

BEAM CURRENT INTEGRATOR LIST OF ILLUSTRATIONS (*SUBSYSTEM)

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The Beam Current Integrator (BCI) designed and built for the Accelerator Laboratory at Ohio University was intended to be part of a total experiment control system. Digital readout, preset capability, automatic monitoring of beam amplitude, beam fluctuation, remote control of most functions, and many other unique features make the BCI the likely center of control for many experiments.

The primary purpose of the BCI is to integrate the proton beam of the 11 Mv tandem accelerator. The amount of charge collected on the target provides an accurate method of normalizing data taken during an accelerator run.

The beam has three modes of operation, any one of which works equally well with the BCI. The beam may be a direct current anywhere in the range from 10^{-10} to 10^{-3} amperes, it may be a chopped beam varying in pulse width to several hundred nanoseconds and in repetition rate from 5 Mhz down to .078 Mhz, or the beam may be chopped and then bunched by a Klystron type bunching system. For the chopped and bunched beam a passive low pass filter smooths the beam for easier handling by the sensitive front end of the BCI. In the chopped and bunched mode the pulse of current is approximately one nanosecond wide and up to 2.5 ma peak current.

The BCI receives this beam of protons and integrates it for either a preset time or for a preset amount of charge. The BCI output is read directly in coulombs (Q), During a typical accelerator run the BCI may be preset to accumulate 100 nanocoulombs of charge and then provide a turnoff signal to several other pieces of equipment such as counters, analyzers, linear gates, etc.

The BCI provides readout via 24 lines consisting of six binary coded decimal numbers. Positive true logic is used and is constantly available for use in experiment control. All inputs and outputs are from the rear of the panel as well as all controls for remote operation. The BCI is meant for continuous operation for best results. Several internal circuits require several hours for stabilization. Due to the accuracy of 0.01% of full scale for integration, continuous operation is a logical choice.

The Beam Current Integrator can be broken down into twenty-three separate sub-systems for a better understanding of the total system. A brief paragraph outlining each will prepare the reader for more detailed systems and sub-system descriptions.

1. BCI PREAMPLIFIER (Fig. 3a)

This subsystem in conjunction with the input current ranging switch functions as a current to voltage converter. The input current times the feedback resistor gives a negative output voltage corresponding to the input current. The K302 amplifier provides the special parameters to do this conversion with extreme accuracy and stability.

The μ A725 is an inverting gain of ten amplifier used to give a full positive ten volt output signal for full input current to the K302. Zero trimming is used to null the output of each amplifier section.

2. MULTIPLIER AMPLIFIERS (FIG. 3b)

The top μ A725 is connected as a non-inverting gain of three amplifier. Offset adjustment allows the amplifier to be nulled to zero output for zero input.

The lower μ A725 is connected as a non-inverting gain of one hundred amplifier. This amplifier also has zero adjustments.

The X3 amplifier serves to allow expansion of the front panel meter to a position nearer the meter center position.

The X100 amplifier allows currents as low as 10^{-11} to be measured, it also functions to lower the preamp input impedance by a factor of one hundred, and can be used as a X100 low pass filter for beams that vary rapidly.

3. POLARITY REVERSAL AMPLIFIER (Fig. 3c)

In the event that negative current from the low energy end of the accelerator should need to be integrated, a flip of the switch inserts this gain of one inverting amplifier (μ A741) into the signal path and negative current can be integrated.

4. VOLTAGE TO FREQUENCY CONVERTER (VFC) (Fig. 4)

This circuit along with the preamp form the critical subsystems. After current is converted to a voltage the VFC performs an ultrastable voltage to frequency conversion over the 0 to +12 volt range. The conversion factor is one hertz per second per input millivolt.

It is composed of a voltage controlled oscillator in the forward direction with a frequency to voltage converter in the feedback loop. The feedback loop is contained in a 65⁰ C oven for extreme temperature stability. Extensive development work on this subsystem has assured excellent performance in accuracy and long term (>6 months) 0.01% stability.

5. MULTIPLIER AMPLIFIER FREQUENCY DIVISION CIRCUIT (Fig. 5a)

This circuitry contained in the upper portion of the schematic automatically divides the frequency out of the VFC by the same amount that the multiplier amplifiers amplified the input voltage to the VFC. This keeps the units correct for charge measurement. The different frequency divisions are gated by the use of open collector TTL.

6. DIGITAL READOUT GATE (Fig. 5b)

Since the VFC is running at a frequency exactly related to the amplitude of the input current it is possible to gate the input to the digital display subsystem for one second and obtain a digital display presentation of the input current. This mode of operation uses a μ L9601 monostable to produce a pulse exactly one second wide. The accuracy is somewhat better than 0.2% for a 30 day test period. Short term stability is 0.01% for comparison purposes.

7. $\div 1$, $\div 10$, $\div 100$, $\div 1000$ PRESCALERS (Fig. 6a)

These three divide by ten integrated circuits provide selectable prescaling of the digital display to allow accumulation of large amounts of charge over long periods of time without resetting and starting the integration over. The decimal point in the digital display is moved with prescaler selection to keep units of charge correct. The digital control gate is also on this section and is used to start and stop the digital integration process.

8. POSITIVE FIVE VOLT LOGIC SUPPLIES (Fig. 6b)

These two 5 volt supplies utilize an integrated voltage regulator, the μ A723. The supply on the left has a large power transistor as a pass stage and powers all of the logic circuits, but one. Current limiting is used to protect against shorts.

The 5 volt supply on the right powers only the μ L9601 monostable in the VFC. The raw supply for this regulator is a regulated positive 15 volt supply. In the development of the VFC it was learned that extremely fine adjustment could be made by varying the 5 volt supply to the monostable. This allows fine trim without removing the VFC from the oven.

9. BEAM FLUCTUATION CIRCUIT (FIG. 7a)

The proton beam is not pure direct current and the amount of ripple and fluctuation are important. This circuit is a near perfect full wave rectifier or absolute value circuit. The perturbations on the beam are coupled through the 1.5 μ f capacitor rectified and filtered, then fed to the beam fluctuation meter to give a reading related to ripple.

10. BEAM LIMIT CIRCUIT (Fig. 7b)

During an experimental run it is often desired to accumulate data only if the amplitude of the beam is within certain limits. This circuit has a lower and an upper limit comparator set by two ten turn potentiometers directly related to the front panel meter 0 - 1 full scale. When this circuit is selected it will stop digital integration if the beam varies outside the upper and lower limit settings.

11. POSITIVE 24 VOLT PRECISION SUPPLY (Fig. 7c)

The current source in the frequency to voltage convertor in the feedlock loop of the VFC requires a highly stable 24 volt supply to assure constant current output. This supply uses a reference amplifier integrated on a single silicon chip to provide a temperature coefficient of .005% per degree centigrade. This supply has 8 hour stability of $\pm 25 \mu$ v.

12. INPUT BEAM CURRENT GATE (Fig. 8)

To actually gate at high speeds a current as small as one nanoampere requires a field-effect transistor and the associated bias driver circuits. The CAG30 is a hybrid circuit containing one gate and driver with TTL interfacing. A series-shunt arrangement is used for accurate results and to give the beam a return path when the series element is open. "Off" resistance is greater than $10^9 \Omega$ and "On" resistance less in all instances than 60Ω . A ratio of nearly 2×10^7 .

13. DIGITAL READOUT PRESET LOGIC CIRCUIT (Fig. 9)

To allow a predetermined amount of charge to be collected and then automatically stop the data taking requires a digital preset circuit. This circuit has six 10 position digital switches to select the proper output of the SN7442 BDC to ten line decoders. When all six selected lines are true, an output appears and the integrator control is connected to ground stopping the integration process.

14. MULTIPLIER GAIN SWITCHING CIRCUITS (Figure 10)

Through this switching arrangement the various gains of one, three, one hundred, and three hundred are selected. This schematic also shows the generation of the +10.000 volt "test" signal; illustrated also is the meter response selection switching circuits.

15. 10.000 Volt Test Generator (Figure 11)

The +10.000 volt test signal is derived from the negative 15 volt supply by an inverting amplifier having a gain of negative $2/3$. By adjusting the amplifier offset voltage the output voltage may be set to three place accuracy using a differential voltmeter.

Since the Voltage To Frequency Converter converts this signal into a precise 10Khz signal a time standard of 0.015% accuracy may be derived. This enables the BCI to control an experiment for a preset time as well as for a preset amount of charge. By using the prescaler; times as long as 27 hours may be preset to control an experimental run.

16. Spare Amplifier (Figure 11)

The spare amplifier was included for a possible later addition to the design of the integrator. Because of the general purpose layout almost any gain configuration can be quickly setup.

17. Nixie Display Circuits (Figure 13)

To display the output of the BCI a six digit Nixie readout was purchased for 180.00. These devices are sold as single decades. Each decade consists of a decade counter (SN7490), a binary to decimal decoder and driver, and a Nixie gas discharge display tube.

Each stage couples into the next giving a total count of 999999. Each display digit has outputs representing each digit in 1248BCD. This output provides for digital readout for remote data logging.

18. Main Power Supply (Figure 14)

The power requirements were for +180, ±36, ±24, ±15, +12, and +5. All were direct current and required regulation ranging from ±3% to 0.01%. Integrated, hybrid, and discrete preregulators and regulators were used to achieve these specifications. A special design line isolation transformer was used to keep AC leakage to a minimum.

19. Preamplifier Input Current Range Switching (Figure 15)

The design of the preamplifier (current to voltage converter) allows the conversion rate to be switched one decade at a time by changing one resistor only. By using a shielded switch of special design purchased from Keithley Instruments, Inc. this switching was done in a make before break (MBB) mode to prevent transients during the switching.

The single feedback capacitor is a very low leakage type glass capacitor made by Corning Components. The insulation resistance is greater than 3×10^{14} and soakage current could not be measured by available means. This capacitor allows the amplifier K302 to integrate noise pulses and the faster beam fluctuations so that they can be more easily amplified by the second stage of the preamplifier.

DETAILED DESCRIPTION OF BCI PREAMPLIFIER AND MULTIPLIER AMPLIFIERS

The output current from the accelerator comes from a source impedance of nearly 10^{16} ohms and can be treated as a true current source. In design, work dealing with very low currents and very high impedances should be kept to a minimum to avoid considerable mechanical and electronic design time. For this reason it was decided to convert the accelerator output current to a voltage at low impedance at the input of the BCI.

The very low input current dictated an amplifier with very low bias current and very high input resistance to prevent errors in the current to voltage conversion. The Keithley model K302 Mosfet input operational amplifier was chosen over both varactor and chopper stabilized amplifiers because of its combination of very low input current (less than 10^{-14} amperes), offset current stability (less than 10^{-15} amperes in 24 hours), input resistance (10^{12} ohms), and overload protection (± 400 volts continuous). No other available amplifier offered the parameters.

Since the source impedance is so high input voltage offset and drift are of little concern; as is voltage noise. Current noise of less than 5×10^{-15} amperes peak to peak represents less than 5 microvolts at the amplifier output.

In the normal current to voltage converter the amplifier output equals the input current times the feedback resistor. For example an input current of one microampere and a feedback resistor of 10^6 ohms would give an output voltage of one volt. The converter is inverting by nature of the design since the noninverting terminal of the K302 is always grounded. A feedback capacitor of 2400 picofarad is used to limit the output slew rate of the amplifier to match that of the following amplifier to prevent summing junction saturation.

The model K302 amplifier was tested for two months for DC drift at a feedback resistance of 10^{11} ohms and was found in no case to exceed ± 3 millivolts at the output. This performance enabled the removal of a troublesome front panel zero control found on many integrators. In use testing for a period of 90 days verifies this stability. Since drift improves a great deal with a reduction in the value of the feedback resistor; operation with a feedback resistor of 10^6 ohms gives excellent results (less than 200uv over thirty days).

In an attempt to avoid precision (0.1%) resistors in the 100, and 1000 megohm range a fraction feedback method was tested in which the feedback resistor is connected by a voltage divider to see only a fraction of the output voltage. This method gave drift nearly 20 times that of the conventional method and was discarded. The largest precision resistor used was 25 megohms (4 each to make 100 megohms) and the 10^9 ohm resistor was a 1% unit selected to be within 0.3%. The cost of a single 1000 megohm resistor at 0.1% was \$310 with no guarantee because of the extremely fine wire used.

The amplifier was connected to convert each full scale input current to -1 volt and then amplify it by -10 to achieve a 0 to +10 output voltage range. The amplifier chosen for gain of ten stage was an integrated circuit made by Fairchild; the μ A725. This amplifier was designed for very low voltage drift over long periods of time and with a 120 db voltage gain for high precision amplifier circuits.

The gain of ten stage is a complement to the input stage since now voltage offset and drift are of prime importance due to the low source impedance of 10 K Ω . Current offset and drift are now of little importance since 10 picoampere into 10K Ω is 10^{-7} volts. Since the input voltage drift is nearly one μ volt per degree centigrade the current errors are swamped out.

The μ A725 amplifier when used in a gain of ten has more than a factor of 100,000 feedback to give excellent gain accuracy. If the gain determining resistors are accurate and stable, and the power supplies are stable and tracking, an amplifier of 0.01% accuracy can be achieved. The resistors have a temperature coefficient, but if they are the same type they will track together and their ratios will remain constant. The source resistance seen by each amplifier input node must be equal so that input bias current drift, while in the same direction, will produce equal and nulling voltages at the amplifier inputs. The voltage offset can be set to zero to correct the amplifier output to zero for a zero input.

The feedback network of the μ A725 was selected to provide minimal loading on the 302 while keeping the source impedance low to avoid current

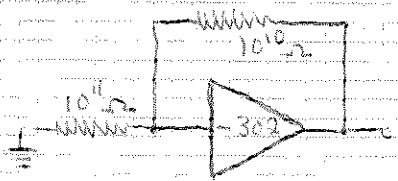
drift errors. The feedback capacitor was selected to match the 10 millisecond response time of the voltage to frequency converter.

The combination of the 302 and the μ A725 give stability of ± 3 MV at the output of the μ A725 for a 60 day period at least. This stability allows operation without everyday adjustment, and maintains accuracy over long experimental runs.

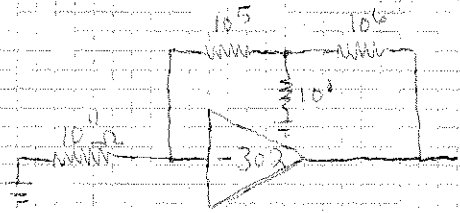
Both the X3 and X100 amplifiers use the μ A725 amplifier connected as noninverting stages. The use of 0.1% resistors and source resistance matching give these amplifiers unusual stability and accuracy for non chopper stabilized amplifiers. Zero trimming sets the amplifiers to null and feedback capacitors limit the bandwidth for the VFC. The bandwidth of the X100 amplifier is more limited in frequency response since smaller currents from the accelerator fluctuate much more.

In the event that negative current from the low energy end of the accelerator needed to be integrated a single stage gain of -1 amplifier is available to invert the signal to give a positive voltage to the VFC. This integrated circuit, the Fairchild μ A741 is a general purpose amplifier with voltage and current drift near 0.003% of full scale signal per degree centigrade. This stability is sufficient for integration of the low energy electron beam for test purposes.

This amplifier section gives long term low drift performance, but to use the X300 section the X100 amplifier must be set to zero since a ± 1 mv error out of the gain of 10 μ A725 would give an error output of ± 300 mv; an error of $\pm 3\%$ of full scale. In the normal mode the maximum error would be ± 2 mv ($\pm 0.02\%$). With the X3 amplifier an error of $\pm 0.06\%$ of full scale could be realized, but most likely would be near 0.02% F.S. due to normal preamp error less than ± 1 mv.



Normal Feedback



Fractional Feedback

1 inch per min 1 volt Full Scale

1 inch per Micro 1 volt Full Scale

Chart Recordings of Drift of Current to Voltage Converters (Normal vs Fractional)
Beam Current Integrator Test Results

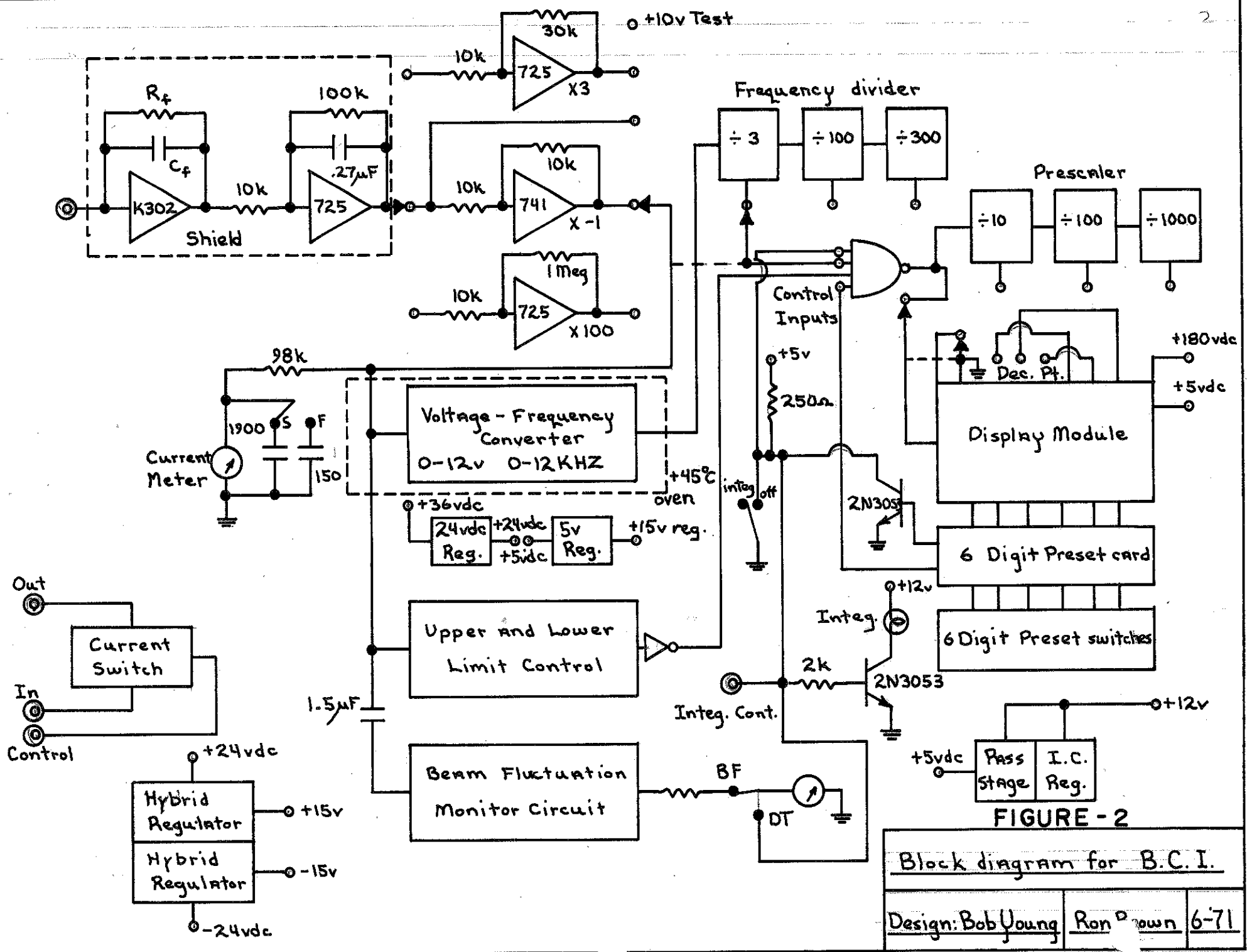


FIGURE - 2

Block diagram for B.C.I.

Design: Bob Young Ron Brown 6-71

Figure 3

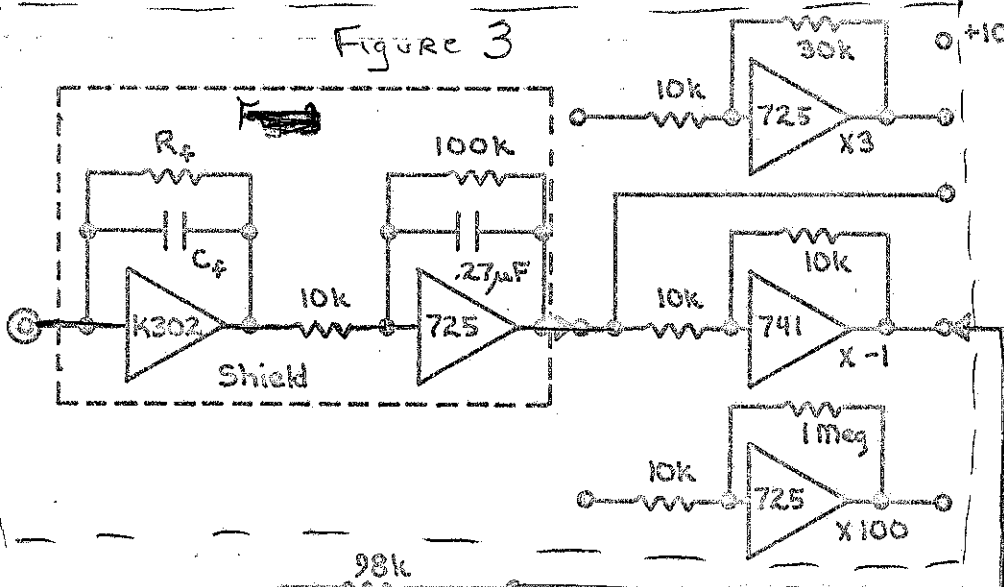


Figure 5

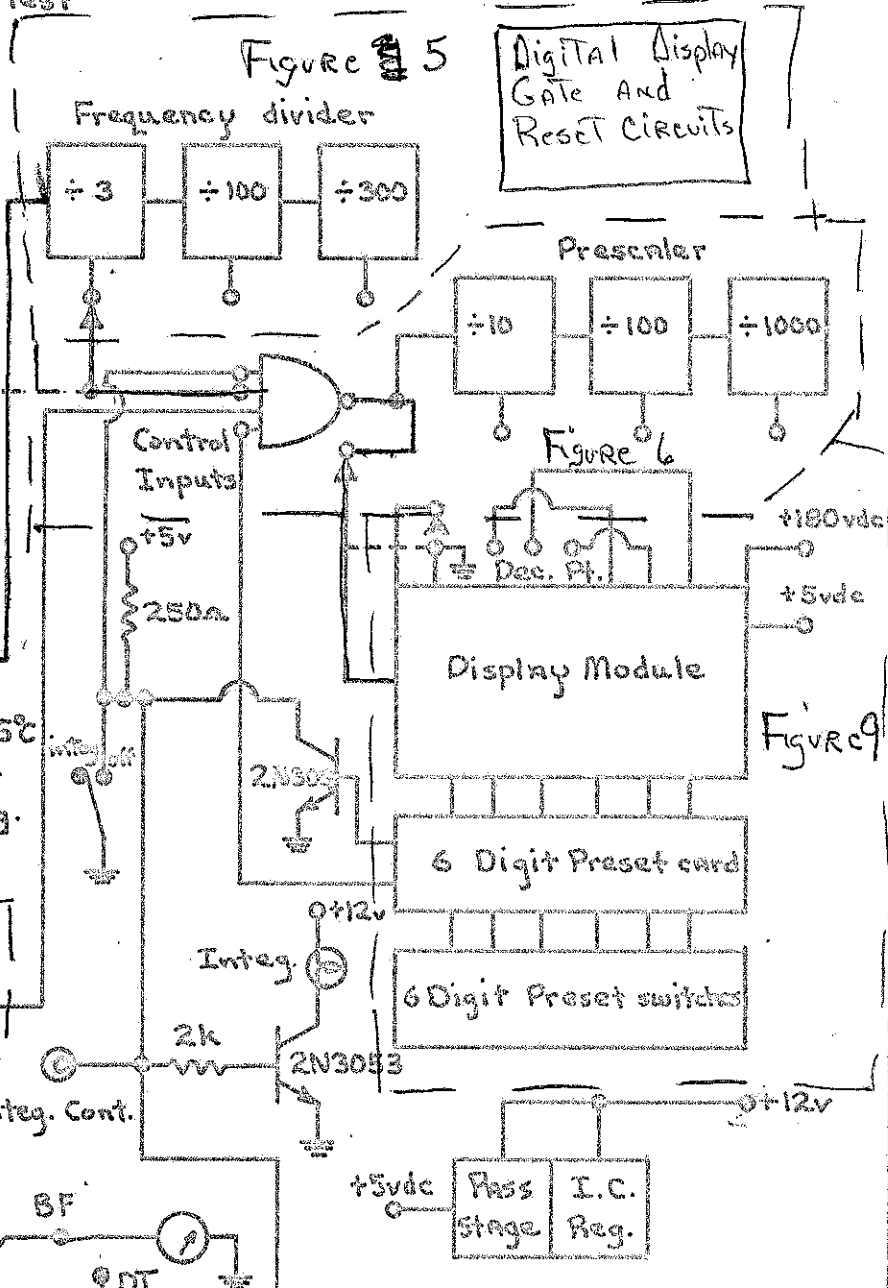


Figure 4
Voltage-Frequency Converter
0-12v 0-12 KHZ

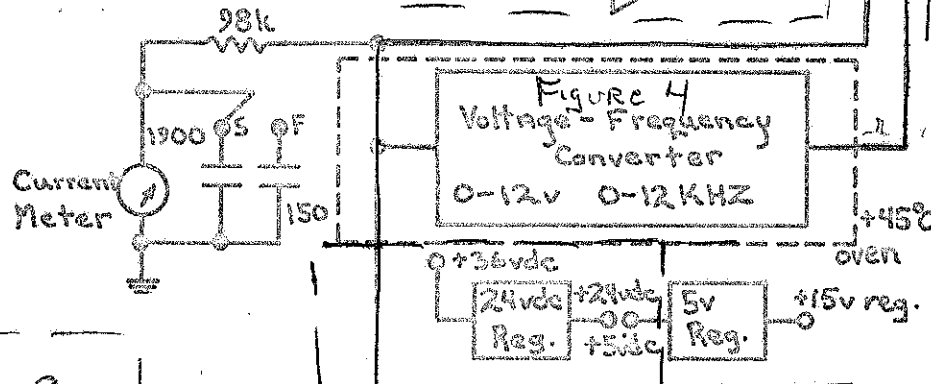


Figure 8

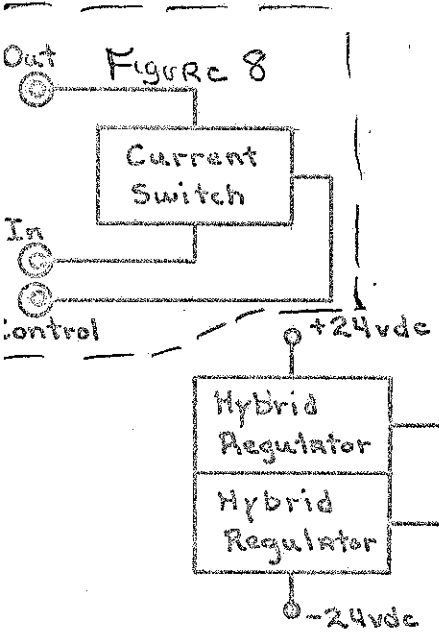


Figure 7

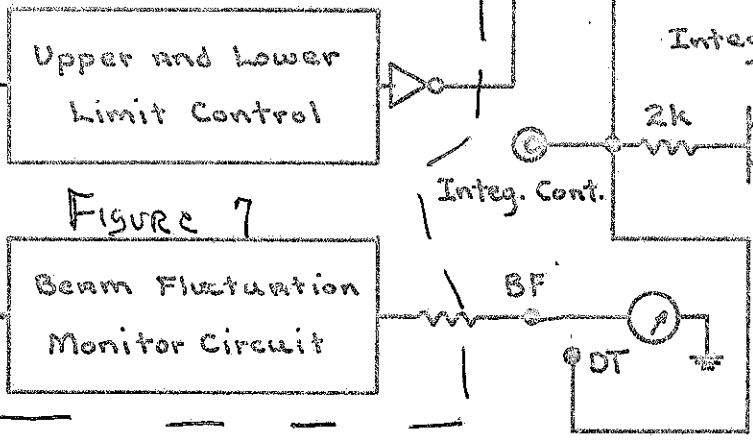


Figure 2
Block diagram for B.C.I.

Design: Bob Young, Ron Brown 6-71

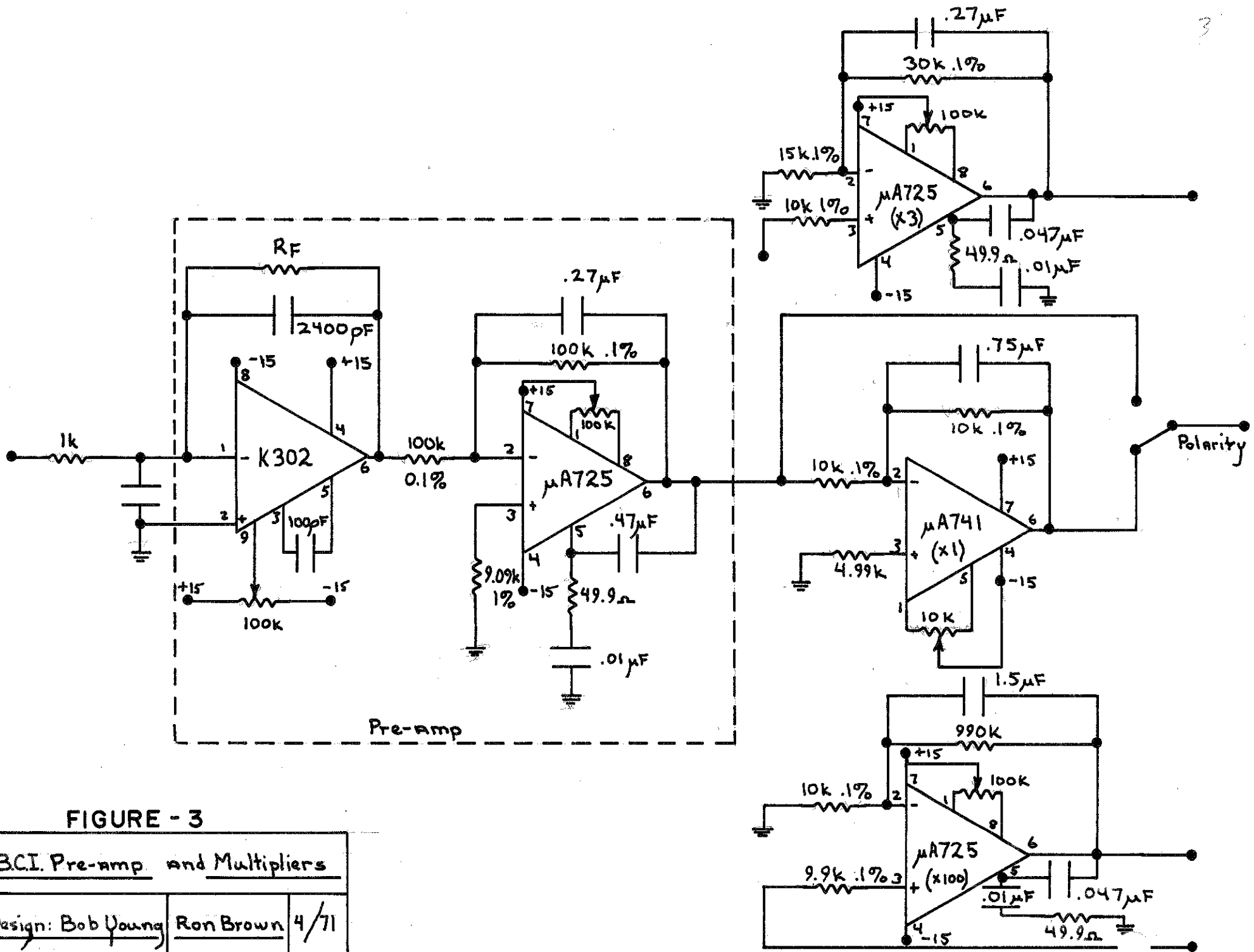


FIGURE - 3

BCI Pre-amp and Multipliers

Design: Bob Young Ron Brown 4/71

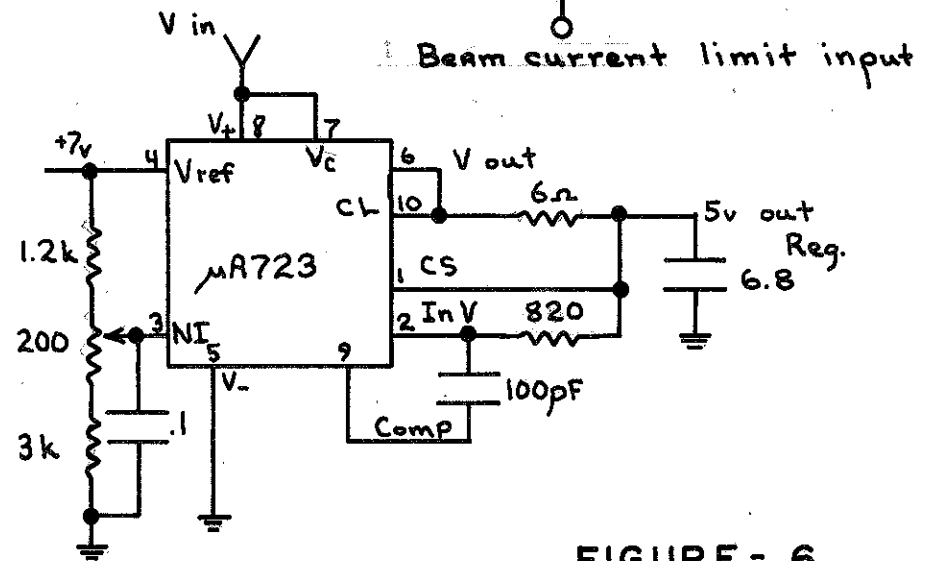
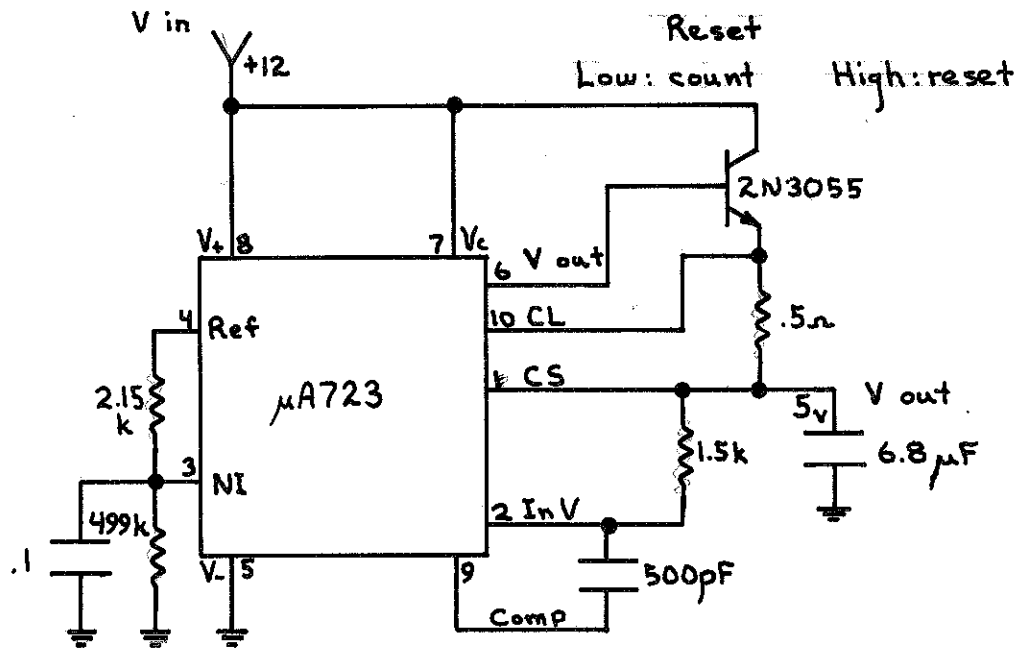
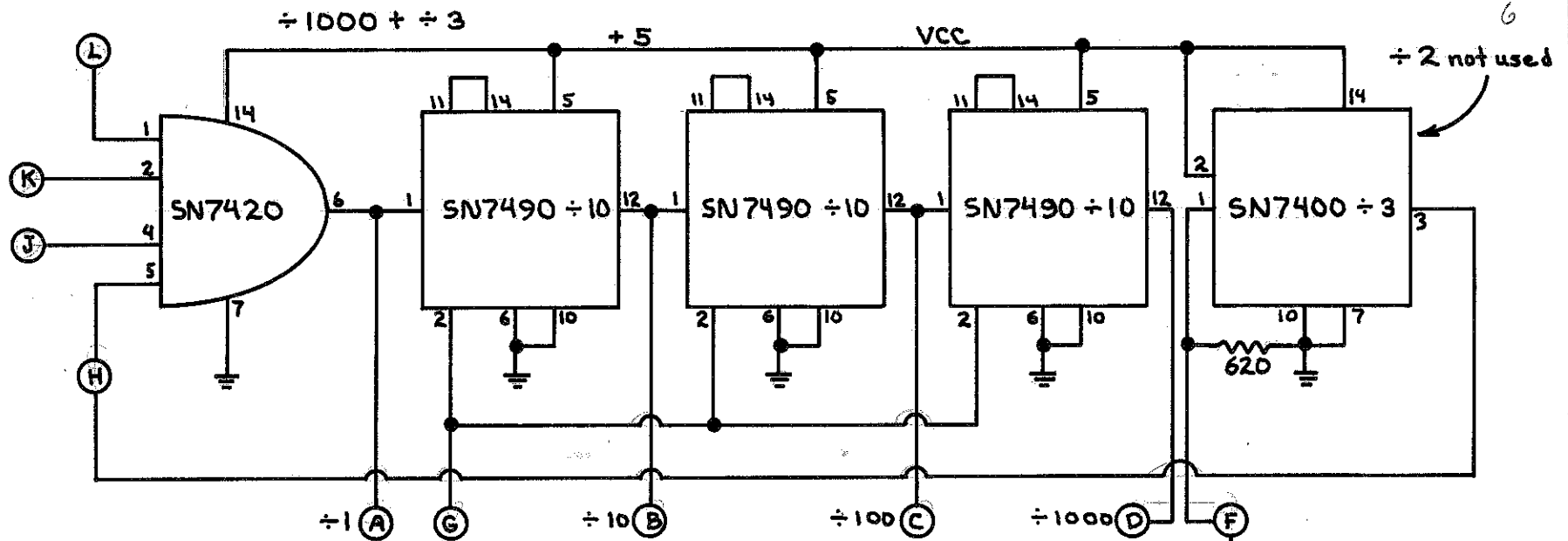


FIGURE - 6

Schematics

Design: Bob Young Ron Brown 5-71

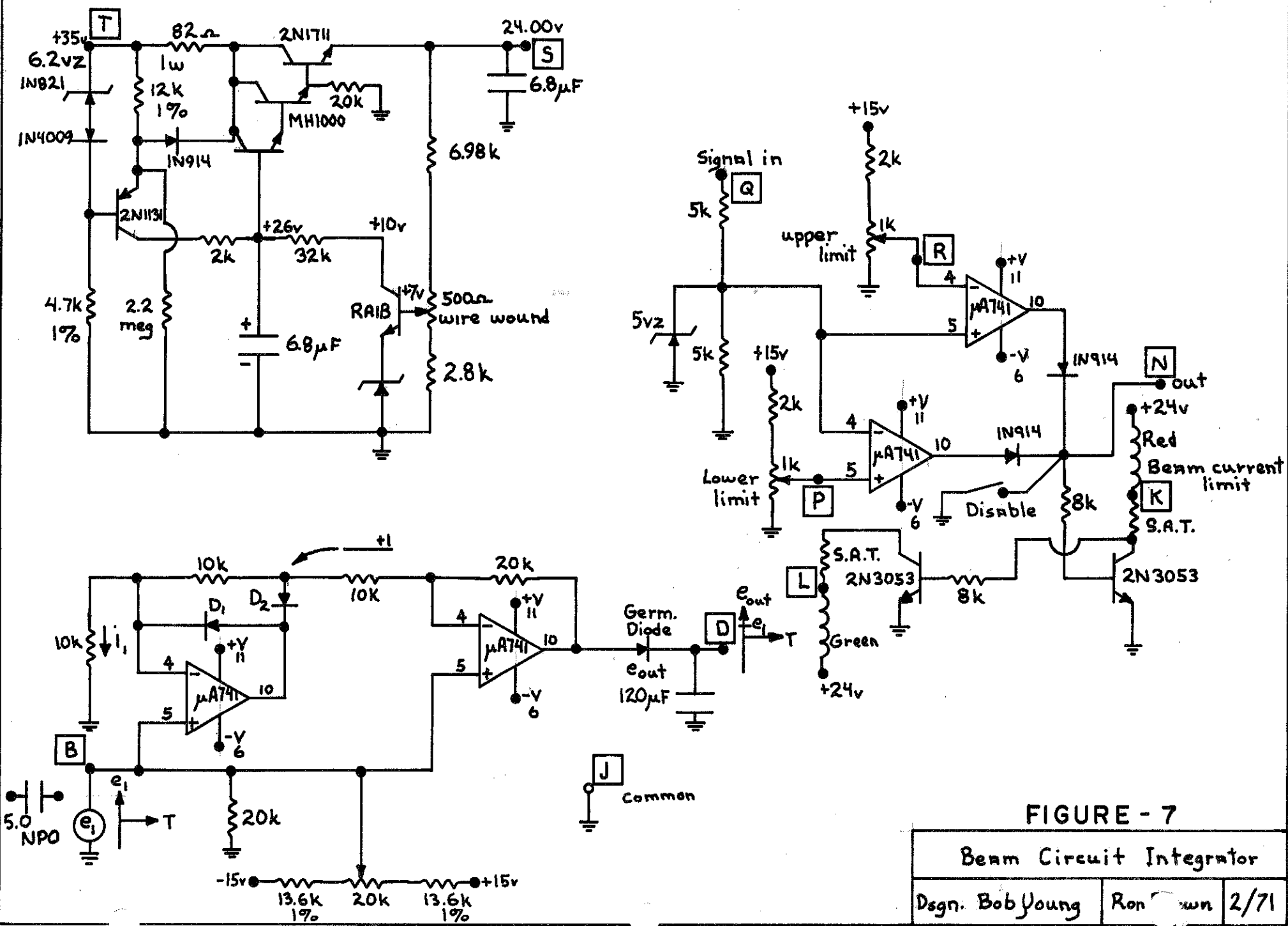
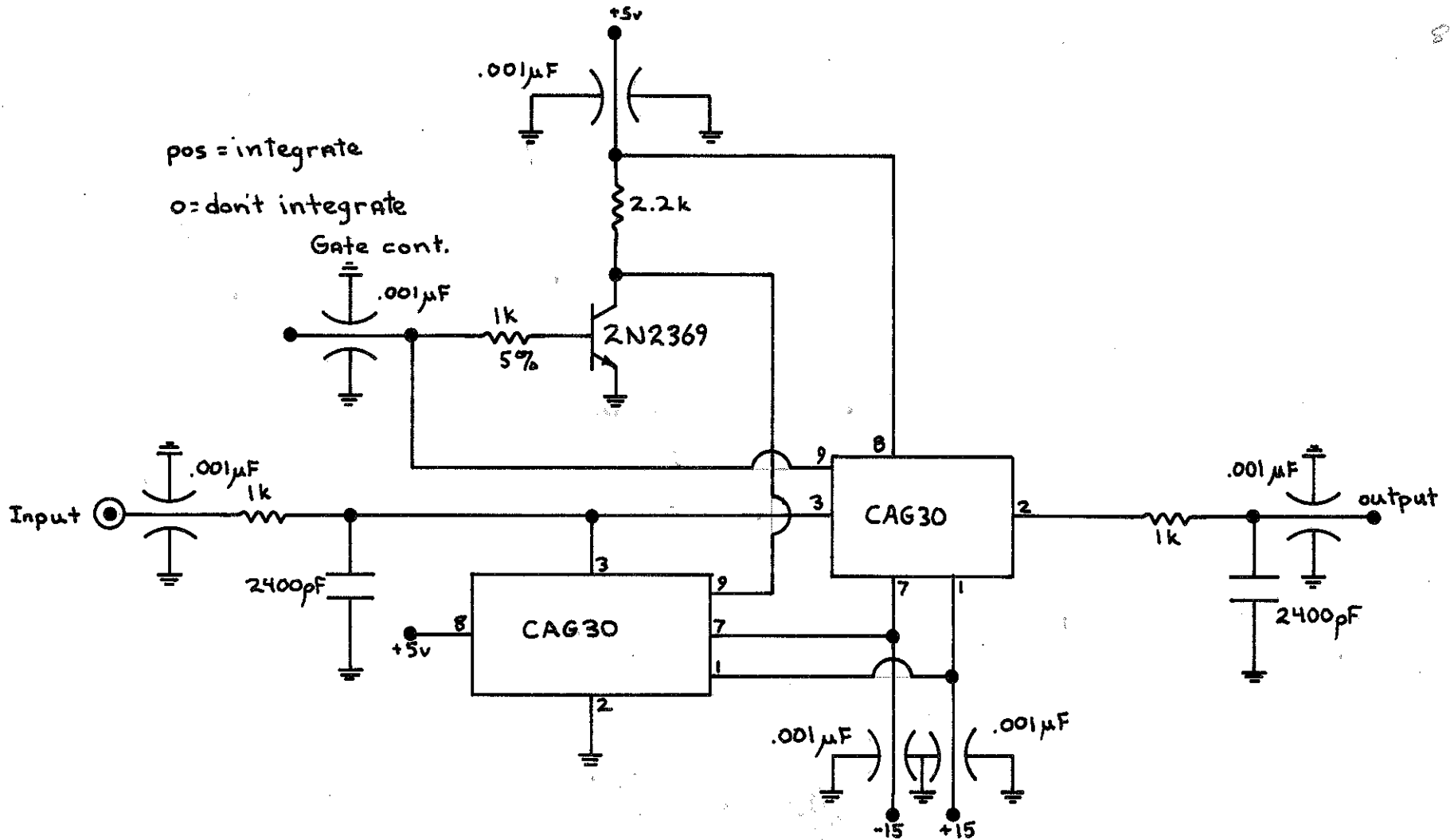


FIGURE - 7

Beam Circuit Integrator

Dsgn. Bob Young	Ron [unclear]	2/71
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$$(\times 10^3) (2.4 \times 10^{-9}) (2.4 \times 10^{-6})$$

FIGURE - 8

Benm Gate

Design: Bob Young Ron Brown 3-2671

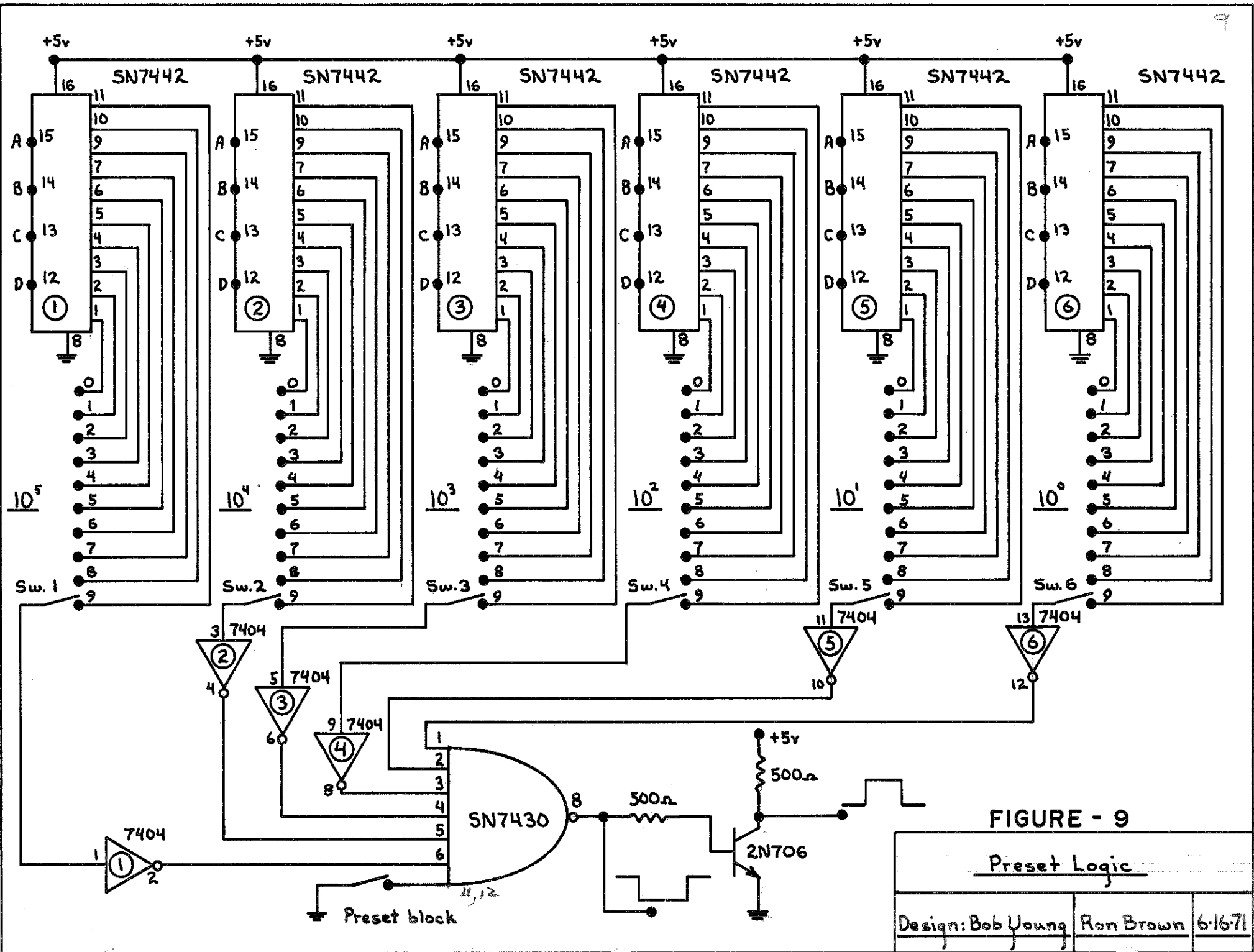


FIGURE - 9

Preset Logic

Design: Bob Young	Ron Brown	6/16/71
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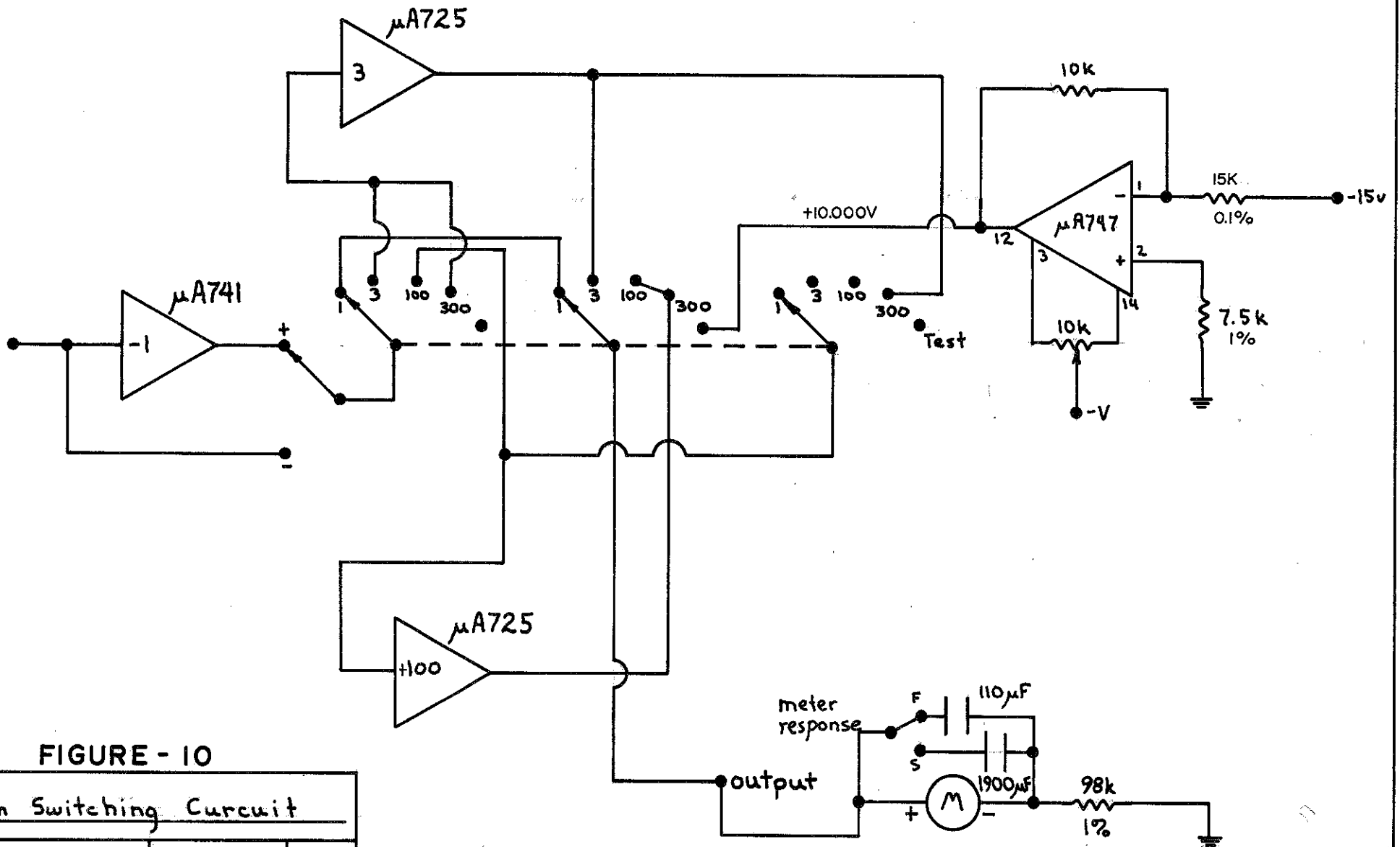


FIGURE - 10

Gain Switching Circuit

Design: Bob Young	Ron Brown	4/71
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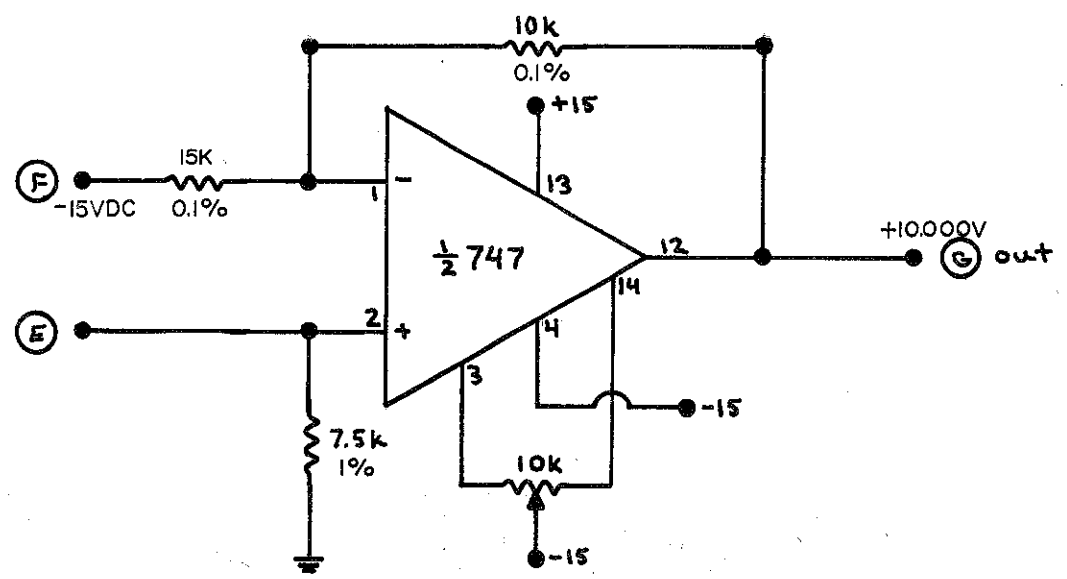
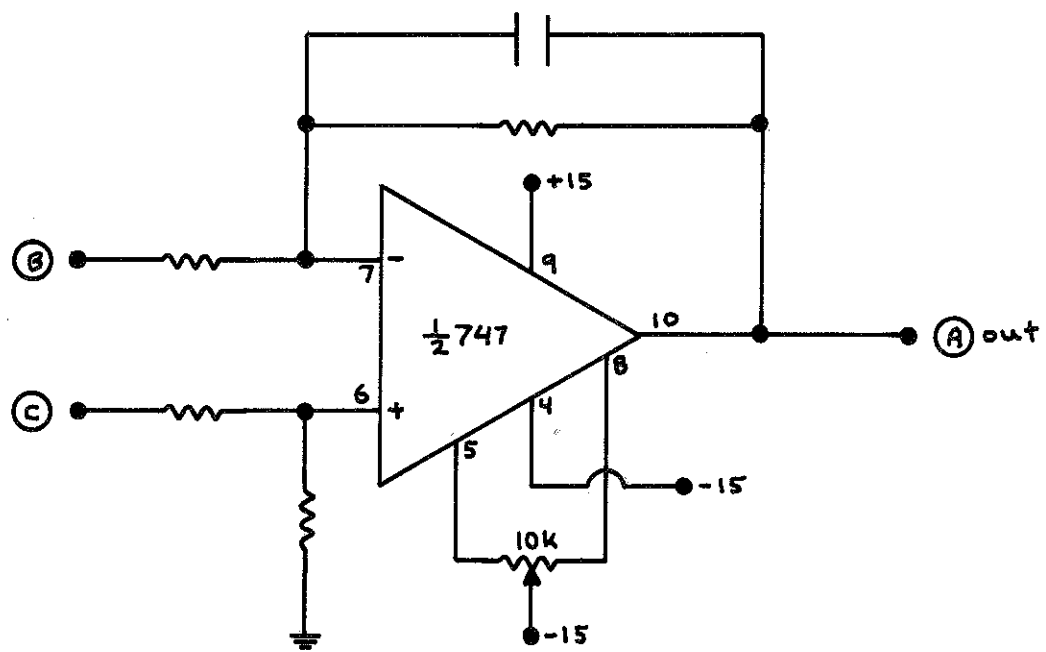


FIGURE - II

Beam Current Integrator

Design: Boh Young	Ron Brown	3-23-71
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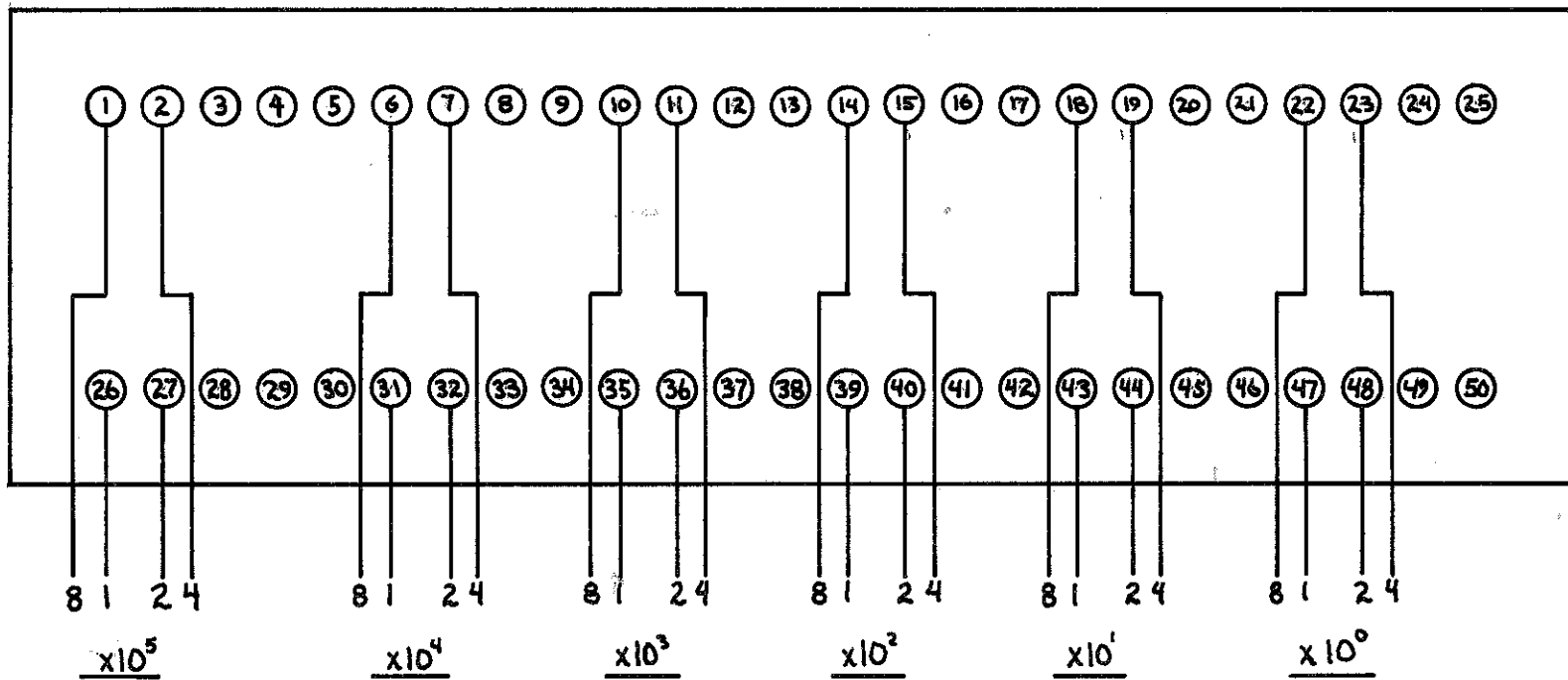
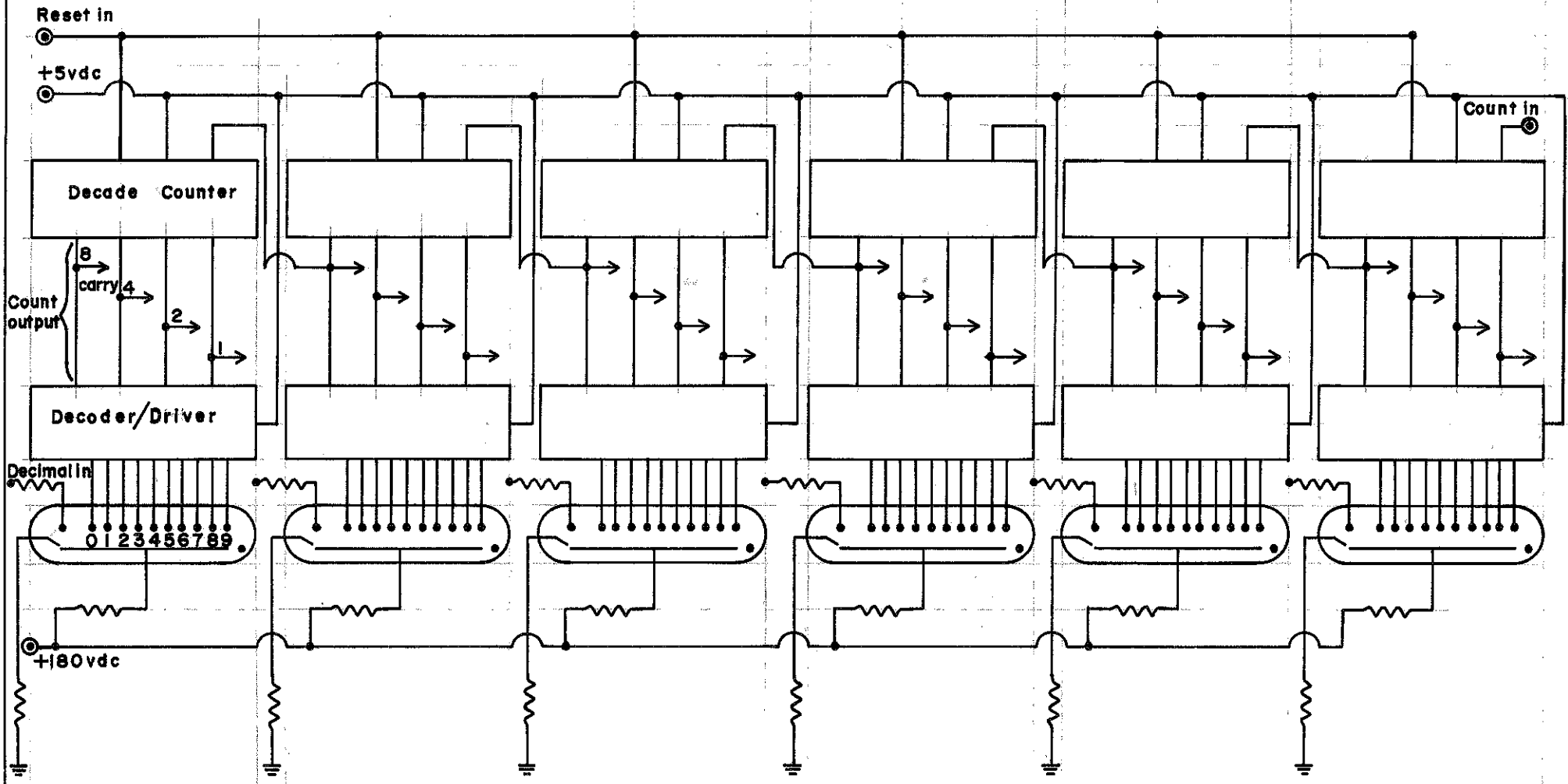


FIGURE - 12

<u>BCD Plug to Scaler</u>		
<u>Design: D. Carter</u>	<u>Ron Brown</u>	<u>6-71</u>



(Each counter DM519)

FIGURE - 13

Scaler Counter Display		
Design: Bob Young	Ron Brown	7-15-71

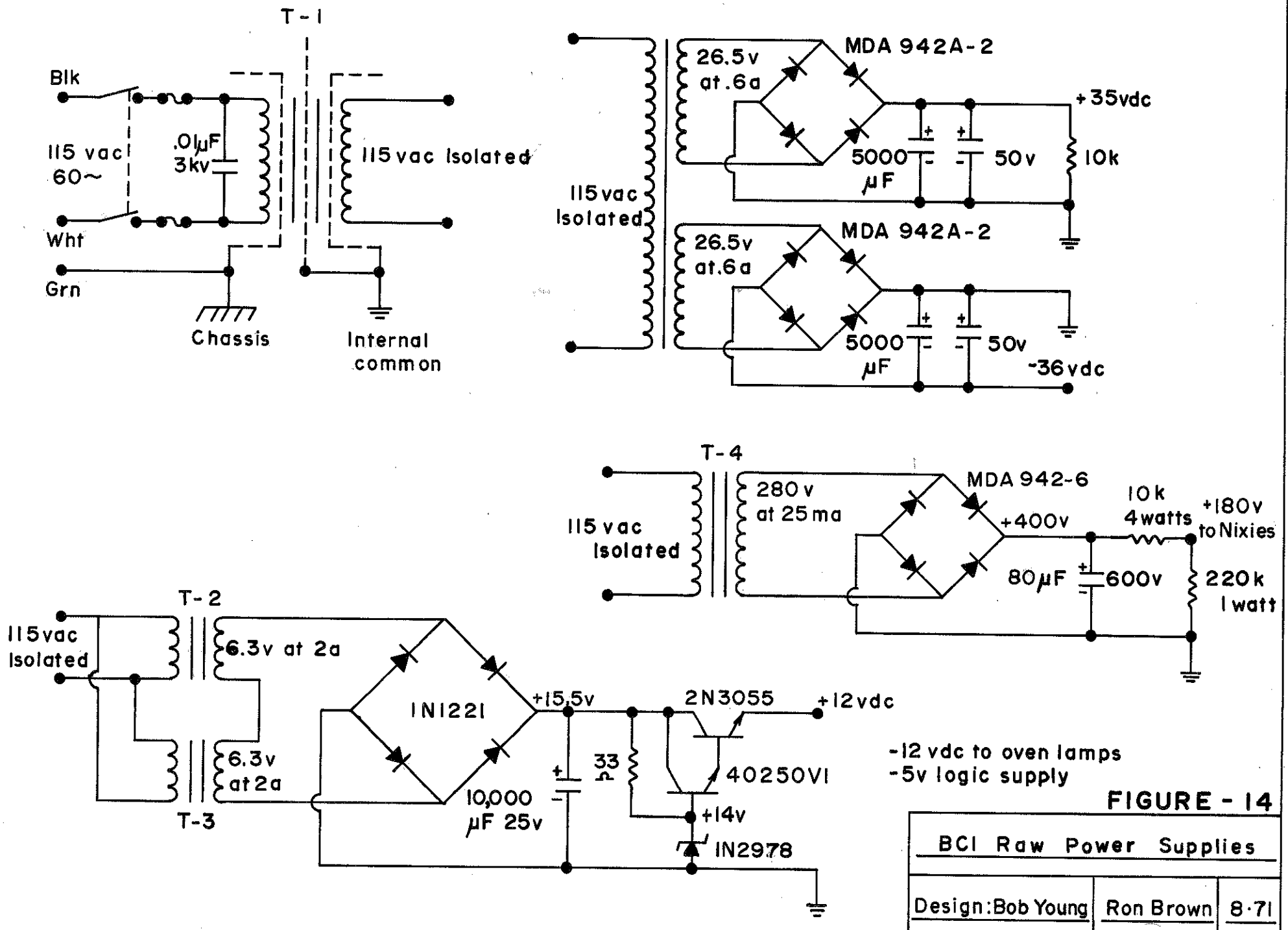


FIGURE - 14

BCI Raw Power Supplies		
Design: Bob Young	Ron Brown	8-71

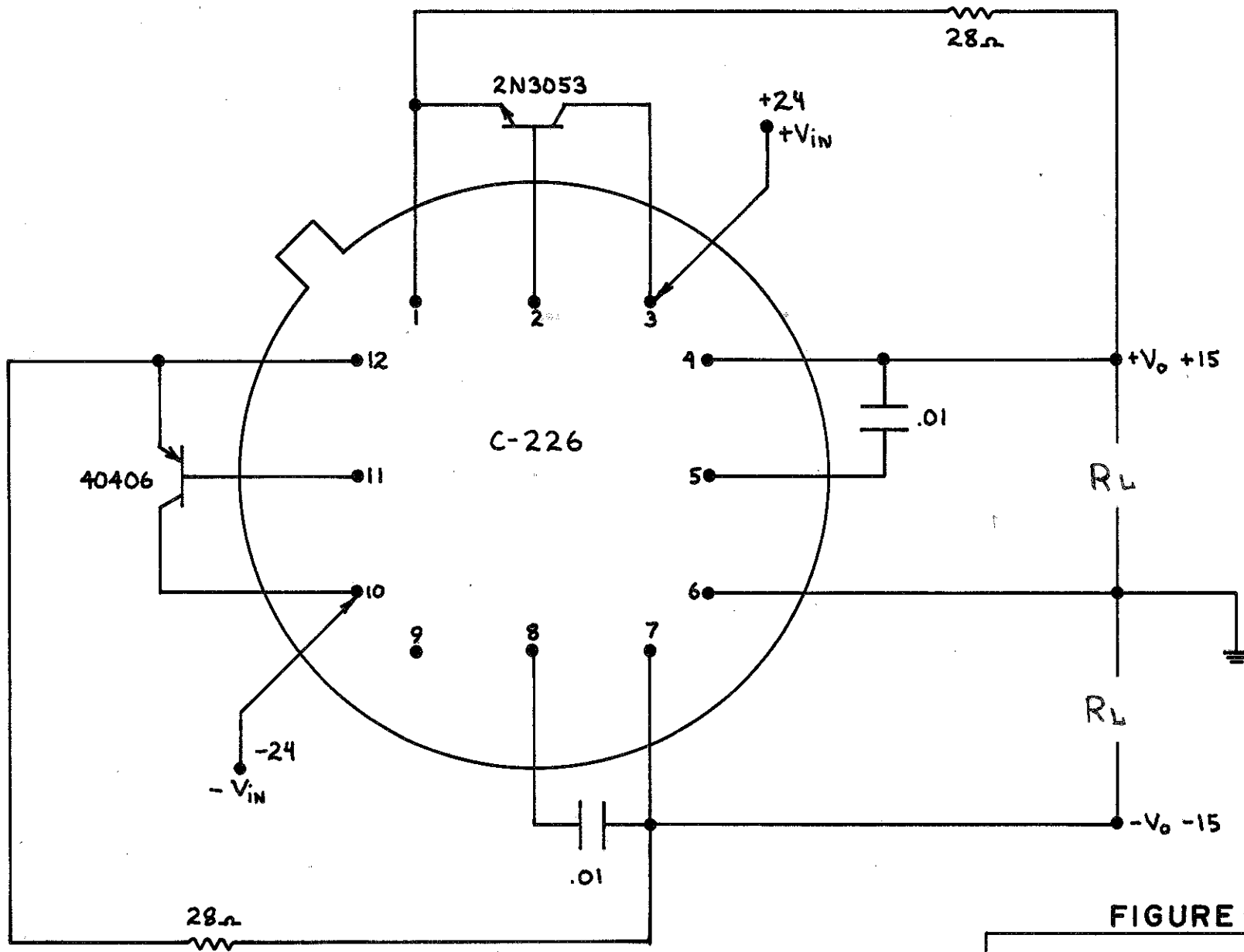
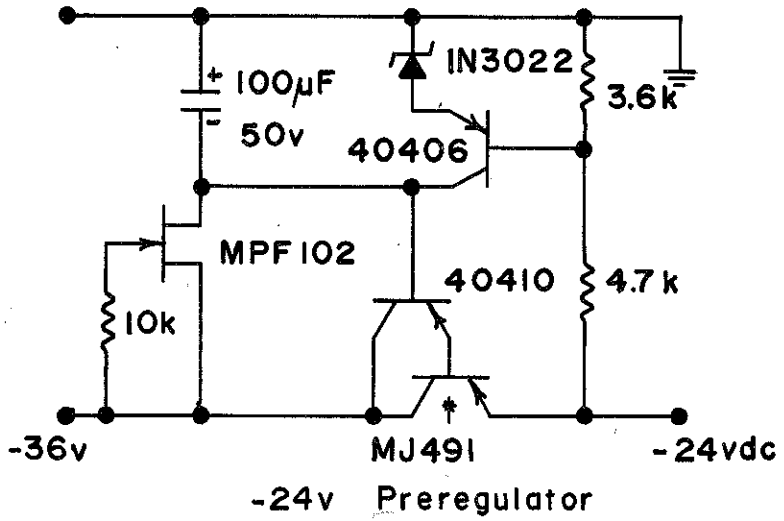
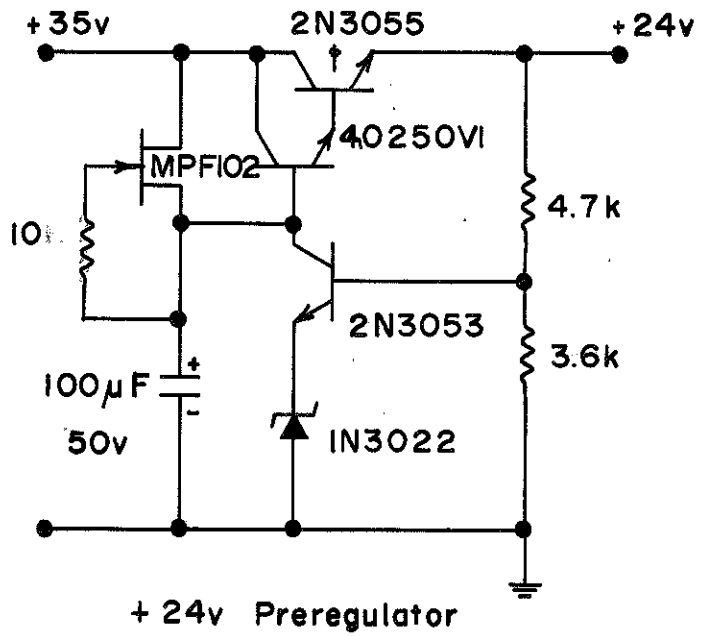


FIGURE - 14

<u>±15 volt regulator</u>		
Design: Bob Young	R.L.B. &	4/71

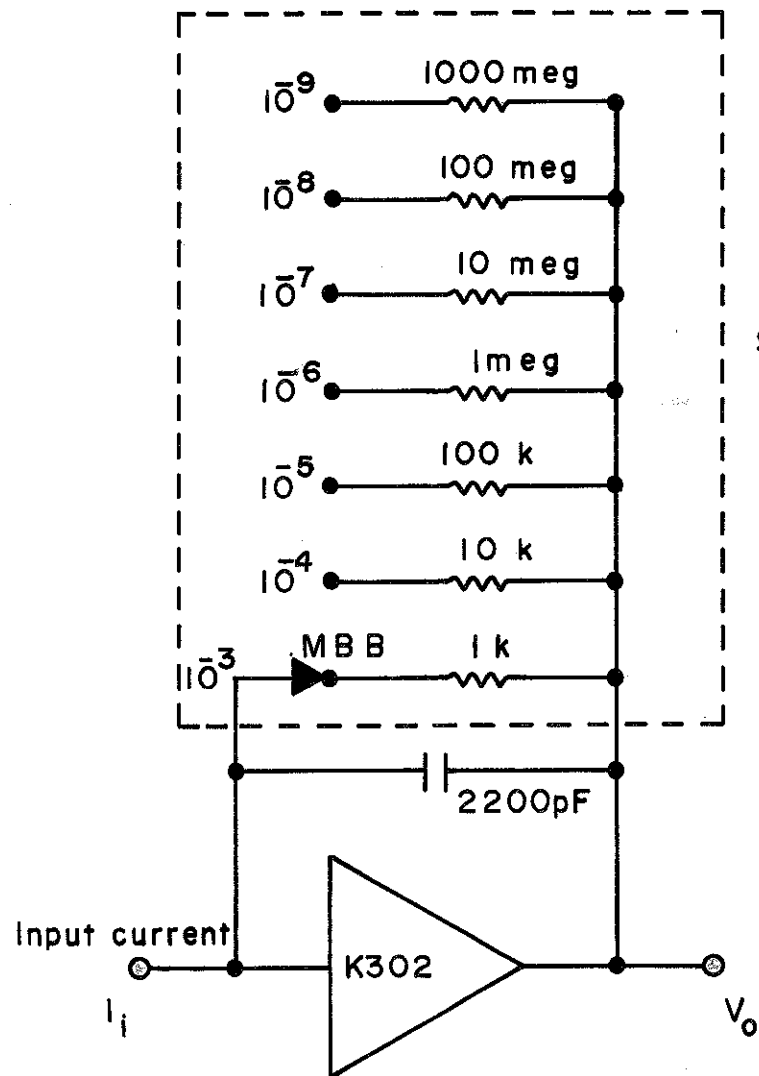
C-226 Bell & Howell Regulator



† Heatsink

FIGURE - 14

BCI ± 24volt Preregulators		
Design: Bob Young	Ron Brown	8 · 71



Shielded switch

Current to voltage converter

Figure 15 subsystem 22

$$V_o = I_i (R_F)$$

K302 $I_{bias} = 2 \times 10^{-13}$ amperes

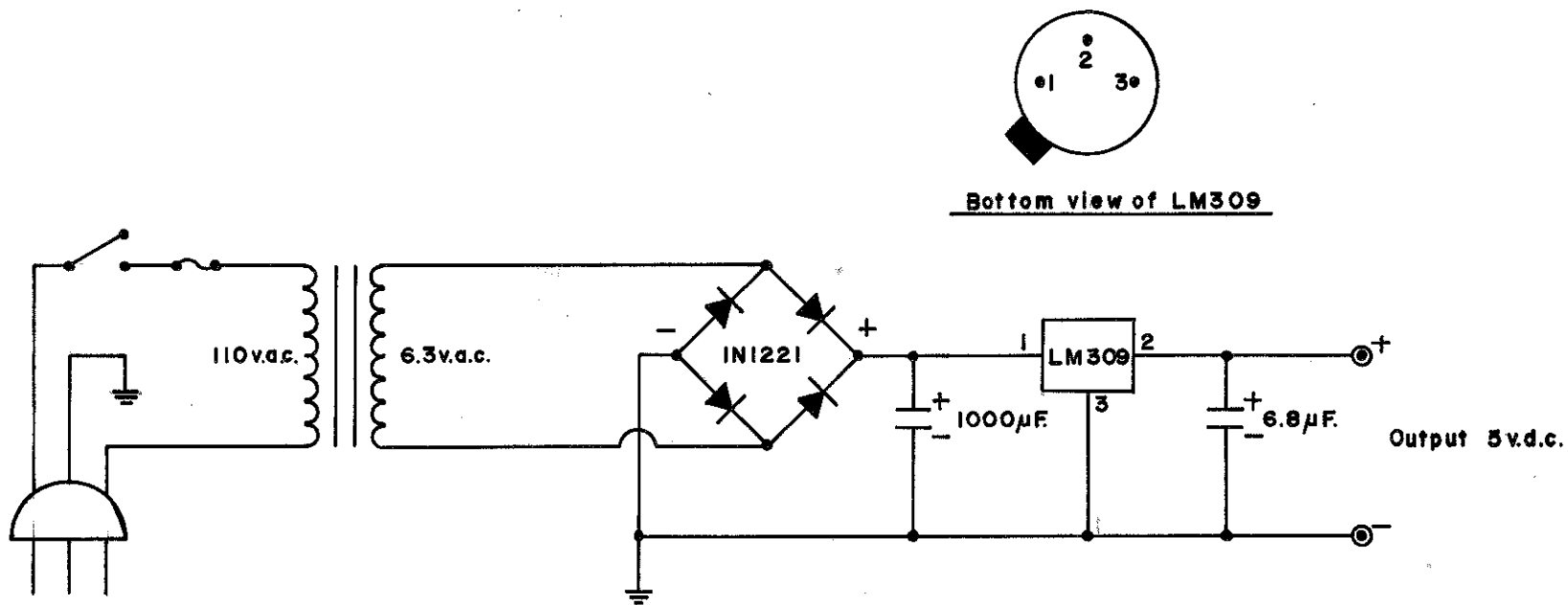
K302 $I_{offset} = 10^{-14}$ amperes

All feedback resistors $\pm 0.1\%$ wire wound

± 10 ppm / $^{\circ}$ C resistance drift

FIGURE - 15

Input Range Switching		
Robert Young	R.L.B	8-71

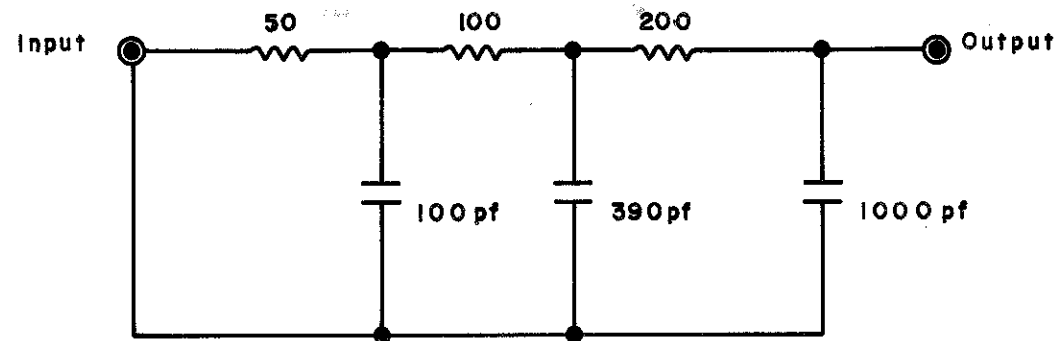


B.C.I. Interface Power Supply

Design: Bob Young

Ron Brown

7-15-71



Pulsed Beam Filter

Design: Bob Young

Ron Brown

7-71