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THE BEVATRON RF MEASUREMENT SYSTEM

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ABSTRACT

The University of California Bevatron rf measurement system provides a means of measuring a varying frequency at thirty-two predetermined points during a nominal frequency variation of from 350 kc to 2,500 kc, and displays departures from the calculated frequency to 0.1%. The display is of the bar-graph type and can be calibrated in terms of the radial position of the beam circulating in the vacuum tank so that the position of the beam at each measurement point can be determined. The rf measurement system uses digital techniques throughout and is completely automatic in operation.

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INTRODUCTION

The proton synchrotron, of which the Bevatron is an example, uses an electric field of varying frequency to accelerate nuclear particles at approximately constant radius in a varying magnetic field. The relation of the oscillator frequency to the magnetic field determines the radius of the orbit and is the most difficult operating parameter to control. As part of this control problem it is necessary to provide instrumentation to monitor this relation while the frequency and magnetic field change during the accelerating period. In the Bevatron, the frequency increases from 350 to 2,500 kc in about 2 seconds during the acceleration, and the cycle is repeated ten times per minute.

The radius of the orbit can be measured directly by use of the ratio of the voltages induced on a pair of electrodes on opposite sides of the radial aperture. At the time of starting the machine, however, if the beam current is too small to give a satisfactory signal from the electrodes it is necessary to measure the frequency itself.

As part of the frequency-control system, timing pulses are produced when the magnet current passes through each of 32 accurately determined values. As the relation between the magnet current and magnetic field was known, to be reproducible it was decided to measure the frequency at each of these points. As a change in the radius of the equilibrium orbit of one inch in fifty feet is significant, an accuracy of about 0.2% was required in each frequency measurement. It appeared that cycle counting would be suitable if the counting time could be made short enough. The frequency measured by this method is the average for the counting period, and differs from the frequency at the time of the initiating pulse by the change in Bevatron frequency during half the counting time. The Bevatron frequency time characteristic has a slope of 12 Mc/sec^2 for the first few measuring points, and gradually decreases to a low value as the highest frequency of 2,500 kc is approached. The rate of rise of frequency can be considered constant within 10%, so that if an error of 0.1% is allowed for this variation, the counting time at minimum frequency must not exceed 600 μsec; as the frequency rises, the possible error due to this cause rapidly decreases.

Another requirement was that the frequency increments be displayed in a manner obvious and useful to the operator. This is done by displaying the departure of the Bevatron frequency from the standard frequency, which corresponds to the radial location of the beam in the magnet aperture at each measuring point. A range of plus or minus 3%, corresponding to the width of the aperture at low frequency, is included on the oscilloscope screen. Identification of the 32 measurements that appear on each magnet pulse is made by distinctive markers, which can be simultaneously displayed.

Crystal oscillators are used to provide the reference frequencies. The Bevatron frequency is measured for the time required to count 992 cycles of the reference frequency at each point. The difference between the 992 and the number of cycles counted is the frequency departure, and this is the quantity displayed on the oscilloscope screen.

It was decided, considering available scaling equipment (10 Mc max), that the ratio of Bevatron rf to standard crystal oscillator rf would be 1/8 for the first six points measured, 1/4 for the next seven points measured, and 1/2 for the remaining 19 points. This limited the maximum counting time of the Bevatron rf to 360 μsec at 350 kc, to 310 μsec at 800 kc, and 333 μsec at 1,500 kc. The range of the standard crystal oscillators then was 2.8 Mc to 5.6 Mc. It further was noted that some of the standard crystal oscillators could be used for more than one point, so that 23 oscillators could serve 32 points. This required more gates and switching equipment, but it was more than justified because of the ease of interpreting the output display as percent frequency error. The final system displayed a straight horizontal line on the oscilloscope when the measured frequency was equal to the calculated frequency (i.e., the error was zero) at each measuring point. It is to be noted that the Bevatron frequency that is measured is different from the Bevatron frequency at the instant the start pulse (a particular current marker) is received.

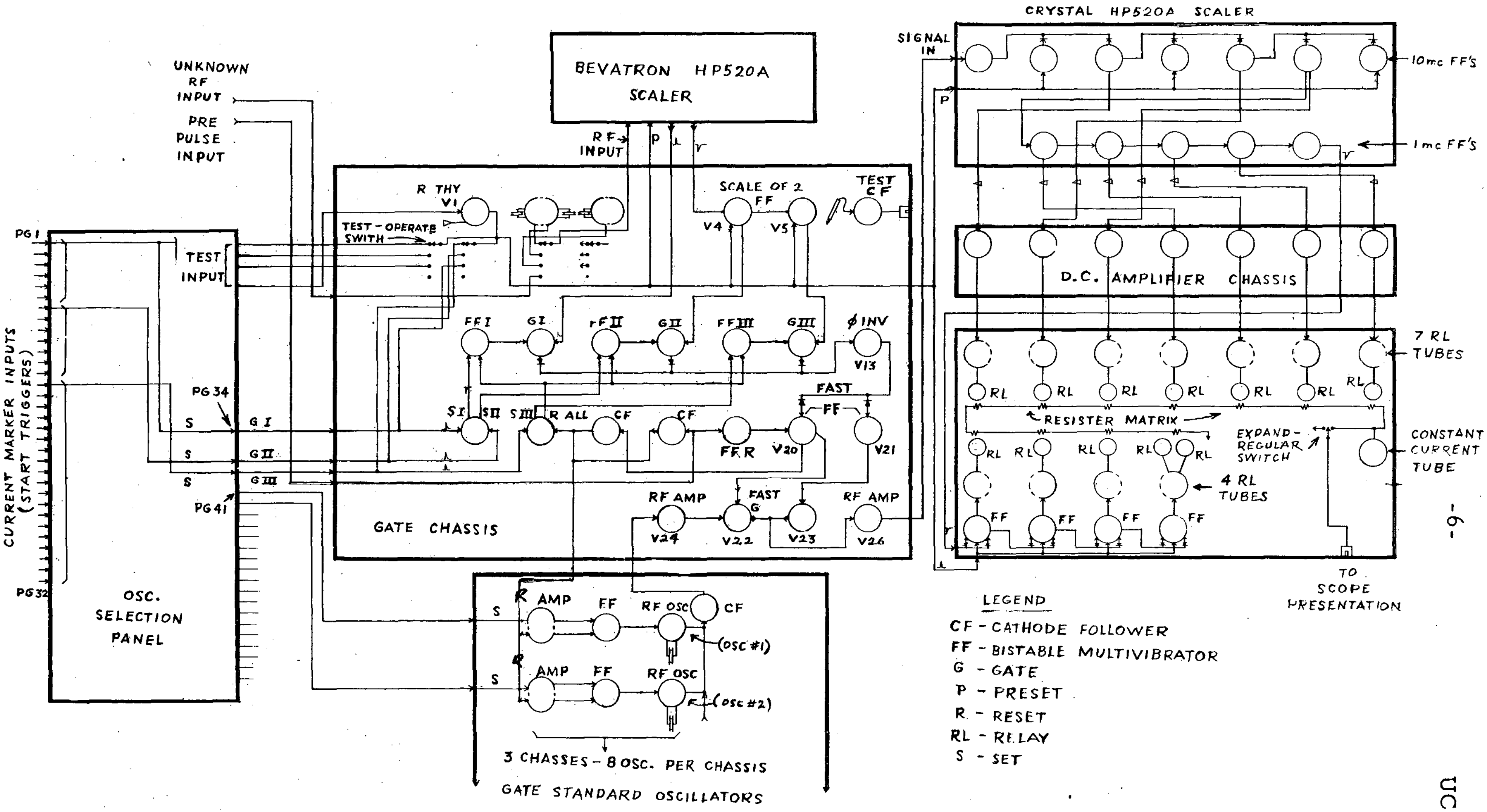
BEVATRON HP520A SCALER
CRYSTAL HP520A SCALER
SIGNAL IN
10mc FF'S
1mc FF'S
UNKNOWN RF INPUT
PRE PULSE INPUT
RF INPUT
TEST INPUT
TEST-OPERATE SWITH
R THY V1
SCALE OF 2 FF
V4
V5
TEST CF
FF I
G I
FF II
G II
FF III
G III
ϕ INV
V13
S I
S II
S III
R ALL
CF
FF R
V20
FAST FF
V21
RF AMP
V24
FAST G
V22
V23
V26
GATE CHASSIS
D.C. AMPLIFIER CHASSIS
7 RL TUBES
RESISTER MATRIX
EXPAND-REGULAR SWITCH
CONSTANT CURRENT TUBE
4 RL TUBES
TO SCOPE PRESENTATION
CURRENT MARKER INPUTS (START TRIGGERS)
PG 1
PG 34
PG 41
PG 32
OSC. SELECTION PANEL
AMP
FF
RF OSC
CF
(OSC #1)
(OSC #2)
3 CHASSES - 8 OSC. PER CHASSIS
GATE STANDARD OSCILLATORS
LEGEND
CF - CATHODE FOLLOWER
FF - BISTABLE MULTIVIBRATOR
G - GATE
P - PRESET
R - RESET
RL - RELAY
S - SET

Fig. 1.

ZN-1215

COMPONENT UNITS OF THE EQUIPMENT

The general arrangement of this equipment with respect to Fig. 1 is as follows.

I. Oscillator Selection Panel — Fig. 2

The function of this chassis is to select any or all current pips and route them to the proper standard crystal oscillator chassis as well as to the gate chassis. The thirty-two switches on the front panel enable or disable their respective input to the diode matrix, which is used to separate the pulses. This matrix also takes pulses from the gate chassis (in test position) and feeds them to the proper crystal oscillators so that the equipment can be self-checked. This does not, however, check all the crystal oscillators (see gate chassis). When the internal test is used, all the switches must be in the off position (down). Any number of frequencies may be displayed by selecting the proper switches.

II. Gate Chassis — Fig. 3

The gate chassis consists of these components to perform the following functions:

(a) A thyratron which provides a reset pulse to the two scale-of-two flip-flops V4 and V5 as well as a preset pulse to the crystal HP520A,* the readout chassis, and the Bevatron HP520A.

(b) Three test crystal oscillators to check the operation of the gate chassis, selectable from the four-position switch on the front panel. (One position is for "operate" and three positions are for "test").

(c) Two F-F's which follow the Bevatron HP520A and extend its count capacity to 256 and 512.

(d) Three slow gates and F-F's to feed the Bevatron HP520A output pulses to the fast F-F and fast gate.

(e) Fast F-F, gate, and wide-band amplifiers to gate a particular standard crystal oscillator through to the crystal HP520A and readout chassis.

(f) A cathode follower (CF) scope probe to check the operation of all circuits.

(g) A test switch with three test positions, arranged so that only one standard oscillator is checked in any one position. See Oscillator Chassis (Part III).

* Hewlett-Packard Model 520A 10-megacycle decade scaler

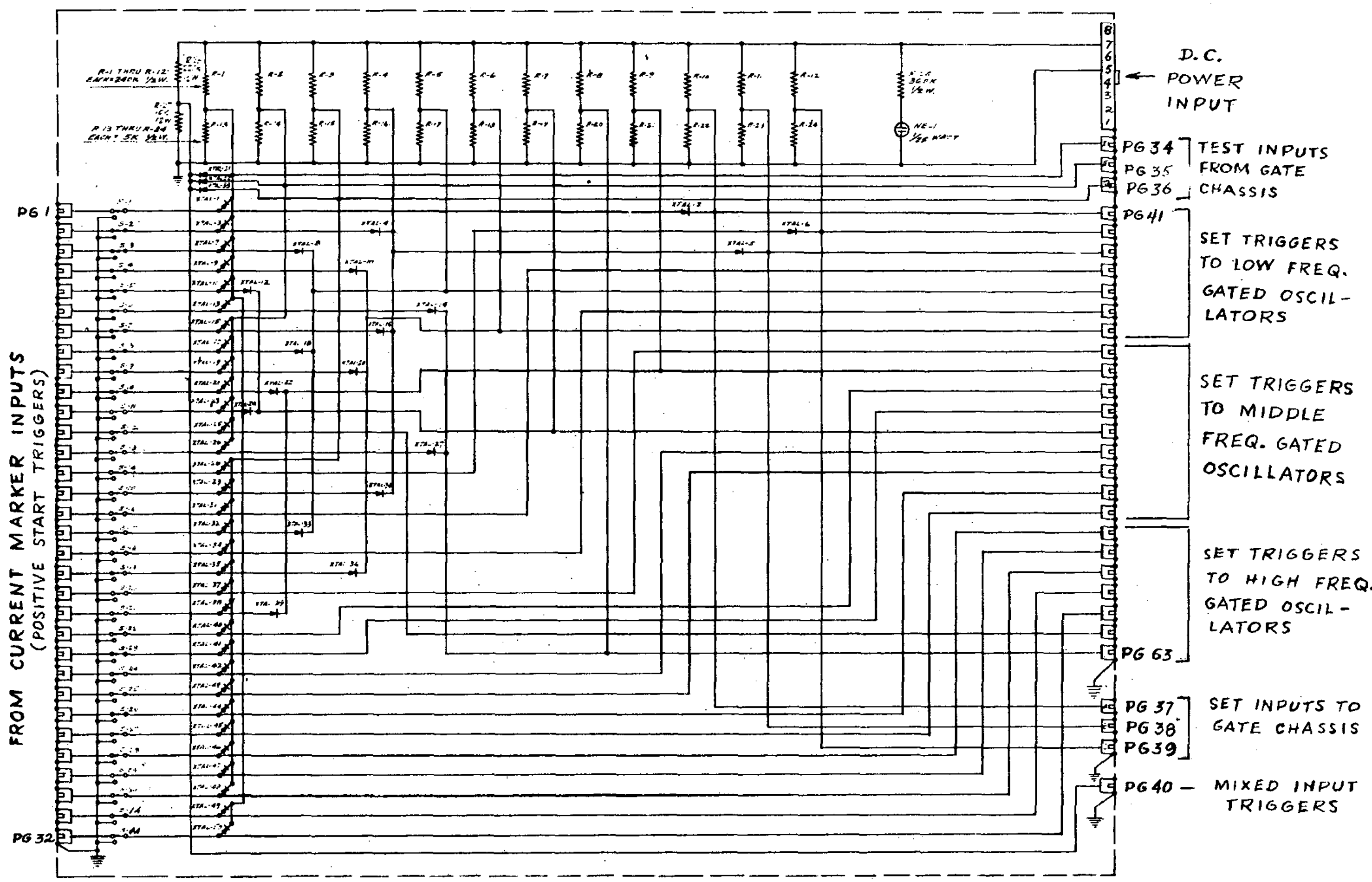
D.C.
POWER
INPUT
PG 34
PG 35
PG 36
TEST INPUTS
FROM GATE
CHASSIS
PG 41
SET TRIGGERS
TO LOW FREQ.
GATED OSCIL-
LATORS
SET TRIGGERS
TO MIDDLE
FREQ. GATED
OSCILLATORS
SET TRIGGERS
TO HIGH FREQ.
GATED OSCIL-
LATORS
PG 63
PG 37
PG 38
PG 39
SET INPUTS TO
GATE CHASSIS
PG 40
MIXED INPUT
TRIGGERS
PG 1
PG 32
FROM CURRENT MARKER INPUTS
(POSITIVE START TRIGGERS)

Fig. 2.

ZN-1222

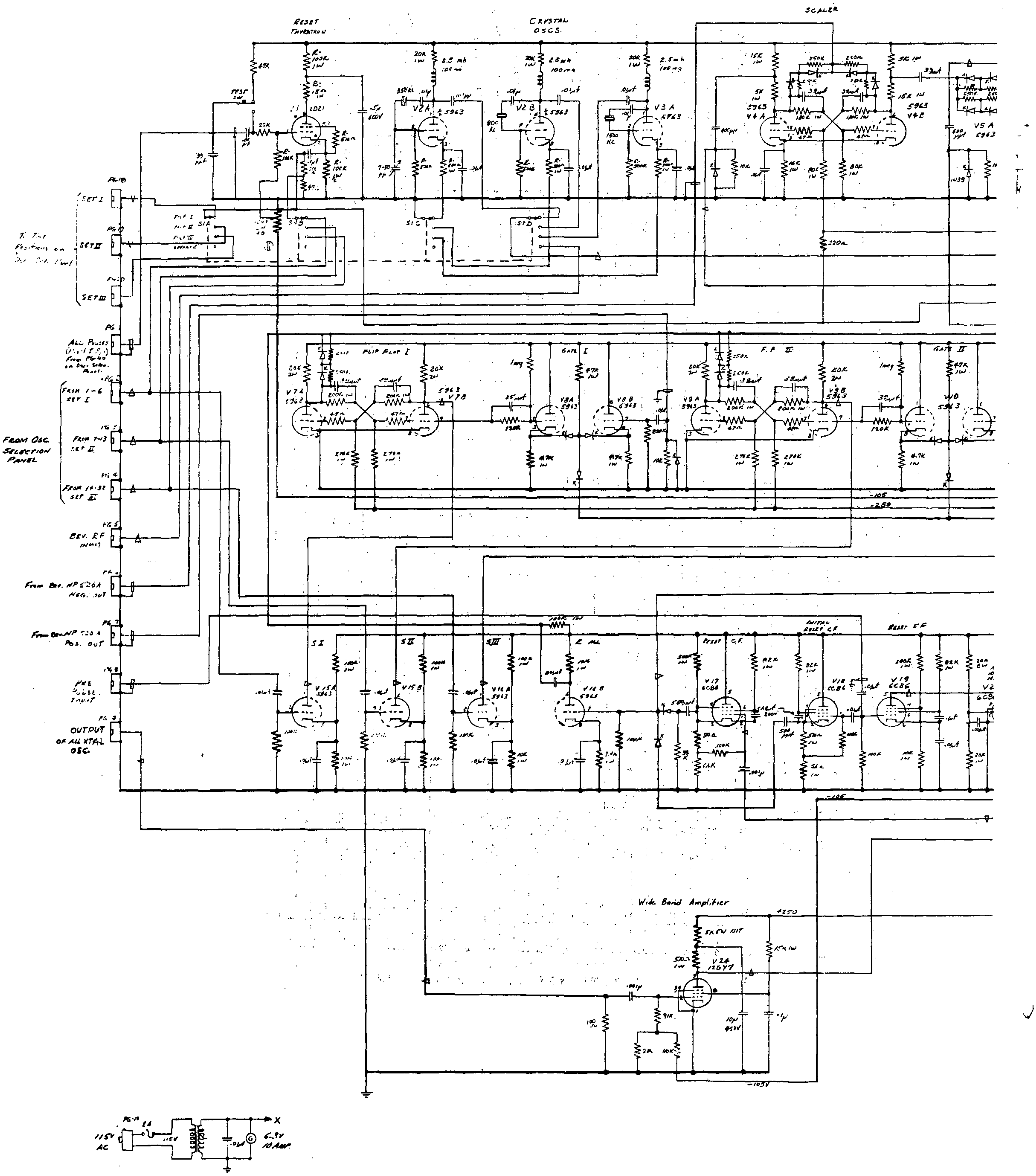
SCALER
CRYSTAL OSCS.
FLIP FLOP I
F.F. II
GATE I
GATE II
Wide Band Amplifier
FROM OSC. SELECTION PANEL
OUTPUT OF ALL XTAL OSC.
115V AC
6.3V 10 Amp.

Fig. 3.

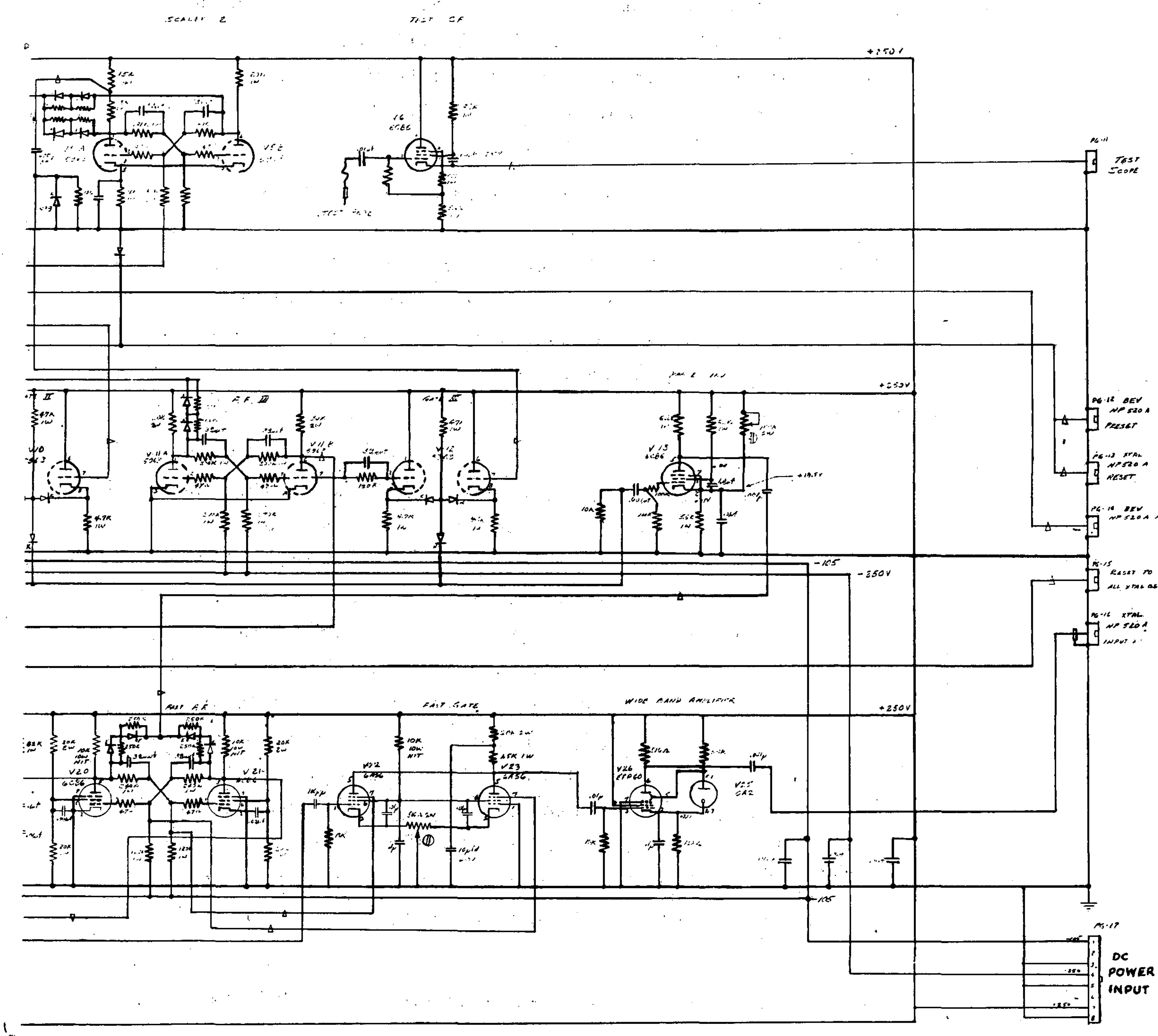
TEST SCOPE
BEV NP 520 A PRESET
XTAL NP520 A RESET
RESET TO ALL XTAL OSC
FAST GATE
WIDE BAND AMPLIFIER
DC POWER INPUT
+250V
-105
-350V

Fig. 3.

ZN-1217

III Oscillator Chassis: 1, 2, and 3 Fig. 4

Each of these chassis contains 8 complete gated standard crystal oscillators and associated triggering equipment. In addition, each chassis contains one wide-band CF to drive the output coaxial cable. Each gated oscillator is reset by a pulse from the gate chassis. The rf outputs of the three gated rf chassis are tied in common and fed to the 12BY7 (V24) in the gate chassis.

IV Crystal HP520A Scaler and Dc Amplifier Fig. 5

This unit as originally produced had a count capacity of 100 and would scale up to 10 Mc/sec. It has been modified so that it now has a scale of 128, and also it can be reset externally. It no longer resets to zero but, in conjunction with four more scales of two, it is preset to 2016 counts. It also has provisions so that the counts it contains can be read out by the dc amplifier and fed to the readout chassis to be displayed.

V Readout Chassis Fig. 6

This chassis converts the counts contained in the crystal HP520A and its own four scales of two F-F's to discrete voltages so that they can be displayed on an oscilloscope. It contains a constant-current source and a string of precision series resistors; each resistor has a pair of relay contacts across it. These resistors are in the binary scaling ratio of 1, 2, 4, etc., to 1024, so that a certain number of counts is displayed as a proportional voltage by operating the proper relays. It contains two ranges selectable from the front panel: "Expanded and Regular". In the regular position, all counts are displayed from 0 to 2047; in the expanded position, 0 to 960 counts are displayed on one line (top of screen) and 1024 to 2047 are displayed on the bottom line. Counts between 960 and 1024, corresponding to plus and minus 3.2% frequency departure, are displayed (proportioned) between the top and bottom line. The scope should always have the current marks displayed also, so that identification of the frequency error is readily possible.

VI Bevatron HP520A Fig. 7

This unit has also been modified for a scale of 128 and can be externally preset. It also has been modified to supply negative as well as positive pulse at its output.

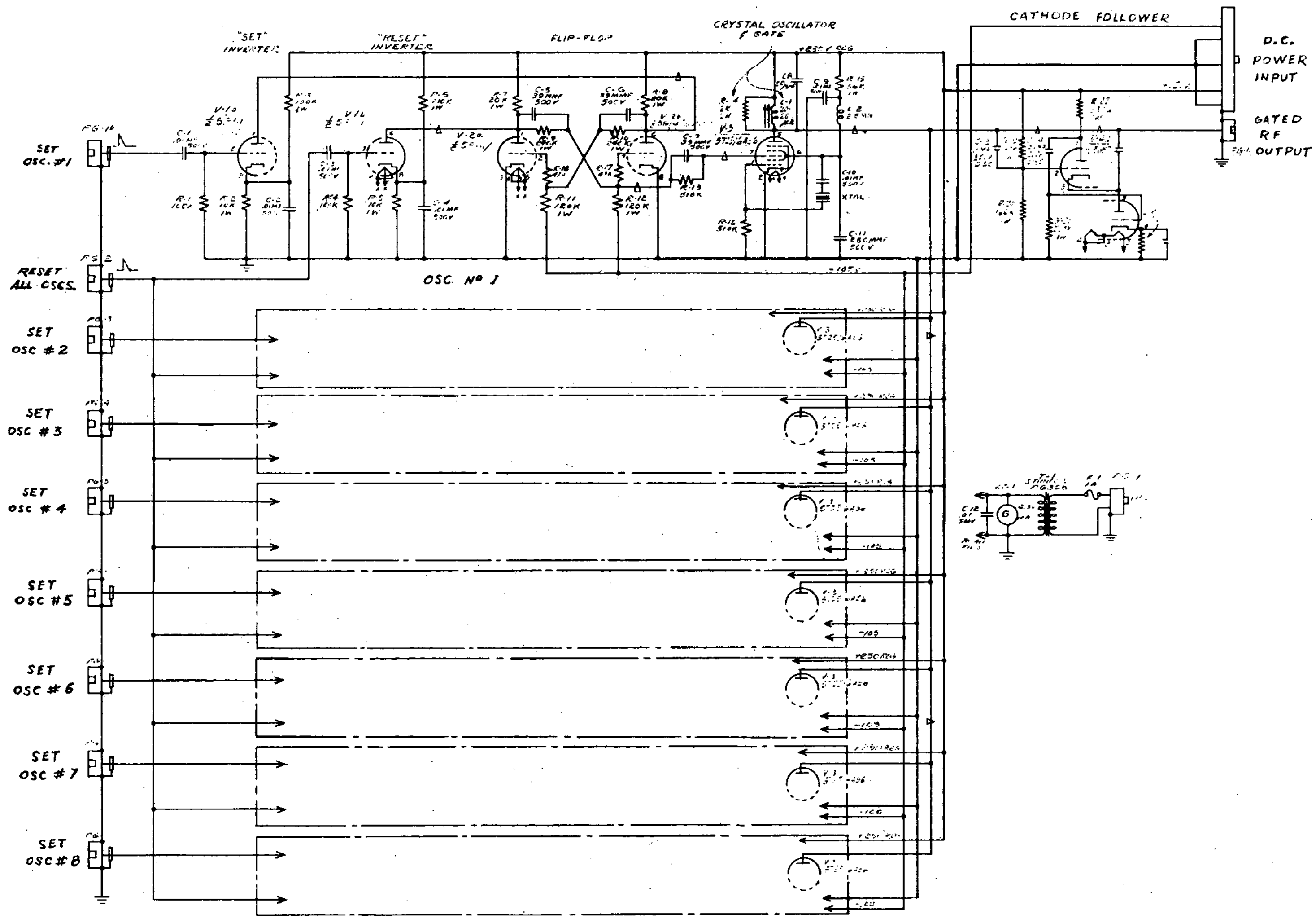
"SET" INVERTER
"RESET" INVERTER
FLIP-FLOP
CRYSTAL OSCILLATOR & GATE
CATHODE FOLLOWER
D.C. POWER INPUT
GATED RF OUTPUT
SET OSC. #1
RESET ALL OSCS.
OSC. No 1
SET OSC #2
SET OSC #3
SET OSC #4
SET OSC #5
SET OSC #6
SET OSC #7
SET OSC #8
XTAL

Fig. 4.

ZN-1214

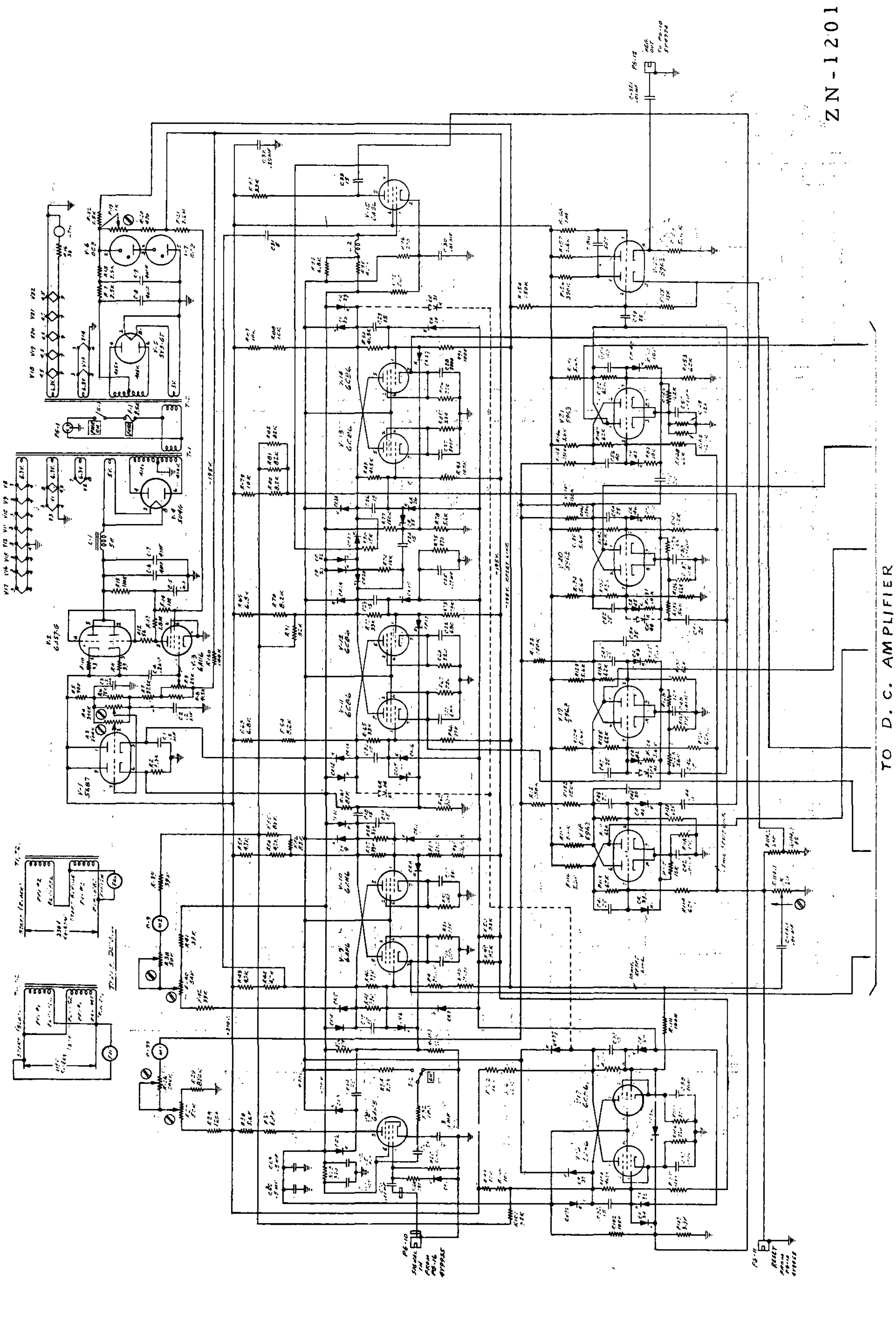

Fig. 5.

ZN-1202

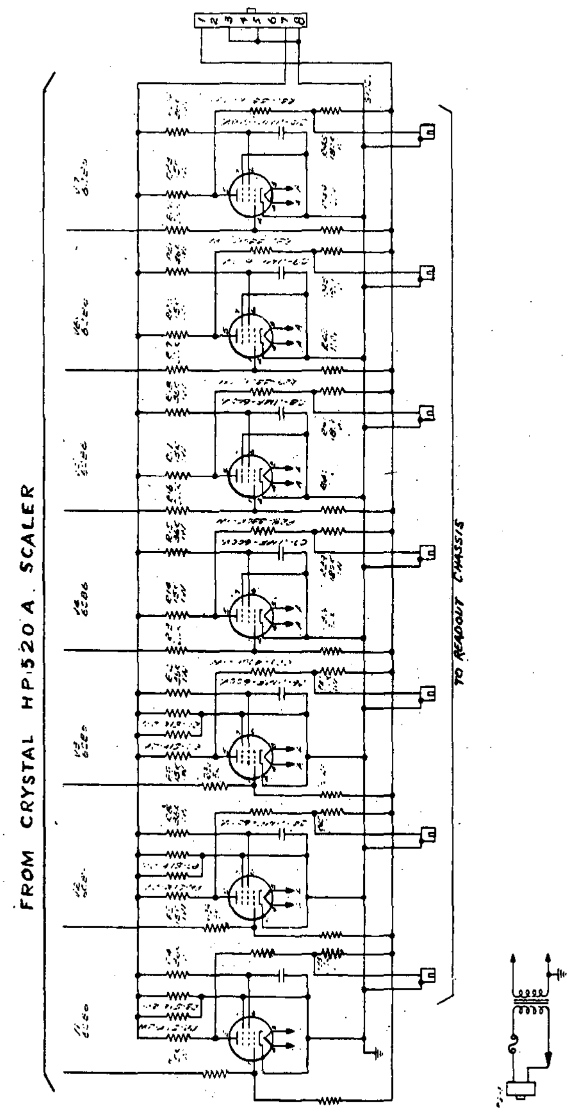

Fig. 5.

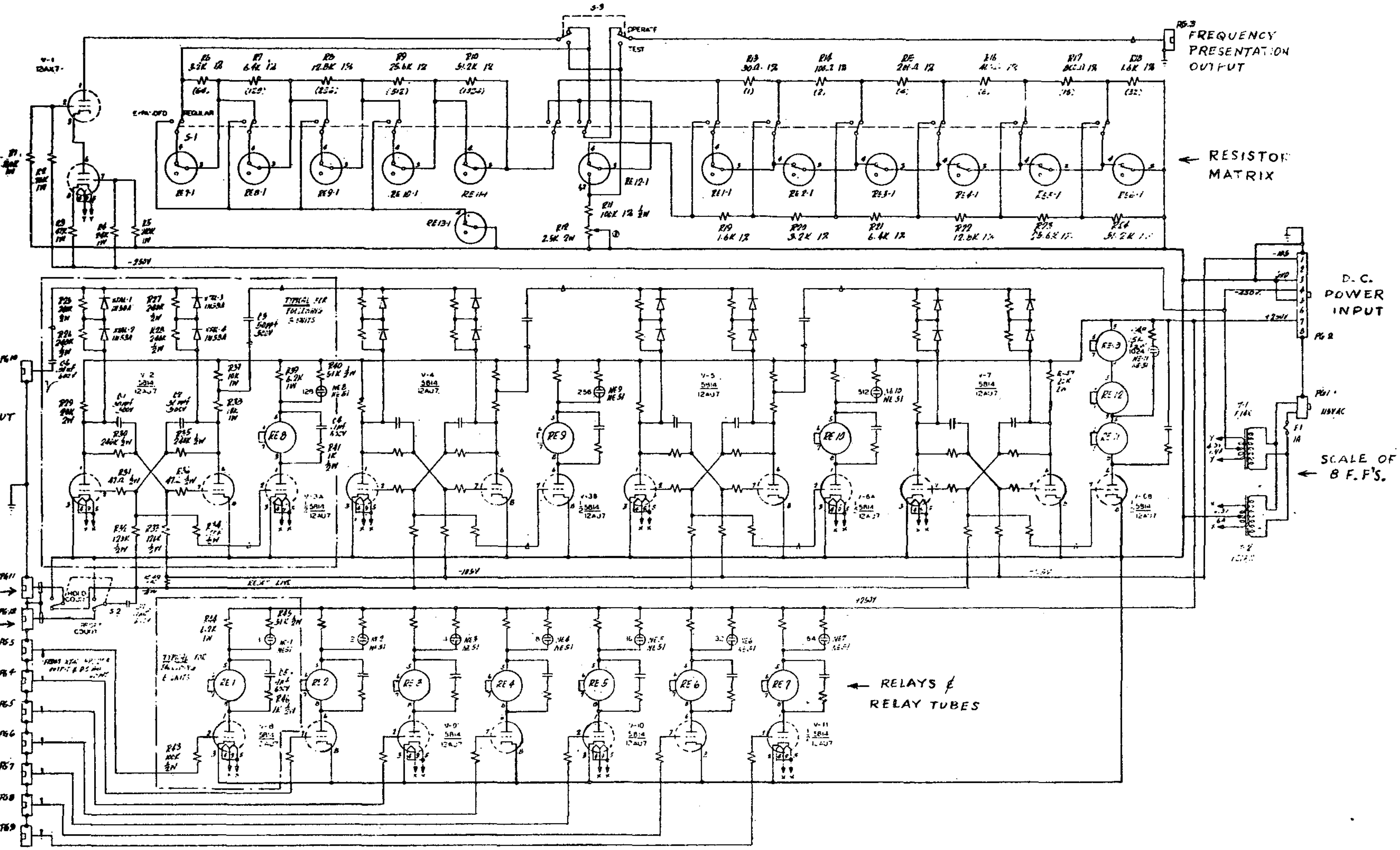
FREQUENCY
PRESENTATION
OUTPUT
RESISTOR
MATRIX
D. C.
POWER
INPUT
SCALE OF
8 F.F'S.
RELAYS &
RELAY TUBES
FROM
CRYSTAL
HP520A
NEG. OUTPUT
CRYSTAL
HP520A
RESET
RESET
INPUT
FROM
D. C.
AMP.

Fig. 6.

ZN-1212

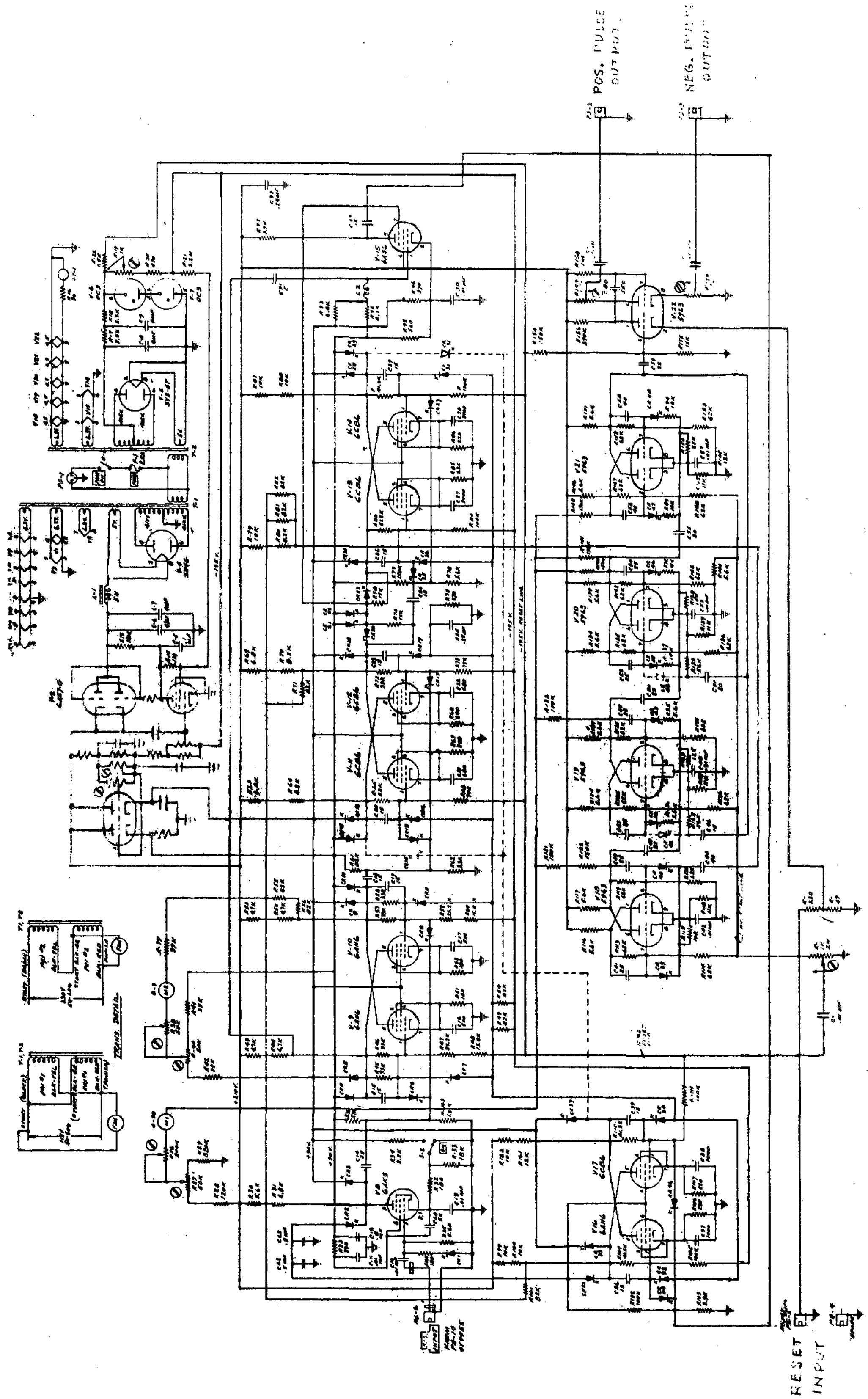

Fig. 7.

ZN-1213

DETAILED DESCRIPTION OF EACH UNIT

I Oscillator Selection Panel (Fig. 2)

The operation of this chassis is based upon the fact that a germanium diode will conduct a positive pulse in one direction only. To aid each diode, a slight reverse voltage (positive) is placed on each diode's cathode terminal. There are 32 input paths, PG1 through PG32, and only 23 output paths, PG41 through PG63. Some oscillators are used two or three times during each pulse of the Bevatron and the diodes separate these pulses and route them to the proper standard crystal oscillators. The outputs PG34, PG35, and PG36 are also furnished to the gate chassis to set one of three F-F's V7, V9, or V11 and to open the proper "slow gate" (V8, V10, or V12).

Each time this unit receives an input pulse on any input plug, PG1 through PG32, a pulse is supplied to the gate chassis through PG40. This output is called "mixed I pips" and is fed to V1(2D21) in the gate chassis.

II Gate Chassis (Fig. 3)

V1(2D21) is used to supply a reset pulse to V4 and V5, a preset pulse to the Bevatron HP520A, the crystal HP520A, and the readout chassis. V1 can be triggered manually with the push button on this chassis or by any or all of the "mixed I pips" from PG40 on the oscillator selection panel.

V6 is a cathode follower probe, so that wave forms can be monitored by a remote scope without loading down the monitored circuit. V7, V9, and V11 (F-F I, F-F II, and F-F III), in conjunction with V8, V10, and V12 (GI, GII, and GIII) are called the slow gates. Their function is to feed the proper pulse to the fast F-F. Gate I is opened when a pulse appears on PG1 through PG6 and PG31, PG32 (oscillator selection panel); GII (F-F II) is opened when a pulse appears on PG7 through PG13 (oscillator selection panel); G III (F-F III) is opened when a pulse appears on PG14 through PG30 (oscillator selection panel). V15 and V16a invert the positive pulses and supply them to F-F I, F-F II, and F-F III. Gate I may also be called the "128 gate". That is, for every 128 cycles of Bevatron rf applied to the Bevatron HP520A, a pulse is supplied the G I. V4 extends this count capacity to 256 and feeds a pulse to Gate II (256 Gate). V5, likewise, increases the count capacity to 512 and feeds a pulse to G III (512 Gate) every time 512 cycles are applied to the Bevatron HP520A. The outputs of gates I, II, and III are fed to V13 and then directly to V20 and V21, the fast F-F, which in turn open or close the fast gate. Since one and only one standard gated crystal oscillator is fed to the fast gate (V22, V23), this is the oscillator which is counted by the crystal HP520A and readout chassis when the fast gate is open. The proper slow gate (proper scaling factor 128, 256, or 512) and proper standard gated crystal oscillator are selected by a particular current pip, so that when the Bevatron frequency is equal to the calculated value (nominal value), the crystal HP520A and readout chassis always contain and indicate 991 or 992 counts. This basically is why there are three slow gates and 23 standard gated crystal oscillators. When the first trigger pulse (initiated by a particular current pip) is supplied to the fast F-F, the fast gate is open and counting starts in the crystal HP520A and readout chassis. After 128, 256, or 512 cycles of the Bevatron rf have been scaled in the Bevatron HP520A, V4 and (or) V5 stages, another trigger pulse is supplied to the fast F-F which resets it and closes the fast gate (stops counting in the crystal HP520A and readout). When the fast F-F is reset it supplies a reset pulse to the reset CF V17 and to all the standard gated oscillators as well as to all three slow gates F-F's. The system now displays the output count until another current pip is fed into the oscillator selection panel. The gate chassis also contains an "initial reset CF" to reset the fast F-F and gated crystal oscillators when the equipment is first turned on.

III Oscillator Chassis (Fig. 4)

This equipment includes three of these chassis, each with 8 gated standard crystal oscillators on them. Each oscillator has two tubes associated with it: a "set-reset" tube and a F-F which operates the 6AS6 gated crystal oscillator. Notice that the crystal is oscillating at all times and that the gating is accomplished by swinging the suppressor grid. The plates of all oscillators are connected to the wide-band CF (5687). Each chasiss has one tuned circuit in the plate circuit of all oscillators. This tuned circuit is resonant at the mean frequency of the eight oscillators on any particular chassis.

IV Crystal HP520A Scaler and DC Amplifier (Fig. 5)

This scaler has been modified, so that it now counts up to 128 instead of 100, by removal of the feedback diodes (it now is a "binary scaler"). It has been modified also so that instead of being reset to zero it is preset to 64. A count of 64 cycles is used as a time delay to allow the proper slow gate in the gate chassis to operate. This was done by reversing the reset lines to V20 and V21. The presetting is done when a trigger pulse from V1, in the gate chassis, is supplied. The dc amplifier is connected to V9, V11, V14, V18, V19, V20, and V21 and amplifies the small voltage swings produced by these scalers. V9, V11, and V14 have their cathode voltages amplified while V18, V19, V20, and V21 have their plate swings amplified. V9, V11, and V14 are fast circuits, so any leads connected to these plates or grids would slow them down. All these amplified voltages are then fed to the readout chassis for display.

V Readout Chassis (Fig. 6)

This chassis contains four scale-of-two F-F's, which follow the crystal HP520A and extend the count capacity to 2048. Each F-F has a relay tube and relay associated with it. Each relay has a neon bulb associated with it, so that counts corresponding to a single point can be read from the front panel.

The F-F's are V2, V4, V5, and V7, and the corresponding relay tubes are V3a, V3b, V6a and V6b.

Seven inputs connecting the dc amplifiers to this chassis are brought in through PG3 through PG9. Each has a relay tube and relay associated with it as well as a neon bulb.

The chassis also has provisions for disabling the preset pulse to the four F-F's and crystal HP520A so that a count average can be taken. Normally when more than one point is to be read the hold count—reset count switch should be in the "reset count" position. The F-F's are connected so that in conjunction with the crystal HP520A, the scalers are preset to 2016 instead of 2048 or 0. This is necessary so that nominal frequency is displayed in the middle of the screen instead of at the bottom. V1, a 12AX7, is used as a constant-current source for the string of precision resistors and to supply a dc voltage proportional to the number of counts in the scalers. The resistor string also contains a multipole double-throw switch. One position, "regular", allows the resistor string to produce a voltage change for all counts in the scalers 0 to 2047. The other position expands this range so that all counts from 0 to 960 are displayed on a common line (top line of the scope) while 1024 through 2047 are then displayed on the bottom line. In the "expand" position, then, the scope displays ± 3% of nominal frequency. To set up the scope, the "test-operate" switch is placed in the test position. A dc voltage corresponding to the maximum count is fed from PG13 (readout chassis) to a scope (on dc position); the maximum downward deflection is then obtained. If the dc signal is then removed from the scope the maximum upward deflection is obtained. Usually the vertical position control is used to set the upward deflection and the "vertical amplitude gain" is used to set the downward position. The scope is now calibrated for all current pips and all magnet voltages as well as "expand" and "regular" readout positions.

VI Bevatron HP520A (Fig. 7)

This unit has been modified to count to 128 instead of 100 by removal of the feedback diodes CR14, CR31, CR41, and CR44. The preset value has been obtained by reconnecting the reset line to the 5963 F-F V18 through V21. In addition, V22 has been modified to produce both positive and negative pulses when it is triggered by V21.

OPERATIONAL SEQUENCE

With reference to Fig. 1 (the functional diagram) a particular current is here followed through the whole circuit.

Take for example the current pip from Regulator 2s, which is applied to PG1 on the oscillator selection panel. This pip corresponds to approximately 357 kc. In the oscillator selection panel, the pulse is fed to PG34 (this sets slow F-F I and opens Slow Gate I on the gate chassis). The pulse is also fed to PG41, which is fed to Standard Oscillator Chassis #1, Oscillator #1 (2.8 Mc). This pulse sets the associated F-F and therefore opens the 6AS6 crystal gate and allows rf to flow to V24 (12BY7) and to V22, V23 in the gate chassis. The pulse that appears on PG1 of the oscillator selection panel is also supplied to V1 (2D21) on the gate chassis.

V1 on the gate chassis then supplies the following pulses:

(a) A preset pulse to the Bevatron HP520A to preset this scaler to 64 counts. Note that this scaler is operating at all times, and when this pulse is supplied the scaler is immediately preset to 64 counts.

(b) A reset pulse to V4 and V5 in the gate chassis.

(c) A preset pulse to the crystal HP520A and readout chassis. This pulse presets the eleven F-F's (7 in the crystal HP520A and 4 in the readout) to a count of 2016.

Because the Bevatron HP520A scaler was preset to 64 counts, it starts scaling towards 128 from there, i.e., 64 counts remain to be scaled. One count is added for every positive going cycle of Bevatron rf. When the scaler contains 128 counts it produces two pulses at its output, one positive and one negative. The negative pulse is not used in conjunction with this particular current mark but it does trigger V4 in the gate chassis.

The positive pulse is fed to Gate I, and since this gate has previously been opened the pulse is fed from it to V13, a phase inverter, and then to V20 and V21, the fast F-F. Since the fast F-F was in the reset position from the previous current mark, it is now set, and therefore opens the fast gate. As rf has previously been supplied to this gate from Standard Gated Crystal Oscillator # 1 (2.8 Mc), this rf then is applied to the crystal HP520A and read-out F-F's, where it is scaled.

The Bevatron HP520A, immediately after reaching 128 counts and putting out a positive and a negative pulse, starts counting again from one towards 128. When it reaches 128 the second time, the HP 520A scaler produces a positive and a negative pulse as before; and since Gate I is still open, this positive pulse is now inverted by V13 and applied to the Fast F-F, resetting it. When the Fast F-F is reset it closes the fast gate and stops the counting. The number of counts contained in the crystal HP250A and readout chassis are then displayed on the scope as a horizontal bar until another current mark is supplied to the oscillator selection panel. When the Fast F-F is reset by the pulse from V13, it also supplied a reset pulse to the slow F-F I(also F-F II and F-F III, which are already reset) and to all 23 standard crystal oscillators. Since only one of them is set, it is immediately reset, and the other 22 oscillators, which are already reset, are not altered. This completes the sequence which occurs for every current mark, i.e., 32 times each time the Bevatron magnet is pulsed.

ACKNOWLEDGMENT

Mr. Dick A. Mack is in charge of the Bevatron Electronic Group, which is responsible for the design and development of all monitoring and control equipment.

All Bevatron work was done under the auspices of the U. S. Atomic Energy Commission.