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VIBRATION-RF CONTROL OF SUPERCONDUCTING-HELIX RESONATORS FOR HEAVY-ION ACCELERATION

by

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VIBRATION-RF CONTROL OF SUPERCONDUCTING-HELIX RESONATORS FOR HEAVY-ION ACCELERATION*

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Summary

An electronic system for the control of the effects of RF frequency oscillations caused by mechanical vibrations in a superconducting helix are described. A combination of frequency modulation and amplitude modulation is used to lock the phase of a self-excited accelerating structure to that of a controlling master oscillator. The system has been used successfully during beam acceleration with a superconducting helix.

I. Introduction

In comparison with other RF structures, the superconducting helix is well suited to the generation of the short-wavelength fields that are needed for the acceleration of slowly moving heavy ions. Moreover, good progress has been made in the development of fields that are high enough to be attractive for a practical accelerator.[1] Before the superconducting helix can be useful, however, one must be able to control the effects of mechanical vibrations, which can cause the RF resonance frequency to vary by an amount that is very much larger than the resonance width of an unloaded resonator.

The nature of the vibration problem is illustrated in Fig. 1. Here we consider the vibration-stability requirements for a half-wavelength superconducting helix that is driven by an RF-power source operating at the frequency f; the resonance frequency is f_o. Consider first an unloaded system with $Q = 2 \times 10^8$ and $f_o = 10^8$ Hz. In order to be on resonance, one requires $(\Delta f/f_o)Q \lesssim \pm 0.1$, which corresponds to $\Delta f \lesssim \pm 0.05$ Hz. This requirement may be compared to a static shift of 400,000 Hz caused by radiation pressure in a typical powered resonator. Also, the frequency shift ±0.05 Hz corresponds to a change in length that is only ±5Å for a typical structure. The stability requirements are not quite so demanding for a loaded system, of course, but even here the frequency shift must be less than a few Hz for the system illustrated in Fig. 1 to remain on resonance. In comparison, vibration-induced frequency changes are about ±150 Hz for a typical $\lambda/2$ helix.

Clearly, the required frequency stability cannot be achieved by mechanical means alone. Indeed, it may be that there is no way in which the instantaneous frequency can be stabilized with the required accuracy. However, for an accelerator, our main concern is with the phase of the RF oscillations. The purpose of this paper is to outline the progress that has been made in the development of an electronic-control system in which a combination of frequency modulation and amplitude modulation is used to lock the phase of a self-excited helix resonator to that of a master oscillator. As is reported elsewhere,[2] this system has now been used successfully during beam acceleration with a superconducting helix.

II. General Description of the Control System

There are two major aspects to our approach to vibration control: (1) the magnitude of the mechanical vibrations is minimized by minimizing the sources of vibration and their coupling to the helix, and (2) the effect of the residual vibrations is then controlled electronically.

The reduction of the mechanical vibrations to an acceptable level has turned out to be relatively easy for the half-wavelength helices studied to date. Important elements in the reduction are (a) the use of light bellows for pumping lines and other connections, and (b) care in the location of new mechanical pumps and other possible vibration sources. After taking these steps, the residual vibration level is typically such as to produce an RF-frequency variation of about ±150 Hz. A representative mechanical-frequency spectrum is given in Fig. 2.

Although the mechanical flexibility of the helix is a characteristic that encourages harmful vibrations, this flexibility may also be used to advantage in frequency control. This is most easily done by making use of the change in mechanical size (and hence in RF frequency) caused by radiation pressure in a powered helix. Thus, the base frequency of the helix may be adjusted and some frequency oscillations may be controlled by varying the power level of the helix. For example, since the static frequency change Δf is typically 400,000 Hz for a fully powered helix and since $d(\Delta f) = 2\Delta f(dE/E)$ (where E is the electric field), a change of only 1% in field causes a frequency shift of 8 kHz. Thus, one is tempted to try to control vibration-induced frequency changes by means of amplitude modulation alone. However, as is now widely recognized,[3] this is not a satisfactory approach because it leads to instabilities caused by electromechanical coupling. Hence, we use frequency modulation as the primary form of control.

Our technique of frequency modulation, which builds on the earlier analysis of Peebles[4] and the experimental work of Dick and Sheppard,[5] makes use of a voltage-controlled reactance (VCX). The basic idea is illustrated in Fig. 3. The resonator is represented here by lumped-parameter elements that are linked to several power ports, through one of which the resonator is coupled to a variable reactance. Clearly, the resonance frequency of the system can be changed by changing the reactance—the only question is whether a large enough change in frequency can be achieved in practice.

Our VCX is a 50-ohm transmission line terminated by a voltage-controlled diode switch. The input impedance Z of the line (assuming it to be lossless) is

$$Z = Z_o \frac{Z_L + j Z_o \tan(2\pi\ell/\lambda)}{Z_o + j Z_L \tan(2\pi\ell/\lambda)}, \qquad (1)$$

where Z_o is the characteristic impedance of the line, Z_L is the load impedance, ℓ is the length of the line, and λ is its RF wavelength. Out of several possibilities, we have chosen to use a 3/8-wavelength line. For it, $\tan 2\pi\ell/\lambda = -1$, and hence $Z = -j\, Z_o$ (capacitative) when the diode switch is closed; and $Z = +j\, Z_o$ (inductive) when it is open. Phase control is achieved by varying the fraction of the time that the switch is closed. Until now, the diode has been switched with cycle periods in the range 20 to 50 μs, but a 10-μs period is the design objective.

As indicated earlier, the RF-frequency change caused by vibration is about ±150 Hz, and hence the VCX needs to be able to change Δf by about ±400 Hz. For a 50-ohm line, this requires that the VCX carry about 1 kW of reactive power. The practical problem involved in the implementation of the VCX-control idea is how to carry this reactive power without having excessive losses, which can cause several kinds of difficulties that will be discussed later.

The main elements of our electronic-control system are summarized in the block diagram of Fig. 4. Loop 1 is used to excite the helix, loop 3 generates a phase-error signal that controls both the frequency and the amplitude modulation, and loop 2 controls fast changes in RF amplitude. Three levels of adjustment and/or control are involved in locking the phase of the helix to that of the controlling master oscillator: (1) first the helix is manually tuned to approximately the desired frequency, (2) then amplitude modulation on a slow time scale accurately adjusts the average frequency (averaged over many mechanical oscillations) to that of the master oscillator, and (3) frequency modulation by the VCX corrects for phase changes that occur on a fast time scale.

Some of the voltage patterns of most interest in the control system are illustrated in Fig. 5. The phase-error signal (which is integrated over many VCX cycles) is only slightly out of phase with the amplitude of the frequency oscillation because of the phase-restoring action of the VCX. Consequently, the duty cycle of the diode switch is also almost in phase with the amplitude of the frequency oscillation. The phase error contains both the slow component used for control of the VCX and a fast component caused by the diode switching. The magnitude of the slow component can be made arbitrarily small by increasing the gain of the error signal fed to the VCX. It is obvious from Fig. 5 that the phase wobble of a controlled resonator is determined by the diode-switching period f_s^{-1} and by the frequency change Δf_c induced by switching the VCX; specifically, it is $\pm 90\, \Delta f_c / f_s$ degrees. The maximum value of Δf_c used in our work to date is ±500 Hz. The phase wobble may easily be made less than a few degrees; our design goal is ±1°. Note that, for illustrative clarity, the diode-switching period shown in the figure is very much longer relative to a mechanical-oscillation period than it is in practice.

III. Performance of the Control System

Although it is still in the development stage, the control system described above has been extensively tested with functioning helices, and quite recently it has been used for phase control during beam acceleration with a prototype accelerator.[2] In the latter tests, the phase was successfully controlled to less than ±2.5° for accelerating fields up to 1.3 MV/m. Even at this rather high field level, the system appeared to be completely stable and the limitation on field was set by the practical problem of heat dissipation in the VCX system. Thus, there is every indication that further refinements will make it possible to achieve phase control at the design level of 2.0 MV/m. An oscilloscope trace of the wave form for a phase-controlled helix is given in Fig. 6, for which the VCX switching cycle was 50 μs and the frequency modulation induced by the VCX was ±150 Hz.

Some details of the control system and its characteristics are given below.

Self-Excitation

The resonator is powered by using the helix as the frequency-control element of an oscillator. A variable phase shifter in the feedback loop is used to set the frequency of the oscillation on the low-frequency side of the helix resonance frequency. This is necessary in order to inhibit the buildup of ponderomotive oscillations, a problem discussed extensively by others.[3, 6, 7]

The amplifier driving the helix consists of two sections. The low-level section is a broad-band unit with a gain of 30 db. The high-level section is a tuned amplifier with a gain of 30 db and a band width of 0.5 MHz. The field level at which the helix operates is determined by saturation in the first stage of the high-level amplifier and is manually adjustable. Modulation of the amplifier is accomplished in the grid-bias circuit of the high-level section.

Amplitude Modulation

Although the instability problem associated with amplitude modulation of the helix is well known, we have investigated the possibility of obtaining partial dampening of some mechanical vibrations by means of AM control. The approach was to break up the composite phase-error signal into its major mechanical-resonance components, to shift the phase of each component by the appropriate constant amount, and to return these shifted error signals through the feedback loop. The frequency excursions of the helix were reduced to about 1/3 of their original value in this way. However, the system had such narrow phase margins that it tended to go into uncontrolled oscillations at the slightest additional disturbance. Consequently, the investigation was discontinued.

In order to avoid the instability problems connected with amplitude modulation of the helix, in our present system the phase-error signal is returned to the RF-power amplifier through a low-band-pass filter that causes the phase-error signal to fall to 0 db well before the first mechanical resonance. Thus, amplitude modulation is used only for fine tuning the average frequency and for controlling very slow mechanical oscillations.

Frequency Modulation

As outlined in Section II, the VCX used to modulate the RF frequency consists of a $3\lambda/8$ transmission line terminated by a diode switch (Unitrobe PIN Diode No. UM7206). A diagram of the system is given in Fig. 7. The 1 μH choke and 200 pF capacitor form a low-pass filter that removes the RF signal from the diode-pulser line. Inductance L serves to compensate for the capacitances of the diodes D_1 and D_2 and for other stray capacitances. The series combination of C_1 and R permits the power loss to be adjusted, as discussed below.

Power losses in the VCX system are much greater than all other losses in the RF system. For example, when controlling Helix G (see Ref. 2) operating at an accelerating field of 1.3 MV/m, about 15 W was dissipated in the VCX system, whereas the loss in the helix resonator was 1 to 2 W. In this instance, the VCX losses result from switching 250 VA of reactive power with a cycle time of 50 μs.

RF-power losses in the PIN diode are at a maximum during switching, when the resistance is momentarily comparable to Z_0 of the transmission line. Therefore, the switching time should be held to a minimum. The measured time required for our pulser to transfer the necessary charge ($\sim 0.4 \times 10^{-6}$ C) into or out of a parallel pair of diodes is about 0.20 μs and 0.25 μs, respectively; the combined losses in the pair caused by switching 250 VA of reactive power with a switching-cycle time of 20 μs is roughly 1.7 W.

When the diode is closed (reverse bias) the effective resistance is so high at the RF frequencies involved that the power losses are negligibly small. For the open condition, however, one may calculate from information provided by the manufacturer that our 300 mA of forward current through a pair of diodes reduces their parallel resistance to about 2.5/2 Ω, for which the power loss is about 1.2 W when the diodes carry 250 VA of reactive power.

The above data indicate that most of the losses in our VCX system are taking place in the 50-ohm transmission line. These line losses are believed to be some five times larger than they should be for a copper-plated line, but we have not yet had time to investigate the problem.

Perhaps more important than the magnitude of the power loss in the VCX is any dependence of the loss on the diode-switching duty cycle. Such a dependence causes the power loss (and hence the power in the helix) to vary in synchronism with the phase-error signal, which in turn is almost in phase with the mechanical oscillations (see Fig. 5). We have found that this feedback mechanism can cause a serious instability when the RF-frequency shift caused by duty-cycle-dependent losses exceeds about 25% of the frequency shift caused by the switching of reactive power in the VCX.

Since the RF losses for the diode-on and -off conditions are not equal, the situation described above exists and indeed is quite serious unless the losses are balanced. This is done by manually adjusting the capacitor C_1 in Fig. 7. A second, more subtle form of unbalance was generated by our first model of the diode pulser, for which the time required for charge transfer in the diode depended on the switching duty cycle. An improved pulser design eliminated this problem.

The need to correct for the relatively small unbalance in power losses for our 3λ/8 line, where the input impedances are largely reactive, suggests that the unbalance problem may be quite severe for a VCX based on a λ/4 line, for which the input impedance is resistive. However, we have not investigated this question.

Work in the near future will be aimed at refining the present VCX system, with special emphasis on the elimination of unnecessary power losses. Our experience to date leads us to believe that the control concept is basically sound and that much of the power loss in the present VCX can be eliminated. If so, it should be a straightforward matter to control the phase of a half-wavelength helix operating with an accelerating field of at least 2.0 MV/m, our design objective.

Preparations for the operation of two independently-phased resonators that are controlled by a single master oscillator are in progress.

References

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5. G. J. Dick and K. W. Shepard, Proceedings of the Conference on Applied Superconductivity (Annapolis, April 1972).
6. M. M. Karliner, V. E. Shapiro, and I. A. Shakhtman, Soviet Physics - Technical Physics II, 1501 (1967).
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FIGURE CAPTIONS

Fig. 1 Illustration of frequency-stability requirements.

Fig. 2 Representative frequency spectrum for mechanical vibrations in a helix resonator.

Fig. 3 Simplified representation of frequency modulation by a voltage-controlled reactance.

Fig. 4 Block diagram of the phase-control system.

Fig. 5 Characteristic wave forms in the VCX. The equation for Max. $\Delta\phi$ assumes $\Delta f_C \approx \pm 500\ H_z$.

Fig. 6 Representative phase-controlled wave form. The oscilloscope is triggered by the clock signal. The observed time jitter in the 92 MHz helix signal is about ± 2°, consistent with the VCX operating conditions.

Fig. 7 Circuit diagram of the VCX.

VIBRATION PROBLEM

UNLOADED SYSTEM

$Q = 2 \times 10^8$

$f_0 = 10^8$ Hz

$\Delta f_0 = 400{,}000$ Hz for $E_{ax} = 2.5$ Mv/m

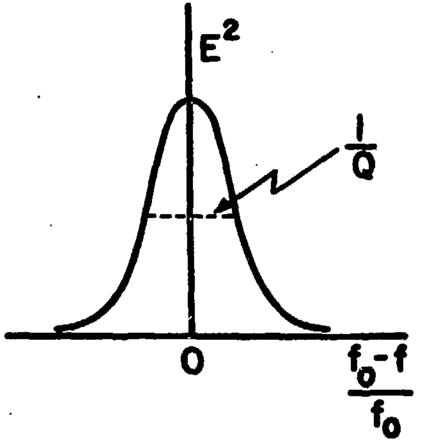
NEEDED:

$$\left(\frac{\Delta f}{f_0}\right) Q \lesssim 0.1$$

$$\Delta f \lesssim 0.05 \text{ Hz}$$

EQUIVALENT CHANGE IN HELIX LENGTH IS

$$\Delta \ell \approx 10 \ell \frac{\Delta f_0}{f_0} = 100 \frac{0.05}{10^8} = 5 \text{ Å}$$



$$Q = 2\pi \frac{\text{STORED ENERGY}}{\text{ENERGY LOSS PER CYCLE}}$$

BEAM LOADING

FOR 1 μA of URANIUM IONS

BEAM POWER ≈ 2.4 kw

POWER INPUT PER λ/2 SECTION ≈ 20 w

$Q = 5 \times 10^6 \rightarrow \Delta f < 4$ Hz

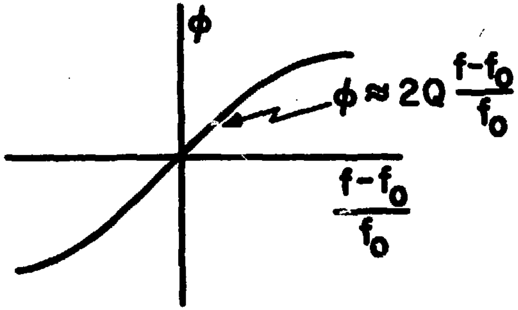


FIG. 1.

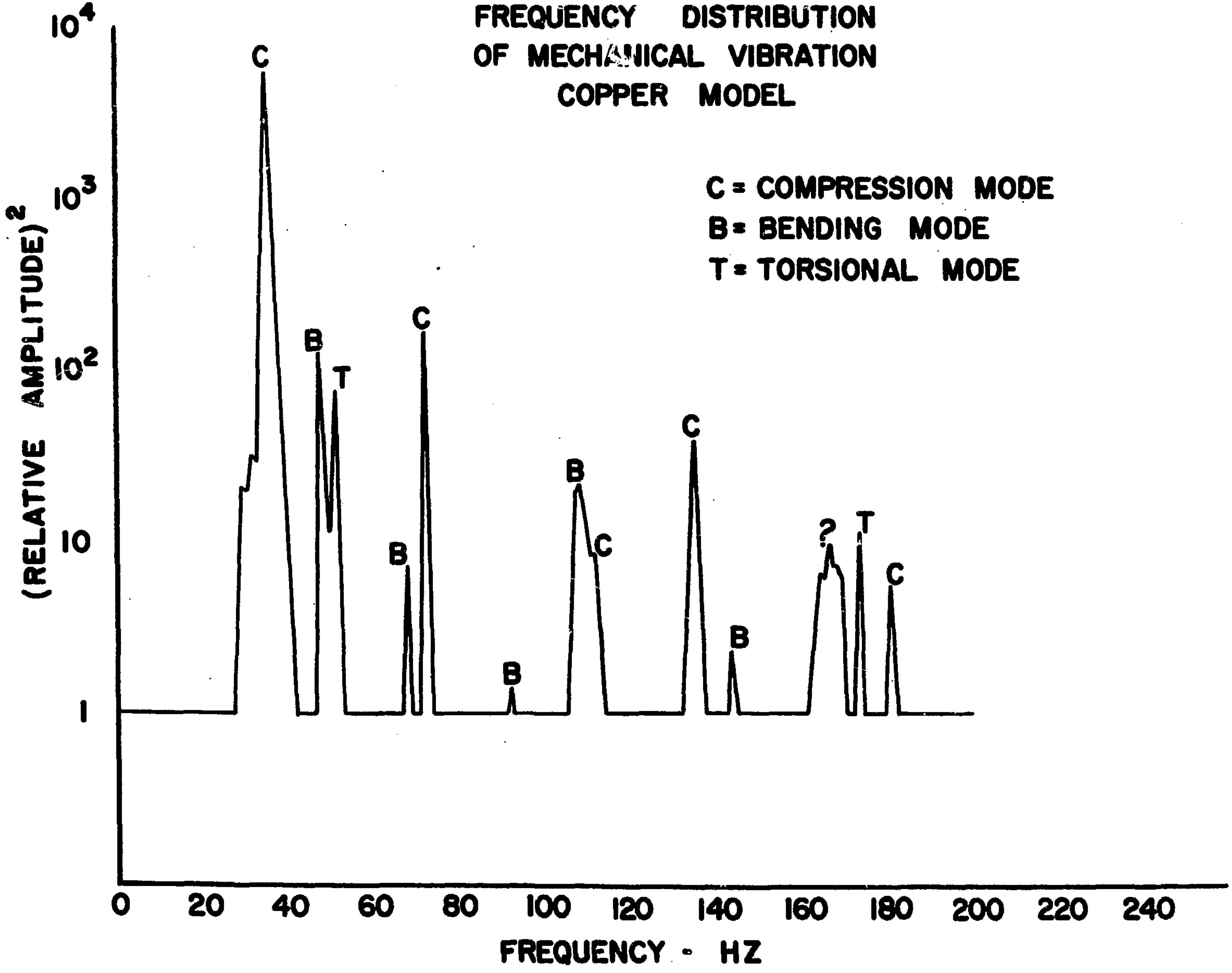
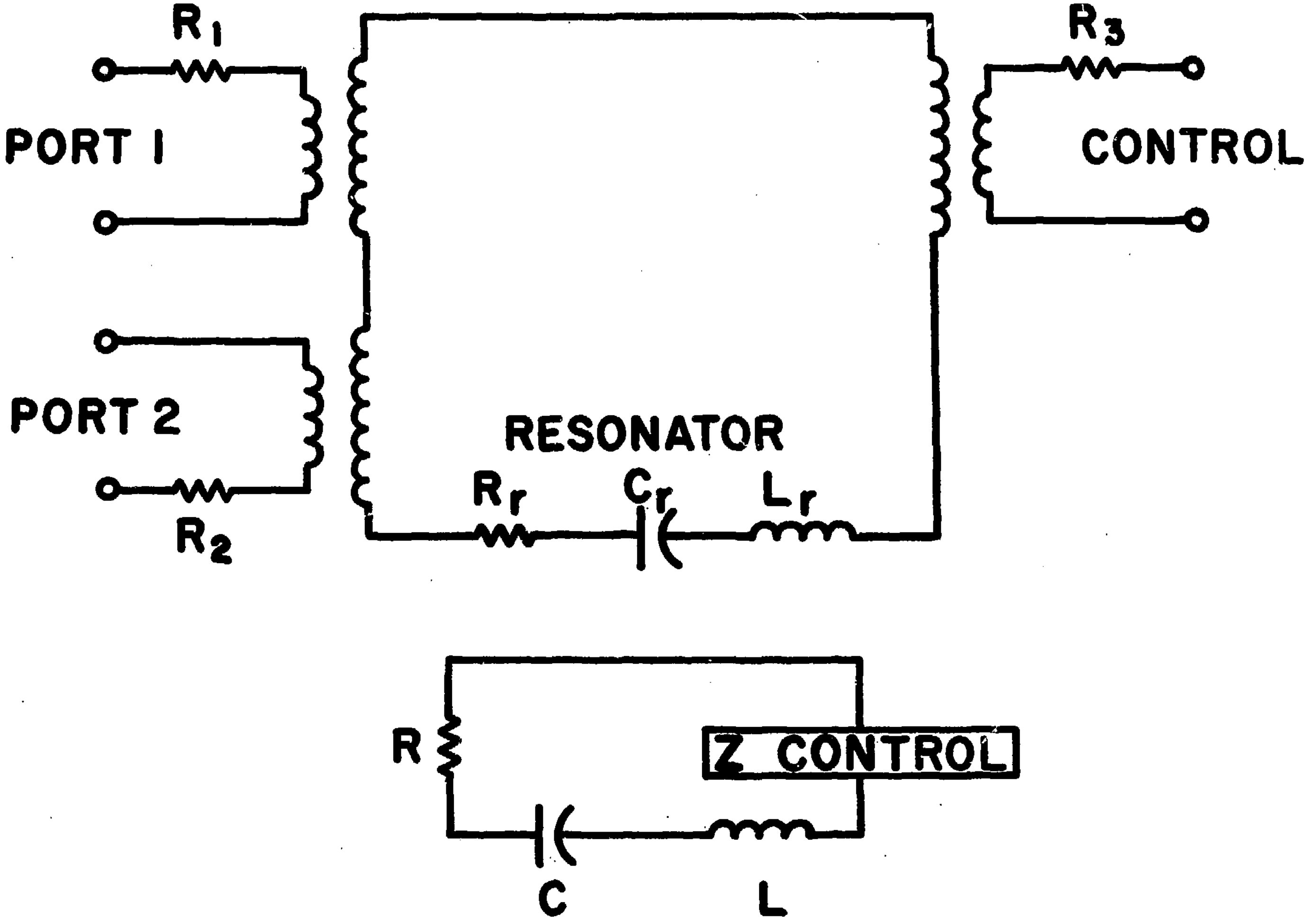

FREQUENCY DISTRIBUTION
OF MECHANICAL VIBRATION
COPPER MODEL
C = COMPRESSION MODE
B = BENDING MODE
T = TORSIONAL MODE
(RELATIVE AMPLITUDE)^2
10^4
10^3
10^2
10
1
C
B
T
B
C
B
B
C
C
B
?
T
C
0
20
40
60
80
100
120
140
160
180
200
220
240
FREQUENCY - HZ

FIG. 2



$$\omega_0 = \frac{1}{\sqrt{L_s \; C_s}} \qquad Q = \omega_0 \; \frac{L_s}{R_s}$$

FIG. 3

R. F BLOCK DIAGRAM

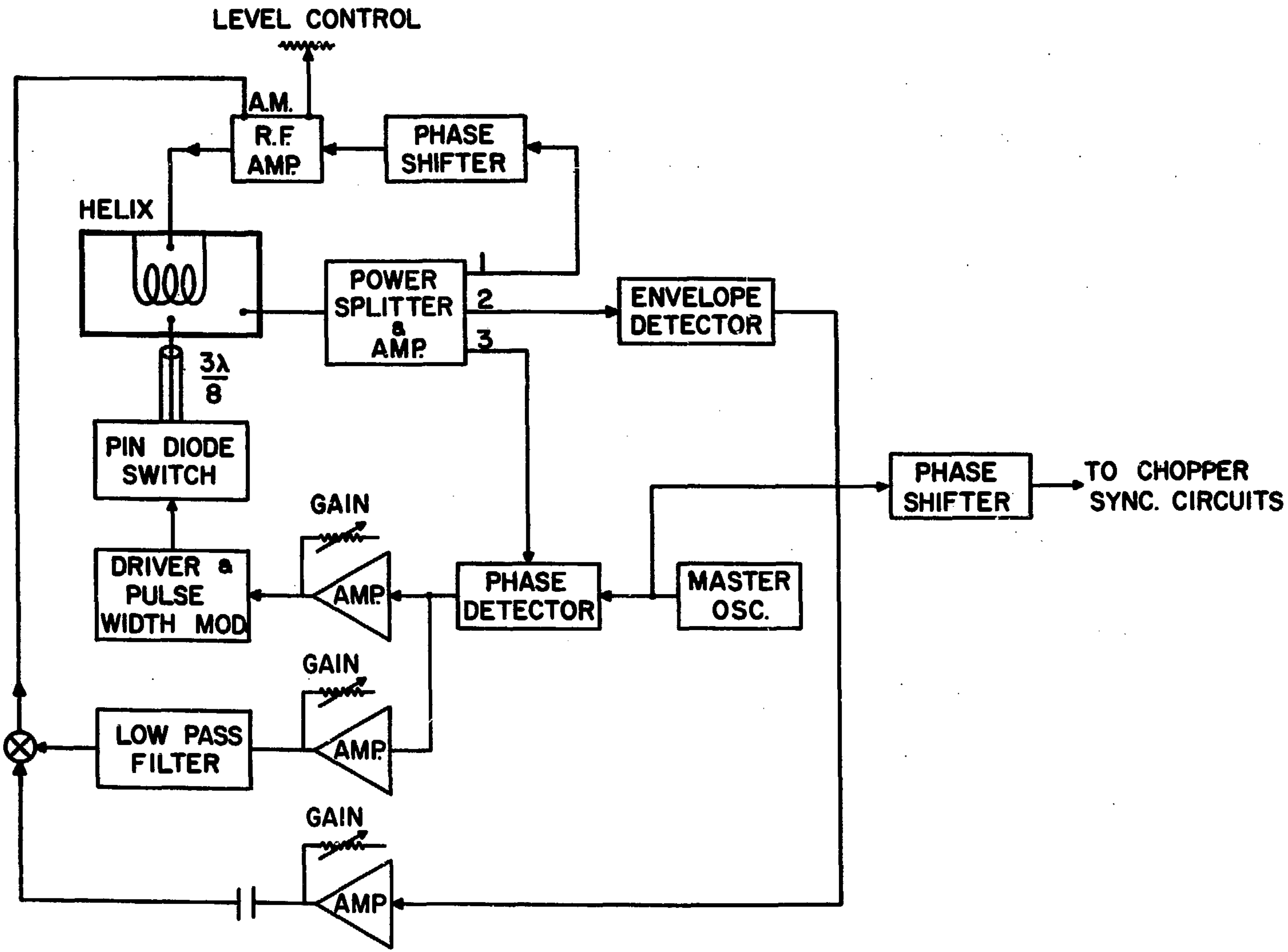


FIG. 4

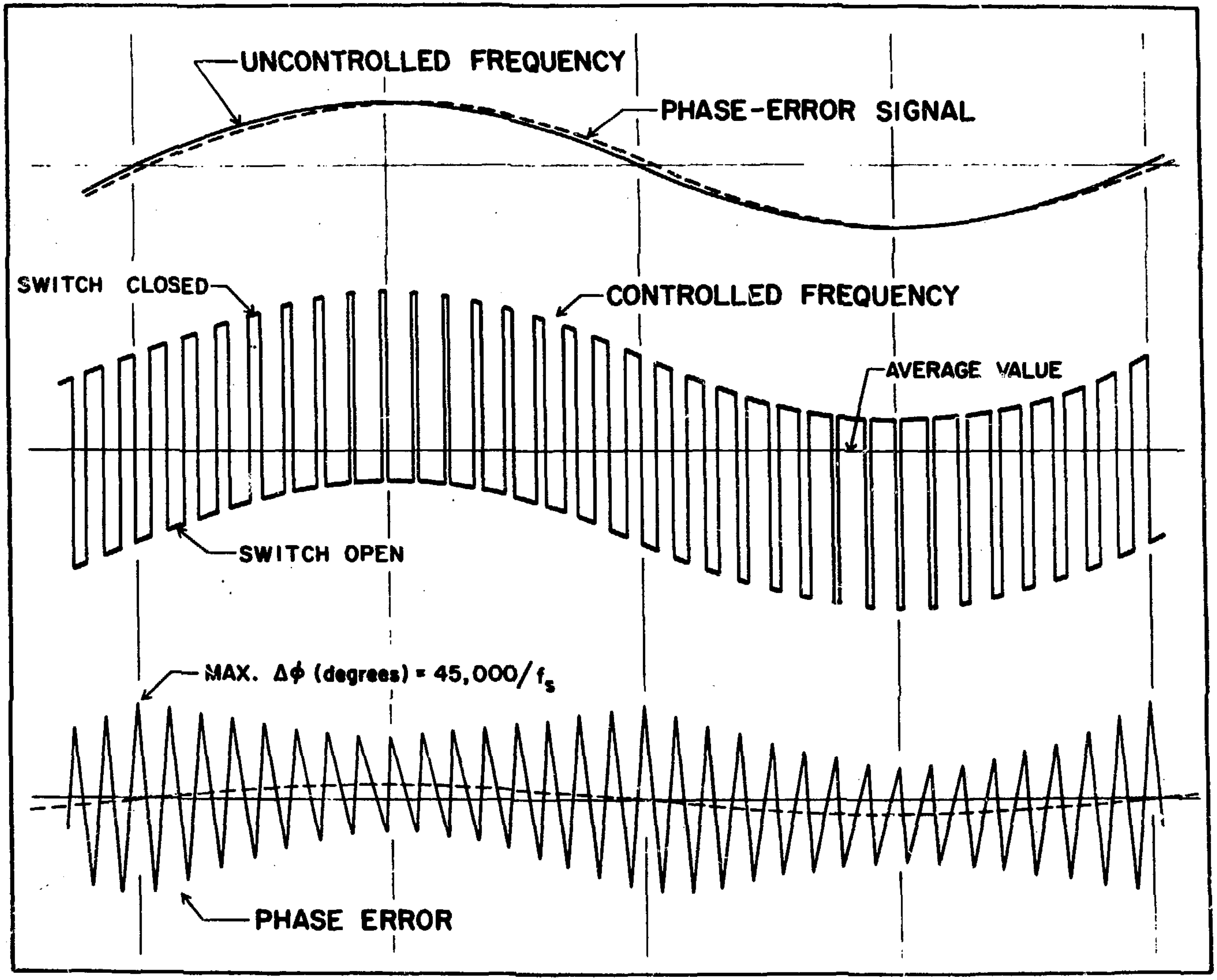
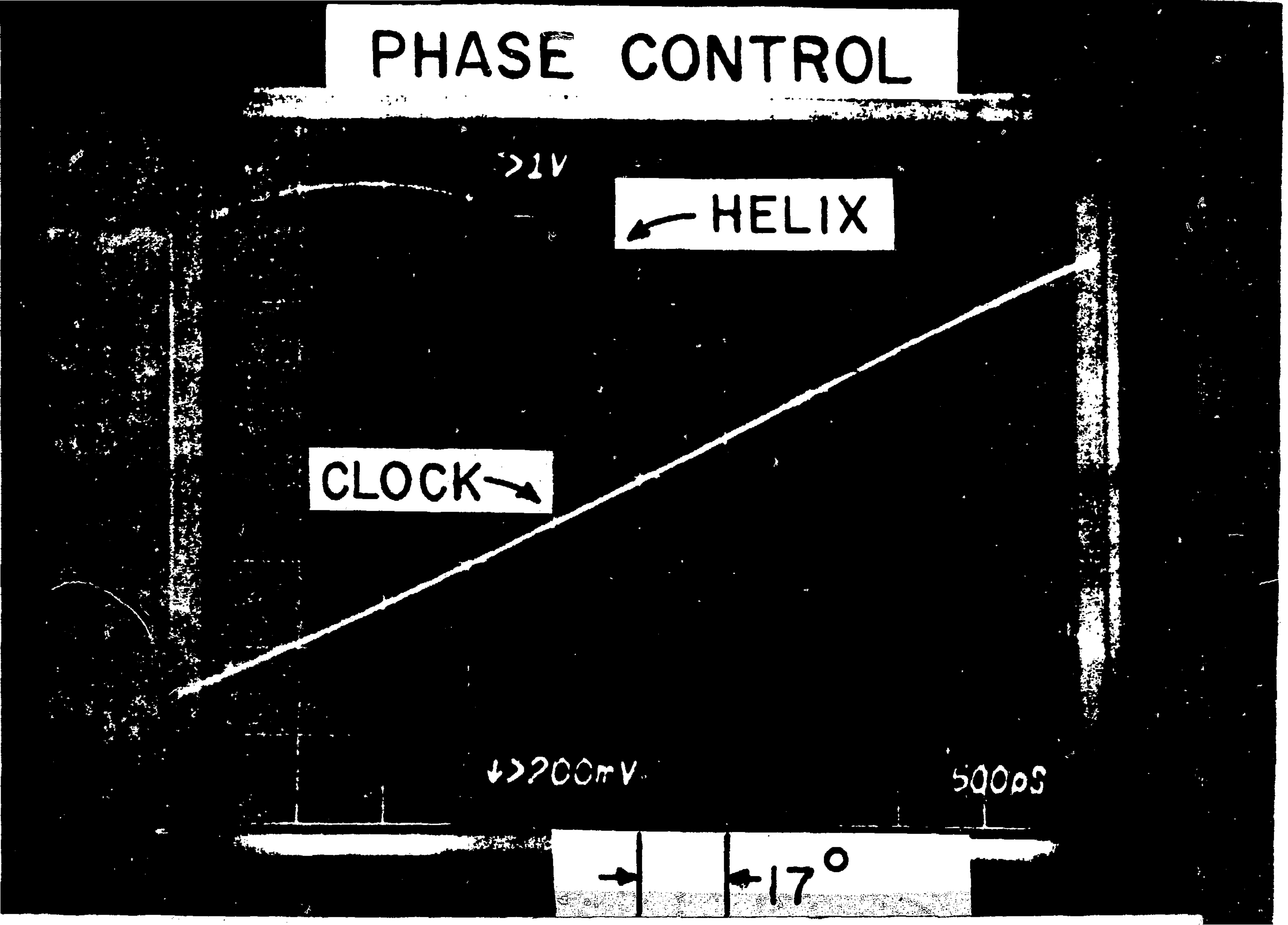

UNCONTROLLED FREQUENCY
PHASE-ERROR SIGNAL
SWITCH CLOSED
CONTROLLED FREQUENCY
AVERAGE VALUE
SWITCH OPEN
MAX. Δφ (degrees) = 45,000/f_s
PHASE ERROR

FIG. 5


PHASE CONTROL
>1V
HELIX
CLOCK
↓>200mV
500pS
17°

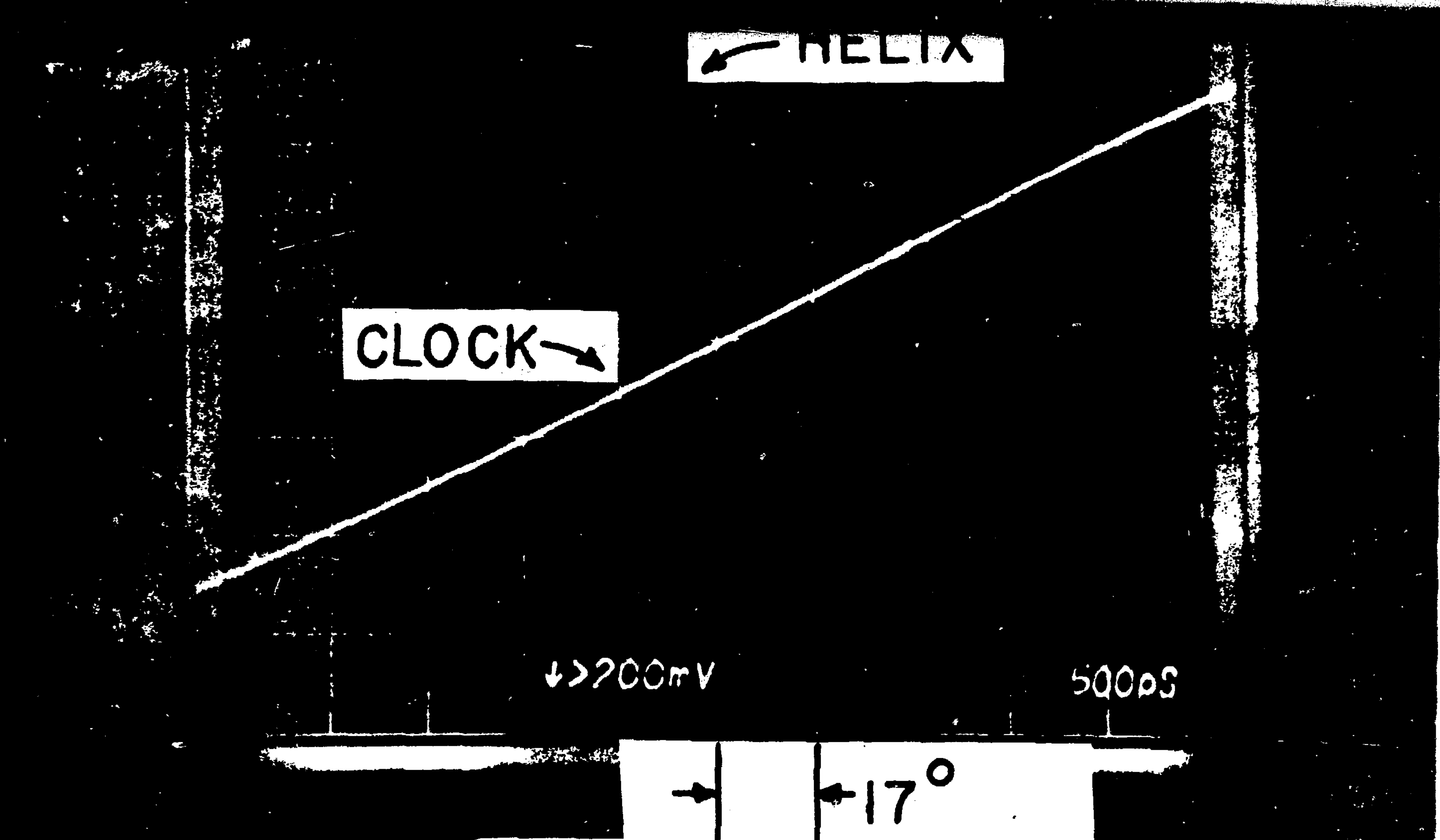


FIG. 6

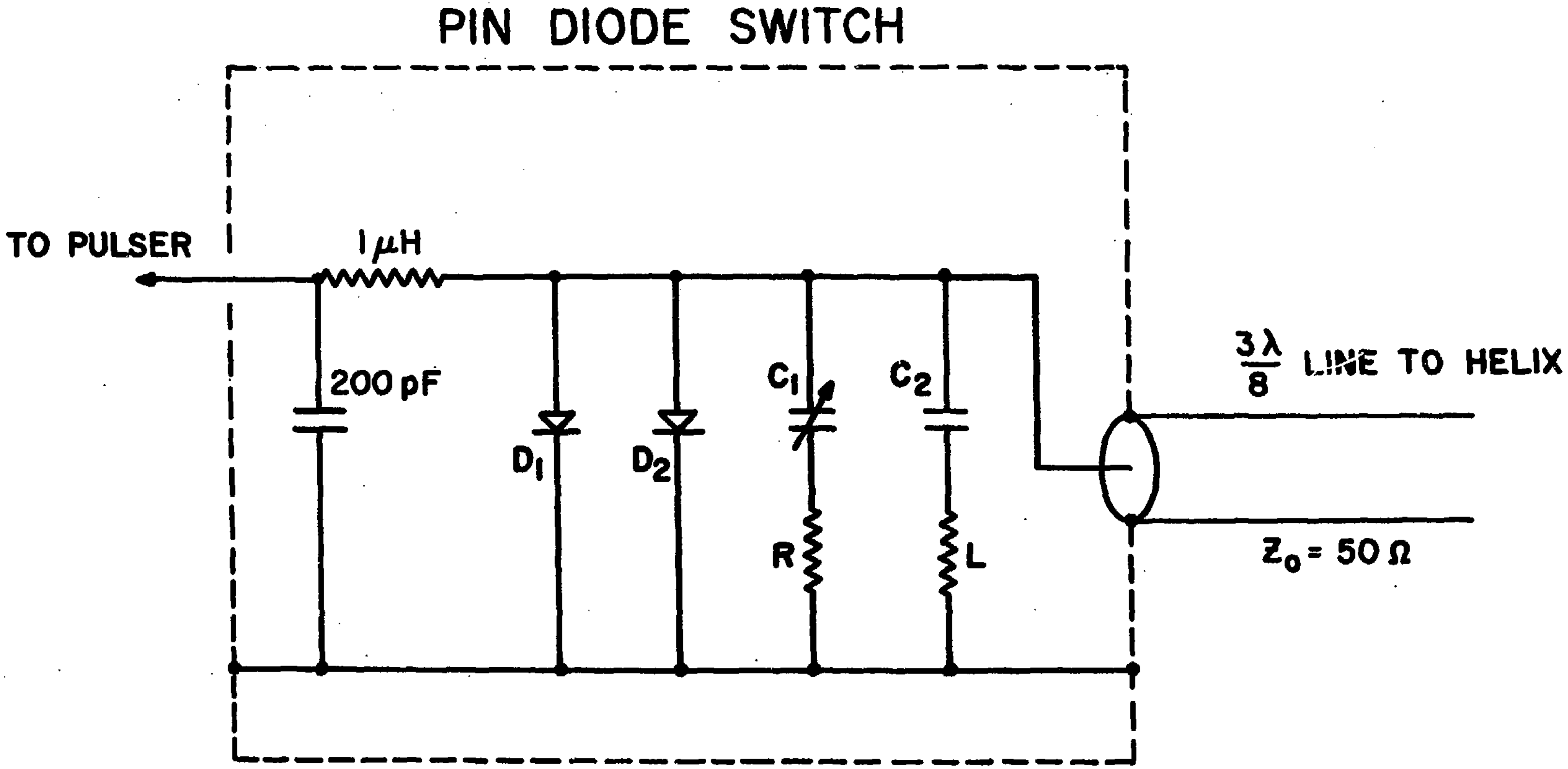

PIN DIODE SWITCH
TO PULSER
1 μH
200 pF
D1
D2
C1
R
C2
L
3λ/8 LINE TO HELIX
Z0 = 50 Ω

FIG. 7