AUTOMATIC ELECTRONIC EMITTANCE DEVICE FOR THE BNL 200 MEV LINAC*

R. L. Witkover and N. Fewell
Brookhaven National Laboratory
Upton, New York

ABSTRACT

A system for the measurement of beam emittance has been designed and installed on the new BNL Injector. It is similar in principle to the single slit-multiple collector device designed at NAL but does not require a digital computer. Emittance data is acquired, processed and displayed in a maximum of 100 beam pulses, which is ten seconds at the linac pulse rate. The data presented include a plot of the emittance and digital displays of the area, the threshold, the percentage beam at threshold and the number of beam pulses used. An alternate mode of beam profile display may be selected.

The design of the electronic and mechanical components and some operating results are presented.

Introduction

An automated system for rapidly obtaining and displaying beam emittance has been developed for the BNL 200 MeV Linac Injector. The technique utilized is similar to that employed at NAL.[1] However, the signal processing and display are performed without a computer. The detector heads are designed to mount in either plane at five locations in the 750 keV drift space or at 10.4 MeV. Details of the mechanical construction and the electronic circuitry employed are described below.

The automatic emittance system utilizes either 75 or 100 beam pulses (depending upon the location) to obtain an emittance measurement in one plane. The measurement may be performed at 750 keV or 10.4 MeV. The emittance is measured by allowing the beam to pass through a slit which determines the position location. The slit is moved through a sequence of positions by means of a stepping motor and gear drive. Divergence information is obtained by means of an array of thirty collecting electrodes which are fixed in position with respect to the slit. The electronics for this system control all parameters of the measurement once the start button has been pushed.

The displayed outputs are a stored scope display of the shape of the phase space area at a specified threshold level, digital readouts of the threshold level, emittance of the displayed phase space shape, the percentage of the total beam contained in that shape and the number of beam pulses taken to complete the run.

An alternative mode of operation gives a stored scope display of the beam profile.

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The threshold, emittance and number of beam pulses are digitally displayed as before but in place of the 'percentage beam', the width of the beam at threshold is presented. The scope presentation is the total beam passing through the slit as it advances through successive positions in the beam.

Description of the Mechanical Design

Factors governing the mechanical design of the emittance device were:

a. Very limited space between the last triplet magnet of the Low Energy Beam Transport and the 10 MeV accelerating tank.

b. High expected beam densities, small diameters and divergence.

c. Number of incremental steps necessary to give a useful display of the phase space shape.

Due to the very restricted area in front of the tank, the emittance units for this position were designed first and the drive assembly for these units was then used in subsequent units.

750 keV Unit Position in Front of Tank 1

Slit and Pickup Head. Due to the small size of the viewing box (VB5) in front of the tank (See Fig. 1) the size of the slit and pickup head was restricted to 2-13/16 in. in length by 2-3/16 wide by 2-3/8 deep. As a similar unit was to be used at 10 MeV it was decided to use a copper foil-mica sandwich as the pickup collectors. This allows sufficient depth for absorption of the 10 MeV particles (range approximately .010 in. in copper) with good heat conduction away from the front edge and close stacking of the pickups. The thickness of the foil used was 0.002 in. separated by mica 0.004 in. thick giving a collector separation of 0.006 in. (See Fig. 2). This foil sandwich was spaced 2.4 in. from the slit, giving a collector interval of 2.5 mrads with respect to the slit and a definition of ± 0.4 mrad. Each foil was 1-3/4 in. long by 5/32 in. wide with a 1/16 in. wide connecting tail extending from the back edge. This 'tail' was staggered by 0.1 in. for each adjacent foil and was soldered to a copper printed aluminum oxide terminating plate. A collector assembly consists of thirty such copper foils and thirty-one mica spacers clamped between two stainless steel plates on which the two terminating alumina printed circuits are attached. Teflon coated wires then carry the signals from the terminating plate through the drive shaft to a vacuum-tight multi-pin connector.

A 0.004 in. by 1-5/8 in. slit is formed by two 1/8 in. thick tungsten plates screwed to a copper water-cooled heat sink which also forms the support for the pickup assembly. The edges of the tungsten plates are ground at 45° to within 0.015 in. of the back edge; this gives a thinner slit depth and a larger surface area in the region of the slit.

Drive Assembly. For a useful phase space display, it was decided to step the slit across the beam in 0.5 mm increments at the maximum beam pulse repetition rate of 10 pps. To achieve this, a 400 oz-in. stepping motor is used--this steps in 1.8° increments. A maximum of fifteen steps could reliably be obtained between beam pulses at this repetition rate, giving a movement of 27°. This drives two 0.2 in. pitch ball screws via a 2 to 2-5/8 step-up gear chain, giving 0.5 mm of travel on a drive plate to which the drive shaft is attached.

Microswitches are attached to the assembly to control the travel and time during which data is being taken. (See Fig. 3.)

750 keV/10 MeV Unit

This unit is basically the same as the previous one except that it fits viewing boxes VB1 to VB4 in LEBT and also the boxes used for the 10 MeV measurements. Due to the larger boxes in these positions, the travel had to be increased, but as there was now room inside the box for the metal bellows, the design was simpler. The extra space allows the pickup electrodes to be spaced further from the slit, and spacings of 1, 2 and 2.5 mrad can be chosen. The length of the slit and pickup foils was also increased to accommodate a three-inch diameter beam in these positions.

Description of the Electronics

The operation of the electronics may best be explained by describing a typical data run:

a. The measurement location is selected by connecting the cable from the pre-amplifiers at the desired location to the main control electronics. At present, three locations can be selected but in the future at least six will be available.

b. The time during the beam pulse at which the measurement is to be made is selected by means of two sets of 3-digit thumbwheel switches. (See Figs. 4 and 5.) The first set of switches selects the starting time of the sampling window (in microseconds after the leading edge of the beam). The second set of thumbwheel switches presets the width of the sampling window. In this way measurements as short as 1 μsec can be made at any position in the beam.

c. The threshold voltage is set by putting the meter selector switch to "threshold voltage" position and setting the multi-turn potentiometer until the digital voltmeter reads the desired voltage.

d. The selector switch is then turned to "percentage beam" position if an emittance is desired, or to "beam profile" if that measurement is required.

e. Upon pushing the "start slit" pushbutton the measurement begins.

Initially the slit-detector housing is in the parked condition where it is fully retracted from the beam pipe. Upon receipt of a forward command, the motor moves the detector head away from the "Park" microswitch and towards the beam. The control panel slit status indicator changes from "Park" to "Forward".

No data is taken until the detector head has reached the region of interest in the beam pipe. This is preset by means of a second microswitch called "Data Switch" which is used to gate the processing electronics. Once past this point an emittance display begins to appear. (A typical set of data is shown in Fig. 6.)

The portion of the beam passing through the slit is allowed to diverge and intercepts the array of thirty collecting strips. Each strip is connected to an identical channel of electronics. A typical channel will be described. (See Fig. 7.)

The signal from the collector is carried to an FET-input operational amplifier mounted close to the emittance device. The amplifier is connected in a non-inverting configuration with a voltage gain of thirty. The collector current is converted to voltage by means of a shunting resistor at the amplifier input. In the 750 keV devices an output of approximately 11 V/ma is used while at 10 MeV the value is approximately 55 V/ma. The signals are sent to the Injector Control Room by means of twisted pair multi-conductor cables. The received signals have typical noise levels of under 50 mV and are capable of one microsecond rise times. The collector signal is applied to an IC comparator which determines if it exceeded the desired threshold voltage. If it does, the comparator output is a logical "zero" level. The use of logical zero for the true state resulted in simplification of other electronics in the memory and multiplexer. This signal is applied to an R-S flip-flop which acts as the storage element of the system, remembering if the collector signal on that channel exceeded the threshold voltage at any time during the preset viewing time (set by the thumbwheel switches). This gating is accomplished by resetting the flip-flop array at the start of the viewing window and transferring the data out of the flip-flops at the end of the viewing time.

The data from all the flip-flops are transferred in parallel to the inputs of a 32-channel digital multiplexer. The multiplexer series read-out is controlled by a gated clock preset to give the thirty-two pulses necessary to scan all the channels. An inverter on the multiplexer output restores the conventional sense to the logical "true" level. The clock pulses are also fed to a digital-to-analog converter to provide the vertical sweep for the storage scope (Hewlett-Packard type 1207B) display. The multiplexer output is applied to the Z-axis input of the scope through an interface circuit such that the trace is unblanked only when a "true" state is read out of the multiplexer. Since the same clock pulse is used to increment the vertical sweep and to increment the multiplexer, the dots appear on the scope in correspondence with specific channels of the collector array.

The multiplexer output is also fed to a digital counter and Nixie-type tube display to indicate the total number of dots on the scope screen. Since each dot represents a fixed increment in position and in angle, the total number of dots is simply related to the emittance. Typical values are 0.5 mm per step in position and two milliradians in divergence.

At the completion of the multiplexer read-out the motor is commanded to move to a new position. The number of such commands is counted and displayed on Nixie-tubes to indicate the number of beam pulses used in the run. The counter output is also used by a digital-to-analog converter to provide the horizontal sweep for the storage scope.

Thus each slit position corresponds to a particular horizontal position on the display.

Circuitry is also provided to measure the percentage beam within the displayed emittance. This is done by means of two integrators, one for the total beam and one for that portion of the beam within the threshold level. The outputs of the integrators are used as inputs to an analog dividing circuit. The output of the divider is displayed on the digital voltmeter at the completion of the data run.

The threshold integrator signals are obtained by passing the analog signal from each collector through a shunt transistor gate which is controlled by the came comparator used to provide the emittance display.

Signals from all channels for the total beam measurement are passed through a summing amplifier prior to going to the integrator. This summing amplifier output represents all beam which passed through the slit at that slit position. It is used as the vertical sweep for the storage scope when the beam profile is desired. In this case the intensity modulation is provided by the signal viewing window so that only the beam current amplitude during the pre-selected viewing time is visible on the display. (See Fig. 8.)

The signals from all of the shunt transistor gates are summed in an identical amplifier and presented to the threshold integrator. Both integrators are gated by the viewing window signal to prevent integrating extraneous signals during the interpulse period. The integrators are reset at the beginning of the data run.

When the slit has completed its travel and made the limit switch contact, the motor is reversed and the slit returned to the parked position. No data is taken on the return run at present. In the future it is planned to display beam profile during this time.

Performance and Results

The emittance system performed in a thoroughly satisfactory manner. It produced an emittance measurement in one plane in 10 seconds at the maximum beam repetition rate. This allowed the beam operator to make an adjustment of the pre-injector or the quadrupoles and view the results immediately. The operation of the device was sufficiently simple to allow a new operator to obtain results without training. One inconvenient aspect, however, was the need to disconnect cables and reconnect others in order to change the location of the measurements. In the future a relay multiplex array will eliminate this problem.

The resolution and range of the device was generally adequate. The use of many thin foils as collectors resulted in a sufficiently large number being intercepted to provide good localization of the emittance shape. The resolution was such that single channels appeared in the data in a convincing manner. Often when the ion source or quadrupoles were improperly set, intricate patterns were produced (See Fig. 9) which clearly showed the resolution of the device. The ability to discern single channels was taken as indicating no serious secondary emission problems existed.

The device and the linac itself proved to give highly reproducible results. Patterns made on successive runs with no setting changes always overlaid properly. Also it was possible to reset the quadrupole currents to levels of several days earlier and get identical emittance patterns and readings.

Reliability of Detector Head

750 keV operation: Emittance measurements have been made with beams in excess of 250 mA with diameters of less than 5 mm. Melting of the tungsten occurs at these densities except in the tapered design of the slit (See Fig. 10). The γ plane unit in front of the tank has made approximately 1000 measurements at this time without damage to the slit area or the pickup head.

10 MeV operation: Only slight marking occurred on the face of the slit plate at 10 MeV with beams up to 200 mA as the beam diameter was large (1½ to 2 ins.). (See Fig. 11.) However, melting may be a problem for units now being made to go between tanks 1 and 2, where the beam diameter will be considerably smaller.

No damage has occurred on the pickup head.

Electronics Reliability

At the present time over 4000 operations of the emittance system have been recorded over a four month period. The only electronic failure was due to a lightning strike in the immediate vicinity of the accelerator. One integrated circuit was replaced and the system resumed operation.

A problem which has arisen several times is that of poor connections. This occurs when the several multiconductor cables required are switched from one set of preamplifiers to another whenever a different emittance location is desired. The repeated handling of these connectors inevitably results in mis-aligned pins and faulty contacts. With the incorporation of a relay multiplex array to do this switching the problem should be eliminated.

Summary

An automated system for rapidly obtaining emittance and beam profiles has been built and extensively used in setting up the 10 MeV section of the BNL Linac. The multiple foil detectors have demonstrated their durability in high current, high density beams at 750 keV and 10.4 MeV˙ The electronics are simple to operate and yield a display of the emittance and run parameters in a maximum of 100 beam pulses. The system provides a reliable inexpensive alternative when a computer is not available.

Acknowledgements

The authors gratefully acknowledge the advice and encouragement of T. J. M. Sluyters and K. Batchelor. Early discussions with M. Shea of NAL influenced the present design. The electronics fabrication was performed by J. Grasso, J. White and E. Heins.

Reference

1. R. W. Goodwin, et al., Paper LCO-058, 1970, Proton Linear Accelerator Conference.

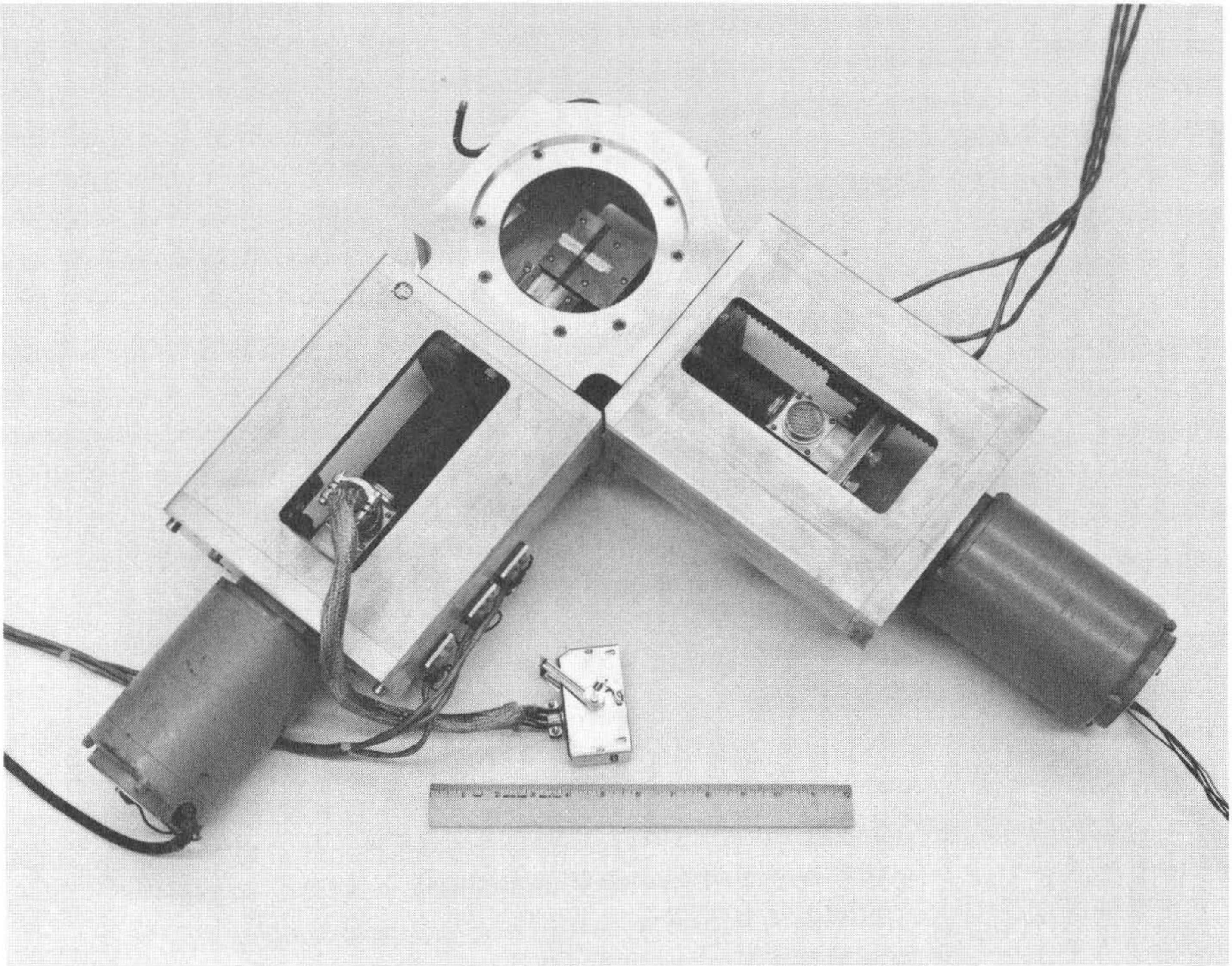


Fig. 1. View of VB5 with units mounted in X and Y planes.

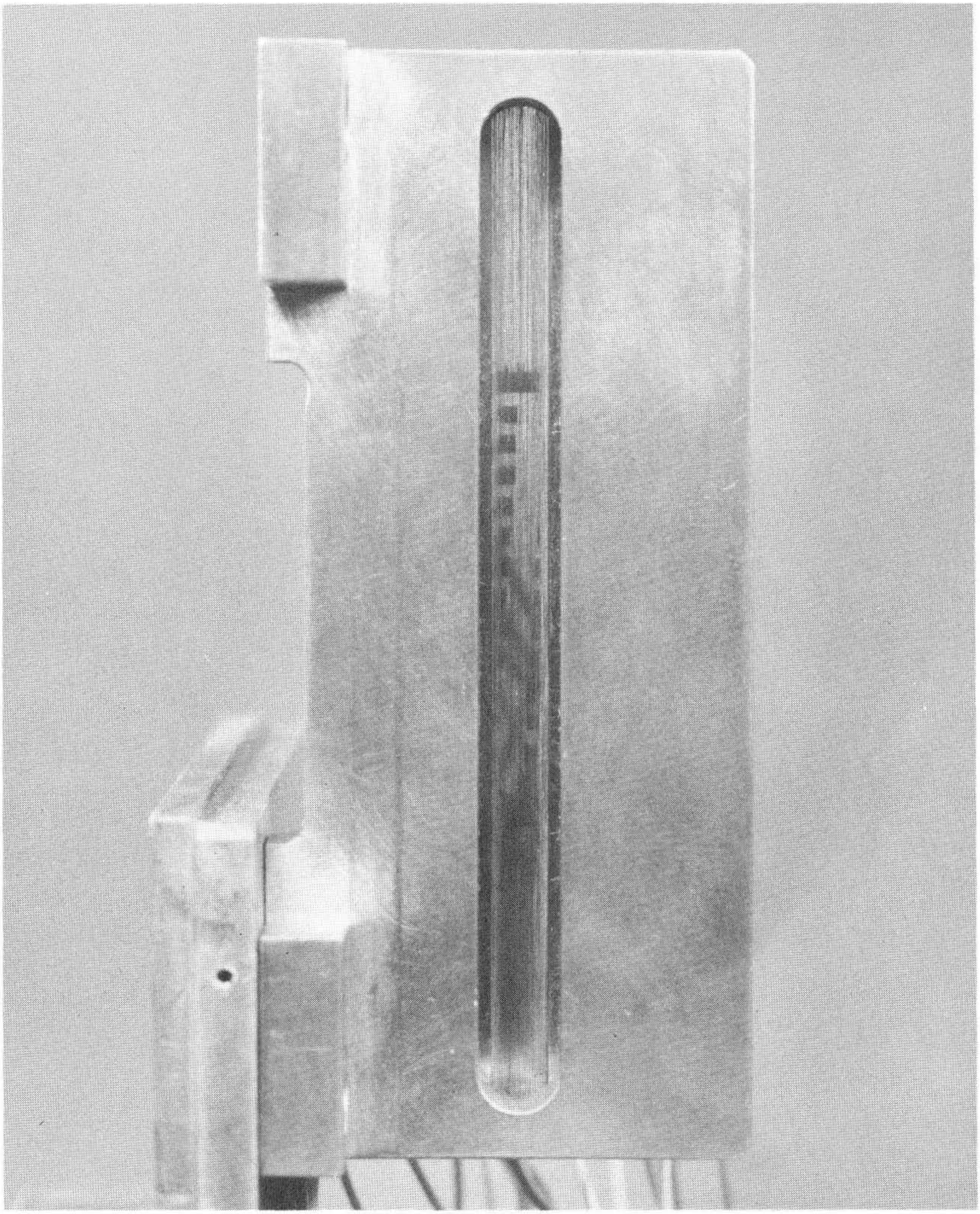


Fig. 2. Close-up of pickup head.

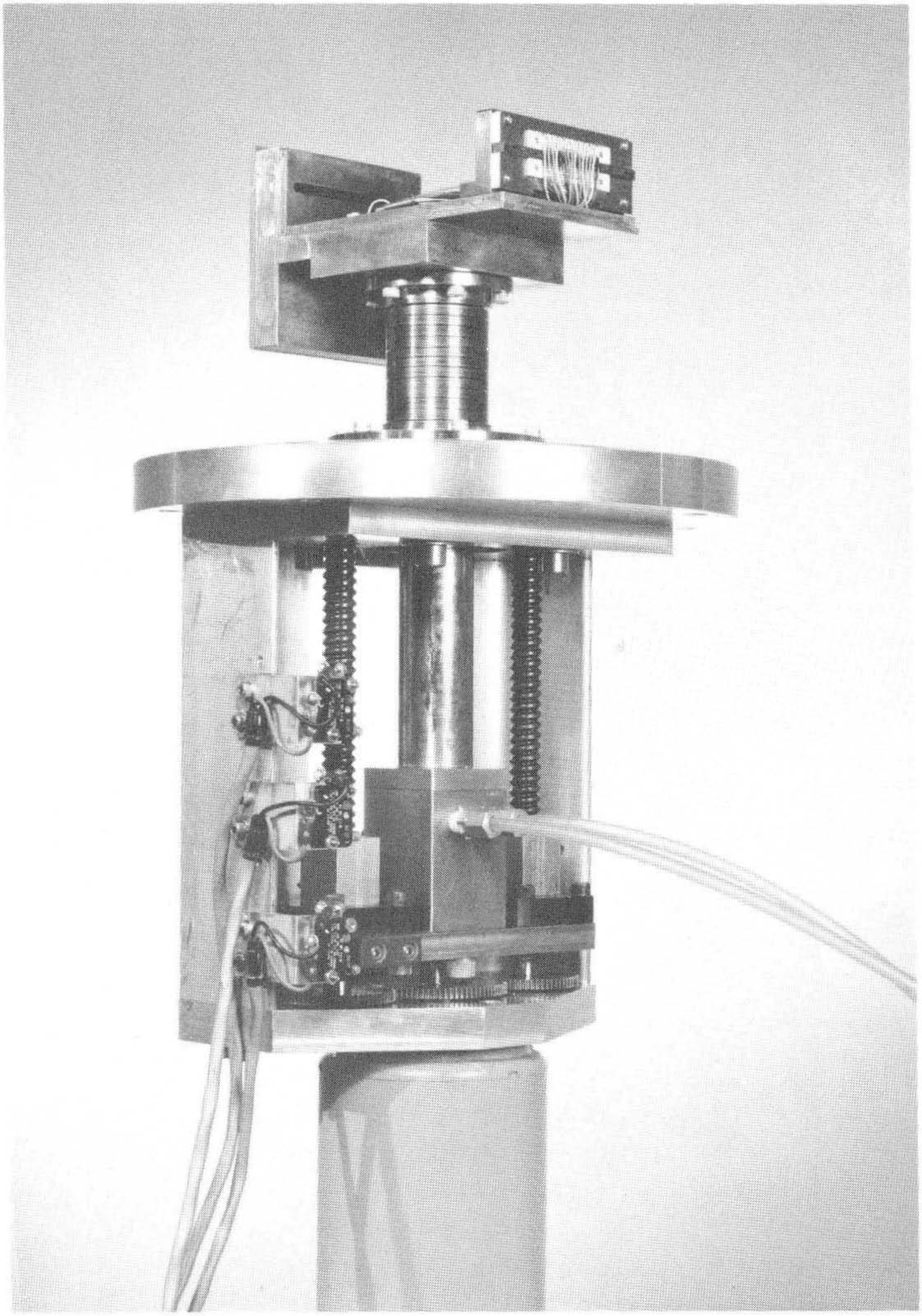


Fig. 3. General view of the 750 keV/10-MeV unit showing drive assembly.

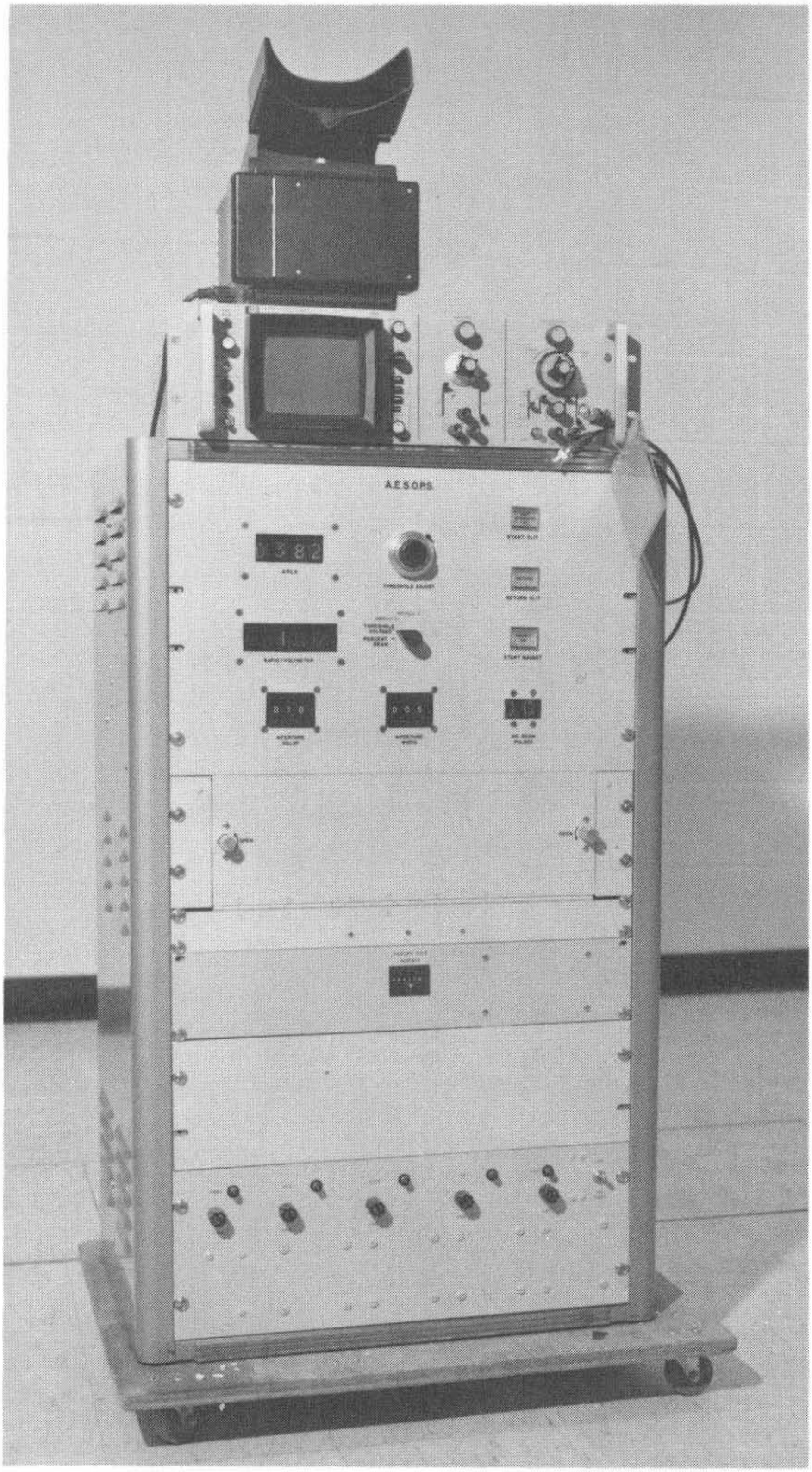


Fig. 4. General view of the electronic control console.

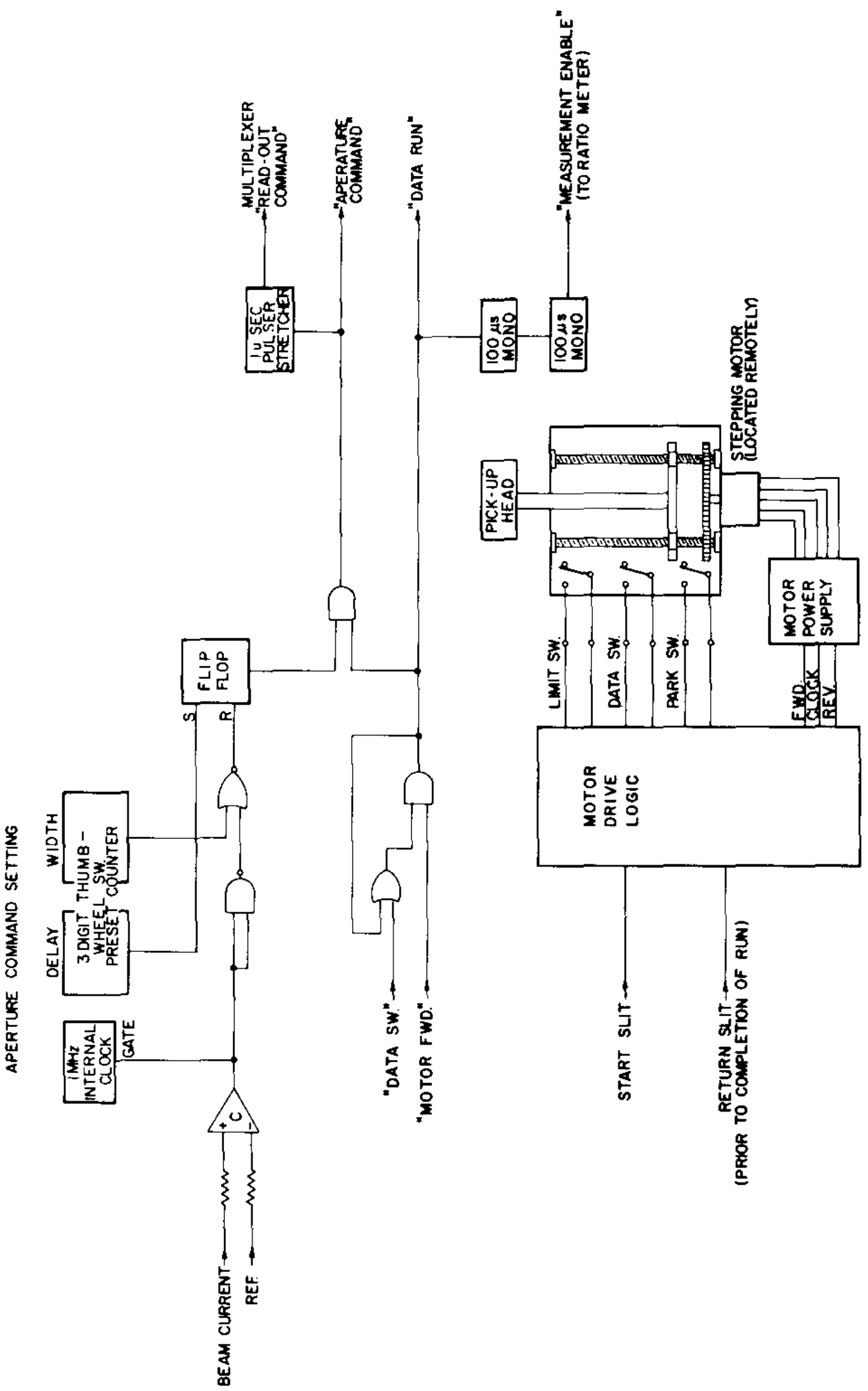
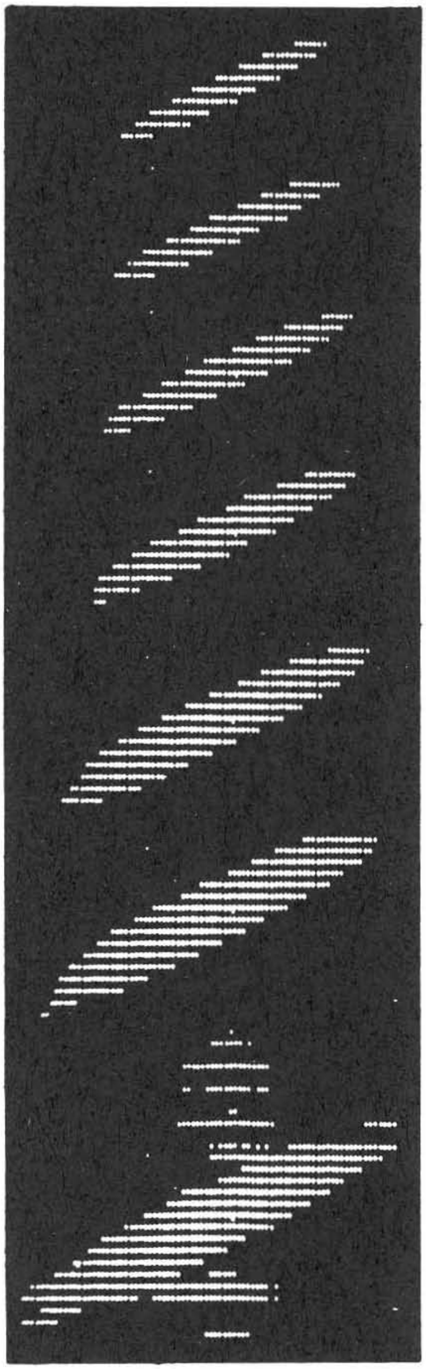


Fig. 5. Block diagram of timing and motor control.



THRESHOLD LEVEL	AREA cm, mrad	BEAM PERCENTAGE
5.V	10.6	68
4.V	12.8	73.3
3.V	15.8	81.2
2.V	19.6	88
1.V	28.1	95
0.5V	34.4	96.9
.25V	57.1	98.2

TYPICAL SERIES OF EMITTANCE PLOTS (10MeV, 120mA)
Fig. 6

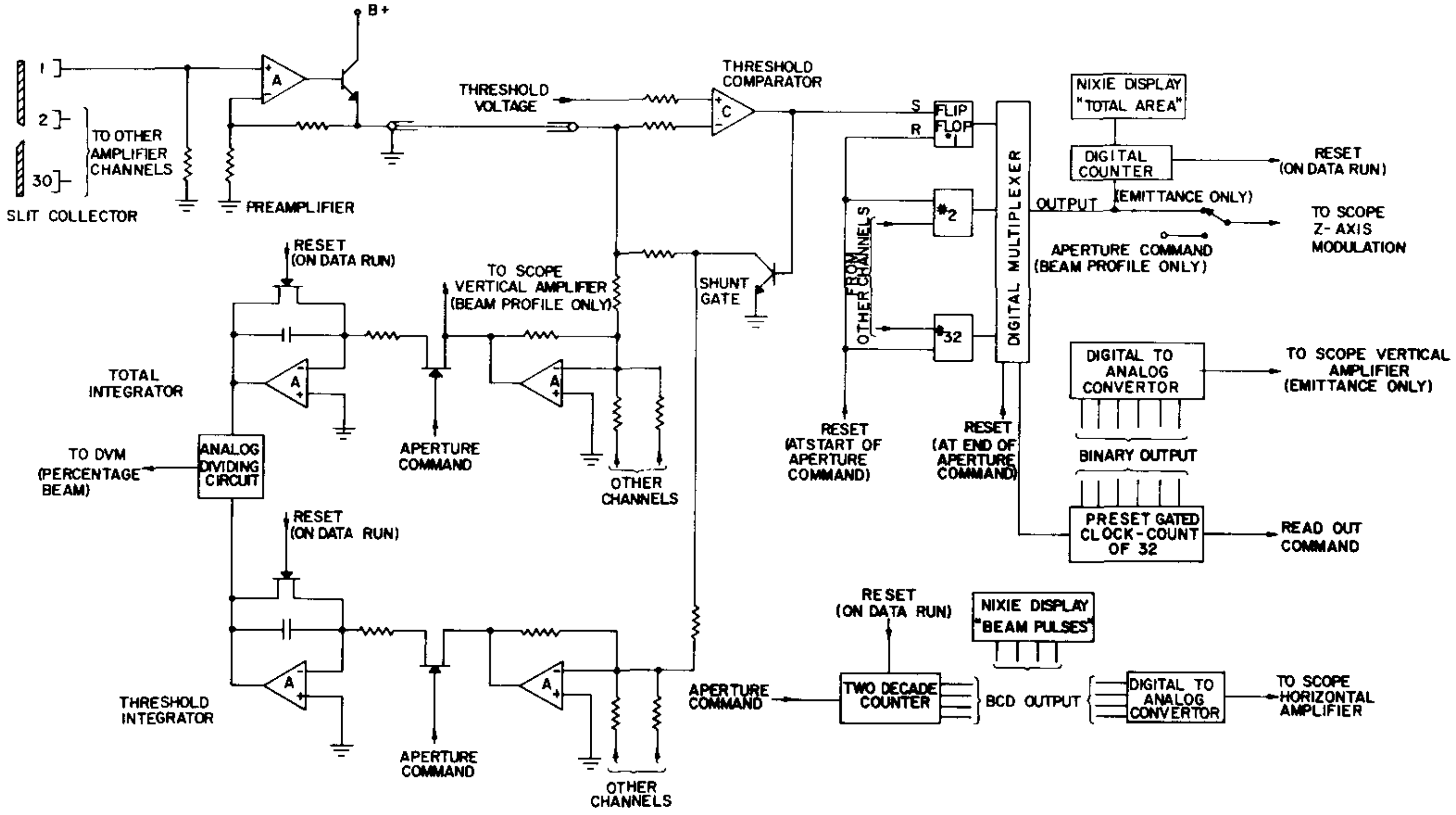


Fig. 7. Emittance processing and display block diagram.

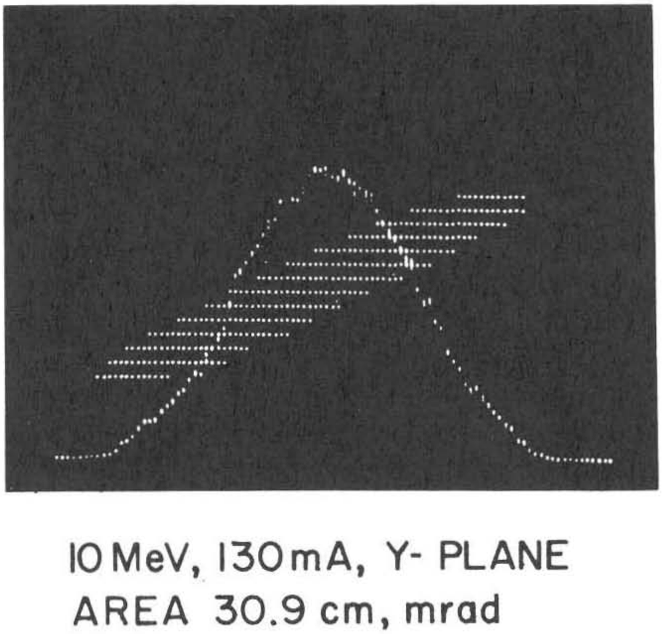


Fig. 8. Typical emittance and profile plot.

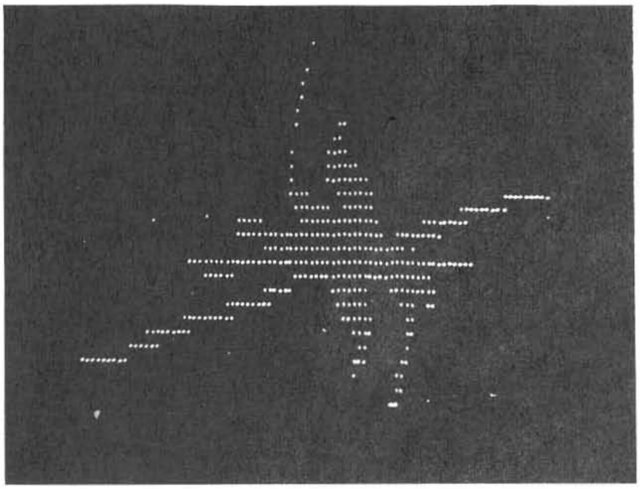


Fig. 9. Emittance plot showing resolution of apparatus.

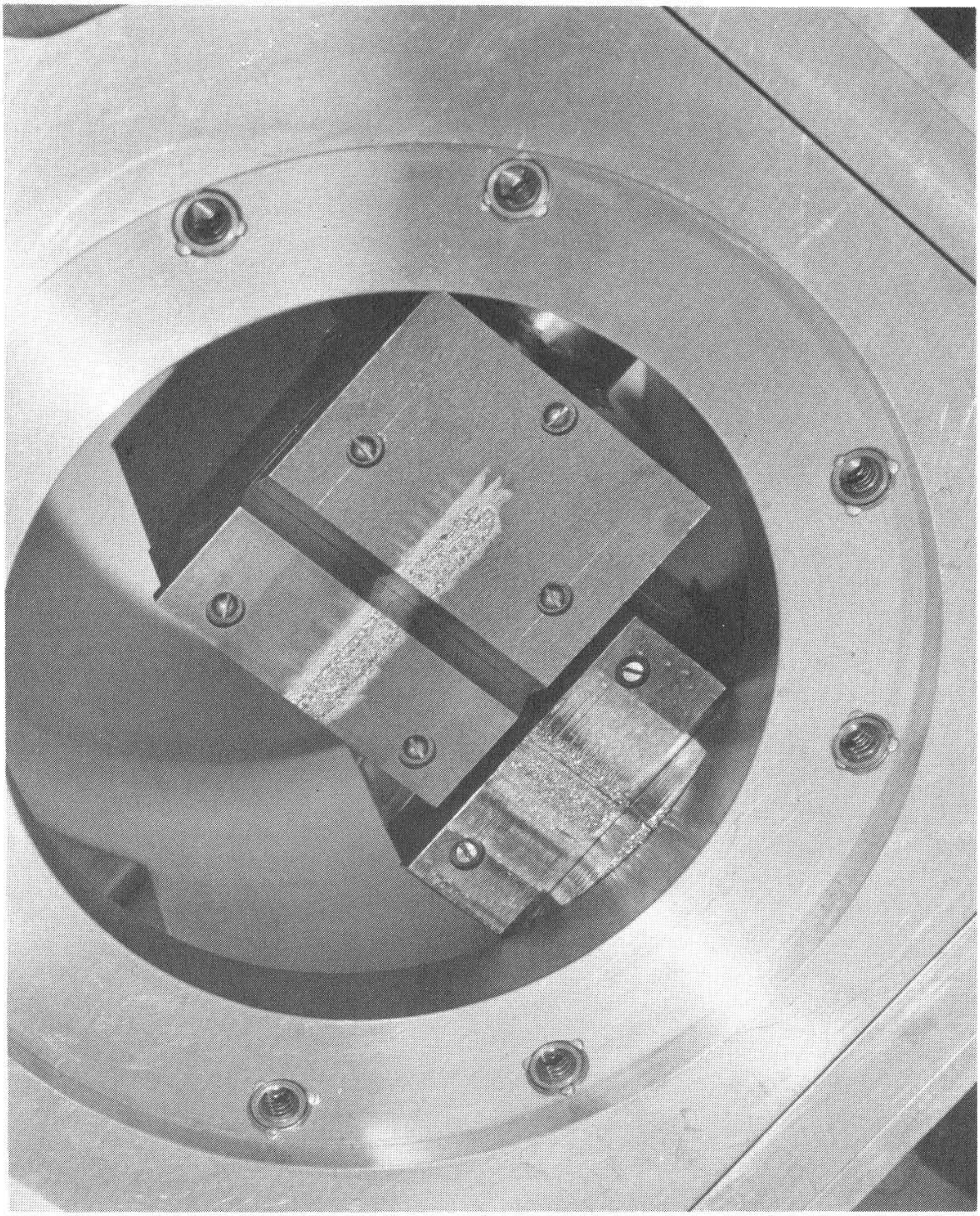


Fig. 10. Close-up of slit showing melting due to high current densities.

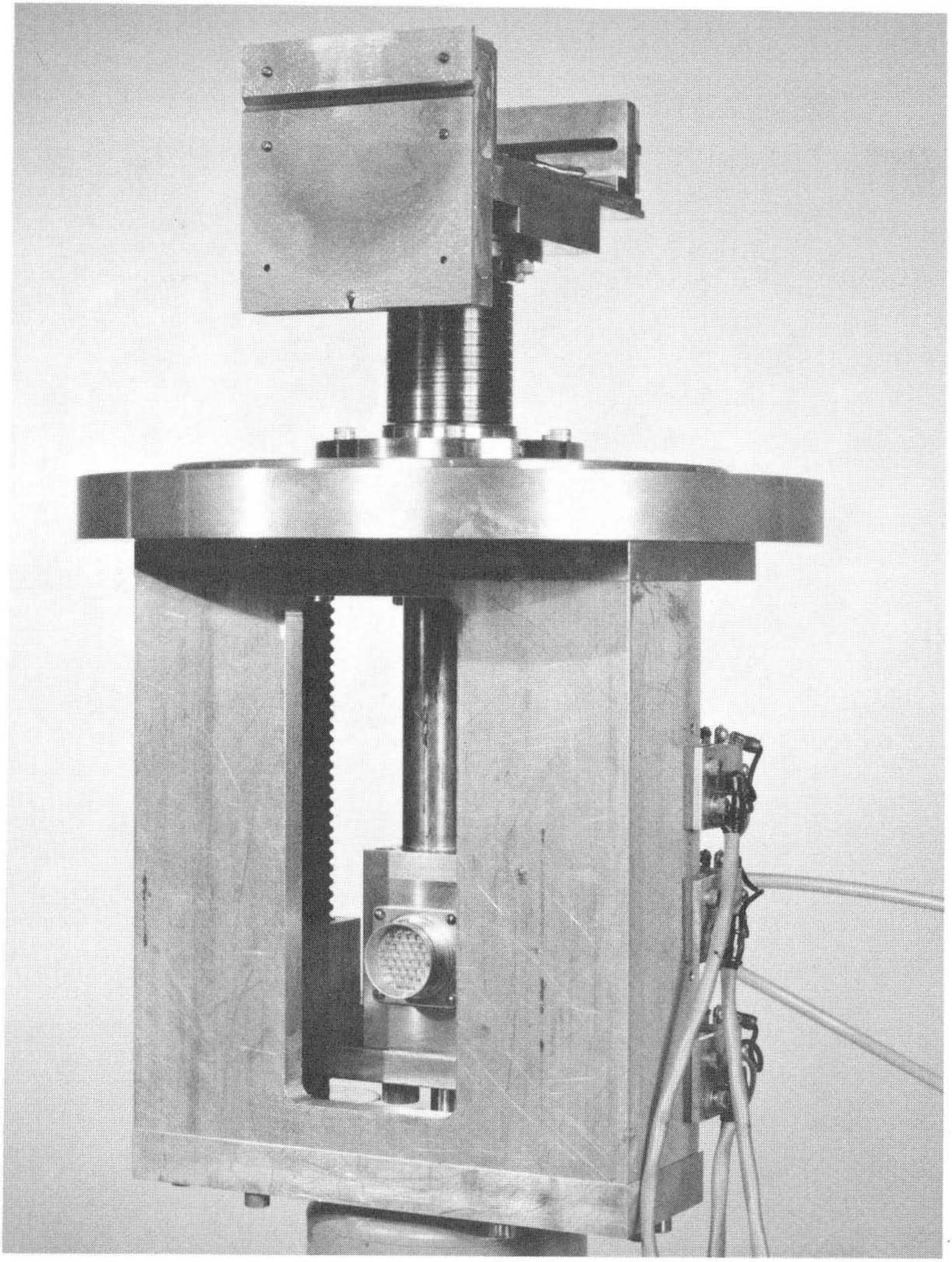


Fig. 11. General view of the 750 keV/10 MeV unit.

DISCUSSION

D. R. Machen (LASL): Can you compare the costs of this system with those of a computer system?

R. L. Witkover (BNL): Including the cost of the oscilloscope, the hardware came to approximately $3200. In terms of man hours, it took one engineer six months and approximately one technician manyear. The mechanical equipment was not included in this; this is only electronics.

E. Regenstreif (University of Rennes): In one of the diagrams you showed, there was definite filamentation of the beam. Do you have any idea where it comes from?

R. L. Witkover: When that photograph was made, the ion source was not adjusted properly. Second, we were running for part of the time with a doublet instead of a triplet immediately following the preinjector. It may have come from that.

E. Regenstreif: So, the admittance of the doublet has shown up to some extent instead of the emittance of the beam.

C. D. Curtis (NAL): With respect to resolution considerations of the emittance probe, if the beam falls on just a few strips, it is difficult to know the emittance exactly. Have you measured the emittance of the same beam for different orientations, say, bringing the beam to different focal conditions?

R. L. Witkover: One thing we did was to make the measurements after the first triplet from the preinjector; we simply switched the polarity of the triplet and got quite different emittances. We also have the ability to move the larger of the two units to any of the first four viewing boxes, and we have considerable data in each of these. This could not be done without opening the system to air, so there was some time lapse between runs.

C. D. Curtis: If the area is large, we do not worry about the resolution problem; if the area is small, we find a great change, depending on the orientation of the ellipse. Our current collector strips are wide compared with the gap between them while yours are narrow compared with the gap. In our case, when the beam falls on a very few collectors, we greatly overestimate the emittance area. In your case, I can think of conceivable cases where you would underestimate the area.

R. L. Witkover: We should be fairly close to actually reading the current at the particular point where the measurement is made. For the wider area of your collector, one tends to integrate over the entire area. In ours, the definition was quite good because of the 2-mil width of the foil.

P. V. Livdahl (NAL): I understand that these probes are used at 750 keV and 10 MeV--what are you planning to use at 200 MeV?

R. L. Witkover: We have given considerable thought to the single-wire technique that you people have been using. In addition, about two years ago the Russians reported at Daresbury on one that they used at 100 MeV, a destructive technique identical to this, and we are going to give some thought to that.

T. J. M. Sluyters (BNL): I think that we shall use both.