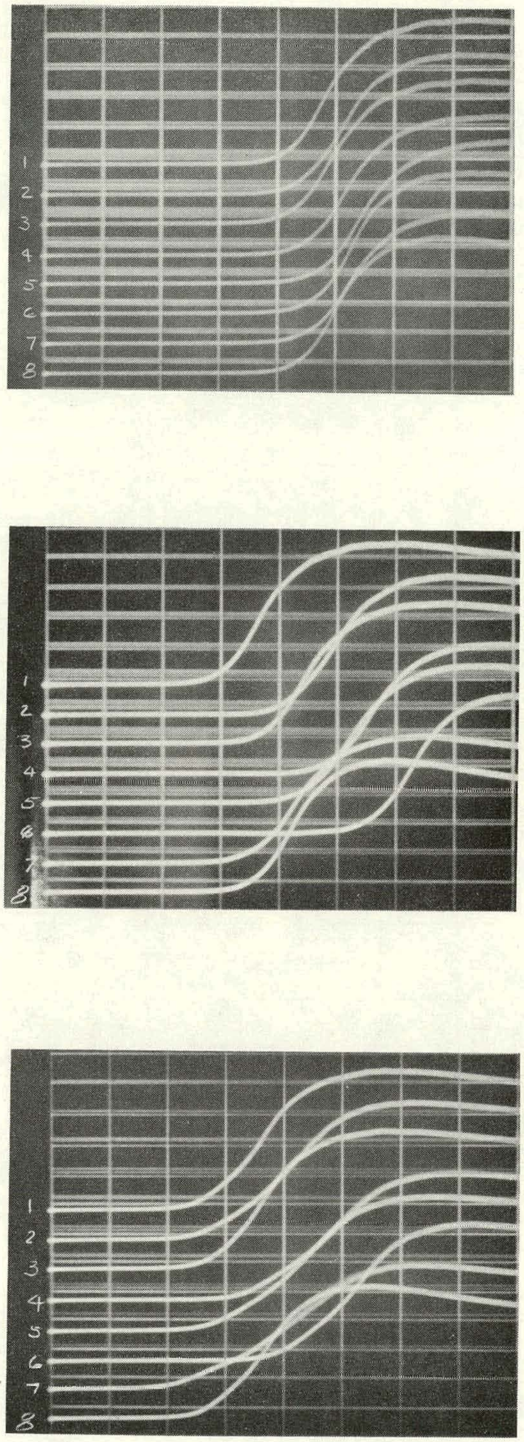
Fig. 10. Waveform of pulse charging of PFN of modulator. Sweep speed 500 μsec/cm, vertical sensitivity 10,000 volts/cm.



TOP TRACE: NORMAL RESERVOIR SETTING 5.1 V
CENTER TRACE: 30 sec. AFTER CHANGING RES. TO 4.4 V
BOTTOM TRACE: 2 min. AFTER CHANGING RES. TO 4.4 V

MUL-15664

Fig. 11. Waveforms of core output showing effects of low reservoir settings. Sweep speed 100 nsec/cm, vertical sensitivity 7000 volts/cm.



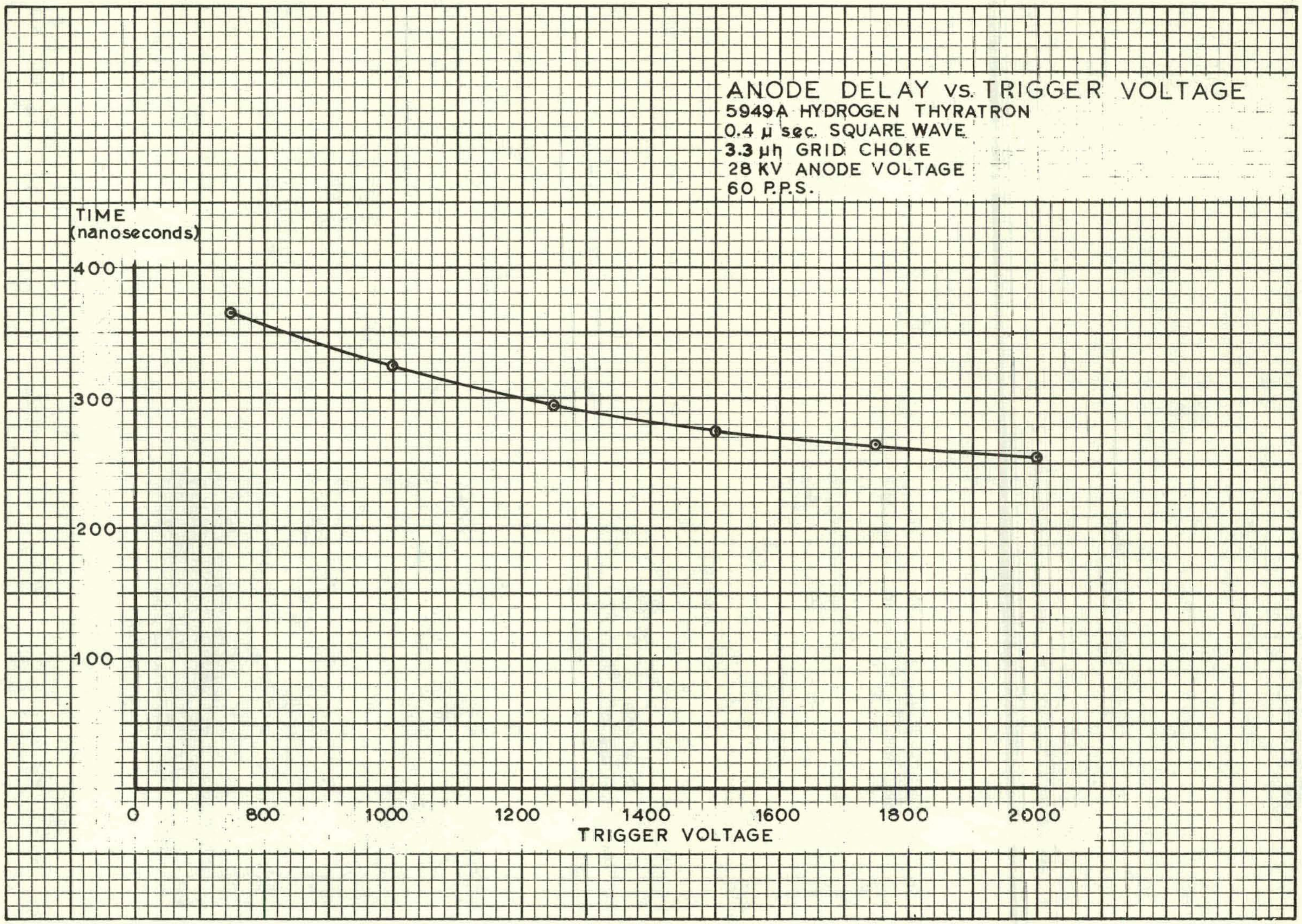
START OF RUN
30 KV
10 P.P.S.

1 MINUTE AFTER
REPETITION RATE
CHANGED TO
60 P.P.S. AT 30 KV

15 MINUTES AFTER
REPETITION RATE
CHANGED TO
60 P.P.S. AT 30 KV

MUL-15663

Fig. 12. Waveforms from eight switch chassis fired simultaneously showing variations in anode delay caused by increasing repetition rate from 10 to 60 pps. Sweep speed 20 nsec/cm.



MUL-15669

Fig. 13. Anode delay vs trigger voltage.