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Pulsed Power Supplies for RHIC

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Collider Accelerator Department

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RHIC PROJECT

Brookhaven National Laboratory

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1. INTRODUCTION

Pulsed power supplies are needed in RHIC to accomplish injection and ejection (beam abort). The intent of this note is to provide feasible engineering design for these devices. It is recognized that these are by no means the final designs. However, they represent a significant step forward from the general description given in the Conceptual Design Report (CDR)[1.] They can be regarded as the first of several iterations that will finally result in the installation of the equipment. Even in this early design stage they will be useful for cost estimating purposes - such an analysis may result in design or specification changes if it is felt the costs are too high.

1.1 RHIC ASSUMPTIONS

The overall design of RHIC is an evolving process; the conceptual design is already obsolescent. Some assumptions about the machine design can have a very significant impact on the pulsed power supplies, other machine changes can be accommodated quite easily. For example, the bunch to bunch spacing is a critical parameter when designing the injection fast kicker system but changes slightly in the deflecting angle can often be achieved by adjusting the maximum charging voltage without changing the circuit design. The following assumptions have been made about the operating characteristics of RHIC and the AGS which may require major changes to the designs presented below if they turn out to be invalid.

Injection

Beam Rigidity	:	100 Tm
Mode	:	Single bunch transfer stacked box car in RHIC
Timing	:	3 bunches in AGS are extracted one at a time at 20 ms intervals. AGS recycles in 0.5 sec and accelerates 3 more.
Nominal bunch spacing	:	114 buckets in RHIC can be filled. In practice several adjacent buckets will be left empty to facilitate beam abort, see below. This implies 112 ns between bunch centers.

Ejection

Beam Rigidity	:	30 to 1000 Tm
Arming Time	:	Time between beam abort command and actual ejection is ≈ 300 μs.
Missing bunches	:	7 buckets not filled, this leads to a time of ≈ 900 ns for rise-time of the ejection kicker.

2. INJECTION

Many injection schemes and the supporting power supplies have been investigated.[2] All share the common concept of a bending magnet followed by a full aperture fast kicker spaced an appropriate integer of 1/4 betatron wavelengths away. In practice, for this stage of design, the choice of vertical or horizontal deflection does not impact significantly on the fast kicker. The bending magnets considered are 'C' magnets with high current septa, a variety of designs have been investigated[3]. Here again many changes can be made without significantly changing the power supply design. The aperture length and deflecting angle set the total stored energy; these parameters are relatively fixed. A more serious consideration involves losses during the excitation period: these must be restored to the power supply before the next cycle (assuming a pulsed supplier is used).

The original specifications for the fast kicker given in the CDR called for a deflection angle of 1.3 mrad with a tolerance of 0.1% - a figure that reflects the portion of the tolerance budget causing emittance blow-up that was assigned to the kicker. This tolerance includes voltage recharge variation and ripple on the waveform that may cause deflection variation between portions of the same bunch. Such a tight tolerance can only be achieved with a traveling wave structure as the deflecting element[4,5]. A design for such a kicker was investigated - the major characteristics are given in Table 1 based on 171 bunch stacking. The strip-line deflector uses both the magnetic and electric field to deflect the beam. However the impedance is relatively high and the operating voltage tends to be high. Suitable switches were not located, although development of the back-lighted thyratron or laser triggered spark gap may result a feasible switch[6].

2.1 Design of "Strip line"

A cavity type structure propagating a TEM wave exerts a force to kick the beam due to both the electric and the magnetic fields of the wave. The two kicks are of equal magnitude. If the beam travels in a direction that is opposite to the velocity of the wavefront then the forces are additive, doubling the magnetic kick; otherwise the forces subtract, and the net kick is zero. Consider a cylindrical cavity with two parallel electrodes as is shown in Figure 1. The electrodes and cavity form two transmission lines. Each transmission line is terminated in its characteristic impedance. The two lines are excited push-pull from two PFN's, with a push-pull output and a common trigger.

The incident wave will kick the beam; whereas reflections due to a mismatch at the termination will not exert any force on the beam.

The electrodes are shaped to produce a uniform field in an aperture of 6 cm by 6 cm. The cylindrical cavity has a diameter of 14.4 cm. The nominal impedance level of the structure is 50 ohms. The electrode shape is specified in Figure 2. All dimensions are given in cm. The shape is scaled from the Los Alamos PSR fast-extraction kicker[7]. The calculations were performed for a nominal impedance of 50 Ω. The design can be scaled to 150 Ω, see below.

The field pattern is given in Figure 3. The field analysis was performed using the program FISH. The contour lines given in Figure 3 describe both the electric and the magnetic fields within the structure. They are lines of constant potential or lines of constant H.

The characteristics impedance Z_0 can be determined from the inductance L of the structure

$$Z_0 = cL$$

where $c = 3 \times 10^8$ meter/sec and L is expressed in Henrys/meter. The value of L can be given analytically by employing the method of geometric - mean distance, as is commonly used in calculating inductance values for long parallel structures. Following the development in Woodruff, and modeling this structure as a rectangle inscribed within a circle[8].

$$L = \left(2 \ln \frac{R}{0.2235 \left(\frac{S}{2}\right)} - 0.5\right) 10^{-7} \; \textit{Henry/meters}$$

where R = radius of cavity, and

S = periphery of electrode

The factor of 0.5 x 10^{-7} is a high-frequency correction, used for the fully developed skin-effect situation. For this structure

$$R = 7.2 \text{ cm}$$

$$S = 20.14 \text{ cm}$$

L is calculated to be 1.84 x 10^{-7} H/meter and Z_0 to be 55.2 ohms

The value of inductance can also be obtained from the programs FISH or PE-2D. These programs also output the stored energy per unit length U:

$$U=\frac{1}{2}\,LI^2$$

where I is the electrode current.

The analytic expression is useful when designing the injector for different impedance levels. A preliminary design for a 150 Ω inflector has been investigated using a 7 cm radius vacuum chamber. The parameters were confirmed using POISSON. The 50 Ω, 171 bunch design has the following nominal parameters:

Length	:	7m	
Deflection	:	2 x 10^{-3}	radian
Rigidity	:	100 Tm	

The field in the aperture is:

$$B = 143 \text{ Gauss}$$

$$E = 4.29 \times 10^6 \text{ volts/meter}$$

The field is uniform (at the median) over a separation of 8.26 cm. The system voltage is 354 KV or ± 177 KV. The current in each line is 3.2 KA. The required voltage is uncomfortably high.

2.2 Lumped Ferrite Magnet Pulser

Recently injection schemes have been proposed which require much lower tolerances for the fast kicker deflection angle[9]. This change permits consideration of the conventional kicker consisting of a ferrite picture frame magnet and deuterium thyratron switch - a circuit which was first developed at BNL for extraction of the AGS beam[10]. These earlier designs used a pulse-forming network consisting of distributed cables and discrete L-C components. Also the circuit consisted of the conventional modulator, in which about one-half of the network charging voltage appears across the load. When very fast rise-times are needed the circuit impedance must be raised to the highest practical value, a level that is usually limited by the hold-off voltage of the switch. During the development of radar modulators in WWII the factor of two between charging and load voltages was a drawback to high altitude operation and Alan Blumlein invented a circuit with two PFN's which resulted in the load voltage equalling the charging voltage[11]. This circuit has been refined for fast kicker applications to a high degree at SLAC, where it is used to produce short, fast rise-time pulses for the positron damper ring injection and ejection kickers[12]. There are drawbacks to the Blumlein - the wavefront in one PFN makes three transversals and dispersion results in some degradation of the rise time. This is not a serious problem for very short pulses which need only a distributed PFN without lumped elements. The basic circuit and waveforms of the Blumlein kicker are shown in Figure 4. The specifications for the RHIC deflector are given in Table 2. The circuit diagram of the Blumlein kicker is shown schematically in Figure 5, this was analyzed using a Microcap simulation program. The waveforms for rise-time and flat-top are shown in Figure 6. The capacitor 'C' in Figure 5 is chosen to cause some ringing and in practice this element may consist of a capacitor with a series adjustable inductor so the current waveform can be adjusted for optimum peak value and minimum rise-time. Other elements in Figure 5 represent stray inductance and capacitance caused by the feedthroughs, switch tube mounting, etc. It can be seen from Figure 6 that the predicted rise-time (1% to 99%) is 80 ns. This allows approximately 10 ns for wavefront propagation in the magnet and jitter.

The computer simulation shows considerable ringing of the magnet current after the pulse is over. This is to be expected when a PFN is discharged into a load with real and reactive components. The only dissapative element in the simulated circuit is the resistor in series with the magnet. Other damping may be needed to prevent ringing persisting 0.9 μsec after the main pulse - the minimum time corresponding to injection of the last bunch into RHIC. It will have to be determined in the prototype if a double-ended thyratron is necessary to handling reverse current in the switch during the post pulse ringing.

The two PFN's comprising each module could be separate or combined into a triaxial structure; a circuit configuration developed at SLAC which leads to a very compact layout. The dimensions of the PFN's are given in Figure 7. Experience at SLAC has also shown that recharging the networks with long terms repetitive accuracy of less than 0.1% can be tricky.[13] The referenced paper discusses means of achieving 0.01%, an accuracy which is unnecessarily tight for RHIC. In order to minimize time on the network at full voltage it would appear quite simple to recharge about 100 μs before firing the kickers; this would require about ~ 100 kW of peak charging power with a resonant supply.

Jitter experienced by the SLAC kicker is about 1 ns, to achieve this a very fast trigger pulse of about 2 kV with 12 ns rise-time is used[14]. Such a pulse couples capacitively into the plate circuit and causes a pre-trigger load current which may exceed the tolerable field levels in the deflection magnet prior to the start of the main current pulse. Elaborate means have to be devised to minimize this effect[15]. It seems very likely that the RHIC kickers could tolerate 2 to 3 ns jitter, which would permit a trigger with a slower rise time and thus avoid significant coupling into the load circuit.

The lumped inductance, picture frame magnet would be built in accordance with standard practices developed for very high vacuum systems such as used in the AGS Booster[16]. SLAC experience indicates adequate frequency response is provided by CMD5005 ferrite*. The magnetic circuit would incorporate a short for flux induced by the beam current in order to reduce the coupling impedance. The transit time of the beam through the four magnets is about 18 ns - a significant percentage of time between bunches. Thus in order to provide a full flat-top during the bunch passage the triggers to the four modules must be appropriately delayed.

2.3 Test of model Blumlein Pulser

A model triaxial Blumlein using a solid-state high speed switches was constructed. The circuit is shown in Figure 8. Dimensions of the pipes are given in Table 3. The values

* Supplied by Ceramic Magnetics, Inc., Sunnyvale, California

shown in Table 3 provide the electrical characteristics shown in Table 4. Although designed for use with oil dielectric it was tested first in air. The solid state MOSFET switch HTS-51 was used for the test. The dc switching test performed on two switch units shows a fast rise time of 2-3ns from 10% to 90% of the full current, at 2000 volt and 69 Ω load condition, as shown in Figure 9a and 9b.

The Blumlein test was first conducted without a strip line deflector. And the storage transmission lines used air dielectric. The initial setup gave a waveform with almost no flat top, as shown in Figure 10. After improvements of the system grounding and cables, a waveform with about 10ns flat top was obtained, as shown in Figure 11. The rise time is fast from 0 to 60% full scale, but slower afterwards.

There are several factors that might affect the pulse shape, such as the switching characteristics, switch "on" resistance, voltage dependence of the switch, grounding loops, the triaxial transmission line inner layer and outer layer impedance mismatch, external loop inductance, device internal inductance, trigger rise time, signal cables and instrumentation, etc.

To correct the leading edge of the waveform, an RC compensated load was tried. The resulting waveforms are shown in Figure 12a and 12b. These waveforms have fast rise-time (≤4ns), and 20ns pulse flat top that matches the designed value. A fast fall-time is not required for 171-bunch injection, because of the bunch-gap reserved for beam extraction.

In the future, the model could be used to evaluate the following problems:

1. Performance of the Blumlein circuit using oil dielectric.
2. Inserting 75 ohm strip line inflector planes, if available.
3. Adjustability of the transmission line.
4. Mechanical structure comparison between the coaxial transmission line pair and the triaxial transmission line.
5. Advanced switch unit test for the full scale system.
6. Construction complexity of the full scale system.

2.4 Septum Power Supplies

The power supplies investigated operate in the usual manner by resonating a large capacitor bank with the magnet inductance to produce a full sine wave current waveform. This leaves the capacitor bank partially charged at the end of the cycle, thus minimizing power requirements for the recharging supply. The SCR - switched capacitor banks for Booster injection into the AGS are typical of this technology[17]. The design for RHIC is based on a 4-turn septum magnet which has been investigated extensively using computer simulation of field and current for such characteristics as field homogeneity, fringe field and losses[3]. A discharge frequency of 70 to 100 Hz appears optimal. The characteristics of the magnet and power supply are give in Table 5.

A problem arises with the recharge; only 10 ms is available to accomplish this, a period that would imply very high power is needed. Thus the simplest solution is to provide three discharge capacitor banks which are all recharged during the 0.5 sec long period when the AGS/Booster is recycling. The economic implications must be investigated, but it seems likely this option will be less expensive than a very high power recharging supply. Alternatively the use of a dc excited magnet may be justified by the high cost of the pulsed power supplies.

3. Beam Ejection

A major problem with ejection is extreme reliability: failure of the system would result in a coasting beam randomly striking the vacuum chamber. This could cause magnet quenching, increased background radiation and possible permanent damage. The kicker has been designed as six independent sections, five can be used to extract the full energy beam. For very low energy beams only two kickers would be used. The kickers charging supply is designed to charge the PFN's after the abort trigger is generated. This avoids the kickers standing for hours with high voltage on the system. At FNAL the kickers are charged all the time, a reliability evaluation of the two options must be conducted. The kickers are quite conventional with lumped - constant pulse forming net works. The specification is shown in Table 6, the kicker specifications are given in Table 7.

The circuit is shown in Figure 13, the predicted rise-time waveform is shown in Figure 14, the complete waveform in shown in Figure 15.

3.1 Abort Kicker Charging

The RHIC beam abort kicker system consists of six kicker magnets. Each magnet is driven by lump-constant delay line or pulse forming network (PFN). To avoid erroneous triggering the pulse forming networks are charged only as a prelude to firing of the abort kicker. A minimum of 300 μ seconds is available for charging of the PFN's. A pre-charged capacitor bank is the source of energy for the PFN's. Energy is transferred from the capacitor bank to the PFN's through a resonant power supply.

Initially, the six PFN's are charged in 220 μ seconds. Each PFN is measured to determine proper energy storage. Failure to charge one of the PFN networks will initiate a second charging of the remaining five PFN's in 80 μ seconds to a voltage level of 1.2 of the original voltage. The resulting magnetic force or kick of the six or five magnets are equal. The capacitor bank is charged to a voltage level that is proportional to the magnetic rigidity of the beam. The maximum voltage required for the PFN is 42 kV for a 1000 Telsa-meter beam.

3.1.1 System Description

The power supply consists of a capacitor bank, a charging supply, switching diodes and charging inductors. See Figure 16 for a schematic diagram.

The capacitor bank is sectionalized into four blocks. The four capacitor blocks are charged in parallel to a voltage that follows the beam energy and is proportional to the beam rigidity. The initial charging of the six PFN's is performed by discharging the four blocks in parallel. If a second charging is required three blocks are reconfigured in a series arrangement to increase the charge of the five PFN's. The circuit configurations is similar to that of the Marx Generator.

Firing of SCR A initiates a resonant discharge of the full capacitor bank. The resonant frequency is determined by inductor L_1 and the capacitance of the bank and the PFN's. The value of L_1 is selected for a half-period (charging time) of 220 μ second.

If it is determined that one of the PFN's fails to charge to full voltage, SCR's B are fired. This initiates a second resonant discharge of the residual voltage remaining on the capacitor bank. For the second discharge capacitor sections C_1, C_2 and C_3 are series connected. The resonant frequency is determined by inductor L_2 and the capacitance of the bank and the PFN's. The value of L_2 is selected for a half-period (charging time) of 80 μ second.

3.1.2 Resonant Supply

The response of a resonant supply is depicted in Figure 17. A capacitor C_1, initially charged to Vo (C_1), charges a capacitor C_2, initially charged to Vo(C_2). On firing of the SCR a half-wave sinusoid of current flows, increasing the stored charge on C_2 by Δ Q. As the current goes through zero the SCR turns off, terminating the cycle. The charging time is controlled by L; the charge transport by the value of C_1, C_2 and the initial voltages.

The design is based on a maximum voltage on the PFN of 42 kV. The cap bank, 94 μF, is charged to 24 kV. Charging of six PFN's ($\Delta Q = 0.56$ C) leaves a residual voltage of 18 kV on the bank and 24 kV on the PFN's.

If a second charge is required C_1, C_2 and C_3 are connected in series forming a second bank of 6 μF charged to 54 kV. Charging of five PFN's ($\Delta Q = 0.094$ C) leaves a residual voltage of 12.78 kV on each section and 50.4 kV on the PFN.

The maximum energy stored in the capacitor bank is 27.072 kJ. The voltage V on the PFN depends on the rigidity of the beam. The value of charging voltage in kV is 0.024 $B\rho$, where $B\rho$ is in Tm.

3.1.3 System Parameters

The parameters of the PFN's are given in Table 8 for the original charging and the second charging.

The electrical design parameters for the capacitor bank and resonant power supply are given in Table 9.

3.2 Abort Septum Magnet

A cursory look has been taken at this magnet based on a current septum type. The magnet may incorporate a gradient to provide defocussing which will reduce the peak heating of the target. The magnet may well be split into two or three electrically independent sections, only one would be used for low energy beam extraction. The values shown in Table 10 are based on a single magnet with a mean gap of 7 cm which varies from 5 to 9 cm in order to provide the field gradient, a laminated yoke is assumed.

4. Acknowledgement

The authors acknowledge enlightening discussions with J. Claus, H. Foelsche, R. Lockey, A. Ratti, E. Rodger and N. Tsoupas.

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17. Booster Design Manual - Septum Magnet Power Supply at F6.

Table 1

Strip Line Injector

171 Bunch Design

Time between bunches	:	52 ns (centers are 74 ns apart, bunch length is 22 ns)
Injector length	:	7m
Propagation time	:	25ns
Beam transit time	:	24 ns
Allowance for current and jitter	:	3 ns
Deflector impedance	:	150 Ω
Deflection	:	2 mrad ± 0.1%
Aperture	:	6 x 6 cm
Voltage	:	± 130 kV
E_{infl}	:	4.3 kV/cm
H_{infl}	:	0.0143 T
I_{infl}	:	1.73 kA
PFN elec. length	:	70 ns
Current di/dt	:	0.7×10^{12} A/s

Table 2

RHIC Injection Fast Kicker Specifications (Ferrite Magnet)

114 Bunch Design

Time between bunches	:	90 ns
Bunch length	:	22 ns
Beam rigidity	:	95-100 Tm
Deflection angle	:	2.5 mrad ± 0.5%
Magnet aperture	:	5 cm gap x 6 cm wide
Magnet length	:	125 cm
Load impedance	:	35 Ω
Magnet inductance	:	2.1 μH
Rise time	:	80 ns
Peak field	:	0.048 T
Magnet current	:	1910 A
Charging Voltage	:	70 kV max (65 kV nominal)
Stored energy in PFN's	:	7 J
Number of modules	:	4
Switch tube	:	CX 1168
Pulser	:	Triaxial Blumlein
St section length	:	5.4m

Table 3 - The pulse forming line specification (model)

center pipe diameter d_a	3/8 inch (nominal)
middle pipe diameter d_b	1 1/4 inch (nominal)
outer pipe diameter d_c	3 1/2 inch (nominal)
length	10 ft.
impedance	37.5 Ω (nominal)
Oil dielectrical constant	2.22 - 2.5
PS voltage	± 1000 v

Table 4 - The theoretical values of the transmission line (model)

Case I - air dielectric	
Inner line impedance	54.98 Ω
Outer line impedance	53.88 Ω
Blumlein pulse width	20 ns
Case II - oil dielectric constant = 2.3)	
Inner line impedance	36.25 Ω
Outer line impedance	35.53 Ω
Blumlein pulse width	30 ns

Table 5

Injection Septum Magnet Power Supply

Magnet aperture	:	5.5 cm x 6.0 cm
Magnet length	:	350 cm
Number of turns	:	4
Inductance	:	102 μH
Resonant frequency	:	72 Hz
Beam rigidity	:	100 Tm
Deflection	:	56 mrad
Maximum field	:	1.6 T
Capacitor bank	:	40,000 μF
Maximum charging voltage	:	1,100 V
Magnet current	:	16.2 kA
Conductor loss	:	4.2 kJ/cycle (inc. leads)
Eddy current	:	6.2 kJ/cycle
Voltage decrement/cycle	:	65%
Lead inductance	:	22 μH
Lead resistance	:	0.6 x 10^{-3} ohm

Table 6

Beam Abort Requirements

Rigidity	100-1000 Tm
Deflection	1 mrad
Rise time	0.9 μs
Pulse length	>12 μs
Space	4.5 m + 4.5 m
Magnet window	7 cm x 7 cm
Number of sections	6

Table 7

Abort Fast Kicker Specification

$B\rho$	:	1 Tm
Maximum field	:	0.125 T
Magnet current	:	7000 A
Each magnet length	:	133 cm
Total magnet length	:	8m
Gap	:	7 x 7 cm
Inductance	:	1.8 μh
Total load inductance	:	2.5 μh
PFN Impedance	:	3 Ω
Operating voltage	:	42 kV
Number of kickers	:	6 per ring

Table 8

Parameters of Charged Pulse Forming Network

Original Charging	
Per Section	C_{in} = 2.225 μF
	V_{MAX} = 42 kV
	Stored energy U_{MAX} = 1963 Joule
6 Units	U_{MAX} = 11.775 Kilo Joule
	C = 13.35 μF
	Maximum stored charge = 0.561 Coulombs
Second Charging	
Per Section	C_{IN} = 2.225 μF
	V_{MAX} = 50.4 kV
	U_{MAX} = 2827 Joule
5 Units	U_{MAX} = 14.153 Kilo Joule
	C = 11.125 μF
	Q = 0.561 Coulombs
	ΔQ = 0.094 Coulombs
	ΔW = 4318 Joule

Table 9
Electrical Design Parameters

Capacitor Bank	
	$C_1 = C_2 = C_3 = 18\ \mu F$
	$C_4 = 40\ \mu F$
	Total Capacitance = 94 μF
	Maximum Voltage = 24 kV
	Maximum Stored Energy = 27.072 kilo joules
	Maximum Stored Charge = 2.25 Coulombs
Inductors	
	$L_1 = 420\ \mu H$
	Maximum Current = 4.04 kA
	$L_2 = 167\ \mu H$
	Maximum Current = 1.84 kA
SCR's	
	Primary Switch SCR A
	I_{max} = 4.04 kA
	PIV = 24 kV
	P Forward Voltage = 12 kV
	Secondary Switch SCR B, 3 Required
	I_{MAX} = 1.84 kA
	PIV = 24 Ka
Charging Supply	
	V_{MAX} = 24 kA
	I_{MAX} = 100 mA

Table 10
Specification for Abort Septum Magnet and Pulser

Central field	:	0.67T
Gradient	:	8 T/m
Total length	:	6m (in 3 sections)
Turns	:	4
Frequency	:	833 Hz
Time to peak	:	300 μs
C	:	240 μf
E charge	:	10 kV
Current, peak	:	~10 kA
Stored energy	:	~10 kJ.

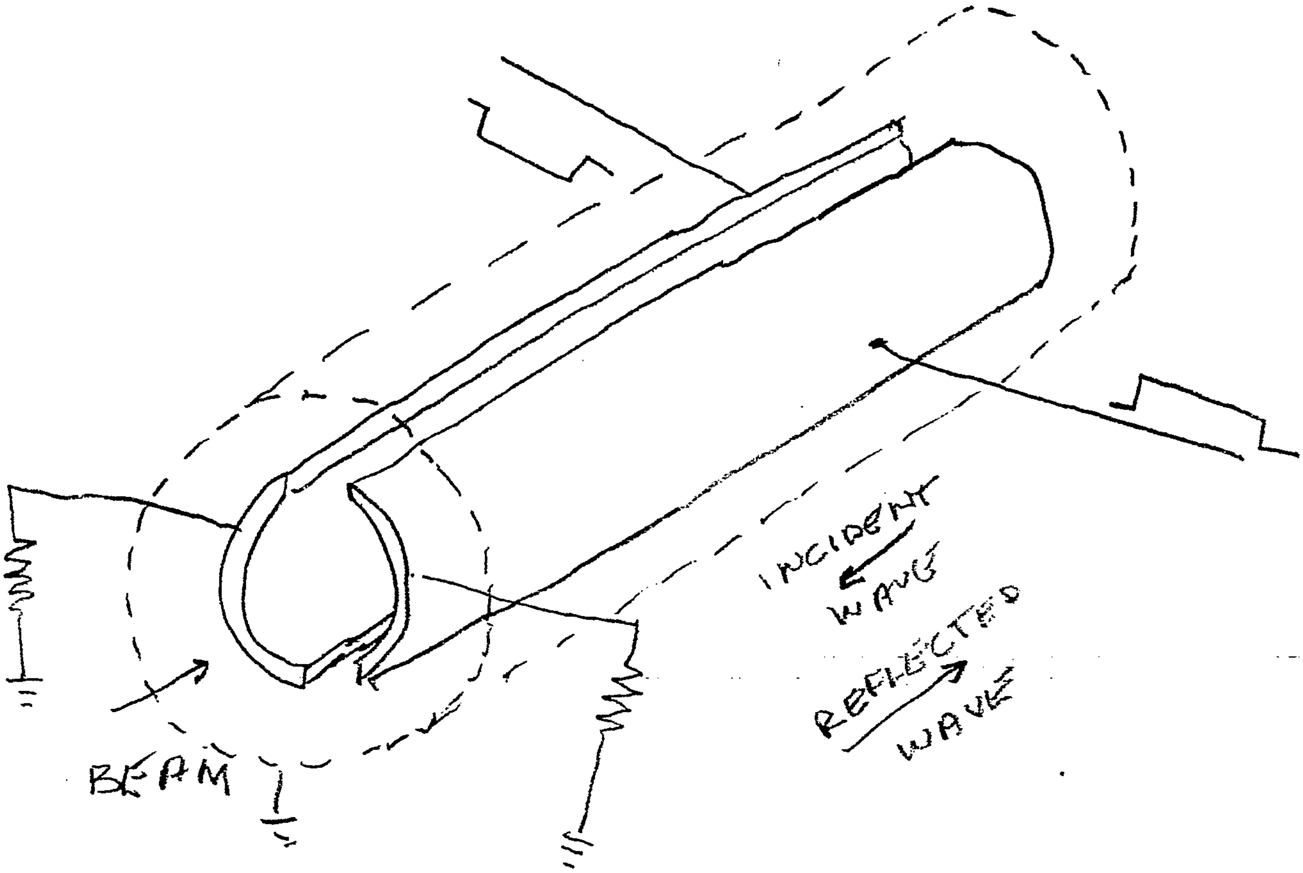
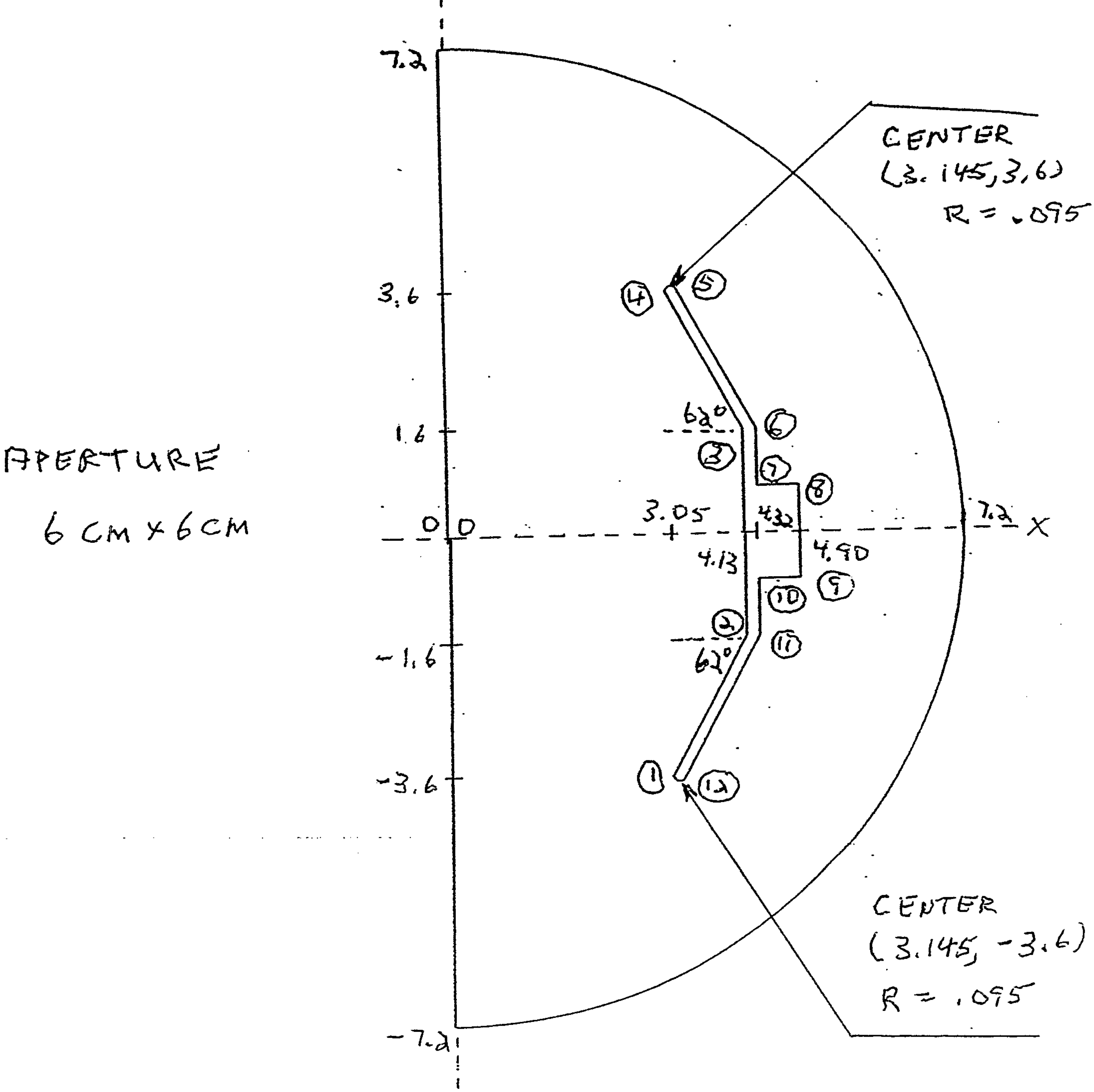


Fig. 1. STRIPLINE DEFLECTOR



① 3.05, -3.6

② 4.13, -1.6

③ 4.13, 1.6

④ 3.05, 3.6

⑤ 3.24, 3.6

⑥ 4.32, 1.6

⑦ 4.32, .77

⑧ 4.90, .77

⑨ 4.90, -.77

⑩ 4.32, -.77

⑪ 4.32, -1.6

⑫ 3.24, -3.6

Fig. 2. DETAILED CROSS-SECTION O
STRIPLINE DEFLECTOR

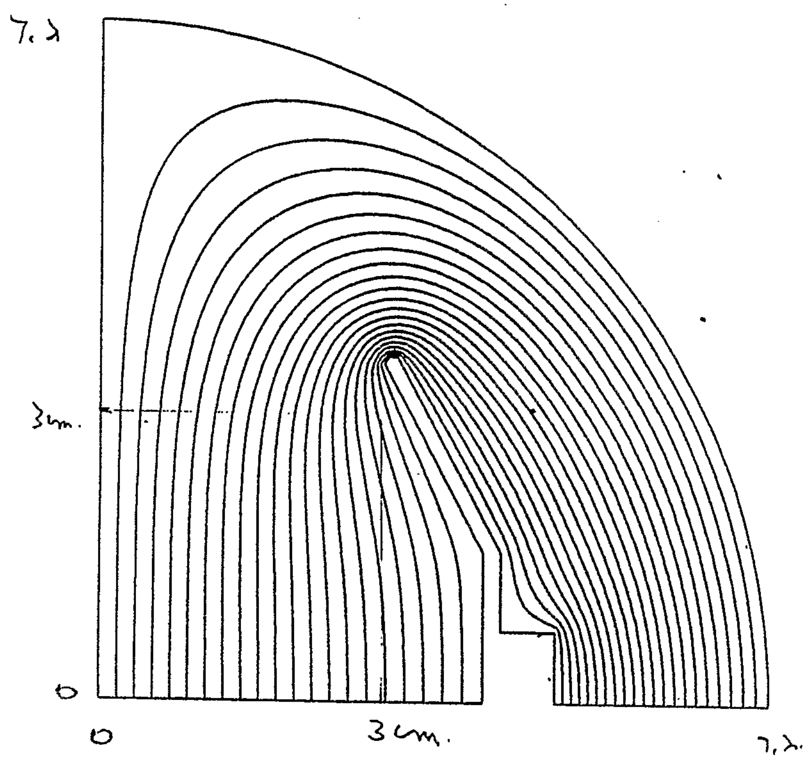
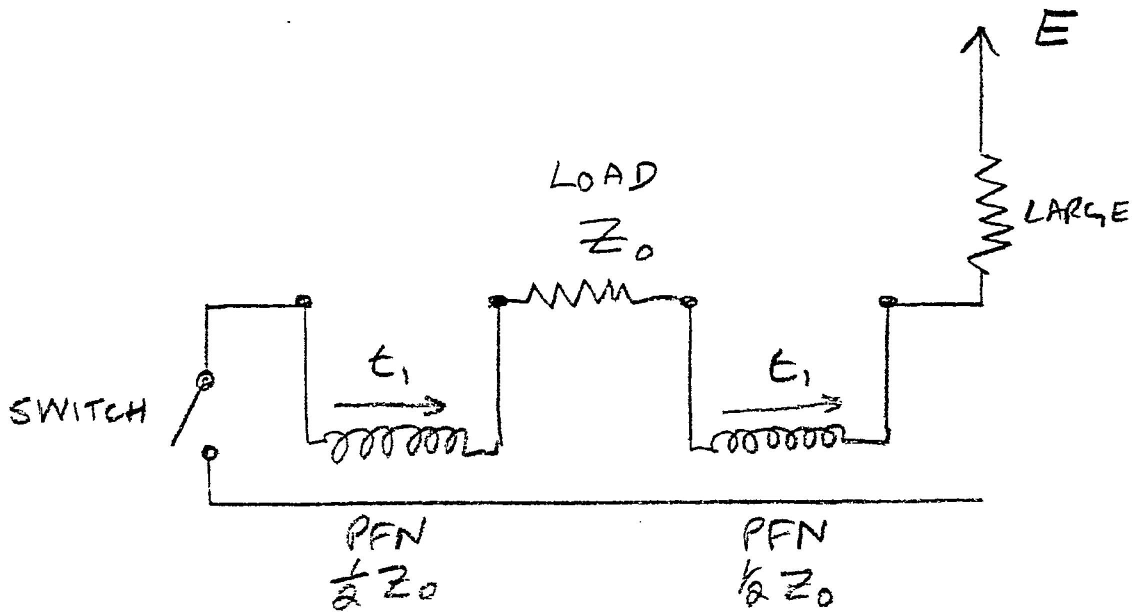
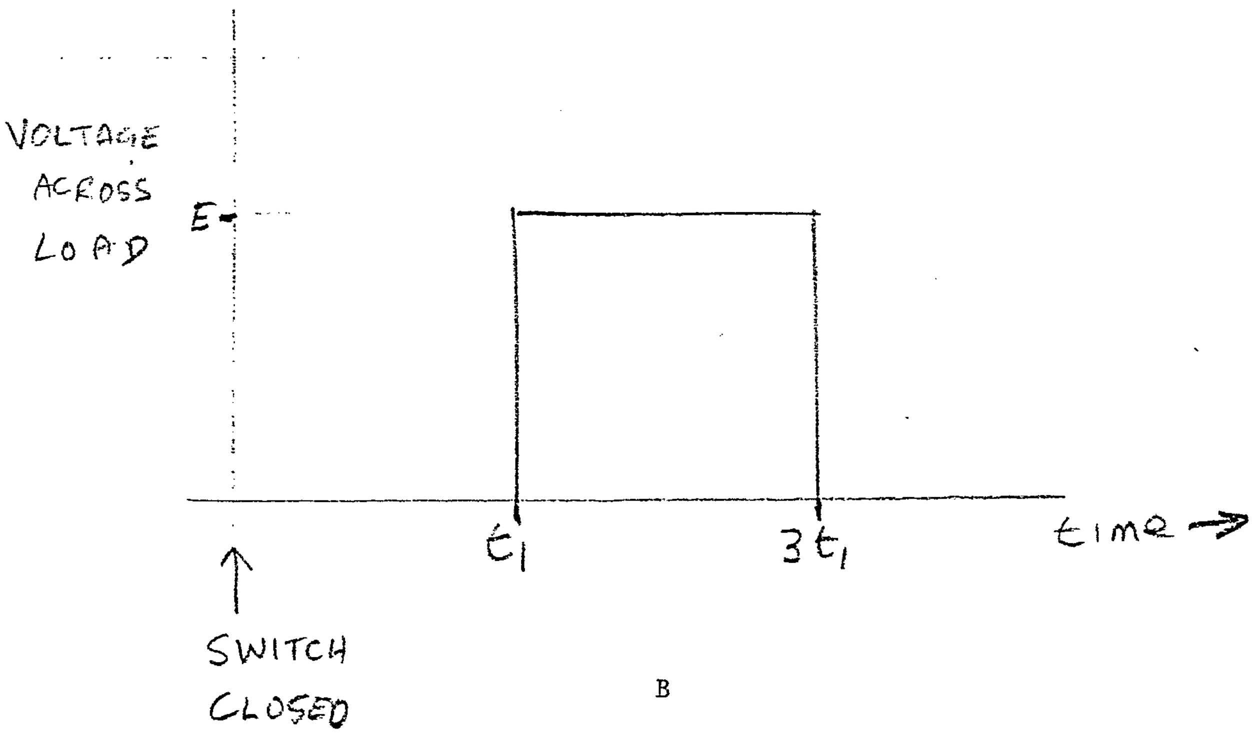


Fig. 3. FIELD PATTERM OF STRIPLINE DEFLECTOR



A



B

Fig. 4. a) BASIC BLUMLEIN PULSER

b) LOAD WAVEFORM

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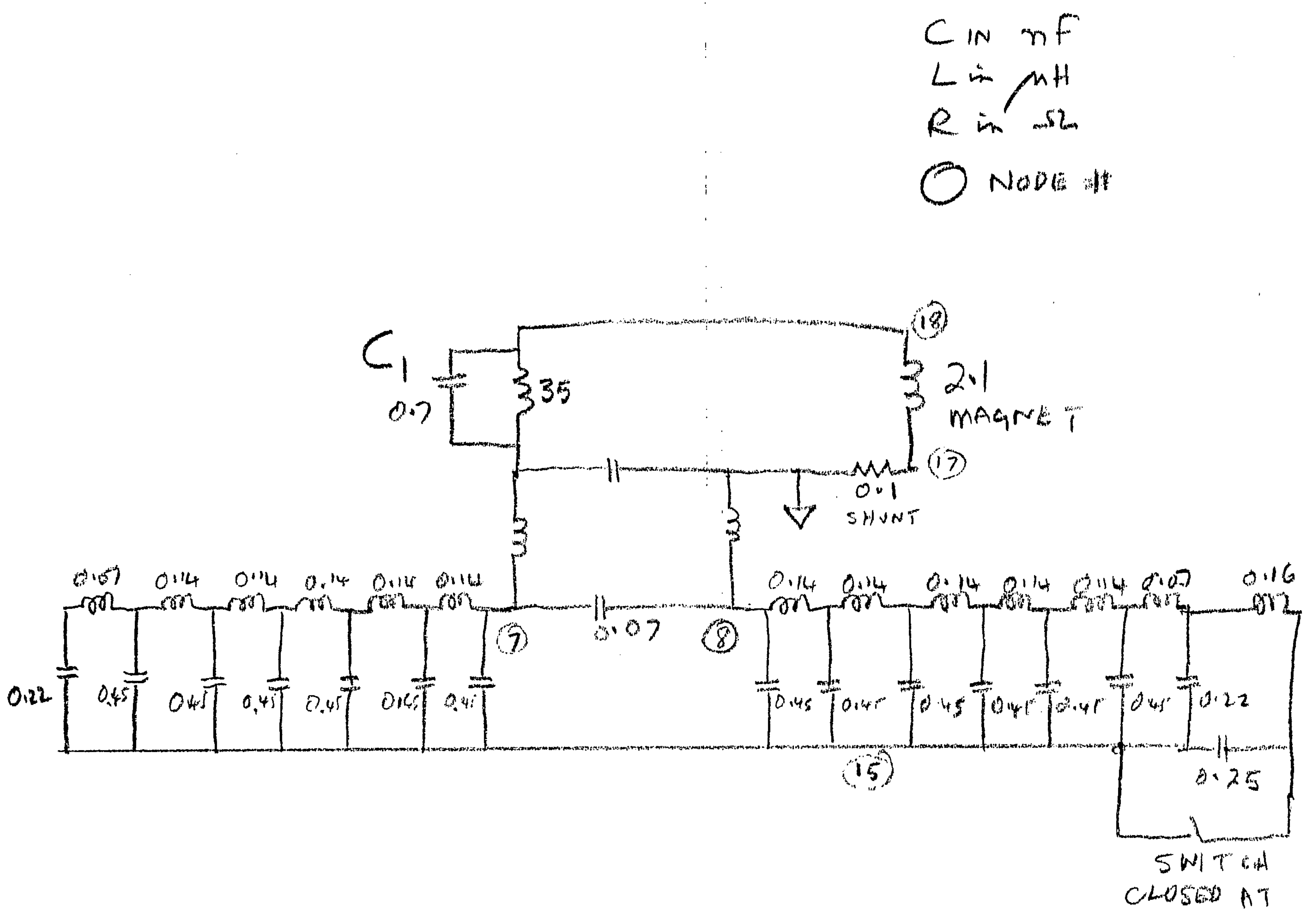

Fig. 5. BLUMLEIN SIMULATION USING MICROCAP. THE LUMPED MAGNET IS THE 2.1 μH INDUCTOR

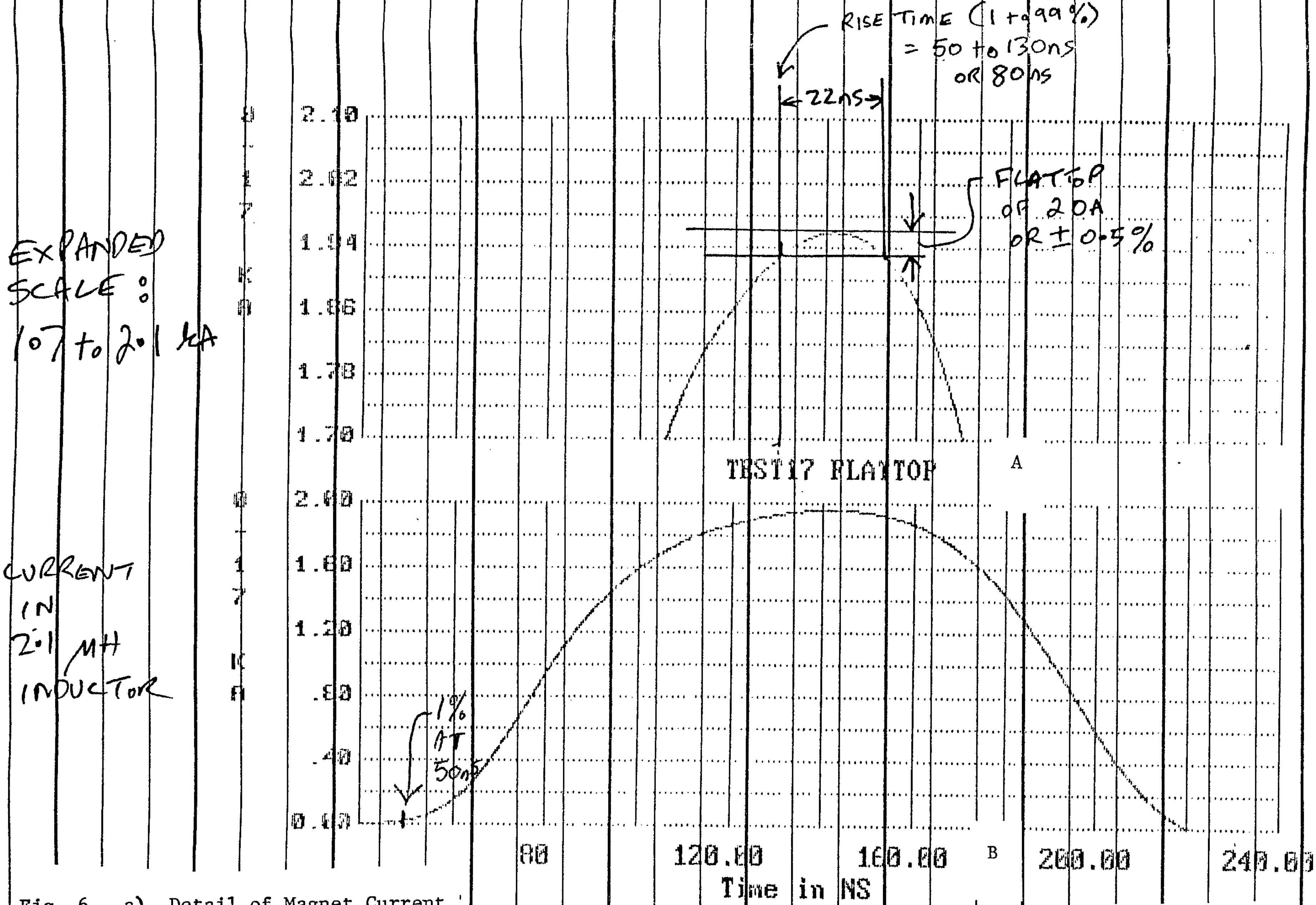

Fig. 6. a) Detail of Magnet Current During Flat-top

Charging Voltage = 65 kV (Node # 15)

b) Magnet Current Waveform

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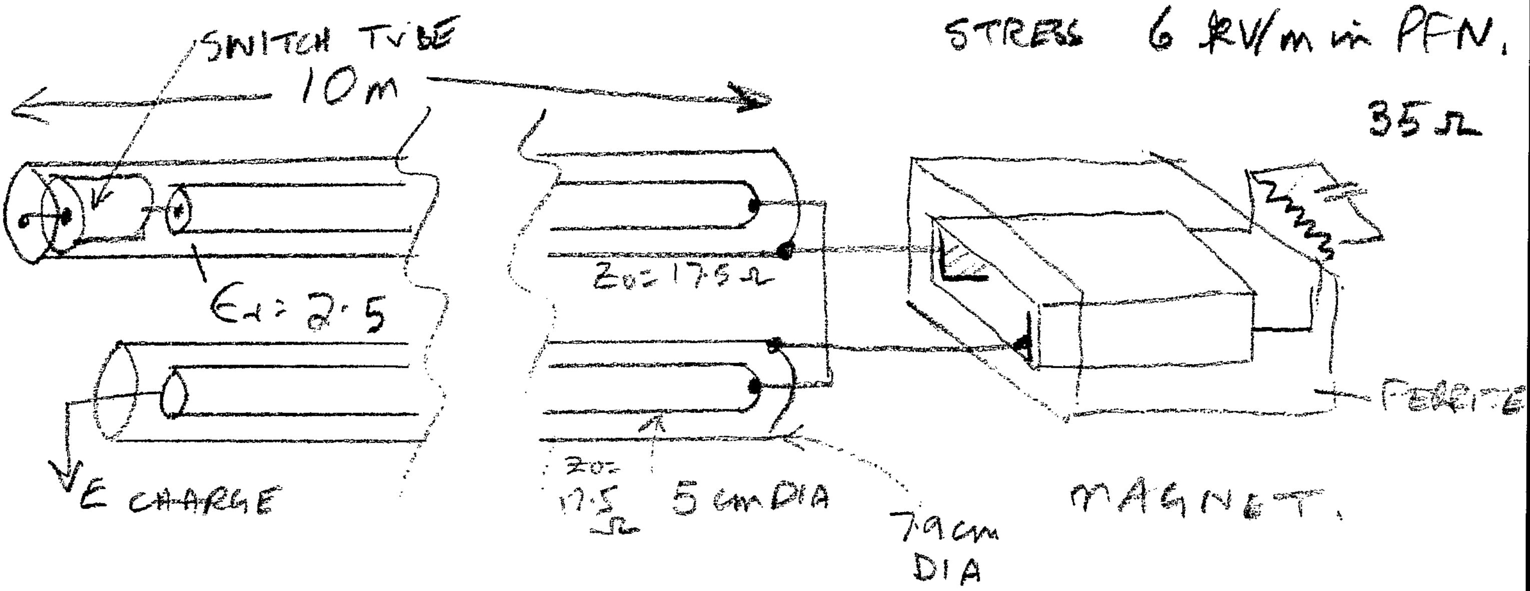

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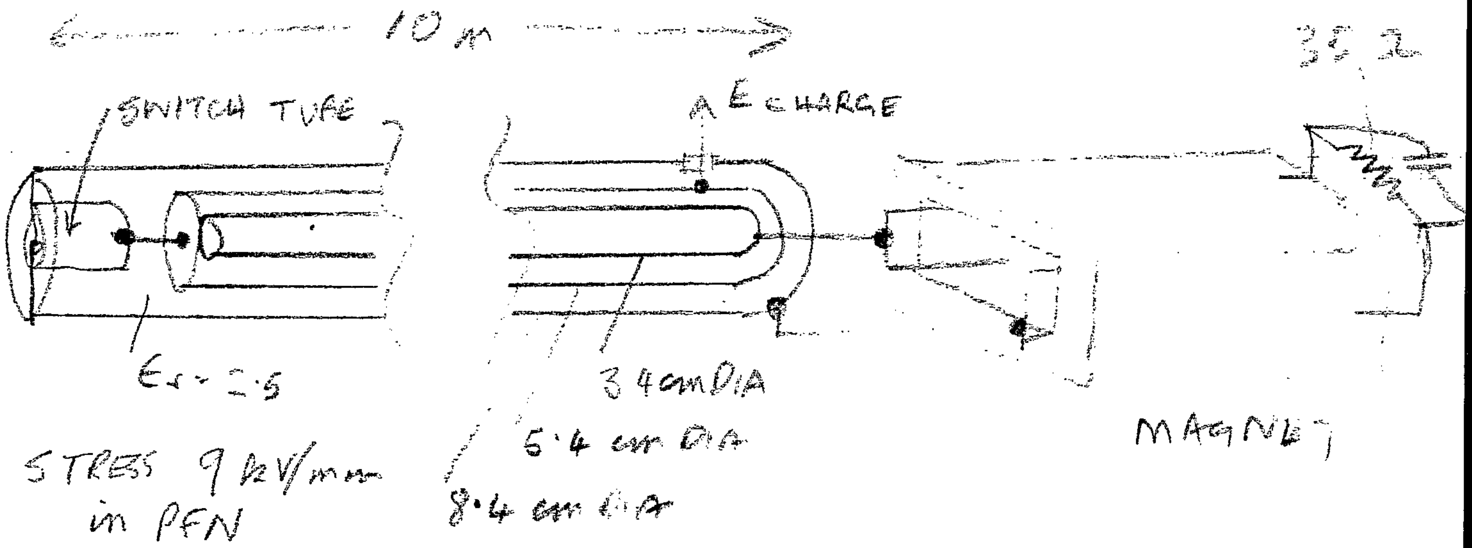


B

Fig. 7. a) DISTRIBUTED LINE BLUMLEIN PULSER WITH COAXIAL PIPES

b) TRIAXIAL VERSION OF BLUMLEIN PULSER

SP 11037A

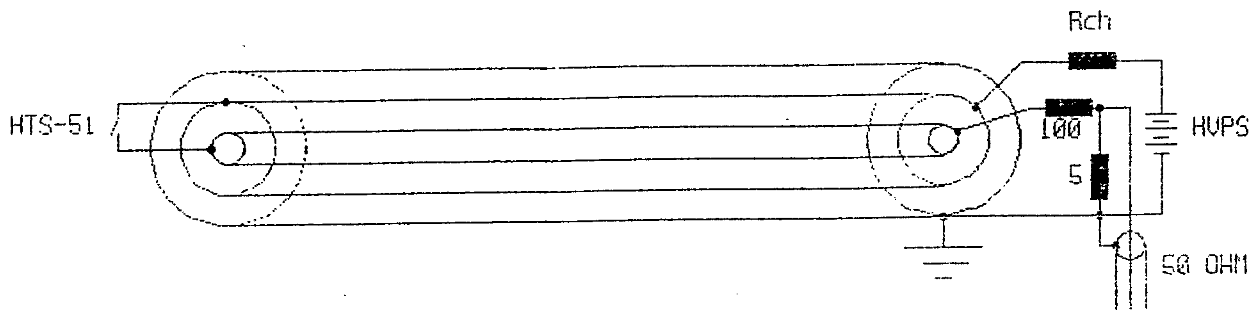
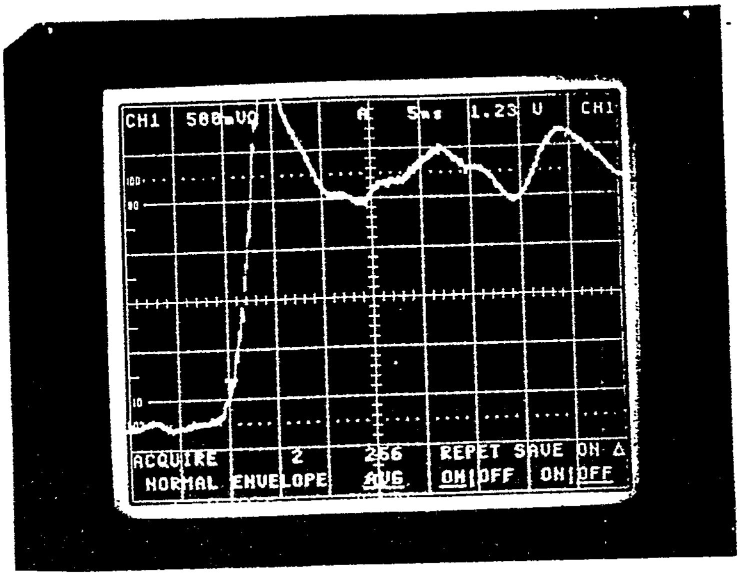


Fig. 8. DESIGN OF MODEL TRIAXIAL
BLUMLEIN PULSER



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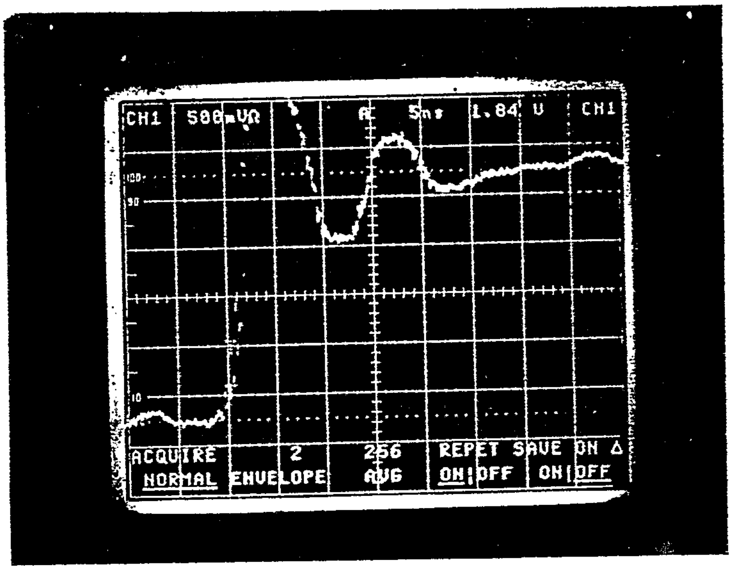


B

Fig. 9. TEST OF MOSFET SWITCHES, TWO SAMPLES ARE SHOWN: a & b. RISETIME IS 2-3 ns with 69 Ω RESISTIVE LOAD

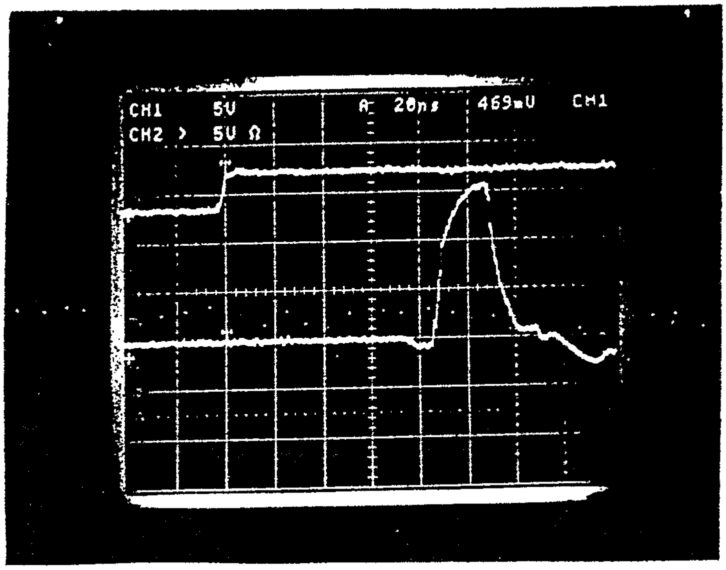


Fig. 10. INITIAL TESTS OF BLUMLEIN
SHOWING LOAD WAVEFORM

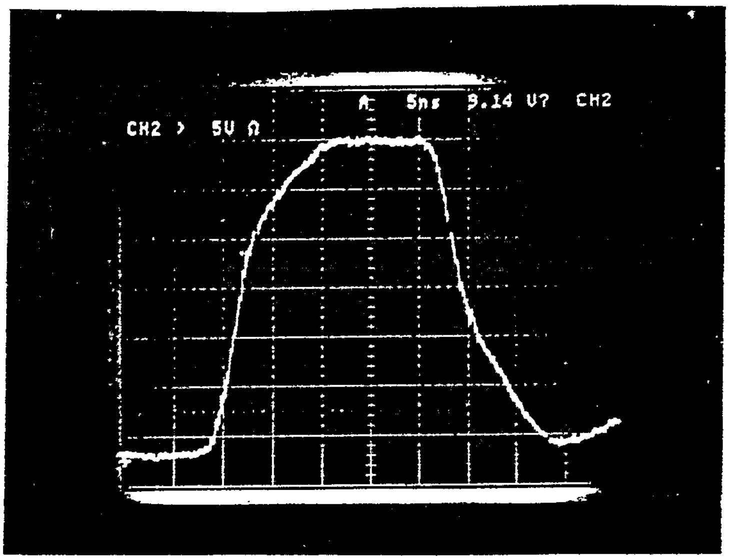


Fig. 11. LOAD WAVEFORM AFTER CIRCUIT
CORRECTIONS AND IMPROVEMENTS

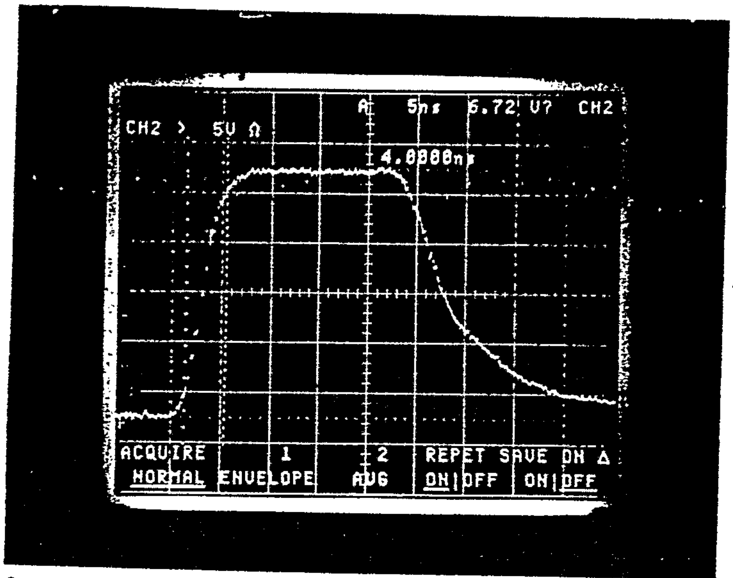


Fig. 12a. THE OUTPUT PULSE WAVEFORM WITH C_2 = 27 pF, C_3 = 38pF, R_3 = 33Ω.

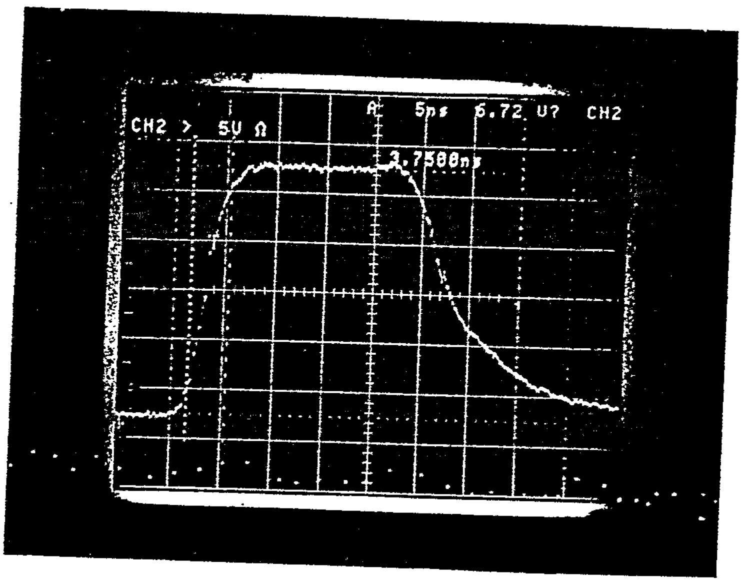
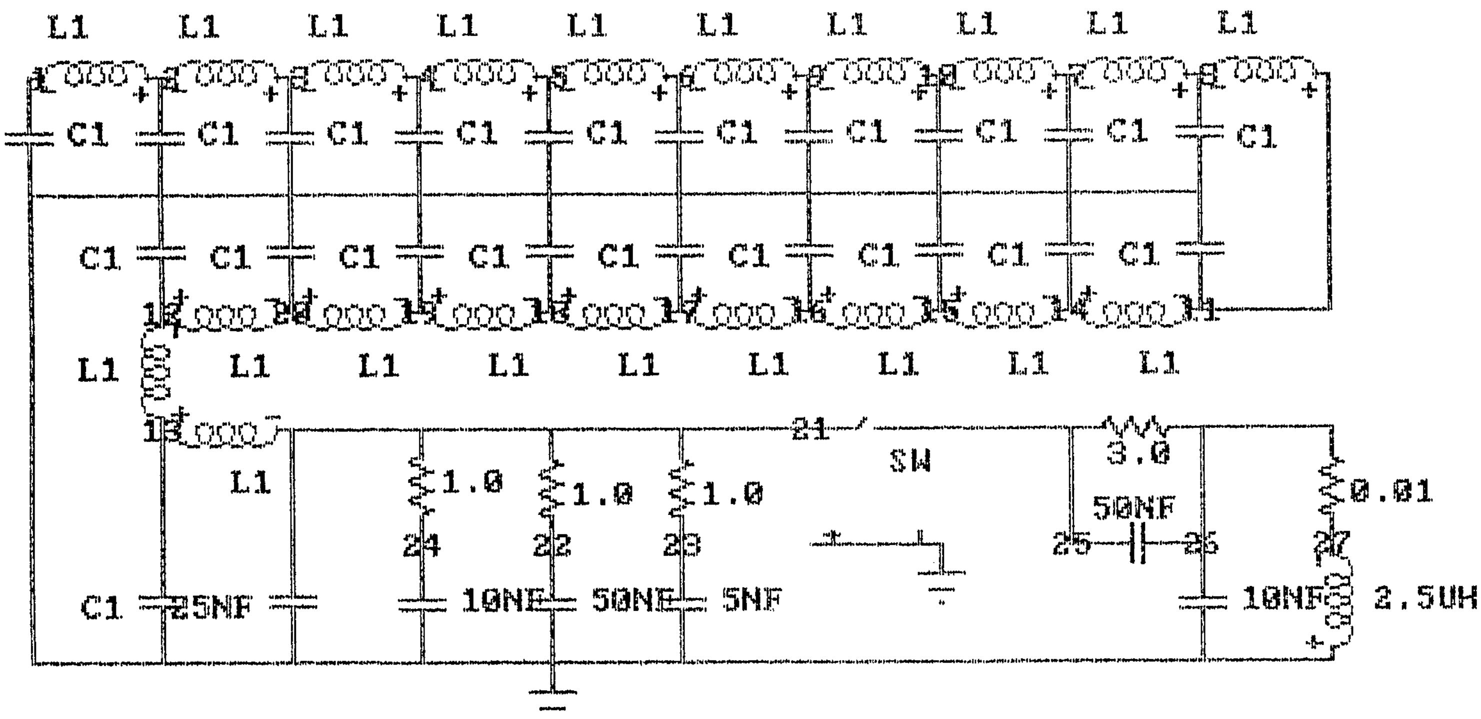


Fig. 12b. THE OUTPUT PULSE WAVEFORM WITH C_2 = 32 pF, C_3 = 38 pF, R_3 = 33Ω.



L1=1.125UH C1=125NF

Fig. 13. CIRCUIT SIMULATION OF EJECTION KICKER MODULE

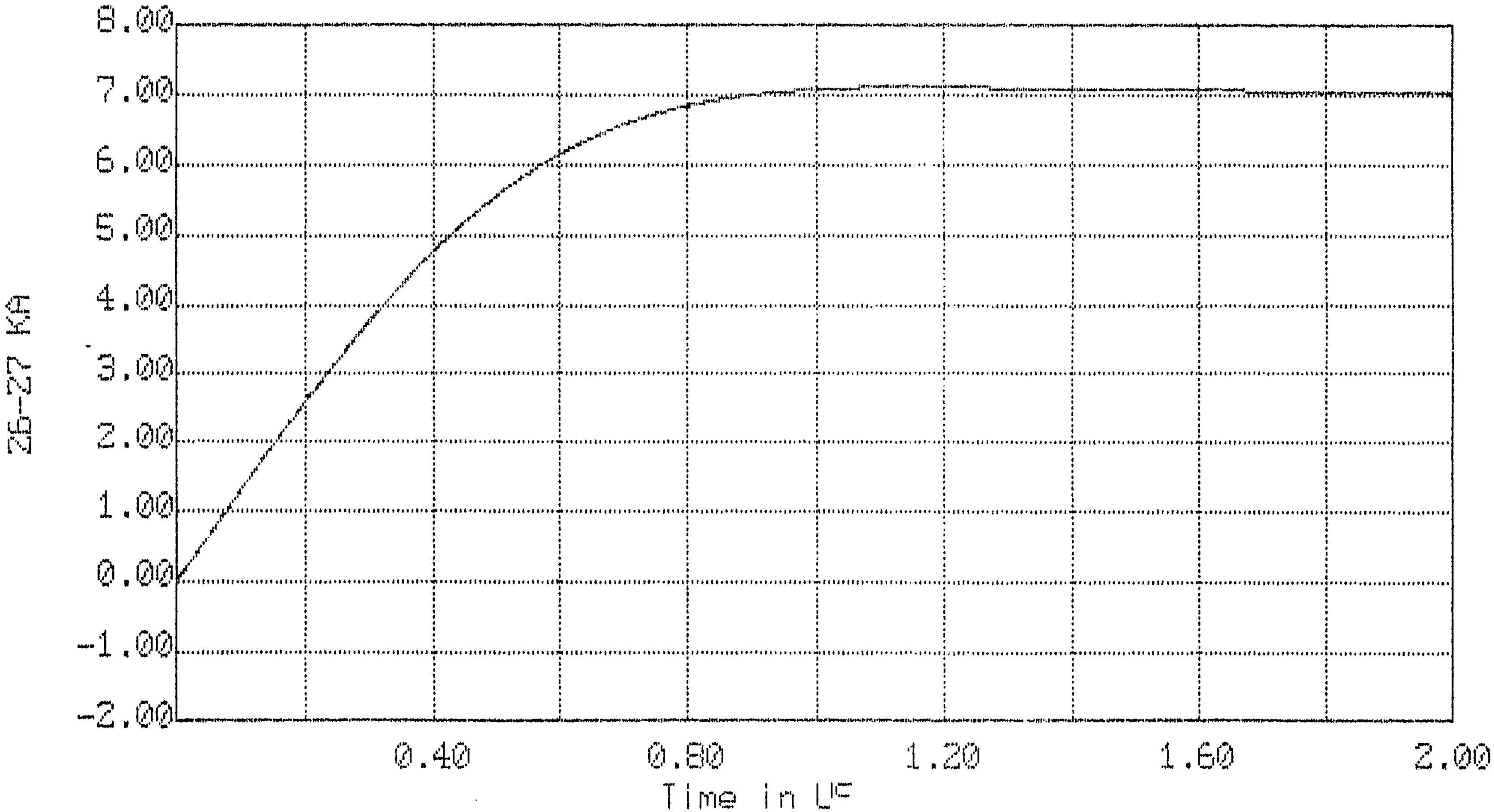


Fig. 14. LEADING EDGE OF MAGNET CURRENT WAVEFORM OF EJECTION KICKER

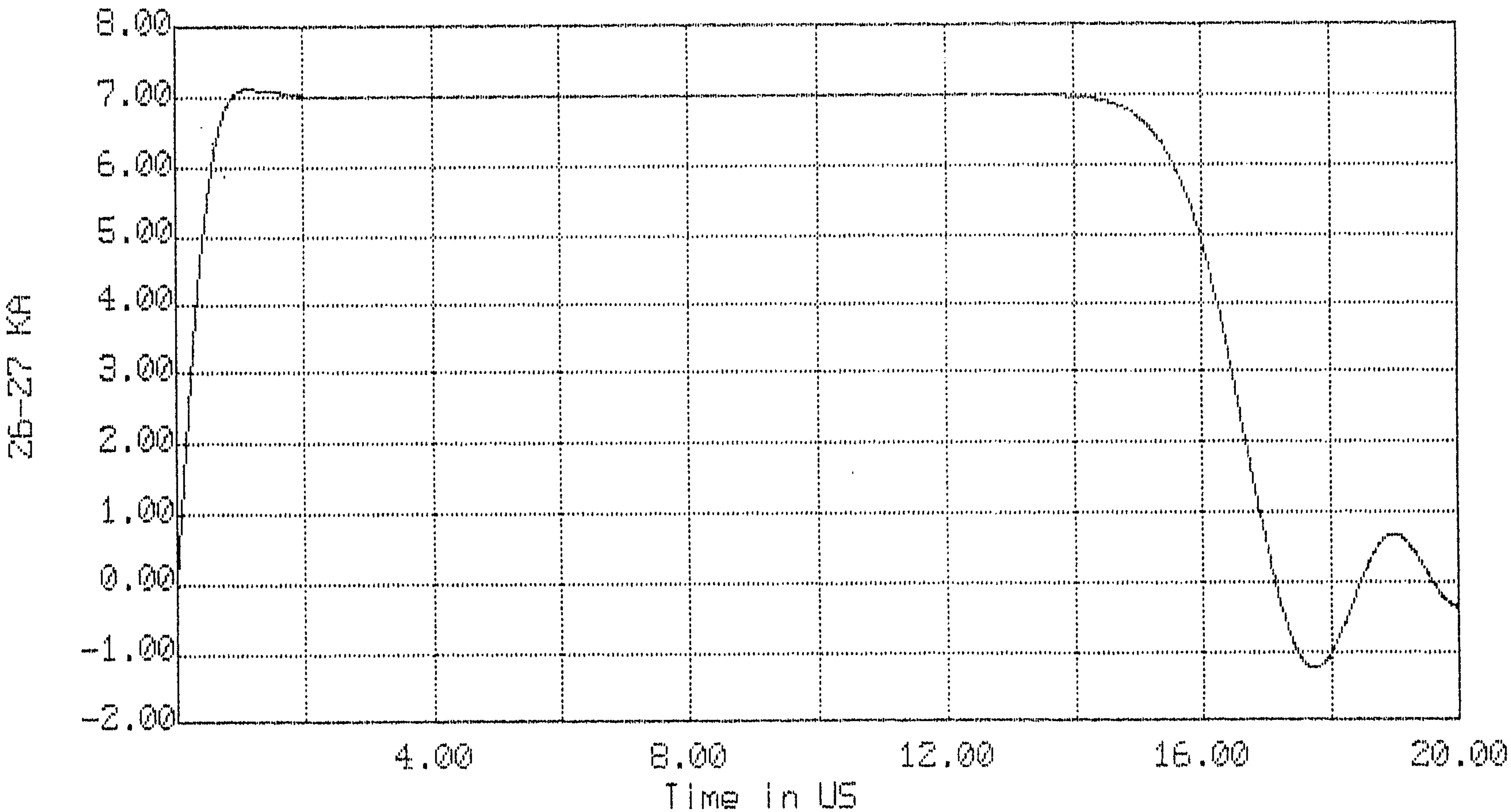
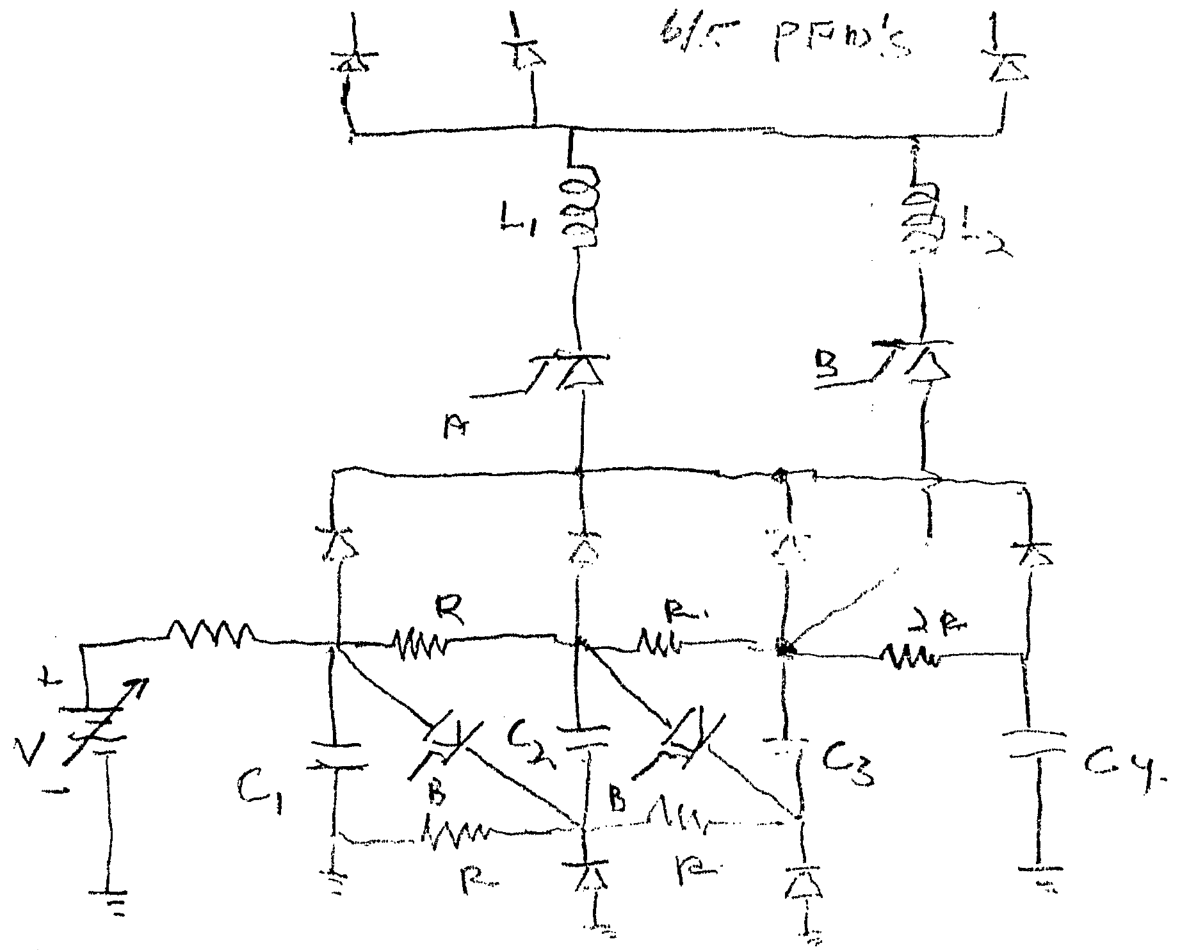


Fig. 15. MAGNET CURRENT WAVEFORM OF EJECTION KICKER



$C_1 = C_2 = C_3 = 18\,\mu F$

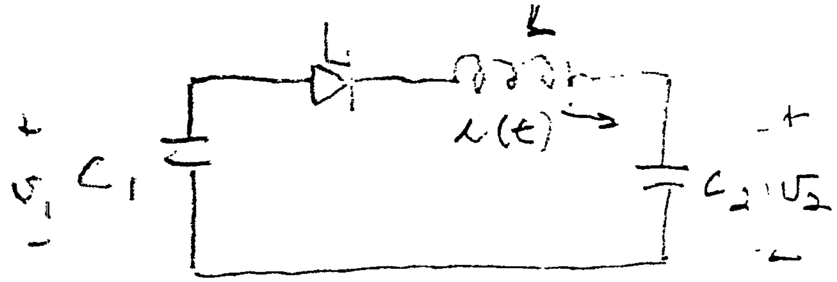
$C_4 = 40\,\mu F$

$L_1 = 420\,\mu H$

$L_2 = 167\,\mu H$

$R = 100\,K\Omega$

Fig. 16. CHARGING SUPPLY SCHEMATIC OF EJECTION KICKER



$V_0(C_1) > V_0(C_2)$

$$i(t) = \frac{V_0(C_1) - V_0(C_2)}{\omega_0 L} \sin \omega_0 t$$

$$\omega_0^2 = \frac{C_1 + C_2}{L C_1 C_2}$$

$$\Delta Q = 2\left[V_0(C_1) - V_0(C_2)\right] \frac{C_1 C_2}{C_1 + C_2}$$

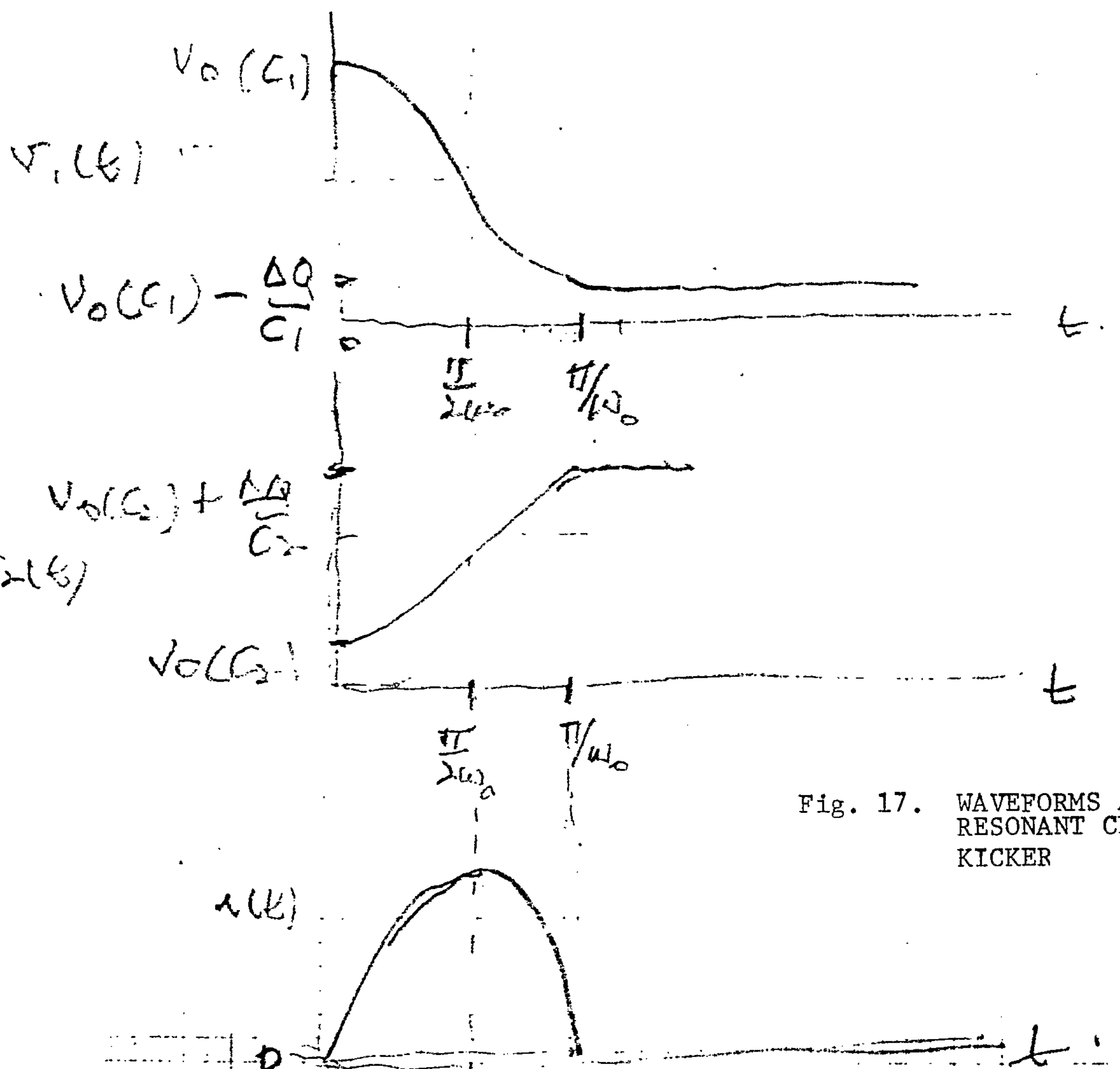


Fig. 17. WAVEFORMS ASSOCIATED WITH RESONANT CHARGING OF EJECTION KICKER