

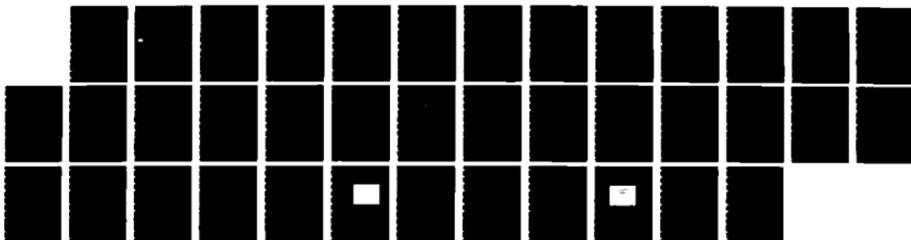
AD-A171 263

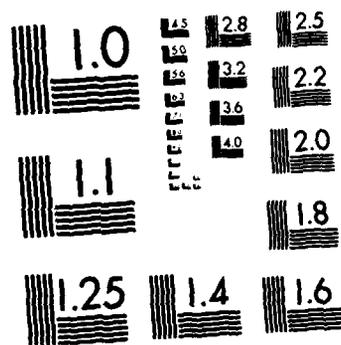
THE MAGNETIC DEFLECTION OCCILLATOR AS A POTENTIAL VERY
HIGH-POWER RF (RADIOFREQUENCY) SOURCE(U) TETRA CORP
ALBUQUERQUE NM J G SMALL ET AL. MAY 86 AFML-TN-85-30
F29681-83-C-0090 F/G 9/1

1/1

UNCLASSIFIED

ML





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

2

AD-A171 263

THE MAGNETIC DEFLECTION OSCILLATOR AS A POTENTIAL VERY HIGH-POWER RF SOURCE

James G. Small
Chris M. Young

Tetra Corporation
4905 Hawkins Street NE
Albuquerque, New Mexico 87109

May 1986

Final Report

Approved for public release; distribution unlimited.

DTIC
ELECTE

AUG 29 1986

B

AIR FORCE WEAPONS LABORATORY
Air Force Systems Command
Kirtland Air Force Base, NM 87117-6008

DTIC FILE COPY



This final report was prepared by Tetra Corporation, Albuquerque, New Mexico, under Contract F29601-83-C-0090, Job Order 57971907 with the Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico. Major Brian J. Kohn (AWPB) was the Laboratory Project Officer-in-Charge.

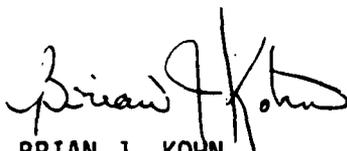
When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely Government-related procurement, the United States Government incurs no responsibility or any obligation whatsoever. The fact that the Government may have formulated or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication, or otherwise in any manner construed, as licensing the holder, or any other person or corporation; or as conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

This report has been authored by a contractor of the United States Government. Accordingly, the United States Government retains a nonexclusive, royalty-free license to publish or reproduce the material contained herein, or allow others to do so, for the United States Government purposes.

This report has been reviewed by the Public Affairs Office and is releasable to the National Technical Information Services (NTIS). At NTIS, it will be available to the general public, including foreign nations.

If your address has changed, if you wish to be removed from our mailing list, or if your organization no longer employs the addressee, please notify AFWL/AWPB, Kirtland AFB, NM 87117-6008 to help us maintain a current mailing list.

This technical report has been reviewed and is approved for publication.

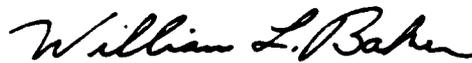


BRIAN J. KOHN
Major, USAF
Project Officer

FOR THE COMMANDER



WINFIELD S. BIGELOW, JR
Major, USAF
Chief, Beam Physics Branch



WILLIAM L. BAKER
Chief, Advanced Technology Division

DO NOT RETURN COPIES OF THIS REPORT UNLESS CONTRACTUAL OBLIGATIONS OR NOTICE ON A SPECIFIC DOCUMENT REQUIRES THAT IT BE RETURNED.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

ADA171263

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED			1b. RESTRICTIVE MARKINGS			
2a. SECURITY CLASSIFICATION AUTHORITY			3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.			
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE						
4. PERFORMING ORGANIZATION REPORT NUMBER(S)			5. MONITORING ORGANIZATION REPORT NUMBER(S) AFWL-TN-85-30			
6a. NAME OF PERFORMING ORGANIZATION Tetra Corporation		6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION Air Force Weapons Laboratory			
6c. ADDRESS (City, State and ZIP Code) 4905 Hawkins Street NE Albuquerque, New Mexico 87109			7b. ADDRESS (City, State and ZIP Code) Kirtland Air Force Base, NM 87117-6008			
8a. NAME OF FUNDING/SPONSORING ORGANIZATION		8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER F29601-83-C-0090			
8c. ADDRESS (City, State and ZIP Code)			10. SOURCE OF FUNDING NOS.			
			PROGRAM ELEMENT NO. 62601F	PROJECT NO. 5797	TASK NO. 19	WORK UNIT NO. 07
11. TITLE (Include Security Classification) THE MAGNETIC DEFLECTION OSCILLATOR AS A POTENTIAL VERY HIGH-POWER RF SOURCE						
12. PERSONAL AUTHOR(S) Small, James G. and Young, Chris M.						
13a. TYPE OF REPORT Final		13b. TIME COVERED FROM 1Sep83 TO 31Mar85		14. DATE OF REPORT (Yr., Mo., Day) 1986 May		15. PAGE COUNT 40
16. SUPPLEMENTARY NOTATION						
17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)			
FIELD	GROUP	SUB. GR.	High power microwaves		Oscillators	
20	14		Magnetic deflection oscillator		RF Oscillator	
			Microwaves			
19. ABSTRACT (Continue on reverse if necessary and identify by block number) A proposed design for a Magnetic Deflection Oscillator to produce intense radiofrequency (RF) radiation is analyzed and theoretical results reported. The Magnetic Deflection Oscillator is an RF oscillator concept which can, in principle, be scaled to very high power levels. This report contains a theoretical study of the oscillator operation and a description of a low power experiment. The experiments did not achieve oscillator threshold due to limits on available beam current and power. The electron beam current required for oscillator threshold is predicted to increase with the square root of increasing frequency. The experiment shows that, at a frequency of 4 kHz, CW oscillator threshold should be reached at a beam current of approximately 1 A. Cathode arcing limited the experiment to pulsed currents near 300 mA. The threshold power for oscillation at 300 MHz is predicted to be near 45,000 W. An oscillator might function at power levels many times above threshold with DC to RF conversion efficiencies comparable to class C vacuum tubes, possibly greater than 70 percent.						
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT UNCLASSIFIED/UNLIMITED <input checked="" type="checkbox"/> SAME AS RPT <input type="checkbox"/> DTIC USERS <input type="checkbox"/>			21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED			
22a. NAME OF RESPONSIBLE INDIVIDUAL Major Brian J. Kohn			22b. TELEPHONE NUMBER (Include Area Code) (505) 844-0121		22c. OFFICE SYMBOL AWPB	

DD FORM 1473, 83 APR

EDITION OF 1 JAN 73 IS OBSOLETE.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

TABLE OF CONTENTS

Section	PAGE
I. INTRODUCTION	1
1. CONVENTIONAL DEVICE LIMITATIONS	1
2. REVIEW OF MDO PRINCIPLES	5
II. UNDERSTANDING OSCILLATORS	10
1. THE VACUUM TUBE RLC OSCILLATOR	10
2. MAGNETIC FIELD QUADRATURE REQUIREMENTS	11
III. COMPUTER SIMULATION OF AN MDO	13
IV. POWER AND FREQUENCY SCALING LAWS	19
1. FIELD REQUIRED TO DEFLECT AN ELECTRON	19
2. FIELDS WITHIN A TYPICAL RF RESONATOR	21
3. FREQUENCY SCALING LAWS	24
V. EXPERIMENTAL CONFIGURATION	26
1. CONTINUOUS WAVE EXPERIMENTS	26
2. RC PULSED EXPERIMENTS	29
VI. CONCLUSIONS	33



Accession	✓
NTIS	
MAY	
1981	
Dist	A-1

I. INTRODUCTION

The radiofrequency (RF) range from HF to UHF, i.e., frequencies from 10^6 to 10^9 Hz, is well investigated today. Transistors and other semiconductor devices can handle all but the highest power requirements in communication and industrial heating applications. In the highest power applications, vacuum tube amplifiers are still used for services such as broadcast television and for some ECM applications. There are probably few transmitters in this frequency range today which operate at power levels above 10^6 W CW or 10^7 W pulsed. Note, however, that higher power levels are achieved at microwave frequencies from pulsed magnetrons and other oscillators and at optical frequencies from pulsed lasers.

There appear to be no fundamental limits to higher RF power levels. Alternating currents are not much different from direct currents in any circuit which is small compared to the operating wavelength. Very high power pulsed DC sources are now available, such as large capacitor banks, homopolar generators, and explosively driven magnetic compression generators (MCGs). Pulse energies above 10^6 J and power levels above 10^{11} W are available at DC and not at RF. On physical grounds there seem to be no real limitations. Such very high power RF devices could have applications in radar, ECM, EMP, and directed energy systems.

Practical implementation of megajoule pulsed RF sources will require new types of hardware devices. The subsections below describe (1) the limitations inherent in gridded vacuum tubes and (2) the magnetic deflection principle. Section II describes the physical requirements for driving resonant oscillators and the implications for Magnetic Deflection Oscillators (MDOs). Section III reports computer simulations of an MDO. Section IV discusses power and frequency scaling laws. Section V reports experimental results of this project and Section VI presents the conclusions of this work.

I. CONVENTIONAL DEVICE LIMITATIONS

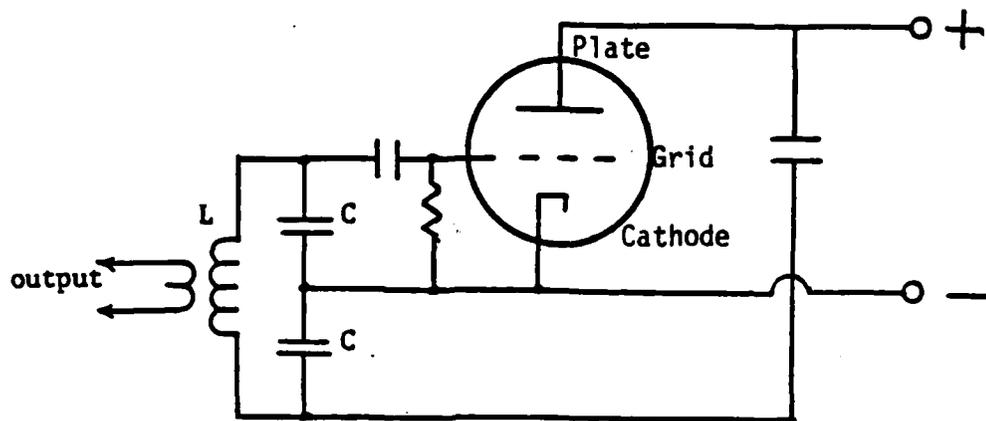
An oscillator to transform a DC pulse to an RF pulse is required. To do that, a nonlinear device is required such as a transistor or vacuum tube. A device is needed to interrupt or reverse the flow of current at a well defined frequency. No linear system of inductors, capacitors, or resistors will do the job.

Figure 1 shows a typical Colpitts oscillator circuit using in case (a) a vacuum triode and in case (b) a field effect transistor. The oscillation frequency is determined by the LC resonator while the active device, tube or transistor, performs a switching or current interrupting function. The DC energy is converted to RF energy stored in the LC resonator. Useful output power may be coupled out of the resonator inductively through the alternating magnetic fields of the inductor, L, or capacitively from the alternating voltages present across the capacitor, C. Most of the RF power circulates as electrical currents and fields in the resonator in a manner no different from the currents and fields of a DC pulse device. The power capabilities of these oscillators are limited by the active switching device. Higher power levels will require only higher powered switching devices. The technology for resonators and antennas is already at hand.

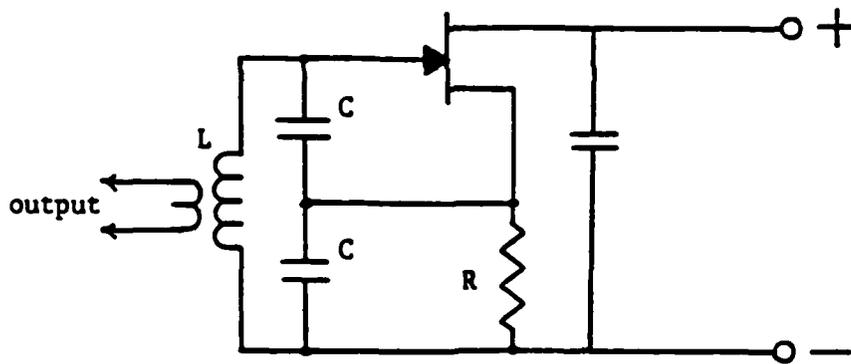
Vacuum tubes represent one class of switching devices. Vacuum tubes are electrostatic devices. Electric fields between the cathode and grid are used to influence the plate current. Though quite successful, the electrostatic method has its limitations. Specifically, it cannot be used to control really large currents. Vacuum tubes are essentially space charge limited devices. Very high radiated powers must come from large currents which require either enormous tube sizes or high space charge and current densities. High space charge densities effectively screen out electric fields making control grids no longer effective; i.e., the electric fields from the control grids must compete with the electric fields from substantial amounts of space charge.

An alternate way to control large currents and large powers is magnetically. Consider that there are few electrostatic motors in use today. Large currents, as in motors, can interact through magnetic fields without space charge limitations. Magnetic control is largely responsible for the high powers achieved in microwave magnetrons as opposed to the more limited power capability of klystrons and traveling wave tubes, which are electrostatic devices.

There are several approaches one might take toward a high power VHF device; e.g, one could construct a low frequency magnetron. The magnetron, shown schematically in Fig. 2, is a proven device and can certainly be scaled to longer wavelengths. Long wavelengths require low magnetic fields, which is an engineering convenience. Long wavelengths also require large resonators which is, again, an advantage for high power operation. The physical dimensions of a magnetron scale directly with wavelength. Thus, a long wavelength magnetron would have a large volume. It could handle large powers without exceeding the



(a) Circuit using vacuum triode.



(b) Circuit using field effect transistor.

Figure 1. Colpitts Oscillator Circuits.

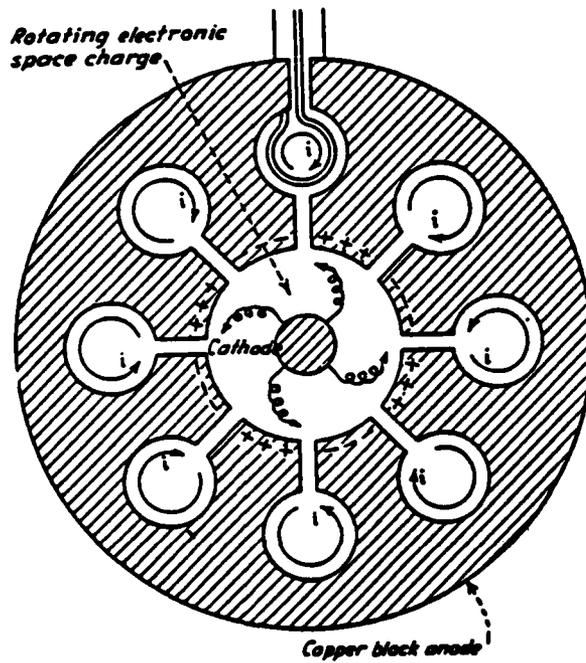


Figure 2. A schematic section through a resonant cavity magnetron showing a rotating space charge.

critical insulator and air breakdown power densities of a smaller device. Note that the magnetron uses a rotating electronic space charge, but the trajectory of the moving electrons is predominantly controlled by DC magnetic fields. The principle disadvantages to magnetrons are that they require hot thermionic cathodes and nearly constant current DC pulse sources. Presently available very high energy pulsed sources would require extensive and probably inefficient pulse shaping to be useful with magnetrons.

2. REVIEW OF MDO PRINCIPLES

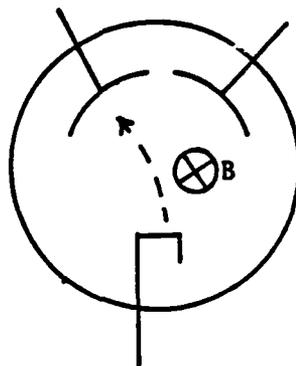
The MDO is shown schematically in Fig. 3. The idea is to use magnetic forces to switch large currents at VHF rates. Fig. 3(a) shows a vacuum dual diode. The cathode emits a loosely collimated electron beam collected by one or the other plate anodes. For low power applications, the device can be constructed as a simple hot cathode vacuum tube. At high powers, the device can operate at hundreds of kilovolts and tens of kiloamperes handling power levels above 10^{10} W. The high powered version can make use of an unheated field emission cathode.

Diode current is switched back and forth between the two plate anodes by a magnetic field which passes through the plane of the page. This device could be used as a one-shot switch for high currents, but the present investigation deals primarily with repetitive switching at RF rates.

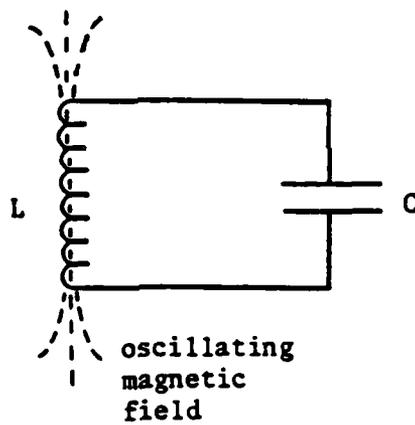
Figure 3(b) illustrates a parallel tuned LC resonator. When externally driven at its resonant frequency, strong circulating currents can be made to oscillate or ring in the resonator. Currents flowing in the inductor, L, produce magnetic fields which oscillate sinusoidally at the same frequency. These oscillating fields will be used to switch the diode currents.

This simple idea might have been thought of by Marconi, Tesla or Helmholtz. However, to this author's knowledge, the MDO has not previously been described or demonstrated.

Fig. 4 illustrates a push-pull MDO. Current switching is caused by coupling the diode device to the naturally occurring magnetic fields of the inductor, L. Oscillation should occur at the natural resonant frequency of the LC resonator. Since electrostatic deflection is not used, space charge densities should not be a limitation to high power operation.



(a) A vacuum diode with dual collecting plates.



(b) Parallel tuned LC resonator.

Figure 3. MDO schematic.

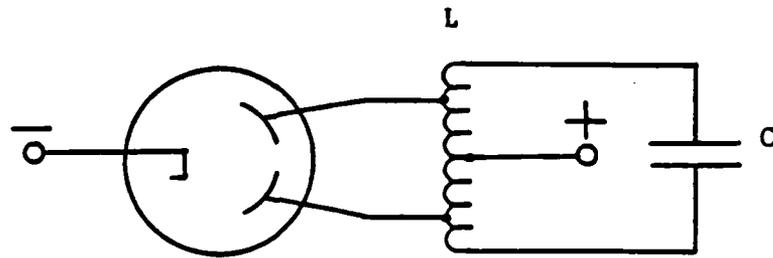
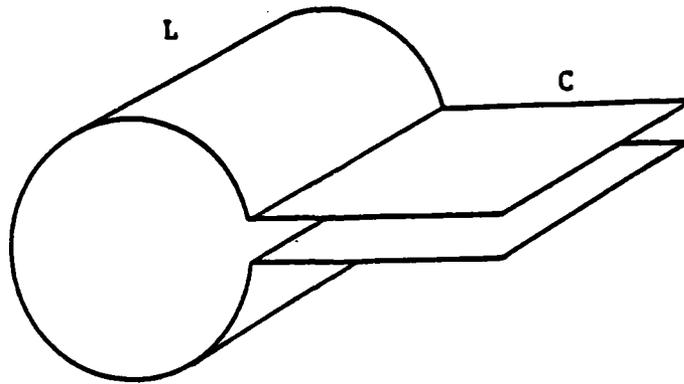


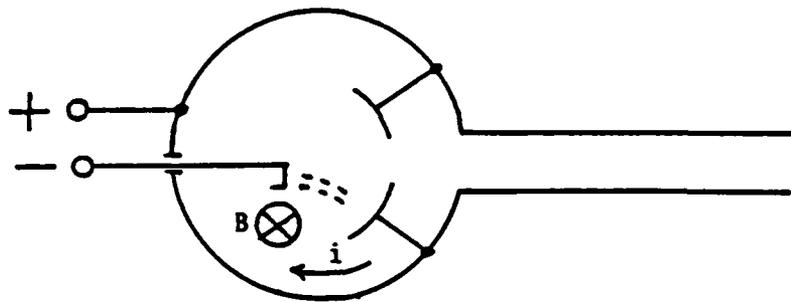
Figure 4. A proposed push-pull Magnetic Deflection Oscillator

Fig. 5(a) illustrates the UHF limit of the LC resonator. The inductor, L, has become a one turn coil of width equal to the width of the capacitor plates. The resonator can be made of a single piece of bent sheet metal.

Fig. 5(b) shows the vacuum diode installed inside the inductor, L, where it will experience maximum magnetic fields. Note that, when current flows to the lower plate, a magnetic field is generated of the correct polarity to deflect the current to the upper plate. The device should be a natural oscillator.



(a) The UHF limit of an LC resonator.



(b) Vacuum diode placed inside the inductor

Figure 5. LC resonator with vacuum diode installed inside inductor.

II. UNDERSTANDING OSCILLATORS

All electromagnetic radiation comes from accelerated charges. High power sources require large amounts of accelerated charge or, simply, large time varying antenna currents.

RF oscillators typically use LC resonators for feedback and for energy storage or flywheel operation. Since the MDO is intended to couple very large powers into and out of LC resonators, it is important to understand how LC resonators may be driven at their resonant frequencies. This section contains a brief review of resonant LC oscillators and a specific application to the magnetically driven oscillator.

I. THE VACUUM TUBE RLC OSCILLATOR

The RLC oscillators are treated in detail in many electrical engineering textbooks (see, for example, *Introduction to Electricity and Optics*, Chapter 9, by N.H. Frank, McGraw-Hill Book Company, publisher). Only features pertinent to the MDO will be reviewed here.

Refer again to Fig. 1(a) as an example of a vacuum tube RLC oscillator. The resistance, R , is not shown explicitly. It consists of circuit losses in the inductor, L , capacitors, C , and output coupling. To simplify the analysis assume that:

- a. the oscillation is steady state. The active device supplies energy at a rate exactly equal to the circuit power losses;
- b. the oscillation is sinusoidal and single frequency. Strictly, this assumption is not true. Most oscillators produce nonsinusoidal periodic waveforms which are rich in harmonics. A very underdamped or high- Q LC resonator is a good filter against harmonics, but often several stages of filters or tuned amplifiers may be needed to reduce harmonics to communications grade levels;
- c. the RLC resonator has low losses and high- Q .

Given the above three assumptions, the voltages and currents in the LC resonator are strictly sinusoidal and described by a simple linear second order differential equation. It is the equation for a driven simple harmonic oscillator with damping.

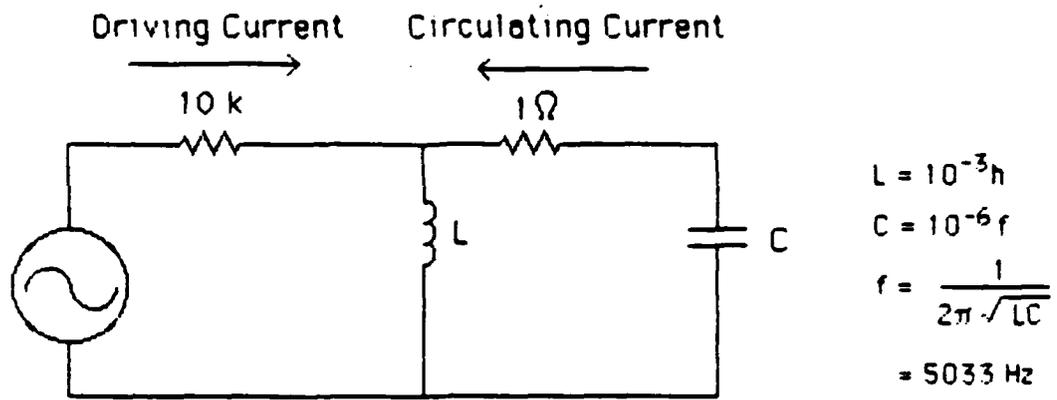
It is well known from analytic solutions to the governing equation and may also be seen in the computer simulations that the voltage and current waveforms differ in phase by 90 deg. In particular, the circulating current is zero at moments of maximum charge on the capacitor. The current increases as the capacitor voltage decreases. Thus, the voltage waveform *leads* the current waveform by one quarter cycle. The 90 deg. phase shift is true to high accuracy for high-Q resonators which are either freely decaying or are being driven in steady-state CW oscillation.

2. MAGNETIC FIELD QUADRATURE REQUIREMENTS

It is not so generally appreciated that a phase shift of injected current is required to sustain CW oscillations. In particular, to overcome circuit losses, an external *current source* must drive the resonator with a waveform that *leads* the circulating *current* by 90 deg. This is a general property of all forced harmonic oscillation. The driving force must lead the oscillating response by 90 deg. It can be seen on a child's swing where the child extends his legs downward at the maximum extent of the swing's motion. Figure 6 shows a computer simulation of a driven RLC resonator. The 90 deg. phase relation is clearly seen.

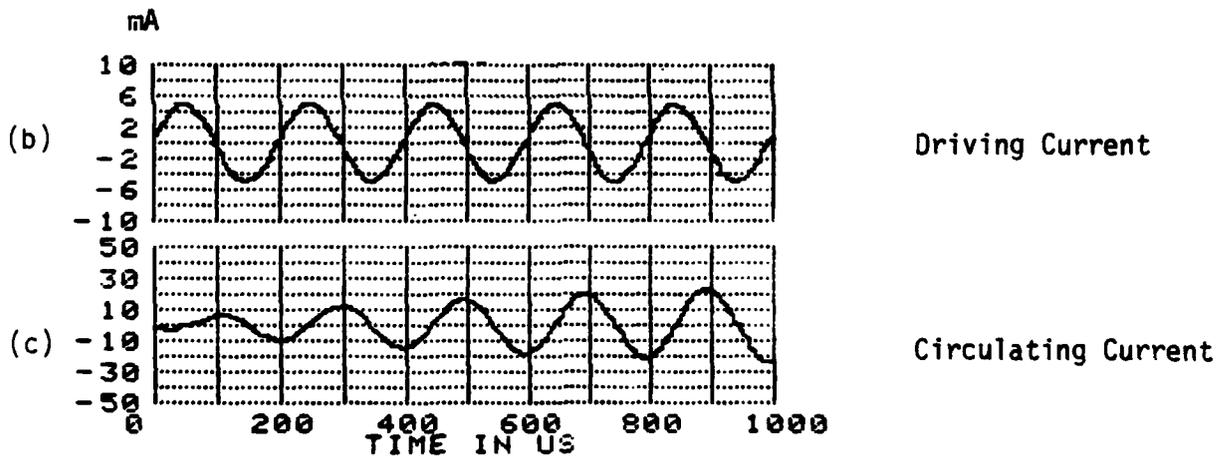
Referring again to Fig. 1, the vacuum tube Colpitts oscillator automatically provides for a 90 deg. phase shift. The vacuum tube may be thought of as a voltage controlled current source. A potential difference between the grid and cathode affects the current between cathode and plate. Here the grid voltage samples the capacitor voltage while variations in the plate current (AC coupled) are injected into the resonator. Since the capacitor voltage leads the inductor current by 90 deg., the injected or driving current also leads the circulating current by 90 deg. or quadrature.

The MDO intends to use magnetic fields from the inductor of the RLC resonator to perform the switching function. The instantaneous magnetic field is directly proportional to the instantaneous inductor current. There is no phase lag or lead, and there can be no oscillation. To allow oscillation, an additional (passive) circuit must be added. This circuit will be discussed in the next section.



Sinusoidal voltage source
 100 V Peak-To-Peak
 5033 Hz

(a) Circuit schematic.



(b) Circuit output.

Figure 6. A computer simulation of a driven RLC resonator.

III. COMPUTER SIMULATION OF A MDO

A computer simulation of a voltage driven current source is shown in Fig. 7. The vacuum tube has been modeled by an operational amplifier (op-amp) which senses the capacitor voltage for its input signal. Current is injected into the RCL resonator through a 10 kohm . Circulating current is monitored through the $1-\Omega$ resistor. Note that oscillations rapidly build up.

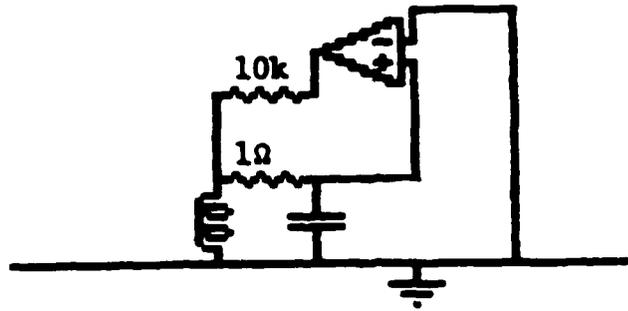
Fig. 8 shows a computer simulation of the MDO as a current driven current source. A $1-\Omega$ resistor in the series RCL resonator samples the circulating current for the op-amp input. The amplifier output voltage saturates at voltage swings greater than 30 V peak-to-peak. The output voltage is applied to a $10 \text{ k}\Omega$ series resistance which largely isolates the amplifier output voltage from the voltages in the RCL resonator. The computer simulation can monitor both the current through the $10 \text{ k}\Omega$ isolating resistor, as the driving current, and the current through the $1-\Omega$ resistor, as the circulating current.

The simulation in Fig. 8 began with an initial charge on capacitor C to produce an oscillation. Notice that the oscillation damped out. Fig. 9 is similar to Fig. 8 except the amplifier polarity has been reversed. Again the oscillation decayed to zero. Neither oscillation allowed for a 90 deg. phase shift of the injected current.

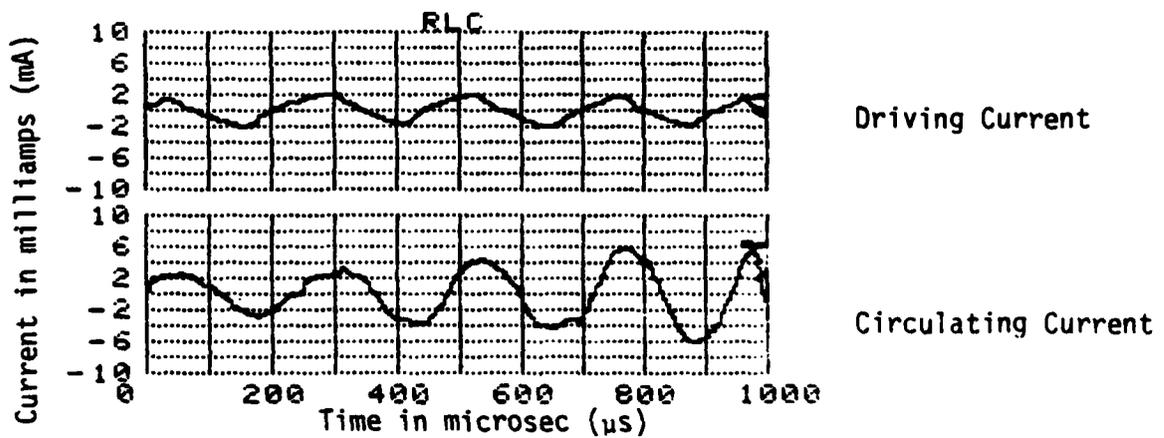
By previous argument, the injected current must lead the circulating current by 90 deg. Since both the MDO and the op-amp simulations respond to instantaneous currents in the RCL resonator, some trick is needed to produce a phase lead. Fig. 10 shows the method.

In steady-state oscillations, a phase lag of 270 deg. is equivalent to a phase lead of 90 deg. for the next cycle. The circuit in Fig. 10 produces a phase delay of 90 deg. with a lumped element delay line. An additional phase delay of 180 deg. comes from a polarity reversal of the op-amp input connections. In an MDO, polarity reversal is accomplished by reversing the magnetic field with respect to the collecting plate connections.

The simulation in Fig. 10 began with a very small initial capacitor charge. Oscillation continued to build up over several milliseconds before reaching steady state. The circulating current is nearly sinusoidal which justifies the previous assumptions. Note also that an injected current of just 4 mA has produced a circulating current of over 20 mA.

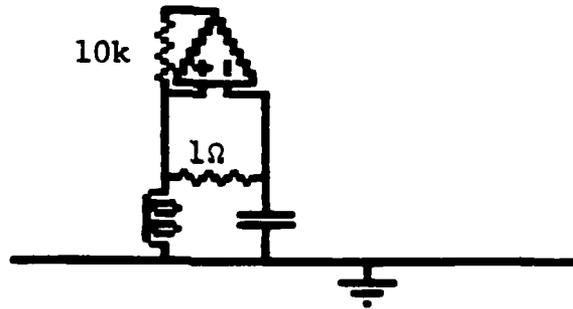


a) Circuit modeled on an Apple IIe microcomputer by a circuit analysis program.

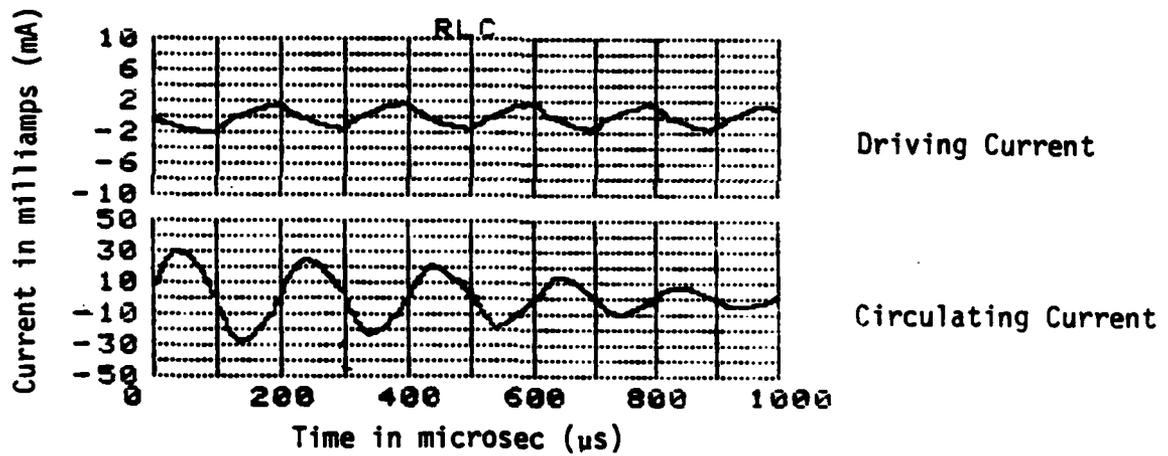


Driving current monitored through the 10-k resistor and circulating current through the 1-Ω resistor.

Figure 7. A computer simulation of a voltage controlled current source.

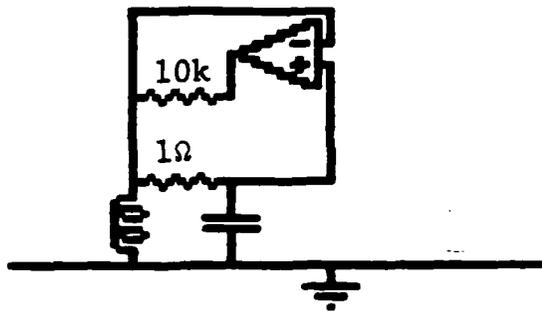


(a) Microcomputer circuit analysis for MDO.

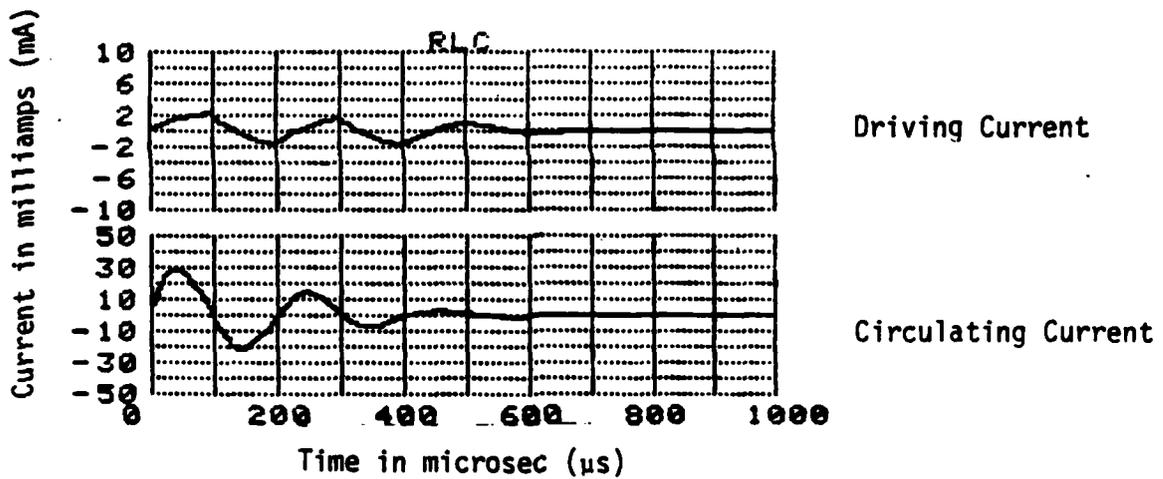


(b) Driving current through the 10-k series resistance and circulating current through the 1-Ω resistance.

Figure 8. A current driven current source.

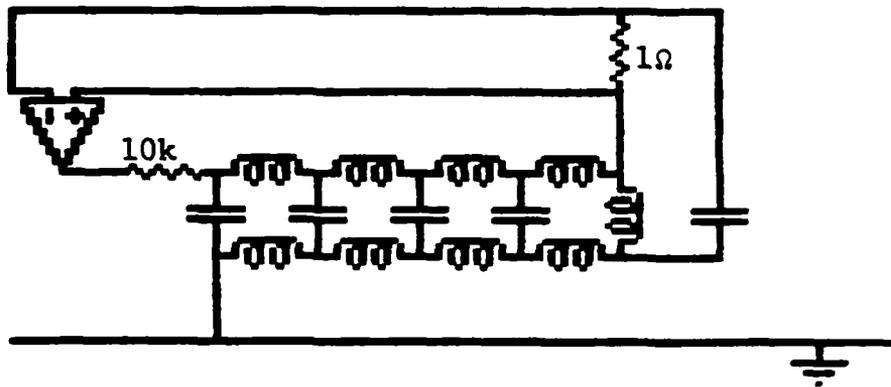


(a) Microcomputer circuit analysis with amplifier polarity reversed.

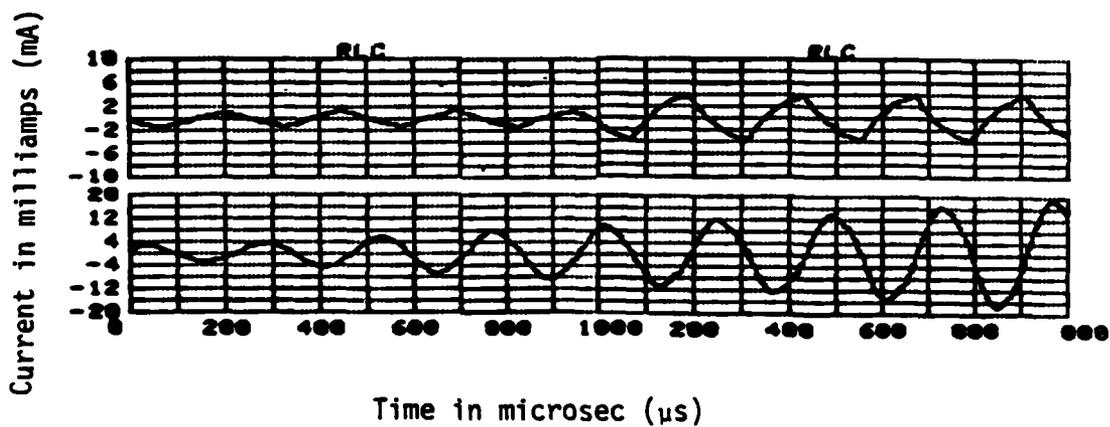


(b) Driving current through the 10-k resistance and circulating current through the 1- Ω resistance.

Figure 9. Current driven current source with reversed amplifier polarity.



(a) Microcomputer circuit analysis with very small initial capacitor charge.



(b) Resultant circulating and injected currents.

Figure 10. The MDO is a successful oscillator when injected current leads the circulating current.

In any regenerative oscillator, the oscillation amplitude will continue to build up indefinitely until something saturates. In the simulation of Fig.10, saturation occurs when the op-amp output voltage reaches its operating limits (in this case, 30 V peak-to-peak). In saturated steady-state operation, the op-amp voltage will swing from its plus to minus limits as a square wave exactly in phase with the circulating RCL current. The lumped element delay line provides the quadrature requirements.

Similarly for an operating MDO, something must saturate. Gain saturation for an MDO occurs when the beam current is completely deflected to one plate. Once saturation occurs, there can be no further increase in oscillation amplitude. Thus for very high power application, the MDO should be designed to saturate at very high magnetic field strengths. High power operation is somewhat incompatible with small signal gain. A high power oscillator will tend to have a fairly high threshold for oscillation startup.

IV. POWER AND FREQUENCY SCALING LAWS

The MDO depends upon the magnetic field from an LC resonator to deflect its beam current. Since the magnetic field arises from ampere-turns of current flowing in the resonating inductor, it is easily seen qualitatively that higher frequencies will require higher powers. The inductor will have fewer turns as the operating frequency increases. Higher circulating currents and, probably, higher operating power levels will be required to deflect an electron beam. This section contains simple analytic calculations. A practical device operating at 300 MHz will require a power input of approximately 45,000 W.

1. FIELD REQUIRED TO DEFLECT AN ELECTRON

Fig. 11 illustrates an electron beam magnetically deflected between two collecting plates. If the electrons are first accelerated by a potential of 1,000 V, they will have a nonrelativistic velocity given by

$$\frac{mV^2}{2} = 1000eV = 1.6 \times 10^{-16} \text{ J} \quad (1)$$

$$m = 9.1 \times 10^{-31} \text{ kgm} \quad (2)$$

$$V = 1.87 \times 10^7 \text{ m/s} \quad (3)$$

Assume the magnetic field is of uniform strength in the region where the electrons interact, then the electrons will be deflected in a circular arc of radius given by

$$R = mV/eB \quad (4)$$

To deflect the beam between the two plates, R must be of the same order of magnitude as the plate separation d. Assume $R = 1 \text{ cm} = 10^{-2} \text{ m}$ then the magnetic field strength required to deflect the beam is given by

$$B = \frac{mV}{eR} = \frac{9.1 \times 10^{-31} \text{ kgm} \times 1.87 \times 10^7 \text{ m/s}}{1.6 \times 10^{-19} \text{ C} \times 10^{-2} \text{ m}}$$

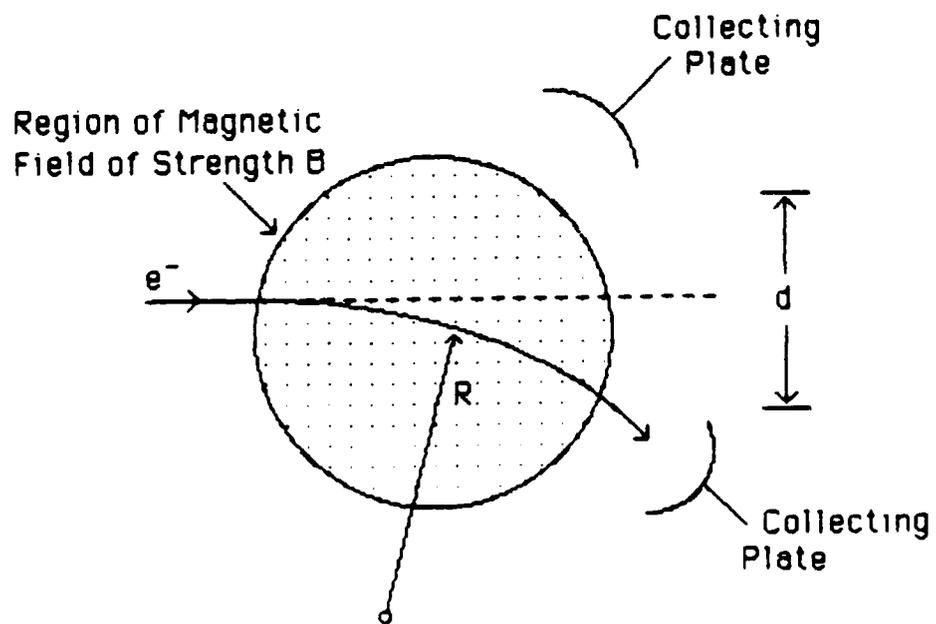


Figure 11. Electron beam magnetically deflected through a circular area.

$$B = 1.06 \times 10^{-2} \text{ Wb/m}^2 \quad (5)$$

$$B = 106 \text{ Gauss}$$

2. FIELDS WITHIN A TYPICAL RF RESONATOR

Fig. 12 shows a typical air core RF inductor of N turns. The inductance of such a coil is given accurately by the empirical formula (from the Radio Amateur's Handbook):

$$L \text{ (in } \mu\text{H)} = \frac{.155a^2 N^2}{3.54a + 3.94b_1} \quad (6)$$

where a = coil radius in centimeters
 b₁ = coil length in centimeters
 N = number of turns

For a = 3.8 cm, b₁ = 10.2 cm, and N = 8 turns, the inductance is given by

$$L = \frac{.155(3.8)^2 (8)^2}{3.54 \times 3.8 + 3.94 \times 10.2} = 2.7 \mu\text{H}; \quad (7)$$

Such a coil might resonate with a capacitor c = 1000 pf at a resonant frequency given by

$$f = \frac{1}{2\pi \sqrt{LC}} = 3.06 \text{ MHz} \quad (8)$$

The magnetic field within such a coil is approximately given by

$$B = \mu_0 \frac{NI}{b} \text{ Wb/m}^2 \quad (9)$$

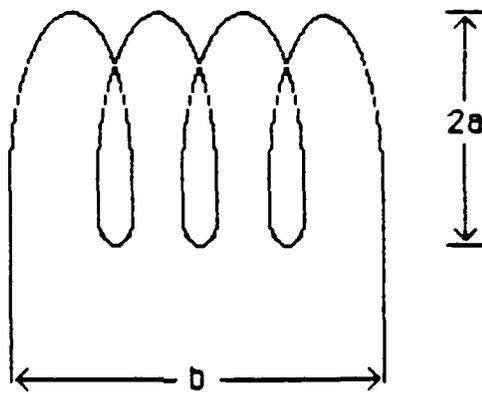


Figure 12. A typical RF inductor of N turns.

where $\mu_0 = 4 \pi \times 10^{-7}$

I is the current in amperes

b is the length of the coil in meters

The current required to produce a magnetic field of 106 Gauss is given by

$$I = \frac{b B}{\mu_0 N} = \frac{0.1 \text{ m} \times 1.06 \times 10^{-2} \text{ Wb/m}^2}{4\pi \times 10^{-7} \times 8} \quad (10)$$

$$I = 105.4 \text{ A}$$

The above current may be a reasonable number for an operational RF tank circuit. It can be simply related to the peak voltage across the resonating capacitor, V_0 . Suppose the oscillating capacitor voltage is written as

$$V = V_0 \sin t \quad (11)$$

Then the current through the inductor is given by

$$I = V_0 \sqrt{C/L} \cos t \quad (12)$$

The maximum capacitor voltage is then given by

$$V_0 = I_{\text{MAX}} \sqrt{L/C} \quad (13)$$

$$V_0 = 105a (2.7 \times 10^{-6} \text{ h} / 10^{-9} \text{ f})^{1/2}$$

$$V_0 = 5,456 \text{ V}$$

This is a reasonable voltage and is typical of the voltages encountered in existing high power broadcast transmitters. Remember, however, the above voltage and current are the minimums required to deflect an electron beam approximately 1 cm at a frequency of 3 MHz.

3. FREQUENCY SCALING LAWS

Higher frequency operation requires that both smaller inductors and smaller frequency be achieved by a linear decrease of both L and C. It is possible, of course, to reduce only C. However, practical constraints based upon maintaining a reasonable circuit Q usually require that the ratio of L/C be nearly constant. We will assume that both L and C are reduced proportionally to any frequency increases.

We may then find the minimum inductor current required to achieve magnetic deflection from the following relations:

$$B = \mu_0 NI/b \text{ in MKS units} \quad (14)$$

$$L = \mu_0 N^2 \pi a^2 / b \text{ in MKS units for a long solenoid} \quad (15)$$

where $b \gg a$.

Eliminating N gives

$$L = \frac{B^2 b \pi a^2}{\mu_0 I^2} \quad (16)$$

$$I = \frac{B^2 a^2 \pi b}{L \mu_0} \quad (17)$$

For a, b, and B constant with increasing frequency,

$$I^2 \propto 1/L \propto f \quad (18)$$

For a frequency increase from 3 to 300 MHz, L must decrease by a factor of 100, C must decrease by a factor of 100, and I must increase by a factor of 10.

At 300 MHz, the minimum current required to deflect an electron beam is of the order of 1,000 A. The voltage across the capacitor, C, will be approximately

55,000 V. The instantaneous energy stored in the LC resonator is given by the maximum voltage on the capacitor of the maximum current through the inductor.

$$E = 1/2 CV^2 = 1/2 LI^2$$

$$E = 1/2 \times 10^{-11} f \times (5.5 \times 10^4 V)^2 \quad (19)$$

$$E = 0.015 J$$

This minimum stored energy must be maintained by supplying power to the resonator sufficient to overcome internal losses, which depend upon the resonator Q. If a resonator Q of 100 is assumed, the minimum power P which must be supplied to sustain oscillation at 300 MHz may be calculated.

$$P = Ef/Q$$

$$P = 0.015 J \times 3 \times 10^8 \text{ Hz} / 100 \quad (20)$$

$$P = 45,000 W$$

V. EXPERIMENTAL CONFIGURATION

1. CONTINUOUS WAVE EXPERIMENTS

Fig. 13 illustrates the experimental attempt to achieve oscillation threshold in its final form. The inductor L was wound with 470 turns of No. 22 gauge insulated copper wire on a ferrite toroidal transformer core. The toroidal core had an inside diameter of 3.8 cm, an outside diameter of 7.2 cm and a rectangular cross-section of 1.25 cm thickness. The ferrite had a permeability of approximately 1600.

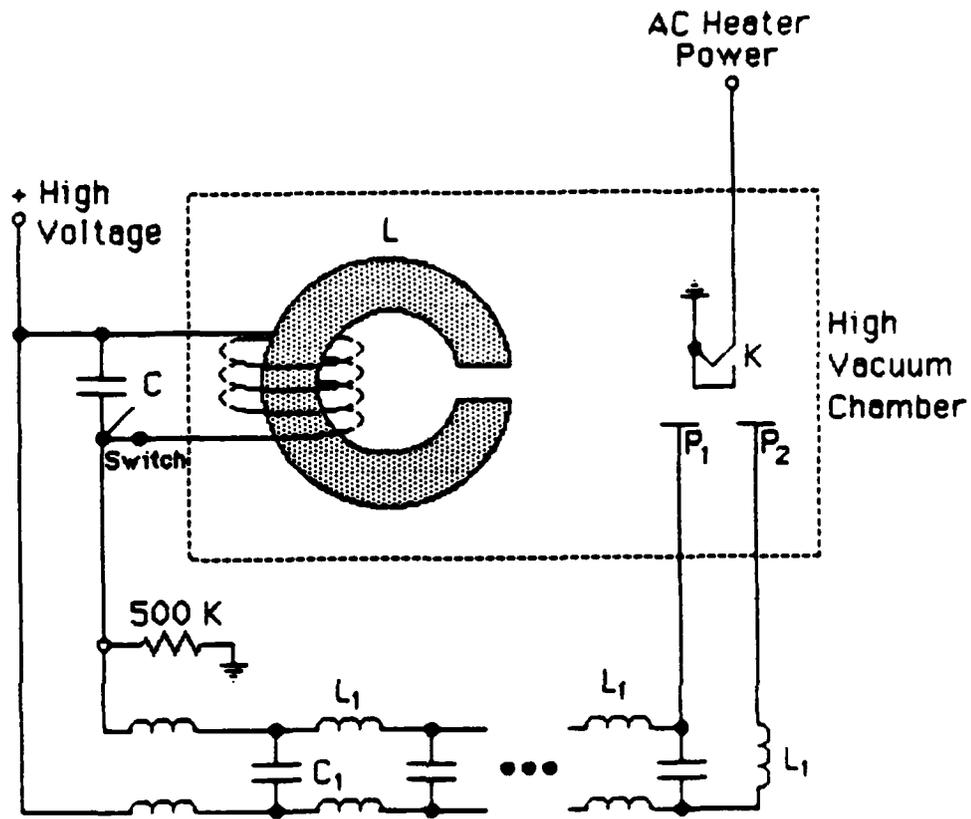
A 7-mm slot was cut from the toroid to expose the magnetic field. Electrons passed from the cathode to the collecting plates through the region of the ferrite slot. The toroidal ferrite served to substantially concentrate the magnetic fields over the case of a linear vacuum core inductor.

The cathode K was a commercial indirectly heated tungsten dispenser cathode from Spectra-Mat, Inc., Watsonville, California. The cathode was a cylinder 3.5 mm dia. and 7.2 mm long with electron emission from the flat cylinder end. According to the manufacturer's ratings, it could deliver up to 800 mA of saturated DC emission. Prior to the use of this cathode, various hot filament tungsten and tantalum wire cathodes were tried, but had lesser emission capabilities.

By direct measurement, a 1 A DC current through the inductor L could produce approximately 50 percent current deflection between the collector plates. It is not necessary that the cathode produce this same 1 A, only that there be 1 A of circulating current in the resonator and sufficient injected current to sustain 1 A.

An initial oscillation can be excited by opening the normally closed switch shown in Fig. 13. With the switch open, capacitor C charges through the 500-k resistor to a DC value equal to the high voltage supply. The resistor has no significant effect on the circuit when the switch is closed. Once C is charged, closing the switch discharges C through L producing damped oscillation. In this case, a charge voltage of 200 V produced 20-A peak current in the LC resonator.

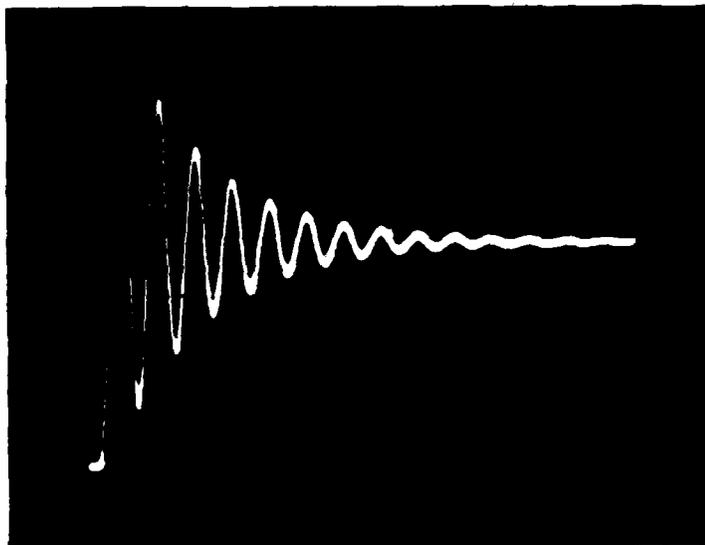
It is interesting to calculate the average power dissipated by the coil resistance and capacitor losses, since that power must be supplied by cathode emission. The data in Fig. 14 were generated in an early attempt to achieve oscillation at 2 MHz using a hot tungsten wire cathode.



12 1/2 Stage Delay Line

Figure 13. Experimental attempt to demonstrate MDO.

50 V/DIV



0.5 μ s/DIV

Figure 14. Damped oscillations in the LC resonator.

At a peak oscillation amplitude of 200 V as shown in Fig. 14, the energy stored in the 0.25 μ f resonating capacitor was

$$E = 1/2 C V^2 = 1/2 (0.25 \times 10^{-6}) (200)^2 = 0.005 \text{ J} \quad (21)$$

The time to dissipate this energy is seen to be approximately 2.5 μ s which also corresponds to an RC decay time with $R = 10 \Omega$. The power dissipation P is given by

$$P = E/T = 5 \times 10^{-3} \text{ J} / 2.5 \times 10^{-6} \text{ s} \quad (22)$$

$$P = 2000 \text{ W} \quad (23)$$

In this experiment, the cathode delivered a maximum of 60 mA at 200 V for a total power of 12 W. It was not adequate to sustain oscillation with such high circuit losses.

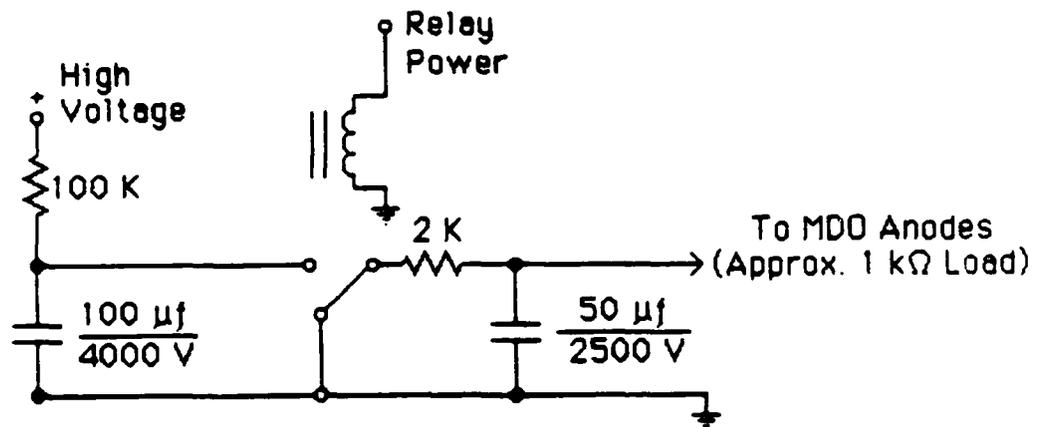
2. RC PULSED EXPERIMENTS

The steep power versus frequency scaling laws and limited CW cathode emission suggested an attempt at low frequency pulsed operation. The resonator and delay line shown in Fig. 13 were excited by a pulsed high voltage source shown in Fig. 15.

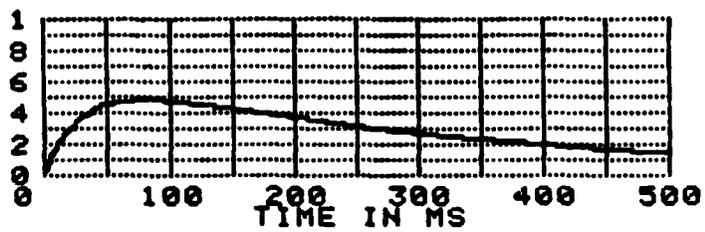
Since the design oscillation frequency was 4.5 kHz, the pulse forming network was required to deliver a pulse at least 100 ns long. A simple LC pulse forming network would require inductors of approximately 100 H, which are too large to be practical. The RC network in Fig. 15 is wasteful of energy. It delivers about 1/4 of the total charging energy to the load, but it is inexpensive and easily constructed.

Fig. 16 shows actual voltage and current waveforms applied to the MDO configurations of Fig. 13. Cathode arcing is seen to occur at an accelerating potential of 700 V and a cathode current of approximately 300 mA. Cathode arcing threshold was consistently observed at an emission of 300 mA. This beam power limitation of 210 W was insufficient to achieve the oscillator threshold.

From DC magnetic field measurements, 50 percent beam deflection requires 1 A of inductor current. If we take an estimate that 50 percent deflection is approximately the oscillation threshold, and if the entire 1 A must come from the cathode, then a beam of power of 550 W is needed at 4.5 kHz for the geometry attempted here.

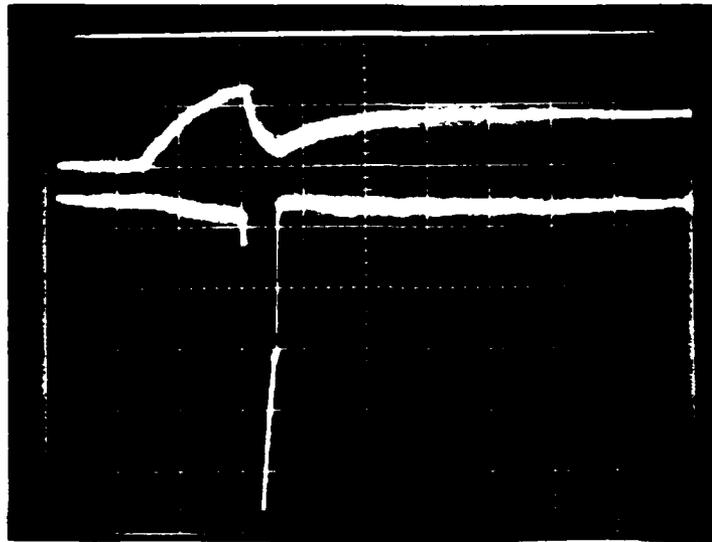


(a) Voltage on the 50 μf capacitor.



(b) Voltage on a 1-kΩ load.

Figure 15. An RC high voltage pulse forming network.



500 V/DIV

0.5 A/DIV

20 ms/DIV

Figure 16. Typical voltage and current waveforms for pulsed operation of MDO.

VI. CONCLUSIONS

Oscillation was not achieved in this geometry, probably because of cathode emission limitations. The power required to sustain oscillation scales approximately in proportion to frequency. The threshold power is approximately 1,000 W at 5 kHz and 45,000 W at 30 MHz. The higher frequency calculations assume deflection of a collimated electron beam. For poorly collimated beams, higher fields and higher powers will be required.

Such a strong scaling law is nearly ideal for a very high power device, but it makes low power testing difficult. Since thermionic cathodes can deliver at best 10 A/cm² reliably, loosely collimated thermionic sources will be limited to around 100 A. The MDOs with thermionic sources will be limited to frequencies below 500 kHz and maximum power levels of the order of 100,000 W in CW operation. These are not particularly impressive levels.

With cold cathodes and pulsed operation, MDOs may deliver prodigious power levels. A 10,000-A beam at 200 kV lasting 0.1 μ s is typical of moderate sized vacuum diode E-beam sources. The resulting beam power of 2×10^9 W could drive a 500 MHz MDO for about 50 oscillation cycles. The total pulse energy of 200 J could be converted to RF with approximately 50 percent efficiency. Although megajoule pulsed sources are available, pulse durations will be limited by plasma closure in the vacuum diodes. Typical closure speeds are 10 cm/ μ s which will limit practical devices to pulse lengths of the order of 1 μ s.

END

10-86

DT/C