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Se[illegible] 1966

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Abstract

To minimize pickup jitter in the Bevatron, and to evaluate the digital control system proposed for the 200-BeV accelerator, we have installed digital control on the Bevatron achromatic inflector. A PDP-5 computer with interfacing provides 40 monitoring and 20 control channels. The interface communicates with the computer and the inflector system through time-division multiplexers. The system provides both automatic and manual control of the inflector deflection and focusing elements.

Using the analog monitoring developed for beam control, the operating parameters of the inflection system have been adjusted for maximum charge survival in the Bevatron. As a result, the injection efficiency increased by 30%. The beam position (at each monitoring station) has also been set by using closed-loop digital control. Resonant induction electrodes are used to detect the center of gravity of the beam. Three-pulse convergence has been obtained, with a resolution of ±0.1 mm.

Introduction

In order to evaluate the use of digital control in a large accelerator, as proposed for the 200-BeV synchrotron,[1] digital control has been installed on the Bevatron injector. The digital system controls the inflection trajectory of the Bevatron linear-accelerator (linac) exit beam.

Although not yet complete, several control experiments have been performed. A description of the system components, programs, and experimental results is given below.

Bevatron Injector Inflection System

As shown in Fig. 1, the inflection system consists of three bending magnets and a short electrostatic inflector. This system has an achromaticity of ±5%. Two triplet quadrupoles are used to match the linac exit beam to the Bevatron acceptance. Three steering magnets are used for beam-center correction. To obtain maximum pick-up in the Bevatron, the inflection trajectory must be placed as close to the electrostatic-inflector septum as possible. Thus the inflection system is quite sensitive to trajectory movements. Because of misalignments in the linac,[2] its exit beam is subject to deflections. These deflections move the inflection trajectory and affect the pickup of the Bevatron. Fluctuations in the accelerated beam, due to these trajectory movements, can be eliminated by increasing the amount of injected beam. However, it is difficult to study the injection process with such trajectory variations. The digital control system was installed to correct for these beam-center movements on a pulse-to-pulse basis.

Closed-loop digital control of the beam's center of gravity is accomplished by using the steering magnets and four position electrodes.[3] A position electrode is inserted into each steering magnet. The beam center is set to the tube axis by tuning for null on the position electrodes with the preceding magnet. The closed-loop system then holds constant the position and angle of the beam center at the entrance of the first inflector bending magnet (IM1).

In addition, the inflection-system deflection and focusing elements can be manually controlled by the digital system.

Control System

Electronics

A PDP-5 computer with interfacing provides 40 monitoring and 20 control channels. The interface communicates with the computer and the inflection system by means of time-division multiplexers (Figs. 1 and 2). These multiplexers are addressable by means of the interface--computer logic.

Control is required only on the pulse which is injected into the Bevatron. The control-signal multiplexers use reed-relay switching, since this pulse occurs once every 6 sec. The use of relays is convenient because of the minimum quantization level of 2.5 mV.

The computer is located 1000 ft from the injector. Digital and video information is sent over a balanced twisted-pair cable.

In order to perform the experiment it was necessary to modify the injector analog monitoring. Considerable work was done to eliminate noise from the magnet-current monitoring and to obtain standard signal levels for the control system. Whenever possible, transductors are used for reading magnet currents. They are installed on the deflection magnets and matching quadrupoles. The steering-magnet currents are monitored with resistive shunts and dc amplifiers. The use of shunts and amplifiers was required because of power-supply voltage limitations.

Pulsed or noise-sensitive analog signals are sampled and held at injection time. Sample time is 13 μsec.

To monitor the beam position, resonant induction electrodes were developed and installed in the inflection system.[2] A pulsed ion chamber (Q electrode) is used to measure charge survival in the Bevatron.

Analog signals derived from magnet current-beam intensity, and beam position are sent in analog form to the 40-point analog multiplexer located in the injector control room. There they are serially converted to digital data by an analog-to-digital converter. These data are sent, through line drivers, over the transmission line. A local interface rack provides the necessary digital logic to input the data into the computer. The total data read time is about 300 msec. The maximum converter input is 10 V, the smallest quantization step is 2.5 mV. Because the absolute accuracy depends on the conversion voltage, all input signals are run at a nominal 9-V level.

The PDP-5 computer is a 12-bit, 4096-word machine, with a minimum cycle time of 6 μsec. A magnetic tape unit is used for loading programs into the memory. Since this is a slow machine (3.5 msec is required for one division), computations, including analog unit scaling, are kept to a minimum. Control of the computer is by means of teletypes. Three are provided; one at the computer, one in the injector control room, and one in the Bevatron main control room. Output is either printed on a teletype or displayed on a 5-in. storage oscilloscope. (The storage oscilloscope is temporary; a large display scope is being installed.) The storage-oscilloscope face is monitored by a video camera. The camera output is then sent over the transmission line to the control areas. Digital control words are computed, under program control, after each monitoring period. These control words are sent over the transmission line to a 20-channel digital-to-analog converter. The digital data operates reed relays, which are connected to resistor ladders, and thereby converted into analog control signals. These analog signals are then sent to the power supplies to provide reference for the supply regulators. Ten-bit conversion is provided for all but IM1, which requires 12 bits.

Because this equipment was installed on an operating accelerator, compromises had to be made to prevent interference with the high-energy experiments. All power-supply references are brought to a transfer panel which permits switching from local analog control to digital control. In order to do this, the digital-to-analog converters are located in the injector control room. Digital reference signals are therefore not carried to each supply. Also, parallel connections are provided for all the monitoring circuits. These parallel connections go to a conventional accelerator-monitoring system. This multiple system, while flexible, required considerable noise debugging. The major noise source, pickup from the Bevatron field, was eliminated by isolating each beam-monitoring element and dressing the cables. The analog-to-digital interface, the data-transmission system, and the computer main frame have been essentially trouble-free with reference to hardware failure and environmental noise interference.

Modular construction is used for the digital interface. Figure 3 is a view of the injector interface rack showing the major digital components and the rack interconnections.

Program

If digital control is to successfully compete with conventional accelerator control, careful attention must be given to the program. Figure 4 is a functional diagram of the control program used for this experiment. The program can be divided into three main parts:

(1) program modification executive routine
(2) control program executive routine
(3) control and display subroutines.

1. Program Modification Routine

This program is a general purpose diagnostic routine, which is used to investigate control program troubles and to insert data or instructions into memory as needed. In addition, the computer can be started at a given location in the control program, or new programs can be called from the magnetic tape. If the control program detects a program error, control is transferred to this routine, and the memory location at which the error occurred is recorded on the teletype. After the error is analyzed the control program can be restarted.

Program commands are entered by teletype. To save typing time, mnemonic symbols are used. The symbols for this program are:

D XXXX: YYYY CR	Print contents of memory from location XXXX to YYYY.
I XXXX CR	Insert into XXXX. The program inserts sequentially until an alphabetic character is typed.
S5 XXXX CR	Start the computer at location XXXX.

A carriage return (CR) is used to delineate all program communication. Tape loading and writing subroutines are part of this executive routine.

2. Control-Program Executive Routine

This routine is the heart of the system's control program. The parameters to be controlled, the display instruments, and the variables to be displayed, are selected by this routine. Five display groups are used. The parameters to be displayed can be put into any group desired. The groups are set up by:

GN XX YYYY QQQQ ....

where G signifies that a change is to be made in display group N, XX is the number of parameters, and YYYY, QQQQ are the names of the parameters to be displayed. For example,

G104 IM1__IM2__IM3__Q---

(Each alphanumeric name must have four characters.) puts the achromatic inflector magnet currents and the circulating charge into group one. A group is called for display by typing DN. Wheneven that group is called, these four variables are displayed.

Although an operator may select the mode of operation, the order in which the subroutines are called is inflexibly established, on a priority basis. The sequence is shown in Fig. 4a. Program modes are selected by choosing the subroutines to be used. For example, the beam-center convergence routine may be used with or without the magnet-setting routine. To select a subroutine, the operator is provided with simple teletype characters that set a variable within the program to a value requesting access. These variables are called flags. Seven flags are provided, as shown in Table I.

In Fig. 4a flags are represented by switches. When a flag is set, the switch is closed, and the selected routine is used. The error-record mode is active whenever either the magnet-current-setting or position-setting subroutine flags are set. Only the mode of error read-out can be controlled. With these control program flags and the program modification routine it is possible to control and monitor the inflection system.

3. Control and Display Subroutines

An interpolation subroutine is used both to set a magnet to a given current and to set the beam position. Linear interpolation is used and data are required from two pulses according to

$$X_r = \frac{(x_n - x_p)(Y_r - Y_n)}{(Y_n - Y_p)} + X_n, \qquad (1)$$

where n is the present pulse, p is the previous pulse, r is the required (future) value, x is the control word, and Y is the monitored value. For example, to set IM1 to 624.5 A, the operator enters the required value in a table by typing SIM1__624.5. The octal equivalent of 624.5 will be entered into the table as a new required current. On the next Bevatron pulse, all the system variables are monitored and the magnet-checking routine notes the change between required and actual value and computes a new control word. This word is transmitted as soon as it is calculated, and the magnet power-supply reference is changed. The interpolative adjustment of the control word continues until the monitored current Y_n is within the permitted error of interpolation. A timing diagram for monitor and control is shown in Fig. 4b. The use of a single basic interpolation routine with tables of required values results in a very flexible program. Within a given mode (such as magnet-current check), the variables to be checked are entered in the appropriate table by inserting the variable name into the memory, using the program modification executive routine.

As an example, suppose it is desired to vary the electrostatic inflector and to observe the circulating charge in the Bevatron. All other parameters, including the beam position, are to be held constant. Errors are to be recorded on the teletype, and a graph plotted on the storage scope. The program commands are:

(1) Set the electrostatic inflector ramp increment:

Step = 0.0005.

(2) Select desired device to be ramped:

Ramp = 0.016.

(16 is the control channel for the electrostatic inflector.)

(3) Select variables to be plotted: (Group 7 is the plot display group.)

G702 Q _ _ _ ESI _ .

(The Y axis is the first entry.)

(4) Turn on the appropriate subroutines, set the display mode, and begin the plot:

F51F41F63F11F22F30F75.

With this command sequence the program monitors all system parameters and generates a graph on the storage scope. Both the magnet currents and beam position are checked by the interpolation routine each pulse. If no error is found, a graph point is plotted. The electrostatic inflector voltage is incremented by 500 V every fifth pulse. If a current or position error is found, the ramp and plot functions are stopped. The interpolation routine readjusts the parameter that has changed. Each pulse requiring adjustment, the parameters being adjusted, and their values are recorded on the typewriter. When the error is reset, the ramp and plot resumes. Figure 5 shows the storage oscilloscope display obtained with the instructions given above.

When the injector is tuned and operating normally, the operator can select numerical display of a parameter group. Figure 6 is a display-group photo taken with an error record. At each pulse the achromatic inflector parameters and the Q electrode were displayed. The error-record flag was set to a one and the error appeared at the top of the display.

We have found this type of control programming to be quite flexible, both for investigation of the inflection-system dynamics and for control of injection into the Bevatron.

Experimental Results

Convergence of the beam center, using the algorithm given above, was investigated for two position-electrode response curves (Fig. 7). The results are shown in Fig. 8. In both cases convergence was achieved, but the nonlinear case required twice as many pulses. In order to minimize the number of pulses required for convergence, the position-electrode electronics is compensated, by diode feedback, to obtain a linear response. The voltmeter response was adjusted using the digital control system in the ramping mode. Figure 9 shows a typical presentation.

Multistation convergence has been achieved and the beam center of gravity held at the nominal geometric axis at the entrance of the achromatic inflector. Each position electrode is nulled sequentially starting from the linear-accelerator exit. The horizontal and vertical beam positions are moved simultaneously. Results of a multi-station convergence are shown in Table II. The beam intensity was 20 mA. The beam-center location is recorded at all electrodes for each pulse. Seven convergence pulses were required at P4, because the beam edge strikes the tube wall. This changes the effective beam center of gravity from pulse to pulse. Position convergence was obtained at all stations to ±0.1 mm. The beam has been converged in this manner over an intensity range of 5 to 35 mA.

The effect of beam centering upon the Bevatron was investigated. The circulating charge and accelerated beam were measured (at 5 BeV) as a function of the injected current, with and without the beam centered. The results are shown in Fig. 10. For a given injector current, more accelerated beam and circulating charge are obtained when the beam is centered. Using the ramping program mode we plotted the circulating charge as a function of IM2 current and the electrostatic inflector voltage. The distributions obtained (Fig. 11) are higher when the beam is centered and less fluctuation of charge occurs. We therefore concluded that closed-looped control of the beam-center position compensates for the deflection of the linac exit beam, resulting in better pickup efficiency. Using this system, we plan to investigate the behavior of the Bevatron at its maximum intensity.

Conclusions

We believe that digital control of some accelerator parameters is feasible. Such control can offer advantages over conventional closed-loop analog control:

(1) With proper programming, several operation modes are possible with the same hardware.

(2) The automatic bookkeeping of a digital system is an aid in finding problems.

(3) Display of data is extremely flexible, and when done on-line (as were the graphs of Fig. 6), judgments about the progress of a development experiment can be made. This results in a saving of development and diagnostic time.

(4) In order to effectively use a digital system, monitoring signals must be standardized. This is a great advantage in itself.

(5) Basic changes in operation can be made by changing programs. In a conventional system, the changes must frequently be made with a soldering iron.

We believe that proper instrumentation is the key to a good accelerator-control system, whether digital or analog. Given the same instruments and slow-enough parameters to control, the digital system seems to be more flexible than conventional control.

Footnotes and References

*This work was done under the auspices of the U. S. Atomic Energy Commission.

1. 200 BeV Accelerator Design Study, Chapter XI, Vol. I, Lawrence Radiation Laboratory, Berkeley (June 1965).
2. R. W. Allison, et al., "Measurements of the Linac Exit Beam of the Bevatron Injector," in Proceedings of the 1966 Linac Conference at Los Alamos, Session II.
3. Allen J. Sherwood, IEEE Trans.Nucl. Sci. NS-12, 925 (1965).

Table I. Program mode selection

Flag	Symbol	Function
1.	F10	Monitor display for typewriter
	F11	Monitor display to scope
2.	F20	Turn off monitor mode
	F22	Monitor every pulse
3.	F30	Output errors on typewriter
	F31	Output errors on scope
4.	F40	Turn off position control
	F41	Turn on position control
5.	F50	Turn off magnet control
	F51	Turn on magnet control
6.	F60	Turn off plot output
	F61	Turn on plot output
	F63	Turn on plot output step x, plot y
7.	F70	Turn off ramping
	F7n	Turn on ramping, increment control word every nth pulse

Table II. Multiplane convergence at 20 mA.

Station being		Beam-centerline displacement (mm)						
converged	Pulse	P2H	P4H	P5H	P2V	P4V	P5V	Comments
SM3H - P2H	1	+2.0	- .37	+2.2	0.8	1.7	6.7	
SM3V - P2V	2	+0.3	+10.1	-2.1	0.03	1.6	6.4	
	3	+0.02	+18.5	-3.0	0.02	1.6	6.2	
SM4H - P4H	1	-0.02	+18.5		0.02	+10.0		Beam lost on tube wall pulses 1-4. No P5H, P5V reading.
SM4V - P4V	2	"	+ 4.6		"	+11.7		
	3	"	- 1.2		"	+ 3.4		
	4	"	- 1.7		"	+ 0.07	+6.7	
	5	"	+10.1	-3.0	"	+ 0.07	+3.4	Vert. plane converged.
	6	"	+ 2.4	+1.7	"	+0.07	+3.4	P4H only adjusted.
	7	"	-0.02	+2.5	"	"	+3.4	
SM5H - P5H	1	"	"	+2.4	"	"	+3.6	
SM5V - P5V	2	"	"	+1.7	"	"	+2.0	
	3	"	"	-0.01	"	"	+0.02	

FIGURE LEGENDS

Fig. 1. Plan view of Bevatron inflection system with control system functional diagram.

Fig. 2. Block diagram of digital control system.

Fig. 3. Interior view of control-system interface rack.

Fig. 4a. Functional diagram of control program.

Fig. 4b. Control timing diagram.

Fig. 5. Circulating charge as a function of electrostatic-inflector voltage, as shown on digital-system display oscilloscope. (a) Point plotted every pulse; (b) points plotted every ramp pulse. (For approximate scale, see Fig. 12.)

Fig. 6. Digital display of inflector parameters, with an error record.

Fig. 7. Position-electrode response curves. (The amplifier was compensated for diode response, and no compensation.)

Fig. 8. Linear and non-linear electrode response for single-plane convergence.

Fig. 9. Display oscilloscope presentation of position-electrode response curve.

Fig. 10. Affect of beam position control on circulating charge and Bevatron accelerated beam.

Fig. 11. Response of Q electrode to IM2 current and electrostatic inflector voltage, for beam centered and not centered.

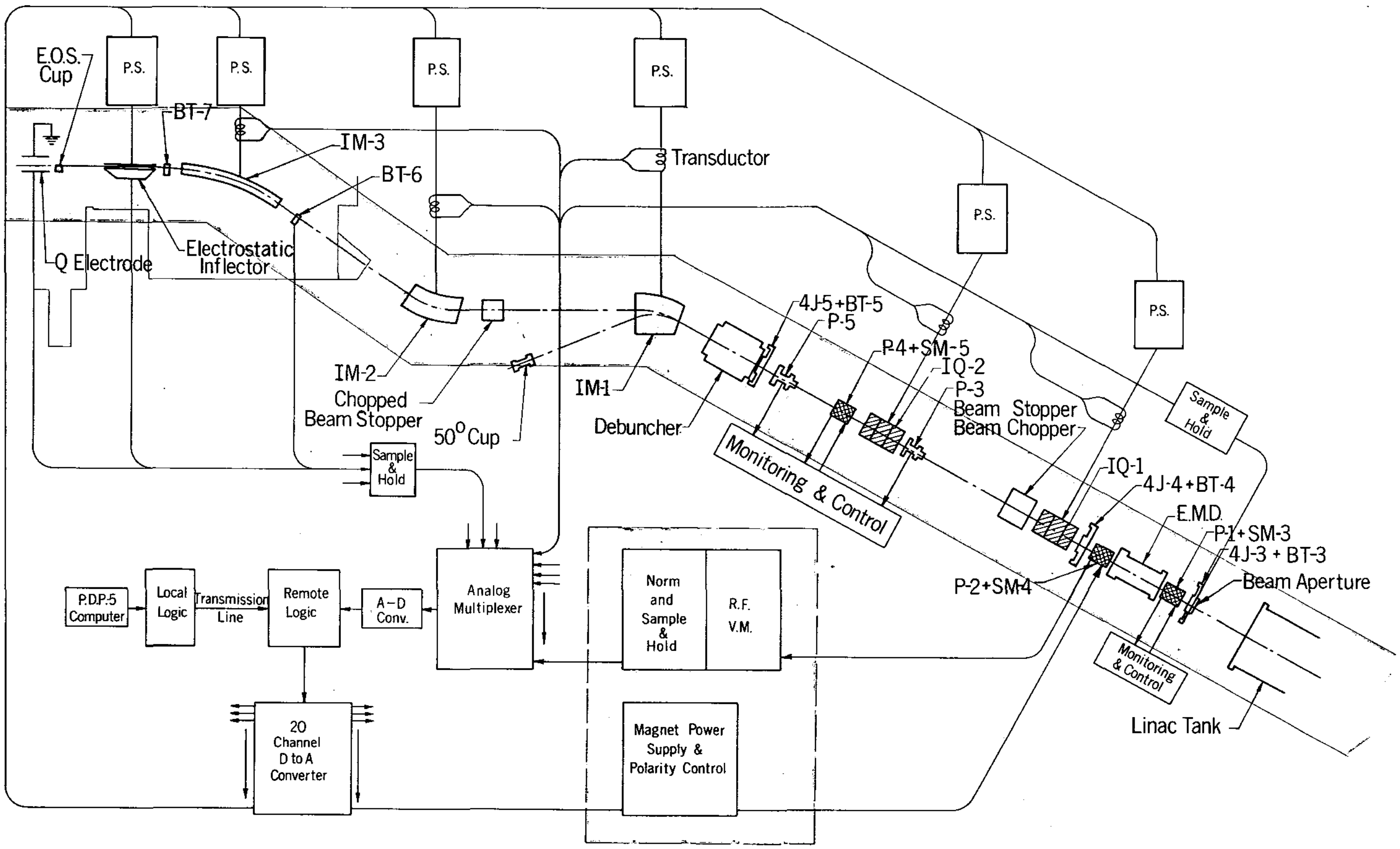

E.O.S. Cup
P.S.
P.S.
P.S.
P.S.
P.S.
P.S.
BT-7
IM-3
BT-6
Transductor
Q Electrode
Electrostatic Inflector
IM-2
Chopped Beam Stopper
50° Cup
IM-1
Debuncher
4J-5+BT-5
P-5
P-4+SM-5
IQ-2
P-3
Beam Stopper
Beam Chopper
Monitoring & Control
Sample & Hold
Sample & Hold
IQ-1
4J-4+BT-4
E.M.D.
P-1+SM-3
4J-3+BT-3
Beam Aperture
P-2+SM-4
Monitoring & Control
Linac Tank
P.D.P.-5 Computer
Local Logic
Transmission Line
Remote Logic
A-D Conv.
Analog Multiplexer
Norm and Sample & Hold
R.F. V.M.
20 Channel D to A Converter
Magnet Power Supply & Polarity Control
MUB-12792

Fig. 1

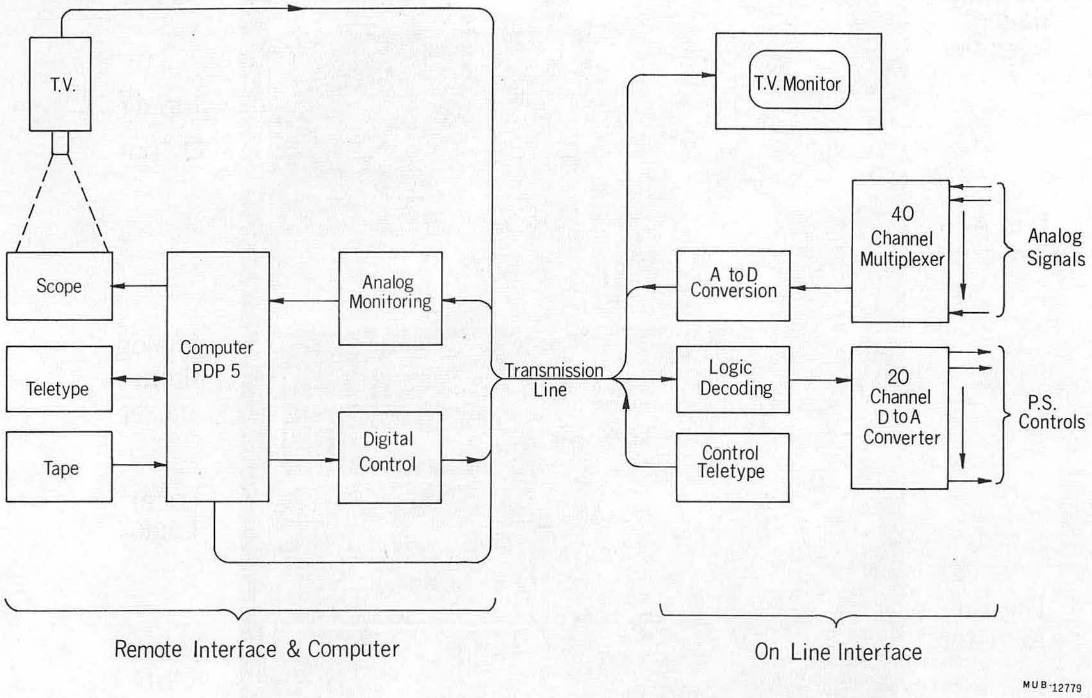
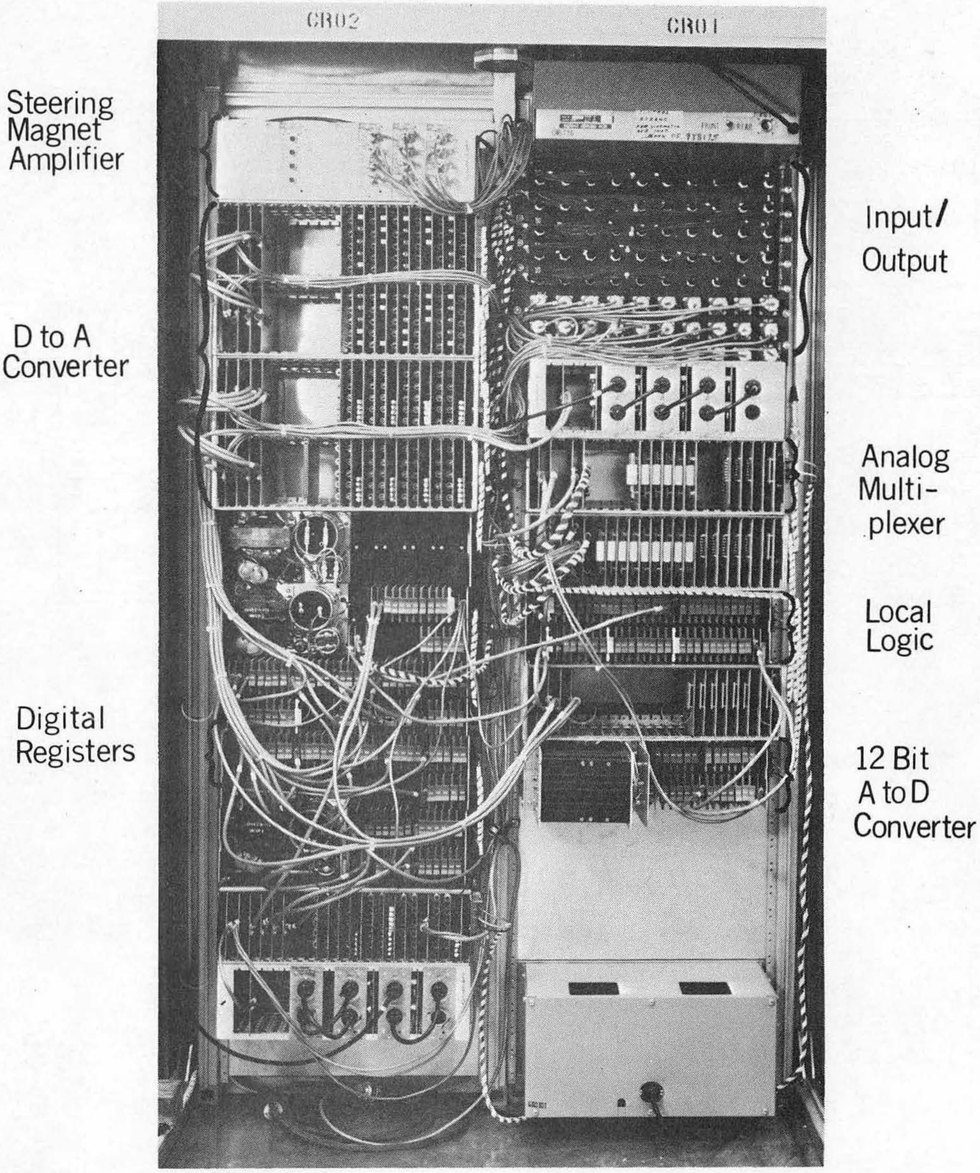
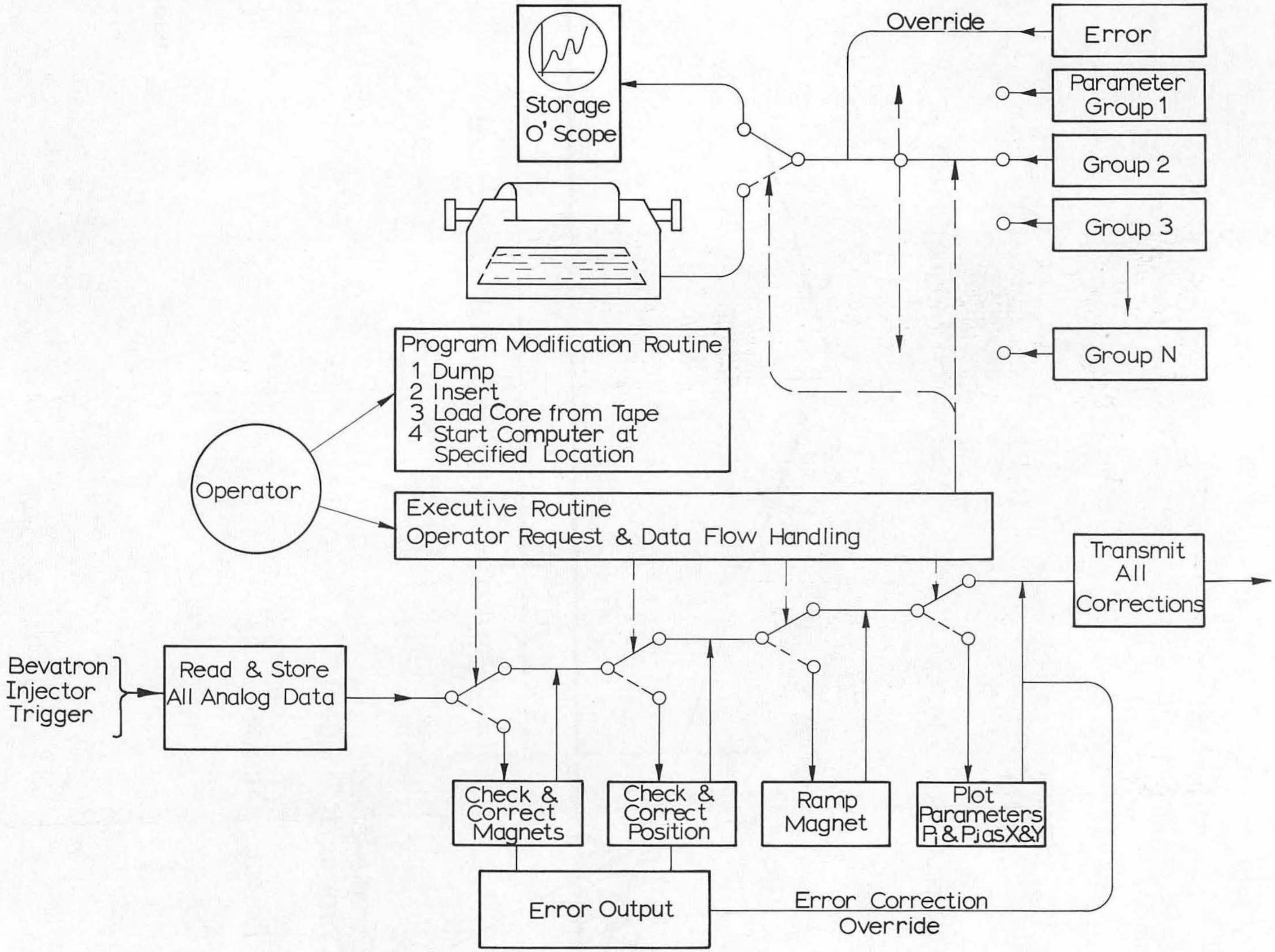

T.V.
Scope
Teletype
Tape
Computer PDP 5
Analog Monitoring
Digital Control
Transmission Line
T.V. Monitor
A to D Conversion
Logic Decoding
Control Teletype
40 Channel Multiplexer
20 Channel D to A Converter
Analog Signals
P.S. Controls
Remote Interface & Computer
On Line Interface
MUB-12779

Fig. 2


CR02
CR01
Steering Magnet Amplifier
Input/ Output
D to A Converter
Analog Multi-plexer
Local Logic
Digital Registers
12 Bit A to D Converter

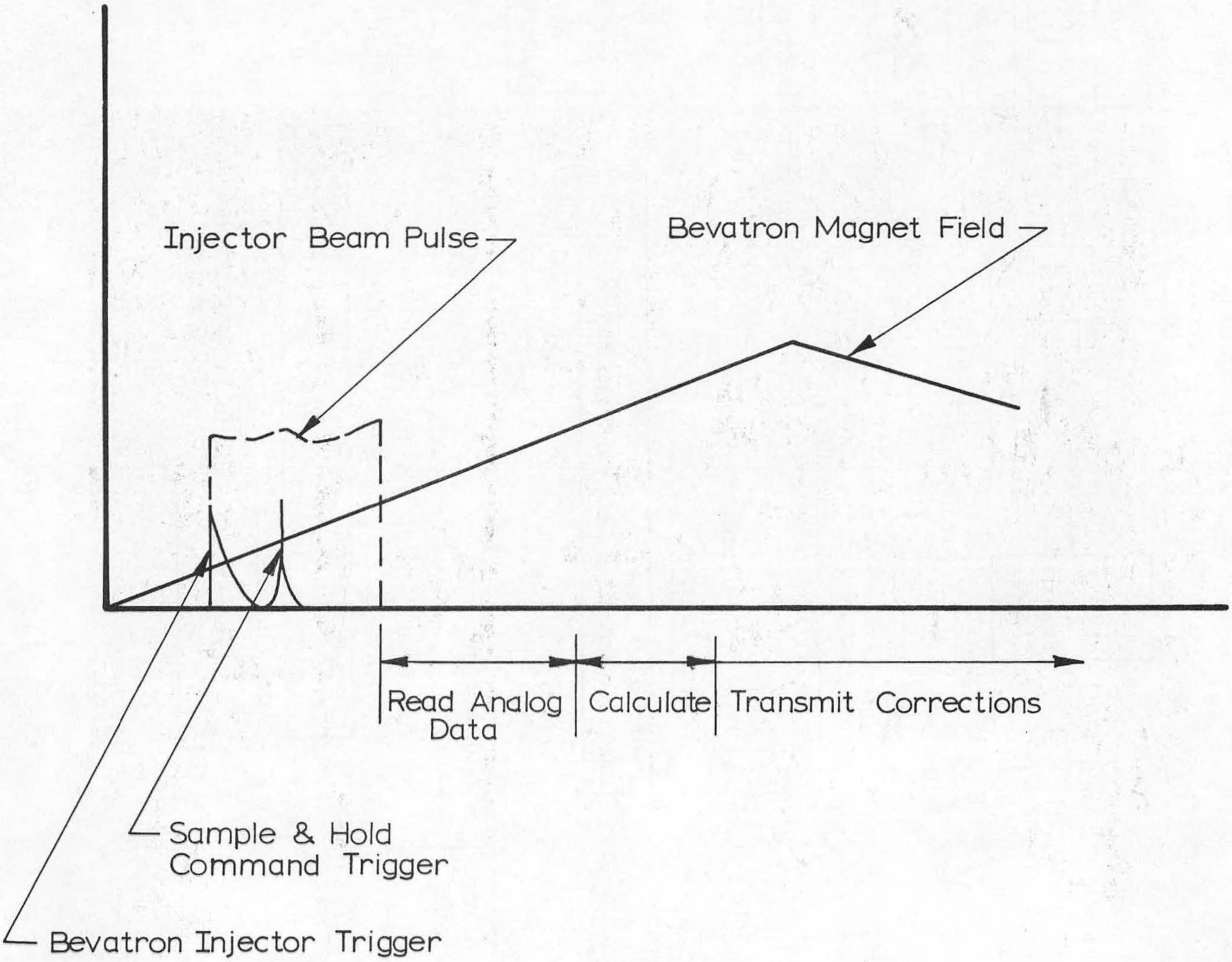
ZN-5912

Fig. 3



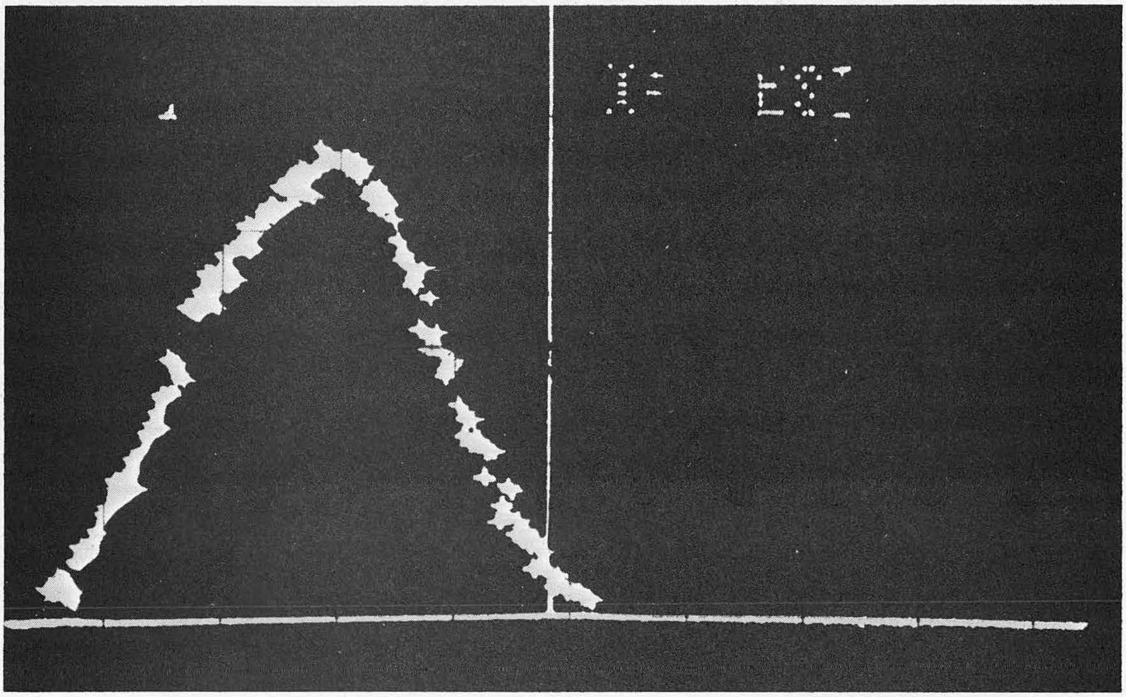
MUB 12846

Fig. 4a



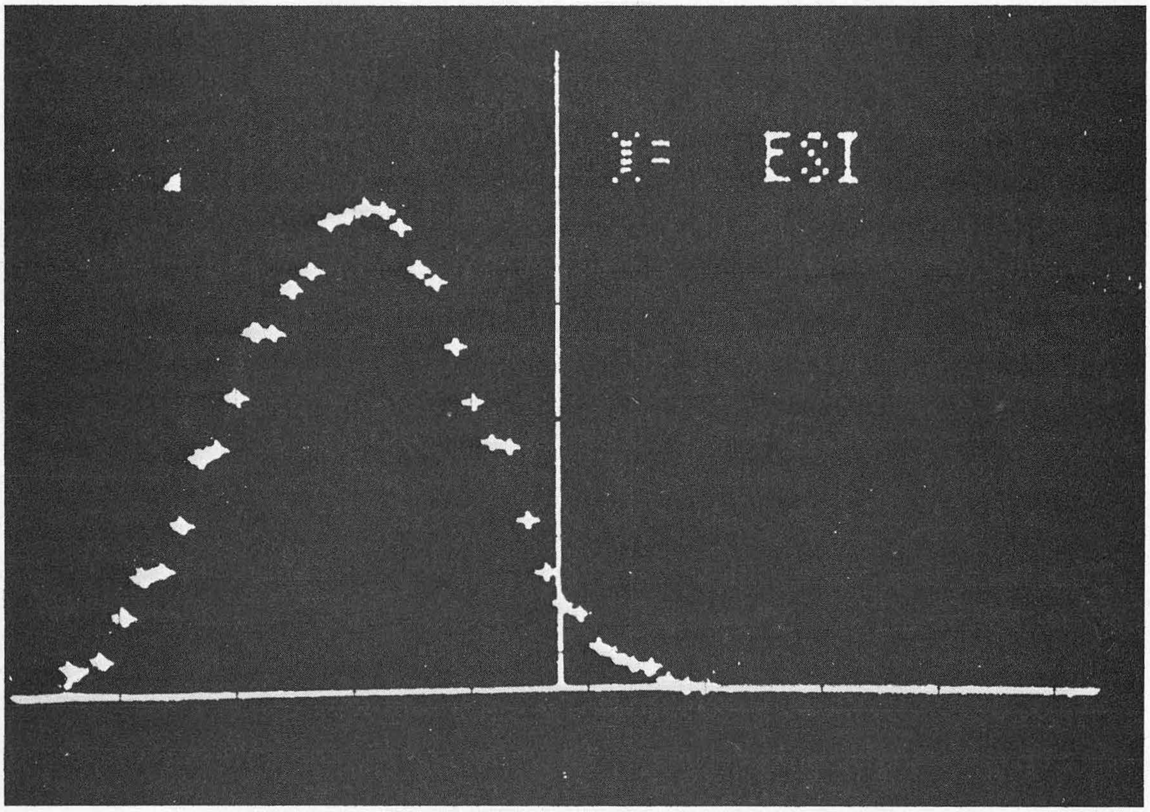
MUB-12844

Fig. 4b



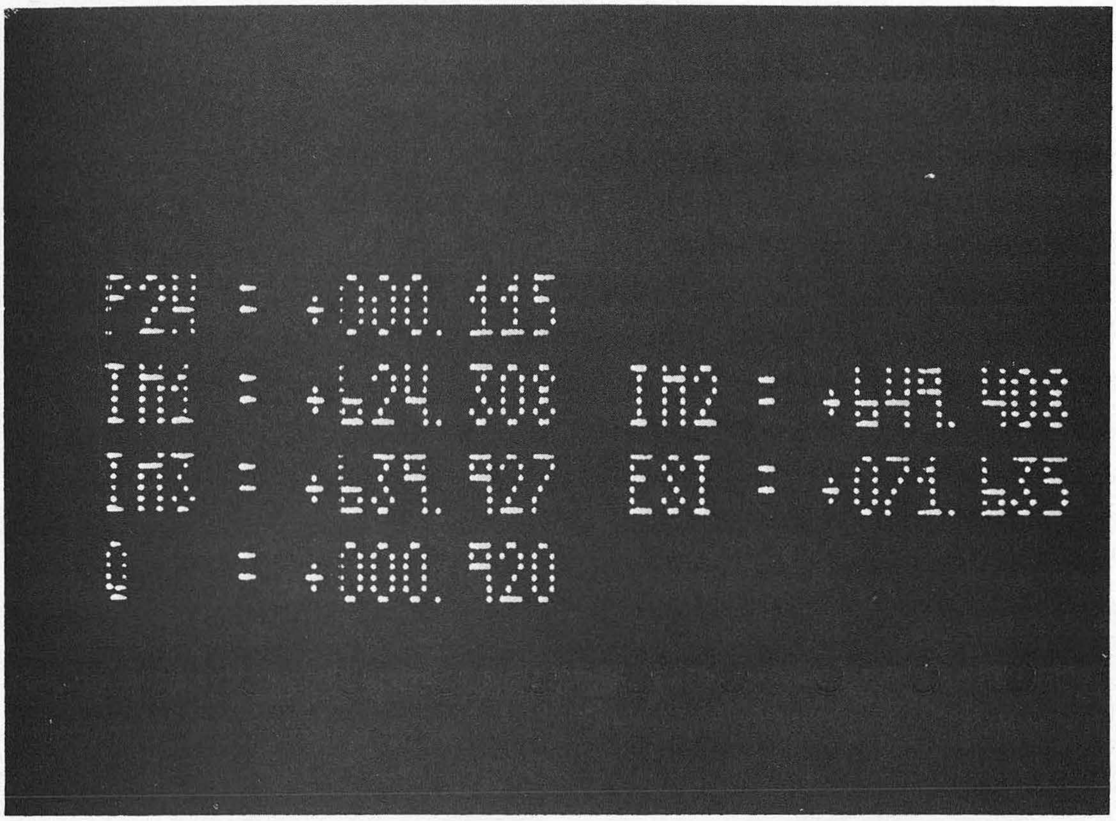
ZN-5909

Fig. 5a



ZN-5910

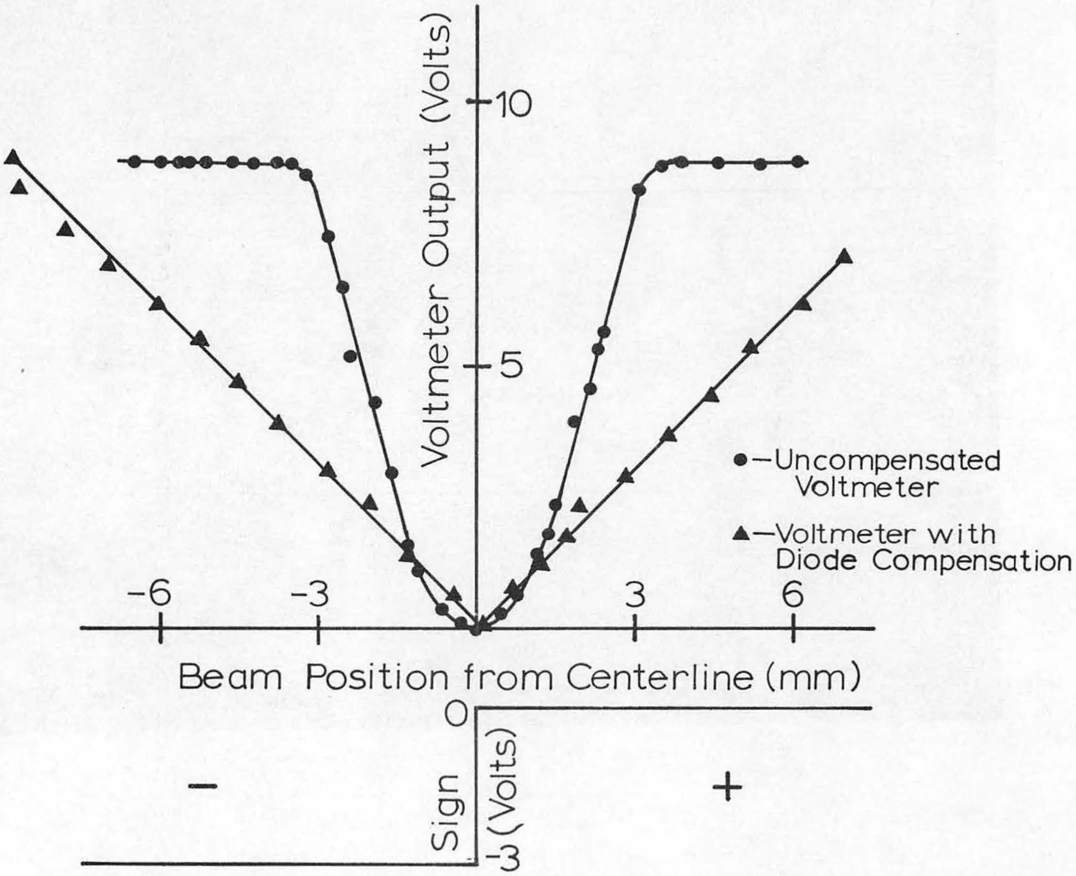
Fig. 5b



```
P2H = +000.115
IN1 = +624.308  IN2 = +649.408
IN3 = +639.927  ESI = +071.635
Q   = +000.920
```

ZN-5908

Fig. 6



MUB-12843

Fig. 7

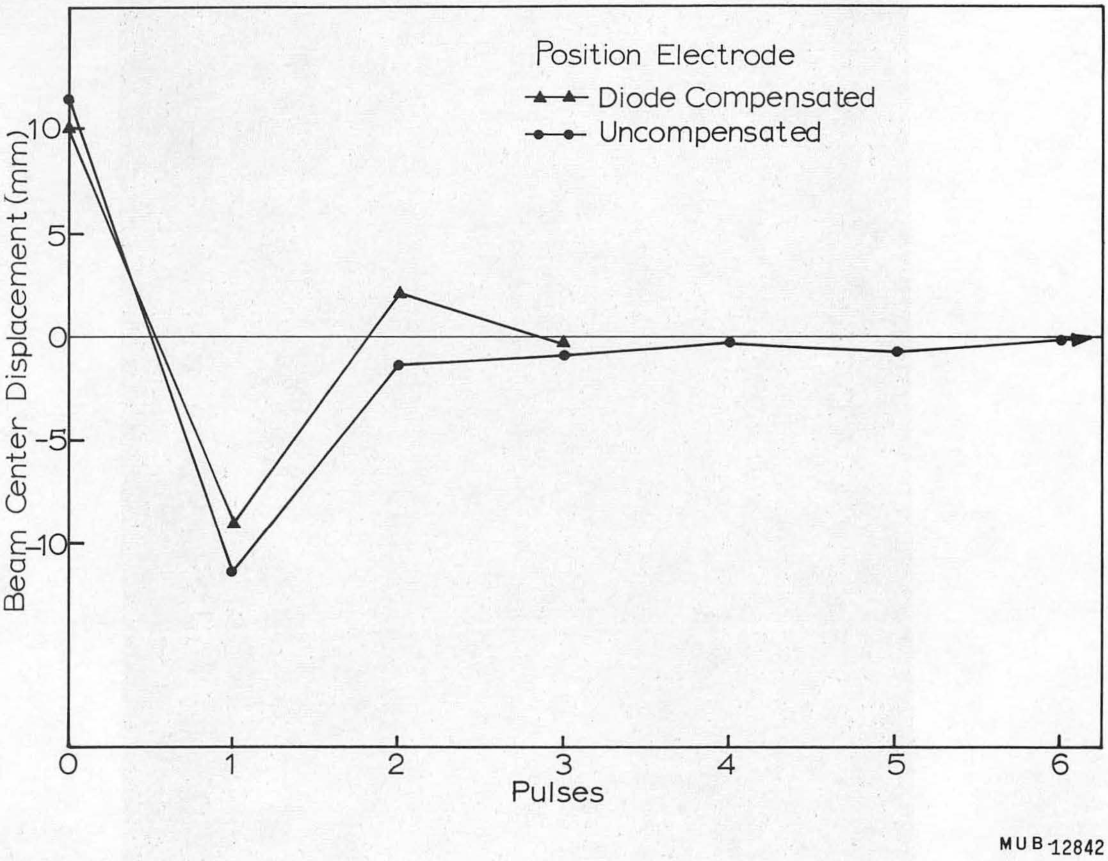
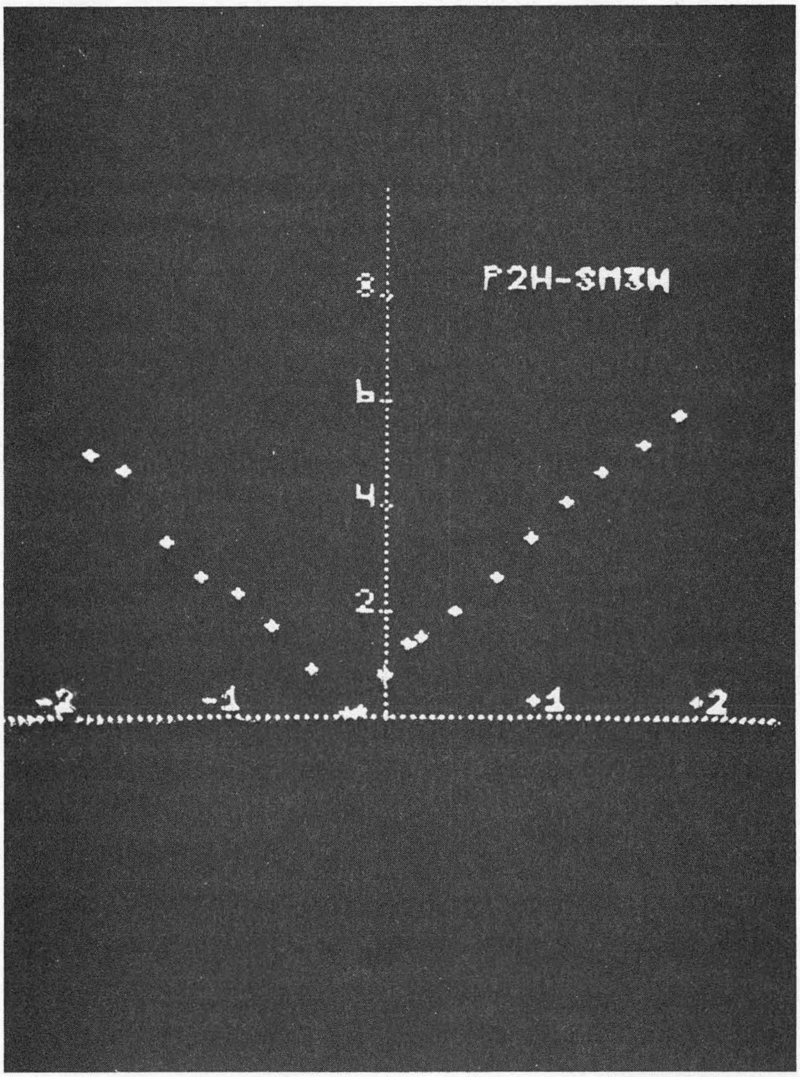
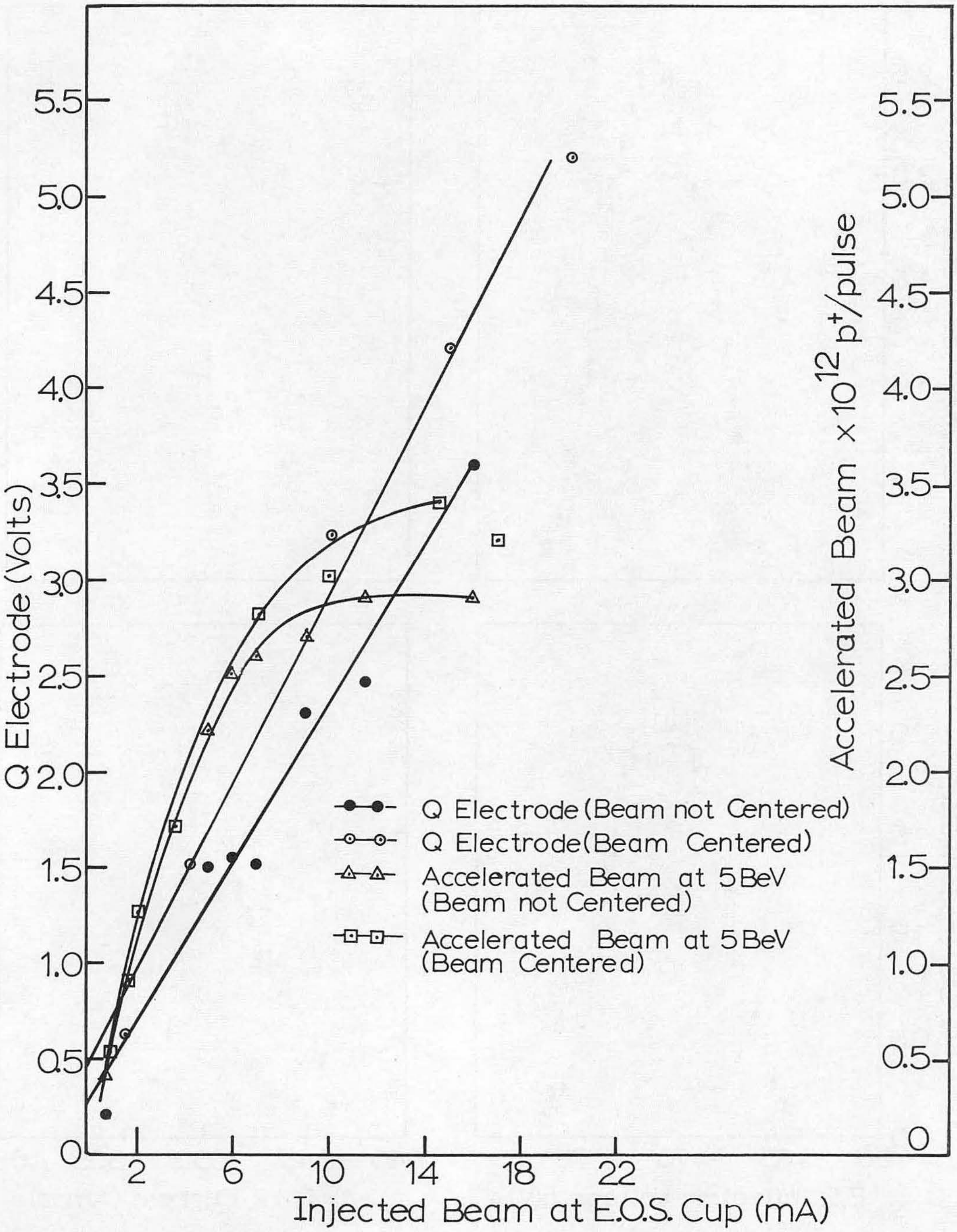

Position Electrode
Diode Compensated
Uncompensated
Beam Center Displacement (mm)
10
5
0
-5
-10
0
1
2
3
4
5
6
Pulses
MUB-12842

Fig. 8



ZN-5911

Fig. 9



MUB-12841

Fig. 10

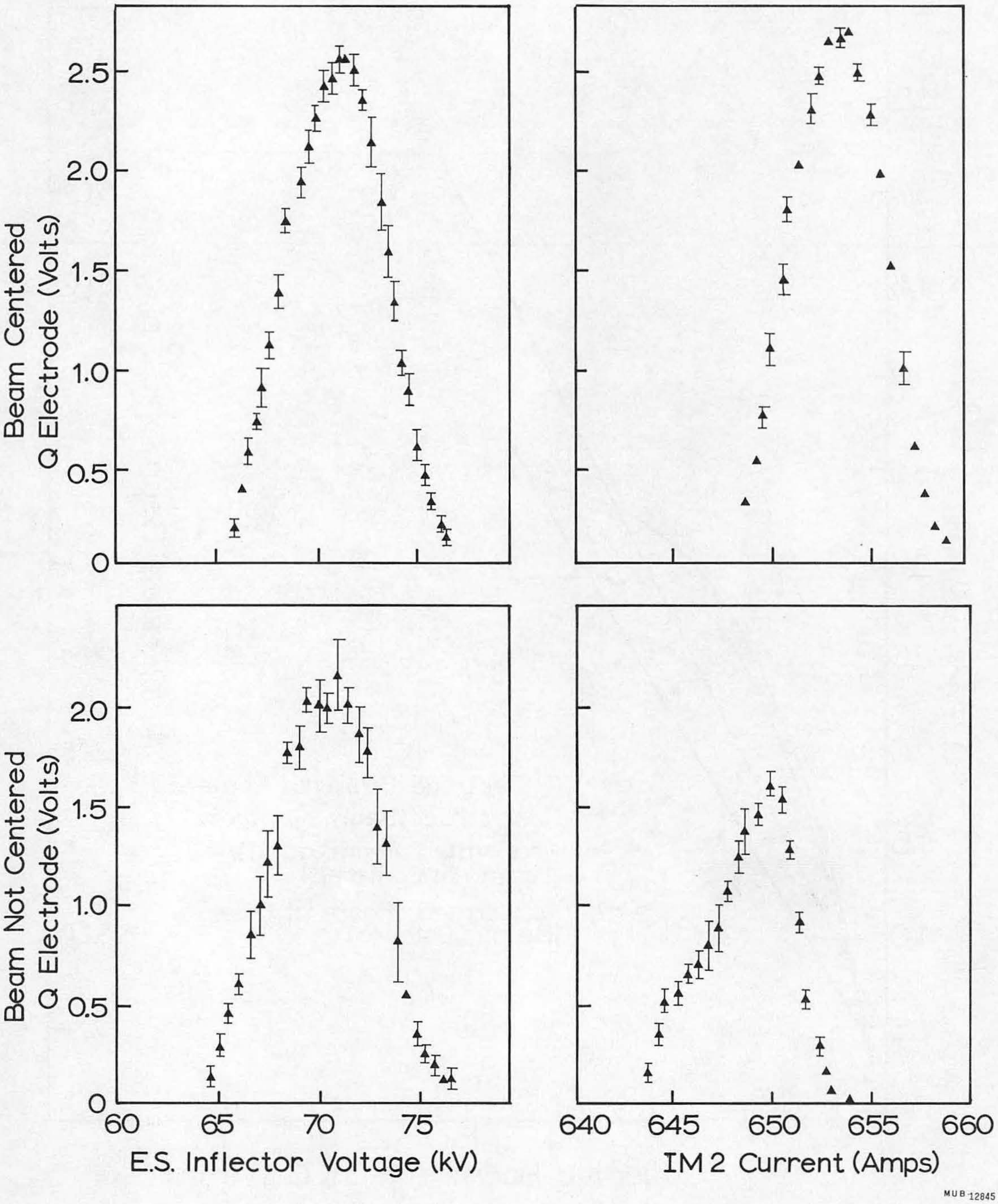

Beam Centered
Q Electrode (Volts)
Beam Not Centered
Q Electrode (Volts)
2.5
2.0
1.5
1.0
0.5
0
60
65
70
75
640
645
650
655
660
E.S. Inflector Voltage (kV)
IM 2 Current (Amps)
MUB-12845

Fig. 11