INSTRUMENTATION AND ELECTRONICS FOR THE SLAC BEAM SWITCHYARD*

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Introduction

The Beam Switchyard for the Stanford Linear Accelerator is a large Y-shaped area (see Fig. 1) containing magnets, slits, collimators, and instrumentation for beam observation. It has three main functions: (1) to momentum analyze the beam and determine energy spread at the exit; (2) to transport the beam to the experiment under selected focusing conditions; and (3) to separate the interlaced beams coming from the accelerator.

Monitors of Beam Characteristics

Throughout the BSY instruments are placed for monitoring the beam position, profile, and current, as well as secondary emission monitors to provide spectrum analysis. Each of these monitoring functions is provided by a separate system of instrumentation.

Beam Current Monitors

Toroidal current transformers have been chosen for measuring the beam current at various locations throughout the Switchyard as shown in Fig. 1.

Monitor--The monitor assembly consists of two three-inch diameter toroids incorporated in a single instrument (with the exception of those in front of certain beam dumps, where a six-inch monitor is employed). One toroid is used as a current monitor, while the other is used in the precise integrator system or as a spare. The core material is Mn-Zn ferrite. Each toroid has one 48 turn winding for signal pickup and one signal turn winding for calibration purposes. The resultant transformer has a signal winding inductance of 24 mh, a sensitivity of 2 volts/amp, 10 nanosecond rise time, and a droop of 0.8% during the 2-μsec beam pulse when terminated by the 95 ohm twinaxial cable used for signal transmission.

Electronics--There are three readout systems associated with the transformers.[1] The video or dynamic display is used to observe beam structure during the pulse and to measure the peak beam current. The second system displays average beam current on a meter. The third system is a precision integrator and display which reads average current and total charge to greater accuracy than the average current meters. This third display uses the second toroid of certain key monitors.

A local preamplifier with balanced input and output and a gain of 25 is placed as close as possible to the transformer but outside the Switchyard shielding so that it is accessible during operation. This amplifier minimizes the effect of noise pickup in the long cable runs to the control room and is used for the dynamic and average current displays. Twinaxial cable is used from the transformer to the preamplifier and from the amplifier to the control room to minimize noise pickup. The frequency response of all of the amplifiers in one channel from the current transformer to the oscilloscope is 20 MHz, corresponding to a 10-90% rise time of 17 ns. The limiting element is the frequency response of the cable; after cable equalization a system response of 30 ns can be achieved for most cable runs. A distribution amplifier with balanced input and unbalanced output buffers the various displays and equalizes the cables.

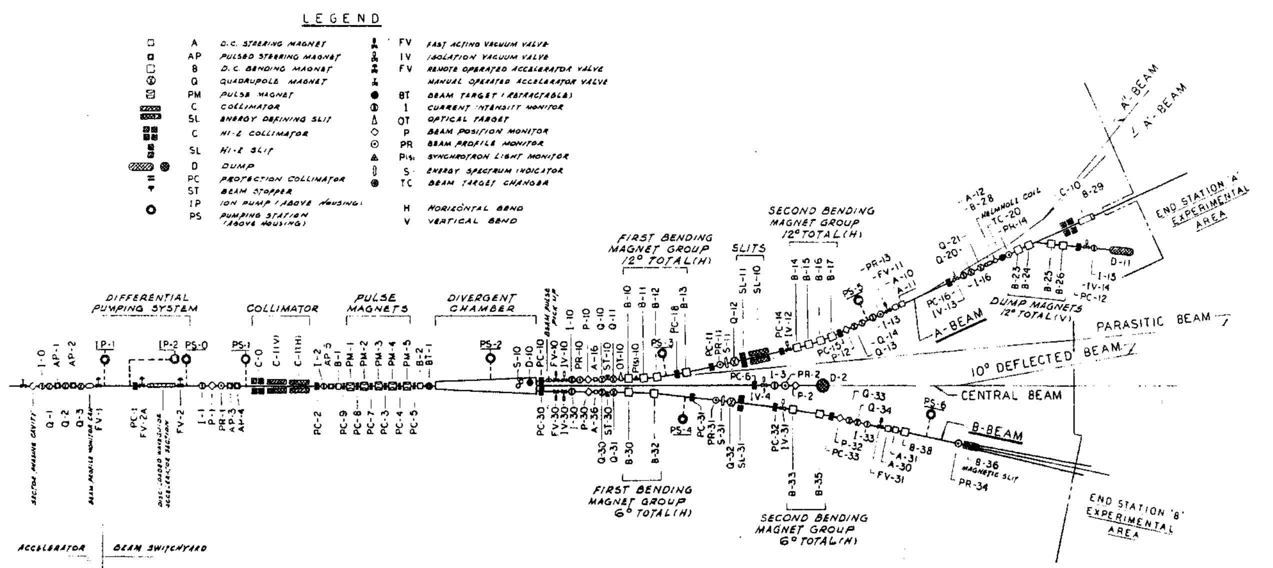

FIG. I — SCHEMATIC LAYOUT OF BEAM SWITCHYARD

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Five outputs are provided with output sensitivities of 50 mV/ma.

The calibration circuit can send a pulse through the one-turn calibration winding on the transformer. This pulse is delayed 100 μsec with respect to the beam to allow continuous calibration during beam operation. Absolute accuracy is better than 3%.

The precision integrator consists of a resonant integrating circuit, a sample and hold and A/D converter, and a totaling display. The sample and hold and A/D converter read the instantaneous integral over each beam pulse and the resulting digital output is totalized by a digital accumulator and displayed as (1) total change over any time period with manual start/stop; (2) Q/sec measured over 0.1, 1, and 10 seconds; and (3) Q/pulse averaged over either 10 or 100 beam pulses. Linearity and reproducibility of the system are better than 0.1%.[2]

Beam Position Monitors

Beam position sensing in the BSY is accomplished by microwave cavities placed in the locations indicated in Fig. 1.

Monitors--The monitors consist of three microwave cavities with two-inch apertures mounted as a single unit.[3,4] The first (intensity) cavity produces a voltage signal proportional to the beam current and is used for normalization of the display. The second two are identical and produce signals proportional to I_0 X and I_0 Y respectively, where I_0 is the beam current and X and Y are the horizontal and vertical components of the beam position.

Electronics--The position monitor circuits are divided into two parts. One is the microwave detector circuit, which is located inside the shielding; the rest of the electronics is in the control room. The location of the detectors is unfortunate but unavoidable, since short cables are essential to limit power loss and phase variations in the cables. Each position cavity signal is combined in the detector chassis with half the signal from the intensity cavity by a hybrid. The rf output of the hybrid is converted into video pulses by thermionic detectors or crystal diodes (tunnel type). The thermionic diodes are more tolerant of large overload signals and are less sensitive to radiation; the crystal diodes were added to cover low currents (down to 0.01 milliamp). These video signals are processed by the control room electronics to provide two displays: A video or dynamic display system which is not normalized, and the average or normalized display system. In the dynamic display the Y-position information is delayed 4 μsec and is presented on the same trace as the X-position. This display is more sensitive than the average display, which works for currents above about 0.5 mA. The video signal is proportional to the beam current times the beam displacement and is used principally for beam centering. The average system produces three signals, each 500 μsec wide and presented on a single trace of an oscilloscope. The three signals are proportional to the logarithm of the charge of the beam pulse, the X-displacement, and the Y-displacement.[5]

Beam Profile Monitors

Monitoring instruments to observe beam profile have been built using two basic principles: the luminescence of zinc sulfide screens and the Cerenkov radiation (light) emitted as the electrons pass through a gas cell. Both of these types of monitors and experiments carried out on a monitor using the synchrotron light radiated by the beam when deflected by the energy analyzing magnets are described in detail elsewhere in these proceedings.[6]

Spectrum Monitors and Secondary Emission Devices

Secondary emission monitors (SEM's) have been used in the switchyard monitors as follows:

(1) In the Spectrum Analyzer and Monitor (see below);
(2) To monitor intercepted beam current at the jaws of the collimators and slits;
(3) To provide beam centering information in front of the high-power dumps; and
(4) To provide signals for equipment protection.

The SEM's do not exhibit saturation effects at high currents, are quite linear and their emission coefficient has been stable. Aluminum foils are used for all SEM's because of their high coefficient of emission strength, and high thermal conductivity.

The Tune-Up Spectrum Monitor[7]--This monitor is composed of a series of vertical SEM's in front of the 50 kW dump (D-11). It is used for coarse tuning of beam energy. There are 38 foils in all, including 6 narrow foils near the center of the dump which give energy resolution of 0.85%. Each of the foils is connected to an integrator in a "local electronics box" located just outside the shielding wall. The low leakage coaxial cable between the foil and this circuit is part of the integrating capacitor; the integrating time constant as well as the total integrating capacitance is selected in the control room. A scanner in the local box sequentially samples the integrator voltages, amplifies them and transmits the resulting multiplexed signal to the control room for display on a single trace on an oscilloscope. The scanner samples the narrower foil integrators for a shorter time to preserve the geometry of the display.

The Spectrum Analyzer[8,9]--This instrument, which is placed in front of the energy defining slits, consists of two foil holders each carrying six foils. The foils are of varying sizes with the narrowest in the center. The widths follow the progression 8, 4, 2, 2, 1, 1 from the outside in on each holder. The narrowest foil corresponds to 0.1% in the A-Beam side and 0.2% in the B-Beam side. The foil holders can be moved in and out of the beam by separating in the center. When the analyzer is not used in the beam, the foils can be retracted to an opening equal to the gap of the slit. Beam interception is avoided in this position while retaining monitoring of the spectrum "tails."

The electronics is made to display the beam energy spectrum in three ways: (a) average spectrum;

(b) sampled spectrum; and (c) video spectrum. The foil outputs are amplified by video amplifiers (gain X 1-A 3000) and then are routed either to integrators for average display or to mixer amplifiers. After integration the average signals are multiplexed in the same manner as the tune-up spectrum monitor described above. The mixing amplifiers used in the other displays combine the A- and B-beam signals into one output. The resulting mixed video signals are connected to 13 triggered sample and hold (S/H) circuits. The minimum sample width of these circuits is 100 ns and the sample time can be delayed to any portion of the pulse width. The outputs of S/H circuits are scanned and displayed on an oscilloscope at the beam pulse repetition frequency; the resulting display represents a sampled spectrum for the 100 ns portion of the beam pulse. Normally, the S/H circuits are reset before each pulse and this gives a pulse-to-pulse spectrum. However, the circuits can average the sampled spectrum over many beam pulses if desired. Also, the sample width can be varied from 100 ns to the entire beam pulse width if desired.

The third type of display is obtained by switching the output of the mixing amplifiers to another oscilloscope. Any four foil signals are displayed; signals from A- or B- beam are selected by shoosing the proper oscilloscope trigger.

Other SEM Monitors--In addition to these spectrum monitors, SEM foil stacks are placed on collimators and slits to provide beam interception data as well as in front of the high power (2 mW) dumps to provide centering information. The foils on SL-10 (energy defining slit for A-beam) are coated with a thin ceramic layer and gold strips are vacuum deposited on the ceramic layer. The strips are arranged horizontally and vertically on consecutive foils to form a hodoscope. These dielectric conduction strips are based on the principle suggested by E. Seppi at SLAC that the conductance of a thin dielectric layer changes when traversed by an electron beam. Tests are still being performed on these foils and definitive results are not yet available.

The beam to be disposed of in the underground dump is characterized by an intense halo caused by multiple scattering in the photon target. A circular four-quadrant SEM monitor with an aperture of three inches was designed to monitor the halo to allow beam centering information on the dump.

The time constant of the integrators for these devices is fixed at 200 ms. The electronics provides two outputs, one for analytical purposes and one for a comparator, which shuts off the beam if the integrator output exceeds a pre-set value (20 mV to 2.5 V).

Transport Control

The equipment to be controlled consists of magnet power supplies and motor drives for slits and collimators. In both cases control is accomplished through the use of a control computer with manual backup provided for all circuits. The latter is used when the computer is inoperable for maintenance and for those magnets to which the computer is not yet connected (steering in all beams and magnets along the B-beam analyzing channel).

Manual Control for Magnets

The power supplies have an internal reference system and potentiometer for local control of the current. By driving this potentiometer remotely with a motor, manual control is achieved. The remote control consists of a double-action lever switch for increasing and decreasing the current and a three position toggle switch for fast-off-slow control.

The operator can read the magnet currents (or any other dc signal in the switchyard) on a high precision digital voltmeter (accuracy 0.01%). The input to the voltmeter is switched by a relay scanner which is operated by a telephone dial.

Computer Control for Magnets

The automatic control of magnet power supplies is split into two parts, a computer-assisted control and full computer control. The former is provided because, while the language of the computer programming system is quite flexible, small adjustments and corrections to magnet currents are most naturally accomplished by the operator using lever switches rather than typing a computer instruction.

Computer-Assisted Control--To allow small corrections to be made to the magnet currents while the computer is operating, two manual control panels have been provided. The panels are identical and consist of 24 latching data pushbuttons, a "release" button, one lever switch, and a speed control knob. Interrupts are sent to the computer by this panel whenever the lever switch is raised or lowered. The rate at which interrupts are produced is determined by the "speed" control. Interface circuits allow the computer to inspect the state of the (latching) pushbuttons. When instructed, the computer will increment or decrement the magnets selected by the pushbuttons once for each interrupt. It is possible to depress from one to twenty-four pushbuttons at the same time. This feature is useful in adjusting a group of magnets simultaneously and in the same proportion. The size of the increment taken for each interrupt is determined by a computer instruction typed on the console typewriter and may be different for each magnet.

Full Computer Control--Full computer control is accomplished through the use of the 925 System Language, described elsewhere in these proceedings.[10] Only the electronic details will be described here. A magnet is controlled by providing the power supply with a stable reference voltage, adjustable by the computer. For most magnets, this voltage (max. 10 V) is produced by a highly stable (± 0.01%/24 hours) digital to analog converter, which operates by selecting resistors in a binary resistance ladder.

The energy analyzing magnets, however, have one special requirement which precludes this type of converter. The high energy of the SLAC beam (24 GeV) requires eight 3-meter magnets to deflect the beam 24 degrees in the A-channel. These magnets are connected in series. In order to insure accurate tracking of the magnetic fields, the current in these magnets must be changed at a constant rate of 3/4% per second. The digital-to-analog converters just described produce transients that far exceed this rate. Therefore, these magnets are controlled by a reference voltage from a multiturn helipot driven by a digital stepping motor. The mechanical nature of such a system precludes transients larger than 0.003% in amplitude.

Readback of the currents is accomplished by two methods. For dc magnets the currents are measured by shunts, whose signals are switched by a precision relay scanner to a digital voltmeter where they are digitized to an accuracy of 0.01%. The currents for pulsed magnets are measured by current transformers and are switched by a solid state multiplexer and fast A/D converter. These channels are read with accuracies of 0.1%.

Slit and Collimator Position Control

The opening of the slits and collimators has to be controlled accurately from the control room, in some cases to less than 0.001 inch. The slits and collimators are enclosed in vacuum tanks; rotating shafts are connected into the tank through magnetic clutches. Readout of position is accomplished by shaft encoders.

Control System Design--The system for position control and readback includes seven basic units: (a) Position Controller, (b) Shaft Encoder Multiplexer, (c) Position Readouts, (d) Position Feedback Multiplexer, (e) Motor/Clutch Selector, (f) Slit Collimator Computer Control, (g) Motor/Clutch on-off feedback.

The central unit is the position controller, from which the operator makes all adjustments. This unit contains the central control logic and all selection circuits; it issues commands to the other chassis to activate the channels selected. The Shaft Encoder Multiplexer connects any of 16 shaft encoders to the two position readouts, which convert the binary gray code to a nixie tube decimal display. The position feedback multiplexer is used in the computer control circuits to transfer 16 bits of data into the computer memory. Ten of the bits are position data from the encoder and six bits form the device code, which identifies the unit selected. The motor/clutch selector receives a control command from either the position controller or the computer control chassis, and controls the appropriate clutches and motor accordingly.

The computer control chassis receives a control word directly from the computer. After decoding the word, it selects the requested slit or collimator, and waits for an acknowledge signal. If that signal returns, it sends the next command to turn on a slow/fast clutch and again waits for an acknowledge. If that signal returns, it turns on the motor. Finally, if the signal returns that the motor is active, the computer is sent a signal that the action is taken, and the operation is complete. If the chain is broken at any point by failure of the slit or collimator to return an acknowledge signal within 1/2 second, the chassis will send a malfunction interrupt to the computer. The motor/clutch on-off feedback chassis provides these acknowledge signals and also contains a lamp display for operator use.

Computer System

The control computer system in the Switchyard is designed to improve efficiency in beam set-up and operation and to provide better flexibility and stability in beam parameters.

The computer is an SDS 925 with 24-bit parallel arithmetic and an 8192 word core memory with an access speed of 1.75 μsec. It is embedded in a system designed to:

(a) Control all magnets, slits and collimators along the beam line with the exception of certain steering dipoles;
(b) Set-up, measure, and maintain the $\int B d\ell$ in the energy analyzing magnets;
(c) Produce upon command a set of punched cards which, when read into the computer at a later time, will reproduce the conditions existing at the time the cards were punched;
(d) Monitor 1008 two-state interlock and status signals 360 times per second and print all changes.

The standard peripheral equipment purchased with the machine consists of a 10 cps teletypewriter, a 200 card/min card reader, and a 100/card/min card punch. Other peripheral devices have been designed for magnet control, slit/collimator control, and status monitoring; some of these have been described previously. A link to a larger machine, the SDS 9300 in End Station A, has been built and partially tested to allow closer communications with the experimenter. This link provides hardware buffered transfers of instructions and data at a maximum speed of about 50×10^3 computer words/sec.

Communications between operator and computer are accomplished either directly by typing on the typewriter, or by punching the instructions on IBM cards and reading the cards into the computer. The instructions are written in "925 system language," the source language for a real-time compiler resident in the computer memory at all times. This program is described elsewhere in these proceedings.

Equipment Protection in the Switchyard

The interlock system in the switchyard is now in the stages of redesign, due to a reassessment of the requirements for multiple beam operation. The new design will be discussed here.[11]

The interlock system uses digital logic extensively and has the following features:

(1) Only those interlocks required for a given beam need be "O.K." for that beam to be operated;
(2) "Errant Beam Protection" causes all beams to be shut off if a beam is detected in an area at the wrong time, i.e., when the interlocks associated with that area are inactive;
(3) If an intermediate energy absorber is used as a dump (e.g., SL-10) a selection system can be used to switch out all interlocks beyond that absorber. This is called "Partial Beam Operation."

The "errant beam" detector consists of a current toroid at the entrance to each area to be protected (I-10 in the A channel, I-30 in the B channel, and I-3 in the central area) coupled to the digital logic. If a current is detected in the toroid during any pattern other than the "correct" one, all beams are shut off. Also, if any ion chamber circuit (see below) trips during the "wrong" pattern, all beams are interlocked.

The output of the logic of the system includes: (1) Display of its status, (2) a "permissive pulse," and (3) a set of pattern interlock signals to disable the trigger generator if a beam is to be shut off. The details of the last two signals are described elsewhere in the proceedings.[12]

The sensors which provide the inputs to the logic include ionization chambers, temperature sensors, secondary emission foils, a pulsed magnet interlock, a differential current interlock, and many slow relay closures activated by flow switches, vacuum valves, and so on. These are briefly discussed below.

Ion Chambers A few beam pulses at maximum power may damage a vacuum chamber or protection collimator. Because thermal sensors are too slow to detect instantaneous local heating, ionization chambers are used. When the beam scrapes a collimator, a burst or radiation is created which is roughly proportional to the power absorbed by the collimator. Therefore, if the output of the ion chamber is integrated, a measure of the energy absorbed is obtained. A low frequency "roll-off" in the integrator circuit with about 0.1 sec time constant (slightly faster than most protection collimators) accounts for the energy removed by the cooling water so that the output voltage of the integrator is roughly proportional to the temperature of the device to be protected. The integrator is followed by an adjustable discriminator and latch circuit to interlock off the beam if the preset level is exceeded.

Temperature Sensors To detect slow temperature rises due to continuous beam scraping on vacuum chambers, platinum resistors are mounted in places where this is likely to occur. They are in bridge circuits which can be adjusted to any desired trip temperature.

SEM Foils Stacks of secondary emission foils have been placed at certain positions (on dumps, slits, etc.) to provide a measure of protection for these devices. The electronics have been mentioned previously in this paper.

Pulsed Magnet Interlock A special circuit has been designed to hold back the beam pulse if the magnetic field will not reach the proper value in the pulsed magnets shortly before beam time. The magnetic field signal is obtained by integration of the output of flux loop coils wound around the magnet yokes.

Differential Current Interlock This system uses two toroids, and produces an interlock signal if less than a certain percentage of the beam passing through the first sensor passes through the second. The system can also be connected to a single toroid and a reference signal, providing current limiting action.

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A more complete discussion of the subject matter of this paper, including many related topics which space did not permit us to cover, is available in the literature.[13]

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