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NANOSECOND PULSER THYRATRONS

Steven Friedman

EG&G, INC.
35 Congress Street
Salem, MA 01970

August 1982

Third Interim Report for Period 1 August 1981 — 30 December 1981

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<td>Significant progress has been made in developing the individual circuit components for the nanosecond pulser, these being the thyatron, load, PFN, and saturable reactor.</td>
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triggers of the pulsed voltage sources, have yielded de-ionization times well within the 50µs required for 20kHz operation, at voltages and pressures well beyond those needed to meet the load voltage rise time and pulse width requirements. An instant-start dispenser cathode suitable for use with HY-3013L-type thyratrons has been developed and tested successfully in similar tubes.

An ultra low inductance PFN/load combination has been constructed, and has produced a smooth 3.5ns FWHM multi-kilovolt pulse across a nominal 50pf load capacitance when switched via a short air gap. The kapton capacitors and ceramic resistor load shunt are theoretically capable of operating at around 200 watts average power.

Three saturable reactor materials have been evaluated theoretically: orthonol, metglas and ferrite. Of these, only ferrite appears usable on a 10ns time scale, metglas and orthonol being unsuitable because of their low resistivity.

Finally, a 20kHz kit has been constructed for high prr testing of the assembled nanosecond pulser circuit.
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ABBREVIATIONS AND SYMBOLS

A  Amperes (DC)
A_m  Magnetic cross-sectional area of saturable reactor material
B_s  Saturation flux density
C  Load capacitance
C_0  Storage capacitor capacitance
d,l,w  Saturable reactor assembly dimensions
DBV  Dynamic breakdown voltage
EIA  Extended interaction amplifier
epy  Thyatron charging voltage
FWHM  Full width at half maximum
i  Current
i_b  Peak thyatron current
k_a  Kiloamperes (pulsed)
k_Hz  Kilohertz
k_v  Kilovolts (pulsed)
K_V  Kilovolts (DC)
L  Inductance
n_H  Nanohenries
n_s  Nanoseconds
p_d  Torr-centimeters
p_F  Picofarads
p_r  Pulse repetition rate
t_f  Thyatron anode fall time
t_r  Thyatron recovery time
u_F  Microfarads
u_s  Microseconds
V  Load voltage (DC)
V_B  Bias voltage (DC)
x  Magnetic saturation front penetration depth
p  Resistivity
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FOREWORD

This is the Third Interim Technical Report for a program of research and development conducted under ERADCOM Contract DAAK20-80-C-0282 entitled "Nanosecond Pulser Thyatrons," and covers the period 1 August 1981 to 30 December 1981.

The work described herein was performed by EG&G, Inc., Electronic Components Division, 35 Congress Street, Salem, Massachusetts 01970.
During the period covered by this Interim Report, the Type II requirements for the nanosecond pulser circuit were changed. The peak forward voltage was reduced from 6 kv to 3.5 kv, and the load capacitance was reduced from 60 pF to 30 pF.

Using these values in the lumped circuit analysis of the Appendix (reprinted from the Second Interim Report) gives 17 nH and 5 kv for the total circuit inductance and thyatron voltage required to generate a 4 ns FWHM load voltage pulse. The load resistance required across the 30 pF comes out to be 13 ohms.

An effective increase in load voltage rise rate, as well as an effective decrease in pulse width, can be obtained by biasing the EIA grid negative with respect to the EIA cathode by voltage $V_B$, and then applying a pulse of magnitude $V_B + 3.5$ kv. The EIA will not generate any power during the initial slow-rising portion of the pulse, so that for operational purposes, only the fast, narrow upper 3.5 kv constitutes the applied voltage. The sharpening effect of this is illustrated in Figure 1. Work reported in the Second Interim Report showed that this technique will probably be necessary to achieve the required load voltage rise time and pulse width. A safe maximum value for $V_B$ is 1.5 KV, so the total pulse voltage would be 5 kv. From the Appendix, the thyatron voltage would then be 7 kv, but experiments described in Section 4 suggest that in practice 10 kv will be required.

In summary, conservative calculations give 17 nH and 10 kv as the circuit inductance and thyatron voltage, respectively, required to generate a 3.5 kv, 4 ns voltage pulse across a 30 pF load.

Thyratrons and PFN/load circuits capable of meeting these requirements have been constructed, and are described in Sections 3 and 4. Succeeding sections describe the saturable reactor, the overall circuit, and our plans for characterizing the circuit at low and high prr.
Figure 1. Reduction of effective pulse width by use of negative bias.
3 THYRATRON DEVELOPMENT

a. Voltage Holdoff

When HY-3013L (Figure 2a) was originally characterized, the load voltage specification was 6 kv. Our plan for achieving the required 1 ns voltage rise time was to operate the thyratron at high pressure, use a saturable reactor, and avoid the slow-rising early part of the pulse by using the top 6 kv of a 10 kv pulse. The resulting thyratron holdoff requirement was 15-20 kv, at 0.7 torr minimum. The DBV (dynamic breakdown voltage) vs pressure plots of Figure 3 show that HY-3013L would have satisfied this only marginally. We therefore proceeded to construct new thyratrons designed for better holdoff.

Since it was believed that the maximum holdoff of HY-3013L was limited to 20 kv by some type of field emission, we did not expect to substantially exceed this voltage. Rather, the intention was to shift the DBV curves to higher pressure, thereby decreasing the current rise time and in turn allowing operation with a pulse having a smaller total voltage.

To accomplish this, the E-E spacing was reduced to 0.050 inch (from 0.080), thus decreasing "pd." Also, the grid and grid baffle aperture widths were reduced to 0.060 inch (from 0.080). Two such thyratrons were constructed, HY-3013L2 and HY-3013L3 (Figures 2b,c).

The resulting DBV curves are plotted in Figure 3. A shift to higher pressure did in fact occur, but only by 10%. More importantly, the holdoff at pressures below 0.95 torr was dramatically higher, indicating that the DBV of HY-3013L was probably being limited by factors not related to its basic design.*

Meanwhile, progress in EIA design had also resulted in the load voltage specification being reduced to 3.5 kv across 30 pF (from 6 kv across 60 pF), thus reducing the projected thyratron holdoff requirements to 10 kv.

Thus, barring severe degradation of holdoff at high prr, all three thyratrons should easily meet the voltage and pressure requirements, with HY-3013L2 and HY-3013L3 being operable at pressures approaching 1 torr. The advantage of such high pressure operation is that the thyratron resistive fall time is reduced, thereby decreasing the anode dissipation as well as the anode current delay time which the saturable reactor must provide. (This second effect reduces the volume

*These factors can include small surface irregularities on the grid, anode, or ceramic insulator, evaporation of cathode coating into the high voltage region during activation, and incomplete aging. The holdoff of HY-3013L will likely improve with additional aging.
Figure 3. Dynamic breakdown voltage vs pressure.
of saturable reactor material required, and hence lowers the inductance of the saturable reactor section.) Saturable reactors are discussed in Section 5.

b. Recovery

During the recovery measurements it was determined that the long and erratic recovery times reported for HY-3013L (see Second Interim Report, p. 15), were caused by false triggering of one of the TM-11A charging modules, and not by actual recovery failure. When false triggering was eliminated, recovery was rapid, as discussed below.

The circuit used to measure recovery time is diagramed in Figure 4. It is designed to simulate a prr greater than 20 kHz. First, epy is applied by TM-11 No. 1, then the thyratron is triggered, and after a variable time delay epy is re-applied by TM-11A No. 2. If the thyratron has recovered, the 150 pF capacitor re-charges to full epy and then discharges exponentially through the 100 kohm resistor. If the thyratron has not recovered, it conducts a second time even though no second trigger is applied, so that the 150 pF capacitor discharges abruptly either before or shortly after reaching epy.

Two TM-11As are required to simulate prr = 20 kHz because the open circuit output voltage of each one alone drops rapidly for prr greater than a few Hz. If TM-11A No. 2 false triggers when the thyratron first fires, then it is not able to put out any voltage when commanded to fire a few microseconds later. The 150 pF capacitor does not re-charge, just as if the thyratron had failed to recover.

Although the erratic nature of the recovery data aroused suspicion, this effect was not discovered immediately because its variation with epy, time delay, and thyratron pressure was qualitatively the same as recovery failure.

Circuit modifications to reduce false triggering included isolation resistors on the terminals of TM-11A No. 2, physical separation of circuit components, and liberal use of baluns and 50 ohm terminations. While these measures did not eliminate false triggering completely, they were successful enough to allow reliable recovery data to be taken.

Figure 5 shows recovery time tr vs pressure for both HY-3013L and HY-3013L2. The HY-3013L data agree with the data given in Figure 7 of the First Interim Report. The faster recovery of HY-3013L2 is due to the smaller E-E space, as discussed in the Second Interim Report.

Recovery is fast enough for 20 kHz operation (tr = 50 μs), up to a pressure of about 0.85 torr for HY-3013L, and 0.95 torr for HY-3013L2. Since load voltage rise rates of 6 kv/ns have been demonstrated at 0.7 torr (Second Interim Report,
Sequence of Events:

1. Pulser P1 triggers TM-11A No. 1 which charges 150 pF to \( V_0 \). Simultaneously P1 triggers P2.

2. A delayed pulse from P1 triggers TM-27 which in turn triggers a 1 kV-10 Ω driver, which triggers HY-3013L about 2 µs after the 150 pF reaches \( V_0 \).

3. Some time after HY-3013L2 fires, P2 triggers TM-11A No. 2 re-charging 150 pF to \( V_0 \), provided the time interval between 2 and 3 is greater than the HY-3013L2 recovery time.

Figure 4. Circuit for recovery time measurements.
Figure 5. Recovery time.

RECOVERY TIME

\( e_p = 10 \text{keV (5}\mu\text{s RISE, 2}\mu\text{s DWELL)} \)

NO REVERSE BIAS ON GRID
Section 3), these recovery characteristics are more than adequate for the ultimate application.

Further shortening of $t_r$ resulted when negative bias was applied to the control grid, accomplished by inserting a 1 µF capacitor between the trigger source and control grid.* Typical triggering conditions for HY-3013L2 were 450 volts egy superimposed on -150 volts negative bias.

With negative bias, $t_r$ for HY-3013L2 was less than 15 µs at all pressures, and for all epy up to about 80% of DBV. (Recovery times shorter than 15 µs could not be measured because the width of the trigger pulse was nearly 15 µs.) All recovery measurements were made at peak currents, $i_b$, of 400 amps.

Negative bias produced similar results in HY-3013L, although the measurements were more difficult because HY-3013L was hard to trigger when negative bias was applied.

Though the recovery characteristics of HY-3013L3 have not been measured, they should be similar to those of HY-3013L2.

c. Thyatron Trigger Requirements

Commutation with low trigger power is desirable not only from the point of view of overall system volume and power consumption, but also because it is usually associated with low jitter.

Trigger modules were available having output impedances of 200, 100, 50 and 10 ohms. While all four modules were able to break down the auxiliary grid of HY-3013L at voltages below 1 kv, the tube failed to commutate with the 100 and 200 ohm drivers. When reverse bias was used (to increase the recovery speed), only the 10 ohm trigger yielded reliable commutation.

HY-3013L2 was nearly as difficult to trigger, despite the absence of an auxiliary grid. The 50 ohm trigger sufficed even when reverse bias was applied, but commutation could not be obtained under any conditions with higher impedance triggers.

During this time, one of the newer production thyratrons (HY-8) was found to have exceptionally low jitter, and to be easy to trigger, due to the unusually small offset between the apertures in adjacent electrodes (0.025 inch, as compared to 0.080 for HY3013L2 and 0.100 for HY-3013L).

*Each time the grid is triggered, some electrons hit the grid and flow to the grid side of the 1 µF capacitor. In between pulses, both grid and driver are open circuits, so these electrons accumulate until there are enough to repel further buildup. The result is a dc negative bias on the control grid.
Thyratron HY-3013L3 was therefore constructed with the same aperture offsets and inter-electrode spacings as the HY-8 (Figure 2c), resulting in a tube which commutated readily with a 200 ohm driver, even with reverse bias. Furthermore, the voltage holdoff was equal to that of HY-3013L2 (Figure 3).

d. Dispenser Cathode Development

Two 3-inch-diameter tetrode thyratrons of the HY-3006 type have operated successfully with a dispenser cathode for over 100 hours. The operating parameters and characteristics are similar to those of a standard-cathode HY-3006, as shown below.

**HY-3006 Operating Characteristics**

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<td>6.3 V</td>
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<tr>
<td>Hydrogen Pressure</td>
<td>450 μ</td>
<td>450 μ</td>
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<tr>
<td>Anode Voltage</td>
<td>25-30 kv</td>
<td>30 kv</td>
</tr>
<tr>
<td>Peak Current</td>
<td>1.5-2 ka</td>
<td>1.5 ka</td>
</tr>
<tr>
<td>DC Average Current</td>
<td>1.5-2 A</td>
<td>2 A</td>
</tr>
<tr>
<td>Keep-Alive Current</td>
<td>50-200 mA</td>
<td>50 mA</td>
</tr>
<tr>
<td>Jitter</td>
<td>2 ns</td>
<td>3 ns</td>
</tr>
<tr>
<td>Anode Delay Time</td>
<td>50-100 ns</td>
<td>40 ns</td>
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<tr>
<td>Trigger Source</td>
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The dispenser cathode being used fits equally well into an HY-3013 type thyratron. A dispenser cathode HY-3013L can therefore be made at any time, but it would be best to await completion of more extensive tests with production tubes, and development of ultra-low inductance cathode-mounting designs.
LOAD AND PFN DEVELOPMENT

The test load should consist of a 30 pF capacitor shunted by a resistor. It has been determined theoretically and experimentally that a 4 ns FWHM voltage pulse can be applied across the load if the storage capacitor is -240 pF, the load resistor is -13 ohms, and the total circuit inductance (including the switch), is 17 nH or less.

In addition, the load and PFN must be rated for at least 150 watts average power (5 kv across 13 ohms, at a prr of 20 kHz and a pulse width of 4 ns).

To simplify construction, the load and PFN configuration was developed using a very short air gap having negligible inductance for a switch. Since the thyatron is ultimately expected to have an inductance of 8 nH, the desired load/PFN inductance was 9 nH or less.

After some experimentation, the configuration of Figure 6 was derived. Storage capacitor C₀ consisted of 10 mils of kapton sandwiched between aluminum plates. Resistor R was a disc of pressed ceramic, rated at 180 watts average power and 10 ohms. Load capacitance C consisted of the capacitance between this resistor and ground, through mylar dielectric. (In the final circuit, described in Section 6, the mylar is replaced by transformer oil, and the air gap by a thyatron.)

The voltage pulse across R produced in this assembly is shown in Figure 5c. Even though C₀ and C were greater than necessary (300 pF and 80 pF as compared to 240 pF and 30 pF), a 3.5 ns FWHM pulse was produced, having an amplitude approximately half that of the initial voltage on C₀.*

The overall inductance, estimated from the voltage waveform is 7 nH. (FWHM ≈ \(2\sqrt{L(C₀ + C)}\).)

Reducing the total capacitance to 240 + 30 = 270 pF, and adding an 8 nH thyatron scales the FWHM to 4 ns. If the top 3.5 kv of a 5 kv pulse were used, the effective FWHM would become, assuming the same shape pulse as in Figure 6c, about 1.7 ns.

*Hence the statement in Section 2 that the thyatron voltage should be double the voltage to be applied to the load.
(a) Circuit schematic. $C_0$ initially charged to voltage $V_0$. $C_1$ and $R$ constitute load.

(b) Circuit assembly. $C_0$ is between aluminum disc and resistor. $C_1$ is between resistor O.D. and ground.

(c) Voltage across ceramic resistor (load voltage). Measured capacitances were $C_0 = 300$ pF, $C_1 = 80$ pF. Peak load voltage = 2.2 kv. $V_0 = 4.3$ kv.

Figure 6. Low inductance PFN/load circuit.
5 SATURABLE REACTOR DEVELOPMENT

a. Ferrite Reactor Design

A saturable reactor will be used to delay the current rise until the thyatron resistive fall is over. This will be necessary not only to sharpen the load voltage pulse, but also to reduce the thyatron anode dissipation which would otherwise be severe.

The saturable reactor section will be coaxial, as shown in Figure 7. The dimensions must necessarily be a compromise among three factors: current delay time, saturation current, and inductance.

Current delays of several nanoseconds require a large magnetic cross section, \( lw \), which can only be achieved by making \( l \) large since \( w \) must remain small to ensure that the entire reactor saturates simultaneously. A low saturation current requires a small diameter, \( d \). Low inductance, however, requires small \( l \) and large \( d \).

Orthonol and metglas are attractive as saturable reactor materials because their low coercive force permits large diameter configurations with low saturation currents. However, low resistivity renders metglas unsuitable, and orthonol only a marginal possibility, as discussed in subsection 5.b.

We have, therefore, chosen ferrites. While the basic viability of ferrite beads was demonstrated by data presented in the Second Interim Report, their high coercive force may necessitate some tradeoff between anode dissipation (which increases with saturation current), and pulse width (which increases with inductance).

Since our work to date has concentrated on achieving the pulse width specifications, the initial saturable reactor design will aim for low inductance (about 1 nH), with a high saturation current (100 amps). The diameter will then be reduced as much as possible without significantly exceeding the inductance required for a 4 ns pulse width. Likely starting dimensions are \( d = 1.5 \) inches, \( l = 1 \) inch.

b. Evaluation of Orthonol and Metglas as Saturable Reactor Materials

In order to have a back-EMF comparable to epy during thyatron anode fall time \( t_f \), followed by saturation at time \( t = t_f \), the saturation flux density, \( B_s \), and the magnetic area, \( A_m \), of the saturable reactor must roughly satisfy
Figure 7. Coaxial saturable reactor using ferrites.
If we assume a coaxial saturable reactor section of length $l$, then $A_m(t_f) = lx(t_f)$, where $x(t_f)$ is the penetration depth of saturation "front" at $t = t_f$. Equation (1) becomes

$$x(t_f) = \frac{\text{epy} \cdot t_f}{1B_S}$$  (2)

Following Nunally, (2) we assume shock-like propagation of the saturation front and get, approximately,

$$x(t_f) = \left[ t_f \frac{\rho}{B_S} \frac{i(t_f)}{\pi d} \right]^\frac{1}{2}$$  (3)

where $\rho$ is the resistivity, $i(t_f)$ the circuit current at $t = t_f$, and $d$ the average diameter of the saturable reactor configuration.

The problem with orthonol and metglas is that their resistivity is too low for $x(t_f)$, as calculated from Equation (3), to satisfy the condition of Equation (2). This will now be shown.

The following parameter values apply:

- $\text{epy} = 10,000 \text{ volts}$
- $t_f = 10^{-8} \text{ second}$
- $B_S = 1.6 \text{ webers/m}^2$
- $1 = 0.1 \text{ meter maximum for reasonably low inductance}$
- $d = 0.05 \text{ meter minimum for reasonably low inductance}$
- $\rho = 50 \times 10^{-8} \text{ ohm-m for orthonol}$
- $\rho = 125 \times 10^{-8} \text{ ohm-m for metglas}$
- $i(t_f) = 100 \text{ amps maximum (10-20% of ultimate peak current)}$.

These give, from Equation (2), a required $x(t_f)$ of $0.625 \times 10^{-3} \text{ meter}$, or 25 mils.

From Equation (3), we get $x(t_f) = 0.056 \text{ mil for orthonol}$, and $0.089 \text{ mil for metglas}$.
Therefore, in order to achieve the required $x(t_f)$, we would need to wrap approximately $\frac{1}{4} \times 25/0.089 - 140$ laminations of metglas, or 225 laminations of orthonol. (The factor $\frac{1}{4}$ is present because the magnetic field penetrates from both sides of the lamination.)

Winding such a large number of laminations would be difficult, especially considering the sensitivity of the magnetic properties of orthonol and metglas to handling.

However, even if we succeeded in constructing such windings, they would still not work under our conditions because the minimum available thicknesses of orthonol and metglas are too great for saturation to be complete by $t = t_f$.

The thinnest obtainable metglas is 1 mil, giving, from Equation (3), a saturation time of 2.3 $\mu$s. At an $i(t_f)$ of 100 amperes, all the charge in the energy storage capacitor would be drained off by the time the reactor saturated.* Thus, metglas is not a viable saturable reactor material for this application.

The thinnest obtainable orthonol is 1/8 mil, giving a saturation time of 50 ns. The charge drained off the energy storage capacitor at $t = t_f$ would be $2.5 \times 10^{-6}$ coulomb, essentially all the charge stored. Increasing $e_{py}$ to compensate is possible but undesirable from a thyatron holdoff viewpoint, and increasing the storage capacitance to compensate would increase the ultimate load voltage pulse width. Therefore, orthonol must be considered as only marginally feasible as a saturable reactor material for this application.

Given the aforementioned practical difficulties involved in winding a suitable orthonol reactor, we will continue to use ferrite beads for the present. Ferrite beads are highly resistive, so the field penetration is effectively instantaneous, and they are also convenient to use.

*240 pF x 10,000 volts = $2.5 \times 10^{-6}$ coulomb. Assuming a linear current rise, $\frac{1}{4} \times 100$ amps x 1.3 $\mu$s = $6.5 \times 10^{-5}$ coulomb.
OVERALL CIRCUIT DESIGN

The complete nanosecond pulser circuit is diagrammed schematically and pictorially in Figure 8. The entire assembly will be immersed in transformer oil for insulation.

Cooling of the saturable reactor section (which must be kept below the 150°C Curie temperature of the ferrites), will be promoted by its being located at an end of the assembly, and by its proximity to the large aluminum top piece. If necessary, this piece can be contoured and/or finned for better cooling.

Parts for the circuit assembly are currently on order.
5.000 DIA. REF.

- TOP
- FERRITES
- FOIL OR STRIP
- KAPTON INSULATION
- LOAD CAPACITANCE
- LOAD RESISTOR
- 0.010 KAPTON (STORAGE CAPACITOR)
- ANODE ADAPTER
- SHROUD ADAPTER
- SHROUD

NOTES:
1. TO BE IMMERSED IN TRANSFORMER OIL.

Figure 8. Circuit assembly.
20 kHz TEST KIT

The 20 kHz test kit, diagrammed schematically in Figure 9, is designed to command charge 500 pF to 20 kv with a 3 μs rise time. The kit is now complete and ready for final checkout.
Figure 9. 20 kHz test kit.
8 FUTURE PLANS

The circuit of Figure 8 will be assembled, tested at low prr and, if necessary, modified until the desired load voltage pulse is produced, after which high prr testing will commence.
9 REFERENCES


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APPENDIX
LUMPED CIRCUIT ANALYSIS
\[ \frac{v(s)}{V_0} = \frac{1}{s} \frac{R/(1 + sRC)}{sL + \frac{1}{sC_0} + \frac{1}{1 + sRC}} = \frac{1}{s^3LC + s^2 \frac{1}{R} + s \left( \frac{1}{sC_0} \right) + \frac{1}{RC_0}} \]  \tag{B-1}

\[ \text{LC} \ \frac{v(s)}{V_0} = \frac{1}{s^3 + \frac{1}{RC} s^2 + \frac{1 + C/C_0}{LC} s + \frac{1}{RLCC_0}} \]  \tag{B-2}

For critical damping this should have the form

\[ \text{LC} \ \frac{v(s)}{V_0} = \frac{1}{(s + \alpha)^3} \]  \tag{B-3}

This requires that "\( \alpha \)" satisfy three conditions:

\[ 3\alpha = \frac{1}{RC} \]  \tag{B-4}

\[ 3\alpha^2 = \frac{1 + C/C_0}{LC} \]  \tag{B-5}

\[ \alpha^3 = \frac{1}{RLCC_0} \]  \tag{B-6}
Then

\[
\frac{V(t)}{V_0} = \frac{3}{2} \frac{1}{1 + \frac{C}{C_0}} (at)^2 e^{-at}
\]  

Eliminating L and R from Equations (B-4), (B-5), and (B-6) gives \(\frac{C_0}{C} = 8\).

FWHM = \(\frac{3.4}{\alpha}\) = 10.2 RC which for 4 ns and C = 60 pF gives R = 6.5 Ω. Returning to conditions (B-5) and/or (B-6) we get L = 8.7 nH.

The maximum value of \(\frac{V(t)}{V_0}\) occurs at at = 2 and is equal to 0.7.