THE APPLICATION OF A DIGITAL COMPUTER TO THE CONTROL AND MONITORING OF A PROTON LINEAR ACCELERATOR*

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Abstract

Preliminary design studies have been carried out on the control system for an 800-Mev proton linear accelerator based on the use of an on-line digital computer as the main controlling element. The accelerator system is divided into fifty-two subsections or modules. A module has complete control of all the equipment associated with it. Selected data and monitoring signals are transmitted on a time-shared basis to a central control computer. The functions which the computer performs in the control of the accelerator may be classified into Operational Control, Operational Supervision, and Data Monitoring and Handling. The operator gives instructions to the computer through interrupt lines. Commands to the modules and displays for the operator time-share a common channel in the computer output system. Synchronization of the input and output data flow is controlled by the computer through a timing unit. A comparison has been made of the computer-based control system with a possible alternate system which does not use a computer. The computer replaces much of the control and data handling equipment required by the alternate system. As a result, the costs of the two systems are comparable. However, the computer-based system is preferable since it has many functional advantages over the alternate system.

Introduction

Design studies are being conducted at the Los Alamos Scientific Laboratory for the construction of a high intensity 800-Mev proton linear accelerator. The proton beam is to be used primarily for the production of secondary meson beams for the study of nuclear structure physics. This paper describes the results of preliminary studies on the application of a digital computer to control the many subsystems which are involved in the operation of the accelerator. The design parameters for the machine are shown in Table I. Some of these particularly affect the design of the control system. The variation in beam conditions requires a flexible system. For example, the energy is to be variable from 200 Mev to 800 Mev. This can be achieved by shutting off the accelerating drive in down-stream tanks and allowing the beam to drift through these tanks. Similarly, debunching can be achieved for energies below 700-Mev by operating some of the accelerator sections on the phase-unstable portions of the RF cycle and allowing the beam to drift through the remaining sections. Furthermore, the pulse rate of the system affects the handling of data and the monitoring of the operation, and the length of the machine affects the trans-mission of data and command signals.

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An artist's view of the facility is shown in Figure 1. The injector building is shown on the left. The linear accelerator channel is buried below grade with an equipment building running parallel to it along its entire length. The experimental building is shown on the extreme right. RF waveguide, control and signal cables and pipes for cooling systems run from the equipment building to the beam channel through a number of service corridors and shafts shown on the back side of the equipment building. The main control room is located in the building approximately midway between the injector building and experimental building. An administration building and nuclear chemistry building are included on the site.

Modular Concept of the Control System

The physical grouping of the RF power amplifiers and the associated accelerator subsystems permits a natural grouping of the controls into modules and sectors (terminology after SLAC). The layout of this modular grouping is shown in Figure 2. There are a total of 52 modules in the present design. The injector systems (high current and polarized sources) and the associated beam transport and buncher systems are treated as one module. There are five modules in the low frequency section with one Alvarez tank per module. The high frequency section has 45 modules with two tanks per module. Finally the controls for the experimental area are treated as a single module. A module has complete control of all subsystems associated with it. Selected data and monitoring signals are transmitted to a central control room where an on-line digital computer performs the primary monitoring and control tasks for the operation of the accelerator.

Computer Functions

The on-line functions which the digital computer performs in the control of the accelerator may be grouped under three general classifications: Operational Control, Operational Supervision, and Data Monitoring and Handling. Examples of some of the major tasks which come under these headings are as follows:

Operational Control

1. The on-off sequencing of the various subsystems to transfer the accelerator from one stand-by

condition to another and to bring the machine into full operation. This includes the turn-on of the injector, the beam transport and buncher systems, the RF power amplifiers and the focusing quadrupole magnets.

2. Generation of gating signals and/or pulse trains for the timing of machine operation.

3. Direct digital control of various sub-systems. An example of this is the control of the water temperature in the cavity cooling systems.

4. Monitor and adjust the set-points of various sub-systems. The operator may specify a particular set-point and the computer generates and transmits the necessary commands to the system to obtain the setting.

Operational Supervision

1. Automatic set-up of the parameters required for various beam conditions. This includes computing the values for and setting the ion source current, machine repetition rate, RF phase and amplitude conditions and focusing magnet currents.

2. Monitor the operation of various sub-systems and generate alarms for out of limit conditions; display sub-system status upon operator demand.

3. Monitor interlock chains and generate interlock logic.

4. Log and tabulate control settings.

5. Generate timing signals for the operation of the input and output data systems.

Data Monitoring and Handling

1. Multiplex and decode input signals.

2. Store data and calibration information.

3. Record, plot and print-out operational data.

4. Provide selectable outputs to displays.

5. Edit data scale, apply zero-offset and non-linearity corrections.

There are also numerous off-line tasks to which the computer can be applied which will assist the operator in maintaining more reliable operation of the facility. Examples of such tasks include the reduction and recording of operational data, the storage and reporting of preventative maintenance data and schedules, the storage and print-out of control channel engineering data (e.g. calibration records, interconnection records), as well as simulation studies, operator training programs and limited scientific and engineering computations.

Basic Computer System and Its Operation

General Requirements

Preliminary design studies of the LAMPF control system have permitted the general requirements of a computer-based control system to be established. The basic computer requirements are shown in Table II and the minimum peripheral equipment required is listed in Table III.

Table II

Computer Requirements

Cycle Time	< 2 μsec
Word Size	24 bits (minimum)
Main Memory	32K words (max.)
Format	Floating Point
Index Registers	3 required
Access Channels	3 fully buffered
Priority Interrupt	≥ 100 channels

Table III

Computer Peripheral Equipment

Console Typewriter	I/O buffered
Magnetic Tape Unit	2 required
Line Printer	300 lines/min
Card Reader	200 cards/min
Card Punch	100 cards/min

A block diagram of the overall control system is shown in Figure 3. All signals from the 52 modules which are required for central control are channeled to the computer via the input system on a time-shared basis. Signals are conditioned and multiplexed at each module and fed to a high speed multiplexer (MXH) at central control. The output of the high speed multiplexer is converted to digital form and then routed to the computer. Timing and sequencing of the multiplexers is under control of the computer through the Timing Unit. Unblanking pulses for monitoring scopes are also supplied by the Timing Unit.

All of the information sinks which are fed from the computer time-share a single computer output line. The computer addresses a particular sink by group and then by channel within that group. Since all command signals are momentary on-off binary signals, all command channels must be terminated in latching circuits. Displays on the operator's console require a holding circuit to permit retention of data until a new sample is inserted.

Computer Input System

A simplified block diagram of the signal flow to the computer is shown in Figure 4. Four general types of data are channeled to computer from the modules. These are high frequency data, low frequency data, binary data and set-points. Each signal channel has a unique location in computer memory. Also stored in memory are the high/low limits or the set-point value for that channel. When data enters the computer it is compared against the reference values and the data is then stored. Upon the arrival of new data for that channel the comparison is repeated and the new data is stored in place of the old. If the limits are exceeded an interrupt is generated within the computer. An alarm is sent to the operator's console and the channel identification, the channel value, the reference data and time of day are printed out. Depending on the channel the computer will execute corrective action, will execute a shutdown procedure or will return to the main program and leave the action to the discretion of the operator.

High frequency data is sampled during the beam pulse and analog to digital conversion is performed during the portion of the pulse when the signal is relatively steady. One high frequency channel is sampled at each module during the pulse, permitting observation of a channel for the entire pulse. Depending on the computer memory size, the output of a limited number of high frequency channels from each module can be stored for a number of pulses. This data is periodically updated by replacing the oldest piece of stored data with new input data. Low frequency data is sampled between beam pulses. Two low frequency channels are sampled at each module between each pulse.

Binary data is already in suitable form for input to the computer. However, an alternate method of handling this data has been considered which reduces the number of additional multiplexed channels required for status information. By combining the binary signals in groups by means of binary-weighted summing resistors, a digital to analog conversion is performed and the data is handled as low frequency data. This method would permit more status information to be transmitted without expansion of the multiplexer capacity.

Set-point data is handled as low frequency data. Each module has a number of local control loops which act independently of the computer. However, each set-point is remotely adjustable at the option of either the operator or the computer. The computer compares the set-point value with the stored value and adjusts the remote set-point control element accordingly.

Commands from the control console enter the computer through interrupt channels. Three types of commands are generated at the control panel.

1. General computer instructions. These include print out and display requests, machine turn on or off commands and requests for specific beam conditions.

2. Binary commands for controlling the accelerator.

3. Set-point control adjustments. The operator can instruct the computer to alter a specific set-point or group of set-points.

Instructions and commands can be entered into the computer by means of a console typewriter, a series of switches or a series of thumb-wheel registers.

An initial estimate of the number of signals from each module indicates that there are 15 high frequency channels and 25 low frequency channels (including binary data and set-points) for a total of 40 outputs. With one high frequency channel being sampled during each pulse, two low frequency channels must be sampled between each pulse in order that all the channels are sampled by the beginning of the 16th pulse. This permits a total of 45 channels to be sampled in 15 pulses, allowing five spare channels.

The required speed of the low-speed multiplexers can be determined from the beam pulse rate and the requirement for scanning three channels per pulse period. At 30 pps, 90 steps per second are required for the multiplexers. At 100 pps, 300 steps per second are required. These speeds are within the range of reed relays and hence this type of relay will probably be used in the low speed multiplexers.

High frequency data must be scanned by the high speed multiplexer during that portion of the beam pulse when this data is relatively constant. Hence the high speed multiplexer must scan all fifty-two low speed multiplexers in this time. If this time is of the order of one millisecond, the multiplexer must have a speed of 52,000 steps per second. This speed requires the use of a semiconductor multiplexer.

Scope jacks are provided so that a given channel may be monitored at the output of the appropriate low speed multiplexer. The signals from a given channel from all modules may be monitored at the output of the high speed multiplexer. The unblanking pulses, which are required for these oscilloscope displays, are provided by the timing unit.

Computer Output System

The computer output system supplies binary command and set-point adjustments to the modules, displays to the operator's console, and alphanumeric data to the peripheral recording and printing equipment. In order to properly handle commands to the modules the system must remember what commands are in effect. To accomplish this, command memories are provided at three locations: the control console, the computer main frame, and the modules. Memory at the control console is provided in the form of toggle switches or digital thumb-wheel switches. Binary commands, addresses and routines for handling command signals are stored within the computer to provide command memory. At the modules the memory takes the form of latching relays or flip-flops.

Binary command signals control the on-off status of approximately eleven circuits within each module. The decoding of binary signals for one module is illustrated in Figure 5. The block diagram shows only a portion of the output system. Similar lines are run to all modules. A single command to any channel is issued from the computer as a 13 bit word; 6 bits for the identification of the module, 6 bits to address the channel and one bit for the command. The decoder located at central control selects the proper module, channel and command line. The address and command signals are transmitted to the memory circuit at the module. In the figure, flip-flops are shown for the command memory.

Set-point adjustment commands are handled in a similar manner. However two command lines are required for each channel; one for "up" and the other for "down". The sink-address decoder selects the proper line and the message decoder transmits the appropriate on/off signal. The computer adjusts the set-point by sending a "set" command to the correct flip-flop and sending a "reset" command when the error signal (the difference between the actual set-point and the requested set-point) is reduced to the proper value. The feedback is compared with the requested value each cycle (approximately 2 times/sec). Therefore, if 0.5% error in the setting is desired, the speed of the set-point drive unit should cover the full range of motion in 100 seconds.

Displays of binary status information and digital data are considered as separate demand groups. A limited number of such displays will be provided on the central control console. The major portion of such displays will be located on secondary racks within the control room.

Programming

It is anticipated that four basic program groups are required for the instruction of the unit. The Run Program performs the functions required to control the accelerator. It will be comprised of several subprograms to handle the various tasks that are required. A Change Program is used to effect parameter and instruction changes through data derived within the computer or entered by the operator. The Input/Output Programs control the signals interfacing with the computer proper. A Utility Program package serves to provide suitable interfaces between the various programs and the console operator.

Alternative Control System Design

Design studies have been carried out in parallel with the computer study on a control system based on special purpose hardware and manual controls. This design includes special data handling equipment for monitoring and recording operational data. The operator initiates binary commands through sequencing equipment to all modules to turn the facility on or off and to change it from one standby condition to another. Monitoring of accelerator operation is accomplished by banks of status lights and by switched analog and digital meters on the operator's console.

Conclusions

The results of design studies of the application of a digital computer to the control of a medium-energy, high-intensity proton linear accelerator have been described. These studies have shown that a computer-based system is a practical approach to the control of the accelerator. An alternative design has also been considered.

A comparison of the two control systems has shown that the computer replaces a large portion of the special data handling equipment and eliminates many of the controls and cable runs required in the alternate design. Cost studies have shown that the cost of the computer-based control system is comparable to that of the system using special purpose hardware. In addition the computer-based system has many functional advantages over the other type of system. These include:

1. The capability of performing many more tasks automatically.

2. Decreased set-up and turn-on time and fewer set-up errors.

3. A reduced number of operating personnel.

4. More flexibility in changing operating procedures and control parameters and in expanding the control system.

5. Less dependence upon operators for reliable status monitoring.

6. More uniformity of accelerator beam conditions.

From these functional and cost comparisons, we feel that the computer-based system is by far the best system for the control of the LAMPF high-intensity proton linear accelerator.

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TABLE I

LAMPF ACCELERATOR PARAMETERS

PROTON ENERGY	200-800 MEV
AVERAGE BEAM	I MA
DUTY FACTOR	6 %
PULSE LENGTH	2 ms
NOMINAL PULSE RATE	30 pps
INJECTION ENERGY	750 KEV
201.25 MC SECTION	ALVAREZ STRUCTURE
805 MC	LOADED WAVEGUIDE
TRANSITION ENERGY	176.5
LINAC LENGTH	2330 FEET

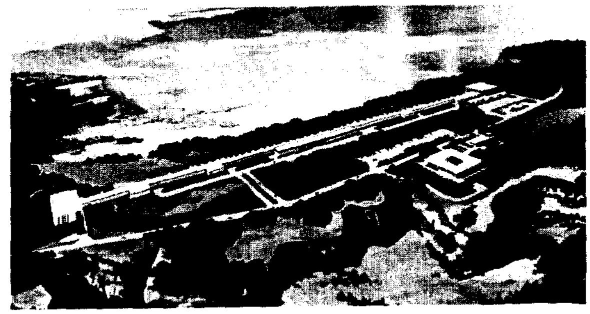


Fig. 1. Artist's view of the Los Alamos Meson Physics Facility.

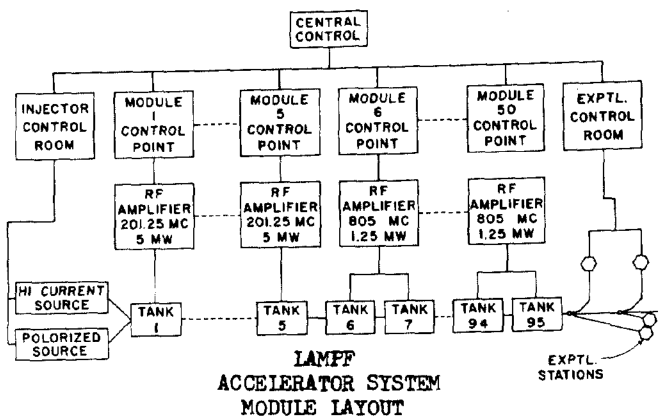


Fig. 2. The LAMPF accelerator system module layout.

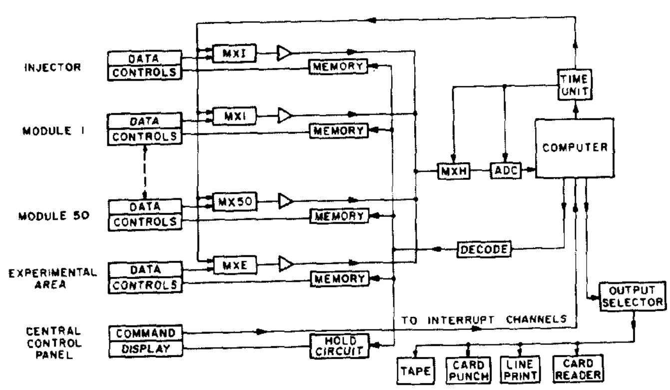
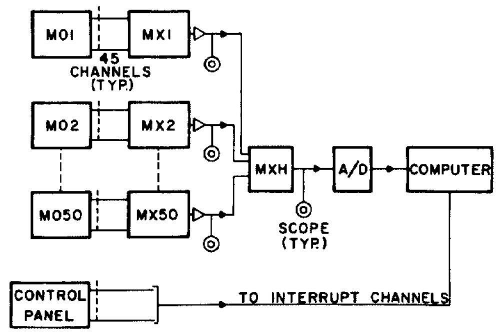
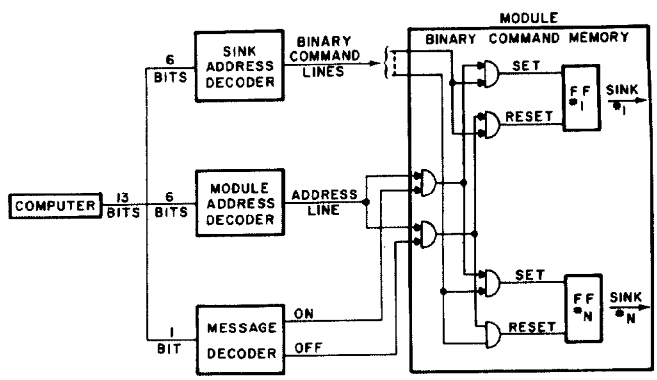


Fig. 3. Block diagram of the LAMPF computer-based control system.



SIGNAL FLOW TO COMPUTER

Fig. 4. Computer input system - signal flow to the computer.



DECODING AND DISTRIBUTION OF BINARY SIGNALS

Fig. 5. Partial computer output system - decoding and distribution of binary signals.