Title
DIGITAL COMPUTER CONTROL OF THE BEVATRON INFLECTION SYSTEM

Authors
Lancaster, H.D.
Machen, D.R.

Publication Date
1967-02-18

UCRL-17273

University of California

Ernest O. Lawrence
Radiation Laboratory

DIGITAL COMPUTER CONTROL OF THE BEVATRON INFLECTION SYSTEM

Berkeley, California

Paper Presented at the
1967 U.S. National Particle Accelerator Conference
Washington, D.C., March 1-3, 1967

UCRL-17273

UNIVERSITY OF CALIFORNIA

Lawrence Radiation Laboratory
Berkeley, California

AEC Contract No. W-7405-eng-48

DIGITAL COMPUTER CONTROL OF THE BEVATRON INFLECTION SYSTEM

H. D. Lancaster and D. R. Machen
February 18, 1967

DIGITAL COMPUTER CONTROL OF THE BEVATRON INFLECTION SYSTEM*

H. D. Lancaster and D. R. Machen

Lawrence Radiation Laboratory
University of California
Berkeley, California

Summary

A program is being carried out at the Bevatron, in cooperation with the 200-BeV Design Study,[1] to investigate the application of computerized digital control to accelerators. Specifically, a digital-computer control system has been placed in operation at the Bevatron injector for investigation of control and operator interaction between an on-line control computer and an operating accelerator. The system controls transport and inflection of the 19.3 proton beam.

The computer, which is remotely located from the accelerator, collects and disseminates control information through time-shared, hybrid (analog -- digital) interface hardware. Data transmission is via twisted pair cable. With this system the beam's center of gravity has been maintained at the entrance of the achromatic inflector, in the transverse planes, to ±0.1 mm and ±0.1 mrad[2] by closed-loop sampled-data control of steering magnets at three points along the beam-transport channel. Beam-position information is obtained from 200-MHz resonant induction electrodes[3] located near each steering magnet.

In addition, the inflector deflection and focussing elements may be set by the operator and then regulated automatically by the computer.

The operator may request typewritten or cathode-ray-tube (CRT) alphanumeric display or a CRT plot of parameters of interest.

Optimization of the circulating charge in the accelerator by automatic adjustment of the inflector magnets and on-line diagnostics of certain injector components during trouble periods are planned.

The Injector Control Problem

Early in 1965 it was decided to implement digital control on selected deflection and focussing elements along the injector inflection channel. The parallel development of 200-MHz resonant induction[2] electrodes would provide beam-position feedback information for the computer. In this way, an effective beam-steering algorithm could be developed.

In addition, the dependency of charge pick-up in the main ring to the magnetic field in the achromatic inflectors would present an optimization control problem worth implementing on a digital control computer. Figure 1 shows the inflection channel with connections to the computer control system.

The most effective way to display operating parameters to the machine operators has been very important in the project. Acceptance of an essentially new method of control presents unexpected problems. The unique abilities of a digital computer to rapidly deliver information to visual display devices has been utilized to the maximum degree.

Major System Components

Aside from the fact that the computer controls a section of a particle accelerator, the computer and interface equipment are general in nature, as shown in Fig. 2. The actual system could control any one of a dozen processes--the only change in going from one process to another would be in the control algorithms.

In September of 1965, a small, 4096-word, 6-μsec memory cycle PDP-5 digital computer was purchased. The machine is equipped with a single 10-character-per-second teletypewriter and CRT X-Y display hardware. A 45-inch per second, 200 - or 556-character-per-inch magnetic tape unit was added. At this point the computer looked like any other small stored-program digital processor. The conversion to a true control computer came with the addition of the data input-output channels.

Two separate time-division multiplexed-data channels were added to the computer. One channel was allocated to analog parameter monitoring, and one to digital control of the various pieces of inflector equipment. Each channel communicates with the computer over a twisted pair transmission line 1000-feet long. The line is transformer isolated and driven symmetrically for each bit during serial transmission of data. Phase lock, pulse-code modulation is used for bit encoding

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

(Fig. 3). Transmission line noise is less than 0.1 volt differentially.

Analog Monitoring Data Channel

The outputs from inflector equipment monitoring transducers are routed to a remotely located 40-point, reed-relay, time-division multiplexer. The desired monitor point is called for by computer command over the 1000-feet telemeter link. The addressed reed-relay applies the dc output voltage from a transducer to a 12-bit analog-to-digital converter. The dc level is converted to a binary word and sent back to the computer for processing. A total of 5-msec is required to access any monitor point and receive the resultant word from the transducer selected. A total of 200-msec is then required for a complete scan of the 40 points. Some inflector parameters are held in analog sample and hold networks because of the time required to access the complete multiplexer.

Contact closure may also be monitored with this system. In such a case, voltage source of a constant value would then be switched to this multiplexer. The presence or absence of the voltage indicates the status of the contact.

Digital Control Data Channel

Control reference voltages for the many time-shared analog devices connected to the computer system are derived from digital-to-analog converters (DAC). The DAC is selected by the computer through the digital control data channel. Upon command, the computer addresses the solid state, time-division multiplexer, thereby addressing a specific DAC. A 10- or 12-bit control word may then be sent from the computer via the telemeter link, through the multiplexer to the DAC serial to parallel converter-register. This register then contains the binary word, which is to be converted into an equivalent voltage and applied to the reference input of the selected analog device.

This conversion (word to voltage) is accomplished by the actuation of reed relays by the bits in DAC register. These relays, in turn, switch the input registers of a binary weighted resistor ladder from ground to a 0.01% regulated 10-volt source. The result is a step-wise quantized "linear" voltage output with increasing control word magnitude.

Although the multiplexer and logic for the digital control data channel are solid-state devices, the data rate is limited to 5-msec per point owing to the reed-relay DAC. A complete change of all 20 points can be accomplished in 1-msec and can be repeated every 5-msec. Note that a factor of 30 increase in data rate could be realized should the analog switches be replaced with solid state devices. A resultant increase in system cost would also be seen, however.

Operator Input-Output

After it was found that the computer could, in fact, be operated remotely in a successful manner--the computer and one-half of the interface logic is located in another building--two teletypewriters were installed in the Bevatron. One teletypewriter is in the injector control room, and the other in the main control room. From these locations, all program operation can be carried out. Even program debugging and construction can be done remotely.

In addition, closed-circuit video presentation of the display tube face is transmitted to both control rooms from the computer area. Both teletype and video are sent along the same cable that carries the digital data for the two data channels. The negligible interference between various types of transmitted data is attributed to excellent common mode rejection of the data link telemetry and the type of data encoding.

All control commands are initiated at present via a teletypewriter. Continuous changes in a parameter such as an inflector magnet current are needed when the beam is manually optimized. Performing this function through the teletype is very clumsy as it requires the typing of a mnemonic plus the set point value for each new change. To alleviate this problem, a separate digital data channel operating through the digital part of the analog data channels has been designed. It is anticipated that the information from a variable-rate integrating-type control knob plus a control-channel selector switch will be transmitted through this data channel.

Control Implemented on the Bevatron Injector

The beam is guided from the output of the linear accelerator to the entrance of the first inflector magnet by means of six steering magnets, three horizontal and three vertical. Beam-position detectors, one horizontal and one vertical located on the down-stream side of the steering magnets, give the computer information concerning the position of the beam's center of gravity. With this information the computer can place the beam anywhere in the beam pipe.

The currents in quadrupole and inflector magnets in the beam channel and the electrostatic inflector voltage can be set to any desired value.

The output control words of all these control loops closed through the computer are calculated by means of the linear interpolation algorithm:

$$X_{n+1} = \frac{(X_n - X_{n-1})(Y_r - Y_n)}{(Y_n - Y_{n-1})} + X_n ,$$

where X_n is the present value of the control word, Y_n is the present value of the monitored variable, and Y_r is the required value of the monitored variable. The interpolation routine is entered each time the variable Y_n is monitored until Y_n approaches Y_r to within the specified tolerance. At this time the computer proceeds to the next downstream variable. After all variables have reached their respective required values, they are monitored and held there by the computer.

The devices controlled all have time constants which are short compared with the sampling period, so no digital compensation is required.

A simple optimization routine has been included in the control program. It works much like and operator would in manually "tuning" a parameter. A variable to be maximized is monitored while a control is coarsely incremented over a given range. The computer remembers the largest value of the variable and returns to it. Then by continually halving the coarse increment and taking increments about the largest preceeding value, the computer makes the variable converge to the maximum. About ten samples are needed when the circulating charge in the Bevatron is maximized by controlling the electrostatic inflector.

Other Interface Devices

Disc Memory

A six-million bit-per-side disc memory has recently been added to the computer. The disc has 128 tracks which are directly addressable through a movable head. Each track holds approximately one PDP-5 core load. In addition, three fixed heads operate on a separate (lower) disc. One of these heads recirculates data on the display scope; the other two are spares. Average time for access to data on a given track is 25-msec. If the head must be moved to a new track to access data, a time of 5-msec times the number of tracks moved, plus a 100-msec head-settling time must be added to the average track-access time.

The disc memory will give added flexibility to the PDP-5. We now will be able to time-share programs so we can run more than one control system, or run data-collecting equipment, such as the emittance equipment, while controlling the linear accelerator inflector system.

Display Scope

A 10 by 10 inch display scope with light pen will soon be functioning through the disc and computer. Points and vectors will be used to plot alphanumeric information on a 1024-by-1024 matrix on the scope face.

Data to be displayed will first be written on the lower disc by the computer, then read and displayed continuously as the disc revolves. This frees the computer for other jobs.

We will use the light pen to investigate its capability as an interface between accelerator operator and control computer.

Beam Emittance Equipment

Equipment is now being completed which will automatically measure and digitize several beam parameters, and will permit, among other things, the calculation of beam emittance. Several seconds will be required to get enough data for a complete emittance plot. A preliminary reduction of the raw data will provide an emittance plot on the PDP-5 controlled display scope. In addition, the raw data will be stored on magnetic tape for a more sophisticated analysis at our computing center.

To accommodate this data, a digital channel separate from the normal control and monitor channels has been added to the PDP-5.

Besides providing a tool for better understanding of factors affecting beam quality, this investigation may lead to a method for on-line control of beam quality.

Computer Program

The success of a computer control system depends importantly on the program written for the computer. The program is as much an integral part of the system as, say, the data transmission link, so it must be carefully written to provide reliable service e.g., the program should not be destroyed by an operator error on the teletype keyboard. In addition, the program must provide for simple and flexible communication between the operator and computer.

The present program for the Bevatron inflector control system has several subroutines which are tied together by an executive routine (Fig.4). Some of the subroutines are entered each time the sample interrupt occurs; the others are entered at the discretion of the operator, who sets flags in the program via the teletype. One of the subroutines is a utility program which provides for loading of core from tape, dumping sections of core, and starting the computer in a specified location.

The subroutines presently included in the main program:

a. Input analog monitor channel data and conversion to display units,
b. Check and adjust magnet currents,
c. Check and adjust beam position,
d. Output errors. If either subroutines b or c found errors, this section will output the names and present values of the variables involved.
e. Ramping. Ramping involves making one of the controlled variables take an incremental step after each nth Bevatron pulse.
f. Graphing output. This section will plot a graph of the successive values of any two variables.

g. Display output. This section outputs a selected group of monitored variables on the display scope.
h. Maximize a monitored variable as a function of a controlled variable over a given range.
i. Outputs all calculated control data.

Subroutines a and i are entered each Bevatron pulse. All others are entered by means of controlling flags. As an example of the latter, an operator typing F22F30F51 would cause all magnets under control to be set to their required currents, with errors being printed on the teletype every Bevatron pulse. Of course, each subroutine has, as necessary, mnemonics which allow the operator to change things such as magnet reference currents, ramping increments, or display groups.

We found this program arrangement to be very flexible, and to use a minimum amount of core memory. The biggest thing against it is that it forces an operator to remember a code (the flags) which is not easily related to the function it performs.

Future of Computers in Accelerators

Because of their facility in performing logical decisions in a speedy, efficient, reliable manner, computers should be the terminus for data gathering in an accelerator. The qualities that have made the computer so attractive in industrial process control are equally applicable to accelerator control. With so many low-cost computers now available, even a relatively small control application becomes economically feasible. It seems reasonable that as our application experience increases, computers will become a standard tool in accelerator control.

Acknowledgments

The help of R. W. Allison, Jr., R. A. Belshe, D. M. Evans, J. B. Greer, E. C. Hartwig, C. D. Pike, R. M. Richter, A. J. Sherwood, and E. Zajec of the Lawrence Radiation Laboratory Staff is gratefully acknowleged.

References

1. 200-BeV Accelerator Design Study Report, Lawrence Radiation Laboratory Report UCRL - 16000, Chapter XI, vol I, June 1965.

2. R. W. Allison, Jr, Digital Control of the Bevatron Inflection Trajectory, Proc. of the 1966 Linear Accelerator Conference, Oct. 3-7, 1966, Los Alamos Scientific Laboratory Report LA-3609.

3. A. J. Sherwood, Electrostatic Induction Electrode System for Beam Position Indication, IEEE Trans. Nucl. Sci. NS-12, No. 3 (June 1965)

FIGURE LEGEND

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

Fig. 2 Block diagram of digital control system.

Fig. 3 Bit encoding for pulse code-phase modulation serial data transmission.

Fig. 4 Functional diagram of control program.

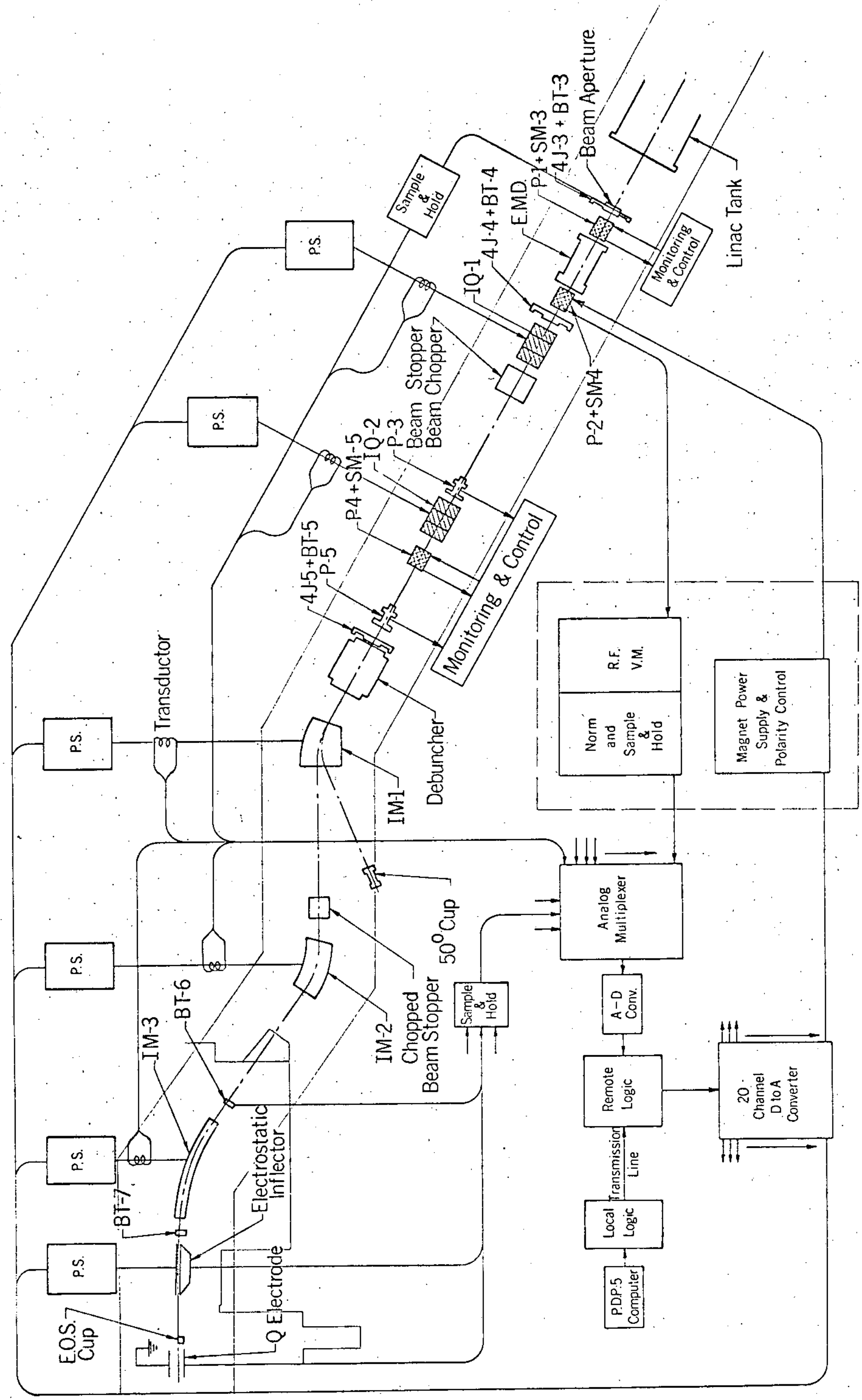

Linac Tank
Beam Aperture
4J-3 + BT-3
P-1+SM-3
E.M.D.
4J-4+BT-4
IQ-1
Monitoring & Control
Sample & Hold
P.S.
Beam Stopper
Beam Chopper
P-2+SM4
IQ-2
P-3
P4+SM-5
P-5
4J5+BT-5
Monitoring & Control
Transductor
Debuncher
IM-1
R.F. V.M.
Norm and Sample & Hold
Magnet Power Supply & Polarity Control
Analog Multiplexer
50°Cup
Chopped Beam Stopper
IM-2
IM-3
BT-6
BT-7
Electrostatic Inflector
Q Electrode
E.O.S. Cup
Sample & Hold
A-D Conv.
Remote Logic
Transmission Line
Local Logic
P.D.P.-5 Computer
20 Channel D to A Converter

Fig. 1

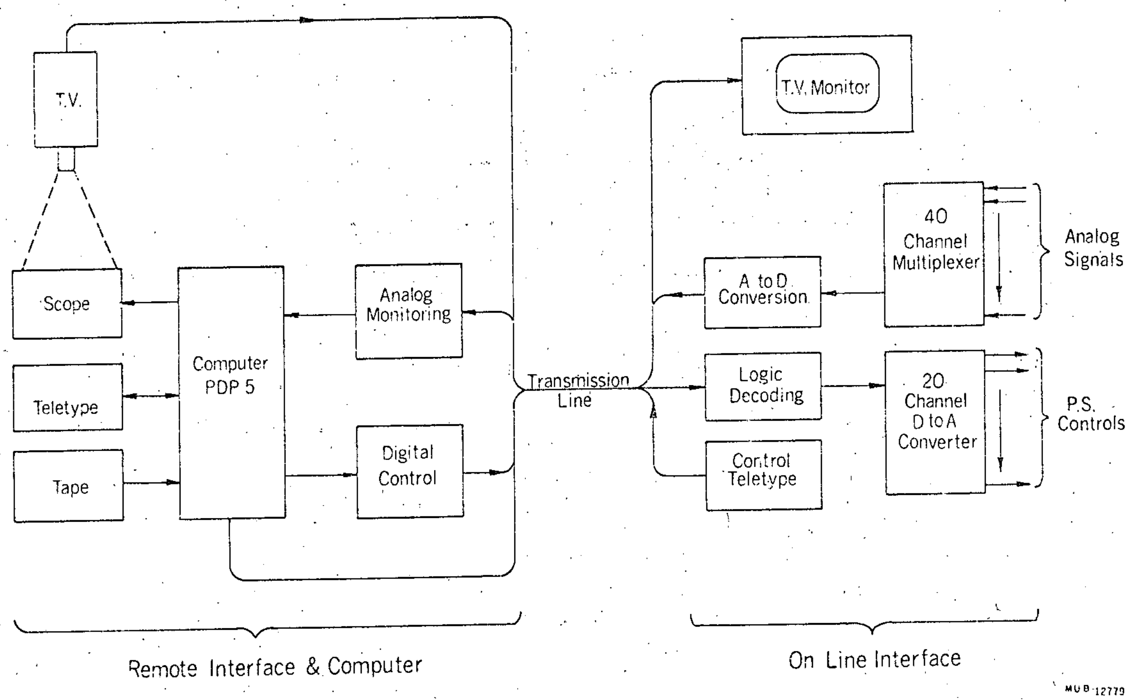
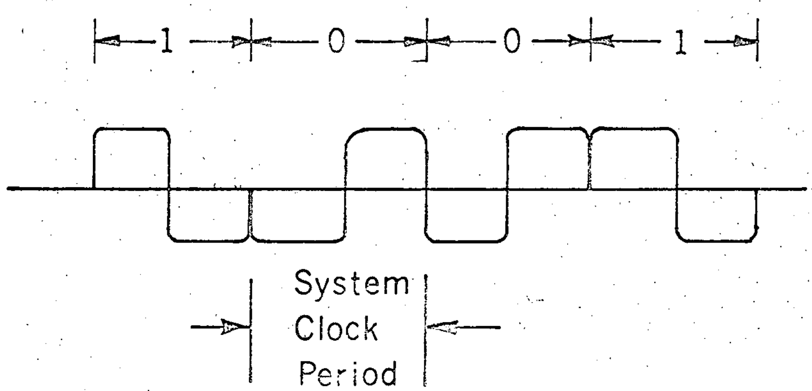

T.V.
Scope
Teletype
Tape
Computer
PDP 5
Analog
Monitoring
Digital
Control
Transmission
Line
T.V. Monitor
A to D
Conversion
Logic
Decoding
Control
Teletype
40
Channel
Multiplexer
20
Channel
D to A
Converter
Analog
Signals
P.S.
Controls
Remote Interface & Computer
On Line Interface
MUB 12779

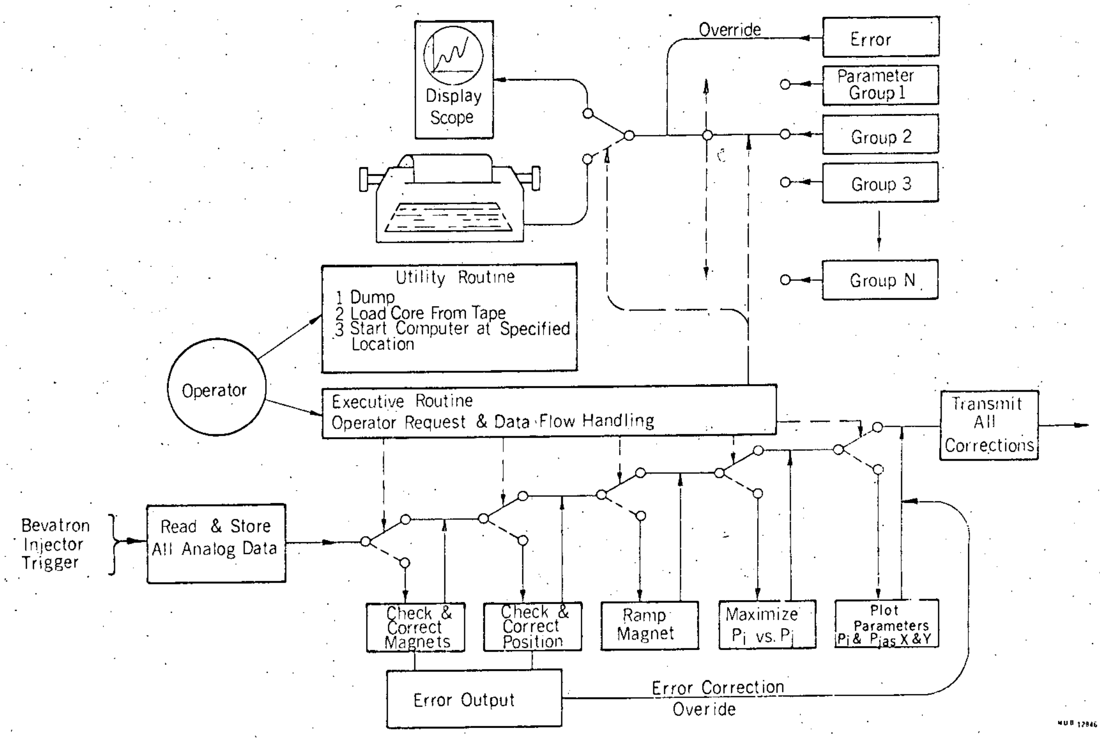
Fig. 2



Pulse Code - Phase Modulation Serial Data Transmission

XBL 672-1162

Fig. 3



Override
Error
Parameter Group 1
Group 2
Group 3
Group N
Display Scope
Utility Routine
1 Dump
2 Load Core From Tape
3 Start Computer at Specified Location
Operator
Executive Routine
Operator Request & Data Flow Handling
Transmit All Corrections
Bevatron Injector Trigger
Read & Store All Analog Data
Check & Correct Magnets
Check & Correct Position
Ramp Magnet
Maximize P_i vs. P_j
Plot Parameters P_i & P_j as X & Y
Error Output
Error Correction Overide

Fig. 4