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THE CONTROL SYSTEM FOR THE STANFORD LINEAR ACCELERATOR*

K. B. Mallory
Stanford Linear Accelerator Center, Stanford University, Stanford, California

Introduction

The control system for the SLAC accelerator was largely shaped by two sets of criteria, one physical and one operational. The primary physical criteria are the 25-foot shielding requirement between the accelerator and maintenance people during operation, the two-mile length of the machine, and the presence of a large number of noise sources such as the high-power modulators. The principal operational criteria are the requirement for multiple beams and the need to centralize enough controls so that one person, possibly assisted by a computer, can operate the machine.

Many of the problems and their solutions were foreshadowed in the following excerpts from the 1957 proposal[1]:

"The first important consideration is that the accelerator tunnel will be uninhabitable while the machine is operating. All equipment that may need frequent servicing should therefore be located in a more accessible area, namely, the klystron tunnel. Whatever equipment is located in the accelerator tunnel must be built and installed in a manner that will allow rapid servicing or replacement in order to minimize the time during which the accelerator is inoperative.

"Since the accelerator is scheduled to operate 24 hours per day, routine maintenance must be accomplished without interfering with operation. Examples of such routine maintenance are the replacement of klystrons; servicing of spark gaps, vacuum pumps, dc power supplies; tuning up the accelerator, i.e., adjusting rf synchronization and power level of the various sections; etc. These operations can easily be accomplished if the accelerator is divided into a relatively large number of 'sectors' (say 40), such that during normal operation the performance of the accelerator will still be satisfactory with one or two of these sectors turned off.

"For tune-up purposes, the sector can be operated as an independent accelerator with its own gun and beam extraction system. This appears to be feasible if the sectors have pulsed injection and extraction systems operating at a low repetition rate, and if the pulse occurs a few microseconds after the normal accelerator pulse.....

"The main control area shall have complete monitoring and control panels for substations, dc supplies and generators, water system, and vacuum system. Operating controls for the accelerator, however, shall be reduced to a minimum. There must be a board of some 1,200 lights to indicate performance or non-performance of each of the major equipment units in the klystron tunnel. There must also be an on-off control for each unit. The operator must have signals from the non-intercepting beam monitors at each sector and from beam monitors in the end station. He must have control of the rf phase shifter, the steering and focusing circuits, and the dc supply voltage for each sector. He must be able to delegate energy control and main on-off control of the beam to the experimenters.

"In addition, the main control area must have a communication system to connect it with the experimental areas and with each maintenance crew....

"The primary expense of the instrumentation of the accelerator is the wiring...It is entirely possible that suitable multiplexing equipment should substantially reduce the wiring."

In the ten years since the original proposal, there have been some changes, but the basic concepts have remained the same. Instead of a "klystron tunnel" we now have a klystron gallery built on top of the fill covering the accelerator housing; this change had no effect on the control system since the machine is still 10,000 feet long and still has multiple target areas allowing one experiment to be built while another is operating.

It was originally proposed that rf phasing would be accomplished by energy-maximization. The individual klystrons in a sector would be phased by an operator at a local console, who would travel from sector to sector as directed by the chief operator in Central Control. Phasing is now adjusted by observing the beam-induced reaction with the accelerator waveguide rather than by energy maximization, and is performed by automatic equipment.[2] Yet the phasing equipment is still located in the instrumentation alcove in each sector, and performs its job at the direction of the chief operator in Central Control.

The proposal introduced the concept of multiple beams and the delayed pulsing by which they are implemented. Full development of the concept awaited the later introduction of alignment[3] and focusing[4] schemes adequate to allow guiding beams of different energies all the way to the switchyard. The excellent alignment technique and the system of focusing quadrupoles now in use allow even very low energy beams to be guided through two miles of accelerator and obviate the need for intermediate injection and extraction points originally assumed necessary.

Only two beam analyzing stations remain. One, after 40 feet of accelerator, is occasionally used for tuning the injector and to insure that the beam is well-started. The other, at Sector 20, allows machine studies and operator training to continue even while the beam switchyard is down for maintenance or installation of new equipment.

A conservative wiring system is used, with a minimum of coaxial cables. Wherever possible, information is converted to low-frequency signals suitable for transmission on telephone-type pairs. A continuing effort is made to keep the number of signals required in Central Control to a minimum. Multiplexing has been used further to reduce the total quantity of wire.

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Distance, Noise and Multiple Beams

The accelerator housing is buried under 25 feet of shielding; as much as possible, all equipment requiring maintenance (certainly all electronics) must be located in the gallery above. The gallery cannot be full of technicians, therefore equipment must run unattended for long periods. The equipment must be self-protecting, self-resetting where feasible, and call for help when required. A large number of status monitor signals are required to alert the operator to the existence of trouble and to indicate at least the first step toward repair.

The number of signals is so large and the distances are so great that multiplexing becomes an attractive method for handling both control and status monitoring signals. The signals transmitted to Central Control must pass along the gallery, filled with high-power modulators. The transmission system must have a high immunity to RFI and, considering the distances involved, to cross-talk. Coaxial cables or individually shielded pairs are extravagant; twisted pairs, with balanced circuits where practical, were chosen for transmitting all but video signals. Voice communications and "high-level" signals, greater than 10 volts peak, are transmitted in separate cables from the low-level signals. In general, circuit impedances are low, 1000 ohms or less. Both in monitor and control circuits, relays are preferred over solid-state circuits, when suitable, not only because of lower cost but also for their greater tolerance to momentary overloads.

This ultra-conservative approach may have been somewhat overdone. The modulators were designed with special attention to shielding, and to a balanced return from the pulse transformer tank to the rest of the modulator. Measurements of modulator leakage in the Klystron Gallery indicate that it is considerably smaller than was anticipated. After filters were added to some of the instrumentation lines coming out of the modulator, the maximum video level on conductors leaving the modulator was about 200 mA. The largest component of this interference appears to be a five-megacycle damped sine wave with a decay period of about five microseconds. As a result, one may operate an oscilloscope immediately beside the modulator and not detect on the screen that the modulator is operating, unless one plugs into a monitor jack.

The most serious interference has come from a few unsuppressed relay coils, which escaped our vigilance. They tripped the release for the in-line vacuum valve in the accelerator, a circuit which had the unusually high input impedance of 30K ohms. Significant cross-talk was observed in unbalanced voice and other audio-frequency circuits. The cross-talk became negligible once the circuits were balanced.

The greatest bulk of monitor signals were for the klystrons. It was already determined that protection for gas bursts in the load, switch-tube overloads, etc., would be handled locally. Regulation was provided through a reference voltage supply to control each Variable Voltage Substation, and the de-Q'ing circuits for the sixteen modulators supplied by the substation. It was determined that three status signals per klystron were adequate for all monitoring except that which required analysis of video signals on an oscilloscope. In order to define the range of regulation for power supplies and water systems, 60 pps was chosen as the minimum klystron operating rate (360 pps was the original design maximum). But now arose an interesting question: Could we operate half the klystrons at 360 pps and the rest at 60 pps, thus producing two interlaced beams, one full-energy pulse followed by five half-energy pulses? This required a means of steering the beams to different targets. A pulsed magnetic deflection system was determined feasible, and the multiple-beam concept was born.

A problem arises when one attempts to imagine the reverse situation: the case in which 60 pulses per second are to be at half-energy and the remainder are to be at full energy. In this case half of the klystrons are to skip one pulse out of every six. With the best of regulators it is difficult to imagine that the first rf pulse after the skipped one will be exactly of the same magnitude as the others. Some means was required to avoid skipping a pulse. The means adopted was to introduce a small pulse-position-modulation, which would delay a modulator pulse a few microseconds when it was not desired for acceleration. This delayed or "standby" pulse occurs after the beam has passed, so that it cannot affect the electron energy, but it serves to keep the average power and the apparent repetition rate of the klystron constant.

As soon as one grants the possibility of multiple beams, it becomes easy to imagine 1 pps beams for bubble chambers, a beam in the central, undeflected portion of the switchyard with occasional pulses deflected into an energy monitoring system, a very-high-current experimental beam and a lower-current tune-up beam at the same energy, all interlaced in some apparently random fashion. An adequate beam monitoring system must do better than averaging the characteristics of all beams, it must measure the characteristics of each beam independently. This is accomplished by measuring the characteristics (current and positron profiles along the accelerator) of each beam pulse and editing the display so that each beam may be examined independently.

System Interlocks for Accelerator

Although most interlock problems can be solved on a local basis, e.g., water, vacuum, for individual pieces of equipment, there are a few system-wide interlock circuits which provide a strong interaction between injector, accelerator, switchyard and end stations. The purpose of an interlock is to override operator control. These circuits are, therefore, quite independent of the rest of the control system. In general, their signals are carried on individual wire-pairs and make no use of the multiplexing systems. There are six such interlock circuits which conspire to shut off the machine under irregular circumstances. They consist of:

1. Access Control System, which prevents entry to a radiation area when the machine is on.
2. Machine Shut-Off System, which shuts off all rf power to the accelerator in circumstances where there is a possible radiation hazard to personnel.
3. Emergency Stop Circuit, which changes the geometry of the beam areas by inserting beam stoppers when excessive radiation is detected in the research yard.
4. Machine Protection System (1 millisecond network), which shuts off the injector in circumstances where there is a probable radiation hazard to equipment.
5. A 50-μsec Protection Network, which shuts off the injector in circumstances where the switchyard is not ready to accept the programmed pulse.

6. Pattern Interlocks, which shut off the program for a beam in circumstances where the beam is not desired by the experimenter or a beam channel is not ready to accept any beam.

1. Access Control System

The Access Control System contains a tone loop with transmitter at Sector 2, interrupts at each variable-voltage substation and a receiver in Central Control. If all substations are off, the loop is closed and permissive signals are sent to relays in each area, interlocked with ventilation and access controls. Release of keys and opening of ventilation hatches also requires explicit signals from the Central Control operator. When any substation is turned on, the loop is broken; interlock relays are released and the Central Control operator has no power to release keys or initiate ventilation.

The major purpose of the Access Control System is to keep the number of people entering the housing, the number of people entering at once, and the duration of each entry, to a minimum. The housing should not be cleared because the beam is coming on but because the need for occupancy is finished.

Entry to any radiation area requires consent of the Chief Operator. Entry to the switchyard or end stations also requires consent of a switchyard operator.

For emergencies, local release buttons are provided behind protective glass panels.

Normal personnel accessways are characterized by having keys in a local keybank and two interlocked doors. One of the doors is locked and serves primarily as access control, the other serves primarily for machine shut-off protection. In general, the locked door will be self-closing so that a person requires a key each time he enters. Each person who enters is expected to take his key along with him. The absence of the key from the keybank is the worker's primary assurance that the accelerator cannot be turned on. The second door is latched open any time a person is working inside, and provides assurance that the machine cannot be turned on. Warning signals such as flashing lights or bells will be interlocked with the closing of this door.

Certain doors in the end stations may not be opened unless uncontrolled access is permissible. Their use automatically requires a full search of the accessible area before operation may be resumed.

2. Machine Shut-Off System

The purpose of the Machine Shut-Off System is to limit the hazard of radiation exposure when personnel are in the housing by turning off all variable-voltage substations which supply high voltage to the klystron modulators.

The interaction of the Machine Shut-Off System and the Access Control System is somewhat like putting two cars in a one-car garage. If any substation is on, there may not be people in the housing. If there are people in the housing, we may not turn on any substation.

The Machine Shut-Off System contains two parallel tone loops which determine that each radiation area is secure. The system recognizes the following separate radiation areas: Injector, Sector 1, Sector 2, ... , Sector 30, Beam Switchyard, End Station A and End Station B. If all of the areas have been secured, the tone loop is completed and a permissive interlock allows the operator to turn on the Variable Voltage substations. If the security of any of the areas is broken, the tone loop is interrupted and all Variable Voltage substations are automatically turned off.

The Machine Shut-Off System has the following inputs: all doors to radiation areas, access keybanks, "emergency off" pushbuttons, beam stoppers, slit positions and pulse magnet interlocks.

The "emergency off" circuit contains a lock-out relay for each area. Each time the emergency off circuit is tripped the area accessible from the vicinity of that button must be searched. Upon completion of this search a reset button within the area must be operated. Simultaneous acknowledgement of the Central Control operator is also required to complete the reset process.

In order to allow experiments to be carried out in one end station while equipment is being set up in the other, an alternative definition of security is required for the end stations. If the pulse magnet modulator for that area is interlocked off, a beam stopper is in position and the slits are closed, the end station may be defined secure and access may be permitted without shutting off the Variable Voltage Substations.

The personnel protection system designed for the housing and end stations is an absolute system: (1) the machine is totally shut off if a person is known to be in a beam area; (2) a person cannot enter an area unless it is impossible for a beam to exist in that area. The limits of an area are defined by geometry: shielding, gates, beam stoppers. Compromise of the security of an area results in emergency shut-down.

More specifically, if a person enters a beam area, the fact can be detected by limit switches which are wired into a fail-safe circuit. His entry is made unlikely by appropriate control of door-release circuits. There is, however, no automatic way to remove the person. If, despite all precautions, he is present in a beam area, it is necessary to shut down the machine.

3. Emergency Stop Circuit

If excessive radiation is observed outside the end stations, it is possible to bottle up the beam in the accelerator housing automatically without resorting to the extreme measure of shutting down the entire machine. Beam stoppers may be inserted in the path of the beam, thus automatically changing the geometry of the system.

In the research area, there will be locations which are presumably safe from the beam, which must be occupied during an experimental run. If the beam, by accident, enters such a location, the only means of detection are radiation monitors which are active devices. Such regions are peripheral areas, which can be made safe by inserting beam stoppers further upstream. This response is less extreme than total shut-down, allows quicker return to normal operation once the fault is corrected and is, nevertheless, quite absolute in its manner of removing the beam from the area.

The radiation measurements determine that the shielding is inadequate to the task demanded. Even though a fail-safe radiation monitor is being developed, this "emergency stop" circuit is considered only back-up if other protection fails. Continuing effort will be spent to insure that operation does not exceed the capabilities of the shielding and fencing.

4. Machine Protection System

The Machine Protection System has a normal response time of one millisecond. Its major component is the one millisecond network, which consists of a Tone Transmitter in CCR, Tone Interrupt Units at the Experimental Areas, Switchyard and each Sector and a Tone Receiver at Sector 0. The network shuts off the gun trigger if the circuit is interrupted at any of the tone interrupt units. The inputs to the Machine Protection System at each sector are those signals indicating those conditions which will cause total loss of the beam or loss of the energy contribution in one or more sectors. The inputs at the switchyard are signals indicating that no beam may safely pass through that portion of the switchyard common to all beams and a radiation monitor in the cooling tower loop for the radioactive-water heat exchangers. Additional inputs of the switchyard and target areas indicate that equipment is actually being overheated by the beam. A long ion chamber[5] which detects excessive beam loss along the accelerator is connected to the system at Central Control.

Any breach of security of any of the radiation areas shuts off the gun through the Machine Protection System in addition to shutting off the Variable Voltage Substations through the Machine Shut-Off System. The Machine Protection System shuts off the injector for a minimum of one second and may be reset by the Central Control Operator only after the trouble has been cleared.

5. 50-μsec Network

Provides a pulse-by-pulse shutoff of the gun in case of failure of any switchyard interlocks or of the pulse magnet to approach the proper field strength for the programmed beam. A pulse generator located at the DAB will generate a 200-μsec pulse approximately 150 μsec in advance of each beam pulse. If the interlock determines that the switchyard is prepared for the beam, the pulse is transmitted to the injector trigger generator and drives a gate which transmits trigger pulses to the gun. A beam thus cannot be accelerated unless the permissive pulse is received from the switchyard.[6]

A similar network arises at the Positron Source. This transmits a permissive signal when the target is clear of the beam and also when it is in all respects prepared to produce positrons. A third circuit will arise at the take-off magnet for the storage ring.

6. Pattern Interlocks

Interlock signals which must operate on the next beam pulse will be handled through the 50-μsec network. This network has no lockout feature. Interlock signals which are to be effective for a longer duration and shall affect only one beam will shut off the pattern for that beam at the pattern generator in Central Control. Examples of such signals are the experimenter's on/off switch for his experiment, interlock signals for the experimenter's equipment and interlock signals for the beam transport system into a target area. Since the other systems necessarily turn off all beams, this is the only system which can handle signals which pertain to a single beam or experiment. It is also the one system through which the experimenter has explicit control over his own beam. The inputs to the system will be dry contact switches which, if opened, shut off a particular beam.

Data Handling System

Data is, for the most part, assembled by sectors for transmission to and from Central Control. Signals within a given sector are distributed by shielded cables or wire pairs in conduit, duct, or wall-mounted tray. The signals exchanged between a sector and Central Control are via shielded multipair cables run in trays mounted on the Klystron Gallery wall.

1. Two-State Status Measurements

These measurements form the greatest volume of signals to be handled for accelerator control. They include such indicators as operational go/no-go or alarms for accelerator components and operational availability of components and subsystems. For these signals the most economical of the available multiplexing schemes is to time-share a single wire-pair among all status signals within a sector. By adding FM transmission of the composite signal, communication performance in the noisy environment is improved at little extra cost.

At communication distances of less than one-half mile the individual wire-pair method for handling status signals might be less expensive. Since there are advantages to be gained by having a standard sector configuration, the time-division multiplexing method is applied for communicating status signals to Central Control from all sectors.

Binary status information at each sector is transmitted to Central Control on a time-shared multiplex system. Each of 100 channels is sampled in sequence at a rate of 180 channels per second. The sampling is synchronous with the 360-pps repetition rate of the accelerator, and provision has been made for synchronizing the 100 channel frames originating from the transmitters in all of the sectors. The multiplex signal is transmitted to Central Control on an FM frequency shift transmission system. Receivers decode the first 32 channels for each sector for continuous presentation at the Central Control Console.

The three receivers that decode the entire set of 100 signals may be switched to any three sectors. Any channel from any sector may thus be monitored on demand.

2. Analog System

Slowly changing analog signals are transmitted to Central Control by means of individual hardwire pairs and will be read on standard panel meters.

In general, the readouts are available on switched panels in Central Control. Two data racks contain the analog switching relays for the switched sector panels.

3. Remote Control

The Remote Control System consists of a transmitter which transmits binary codes and a receiver in each sector which translates the codes into a signal to actuate a relay or motor. Remote control signals are sent to each sector as binary coded signals which may operate one control relay or motor at a time. A few signals are transmitted directly on hardwire transmission line-pairs, for control of steering dipoles.

The remote control receivers, each equipped for 64-channel operation, and the transmitter-encoders use relay logic exclusively.

4. Video Cable System

Video repeater units have been installed in each I/C Alcove along the accelerator. Compensation for reduction of rise time of transmitted pulses due to cable effects is provided at each third sector, and video signals can be introduced at any sector.

Two coax cables have been installed the length of the Klystron Gallery. With repeater amplifiers in each sector, the cable may be opened at any sector to allow transmitting to Central Control. The system has been used to transmit TV signals from profile monitors, signals from the beam monitor toroid in Sector 19, and signals from the phasing system.

Remote-controlled switches to aid selection of input signals from Central Control are now being installed.

Beam Monitoring

The beam monitor system for the accelerator reports beam position and intensity as observed at the end of each sector. The information is generated in the form of three pulses: (1) a pulse proportional to the instantaneous beam current; (2) a pulse proportional to the instantaneous beam current times the horizontal displacement; and (3) a pulse proportional to the instantaneous beam current times the vertical displacement. The position signals come from a microwave monitor; a microwave intensity monitor provides the normalization signal[7]; and a toroid current monitor provides the signal for the precise determination of q. The information is conditioned and presented to the beam operator in Central Control in the form of charge and horizontal and vertical displacement for each sector.[8] Because of multiple beam operation, the information is transmitted on a pulse-by-pulse basis to Central Control, where the information for each beam is separated and displayed. The output from the microwave position monitors is integrated to achieve a quantity $q \cdot \Delta x$, for example, where q is the total charge passing through the sensor at a distance Δx from the accelerator axis. The wide dynamic range of the quantities involved demands the use of a logarithmic amplifier for scale contraction. The following advantages are thus derived: (1) remote gain control is obviated, (2) the signal excursions of $\pm$ 2.5 volts match the data transmission handling capacity, and (3) normalization is easily achieved to obtain a quantity proportional to the displacement only. The analog operation of the normalization is:

$$\log\left\{V_1 + \frac{V_2}{2}\right\} - \log\left\{V_1 - \frac{V_2}{2}\right\} \approx \frac{V_2}{V_1}$$

where V_1 = signal proportional to the charge q

V_2 = signal proportional to the produce of $q \cdot \Delta x$.

The output from the normalization circuit is thus proportional to Δx with an error of about 3% when $V_2 \leq 0.5\, V_1$.

Beam monitoring signals are transmitted to Central Control in two forms:

(a) An FM signal which gives an accurate representation of the charge per pulse (q) at each sector, and

(b) A multiplexed baseband signal which transmits three variable-amplitude pulses per beam pulse representing log q, x, and y for each beam pulse.

In Central Control there is a multiplexer for each set of signals. One samples the 30 FM signals and presents them on an oscilloscope to give a trace which reports the beam intensity as a function of sector number for each pulse. When the operator is dissatisfied with the beam transmission through the accelerator, he may deduce from this display where the beam is being lost. The second multiplexer takes 90 samples from the three baseband inputs from each sector and displays log q, x, and y on three separate oscilloscopes. From this display the operator can determine the appropriate steering corrections to be made.

In addition to position and intensity monitors, there are profile monitors using a Cerenkov radiator, a television camera (which violates the rule to have no electronics in the housing) and a monitor in Central Control. The beam spectrum is monitored with arrays of secondary-emitter foils after a magnet. Their outputs are multiplexed to present a histogram on an oscilloscope.

Trigger System

The purpose of the trigger system is to provide timing pulses to turn on the various components and subsystems in the accelerator and research areas in the proper sequence with respect to each beam pulse and at repetition rates as required by the experimental program.[9]

A simplified block diagram of the trigger system is shown in Fig. 1. Briefly, the trigger system operates in the following manner: A Master Sequence Generator in Central Control produces a basic 360 pps signal locked to the power line frequency. From this signal, the Master Trigger Generator located near the injector produces a 25 μsec pre-trigger and a main Clock pulse 360 times per second. These pulses are transmitted on the Main Trigger Line to local Trigger Generators (injector trigger generator, sector trigger generators, etc.) located near the equipment to be driven. A gate in the local trigger generator selects which clock pulses shall be used for each piece of equipment. (For example, if the gun is to deliver 60 pulses per second, every sixth clock pulse will be selected, the other clock pulses are ignored.)

In order to reduce the complexity of the trigger generator, the gate is operated by a pattern signal consisting of audio-frequency pulses, transmitted directly from Central Control. Separate pattern signals are used for each trigger output (or group of similar outputs) of the trigger generator. The programming and generation of the pattern signals is accomplished in the Pattern Generator.

The patterns occasionally will be irregular during multiple-beam operation; it is required, nevertheless, that the Klystron Modulators be operated at a regular rate (0, 60, 120, 180 or 360 pps). Separate gating signals called rate signals are synthesized at the Rate Selector. These signals enable the trigger generator to furnish "standby" trigger pulses with a small delay of, say, 25 μsec, which fill in gaps in an irregular pattern but do not contribute unwanted acceleration energy to the beam.

The output of the Master Trigger Generator consists of a 360 pps negative-positive pulse pair with a spacing of 25 μsec. The later pulse is used to trigger the beam and most accelerator equipment (klystrons, beam monitors, etc.).

The main transmission line is a 1-5/8" diameter coaxial line using a propagation velocity of 92% of the velocity of light. It distributes the clock output pulses to each sector, the injector, Central Control, the switchyard and each end-station area. A fraction of the energy of the clock pulses is coupled from the main trigger line to adjacent trigger generators.

In each trigger generator, clock pulses are combined with signals from the programmer at Central Control to produce pulses at any required repetition rate (360 pps, 2 pps, etc.). In the sector trigger generators, the clock pulses and pattern are combined in a gate to produce "prompt" pulses. Delayed clock pulses and a rate signal are combined in another gate to produce "standby" pulses. Since a piece of equipment is triggered only when a pattern signal impulse is transmitted, it is possible to produce beams of different energy and to steer the beam to different targets on successive beam pulses by sending different patterns to each sector and to the pulsed magnets.

Each different program of pieces of equipment to be triggered for a given pulse can be considered the program of a separate beam. One might thus program two separate beams of the same energy, to go to the same target area, differing only in the injector pulse length.[10] (This might be required, for example, if the very short pulse desired by the experimenter contained too few electrons to allow satisfactory steering. For tune-up, a beam of longer pulse length would then be used.)

Consider the following example, cooked up to illustrate pattern signals--not a real experiment. A spark chamber operating in area B requires 60 pps at 10 BeV but there must be no pulse in the accelerator 1/360 sec before, in order to reduce the probability of stray background tracks. The experimenters in area A desire 20 BeV, using every available pulse left over. It is clear that the entire accelerator must contribute to four successive pulses to area A, the entire accelerator must be off for the next pulse and half the accelerator will then contribute to one pulse for area B. Typical pattern signals for this type of operation are shown in Fig. 2.

The pulse patterns are irregular; this is a natural result of using multiple beams. The klystrons will be triggered by the delayed "standby" trigger when the pattern signal is off and thus will operate at a regular rate (in this example, 360 pps for all klystrons).

One function of the Pattern Generator is to determine which beam will be accelerated during a given machine pulse, and the other is to program the beam characteristics and the target area to be used for each beam. The following programming features are supplied:

1. Provision is made for resolving overlapping requests, i.e., two or more requests for the same beam pulse.
2. It is possible to switch back and forth between any two beams of the same energy but differing in other characteristics such as pulse length, intensity, repetition rate, etc.
3. It is possible to program klystron pulse magnets, experimental equipment, etc., for a new beam before prior experiments are terminated. It has been determined that it may take as much as two hours to set up a high energy run after a low energy run. More than one hour of this time can overlap the previous experiments if the new beam is programmed while the former experiments are still in progress. Even more of this time can be saved if the new beam or new experiment can be tuned up by stealing a few pulses per second from the prior experiments.

In order to produce the desired pattern signals, it is first necessary to determine which beams are desired. In the example above, area A is willing to use all leftover pulses; it is "requesting" a 360 pps beam. Area B is requesting a 60 pps beam, but it is also requesting no beam on the preceding pulse. Such a required "null-beam" must be programmed just like any other beam. Area B is thus requesting a 60 pps null-beam immediately preceding its 60 pps 10 BeV beam. (For the purposes of this example, it is assumed insufficient merely to turn off the gun; too many stray electrons would be accelerated if the rf power were coherent throughout the length of the accelerator.)

Since it is impossible to handle two different beams during one pulse, it is necessary to cancel area A's request for a 20 BeV beam whenever area B requests its null-beam or its 10-BeV beam. A "priority circuit" sorts out the requests to determine which beam shall be delivered on each machine pulse. The resultant output signals are the "beam pattern signals" which will then be used to generate the pattern signals for the equipment. The purpose of the priority circuit is two-fold: (1) It provides a very simple means of generating the irregular beam pattern signal for area A, and (2) it allows area A to receive all pulses automatically any time B interrupts experiments and cancels its requests. There need be no wasted pulses; an area willing to accept all leftover pulses will indeed get a beam pulse, of the proper energy, every time another experiment is not using the beam.

Central Control (CCR)

Central Control contains a number of equipment racks and three console areas: the Operations Console, the Maintenance Console, and the Backup Console.

The Backup Console contains analog displays from all thirty sectors, trigger programming equipment, radiation monitor readouts, and display and control panels for specialized equipment such as the master trigger generators, the master oscillator and main boosters, water towers, etc. The complement of equipment in this area is reasonably stable.

The Operations Console is the most fluid of the three areas. The Operations Console contains injection controls, beam monitoring displays, beam guidance controls, a panel which can be switched to display status and analog signals and to operate controls in any one sector at a time, and a summary panel to alert the operator which sector is likely to contain the source of trouble when he cannot obtain a beam.

The Maintenance Console contains two panels for monitor and control of individual sectors, a continuous display of much of the status information from all thirty sectors, and some of the injector and Beam Switchyard monitors and controls.

Local Control Areas

In general, complete local control and monitoring exists for ease of maintenance of all equipment. Only those operational adjustments which are expected to require attention from day to day are duplicated in Central Control.

Alignment

The alignment system is controlled from the Alignment Observation Room at the end of the accelerator housing behind the injector. The wiring for the alignment system is separate from the controls for the rest of the accelerator. Alignment is in principle an off-line process; there is no need for Central Control to be involved.

Injector

A complete console for operation of the injector, 40 feet of accelerator and the first Beam Analyzing Station is located in the injector area. For the first two months of operation, the injector console was manned. Since that time, the injector has been operated satisfactorily from Central Control, and the injector console has been visited only at the beginning and end of shutdown periods of a weekend or more.

Sector Alcoves

An instrumentation and control alcove in each sector serves as a data assembly point for all signals to and from Central Control. Local interlock logic and automatic control equipment are also located in the alcove. All signals to and from Central Control can be monitored and tested, and it is possible to operate the entire sector from the alcove. Initial tests of the accelerator were made using the injector, sectors 1 and 2 and a temporary beam analyzing station located at the beginning of sector 3. The sector 2 I & C alcove served as temporary "Central Control" for these tests.

Positron Source

The I & C alcove in sector 11 has been fitted with a console for control of the positron source and of special beam guidance equipment in the next four sectors. Once some operational experience has been gained, the necessary signals may be transmitted to Central Control; the sector 11 console will thereafter, like the injector console, be manned only for trouble-shooting or major shut-down.

Data Assembly Building

The control room in the Data Assembly Building operates the switchyard magnets, slits, and collimators, monitors all interlocks in the switchyard, and has complete information about the beam from the end of the accelerator itself through the target areas to the ultimate beam dump.[11] It is manned continuously during operation. To date, only a rudimentary set of signals for analyzing and controlling the quality of the beam is transmitted between Central Control and DAB. This situation has created a division of responsibility between the two control areas. The advisability of unifying the two control rooms by consolidating them into a single control center is presently being considered.

Computer Control

Since the beginning of the project, computer control of the accelerator itself has always been in the unforeseeable future. Nevertheless, convertibility to computer control has continued to be one of the guidelines for design decisions for the control system. It was expected that a control computer should monitor status changes of the accelerator and its components, provide an operational log and allow analysis of operation. It also was to assist in programming of the beam, energy control, and beam guidance.

If the accelerator were instrumented like Stanford's Mark III accelerator, twenty-five thousand signals would be required in CCR. Two design decisions allowed this number to be reduced by an order of magnitude to a quantity which could reasonably be fed into a computer. The first decision was that reflex action should not involve equipment or people in Central Control. Thus, any signal which represents a modulator fault is used locally to turn off the modulator directly. The operator is informed about the action after the fact. The second decision was to summarize local indications; Central Control receives just enough information for the operator to determine if abnormal operation is due to equipment malfunction and for the maintenance personnel to identify the piece of equipment causing trouble.

One "obvious" requirement for the control system is a means of automatically logging changes of status of the machine and its components. During the initial conceptual design, automatic fault-recording equipment was investigated, and the cost was found to run about $50 per point; we had some 3000 points to monitor; for this cost, we could have a rather large computer, with control as well as logging capability. All consideration of special-purpose data-logging equipment was dropped.

Small computers were investigated (installed cost under $50K) and found wanting. One process-control computer, for example, would have been saturated just monitoring and reporting changes of 3000 binary points. A computer in the $100K class would be capable of keeping up with the data-logging and other programs such as steering, energy control, and consideration of equipment status in the programming of the accelerator itself. This size of computer, however, lay far outside our budget. The net result is that we still have no automatic data-logging.

It was presumed that a computer would not analyze video signals directly. Some sort of predigestion must be performed. Typically, a video signal will be integrated or analyzed by a sample-and-hold circuit; the resulting analog output might then be used as an input to the computer. An early proposal for an extensive video system was turned down because of its high cost. It was then decided that all video signals were to be conditioned locally. Locally conditioned signals include klystron modulator voltage, current and reflected rf power, used for local protective circuits; rf phase, used locally in the automatic phasing system; rf output power, transmitted to Central Control as a status signal; beam charge per pulse and horizontal and vertical position signals, and the signals from secondary emission foils adjacent to the energy-defining slits.

There is, of course, a computer in the Data Assembly Building, but it is used only for control of magnets and monitoring of interlocks in the switchyard.[12] There are other computers in use for on-line data acquisition for experiments. But the control system for the accelerator itself was designed for operation by one man. It has been found that he can operate it. It is, therefore, difficult to demonstrate that a control computer for the accelerator is necessary.

Summary

The control system for the accelerator has been shaped by a number of influences: the length of the machine, the noise environment, the multiple beam concept and the desirability of single-operator or computer control. Although the system has evolved considerably in the past ten years, it still strongly resembles the system described in the original proposal.

Turn-on of the machine is reasonably quick: under favorable circumstances it is accomplished in less than half an hour once the beam areas have been cleared. Another half-hour, perhaps, is required for establishing a new beam once the first is running.

Credit for the success of the system must be given to K. Brown, L. Johnston, the engineers who built the equipment and the operators who have made it work.

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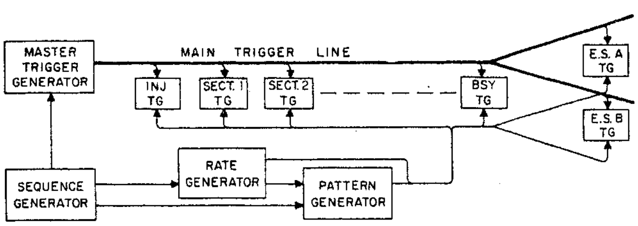

Fig. 1. Trigger system block diagram.

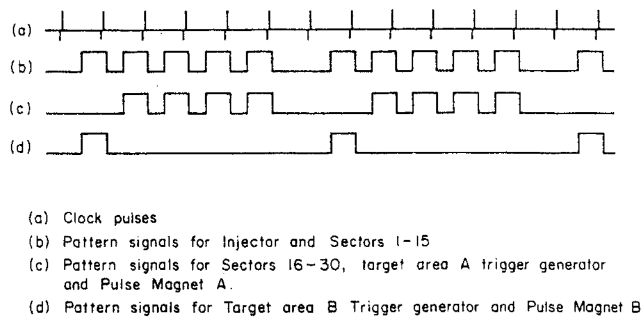

Fig. 2. Pattern signals for 60 pps OFF, 60 pps at BeV to area B, remainder at 20 BeV to area A.