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COMPUTER CONTROL OF THE LAMPF ACCELERATOR*

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Abstract

A data acquisition and control system for the 800-MeV proton linear accelerator for the proposed Los Alamos Meson Physics Facility has been designed in depth on the premise that an on-line digital computer affords the best means of maintaining operational control over the machine. This paper describes how the three basic functions of any control system – data acquisition, display, and control – have been implemented with the aid of a computer.

The system as presently designed has the capability for sampling any one of 63 analog or binary data channels at any of the 55 modules in the facility (or one channel from all 55 modules simultaneously). Similarly, the system can adjust any one of the 63 control channels at any or all modules. In addition, the system can select remotely any two video channels (of a possible 31 at each module) for display in the central control room. As an example of the speed of the system, it can sample and store in the computer's memory 10 binary status indications from each of the 55 modules in less than 250 microseconds.

All information regarding the operational status of the accelerator is available to the operator on just two partial racks. The ability to adjust any control channel in the facility is provided on the same two racks. The system, which incorporates a versatile display scope, allows the operator to execute such varied and sophisticated tasks as steering the beam to compensate for misalignments of the accelerator, making phase space plots of the beam, and performing parametric studies of the effect of any control channel – all on-line.

The concepts and operational procedures embodied in the LAMPF computer control system will be tested and evaluated in a series of experiments referred to as the mockup program. The status of the hardware to be used in this program is described.

Introduction

A control system to operate a complex installation, be it an oil refinery, a steel mill, or an accelerator, must be able to perform three functions: acquire data, display it, and effect changes in the data source. The data acquisition function permits the operator(s) to sense the status of the process or facility being controlled (in this case, an accelerator). The data must then be displayed for the operator in an easily comprehensible format. The display device can be a status light, a meter, an oscilloscope, a typewriter, or an elaborate digital CRT so long as the display conveys the information in a meaningful way. If the operator decides that the data being displayed indicates an unsatisfactory state, a link must be provided by which an appropriate change can be induced in the data source. That these three functions are sufficient to permit the operation of a complex machine such as the LAMPF accelerator is not so surprising when one realizes that a modern digital computer can do nothing more advanced than add, subtract, multiply, and divide, and yet it is commonplace for such computers to solve complicated sets of equations by a programmed sequence of these simple operations.

The way in which the data acquisition, display, and control functions are implemented in the proposed LAMPF control system with the aid of an on-line digital computer and the way in which complicated procedures associated with operating an accelerator can be readily programmed are the subject of this paper.

Modular Structure of the Accelerator

In order to place the computer control system for the Los Alamos Meson Physics Facility in its proper perspective, it is desirable to review the design parameters and organization of the accelerator because these factors dictated to a large degree the structure of the control system.

The heart of the facility is a linear accelerator designed to produce a proton beam with an energy variable up to 800 MeV and an average current variable up to one milliampere. This proton beam is to be used primarily to produce intense secondary meson beams for the study of nuclear structure. The accelerator will pulse 120 times per second with a pulse length of 500 μsec, giving a 6% duty factor. Provisions are being made to increase the duty factor to 12% at a later date. The total length of the accelerator is approximately 2700 feet.

The distribution of power amplifiers, accelerating cavities, and various other subsystems along the length of the machine suggested that the accelerator be organized into modules and sectors (nomenclature after SLAC). A layout of this modular grouping is shown in Fig. 1. There are a total of 55 modules in the present design. Each injector and its associated beam transport system constitutes one module. The buncher and its beam transport system make up another module. There are four modules in the low frequency (201.25 MHz) section of the accelerator, each with

*Work performed under the auspices of the U. S. Atomic Energy Commission.

one Alvarez tank. The high-frequency section (805 MHz) has 45 modules with one, two, or four tanks per module. The several sector control points are grouped together to form a final module.

In designing the control system, it proved convenient and desirable to make use of the inherent modularity of the accelerator. This was done by establishing a centralized control point at each module. Through this control point it is possible for the accelerator operator to exercise complete control over all the subsystems comprising the module. All data required to monitor the status of the module and all signals needed to effect control over its operation are channeled through the module control point. The basic structure of the control system was established by linking all the control points together in a central control area.

Decision for Computer Control

Having established the modular structure of the control system, the remaining problem was to determine the precise way in which the operator would communicate with any given module control point. The increasing availability of small digital computers specifically designed for control applications suggested that the control system be organized around an on-line computer. Adoption of the modular structure during the preliminary design period did not require or preclude the existence of a computer in the control system. However, the way in which the operator-accelerator interaction was implemented did depend strongly on the presence or absence of a computer. To provide the rational basis for a decision, a study was made of two possible control systems — one based on automatic sequencing hardware, the other designed around an on-line digital computer. The conclusion reached in the study[1] was that the computer replaced enough special-purpose control and data-handling hardware to pay for itself. In other words, the cost of each system was approximately the same but the increased reliability and flexibility of operation plus the capability for expansion available with a computer made the computer-based control system appear much more desirable for the LAMPF installation.

From the outset of the design effort, it was clear that there were several tasks which the computer could not perform; specifically, those tasks which required microsecond response times. For example, the computer could not close the loop in the fast phase control circuit. This system must react in microseconds to compensate the rf phase for beam loading. No digital computer on the market (with a finite list price) has sufficient speed to permit it to sample and convert the error signal, input the result into the computer where a program can generate and output a corrective signal to a fast-acting device, all in one or two microseconds. Hence, the fast phase control loop was designed as a self-contained system which receives only an operating set point from the computer.

A second task beyond the speed capability of present computers is the fast shutdown chain. If any subsystem in the accelerator malfunctions in a manner which admits the possibility of a beam spill along the accelerator, a signal must reach the injector within a few microseconds to turn it off or inhibit its operation. Present computers are not quite fast enough to respond to alarm signals on this time scale, even through the use of priority interrupts. Since protective interlocks on equipment fall into this same general category, all safety systems and all systems related to the operational integrity of the accelerator are hardwire-interlocked. The computer is alerted via a priority interrupt signal to any malfunction and can initiate procedures to diagnose the fault and even instigate a general facility shutdown, but the initial injector inhibit signal does not proceed serially through the computer.

These two exclusions from the task list for the computer are relatively insignificant when compared to the overall capabilities of the computer control system. Examples of some of the major tasks which can be performed by the computer in the control of the accelerator were listed in a previous paper[2] and included direct digital control of those systems having a response time measured in seconds. Those examples remain perfectly valid and fully admissible as evidence in support of a computer-based control system.

However, the real power provided by the computer doesn't become apparent until one explores the man-machine interaction at the operator's console. The presence of a computer in the control system makes it possible to compress the active area of the operator's control console into two racks, each having only 30 inches of vertical panel space. All data pertaining to the status of the accelerator, as well as all accelerator control functions, are available to the operator on these two partial racks. The layout of the racks as they will appear in the LAMPF Mockup Facility* is shown in Fig. 2. While the mockup program encompasses just four modules and one sector, only minor modifications are needed in these racks to provide for handling a full complement of 55 modules from Central Control.

The Display Function

Although the data acquisition function was cited first in the Introduction, it is more convenient to consider initially how the requirement for a display function is fulfilled in the two main racks of the operator's console. The upper left-hand panel is a status panel. Binary status indicators are provided for any one of four modules. The module whose status is currently being displayed will be identified by lighting one of the four indicators on the bottom of the panel. If an operator desires to know the status of any module, he has only to press the appropriate Module Status Selector button on the bottom left-

*Details of this facet of the LAMPF project are given later in this paper.

hand panel. The button will light and the computer will set the status of the selected module in the binary indicators. If the computer detects a fault or marginal operation in one of the modules, the corresponding Module Status Selector button will flash, alerting the operator to press the button and check the binary status indicators for a diagnosis of the problem. Also on this panel are lamps to indicate the status of the computer and of the sector. These are displayed continuously.

The second display device is a dual beam oscilloscope in the middle of the left-hand rack. The traces which appear on this oscilloscope are selectable from the Video Control area on the bottom left-hand panel. With this facility, an operator can select remotely two signals from any one module or one signal from each of two modules. To obtain, for example, the rf amplitude (channel 6) from module 1 as the lower trace, the operator would dial Module 1, Channel 6, in the lower pair of thumbwheels and press the lower Execute button. The computer would make the necessary remote connections to route the signal to the lower beam.

By far the most important and versatile display device on the control console is the digital CRT display which will be referred to hereafter as the Display Scope. This device makes it possible to display continuously (flicker-free) as many as 1500 alpha-numeric characters or 500 vectors or some intermediate mix of characters and vectors. Within these loose constraints, it is possible to construct a wide variety of displays.

Figure 3 shows a typical alpha-numeric display providing information simultaneously on the status of Injector A and Module 1. For each channel displayed there is a channel designator, a description of the quantity being monitored and a measured value for the channel. The value is updated nominally once per second. At the bottom of the display there is room for a series of operator messages. As an example, an alarm message about the klystron is shown. This message would appear more intense than the others and could even be made to blink. In response to this message, which would also be logged on a console typewriter not shown in Fig. 2, the operator would press the corresponding Module Status Selector button to get additional information on the status panel. Also, the operator would probably select a diagnostic display by pressing the appropriate Display Selector button on the bottom right-hand panel of Fig. 2. These Display Selector buttons cause the computer to present some packaged display which has proved to be frequently useful such as the display in Fig. 3. Less frequently used displays are selected with the light pen from an index of displays projected on the Display Scope.

Should an operator desire to construct a display similar to the one in Fig. 3, but with a non-standard list of channels, he has only to dial into the thumbwheels below the Display Scope: (1) the module number, (2) the channel designator, (3) the line (Display Location) on the scope face where the display is desired, and (4) press the Execute button above the Display Location thumbwheels. The computer would respond by presenting a one-line display at the specified location. Repeated execution of the above steps would produce the desired display. Lines no longer wanted could be erased with the light pen.

Figure 4 is a display which is more pictorial in nature. It shows a schematic diagram of the vacuum system in the first module of the high-frequency portion of the accelerator. The pressure being monitored at each ion pump is displayed and updated nominally once each second. This particular display will probably evolve into a profile of the vacuum measurements down the length of the accelerator and is included primarily to indicate the capabilities of the scope.

The Control Function

The second important attribute of a control system, namely, the control function, has been implemented in the control console in at least three ways. Since no control console would be complete without a group of potentiometers so familiar in analog control systems, three slewing controls which closely approximate a potentiometer have been located in the Channel Control area on the bottom left-hand panel of Fig. 2. Their operation can be demonstrated with the aid of Fig. 5 which shows a graphical display of the beam position in both the horizontal (x) and vertical (y) directions at each point where it is measured along the accelerator. Suppose that there has been a slight but steady increase in the level of radiation monitored by one of the detectors along the accelerator. It is entirely possible for the computer to detect this trend while the radiation level is still below tolerance and flash an operator message on the Display Scope directing the operator to call for the display in Fig. 5 by pressing the appropriate Display Selector button. The operator could see that one of the steering magnets along the accelerator needed adjusting. By dialing the module and channel number of the errant steering magnet in one set of thumbwheels under Channel Control and pressing the Up or Down (increase/decrease) button, it would be possible to steer the beam along a more desirable trajectory. The computer will effect the changes and update the display several times a second so that the operator can observe promptly the effect of the correction. The Up/Down buttons provide corrections to the selected channel at a rate of one percent per second. A momentary depression of the button provides a single 0.1% change in the channel variable.

Another control area has been provided under the Display Scope. If an operator desires to set a channel to a given value, that value is dialed in the Analog Demand thumbwheels along with the module and channel numbers and the left-hand Execute button is pressed. The computer will make the desired setting. If a valve is to be opened/closed (a binary channel), the operator dials the module and channel numbers in the thumbwheels and presses On/Off to cause the computer to initiate the change provided no interlock rules are violated in which case the TS light would come on to indicate an operator error.

A third and more powerful form of operator control has been provided with a series of Program Selector buttons. Each of these buttons causes the computer to execute a sequence of steps which may be as simple as typing out an operations log or a complex as a cold start turn-on of the accelerator. As an example of the variety of operations which can be provided by these buttons, consider the Vary program. It permits the operator to specify (probably via the console typewriter) a dependent and an independent channel (variable) together with a series of values for the independent variable. From these input data, the computer will produce on the Display Scope a graph showing the value of the dependent variable corresponding to each specified value of the independent variable. Since a sufficient number of buttons are not provided for all the available programs, those programs used less frequently will be selected with the light pen from a program index projected on the Display Scope.

The Data Acquisition Function

The data acquisition portion of the LAMPF control system is structured as a large programmed multiplexer rather than an array of free-running multiplexers. This is more in keeping with the concept of a computer-based control system in which the computer (or the operator through the computer) requests the data needed for the orderly operation of the facility rather than having to digest data forced on it by one or more active (free-running) sampling devices.

The LAMPF system has been structured to allow the computer to sample any of 63 possible data channels within any of the 55 modules. In addition, it is possible for the computer to sample any desired channel in all modules simultaneously or to sample a channel in all modules of a special group (e.g., all modules in a given sector). This parallelism in the data acquisition process greatly enhances the speed of the system.

Data channels are classified as binary or analog. A single binary channel can carry as many as ten binary status indications (10 bits). An analog channel corresponds to a single analog signal and the A/D conversion of the signal is carried to 0.1% (10 bits plus sign). Two types of analog signals are recognized — those which must be measured during the pulse (high frequency) and those which can be measured between pulses. If the system is taking high-frequency data, sampling is performed during a reasonably stable portion of the pulse and the information stored for later transmission. Data not associated with the pulse is sampled during the beam-off period when the noise environment is assumed to be minimal. The remainder of the time between pulses is used for collection, storage, and processing of data. The times at which sampling and collection begin for both types of data are under program control.

It is anticipated that all data channels will be sampled once per second. This scanning will be initiated by a signal from the real-time clock. The data scan program will sample each channel, check the measured value against limits, and add the sample to the data bank. One second later, the data in the bank will be updated. Any program needing data can reference the data bank or collect fresh data.

Implementation of Control System

To understand how the LAMPF data acquisition and control system has been implemented, it is necessary to turn attention to Fig. 6. In Central Control are located: (1) the control console including the CRT and video displays shown in Fig. 2, (2) the computer and its associated peripheral equipment and (3) the CIU — Computer Interface Unit. At each module corresponding to the module control point in Fig. 1, there are: (1) the RICE — Remote Information and Control Equipment, (2) the MIU — Module Interface Unit, and (3) the VCU — Video Control Unit. The computer in Central Control and each module control point are linked by only four pairs of wires at present and this number is expected to decrease by the time the mockup program is complete. Two more cables from each VCU back to the control console are required to carry the remotely-selected video signals.

The control console is linked to the computer through the two 16-bit buffers. By pressing buttons and dialing thumbwheels on the console, bits are set in these buffers and a priority interrupt is sent to the computer. In response to this signal, the computer suspends its current task long enough to bring into memory the contents of the two buffers and to decode them to learn what was requested by the operator. The computer then schedules the request with the Executive program and returns to the task it was performing before the interruption. Within a few milliseconds, the computer will begin to execute the new job.

As an example, suppose the new job was a request for a profile of the rf amplitude at every high-frequency module on the next pulse. The picture on the Display Scope would appear as a bar graph with the height of each bar measuring the rf amplitude at that module. To obtain the necessary data, the computer must link to the real world of the accelerator. This is done through the CIU-RICE-MIU chain. The computer communicates the request for data to the CIU in the form of two 16-bit words. These bits indicate the operation to be performed (data acquisition), the modules at which data is to be collected (all high-frequency modules), the channel to be sampled (rf amplitude), and how long after the start of the next pulse the sampling is to take place. The CIU transmits over two pairs of wires to each of the selected modules both the operation code and the channel address, along with a parity bit to validate the transmission. The RICE responds by connecting the selected channel (an analog signal which has been conditioned in the MIU) to the A/D converter located in the RICE. On a signal from the CIU, the RICE converts the signal (10 bits plus sign) and stores the result in the RICE data buffer. At a later time, the computer collects the data over the third pair of wires and stores it in specific locations in a 55-word buffer memory in the CIU. This buffer memory facilitates the collection of data simultaneously from all modules and leads to a faster data system. As a final step in the process, the computer block transfers the data from the buffer memory into computer memory and signals other programs that the data is available. In this example, a display program would format the data for presentation on the Display Scope.

Acquisition of binary data is accomplished in a similar manner except that no A/D conversion is necessary. Ten binary status indicators are read simultaneously into the RICE data buffer to await collection by the computer. The time required to sample and store in the computer's memory 10 binary status indications from each of the 55 modules is less than 250 μsec.

From Fig. 6, it is evident how the display and control functions built into the control console and discussed earlier are implemented. The binary indicators on the Module Status panel are updated with binary data collected from the selected module in the way just described. Displays such as Figs. 3, 4, and 5 are generated by formatting data collected by the computer. A request from the operator for a video display goes through the computer, the CIU, and the RICE to the VCU which switches the requested video signal to one of two cables returning to the video oscilloscope on the control console.

The control functions on the console are handled in a similar way. A request from the operator for an analog set point goes via the computer and the CIU to the RICE where it is stored in a command buffer. From there, it drives a digital stepping motor through the MIU to turn a potentiometer. A request to open or close a valve follows the same route to the MIU where the appropriate relays are activated. Once the relays have responded or the potentiometer has been set, the RICE signals the computer (over the fourth pair of wires to the CIU) that the command buffer is free for another command. The computer keeps track of the status of each command buffer — busy or free.

The Mockup Program

In order to develop and test many of the critical subsystems which will be incorporated in the Los Alamos Meson Physics Facility, a mockup program has been initiated. Its goal is to develop, assemble, and test prototype sections of the accelerator. The repetitive nature of the modules comprising the accelerator makes it imperative that full-scale prototypes be tested at full power to insure that no errors are made in the design which will jeopardize or delay the ultimate success of the project. Major component parts of the mockup sections will include vacuum tanks, quadrupole magnets, wave guides, rf power systems and (of particular interest here) monitoring and control devices.

Designs are being developed to provide computer control of four modules and one sector. The four modules include one ion source-injector combination, one low-frequency prototype, and two high-frequency modules. The necessary interface equipment (i.e., CIU, RICE, etc.) is being fabricated. A small control computer, an SEL-810A*, has been ordered and is scheduled for delivery in early January. The necessary programming is well advanced and debugging runs are being made with the aid of a simulator program which makes one of LASL's large-scale computers operate like the SEL-810A. By the end of next year, it is anticipated that sufficient operational experience will have been gained to allow specification of the final LAMPF control system.

Summary

A comparative study of control systems indicated that a computer-based system offered LAMPF many advantages over a conventional system at essentially no extra cost. Hence, the LAMPF control system has been organized around an on-line digital computer. The three basic attributes of a control system — display, control, and data acquisition — have been implemented in a general way and the operator's console has been designed to provide for a powerful and flexible man-machine interaction. The proposed system will be tested and evaluated in the LAMPF mockup program in order to prove the concepts and refine the operational procedures.

Acknowledgments

A task having the magnitude of the LAMPF control system obviously requires the concerted efforts of a group of people. Group MP-1 at Los Alamos is charged with the instrumentation and control aspects of the LAMPF project. The authors would like to acknowledge specifically contributions by the following people: Ezra Budge+ — the operator's console; Dale Van Buren — the RICE; J. H. Richardson — the MIU; David Weber — the VCU; and T. M. Schultheis — instrumentation for the Mockup Facility.

Appendix

LAMPF Control Computer Configuration

1. Central Processor — SEL-810A with 8192 words of core memory, 16 bit words, 1.75 μs cycle time, ASR-33 console typewriter

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*The configuration of this computer is given in the Appendix.

+On loan from EG&G, Inc., Las Vegas, Nevada.

with paper tape unit, memory parity checking.

2. Power Fail-Save & Restore – Provides an interrupt in the event of a power failure and a second interrupt when power is restored; permits automatic restart in the event of a power failure.

3. Hardware Mult/Div – 7 μs Mult, 10.5 μs Div.

4. Elapsed Time Counters (3) – 60 cys/sec, 20 kc and 572 kc.

5. Block Transfer Channel (2) – Allows input/output at a maximum rate of 572,000 words/sec.

6. Priority Interrupt System – 30 levels.

7. High Speed Paper Tape Unit – 110 cps punch, 300 cps read.

8. Line Printer – 300 lpm of 120 char.

9. ASR-33 – For accelerator operator; identical with console unit.

10. Disk File – $1.5x10^6$ 16-bit words; 25 ms max access time on same track; 30-145 ms track seek time; 10 surfaces & 10 heads on one spindle; 78,000 word/sec transfer rate.

11. CRT Display Scope – 500 24-bit word core memory individually addressable; 40/sec refresh rate; vector generator (analog); character generator (5x7 dot matrix); light pen.

References

[1] Los Alamos Meson Physics Facility Controls System – Preliminary Design Study Report, R. L. Hammon, Tech Report No. 675, AEC No. 1183-1069, EG&G, Inc., August 28, 1964.

[2] The Application of a Digital Computer to the Control and Monitoring of a Proton Linear Accelerator, T. M. Putnam, R. A. Jameson, and T. M. Schultheis, IEEE Transactions on Nuclear Science, Vol. NS-12, No. 3, June 1965.

DISCUSSION

H. S. BUTLER, LASL

TUNNICLIFFE, Chalk River: Perhaps I missed it, but what do you use the disc files for?

BUTLER: We use the disc files to store programs that we cannot hold in memory. We have 8000 words of core memory. The disc files hold 1-1/2 million words. It takes about 25 msec on the average to bring in, say, a 1000-word program from the disc.

TUNICLIFFE: This leads me into a comment. In control computer experimental studies at Chalk River, we have found a very valuable feature, from the point of view of the operators, is to be able to display on the oscilloscope the past history of various combinations of variables in a reactor system. This is particularly valuable in diagnosing faults and in adjusting various parameters in the system. I wonder if you had considered putting such a facility into your system.

BUTLER: That facility is already built in. Normally, the computer scans all data channels once per secons, and it stores the information in a data bank in the core memory of the computer. All programs which need data can access this data bank. At the end of each second, some of this data can be written out on the disc directly, or averaged, or processed in some way and stored to keep a history on the disc. If the operator wants some display of that past history, he could press the appropriate display selector buttons, and a program would be brought into the memory of the computer which would, in turn, bring in the data and put it on the display scope in the requested format.

HEREWARD, CERN: Can you give us an idea of the number of man-years involved in producing these programs and other software?

BUTLER: We made an estimate of approximately two man-years to get a basic operating package for the mockup program. This is something like 10,000 words of programming. This package inevitably will expand as we find need for new programs We have approximately five people programming, so that we can compress this two man-years down into the allotted number of months.

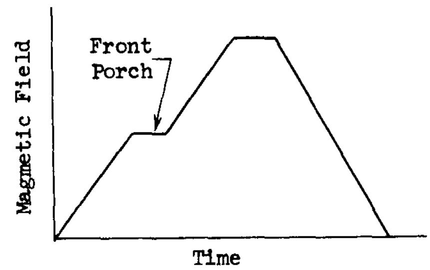
ALLISON, LRL: I would like to add a comment on that too. We have a very modest operating program of 4000 words. If, for example, on the 200-BeV machine, we were to receive authorization now and have a five-year construction period for the injection system, the injector programming would have to start on the day authorization began.

We found that there is a limit to how many people you can have writing programs and have continuity. Programming in this type of system is the real program. We are on our third version, so even now it is not terribly convenient; but, as you get more and more experience, it becomes faster. A very important thing, and one that people who are used to analog control systems tend to overlook, is that a digital system is extremely flexible, but only if you have decided what your programs have to be. You have to decide this first of all before you can do anything with the system.

BUTLER: There is a book by Martin called "Programming Real Time Computer Systems," (Prentice-Hall), and in Chapter 37 the author gives a table of the number of instructions per day that can be expected from a programmer for different types and sizes of programs. A rule of thumb from this table is that one programmer can average eight instructions per day averaged over the whole period of program writing. I first heard this from Jim Leiss at NBS and scoffed. However, my own personal experience tends to validate the rule. There are, of course, exceptions. Hence, if you are calculating how much programming effort is needed, numbers such as , 10 instructions per day divided into the total number of instructions you would expect to need, will give you a very good estimate.

LIVDAHL, ANL: If there are no more questions, I would like to take the liberty of making a comment here. At the ZGS, we have a control computer system which is not nearly as sophisticated as the one that is described in this paper, but over the past few weeks we have had some experience which I think is very pertinent here and shows what a tremendous amount of flexibility this kind of system can give you.

There was a high-energy physics experiment completed on the ZGS about two weeks ago which required a spill at an energy in the external proton beam from the machine, which was varied at discreet intervals for periods of time varying from one hour to twelve hours depending upon the momentum of the particles that the experimenter wanted. Previous to this time, any efforts to set up extraction in this way had been done by manual manipulations of the sequences involved by operators, and this required something of the order of an hour or two of operator time. The magnet cycle of the ZGS during this experiment was as shown in this diagram:



The front porch is created at the field corresponding to the momentum of the protons which the experimenter wants, and the beam was spilled during the elevation of this front porch for a length of about 250 msec. Then the remaining beam was carried on to full energy and used at the momentum desired by the other experimenters, which was about 12 BeV at this time. Changing the position of this front porch on the magnetic field ramp and adjusting the corresponding spill was done each time a new momentum was required. If these adjustments had taken a long time to accomplish and had interrupted other concurrent experiments, it would almost have precluded doing this experiment. In the course of the experiment, there were measurements made at 40 different momenta, that is, 40 different front porch magnetic fields were used by merely inserting the new program which contained the new set of conditions. When the new program was executed, the next pulse was at the new condition, the spill was adjusted, and the experimenter was ready to go. In general, it would take five minutes to check that everything was reset, and then the experimenter would resume taking data under a new set of conditions. With 40 variations like this in the course of this experiment, any effect of these changes on the experiments that were using the full energy beam would have caused chaos; but, as it was, there were absolutely no problems. I have become extremely enthusiastic about this type of an approach because I think it is the real way to run a machine. Although five years ago I was very skeptical about this being a useful device, I find that it is extremely useful, and I now believe we should rapidly expand the utilization of this equipment.

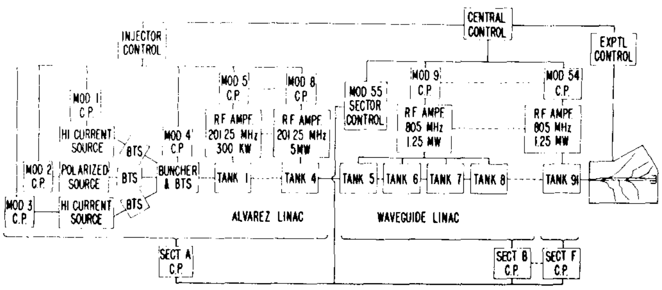


Fig. 1. Modular structure of LAMPF accelerator.

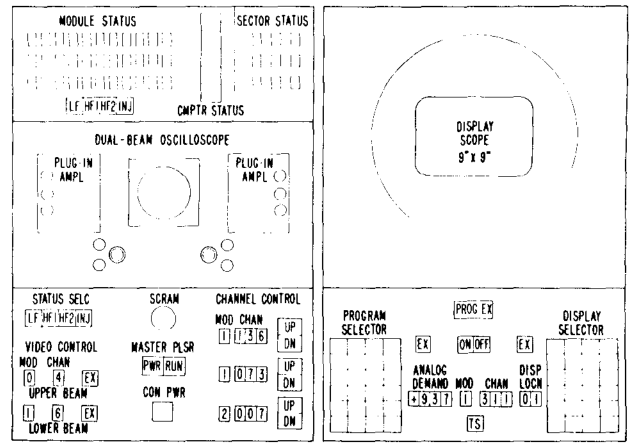


Fig. 2. Control console for the Mockup Facility. Detailed labeling has been omitted for clarity.

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                 INJ A

JA 5 23 1A  BEAM POSITION (VERTICAL)    20 MM     LOW
JA 5 23 2A  BEAM POSITION (HORIZ)        1 MM   RIGHT
JA 5 20 1A  BEAM CURRENT               4.5 MA
JA 8  1 1A  CW HI VOLTAGE              750 KV

                 MOD 1

01 2 36 1A  BEAM PHASE SHIFTER POS      70 P/C FS
01 2 31 1A  BEAM VELOCITY PHASE POS     80 P/C FS
01 7 03 1B  PA PLATE SPARK INTL            OFF
01 8 70 1B  IPA PLATE SPARK INTL           OFF
01 4 22 2A  TANK VACUUM              5.E-8 TORR
01 7 43 8B  WAVEGUIDE SPARK INTL           OFF
01 2 81 1A  DRIVE LINE SLO PH POS       24 P/C FS
01 2 88 3A  DRIVE LINE PH REF POS       30 P/C FS
01 2 61 1A  RF TANK AMPLITUDE           89 P/C FS
01 2 68 1A  RF DRIVE SLO PH POS         38 P/C FS

VDO-UP   INJ   HD VLTG
VDO-LO   HF    RF AMPL
```

Fig. 3. Typical alpha-numeric display on the Display Scope.

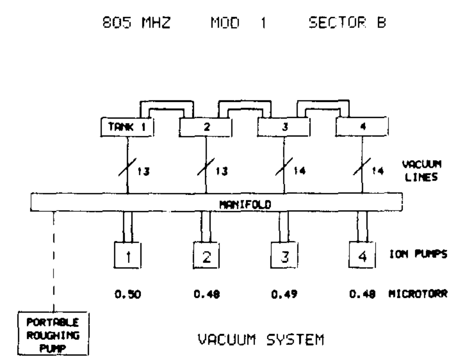

Fig. 4. Example of a pictorial display on the Display Scope.

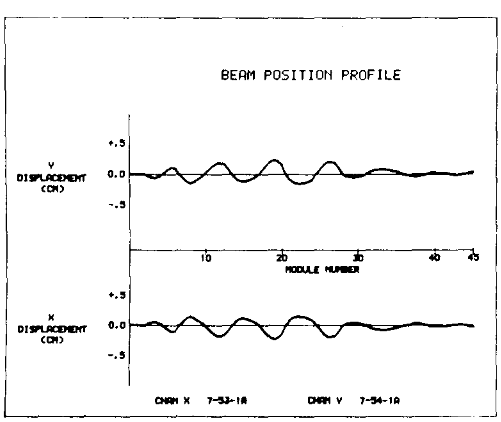

Fig. 5. Example of a graphical display which could be used to aid in steering the beam.

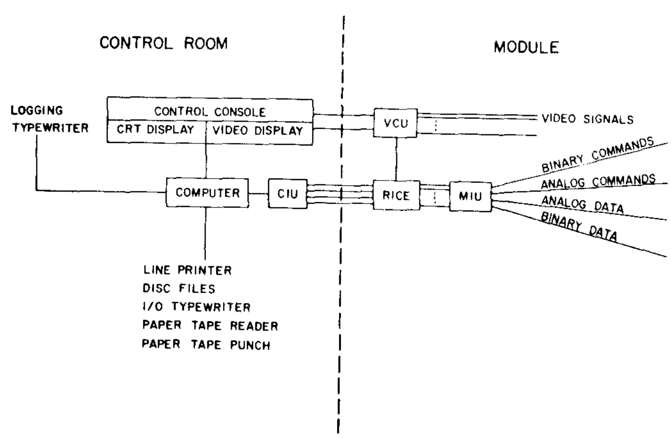

Fig. 6. Structure of LAMPF Control System showing linkage between Central Control and each module control point.