L.B. Hallett

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METROPOLITAN-VICKERS ELECTRICAL CO. LTD.

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TRAFFORD PARK, MANCHESTER, 17.

RESEARCH REPORT.

A PHASE-CORRECTING SERVO-SYSTEM FOR THE LINEAR ACCELERATOR AT HAMMERSMITH HOSPITAL

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CONFIDENTIAL

RESEARCH DEPARTMENT.

REPORT N°. 10,424

DATE OCTOBER 1953

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METROPOLITAN-VICKERS ELECTRICAL CO. LIMITED

RESEARCH DEPT.

CONFIDENTIAL

REPORT

ON

A PHASE-CORRECTING SERVO-SYSTEM FOR THE LINEAR ACCELERATOR AT HAMMERSMITH HOSPITAL

COPY TO:-

Mr.L.B.Mullett - Atomic Energy Research Establishment,
Telecommunications Research Establishment,
Malvern.

REPORT OR REFERENCE No. 10,424

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MANAGER

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METROPOLITAN-VICKERS ELECTRICAL CO. LIMITED

RESEARCH DEPARTMENT.

Date issued OCTOBER 1953 Report No. 10,424

Subject: A Phase-Correcting Servo-System for the Linear Accelerator at Hammersmith Hospital

Investigation by: Radiation Laboratory

Author(s): M.C.Crowley-Milling

Approved: C.W.Miller Countersigned: J.M.Dodds

SUMMARY

(Object, Synopsis, Conclusions)

This report describes a servo-system designed to correct the phase of the power from the output end of the accelerating guide fed back into the hybrid junction, so as to maintain maximum power into the guide.

The component parts of the system include crystal pick-up units, a double channel pulse amplifier and balancer unit, and a motor-operated phase shifter.

RESEARCH DEPT.

CONTENTS

A PHASE-CORRECTING SERVO-SYSTEM FOR THE LINEAR ACCELERATOR AT HAMMERSMITH HOSPITAL

1. INTRODUCTION

When the design of a linear accelerator for Hammersmith Hospital was first considered, it was intended to use a directly fed accelerator, in which the residual power at the output end of the corrugated guide would be absorbed in a resistive load. Consideration of such a scheme, however, indicated that the frequency tolerance which would have to be imposed on the R.F. generator was such that some form of frequency stabilization would be required. This would not be an easy problem since magnetrons were the only suitable R.F. sources available. About this time, Harvie and Mullett[1] proposed a feedback scheme to increase the power flow through the corrugated guide to a value greater than that entering the system, by combining in correct phase relationship, the residual power from the output end of the corrugated guide with the incoming power from the source, by means of a waveguide bridge circuit. Fig.1 shows the circuit arrangement of the feedback circuit, using a waveguide bridge of the type known as a "rat-race", and its low frequency analogy. The resistive load is necessary to absorb some power during "build-up", and also under steady state conditions, if the bridge ratio is not the optimum for the guide attenuation.

The increase in power flow in the guide obtained by this method enabled an increase in the iris diameter of the corrugated guide to be made, which increased the group velocity, and so widened the frequency tolerance. It was thought desirable to have some automatic control of the phase of the power fed back from the output end of the guide, to compensate for small frequency variations, and for changes in the electrical length of the corrugated guide due to temperature variation.

Miller and Mullett[2] showed that if pick-up loops are inserted into the rat-race at two positions (A and B in Fig.1) equidistant from the arm joined to the resistive load, then equal currents are induced into the two loops when the conditions of optimum power build-up have been achieved. If the phase of the power fed back is altered in one direction, then the current induced in A will be greater than in B, and vice versa for alteration in the opposite direction. If these currents are rectified, voltages can be obtained to control a servo-system, to maintain optimum phase conditions.

This report describes the servo-system which was developed for this purpose.

2. OUTLINE OF SERVO-SYSTEM

It was decided that the servo-system should be of the "on-off" type, which is quiescent until the phase error exceeds a certain amount, in this case specified as ±5°, and then starts to restore the phase to the optimum. It was also decided that it would be desirable for the restoring system to overshoot slightly as the phase error was expected to drift slowly in one direction, due to warming up of the guide, etc., and the overshoot would reduce the number of times the servo had to operate.

The output from the magnetron is in the form of pulses, about 2 microseconds long and at a repetition frequency of from 50 to 500 pulses per second. Therefore the output from each pick-up point will also be of this form. An amplifier, which has separate channels for the two signals, supplies output voltages which are proportional to the amplitudes of the pulses, and independent of the repetition frequency. If the difference between these output voltages exceeds a preset amount, relays are operated to energise a small a.c. motor which drives a phase-shifter, inserted in the waveguide, so as to restore balance.

3. COMPONENT PARTS OF THE SYSTEM

(1) Pick-up Loops and Crystal Rectifiers

The whole waveguide system is evacuated, to prevent breakdown due to the high peak power transmitted and so any pick-up loop must be inserted through a vacuum seal. Due to the high level of power flow in the rat-race, sufficient current can be induced into the loops without protruding them into the rat-race; it is sufficient to place them near to holes cut in the side wall. The mechanical layout is shown in cross-section in Fig.2. A thin glass window is sealed on to the end of a thin wall Fernico tube. This is soldered into a brass piece (1) which is screwed into the side wall of the rat-race, opposite a coupling hole. A vacuum seal is obtained at this point by means of a rubber ring (20). The gap round the outside of the Fernico tube is made half a wavelength long at the operating frequency, to prevent build-up of voltage between the end of the tube and the edge of the coupling hole. The loop is supported by a brass tube which can slide in the Fernico tube, to adjust the coupling. The body (2), into which the brass tube is soldered, houses a crystal rectifier (9), and has a screwed portion (10), which, together with the rings (4) and (5), enables the position of the loop to be set and locked. The output from the crystal, which is a B.T.H. silicon rectifier, type CS2A, is conducted to the amplifier by means of the lead (15).

(2) Amplifier Unit

A circuit diagram of the amplifier is given in Fig.3. The maximum safe output voltage from a crystal of the type used is 2 volts, and so the amplifier was designed for a normal input of

0.5 volt. A separate channel is provided for the output from each pick-up point, and as these are identical, it is only necessary to describe the operation of one channel. With reference to Fig.3, V_1 and V_2 form a two-stage amplifier, with a voltage gain of about 100. The resistors R_{35} and R_{37} provide some negative feedback to reduce the effects of change in valve characteristics on the gain of the amplifier. The output from the amplifier, in the form of positive pulses of about 50 volts amplitude, is applied to the grid of V_3, a tetrode which can pass a very high peak current. During the pulse, the increase of cathode current of V_3 causes an increased voltage drop across R_7 and R_8, and increases the charge on C_5, through the diode V_4. C_5 is sufficiently small that it can charge almost to the full amplitude of the applied pulse in the 2 micro-seconds duration. At the end of the pulse, V_4 ceases to conduct, and C_5 discharges through R_9 and R_{11}, the time constant being about 2 milliseconds. V_5, V_6 and C_6 form a second stage of "pulse lengthening", the final time constant being 1 second. Thus, even at the lowest repetition frequency of 50 pulses/second, the voltage across C_6 will drop a negligible amount between pulses, and this voltage will vary with slow variations of the peak pulse voltage from the crystal. This voltage is applied to the grid of V_7, and the voltage from the other crystal, via the other amplifier and pulse lengthener, is applied to the grid of V_{14}. V_7 and V_{14} form a differential amplifier, their cathodes being coupled by the variable resistor VR_3, by means of which the differential sensitivity can be controlled. Fig.4 shows the variation of anode current of V_7 and V_{14}, when the pulse voltage applied to VR_1 is varied, for constant input to VR_4, at the extreme settings of VR_3.

The anode current of V_7 flows through coil A_1 of relay A, and coil B_2 of relay B, and the anode current of V_{14} flows through coils B_1 and A_2. These coils are connected so that the currents from the two valves tend to oppose in each relay. The resistors R_{15} and R_{30} (with VR_2 and VR_5) allow steady currents to pass through coils B_2 and A_2, from the H.T. line, to polarize the relays. Each polarizing current is set to be equal to the "drop-out" current of the relay. Assume that the anode currents of V_7 and V_{14} are equal, and neither relay operated; then if the anode current of V_7 is increased, and that of V_{14} decreased, there will be no effect on relay A_1 as the current difference will be tending to oppose the polarizing current. In relay B_1 however, the current difference aids the polarizing current, and causes the relay to operate, if it exceeds 2.5 milliamperes, which is the difference between the "pull-in" and "drop-out" current of the particular relays used. When relay B operates, it energizes the motor, causing it to drive the phase-shifter in the direction to restore balance. However, at the balance point, the polarizing current will still hold in relay B, and so it is necessary for the phase-shifter to be driven slightly beyond the balance point, before relay B drops out. This provides the required overshoot. The approximate relay pull-in points are marked in Fig.4 and it can be seen that the "dead-spot" can be varied between about 30 millivolts and 600 millivolts by variation of VR_3. This sensitivity is almost unchanged over a range of 4 to 1 in mean input level, as can be seen from the table below, measured at maximum sensitivity.

Channel 2 input	Channel 2 input to operate	
	Relay A	Relay B
mV.	mV.	mV.
475	447 (-28)	500 (+25)
238	212 (-26)	267 (+29)
119	95 (-24)	150 (+31)

The double channel amplifier and balancer, with the two relays and power supplies, are mounted on one chassis, of which Fig.5 is an outline drawing.

(3) Motor-driven Phase-shifter

The motor is a two-phase induction motor, type FC1/A, manufactured by Evershed and Vignoles. This is shown as M_1 in Fig.3, where it can be seen that one winding can be excited directly from T_2, while the other winding is excited in phase quadrature, due to the capacitor C_{15}. The direction of rotation of the motor is dependent upon whether relay A or relay B is operated. Contacts a_2 and b_2 prevent the secondary of T_2 from being short circuited should both relays accidentally be closed.

A cross-section of the phase-shifter assembly is shown in Fig.6. A strip of ceramic material of high dielectric constant (1) is supported in a piece of waveguide by means of two ceramic rods fixed to the strip by fused glass. The ceramic rods are secured to a block (2) which can slide on guide bars, so that the ceramic strip can be moved across the waveguide. The ceramic strip has tapered ends, and the spacing of the rods is chosen to introduce minimum change of standing wave. The position of the strip is set by shaft (3), which has a threaded portion which engages with the block (2).

As the waveguide is evacuated, and it is inconvenient to provide a vacuum-tight seal where the ceramic rods pass through the wall of the waveguide, the block (2) and its guides are mounted in a vacuum-tight enclosure fixed to the side of the waveguide. The shaft (3) is brought out through an oil-filled seal and is rotated by the motor (4) through a train of gears. The value of the capacitor C_{15}, which determines the quadrature component of the motor field supply, was chosen to limit the torque of the motor, to prevent damage if the phase-shifter should be driven to the ends of its travel.

4. PERFORMANCE

Fig. 7 shows curves of the crystal output voltages for variation of the phase from that for optimum build-up. The operating points for the servo-system, at maximum and minimum sensitivity are also shown, and it can be seen that the minimum "dead-spot" is under half the required $\pm 5^\circ$. The maximum dead-spot is about 50° wide, so an adequate range of setting is available.

When the servo-system was first fitted to the accelerator it was found that the phase-shifter had insufficient range to allow for the frequency variations encountered in adjusting the machine. The original ceramic strip could give a maximum phase variation of 60°, and this was replaced by a longer strip, which allowed 140° variation, and this proved adequate for the normal running of the magnetron. However, during the "degas" period, when the magnetron is run at reduced power, the frequency is altered sufficiently to make the servo-system drive the phase-shifter to the end of its travel. Also, due to the deliberate overshoot, if the servo was making a correction at the moment the H.T. to the magnetron was switched off, the servo would continue to drive the phase-shifter until it reached the end of its travel. If the H.T. was then switched on again, there would be a period of several seconds before maximum output was achieved, as the servo-system would have to move the phase-shifter over perhaps half its total range. To overcome this trouble, it was arranged that the transformer T_2, supplying the motor, is only energized when the modulator is switched to the "Run" position.

5. ADJUSTMENT

The plug P_1, connecting the motor to the amplifier unit should be disconnected, and the servo-operated phase-shifter set to about the middle of its travel. Then, with the magnetron running at full H.T. voltage, the desired build-up conditions should be attained by adjustment of the manual phase-shifter.

The crystal probe units should then be adjusted for equal output as measured by a peak-reading pulse voltmeter, having an input resistance of about 5000 ohms. The loop insertion should be adjusted in each case to give about 450 millivolts peak. The crystal probe units should then be connected to the amplifier, and 0 - 10 mA meters plugged into the two jack sockets JK_1 and JK_2. The preset potentiometers VR_1 and VR_4 should then be adjusted until the currents are equal, and about 5 mA each. This can best be done with VR_3 set near maximum sensitivity.

In the case of the routine replacement of one crystal, if a pulse voltmeter is not available, and the settings of VR_1 and VR_4 have not been disturbed, the insertion of the probe unit containing the new crystal should be adjusted for equality of the currents measured at JK_1 and JK_2.

The motor can then be reconnected, and VR_3 adjusted to give the required width of "dead-spot".

Valve changes should not affect the operation of the servo-system, although it is desirable that the characteristics of V_7 and V_{14} should be similar. However, it is advisable that the currents at JK_1 and JK_2 should be checked for equality, after a valve change, with P_1 disconnected and the accelerator operating under the desired build-up conditions.

If at any time it is necessary to replace the relays A or B, then VR_2 or VR_5 should be adjusted so that the relay will only just hold in under balance conditions. As the relays may vary considerably in their characteristics, it may be necessary to change R_{15} or R_{30}, if there is insufficient range of adjustment of VR_2 or VR_5.

McCrosby Philling

RESEARCH DEPARTMENT
Radiation Laboratory

REFERENCES

(1) Harvie, R.B.R-S-., & Mullett, L.B., Phys. Soc. Proc. 1949 (B), Vol. 62, p. 270

(2) Mullet, L.B., & Miller, C.W., British Patent Specification 673,957

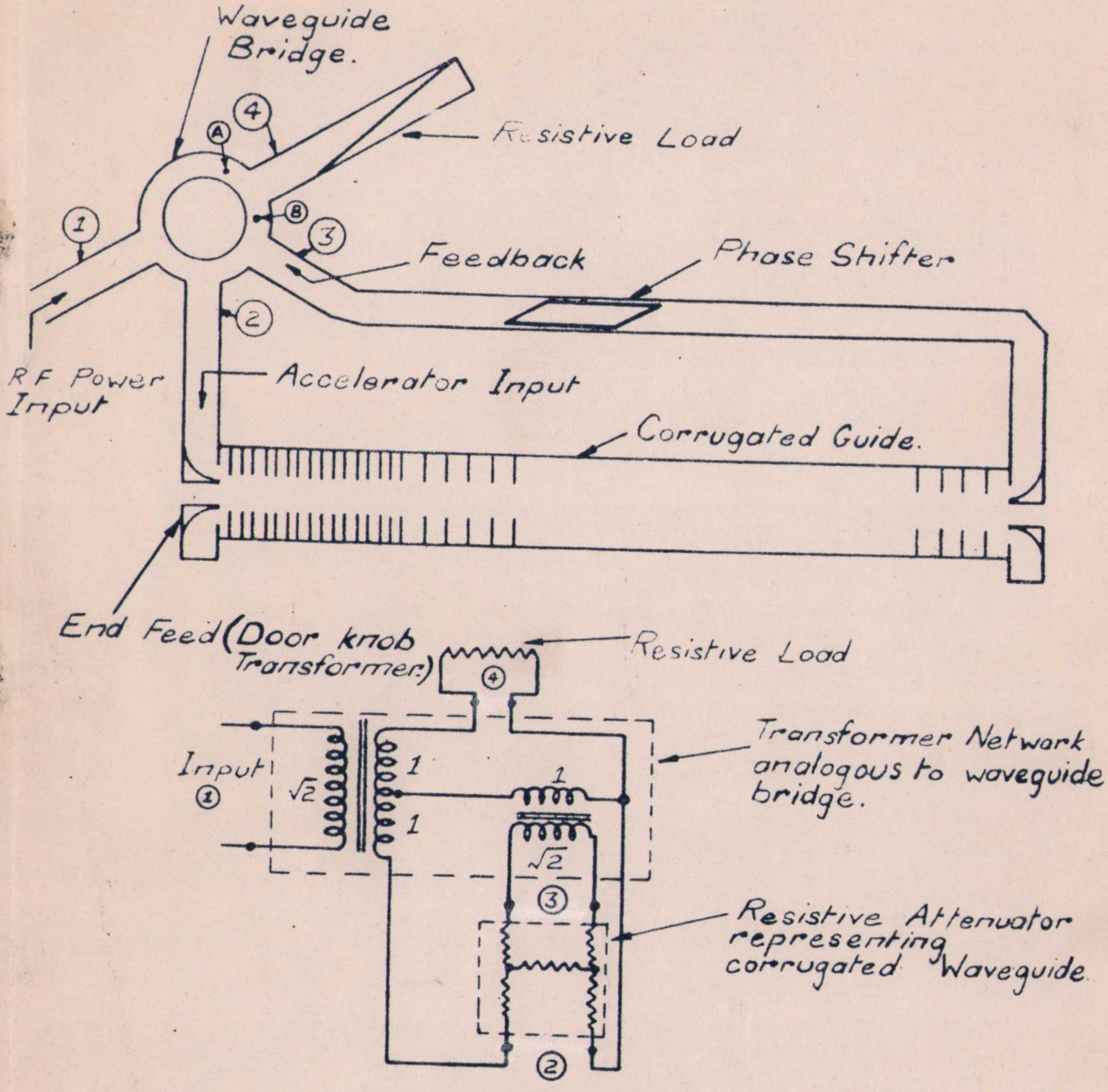


FIG. 1.
DIAGRAM OF R.F. POWER FEED BACK CIRCUIT WITH LOW FREQUENCY ANOLOGY.

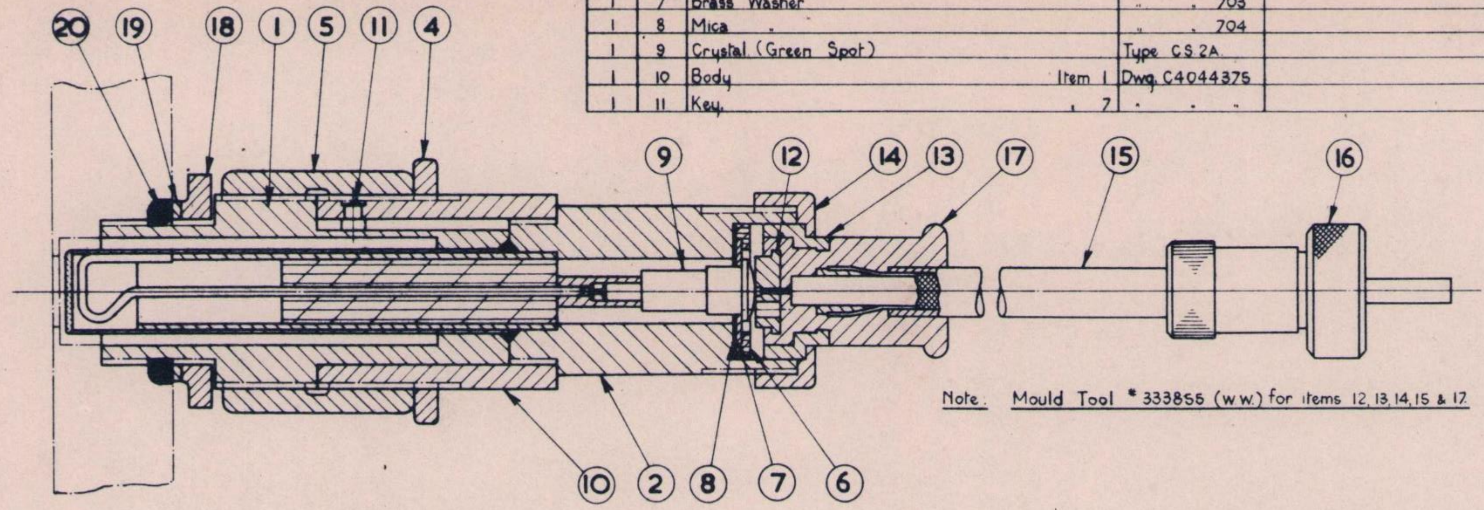
Note:- Numbers on transformers refer to turns ratio for unity bridge ratio.

REPORT No. 10, 424 SEPT. 1953	METROPOLITAN - VICKERS ELEC. CO. LTD. RESEARCH DEPT. MANCHESTER.	SHEET No.

1	12	Insert	Dwg. E6026937	
1	13	Collar	" " 938	
1	14	Cable Nut	" " 939	
1	15	Uniradio Cable 36" lg.	Type A.P. 13832	
1	16	Cannon Plug	S* 247027	Res. Strs.
1	17	Polythene Moulding		
1	18	Nut	Dwg. E6027941	
1	19	Washer	" E6027942	
1	20	Seal	" E6027943	

DWG. C — BILL OF MATERIAL — TITLE

COLUMN A	ITEM No.	DESCRIPTION, SIZE OR WEIGHT		PATT., STYLE, CAT. OR DWG.	REMARKS
1	1	Window Tube		Dwg. C4044374	
1	2	Body		" " 375	
~~1~~	~~3~~	~~Locknut~~	~~Item 1~~	~~" E6027681~~	
1	4	"	" 2	" E6027681	
1	5	Traverse Nut		" " 682	
1	6	Polythene Ring		" " 702	
1	7	Brass Washer		" " 703	
1	8	Mica		" " 704	
1	9	Crystal (Green Spot)		Type CS 2A	
1	10	Body	Item 1	Dwg. C4044375	
1	11	Key	" 7	" " "	



Note. Mould Tool * 333855 (w.w.) for items 12, 13, 14, 15 & 17.

FIG. 2.

All Dimensions with Symbols are to be made to Gauges.
Any size between Limits is correct.
Unlimited dimensions to be correct within ±
Unlimited overall dimensions to be correct within ±
Unlimited Machining dimensions to be correct within ±·01

P.R.

C4044335

1	Date 11.10.49. Checked E.W.	Items 10 & 11 added. Dwg. modified in line with details.
2	Date 18.2.50. Checked F. Bradley	Items 12 to 17 added
3	Date 22.2.50 Checked E. Willdig.	Item 1 modified. " 3 cancelled. " 18, 19, 20 added
4	Date 23.6.50 Checked F. Bradley.	It 18 was It 1. Sk 4765 Sh. 4; " 19 " " 2 " " " "; " 20 " " 3 " " " "
5	Date 18.7.50. Checked K.T.	Drg. Traced
6	Date 25-8-53 Checked	

Drawing issued by Research D.O.
To O.C. Res. (2) W. Wks. 5.

Assembly Dwg.

METROPOLITAN Vickers ELECTRICAL CO. LTD. MANCHESTER AND SHEFFIELD ENGLAND

WAVEMETER PROBE WINDOW.

10 cm. BRIDGE.

10 MeV LINEAR ACCELERATOR.

SCALE = 24": 1'-0" S.O. C4044335

REPORT No. 10.424. SEPT. 1953.

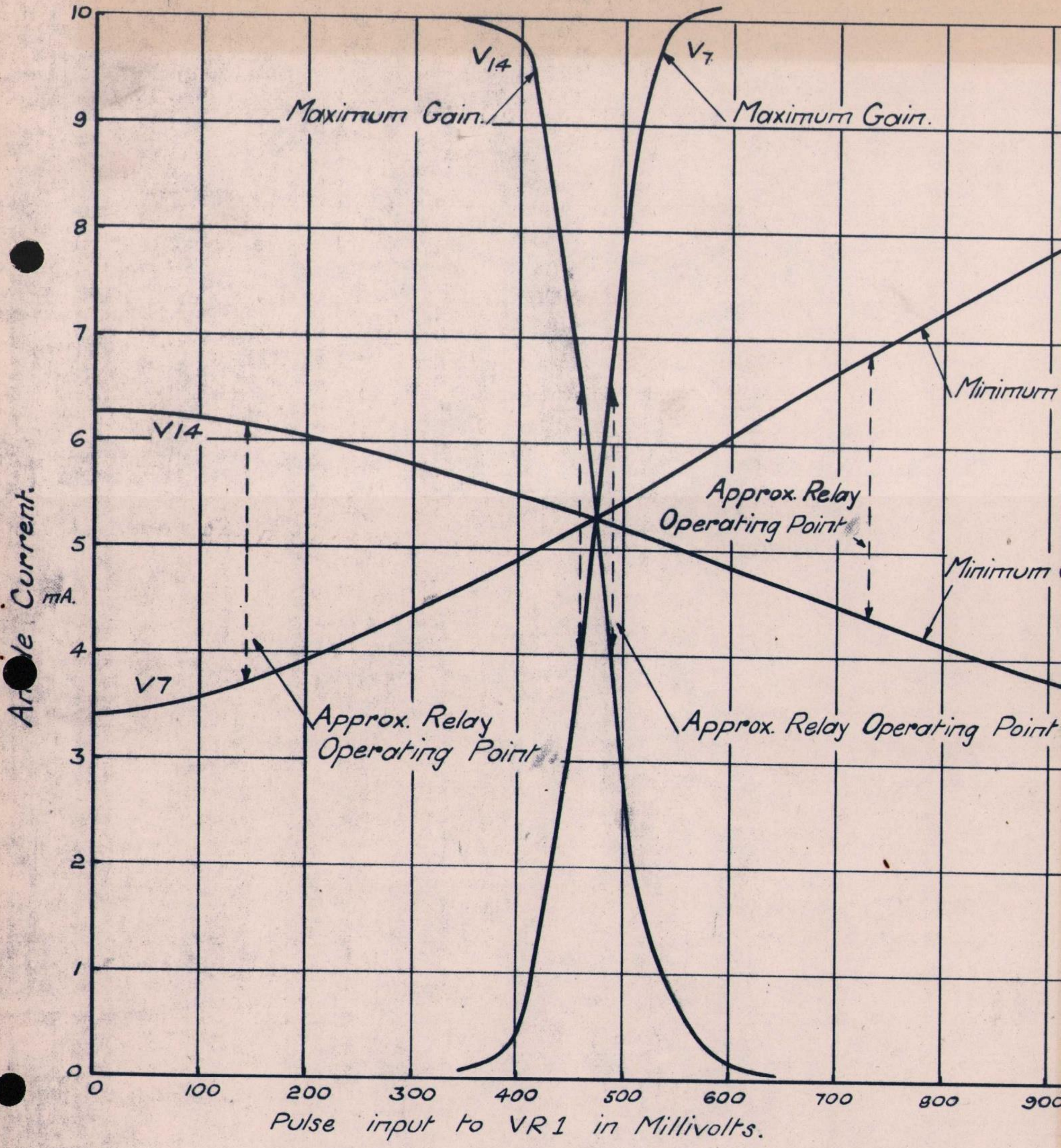
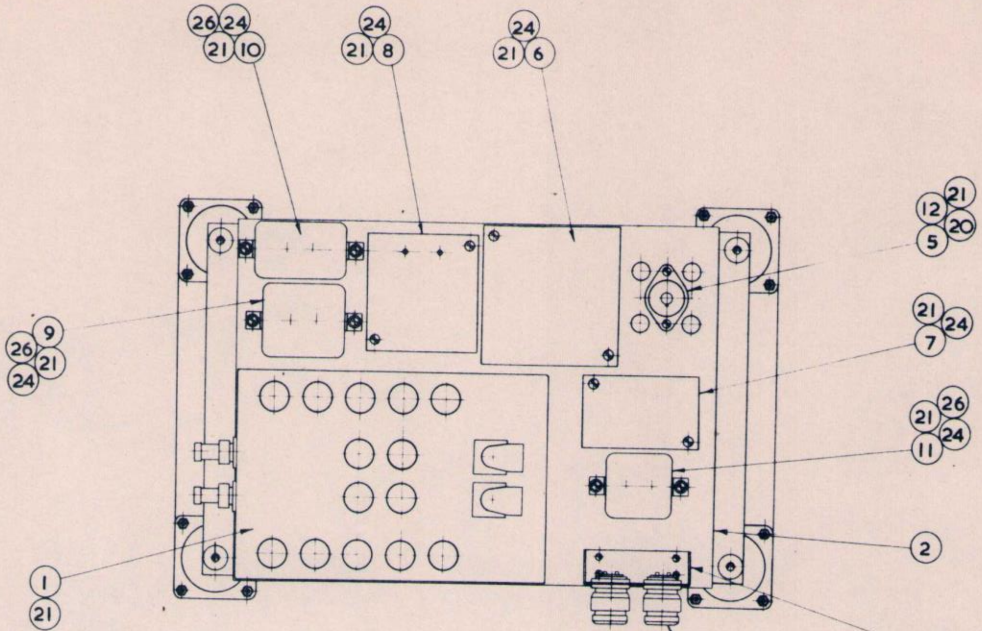
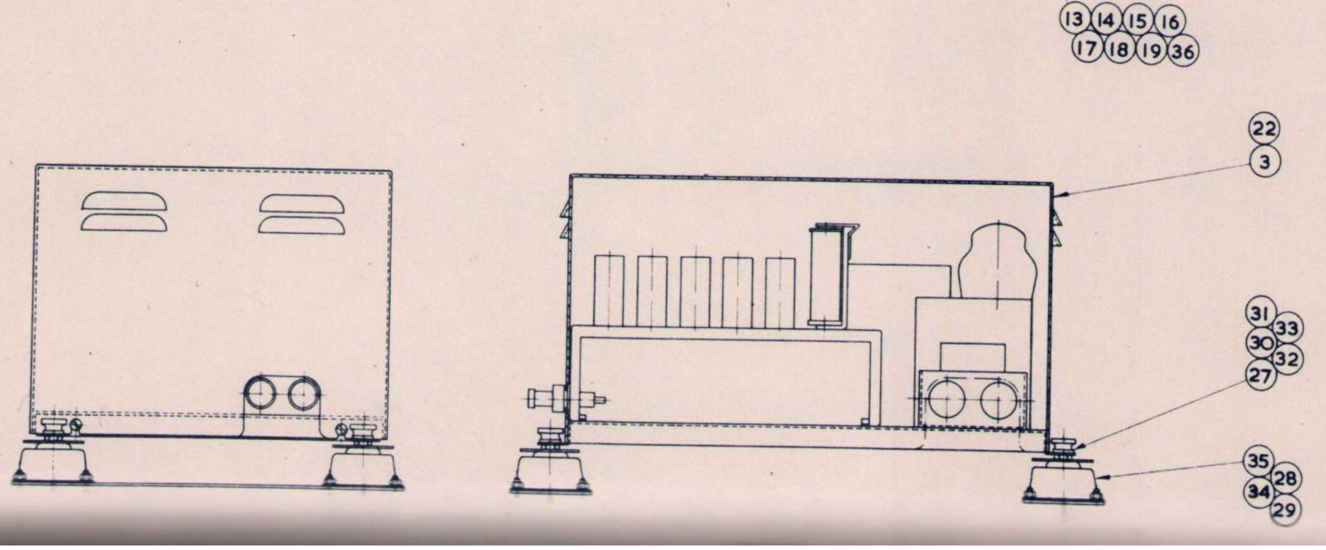


FIG. 4.
SENSITIVITY CURVES OF AMPLIFIERS.
Pulse Input to VR4 Constant 475 mV.



Plan with Item 3 removed



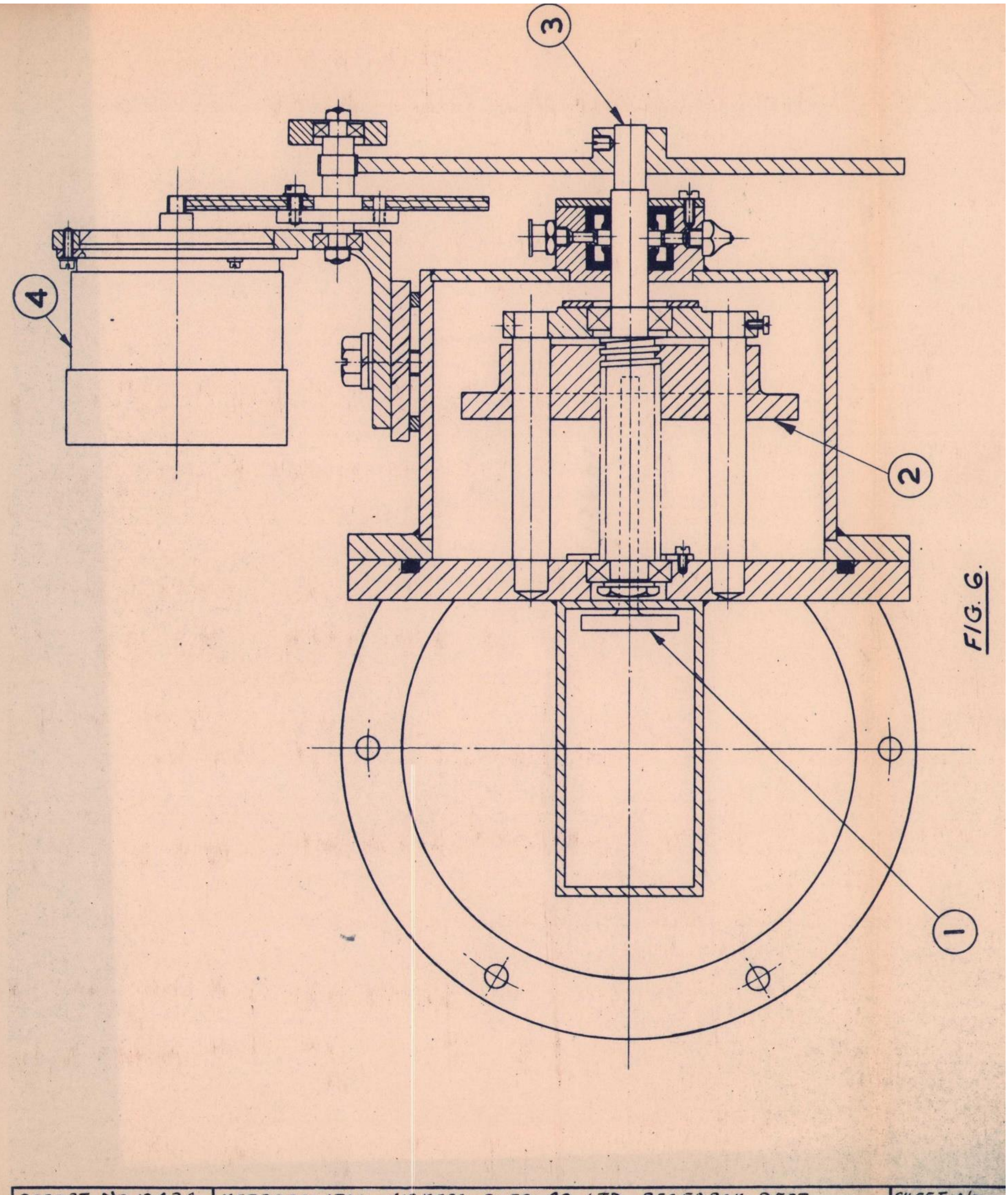


FIG. 6.

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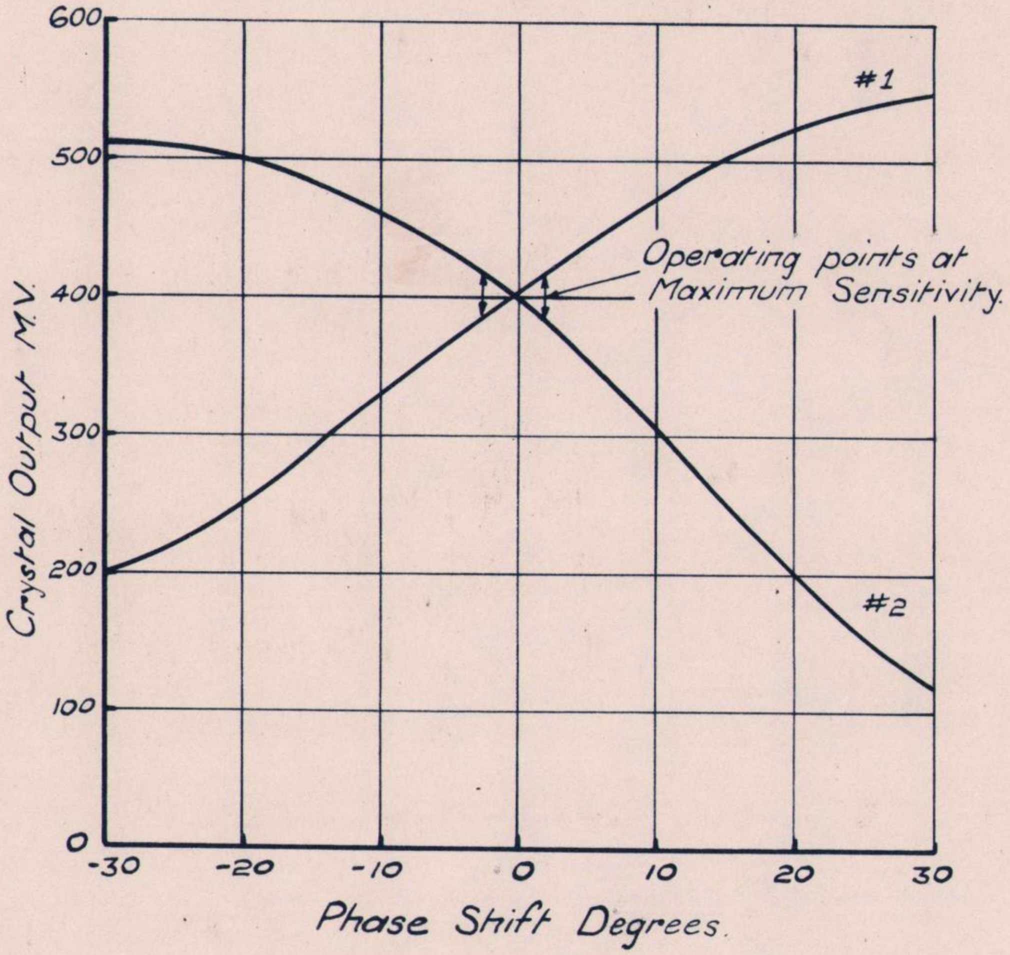

FIG. 7.
VARIATION OF CRYSTAL OUTPUT WITH
PHASE SHIFT IN FEEDBACK LOOP.