19

INSTRUMENTATION AND ELECTRONICS IN THE BEAM SWITCHYARD

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The instrumentation for the SLAC beam switchyard (BSY) can be grouped into four basic categories: beam monitors, transport control system, equipment protection system, and magnet power supplies.

19-1 Introduction (RAS)

Beam monitors include current-measuring toroids, beam position monitors, equipment for observing beam profile by optical (TV) means, and secondary-emission monitors for measurement of intercepted beam current on energy absorbers, for observing energy absorbers, and for observing energy spectrum.

The *transport control* system controls magnet currents and slit and collimator position, and also includes associated measurement equipment for monitoring magnet currents and fields and the positions of energy-absorbing devices. This system includes a control computer for automatic setup of the transport parameters.

The *equipment protection system* consists of sensors in the BSY to monitor radiation, temperature, water flow, the positions of energy absorbers and other movable instruments, vacuum system pressures, and so on; sensor electronics in the control room for signal conditioning; and a summary circuit to provide the necessary signals for the master machine protection circuitry at the Central Control Room (CCR) and the injector. This system protects the instruments from beam-induced damage and is not intended for protection of personnel. (Personnel protection is described in Chapter 21.)

The *magnet power supplies* provide the pulsed and dc power for all of the magnets in the transport and deflection system.

Each of these four will be described in greater detail below, but a few general remarks will be made here. Because of the high radiation levels associated with the interception of the beam by energy absorbers, the BSY is a closed structure under many feet of earth and concrete shielding. This closed structure causes several problems in the design of equipment and sensors to be located there. First, radiation-induced chemical reactions between the nitrogen, oxygen, and water vapor in the air cause a slow buildup of nitric acid fumes. These fumes attack copper and aluminum, especially in thin sections. For this reason, extensive use was made of stainless steel and other inert materials, particularly for thin elements and for components that are difficult to replace or repair.

The high radiation levels also prevent frequent access to the BSY for maintenance purposes; delays of many days could easily be required if the device needing service were near a beam dump, for example. This situation made it necessary to design each instrument for high reliability, using radiation-resistant components, and prevented the use of materials or parts that require routine service (vacuum tubes, for example). Where this principle could not be adhered to for reasons of economy or lack of availability of suitable materials, the component was placed either in an alcove or other partially shielded area. Certain pieces of equipment were mounted so that removal could be effected remotely by the use of special tools produced for that purpose.

The layout of the major components and instruments in the BSY was shown in Fig. 17-1. As can be seen in the figure, the switchyard is roughly Y-shaped. The upper leg leads to the "A" experimental area and is called the A analyzing channel; similarly, the lower leg is called the " B " channel, whereas the beam transport system collinear with the accelerator is called the " C " beam channel. This terminology will be used below when discussing instrumentation differences in the various areas. For a complete discussion of the criteria and analysis of the optical properties of the system, see Chapter 17.

19-2 Beam monitors

Beam current monitors (BCM's) (DRO)

Current transformers are used for measuring the beam pulse current at various locations throughout the switchyard. A toroidal transformer can be considered approximately as a current source supplying a pulse current I/N into the cable with impedance R. The output voltage on the cable is, thus,

$$V = \frac{I}{N} \cdot R \tag{19-1}$$

where I = the beam pulse current; N = the number of turns on the toroid; and R = the cable impedance.

Equation (19-1) is approximately true for a current pulse as long as

$$\frac{L_T}{R} > t_p$$

where

$$\frac{L_T}{R} = \frac{\mu\mu_0 N^2 \cdot A}{2\pi r R} \text{ sec} \tag{19-2}$$

in which

L_T = the toroid inductance
t_p = the beam pulse length (1.6 μsec)
A = the cross section of the core
r = the mean radius of the core
μ = the initial permeability of the core

The droop in the output voltage is

$$D = \left|\frac{\delta V}{V}\right| = \frac{Rt_p}{L_T} = \frac{2\pi r \cdot R}{\mu\mu_0 N^2 \cdot A} \cdot t_p \tag{19-3}$$

It is desirable to have a large output voltage V and a small droop D, so it is necessary to compromise on R and N. The values selected are given in Table 19-1.

The 3-in. beam aperture current intensity monitor assembly incorporates two toroids. One toroid is used in the current monitoring system. The other is used in the precise integrator system or serves as a spare. Each core is surrounded by an open aluminum case which acts as a Faraday shield and also as a support for the core inside the vacuum housing. The two core assemblies are insulated from each other and from the vacuum housing by ceramic beads. The signals are brought out through standard ceramic-to-metal sealed vacuum feedthroughs to radiation-resistant, 95-ohm, fiberglass-insulated twinaxial cables. These cables extend to the upper housing of the switchyard, where they are spliced (and matched) to RG/22/U polyethylene cables.

A current transformer with an aperture of 6.35 in. is needed in front of beam dump D-11 and in front of beam dump east. The core data for this transformer are shown in Table 19-1 and the construction is very similar to the 3-in. transformer. The 6-in. transformer is built into one housing with the four-quadrant secondary-emission monitor. The assembly of these two monitors is called the dump monitor.

Electronics

There are three readout systems associated with the beam current transformers.[1] The most fundamental one is the video or dynamic scope display of the actual beam pulse waveform. The video display provides a direct observation of the beam structure as a function of time and is used also to

Table 19-1 Data on beam current monitors

Item	*Description*
	3-in. aperture current transformer
Core	Four rings: 6 in. o.d., 3.675 in. i.d., each ½ in. thick
Core material	Mn-Zn ferrite; Ceramag 24 (Stackpole Carbon Comp.)
Beam aperture	3 in.
Initial permeability	3600 (measured value); catalog value = 2500
Radiation threshold	$>2 \cdot 10^{11}$ ergs/g
No. of turns	48 for output signal; 1 for calibration input
Windings	Fiberglass insulated stranded copper wire
Cables	Output signal 95-ohm twinaxial (T-95 and RG/22/U); calibration signal 50-ohm coaxial (B-50 and RG/63/U)
Shielding	Transformer—aluminum can insulated from vacuum housing; cables—copper shield up to preamplifier
Inductance	24 mH
Sensitivity	2 mV/mA
Noise level	100 μV (equivalent input noise of system)
Droop	0.8% (2-μsec long beam pulse)
Rise time	Transformer proper—10 nsec; on scope in control room—30 nsec.
	6-in. aperture current transformer
Same as 3-in. transformer with the following exceptions:	
Core	Three rings: 10 in. o.d., 7½ in. i.d., each ½ in. thick
Beam aperture	6.35 in.
Droop	Approximately 2½%
Feedthrough	Stainless steel, MgO-insulated cables welded into housing

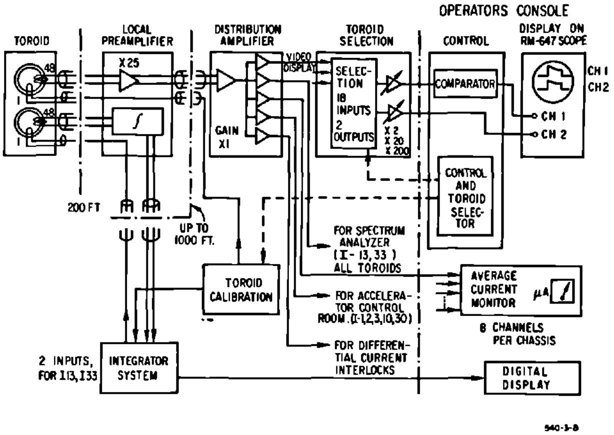
measure the beam peak current. The second readout system displays average beam current (microamperes) on a meter. By comparing average beam current readings at various points in the BSY, an indication of the magnitude and location of beam losses may be obtained. The third readout is an integrator system which reads average current and total charge with higher precision. The characteristics of the three readout systems are summarized in Table 19-2. A block diagram of the current monitoring system is shown in Fig. 19-1a.

The local preamplifier (BCM local electronics chassis) is placed as close as possible to the current transformer but outside the switchyard shielding so that it is accessible when the electron beam is turned off even when there

Table 19-2 Characteristics of current monitor readout

Monitor readout	*Description*
1. Dynamic pulse readout	
Display	On 647 oscilloscope
Amplitude measurement	Can be measured with 0.3% precision using a comparator circuit
Absolute calibration accuracy	3%
Frequency response	30 nsec with compensated cables
Range	Min. 50-μA peak current, signal/noise = 1; max. 100-mA peak current
Electrons–positrons	Polarity of scope signal reverses; polarity of comparator on control chassis can be changed
2. Average current readout	
Display	4-in. scale meter
Precision	2%
Range	0.03–100 μA full scale
Electrons-positrons	Polarity can be switched on front panel
3. Integration circuit	
Display	Digital (Nixie tubes)
Precision	0.3% relative; 1% absolute
Range	0.001 and 100 μA
Readouts	Total charge over any time period (manual start–stop); Q/sec measured over 0.1, 1, 10 sec (μA); Q/pulse averaged over 10, 100 beam pulses (coulombs)
Electrons–positrons	Polarity can be switched on front panel

Figure 19-1a Beam current monitoring system.



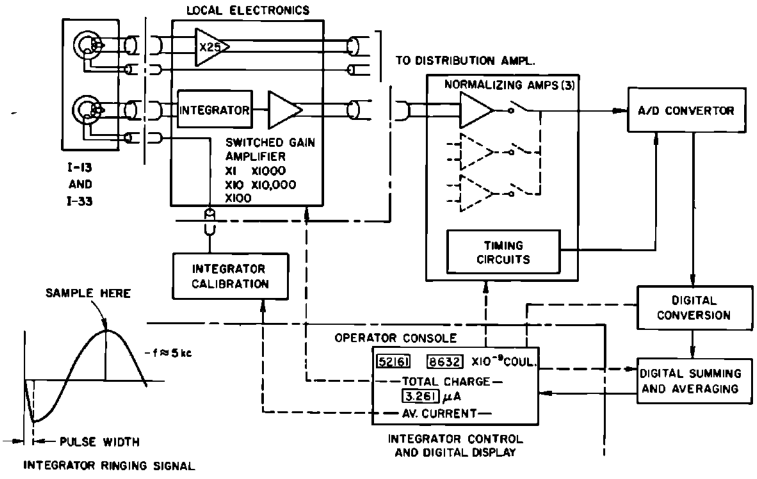


Figure 19-1b Beam current integrator system.

is significant residual radioactivity at the location of the monitor. The preamplifier has a gain of 25 and a balanced input and output. The purpose of the preamplifier is to minimize the effect of noise pickup in the long cable runs to the control room.

Twinaxial cable (RG/22/U) is used to minimize noise pickup over the long transmission distances (400 to 1000 ft) after the preamplifier. The cable from the toroidal current transformer to the preamplifier is totally shielded by a combination of flexible bronze tubes and copper pipes. The frequency response of all the amplifiers in one channel from the current transformer to the oscilloscope is approximately 20 MHz. This corresponds to a 10–90% rise time of 17 nsec. The limiting element is the twinaxial cable. The frequency response of the cables may be equalized, but for the longer cable lengths (1000 ft) the rise time might be as long as 50 nsec. The total linearity of all amplifiers is better than 0.3% over the operating range. The gain stability is better than 0.3% for the anticipated temperature fluctuations.

The distribution amplifier shown in Fig. 19-1a serves to adjust the gain of each transformer channel to 50 mV/mA and to provide five separate buffered outputs. The buffered outputs are typically used for the following:

1. Video display system.
2. Average current display system.
3. Current display system in the accelerator control room. The signals from I-1, -2, -3, -10, and -30 are processed by the linear-Q circuit[2] in the sector electronics. This circuit integrates the video signal and sends a signal which is proportional to the charge per pulse to the CCR.
4. Differential current interlock circuits.
5. Other purposes: the analyzed beam current signals from I-13 and -33 are combined with other signals in the display of the spectrum analyzer.

The monitor calibration circuit (BCM system calibration chassis) can send a pulse through the calibration winding of the transformer. The controls for this circuit are integrated with all other controls in one panel (BCM video control chassis). The calibration pulse is delayed 100 μsec with respect to the beam pulse in order to allow calibration during beam operation. The absolute accuracy of the calibration system should be better than 3%.

The basic criterion of the video display is to observe on an oscilloscope simultaneously the output signal of any two current monitors along one beam, e.g., either I-10 and -13 or I-10 and -15. It is also possible to display simultaneously monitor signals from two different beams. The total linearity and stability of all amplifiers is better than 0.3%.

The control chassis shown in Fig. 19-1a (BCM video signal control) contains thirty-six current monitor selection switches, eighteen for oscilloscope channel 1 and eighteen for channel 2, in such a way that any monitor may be displayed on either channel. A comparator circuit in this chassis produces a precise dc offset voltage which is used to measure the pulse amplitude.

The switches for monitor selection and two amplifiers each with gains of ×2, ×20, and ×200, are mounted in a separate chassis (BCM video selector chassis). The purpose of these amplifiers is to present a reasonably high voltage which is a decimal function of the beam current (0.1 V/mA, 1.0 V/mA, 10 V/mA) to the oscilloscope. They also provide filtering which can reduce the high- and low-frequency noise.

The average beam current display consists of three chassis, each of which contains eight separate meter displays. Each chassis is separately synchronized by a synchronization pulse 1.5 μsec before beam time. The chassis has a front panel switch which allows the selection of two synchronization pulses. With this arrangement it is possible to display alternatively the current from two interlaced beams on the same meter.

The maximum zero offset on the meters is due to system noise, and dc drift is less than 10% of the most sensitive reading (0.003 μA). The precision is about 2%.

The purpose of the beam current integrator[2,3] is to provide a precise measurement of the beam current at the end of the beam energy analyzing system. At present, one integrator readout system is built which may be switched to read the current in either the A or B beam (I-13, I-33). The integrated current can be displayed on two digital readouts. One display represents the total charge over an arbitrary period of time (selected by the operator pushing a "start" and a "stop" button). The second readout displays the average beam current in either microamperes or average charge per pulse.

The integrator circuit is located in a local electronics box as close as possible to the current transformer but outside the radiation restricted area and consists of a capacitor connected directly across the twinaxial cable from the second transformer of the current monitor. The sensitivity of this resonant integration is

$$V_{\text{out}} = \frac{I \cdot t_p}{N \cdot C} \tag{19-4}$$

where C = the integrating capacitance.

After the integration period t_p, the capacitor and transformer inductance L_T produce a damped oscillation, as shown in Fig. 19-1b.

The local switched gain amplifier is provided to build the signal level to the highest possible value before transmission to the control room. In the control room, each of the two inputs (I-13 and -33) goes to a separate amplifier which compensates for differences in gain as a result of differences in cable length.

The integrator control and display chassis selects the integrated signal from any of the three monitors and connects it to the analog-to-digital (A/D) converter. The A/D converter includes a sample-and-hold circuit which samples the second peak of the oscillation [Fig. 19-1b]. This quantity is measured with a precision of 0.1% and is proportional to the integral of the beam pulse current.

The A/D converter is a 14-bit bipolar unit with binary output. The output of the A/D converter goes to the digital circuit, which converts the binary signal to a decimal form and connects to the two readouts mentioned above.

The linearity and reproducibility of the system is better than 0.1%. The accuracy between the various ranges is better than 0.05%. The absolute calibration will at best be of the order of 0.3 to 1%. The minimum observable signal is limited by the amount of coherent noise in the system.

The integrator calibration chassis discharges a precisely known amount of charge through the toroid calibration winding.

Position monitors (DRO)

A block diagram of the beam position monitor system is shown in Fig. 19-2a. The basic position detector is a microwave cavity; these cavities and the diode detectors are discussed in Chapter 15.

The calibration curves shown in Fig. 19-2b are based on measurements taken on position monitors P_1 and P_2 during a beam test run in June 1966. They were taken with a gain setting equal to 1. The curves depend on the system gain which can be adjusted internally.

The microwave position monitor has two display systems: the video or dynamic oscilloscope display system and the average or normalized display system. The primary use of the microwave cavities in the switchyard is for beam centering. A secondary use is to measure the actual displacement of the beam.

The output of the video display system provides the most sensitive indication for beam centering. As shown in Fig. 19-2a the x and y position signals of any two monitors may be viewed simultaneously on the Type 551 oscilloscope.

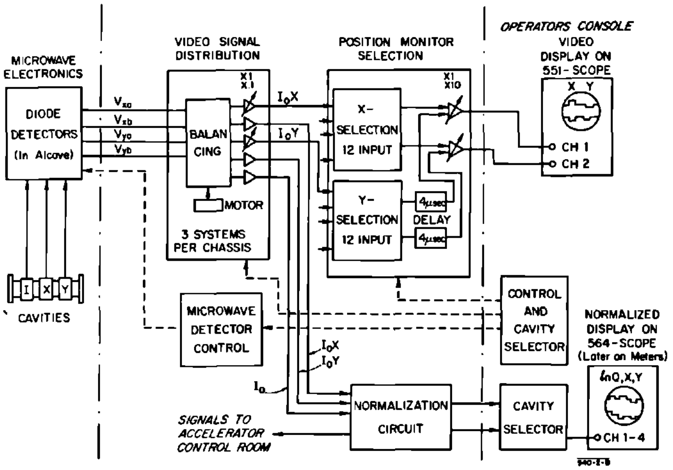


Figure 19-2a Beam position monitoring system.

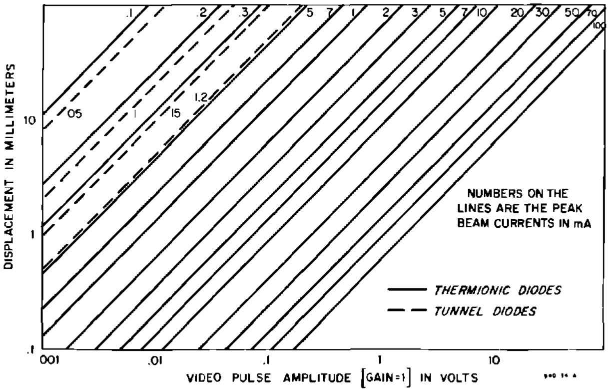
In this display, the y signal is delayed by 4 μsec and combined with the x signal so that both are displayed on the same trace of the oscilloscope.

The video signal distribution circuit [beam position monitor (BPM) video distribution chassis] reduces the outputs from the microwave detector diodes. This chassis combines the signals V_{xa}, V_{xb}, V_{ya}, V_{yb}, and produces five output signals: two position signals proportional to Ix, two position signals proportional to Iy, and one current signal I (I = beam peak current measured in the beam current monitor cavity).

Because the diodes do not track over the operating range, the signals V_{xa} and V_{xb} must be balanced each time the beam current I is changed.

The output to the video system may be range-switched through relative gains of 0.1, 1, and 10 so that the operator can adjust the scope display to suit his requirements.

Figure 19-2b Microwave position monitor calibration.



The control chassis (BPM video signal control) selects the cavities that are displayed on the scope and provides controls for balancing, phase adjustment, and diode switching in the microwave detector chassis.

The chassis marked microwave detector control in Fig. 19-2a is used to multiplex the control chassis to the various position monitors.

A position signal independent of the beam current is produced in the normalization circuits. These circuits are the same as those used for the position monitors along the accelerator (see Chapter 15). The inputs to these circuits are the video position signals Ix, Iy, and I signal. The outputs produce three pulses, each 500 μsec wide. The first is proportional to the logarithm of the charge of the beam pulse, the second is proportional to the x displacement, and the third to the y displacement. They are displayed in a row on one trace of a Type 564 oscilloscope. The oscilloscope has four traces so that the outputs of four monitors are displayed simultaneously.

Beam profile monitors (RWC)

In the BSY, three different types of monitors are used to measure the cross-sectional profile of the beam as it is shaped by the accelerator and the transport system. Although the principles of operation of the three devices are quite different, they share the common characteristic of producing a beam of light, which when focused onto a suitable detector (in this case the vidicon tube of a television camera) gives an image of the profile of the beam. The three sources of light are synchrotron radiation, Cerenkov radiation, and beam-induced phosphorescence. Each effect and the way it is used in the BSY will be described separately. It should be mentioned, however, that the optical and TV system is basically the same for the three monitors. The light is reflected by a series of mirrors from its source in the lower half of the double tunnel structure of the switchyard to a radiation-resistant telescope and television camera mounted in a shielded sleeve in the upper part of the tunnel.

SYNCHROTRON LIGHT. Electromagnetic radiation is emitted tangentially to the path of an electron deflected in a magnetic field. For most of the magnets in the beam switchyard, the wavelength of this radiation covers the visible spectrum. This phenomenon has been used after the first bending magnet B-10 in the A-beam of the switchyard as a nonintercepting means of visual observation of the beam spot.[4] The radiation covers a wide frequency spectrum which is dependent upon the bending radius in the magnet and which shifts toward the shorter wavelengths with the third power of the beam energy:

$$\lambda_c = 5.59R \cdot \left(\frac{1}{E}\right)^3$$

where λ_c is the shortest wavelength in angstroms radiated, E is the energy in gigaelectron volts, and R is the bending radius in meters.

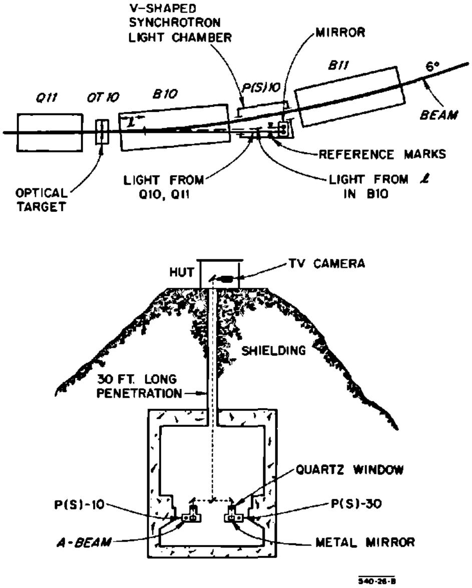


Figure 19-3
Synchrotron light observation.

The bending magnet has a bending radius of 57 meters, and the synchrotron radiation is, therefore, in the visible spectrum if

$$E = \left(\frac{5.59 \times 57}{5000}\right)^{1/3} = 0.4 \text{ GeV or higher}$$

The photons are emitted in a forward cone with an angular distribution extending to 1.5 mrad (half-angle),[4] the number of photons in the visible range emitted per second for each microampere of beam current being

$$N = 2.4 \times 10^{12} \frac{l}{R^{2/3}} \text{ photons/sec/}\mu\text{A}$$

where l = length of the path the electrons travel in the magnetic field. The optical system is arranged to accept light from the first 12 in. of the effective magnetic length of bending magnet B-10 (Fig. 19-3).

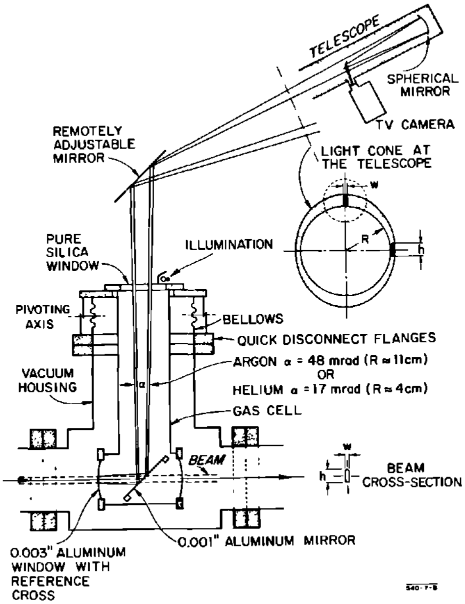
The theoretical light production in this length is 4.9×10^{10} photons/sec/μA and all of the transmitted light will be collected by a 4-in. diameter mirror at a distance of 7 meters. The light is reflected by four front surface aluminized mirrors (reflectivity = 90%), and passes through one $\frac{3}{8}$-in. quartz window (transmission 95%). Assuming a beam spot size in B-10 of 2×15 mm and a demagnification from the beam to the vidicon faceplate of 1/30, we find a light level on the photocathode of approximately 18.5×10^{11} photons/cm^2/sec/μA. The RCA 7735A vidicon tube, when adjusted for maximum sensitivity, operates with a faceplate illumination (highlight) of 0.1 ft-c = 4×10^{11} photons/cm^2 (according to the manufacturer's brochure). This corresponds to a beam current of 0.22μA. For our purposes, a useable image can be obtained with lower light levels and we have observed experimentally that the beam is still visible at average currents of less than 0.01 μA.

The special V-shaped vacuum chamber located after B-10 contains a mirror which is adjustable manually via a three-point support from outside the vacuum box. Initial alignment of the mirror is accomplished by using the optical target OT-10 in front of B-10 and the reference marks (cross wires) fixed inside the V-shaped chamber (see Fig. 19-3). The mirror consists of a $\frac{1}{4}$-in. thick piece of polished, high-purity, fused silica, the front surface of which is aluminized. A 12-in., quick disconnect, vacuum flange enables the section containing the mirror and quartz viewing window to be replaced easily.

CERENKOV LIGHT. Cerenkov light is emitted by charged particles moving through a medium with a speed greater than the phase velocity of light in that medium. In the profile monitors for the switchyard[5] the Cerenkov light is observed when the electrons pass through a gas at atmospheric pressure. The number of Cerenkov photons produced in a gas and their angle of emission are given by

$$N_\phi(3500\ \text{Å} < \lambda < 6000\ \text{Å}) \approx 900(n\beta - 1)\ \text{photons/cm/electron}$$

Figure 19-4 Principle of Cerenkov light monitor.



and

$$\theta = \cos^{-1} \frac{1}{\beta n}$$

where n = the refractive index, and $\beta = v/c$ so that a light cone is developed in the gas with an opening angle $\alpha = 2\theta$. The beam image is observed by looking along one part of the cone. This introduces a distortion along one axis equal to $l \sin \theta$, where l is the effective length of the gas cell. The construction of the Cerenkov profile monitor is shown schematically in Fig. 19-4. The gas in the cell flows through when the monitor is in the beam at a flow rate of 1 cm^3/sec. Both argon and helium have been used at different times. Argon produces more light, but helium reduces the distortion as well as the beam scattering. The gas cell is built in a tubular hammerhead configuration and has 0.003-in. thick hard aluminum beam entrance and exit windows. The light cone is reflected vertically by a mirror placed in the beam at 45°. The mirror consists of a 0.001-in. thick mechanically and chemically polished foil stretched over a ring, using a drumhead tightening principle. The gas cell swings about a pivot axis and is moved into the beam by the application of air pressure to a small cylinder. A counterweight (see Fig. 19-5) moves the cell out of the beam when the air pressure is released. Except for a beam position reference cross, the input window is blackened using a graphite spray (Aquadag, ammonium hydroxide, and water).[6] The blackening

Figure 19-5 Cerenkov light profile monitor.

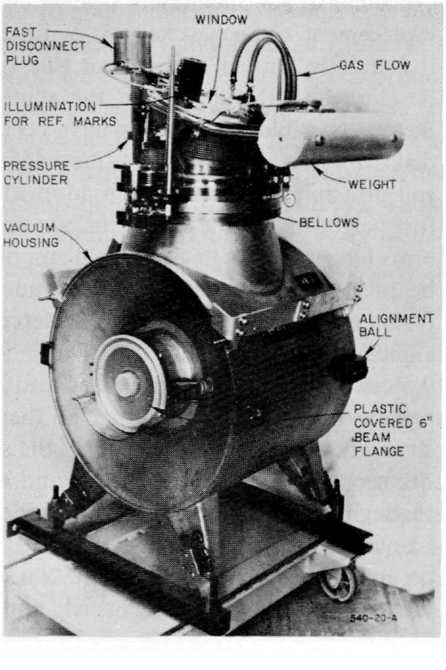


Table 19-3 Comparison of two types of multiscreen monitors

Characteristics	*Cerenkov cell*	*ZnS screen*
Sensitivity	(He)10^{-9} A/cm^2 (Ar) 3×10^{-10} A/cm^2	10^{-9} A/cm^2
Spot definition	1 mm	1 mm
Max. aperture	3 in. in diameter	8 in. wide, 2 in. long
Material in beam	2 Al windows 0.003 in.; 1 Al mirror 0.001 in.; 20 cm gas; 0.001 in. graphite (Aquadag) on one window	0.002-in. Al foil at 65° or 90° to beam 0.001-in. and 0.004-in. thick zinc sulfide Sylvania (P-402)
Rad. length in Beam	6×10^{-3} rad l (Ar); 2×10^{-3} rad l (He)	1.3 to 3.5×10^{-3} rad l
Mechanical	Moved into beam by air pressure, out by gravity	Selected and operated by electric motors
Expected life	Mirror 1.5×10^4 μA hour/cm^2	10 μA hour/cm^2 per screen

carbon is molecularly bonded to the window and is, therefore, permanent. The cross can be illuminated with a lamp mounted outside the viewing window. Table 19-3 gives the characteristics of both the Cerenkov cell and the zinc sulfide screen profile monitors.

ZINC SULFIDE SCREENS. Zinc sulfide screens are easy to make and have good sensitivity; however, they have the disadvantage of losing luminescence after exposure to an integrated beam current of about 10 μA/hour/cm^2. The replacement of such screens is a difficult task in the switchyard because of the severely limited access. For this reason, an automatic device has been developed that will replace the screens after they have become inactive. Several possible mechanisms have been considered, among which are a large disk with its axis of rotation tilted 45° with respect to the beam, and the film roll principle. The mechanism adopted for the switchyard is a carrousel with forty-eight independent screens, shown in Fig. 19-6. The forty-eight screen arms hang on balls in the slotted rim of a 10-in. wheel. The screen frames can be raised into the beam by the blade lift mechanism. The U-shape of the frame ensures that the beam is intercepted only by the 0.002-in. thick zinc sulfide-coated aluminum foil. The index drive mechanism rotates the wheel 7.5° so that a new screen comes into the lift position. The carrousel can be removed from its housing when all the screens have been used. The individual screen frames can be lifted out of the slotted rim for replacement. The image of the beam spot on the screen and position reference marks are observed through a fused silica vacuum window at the top of the light pipe and a front surface mirror at the lower end of the light pipe. The adjustable mirror on top of the light pipe and the two drive motors, shown in Fig. 19-7, protrude into a slot in the 2-ft thick concrete shielding floor. In this way they

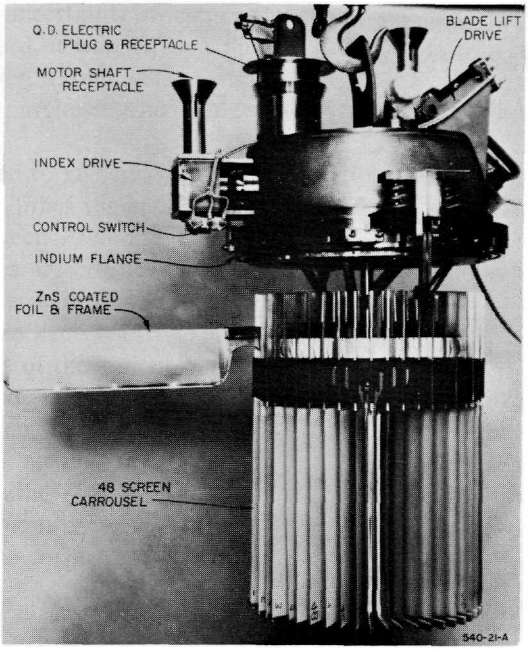


Figure 19-6 The ZnS screen changer lifted out of vacuum housing.

are shielded from radiation and are easily accessible. Figure 19-7 shows various other details designed to make remote replacement possible: a fast disconnect, two plug-in-type drive motors, assembly guide rods, a 12-in. fast-disconnect, vacuum flange, and lift eyes. Two types of the multiscreen profile monitors described above have been built, the carrousel being identical in each case. One is for a 6-in. beam pipe (4-in. wide screen) and the other is for a 12-in. beam pipe (8-in. wide screen). The only difference between the two types is the angle at which the screen is presented to the beam (see Table 19-3). The screens are sprayed at a temperature of about 80°C, using a suspension of 10-μ P-4 phosphor in glycerin, sodium silicate, and water, by a process developed by W. Schultz.[6]

OPTICS AND TV SYSTEM. A 735 scan line I.T.T. closed-circuit television system is used, its optimum resolution of 520 lines both horizontal and vertical being below that of the optical system. There are a total of eight cameras in the switchyard, and the video signals and the controls for the instruments are multiplexed into two display channels. The vidicon tube selected for the television cameras is the RCA 7735A, which is available either with a standard faceplate or (at a much higher price) with a non-browning faceplate. Radiation levels in the switchyard are still low and the standard tubes will be used until faceplate browning rather than photocathode

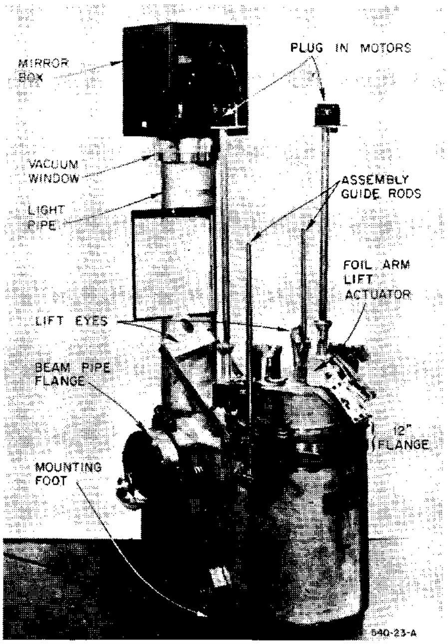


Figure 19-7 Complete multiscreen ZnS monitor.

degradation limits tube life. The photocathode of this tube has a fairly sharp spectral sensitivity curve with a peak at 5500 Å, so that other optical components in the system were chosen to match this wavelength where possible. The light is focused on the vidicon tube with a reflector telescope using spherical, front surface, aluminized mirrors (Liberty Mirror No. 756). The advantages of the telescope are that the mirrors are less expensive, are better resistant to radiation than nonbrowning lenses, and, using the Newtonian arrangement with the camera perpendicular to the telescope, the camera can easily be shielded from radiation. Light from the monitors passes in each case through a radiation-resistant vacuum window (Corning pure fused silica, code 7940) and is directed into the telescope by a remotely adjustable front surface mirror. This mirror can be rotated through small angles about two axes by electric motors driving cams, the cams being contoured to give two speeds. The front surface aluminized mirrors are unaffected by radiation but are very sensitive to nitric acid corrosion. Other metallic coatings such as gold, titanium, and chromium are resistant to nitric acid corrosion but have a low reflectivity. The reflectivity of a front surface chromium-on-glass mirror was increased to about 90% at 5500 Å by the application of several quarter-wavelength-thick layers of magnesium fluoride and titanium dioxide. This mirror was found to be unaffected by nitric acid and no significant changes in reflectivity could be found after exposure to a radiation dose of

10^{10} ergs/g. Because of the uncertainty in estimating the nitric acid vapor concentration in the switchyard, it was felt that the expense of these mirrors could not be justified. However, a fully dielectric commercial mirror (Liberty Mirror No. 90-500) has been purchased and installed on one of the Cerenkov cells for further evaluation.

The telescopes are designed to give an overall magnification on the 17-in. TV monitor between 1 and 2 times the actual beam size. The spherical mirrors vary in focal length between 10 and 20 in. for the different monitors in the switchyard. The telescopes are constructed in such a way that they will accept any $4\frac{1}{4}$-in. diameter mirror in this range. Coarse focusing is provided by means of a thumbscrew on each telescope; fine focusing is provided by remote control of the position of the vidicon tube inside the TV camera.

In the case of the zinc sulfide screen changers, where viewing angles introduce different distortions along the two axes, an elliptical disk is mounted just out of the beam path in such a way that it corresponds to a circular beam spot and can be seen on the TV monitor when there is no screen in the beam. By adjusting the TV monitor so that this disk appears circular, the distortion of the system can be corrected.

Secondary-emission monitors (*SEM's*) (JNH)

Low-energy secondary electrons (<30 eV) are emitted from the surfaces of material when it is traversed by high-energy (>75 keV) charged particles. The secondary emission shows little dependence on primary particle energy above 150 keV. It is linear with current and there is no saturation. SEM's are useful in the switchyard for their linearity and wide dynamic range but can be used only where an intercepting-type monitor is permissible.

Secondary-emission monitors are used in the switchyard, in the following applications:

1. The tune-up spectrum monitor (TSM).
2. A- and B-beam spectrum analyzers (SA).
3. For beam centering into the high-power dumps (four-quadrant SEM) and collimators.
4. On the slits to provide spectrum centering information (spectrum drift indicator—SDI).
5. Applications 3 and 4 above are also used to provide interlock signals to the summary interlock system for equipment protection.

The theoretical secondary-emission coefficient, η, is approximately 4% for aluminum. The coefficient is very dependent on surface conditions. Aluminum foils are used for all SEM's in the switchyard, and for calculation purposes η was assumed to be 3%.

SEM FOILS ON SLITS, COLLIMATORS, AND TUNE-UP DUMP. Sets of three parallel SEM foil emitters are mounted on the front and back of C-0, C-1, and SL-10 and on the front of SL-31. Two of the foils on the front of C-0, C-1, and SL-10 are experimental gold-plated conduction foils. Two sets of parallel SEM foils are mounted at each edge of the tune-up dump. These protect the dump edge from beam powers above 50 kW.

FOUR-QUADRANT SEM (4-Q SEM). This SEM is a circular structure 8 in. o.d. × 3 in. i.d. It is divided into four quadrants: top, bottom, right, and left. Each quadrant consists of a set of three 0.005-in. thick emitting foils in parallel.

A 4-Q SEM is mounted in front of the window of the A-beam dump and beam dump east. The monitor is used to steer the beam into the center of the window. The permissible power density on the window is highest in the center. Very intense beams must be carefully centered to avoid overstressing the window near its edge.

ELECTRONICS. The SEM electronics provide two signals, an interlock level and a dynamic presentation of SEM signals. Each foil is connected to an RC integrator (T = 200 msec). The integrator voltage is monitored by a variable threshold comparator (+20 mV to + 2.0 V). The comparator outputs are connected to an OR gate and used as the SEM interlock signal.

For dynamic presentation, the integrator voltages may be viewed on an oscilloscope which is connected to the electronics through a multiplexer and a selector panel (see Fig. 19-8).

Beam spectrum instrumentation (JNH)

A low-resolution spectrum measurement can be made with the tune-up spectrum monitor S-10, located in front of the tune-up dump D-10. A more precise measurement of the deflected A- and B-beam spectrum is made with identical analyzers S-11 and -31, located in front of the slits SL-10 and -31. (See Table 19-4.)

Figure 19-8 Secondary-emission monitor electronics.

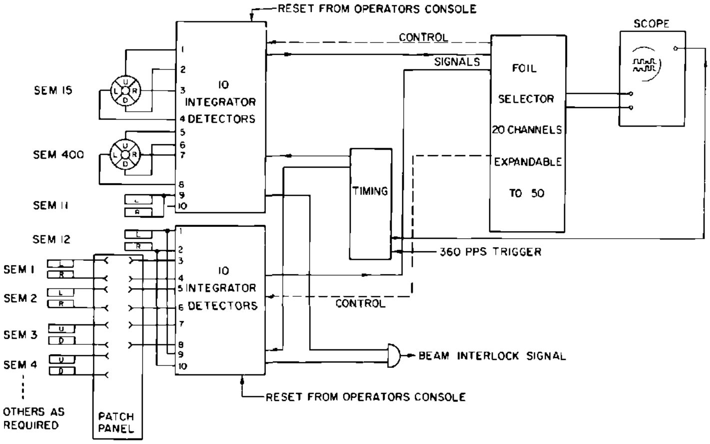


Table 19-4 Data on spectrum instrumentation

	Spectrum monitor S-10
1. Data on foils	
Material	Aluminum 0.005 in. thick
High-resolution side	22 foils covering $\alpha = 4.0$ to 7.5 mrad deflection
Low resolution side	16 foils covering $\alpha = 1.58$ to 4.0 mrad deflection
SEM-11 A and B	SEM protection foils
2. Signal integrator	
Time constants	$\frac{1}{3}$, 1, 3 sec
Signal attenuation	$100 \times (1 \mu F)$, $10 \times (0.1 \mu F)$, $1 \times (0.01 \mu F)$
Noise level	0.5 nA avg. beam current
Trigger rate	60 pulses sec synchronized with beam
Scan time	270 μsec/channel—low-resolution foil 100 μsec/channel—high-resolution foil
Display	Oscilloscope (shared with spectrum analyzer 2 and 4)

	Spectrum analyzers S-11 and -31												
1. Data on foils													
Width	mm,	40	24	12	12	6	6	6	6	12	12	24	48
S-11 $\Delta P/P$	%,	0.8	0.4	0.2	0.2	0.1	0.1	0.1	0.1	0.2	0.2	0.4	0.8
S-31 $\Delta P/P$	%,	0.16	0.8	0.4	0.4	0.2	0.2	0.2	0.2	0.2	0.2	0.8	1.6
Maximum opening between foils	6 in.												
Material	Aluminum 0.001 in. thick												
2. Average spectrum display	See detail 2 of spectrum monitor												
A-beam	12 foils from S-11 + current signal from I-13												
B-beam	12 foils from S-31 + current signal from I-31												
Scan time	100 μsec/channel												
3. Video spectrum display	Any combination of four out of the 26 video signals can be displayed on a Tektronix 551 scope												
Equivalent input noise	30 μV												
Response time	30 nsec												
4. Sampled spectrum display	See detail 2 of spectrum monitor												
Synchronization	Every beam pulse												
Sample width	100 nsec; sample can be taken at any point of beam pulse length: 0–2.2 μsec												

TUNE-UP SPECTRUM MONITOR S-10. The TSM consists of a row of SEM foils mounted in a wide vacuum chamber in front of the tune-up dump D-10. The TSM and the tune-up dump were made as wide as possible to provide maximum energy acceptance during accelerator tuning.

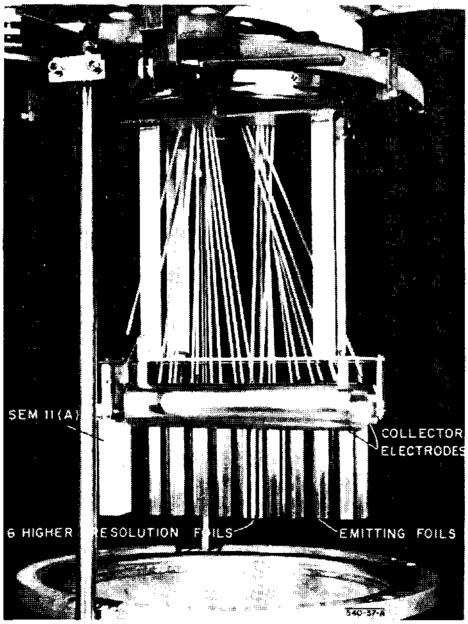
The TSM has been split into two halves. This allows each half to mount on a standard 12-in. fast disconnect vacuum flange. The half located closest to the A-beam is shown in Fig. 19-9. It contains six narrow high-resolution foils each corresponding to $\Delta P/P = 0.86\%$. The beam is normally tuned on these foils before deflecting into the A- or B-beam vacuum pipe. The other half of the TSM is constructed in the same way but has no high-resolution foils.

The foils are 0.005-in. aluminum. They are spot-welded to nickel tabs which are, in turn, brazed to metallized areas on a rectangular ceramic bar. Each foil is brazed on the alternate side of the ceramic bar, allowing the foils to be positioned with no gap or overlap between them.

At each edge of the TSM there is a stack of interlock SEM foils (SEM-11). These are used for interlock protection of the edges of the tune-up dump (see above).

The tune-up dump spectrum monitor electronics is shown in Fig. 19-10. Each of the thirty-eight individual foils is connected to an integrator in the local electronics box. The low leakage coaxial cable between the foil and this

Figure 19-9 High-resolution tune-up spectrum monitor.



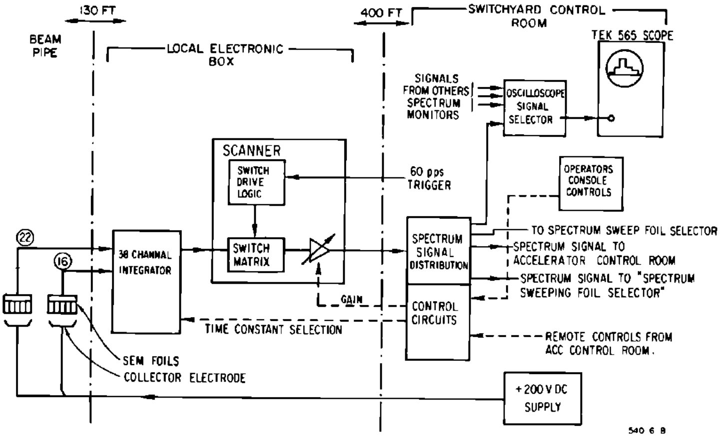


Figure 19-10 Tune-up spectrum monitor system.

circuit is part of the integrating capacitor. The discharge time constant and integrating capacitor of each integrator are remotely adjustable.

The scanner sequentially samples the voltage on each integrator and amplifies the output signal (gain adjustable from 1 to 20). The spectrum signal is then transmitted to the switchyard and accelerator control rooms.

A selector is used to separate one foil signal in the spectrum display for plotting the spectrum as a function of deflecting magnet current. To obtain a spectrum using this procedure, one has to sweep the beam across the foil.

THE SPECTRUM ANALYZER. A complete spectrum analyzer is shown in Fig. 19-11. The 0.001-in. SEM foils are supported in a unique, spring-loaded, foil holder assembly. The foil holders are mounted on pivoted motor-driven arms. This allows the foils to be retracted or inserted into the beam as necessary.

All electrical connections to the foil holders are shielded by a cover plate. This prevents deposition of any material on the ceramic insulators, which might cause leakage.

The spectrum analyzer electronics system is shown in Fig. 19-12. It is designed to display beam energy spectrum information in three ways: (a) average spectrum, (b) sampled spectrum, and (c) video spectrum.

The signals from the spectrum analyzer include a signal from the current monitor (I-13 or -33) located after the slit. The gain of the amplifier for this current monitor signal is proportional to the inverse of the selected slit opening. The amplitude of the current signal is brought in this way into proportion with the foil signals for various slit openings.

The average spectrum displays use essentially the same electronics as the TSM. One difference is the method of getting the video signal into the integrators. The mixed video signals are connected to thirteen triggered

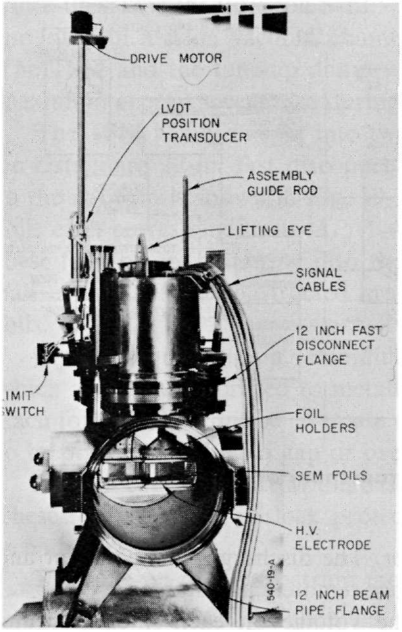
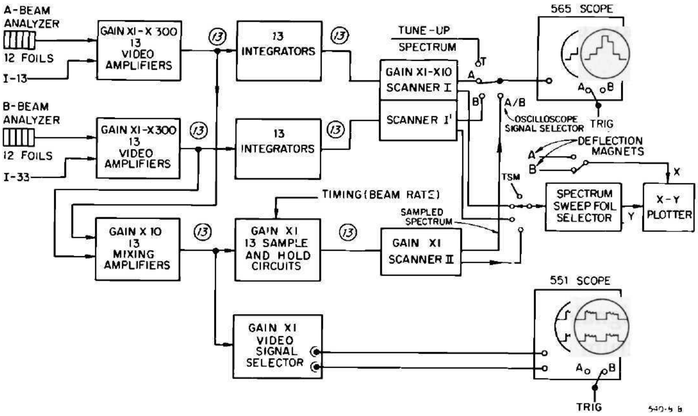


Figure 19-11 Spectrum analyzer.

sample-and-hold circuits. The sampling time of these circuits is 100 nsec, so that many beam pulses are included in the sample.

It is also possible to increase the sample time from 100 nsec to the full beam pulse length. This allows a display of the normal beam spectrum on a pulse-to-pulse basis. The spectrum display signals may be used for plotting a spectrum using the spectrum sweep foil selector.

Figure 19-12 Spectrum analyzer system.



SPECTRUM DRIFT INDICATOR ELECTRONICS. The SDI is used for two purposes: (a) to provide the accelerator operator with a simple monitor showing slow drifts in spectrum during operation and (b) as a backup for the spectrum analyzer in the event of damage to the foils or other delicate parts.

The signals for the SDI are derived from the two SEM foils on the front end of the slits and the current monitor downstream of the slit (I-13 or I-33). These signals are integrated, mixed, and displayed on three panel meters which show both the direction of spectrum drift toward higher or lower energy and the transmitted current.

Meter displays and gain controls are located in the switchyard and accelerator control room.

Transport control (RAS)

The transport control system includes means for switching magnet power supplies on and off and for regulating their current and polarity. It also includes equipment for magnet field and current measurements and for slit and collimator control. Most of the major magnet and slit or collimator adjustments can be made in either of two ways—manually or through the use of a control computer. One element, the long-coil integrator in the reference magnet used for setting the energy analyzing magnets (see "Magnetic Measurements" below), is controllable only through the computer. On the other hand, at the time of writing (July 1967), current adjustments on certain small steering dipoles must be made manually.

MANUAL MAGNET CONTROL. As mentioned above, most magnet currents may be adjusted either manually or by computer. The manual system is used as a backup in case the computer is down for maintenance. All power supplies have internal references that are adjustable by a front panel potentiometer. It is by driving this potentiometer remotely that manual control is achieved. On most of the supplies in the switchyard this is accomplished by the use of a motor mounted on the power supply front panel; a rim drive through a rubber wheel turns the potentiometer. The motors used are the low-voltage dc type and are geared down for better speed control. Two speeds are provided, one by applying full voltage to the motor winding and the other by applying a square wave of full voltage with a 20% duty cycle at 20 counts/sec. The latter method of driving the motor more closely preserves the full speed torque while slowing the motor down. Adjustments are made by the operator with a three-position lever switch (up–off–down with a spring return to the "off" position). The controls are not multiplexed; there is one lever switch for each magnet supply. Certain supplies are operated by a stepping motor, again running at two fixed rates; the operator controls are identical to those just described.

Manual control of the energy-defining magnets is accomplished through the use of a stepping motor, but because of the special requirements on the rate and magnitude of the current changes (see Chapter 18) the operator controls are different from those described above. In this case a set of rotary switches can be set by the operator to correspond to the number of steps the motor is to take. The motor will start on pushbutton command and stop after having taken the number of steps indicated by the switches. The motor runs at a fixed rate corresponding to a rate of change of current of 6 A/sec in the magnets. One control panel is used for both the A and B magnet systems.

Readback of magnet current is accomplished in two ways, depending upon the type of power supply (dc or pulsed). The dc currents are converted to voltages by ohmic shunts and are subsequently read by a digital voltmeter, switched by a relay scanner. Any dc signal from the switchyard can be read to 0.02% absolute accuracy in this way. Pulsed magnet currents are converted to voltage by a pulse transformer and are read by a sample-and-hold circuit and an analog-to-digital converter capable of reading rates up to 360 pulses sec. This counter is switched by a second relay scanner, and absolute accuracy is better than 0.1%. The pulsed system has one fixed range of 10 V full scale with a resolution of 0.001 V; the dc system has ranges of 1000, 100, 10, 1.0, 0.1. and 0.01 V full scale with a resolution of five digits (0.1 μV on the smallest range).

MAGNETIC MEASUREMENTS (RAS). A system for remote measurement of magnetic fields has been provided. This system includes residual field detectors, NMR probes, and flux loop integrators (an integrator connected to a loop around the magnet yoke).

The residual field detector is a flux-gate magnetometer. The probe consists of a pair of strips of high-permeability magnetic material, each wound with a "primary" coil. The primaries are connected in series, opposing. A 1000-Hz signal applied to the primary windings then alternately saturates the cores in opposite directions. A pickup "secondary" coil is wound around both strips. The signal in this coil (to first order) does not contain any 1000-Hz components because of the opposing primary currents. If a small dc magnetic field is applied parallel to the strips, a 2000-Hz voltage appears across the secondary, because on each half-cycle of the primary current one of the cores is easier to saturate than the other, "unbalancing" the primary currents. This signal is passed through a 2000-Hz, narrow band filter and applied to a high gain amplifier. The output of the amplifier is synchronously detected using the primary signal for phase reference. The resulting dc output is proportional to the field in the probe and is displayed on a panel meter. Sensitivity of the meter is about 2.5 G full scale. This method was chosen to allow the use of a passive probe structure; the probe consists entirely of radiation-resistant materials and can be operated up to 2000 ft from the electronics.

Nuclear magnetic resonance probes are placed in the energy-defining magnets B-10 to B-13 and B-30 to B-32, and in the reference magnets (two reference magnets B-100 and -300 are placed in the control room building and are electrically in series with the energy-defining magnets in the A-beam and B-beam). The NMR circuit is a modified Pound-Watkins-Knight marginal oscillator[7] and offers no unusual design features. The probe itself consists of a quartz tube with a volume of 0.03 cm^3 surrounded by a solenoid, which acts as the RF circuit of the oscillator. The liquid is a 0.1-mole solution of $MnSO_4$ in saturated $LiCl_2$ in water and provides two resonances: ^1H at 4.2577 MHz/kG and ^7Li at 0.23487 MHz/kG. This double-resonance technique allows coverage of a wider field range without frequency range switching in the electronics. No sweep coils were provided because the dimensions of the probe had to be made as small as possible ($\frac{3}{8}$-in. o.d.) to avoid interaction with the beam in the narrow magnet gaps. A sweep field is obtained by shunting the magnet with a transformer operated from the 60-Hz power line via dc blocking capacitors. A signal-to-noise ratio of 10 to 1 is obtained in the final system with connecting cables as long as 1000 ft.

A simple integrator system has been provided to allow crude field measurements in the dc magnets. The purpose of these measurements is to allow detection of shorts or other changes in the magnet coils at a remote location. The pickup coils (flux loops) consist of several turns around the return yokes of the magnets. These coils are connected by a selector to a stable dc integrator. The system is used as follows. The magnet is turned on to a preset current and the integrating capacitor discharged. The magnet is then turned off, and the resulting output from the integrator is read on a digital voltmeter. The system measures magnet characteristics to better than 1%.

Stationary flux loops on the pulsed magnets PM1 through PM5 are used to integrate the magnetic field in these magnets every beam pulse. The output is used not only to measure the field but also to interlock the beam in the event of misfiring of a magnet modulator (see Section 19-3).

A special rotating flux coil is used in the reference magnets B-100 and -300. This coil can be rotated 180° in the gap of these magnets. The coil output voltage is connected to a voltage-to-frequency converter, and the number of pulses emerging from the converter is proportional to the integral of the field along the coil length. Because the coil is made long enough to include most of the fringing fields, it measures the $\int B\,dl$ to high accuracy. The absolute accuracy of the method is not well defined because of the lack of a suitable comparison standard, but rms deviations in the measurement are typically less than 5 parts in 10^5 over a 1-hour interval. The rotating flux coil is used by the computer (see below) to set the energy acceptance of the BSY.

COMPUTER SYSTEM (RAS, SKH). The transport control system includes a small digital computer to aid in setting up the complex set of parameters in the BSY. The computer (SDS 925) has an 8192-word core memory (24 bits per word) and a 1.75-μsec cycle time; it is a fully parallel, binary oriented machine. Standard peripheral equipment includes a card reader (200 cards/min), a card punch (100 cards/min), and a pair of teletypes, one in the BSY control room and one in the CCR.

Through the use of a number of SLAC-built interfaces, the computer can read, log, and control status information; control magnet, slit, and collimator settings; determine the energy of the various beams in the switchyard to better than 0.05%; and communicate with a larger computer (SDS 9300) in the experimental areas. The operation of these interfaces and associated equipment will be described below.

The interlock and status scanner reads, every beam pulse (2.8 msec), the 1008 two-state status signals in the BSY. The computer scans these signals, detects changes in them, and notifies the operator of the changes. The time required by the computer for scanning, detecting, and identifying the signals is less than 400 μsec. Additional time is required for processing if changes occur.

The scanner is basically a digital multiplexing system controlled by the computer; it transfers 1008 input signals to its output, sixteen signals at a time. Along with each group of sixteen data signals, 6 bits of address information are presented at the output to identify the group being transferred. Thus 22 bits of information are presented to the computer at a time. The computer must accept 63 such transfers to get all of the 1008 signals. When all of the information is stored in the computer memory, the data are compared bit by bit with the previous scan, and the changes recorded. At the time of writing (July 1967) the changes are printed on a small digital printer (maximum speed ≈20 lines/sec), but plans are underway to add an oscilloscope display to the system, which would be used to provide a more sophisticated presentation.

Computer magnet control involves five basic equipment modules: digital-to-analog converters to control magnet currents; analog-to-digital conversion equipment to read those currents; the long flux coil (see "Magnetic Measurements," above) interface to read $\int B\,dl$ in the energy-defining magnets; the "tune box" to provide the operator with facility for making small changes in the settings; and a set of status control channels for controlling magnet power supply "on–off" and reversing. Two interfaces are used for digital-to-analog conversion, and each operates a different type of converter. The most common type consists of a 15-bit binary resistor ladder switched by mercury-wetted reed relays. The relays are of the magnetic latching type, and thus form the memory as well as the switching and isolation functions. Reference voltage for the resistor ladder is supplied by a highly stable (±0.01%/24 hours) power supply that is shielded and guarded from the chassis ground. The resistor ladder contains thirty-one resistors, matched to ±0.002%, and is also guarded. The 15-bit resolution allows steps of 1 part in 32,768 of the full-scale output voltage of 10 V, or about 300 μv. The present system includes twenty-six such converters, with provision to extend this number to sixty-four.

The energy-analyzing magnets, however, have one special requirement which precludes the use of this type of converter. The high energy of the electron beam (24 GeV) requires eight 3-meter magnets to deflect the beam

24° in the analyzing system (for A-beam; the B-beam uses four magnets to deflect the beam 12°). These magnets are connected electrically in series, along with a reference magnet (which is placed in the control room for measurement purposes). In order to ensure accurate tracking of the magnetic field, a necessity if the reference magnet measurements are to be meaningful, the current in these magnets must be changed at a relatively slow rate (0.75%/sec).

The digital-to-analog converters mentioned above inherently produce transients that far exceed this rate. Therefore, these magnets are controlled by a reference voltage from a multiturn potentiometer driven by a digital stepping motor. The mechanical nature of such a system precludes transients larger than about 0.003% in amplitude. The interface contains a pair of counters (one for A-beam and one for B-beam) which are loaded by the computer with the number of steps the motor is to take. The interface detects the sign of the number (it is loaded in two's complement) and, if negative, counts the counter up and the motor counterclockwise; if it is positive, the interface counts the counter down and the motor clockwise. A pulse is counted by the counter for each pulse sent to the motor. When the counter reaches zero, the clock pulses stop (stopping the motor) and the computer is interrupted.

Readback of magnet currents is accomplished by two methods. In the case of dc magnets, the currents are measured by shunts ($\approx 1.2 \times 10^{-3}$ ohm), and the shunt signals are switched through a precision relay scanner to a digital voltmeter, where they are digitized to an accuracy of better than 0.01%. Of course, any dc signal can be read through this system. For the pulsed magnets, a solid-state differential multiplexer and a fast analog-to-digital converter with a sample-and-hold circuit provide the computer with measurement ability. The computer selects both the channel and trigger time of the sample-and-hold circuit.

The long flux coil interface contains circuits to control the motor and clutches on the coil mechanism, and to count the pulses from the voltage-to-frequency converter. The circuits work in the following way. Upon issuance of a command by the computer, the motor starts to turn and the clutch engages, starting the coil in motion. The output of the coil is connected to a voltage-to-frequency converter with high stability. Since the output of the converter is a train of pulses the frequency of which is proportional to the input voltage, the number of pulses is proportional to the integral of the input voltage. These pulses are counted by a register in the interface, and a set of microswitches on the coil mechanism stops the motor and provides an interrupt to the computer when the rotation has ended. Upon interruption the computer reads the number in the register, resets it, and starts the coil rotating in the opposite direction. The program always averages two successive "flips" of the coil to eliminate the effect of zero drift error in the voltage-to-frequency converter. The resulting number is precisely proportional to the $\int B\,dl$ in the magnet, which is, in turn, proportional to the energy of a particle passing through the center of the slit. Root-mean-square deviations of the measurement are typically less than 5×10^{-5} over a 1-hour period, with the coil making three flips a minute.

The "tune-box," or magnet manual control panel, consists of twenty-four pushbuttons, one lever switch (three position momentary), 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 these interrupts are sent to the computer is controlled by the speed control (1 per switch operation, or a steady 1, 5, or 25 per second). When so programmed, the computer will interpret the selected pushbuttons as magnet supplies, inspect the pushbuttons, and increment or decrement the magnet currents selected depending upon the position of the lever switch. There are two such panels provided. Since the interface is designed such that the interrupt is not required for the computer to inspect the pushbuttons, this panel can also be used in other ways, one of which is to print out on the typewriter the currents (in equivalent gigaelectron volts) of all magnets selected. This is done through a typewriter instruction (see the discussion of the computer program below). The tune-box was provided primarily to allow the operator to make small adjustments to the magnet currents in a manner more natural than typing a series of instructions on the computer typewriter.

The final interface used for magnet control is a set of sixteen mercury-wetted relays (the system is expandable to sixty-four such sets) of which the positions are individually under computer control. This interface allows the computer to turn on and off and reverse power supplies, or to control other status in the switchyard and research areas.

A computer–computer link has been designed between the SDS 925 in the switchyard and the SDS 9300 in the experimental area, about 1000 ft away. The link system contains two buffers, each 24 bits long, to hold data from one computer until the other can respond and read it. The data word is transferred, along with an interrupt, in parallel along coaxial lines. Maximum transfer rate is limited by the speed of response of the computers to the interrupt, but could, in principle, exceed 50×10^3 full computer words per second.

The entire computer system, including the slit and collimator control system, is shown in Fig. 19-13.

Control of the slits and collimators is a complex task involving a separate system. The computer can control them through the slit/collimator (S/C) computer control unit, a portion of the S/C control system. The entire system will be described later.

Communications between the operator and the computer are accomplished either directly by typing the instruction on the typewriter, or by punching the instructions on IBM cards and reading the cards into the computer. The execution of the instructions is accomplished through the use of the "925 system language," the source language for a real-time compiler which is resident in the computer at all times. The real-time compiler reads instructions from the typewriter (or card reader) on-line and in what is essentially

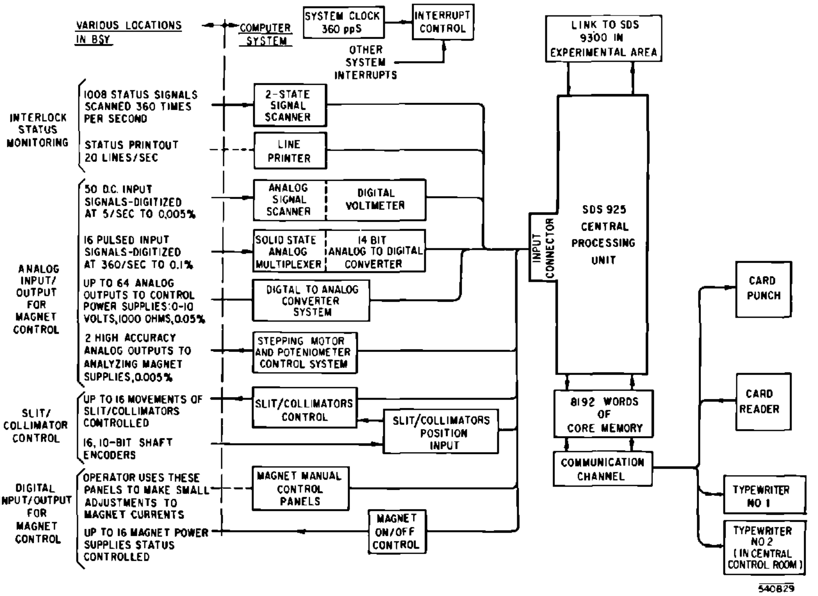


Figure 19-13 Switchyard computer system.

English language. It interprets them, compiles the machine language instructions necessary to execute them, and performs the actual execution, all automatically and in real time. Statements in the instruction may be included to modify or delay the execution time, if desired.

The following section describes the instructions programmed for the switchyard computer system. A list of these instructions is shown in Table 19-5.

An instruction is a series of words, separated by one or more spaces or carriage returns, terminated by a semicolon word, " ; "

In case of confusion, e.g., two instructions before the semicolon, the computer takes the last (or rightmost) one. If there is no meaningful instruction between semicolons, the computer types out "ERR" and is ready for another try.

1. Modifiable instructions

STEP ⟨elt⟩ BY ⟨no.⟩ ;	Causes specified magnet power supply to increase its current by the specified fraction of its present value.
FLC ;	Starts the flip coil on a single flip, which takes about 20 sec to complete.
CARDS ;	Causes the input source to be the card reader, i.e., the program now takes its input from the card reader until an "end of file" character is sensed. This character is the "$\surd$" (8-7 punch on cards).

(Continued on p. 681)

Table 19-5 List of computer instructions

Modifiable instructions—clauses may be added.

```
SET BOX1 = ⟨no.⟩;
STEP BOX1 BY ⟨no.⟩;
TOLSCAN BOX1;
TOLSCAN BOX1 Δ= ⟨no.⟩;
OUTPUT BOX1;
RECORD BOX1;
SET ⟨elt⟩ = ⟨no.⟩;
STEP ⟨elt⟩ BY ⟨no.⟩;
TOLSCAN ⟨elt⟩;
TOLSCAN ⟨elt⟩ Δ= ⟨no.⟩;
OUTPUT ⟨elt⟩;
RECORD ⟨elt⟩;
SEND ⟨string⟩;
TIME;
CLOCK (⟨time⟩);
CARDS;
FLC;
```

Fixed instructions—all clauses are ignored.

```
SCALE ⟨elt⟩ BY ⟨no.⟩;
KILL ⟨label⟩;
TUNE ⟨elt⟩ BY ⟨no.⟩;
TUNE ALL BY ⟨no.⟩;
CLEAR;
RESET = ⟨no.⟩;
```

Clauses

EVERY ⟨time⟩ AT ⟨time⟩ UNTIL ⟨time⟩	—time clauses
TO ⟨destination⟩	—destination clause
⟨label⟩:	—label clause

⟨time⟩ format examples

(9HR) (9 : 00MIN) (9 : 00 : 00SEC)	refers to 9 o'clock or 9 hours
(T+ 5MIN) (T+ 5 : 00SEC)	refers to current time plus 5 minutes

⟨destination⟩ list

2—typewriter output
3—card output
4—link output
anything else—typewriter output
no destination clause—typewriter output

⟨string⟩ definition—any sequence of characters, not spaces or carriage returns, the first of which is a letter or the character "*"

⟨label⟩ definition—any string

⟨No.⟩ definition—any sequence of digits with one decimal point somewhere in it. The sequence may be preceded by a minus sign "—"

⟨elt⟩ list

PM1A
PM2A
PM3A
PM4A
PM5A
AP5
Q10
Q11
Q12
Q13
Q14
Q20
Q21
ADUM
B1A
BIT
B29
Q400
Q401
ABEN
EFA

OUTPUT ⟨elt⟩ ;	Causes current of specified magnet (or width of specified slit) to be packaged as output.
RECORD ⟨elt⟩ ;	Causes scale factor of specified magnet (or width of specified slit) to be packaged as output in a format which is reloadable, i.e., the format is in the 925 system language.
SCALE ⟨elt⟩ BY ⟨no. ⟩ ;	Causes the SCALE factor of the specified magnet to be loaded with the given number. The assumed units are kilogauss/(GeV/c). This number uniquely determines the "focal length" of the quadrupole and hence all of its focusing characteristics.
SEND ⟨string⟩ ;	Causes specified string (note—a space is the delimiter and hence the string contains no spaces) to be packaged as output.
TIME ;	Causes the time to be packaged as output.
CLOCK (⟨time⟩) ;	Sets the computer clock to the specified time of day.

Examples :

```
STEP B1 BY .01 ;
OUTPUT EFA ;
RECORD Q10 ;
CARDS ;
SEND THIS . IS . A . TEST ;
TIME ;
CLOCK (9:00 MIN) ;
```

2. Clauses

Clauses may be added to these instructions to give them flexibility. The types of clauses are given below. In case of confusion, e.g., two clauses of same kind in a single instruction, the computer takes the last (or rightmost) one.

TIME CLAUSES. Each of the above instructions causes a single action to take place. This action may be taken at a specific time, repeated at periodic intervals, and stopped at another specific time by adding the following clauses (in any order appearing anywhere before the final semicolon).

```
EVERY (⟨time⟩)
AT    (⟨time⟩)
UNTIL (⟨time⟩)
```

Examples:

AT (9:05MIN) EVERY (15SEC) UNTIL (9:20MIN) STEP B1 BY .01 ;
(Causes the current to be increased (by 1% of its value) every 15 sec until 9:20.)

AT (T + 30SEC) EVERY (20SEC) UNTIL (T + 10:30SEC) FLC ;
(Will cause the flip coil to begin a flip every 15 sec for 10 min. Time may be expressed in either HR, MIN, or SEC or PUL (beam pulses).

Thus,

(9HR)
(9:00MIN)
(9:00:00SEC)
(9:00:00:000PUL)

all express the same time.)

DESTINATION CLAUSE.

TO ⟨integer⟩

This clause is used with any of the digital output instructions, that is, with

OUTPUT
RECORD
SEND
TIME
TOLSCAN

and directs the output to the specified destination. If there is no destination clause, the program assumes typewriter output. The destinations currently available are

integer	*destination*
1	no dest (i.e., ignore the output)
2	TWR
3	card punch
4	Link

Example:

AT (9:05:20SEC) EVERY (20SEC) UNTIL (9:20:20SEC) OUTPUT B1 TO 3
(Causes the current in B1 to be punched on cards every 20 sec, but 20 sec behind the execution time of the previous example.)

LABEL CLAUSE. Each of the above instructions may be given a label by the user, so that it may be singled out by the computer later (to be deleted or related to the output produced). Instructions without a label clause are implicitly given the label "XX." The label clause

⟨label⟩ :

may appear anywhere before the final semicolon.

Example:

LABL : EVERY (1 MIN) OUTPUT ADUM ;
(Causes ADUM current to be printed on the typewriter every minute indefinitely.)

3. *Fixed instructions*

The instructions below ignore any clauses and will be executed just once.

KILL ⟨label⟩ ;	Kills the instruction having the specified label.
SET ⟨elt⟩ = ⟨no.⟩ ;	Set magnet current (or slit width) to specified value.

TUNE ⟨elt⟩ = ⟨no.⟩ ;	Loads scale factor for specified magnet (or for all magnets) connected to the tune box into the computer. Then each time the lever on the tune box is pushed, the current in magnets selected on the tune box panel are increased by (new current) = (1 + scale factor) (old current).

Examples:

KILL LABL ;	Kills the instruction in examples in label clause section.
SET EFA = 4.5 ;	Sets the current in magnet EFA (the BSY 3° bending magnets) so that the design momentum of beam through the switchyard is 4.5 GeV/*c*.
TUNE ALL BY 0.01	Loads scale factor of 1 % for all elements connected to TUNE box. Then, on "Magnet Manual Control" panel, buttons for 1 or more elts may be pushed. This activates them for 1% changes. In SINGLE STEP mode, each time the lever is pushed up they are increased by 1%. Each time it is pushed down they are decreased by 1%. The 1% factor is changed by the TUNE instruction.
SET BOX1 = 18.0 ;	Will adjust the currents of all magnets corresponding to buttons pushed on the "Magnet Manual Control" panel so that 18.0-GeV electrons will pass. For quadrupoles the appropriate SCALE factors must have been previously loaded, as they are required to compute the current of the quadrupole.

SLIT/COLLIMATOR CONTROL (MJH). The positions of the slits and collimators must be precisely controlled and accurate measurement of their position made remotely at the control room. The collimators consist of a pair of jaws, one closing in the vertical direction and one in the horizontal direction. A slit is half of a collimator, opening only in the horizontal direction.

The slits and collimators are enclosed in vacuum tanks (see Chapter 20 for a complete discussion of these devices). The various units used in the switchyard are listed in Table 19-6. The mechanical motion to open or close the jaws of the devices inside the tank is obtained by rotating shafts coupled into the tank through bellows. The rotating shafts are linked to drive motors through magnetic clutches and gear trains. The motor housing contains the motor, gear trains, position readout devices, and magnetic clutches, and is mounted in the upper housing of the BSY to minimize radiation damage to its contents.

There are two types of controls. One type controls the open–close motion of the jaws inside the tanks, whereas the other moves the tank itself transversely in a direction parallel to the faces of the jaws. This latter control is

Table 19-6 Data on slit and collimator position control

Name	*Designation*	*Type*	*Speed*	*Motor*	*Encoder*	*Potentiometer*	*Mechanical counter*	*Travel (in in.)*	*Readback precision (in in.)*
High-Z collimator	—	H V	Slow/fast	1	2	2	2	3	0.0029
High-Z slits	SL-11	Single	Slow/fast	1	1	1	1	3	0.0029
	SL-31	Single	Slow/fast	1	1	1	1	3	0.0029
High-power slits	SL-10	F R	Slow/fast	1	2	2	2	3	0.0029
	SL-30	F R	Slow/fast	1	2	2	2	3	0.0029
High-power collimator	C1-H	F R	Slow/fast	1	2	2	2	0.75	0.0007
	C1-V	F R	Slow/fast	1	2	2	2	0.75	0.0007
Photon collimator	C-10	H V	Slow/fast	1	2	2	2	3	0.0029
Photon collimator (tank)	C-10 (T)	up-down left-right	Slow	1	2	2	2	3	0.0029
High-power slits (tank control)	SL-10	Up-down	Slow	1	None	1	1	7	0.01
	SL-30	Up-down	Slow	1	None	1	1	7	0.01
High-power collimator (tank control)	C1-H	Up-down	Slow	1	None	1	1	7	0.01
	C1-V	Left-right	Slow	1	None	1	1	7	0.01

required to extend the life of the jaws by changing and thus extending the beam interaction area. The jaws can be controlled at variable speeds, the tanks at only one speed.

The 16-ft long jaws of the high-power (2-MW) collimator C-1 and the high-power slits SL-10/SL-30 require two independent drive mechanisms, one at the front end of the jaws and one at the rear. Magnetic clutches are required to switch over from high drive speed to low drive speed.

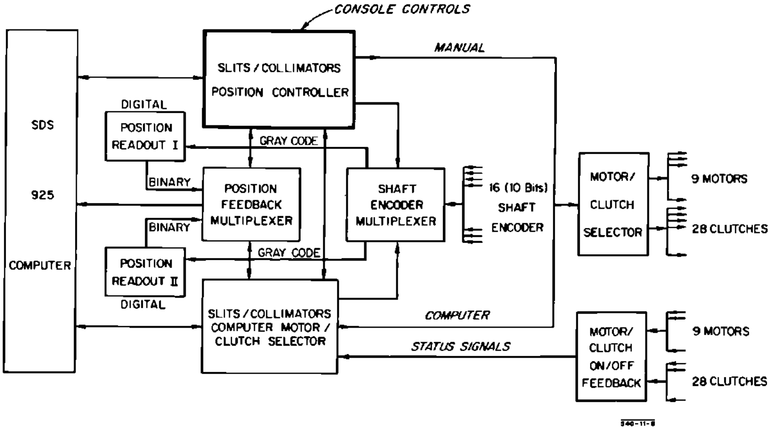
The slit and collimator jaw position is read back digitally by means of shaft encoders. In addition, potentiometers are provided to back up the encoders and to give an analog jaw position signal for readout in the accelerator control room.

The position control and readback system for the slits and collimators is shown in Fig. 19-14 and consists of the following units:

1. Slit and collimator position controller
2. Shaft encoder multiplexer
3. Position readout I and II
4. Position feedback multiplexer
5. Motor/clutch selector
6. Slit/collimator computer control
7. Motor/clutch on–off feedback

The central unit from an operations point of view is the slit and collimator position controller. This panel has a switch to select three modes of control: manual, manual–computer, and computer. The latching selection pushbutton connects both the readout and control electronics to the selected slit or collimator. Two rows of lever switches are used to control speed and direction (open–close). In the manual control mode, the operator is able to select any slit or collimator to be read out and controlled. In the manual–computer mode, the computer samples the position of the slit or the collimator selected by the operator. In this mode the operator is not able to make another

Figure 19-14 Control of slits and collimators.



selection until the computer has had a chance to store the previous setting into its memory. In the computer control mode, the operator can selectively control any slit or collimator through the use of the system program language on the typewriter or through the punch-card reader. The computer then makes the necessary decisions required to set the slits or the collimators as specified by the program.

The slit and collimator position controller becomes disabled, in the manual and manual–computer modes, if 3 min have elapsed since the last change was made by the operator. The shaft encoder multiplexer contains sixteen input channels and two output channels. Each input channel is connected to one shaft encoder and the output channels are connected to position readouts I and II, respectively.

The position readout devices I and II receive position information in gray code from the shaft encoder multiplexer. The readout devices convert the 10-bit gray code information into binary form, then from binary into 8421 BCD-code,[8] and finally from 8421 BCD into a decimal display. The 10-bit binary information is sent to the position feedback multiplexer.

The position feedback multiplexer, under computer control, transfers 16 bits of data into the computer memory. Ten of the bits originate in one of the readout devices, whereas 6 bits represent the device code.

The motor/clutch selector receives a control command from either the S/C position controller or the S/C computer control, and controls the appropriate clutches and motor accordingly.

The logical design of the S/C computer motor/clutch selector is such that the computer is able to select any device and to change the speed and direction of the device. Basically, the S/C computer motor/clutch selector works as follows.

A control word, which contains 1-bit read/control, 6-bit slit/collimator device code, 2-bit speed code, and 2-bit open/close code, is sent by the computer to the S/C computer motor/clutch selector. Once the S/C computer motor/clutch selector receives the control word, it decodes the words. If the first bit (read/control) is a zero, then the S/C computer motor/clutch selector allows the computer to sample the S/C position feedback multiplexer. However, if the first bit is a 1, then the S/C computer motor/clutch selector selects the slit or collimator, and waits for an acknowledge signal from that slit or collimator. If the signal returns, it sends the next control command to turn one of the two speed clutches on, and waits for the second acknowledge signal from that speed clutch. Finally, if the clutch signal returns, it sends a signal to turn the motor on. If the motor is turned on, then the S/C computer motor/clutch selector sends a signal to the computer indicating that everything is set, and the computer will proceed to sample the S/C position feedback multiplexer. Suppose, after the computer has sampled a few times, it decides to make a change. The computer would then send another word to the S/C computer motor/clutch selector. The S/C computer motor/clutch selector then, in turn, stops the motor, changes speed if required, changes motor direction if required, and informs the computer that it has made the change. No matter what signal the S/C computer motor/clutch selector sends out, it always waits to receive a return acknowledge signal from the clutches or the motors. If no signal returns within $\frac{1}{2}$ sec, then the S/C computer motor/clutch selector will send a malfunction interrupt to the computer. The computer will inform the operator.

The motor/clutch on/off feedback provides the S/C computer motor/clutch selector with the necessary information for sequential operation, and also provides the operator with a lamp display showing which clutches and motors are in use.

The entire slit and collimator position control and readout consists of thirteen chassis. The function of each chassis is described in detail by Hu.[9]

19-3 Interlock system—equipment protection (RAS)

In the accelerator, all the interlaced beams traverse a common beam channel —the accelerator waveguide. For this reason if an interlock action for machine protection is sensed, there is usually no way to detect which of the beams "tripped" it, and all beams must be shut off. These interlaced beams are separated by the pulsed magnets in the BSY, however, which send them to different experiments in widely separated end stations through separate beam channels. This separation allows the machine protection system in the BSY to assume an added flexibility by turning off the beam which tripped an interlock, leaving the others on and their associated experiments still running. This flexibility is desirable not only to avoid interruption of experimental time on the unaffected beams but also to allow one experiment to run even if others have been disassembled and their interlock chains broken.

In order to achieve true separation of interlocks, the beams must be separated; this is because the slow nature of many of the sensors (e.g., temperature sensors—response time ≈ 30 msec) precludes distinguishing between two beams only 2.8 msec apart in time and because many interlock functions (e.g., water cooling of protection collimators) are necessary if *any* beam is on. This separation of the beams is a trickier proposition than one might first imagine. Although it is true that the pulsed magnets will (barring failure) separate the beams, they must also always send the right beam to the right place. Suppose the beams are numbered 1 through 6; then if the interlock system is wired to expect beam 1 in the A-analyzing channel, beam 1 will be turned off in the event of water flow failure to slit SL-10, for example. Suppose now that by accident beam 2 enters the A-beam channel, and water flow stops in the slit. The system would turn off beam 1, leaving beam 2 to continue to run, perhaps damaging the slit.

To provide some protection against accidents of the above type, one of several techniques can be adopted. For example, the interlocks could be wired to the switches for the pulsed magnets so that they would always shut off the beam programmed to come into their channel. This is quite complicated, because the direction and magnitude of deflection is a function of the polarity, number, and setting of the pulsed magnets as well as the sign of the charge of the particle. In addition, the emergency magnets B-1 and B-2 can be used in lieu of (or even conceivably in conjunction with) the pulsed magnets. Also, this scheme would not protect against failure of the deflection magnet systems. Alternatively, a set of switches could be provided, indicated desired beam "destinations" and the interlock system could inspect the *actual* beam geometry (as measured by the various current toroids and ion chambers in the BSY), the beam could be turned off if agreement were not achieved on each beam pulse. If this same set of switches were to "connect" the interlock system to the beam shutoff network, then the interlock circuits would essentially be comparing the actual beam geometry with the one protected. This second method is the one employed in the BSY summary interlock; it is called "errant beam" protection. In the above example, if beam 2 entered the A-beam channel, the interlock system would detect this condition by noting a current in I-10 at the wrong time and would shut off *all* beams until the problem was corrected. Correction could be made either by changing the "geometry selector" so that beam 2 could enter the A channel (the water flow loss in SL-10 would then shut off beam 2 also), or by readjusting pulsed or emergency magnets so that beam 2 could not enter the A channel.

In addition, the interlock system in the BSY must be switchable to handle experimental changes. That is, not all interlocks are used in each of the several possible beam configurations; indeed, some of the interlock conditions are mutually exclusive. Thus, whole areas of the BSY interlock system can be switched out at will by the operator; the summary circuits inspect the conditions that allow the selection, and if at any time they are not satisfied, the beams are switched off.

Electronics

The summary circuit for the BSY inspects the beam conditions selected by the selection circuits on a pulse-to-pulse basis and provides the permissive pulse to the injector circuits, the pattern interlock signals to the CCR, and the necessary status signals to the BSY operators. The permissive pulse and pattern interlock circuits are described fully in Chapter 21, and will only be touched on here.

The permissive pulse gates the injector trigger, and thus if it is absent the beam will be inhibited. It is generated on a pulse-to-pulse basis in the switchyard summary circuits when the switchyard is operating. The accelerator generates its own permissive pulse for accelerator tests (see Chapter 21). It is this signal which allows the beam to be turned off immediately if necessary. There is no time lag involved. However, since the pulse involves only the injector, the klystrons don't "know" there is no beam, and stay on in the "accelerate" mode. Therefore, any stray electrons ("dark current") will be accelerated and produce a small but nonzero beam in the switchyard. The pattern interlocks have an inherent one-pulse delay—they always allow one pulse to be produced after detection of the fault condition. They, however, remove the accelerate triggers from the klystrons and, thus, reduce the dark current to negligible values. A disadvantage (in addition to the delay) of the pattern interlocks is that the triggers to the BSY equipment and experimental areas are also removed. These two interlock methods are used in conjunction with one another as the situation requires.

The summary circuits for the BSY interlocks work in the following way. The A-beam interlocks are gated by the A-beam pattern (as selected by the "geometry selector"); the B-beam interlocks are gated by the B-beam pattern, and so on. The resultant signals are combined (OR'ed) and gated by the common beam interlocks (those signals from sensors in the area where the beams share a common beam channel, i.e., before the pulsed magnets). The result is an ac signal which, when gated by a 360/sec trigger at the proper delay time, provides the permissive pulse generator with a trigger. Thus a permissive pulse is generated if either the A-beam is OK when the A pattern pulse is "due," *or* the B-beam is OK when the B pattern pulse is "due," *or* the C-beam is OK when the C pattern pulse is "due," and so on, *and* the common gate is OK. The errant beam detector consists of a flip-flop that is actuated if a current is detected in its associated toroid or ion chamber when there is *no* pattern signal for that area. There is one flip-flop for each beam area. The outputs of these flip-flops are connected to the COMMON beam gate.

After most interlock faults, relays in the selector circuits latch out and keep the beam off until reset. These relays do not drop out for certain "suppression functions," such as the pulsed magnet interlock or beam hold during profile monitor movement, to avoid excessive loss of beam time due to repeated resets. Normally, the pattern interlock signal is broken when this relay drops out, but for those cases where loss of triggers cannot be tolerated, a switch is provided that maintains a steady pattern interlock signal independent of the state of the summary circuits. Also, two signals are accepted from each experiment in addition to the interlock circuits. These two signals come from switches in the experimenter's setup. One "suppresses" the beam; that is, it removes his permissive pulses from the permissive pulse train without either dropping out the latch relay (which would require control room reset) or interrupting the pattern interlock circuits (which would remove his triggers). The other breaks the pattern interlock circuit without dropping out the latch relay. The latter interrupts the beam *and* removes the triggers on that pattern. Each experimenter can individually suppress his own beam and triggers without affecting the other experiments.

Ionization chamber interlocks

A few beam pulses at maximum beam power may damage a vacuum chamber or a protection collimator. Since thermal sensors are too slow to detect instantaneous local temperature changes, ionization chambers have been

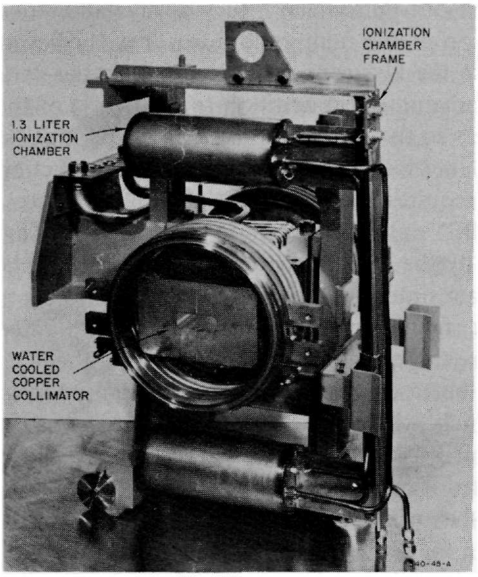


Figure 19-15 Protection collimator with ionization chambers.

used because of their quick response for these purposes. Ionization chambers have the advantages of being simple in construction, easy to make radiation-resistant, and of operating physically independently of the equipment to be protected. Their disadvantages are (1) they saturate easily, (2) they are very sensitive to geometrical arrangement with respect to the radiation source, and (3) they are somewhat difficult to calibrate.

The ionization chambers used in the switchyard (Fig. 19-15) consist of a number of parallel aluminum plates with $\frac{1}{4}$-in. spacing connected alternately to a signal lead and a high-voltage lead (300 V). The welded stainless steel housing contains helium at atmospheric pressure. The active volume is 1.3 liters. The output signal from the ion chamber is roughly proportional to the power of the absorbed beam. For the protection collimator shown in Fig. 19-15, the charge collected by the chamber is of the order of 10^{-10} C/J of absorbed beam in the protection collimator. Thermometers at the inlet and outlet of the cooling water for the protection collimator and a water flowmeter make it possible to calculate the absorbed beam power directly and can be used to calibrate the ionization chambers. The ionization chambers do not saturate if a pulse of a 2-MW beam hits the protection collimator.

Two long, coaxial, ionization chambers are used in the switchyard to protect long drift sections in the vacuum pipe. These coaxial chambers consist of lengths of Andrews Heliax $1\frac{5}{8}$-in. coaxial cable filled with helium (or argon). A positive high voltage is applied to the inner conductor; the charge is collected from the inner conductor through a capacitor.

A gas flow system[10] delivers continuously a small flow of helium slightly above atmospheric pressure to the ionization chambers.

The gas is supplied by a double bank of twelve bottles with automatic changeover. After a 20-psi regulator, the supply line divides into four branches; three branches supply the ion chambers and the fourth branch supplies gas for the Cerenkov cells.

The ion chambers in each branch are connected in series. The flow is metered and controlled by a needle valve at the input side and monitored on the return with a low-flow alarm detector. A back pressure regulator in the return line maintains a constant upstream pressure (referred to vacuum).

The low-flow alarms operate warning lights but do not inhibit the beam.

IONIZATION CHAMBER DETECTOR CIRCUITS. The pulsed current produced in the ionization chambers is roughly proportional to the power absorbed in the protection collimators. The current pulses are integrated in a circuit using an operational amplifier. The ion chamber is a high impedance current source, and, therefore, the input resistor of the integrator has little influence as long as it is low. It is made equal to the cable impedance (95 ohms) to avoid reflections. The integrator is followed by an adjustable discriminator and a latching output circuit. The integrator time constant is 0.1 sec, which is slightly faster than the thermal time constant of the protection collimators. The protection collimators can absorb an average beam power of 20 kW. The trip level at this power absorption level is reached in 100 msec. When the protection collimator is hit by a beam carrying the full 2-MW beam power, the trip level will be reached about 100 times faster (1 msec), so that the beam will be switched off before the accelerator will send the next beam pulse (beam pulses are spaced by 2.78 msec).

The output signals from the integrating circuits are terminated in a plug on the rear of each detector circuit. These signals can be connected to a patch panel for meter readout. The signals are extremely useful for beam-steering purposes.

The detector circuit for the long ionization chamber is slightly different from that of other ion chambers because of a different signal polarity.

Some of the ion chambers located near the collimators and dumps are not used for interlock purposes but for reading the charge intercepted by these absorbers. A special integrator is built for this purpose with a digital display reading out the "charge intercepted" by the devices with which these ion chambers are associated.

Thermal protection

A slow temperature rise may occur from the continuous scraping of the beam on the vacuum chamber wall. In places where this is likely to occur, surface temperature sensors are mounted on the outside of the vacuum chambers and are arranged to trip the beam if the temperature exceeds a preset level.

The sensors used are 100-ohm platinum resistance elements mounted in platinum cases and insulated with ceramic material. Radiation exposure tests have shown that these devices are very reliable up to doses of 10^{13} ergs/g. The sensors are spot-welded to small copper pads which are mounted in many cases against the vacuum chamber with a fitting that allows easy replacement. In other cases the sensors are an integral part of a device, such as those on a magnet chamber.

In addition to vacuum chamber surface temperature measurements, water temperature measurements are made on the cooling water supply and return line of slits, collimators, water-cooled vacuum chambers, and dumps. In areas where the radiation levels are very high and where measurements have to be made in the radioactive cooling water lines, a stainless steel thermal well is welded into the pipe at each measuring location and a radiation-resistant immersion sensor is screwed into the well. These devices have basically the same element as the surface sensor, namely 100-ohm platinum resistance wire, ceramic-insulated, but in this case it is in a stainless steel housing with an integral electrical receptacle. Connection is made through stainless steel-jacketed magnesium oxide-insulated cables.

Where the environment is less severe, similar but slightly less expensive sensors are used as direct immersion devices with no thermal wells. The electrical connections are made through fiberglass-insulated cables.

TEMPERATURE DETECTOR CIRCUITS. The two basic temperature detector interlocks circuits are an absolute circuit (measuring temperature at various locations on vacuum chambers, etc.) and a differential circuit (comparing inlet and outlet temperatures of the cooling water in various beam-absorbing devices). Each of the differential resistance thermometers is connected in one arm of a bridge circuit. The absolute temperature interlock circuit uses a fixed 100-ohm resistor in the second arm of the bridge. The bridge current is limited to 5 mA to prevent self-heating. A 5-mA current results in a sensitivity of 2 mV/°C.

The trip circuit uses a magnetic differential detector. This unit consists of a magnetic current-to-polarized-voltage pulse converter followed by a solid state on–off output stage. The trip level is set by adjusting the bias of the magnetic converter.

The input impedance of this circuit is 2 kohms, which results in a trip accuracy of about 1°C, which is adequate for this application.

An output signal from each resistance thermometer is also brought to a patch panel, which makes it possible to measure the various temperatures by means of a three-digit digital temperature readout.

To increase reliability, a test circuit is built which tests the electronics of the temperature detector circuits and the ion-chamber detector circuits. This test circuit checks the tripping action of the detectors as well as the continuity of the cabling system. The test is done automatically after each beam shutoff, but can also be started manually or on a programmed basis.

Secondary-emission foil signals

The interlock circuit for the SEM devices has been described previously. It is made very flexible to allow for changes that may be required after experience is gained with high-power beams.

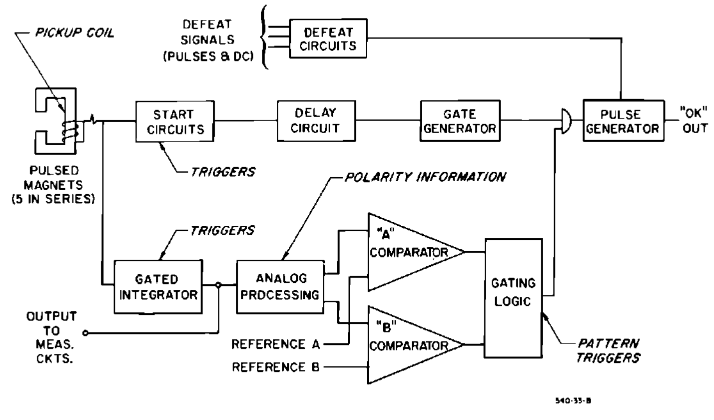
Pulsed magnet interlock

A special interlock circuit has been built for the pulsed magnets. It holds the beam pulse if the magnetic field has not reached the proper value shortly before beam injection. A block diagram of this circuit is shown in Fig. 19-16.

When the modulators for the pulsed magnets receive a trigger signal (approximately 416 μsec before beam time), a large transient voltage appears across the pickup coils. This transient is detected by the start circuits, which begin the timing of a 203-μsec delay circuit. Triggers are injected into the start circuit to prevent an output if the modulators fire too early or too late. The delay, in turn, actuates a gate generator, which produces a 10-μsec gate, 203 μsec later or 213 μsec before beam time.

While the delay is in progress, the gated integrator is producing a signal which is proportional to the $\int B\, dl$ through the pulsed magnets. This signal is passed through the analog processing circuits, which divide it by $\sqrt{2}$ and invert it if required by the polarity signals. The resulting processed signal is compared to a reference voltage. The references are derived from the analyzing magnet power supplies and are proportional to the beam energy settings in the A- and B-beams. When the processed analog signal is equal to the reference, a pulse appears at the output of the comparator. This pulse is passed through the gating logic, which ensures that the "A" comparator is inspected during "A" patterns and the " B " comparator during " B " patterns.

Figure 19-16 Pulsed magnet interlock.



Since the pulsed magnet current waveform is a sine wave with a period of 1666.6 μsec, the $\int B\,dl$ will reach $1/\sqrt{2}$ of its peak value in 208 μsec. The output of the gating circuit is a pulse which occurs when the $\int B\,dl$ reaches $1/\sqrt{2}$ of the desired peak value. If this pulse occurs during the 10-μsec gate (i.e., 20 ± 5 μsec after the start of the waveform), the output pulse generator is enabled. The pulse generator then produces an output signal 208 μsec before the beam injection time. This signal is part of a chain which gives a permissive pulse to the injector.

The defeat circuits shown in Fig. 19-16 allow the beam to be enabled during tune-up periods (e.g., when a third beam is to be deflected to the tune-up dump while the A- and B-beams are on). The system can be defeated on a pulse-to-pulse basis, as required by the above example, or permanently by a dc signal.

Differential current interlock

This circuit provides protection against beam deflection errors and will back up the devices discussed in the previous sections. The circuit uses the signals from two current transformers. One transformer is located in the common beam at the beginning of the switchyard and a second one at the end of each electron beam. The circuit will produce an interlock signal if less than a certain percentage (say 10%) of the beam arrives at its destination. The circuit operates at higher beam currents only; at low currents it switches off automatically.

Instead of a signal from a second transformer, the circuit may also operate with a signal from other reference sources, such as a dc signal.

19-4 Pulsed bending magnet supplies (ICL)

General

The pulsed magnet power supplies have the capability of energizing the magnets with a field of either direction (for right or left beam deflection) on a pulse-to-pulse basis, at repetition rates up to 360 pulses/sec, and of recovering most of the energy at the end of the pulse. The basic circuit used consists of silicon-controlled rectifiers (SCR) to switch energy stored in a capacitor bank to the magnets and back to the capacitor bank with relatively small losses, and a dc supply to recharge the capacitor bank between pulses.

Power supply circuit

The power supply can be divided into three functional blocks: (1) the energy storage capacitor bank with the associated means of regulating the amount of stored energy, (2) the SCR's used to connect the energy storage capacitor bank to the magnet, and (3) the dc charging supply to recharge the capacitor

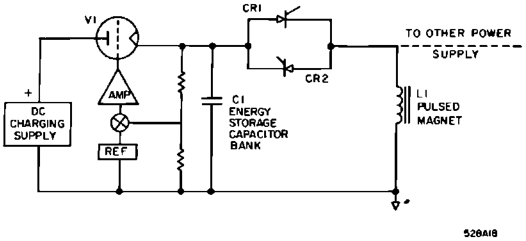


Figure 19-17 Basic circuit of pulsed power supply.

bank at the end of the current cycle. The basic circuit of the pulsed power supply is shown in Fig. 19-17, and the sequence of operation is as follows:

1. A signal is applied to the grid of the series regulator tube (V1) allowing the dc charging supply to charge the energy storage capacitor bank to the desired voltage level; then the grid is biased negative so that the tube is cut off.

2. The SCR switch (CR1) is then triggered, allowing the capacitor bank to discharge into the pulsed magnet (L1). A sine wave of current builds up in the magnet at a resonant frequency determined by the capacitance of the capacitor bank (C1) and the inductance of the pulsed magnet (L1). During this time V1 is kept cut off so that the capacitor bank is isolated from the dc charging supply, and the voltage across the capacitor bank decreases with a cosine wave shape as the energy is transferred from the capacitor bank to the pulsed magnet. When the magnet current reaches its peak value, the voltage on the capacitor bank is zero and all the energy of the system is stored in the pulsed magnet. Because of the relatively high-Q resonant circuit, the magnet now acts as a source of energy and discharges back into the capacitor bank, charging it to a negative polarity. The current continues to flow through CR1 until the energy stored in the magnet has been transferred back to the capacitor bank, at which time CR1 prevents the current from reversing. The capacitor bank remains charged to a negative polarity.

3. The second switch (CR2) is then triggered, allowing the capacitor bank to discharge again into the magnet in order to reverse the polarity of the voltage across the capacitor bank to its original polarity. CR2 conducts until the current tries to reverse, when the energy has been transferred from C1 to L1 and back to C1, at which time CR2 effectively opens the circuit, leaving the capacitor bank charged to its original polarity.

4. A signal is again applied to the grid of V1, which recharges C1 to make up the losses during the previous cycle. When C1 has been recharged to the desired voltage, V1 is biased off and the power supply is ready for the next beam pulse.

A resonant frequency of 600 cycles/sec between C1 and L1 has been chosen so that the above sequence of operation can be accomplished in less than 2.7 msec, thus allowing the pulsed magnets to be pulsed at 360 pulses/sec, the maximum repetition rate of the accelerator. The chosen resonant frequency of the circuit is a compromise between the peak voltage required on the magnet, the time allowed between pulses, the peak recharge current required, and the amount of heating allowed in the magnet.

Operation

Two power supplies are connected to each pulsed magnet, one typically connected such that its capacitor bank is charged to a positive polarity and the other such that its capacitor bank is charged to a negative polarity, thus allowing a deflection of an electron beam from the accelerator to either the right or left, as desired, on a pulse-to-pulse basis. The power supplies are independent and their capacitor banks can be charged to different voltages, if desired, allowing beam pulses of different energies from the accelerator to be deflected to the two experimental areas.

A "command" pulse is sent to the power supply to trigger the SCR switch only when it is desired to use that power supply to energize the pulsed magnet for a particular beam pulse. This command pulse is derived from the operational pattern signal of the accelerator. In order to assure that the energy storage capacitor bank is kept charged to the desired voltage level, a "recharge" pulse is sent to each power supply and applied to the grid of the series regulator tube at a constant 360-pulses/sec repetition rate. This recharge pulse is derived from the accelerator clock signal.

Energy storage capacitor bank

The energy storage capacitor bank is made up of several pulse capacitors in parallel to give a total capacitance of 32 μF as required to obtain a 600-cycles/sec resonant frequency with the pulsed magnet inductance of about 2.2 mH. The capacitors are built with a polyethylene dielectric and silicon fluid impregnant in order to achieve a low-temperature coefficient of capacitance. Changes in the capacitance of the bank will result in a change in the resonant frequency and, hence, would require a change in the peak voltage required to give the desired peak current in the magnet. The cases of the capacitors have water-cooling tubing soldered to them, through which temperature-regulated water is circulated to eliminate variations due to changes in ambient temperature.

Series regulator tube

The series regulator tube (V1) is a transmitting-type vacuum tube (3W5000) which is capable of supplying the required peak charging current at a reasonable tube drop and of withstanding the high voltage impressed between the filament and plate during the magnet current cycle. During the period available for recharging the capacitor bank, the grid is driven positive about 150 V until the desired voltage level on the capacitor bank has been reached at which time the grid is driven negative about 2500 V to cut the tube off. The tube is kept cut off during the rest of the time until the next recharge time period. The capacitor bank can be charged to any desired voltage up to 3000 V by the series regulator tube and the associated voltage regulation circuitry. The circuitry is designed to regulate to 0.1% of the desired voltage between the values of 1500 and 3000 V dc and regulates very well as low as a few hundred volts.

Silicon-controlled rectifier switch

The silicon-controlled rectifier (SCR) switches CR1 and CR2 are each made up of eight, type C181P, SCR's connected in series. These SCR's have a voltage rating of 1000 V dc and a current rating of 235 A rms. Each SCR switch conducts for one-half of the sine wave magnet current cycle. The maximum design value of peak current through each SCR switch is 316 A, the corresponding rms current is 122 A, and the average current is 61 A. The SCR gate pulses are supplied from a pulse transformer having a separate winding for each SCR.

Dc charging supply

The dc charging supply is a solid-state three-phase rectifier power supply operating from 470-V, 3ϕ, ac line voltage. The ouput voltage is constant at about 4000 V dc.

19-5 Pulsed steering magnet supplies (ICL)

The power supplies used with the pulsed steering magnets are of the same design as those used with the pulsed bending magnets. They differ only in that they have smaller ratings on peak current and voltage and have reversing relays built in to reverse the polarity of the voltage on the energy storage capacitor bank when the output current is reduced to zero. The supplies are designed to supply a peak current of 23 A into the steering magnet inductance of 18 mH. The energy storage bank capacitance is about 3.2 μF and the maximum charge voltage is about 1550 V dc. Type 6JE6A vacuum tubes are used as series regulators and the dc charging supply operates from 117-V, 1ϕ, ac line voltage.

19-6 Dc power supplies (CAH)

The power supplies required for the BSY dc magnets were purchased to satisfy various performance specifications. These power supplies are all located in the Data Assembly Building with copper cables carrying the required dc current to the respective magnets for an average distance of 150 ft. The electrical ratings of these power supplies were chosen to minimize

Table 19-7 Beam switchyard dc power supply ratings

Magnet designation	*Required power at 25 GeV* (*A*)	(*V*)	*Power supply ratings* (*A*)	(*V*)	*Specified regulation* (%)
1. A dump B-23, -24, -25, -26	950	380	1050	660	±0.25
2. A bend B-10 to B-17, B-100	765	724	805	832	±0.01
3. Q-10 (8-cm quad)	452	39	550	50	±0.1
4. Q-11 (8-cm quad)	473	41	550	50	±0.1
5. Q-12 (18-cm quad)	315	50	550	50	±0.1
6. Q-13 (8-cm quad)	474	41	550	50	±0.1
7. Q-14 (8-cm quad)	445	39	550	50	±0.1
8. B-1, B-2 (emergency switching)	500	50	850	65	±0.1
9. Q-20 (8-cm quad)	850	65	850	65	±0.1
10. Q-21 (8-cm quad)	850	65	850	65	±0.1
11. B-29 and -29A (clearing)	1000	113	1000	120	±0.1
12. B bend B-30, -32, -33, -35, -300	765	406	805	408	±0.02
13. Q-30 (8-cm quad)	472	40	550	50	±0.1
14. Q-31 (8-cm quad)	500	43	550	50	±0.1
15. Q-32 (18-cm quad)	283	45	550	50	±0.1
16. Q-33 (8-cm quad)	800	64	850	65	±0.1
17. Q-34 (8-cm quad)	800	64	850	65	±0.1
18. B-36 or B-37 (bending)	850	55	850	65	±0.1
19. B-38 (bending)	850	55	Shared with PB36		
20. A-10, -11, -30, -31 (steering)			25	135	±0.1
21. A-400, -401, -12 (steering)			36	200	±0.1
22. B-28 (steering)			81	10	
23. A-16, -36 (steering)			10	18	

the number of types which had to be procured. A comparison of the power supply ratings and the requirement for handling 25-GeV electrons is given in Table 19-7.

The required power supplies may be divided into four main groups according to use:

1. A-beam dump magnets, 693 kW at ±0.25% regulation
2. A- and B-beam bending magnets, 582 and 326 kW at ±0.01% regulation.
3. Quadrupole and other miscellaneous magnets, 27.5, 55, 120 kW at ±0.1% regulation.
4. Steering magnets (dc); ten units ranging from 0.18 to 7.2 kW at ±0.1% regulation.

The main characteristics of each of these groups of power supplies will be discussed in the following sections.

All of the dc power circuits of the magnet power supplies are designed and insulated so that any point of the system may be connected to ground without disturbing the precision of current regulation or causing excessive voltage gradients. The dc system is then grounded at the point desired, usually at the current monitoring shunt, through a resistance of 10 to 100 ohms that serves to limit any ground fault current resulting from an insulation failure of some part of the system. The current through this grounding resistor is monitored with an alarm circuit that turns off the power supply in case of excessive ground currents.

The off and on circuits and control systems in the BSY control room are based upon 24 V dc; therefore, a special relay conversion panel is required to control the 117-V ac interlock circuits of the various power supplies.

The current from each power supply is monitored with a digital voltmeter located in the BSY control room. The shunts (100 mV, 1000 A) used for monitoring the A and B bending magnet currents are mounted in a temperature-regulated oil bath to stabilize these measurements. The other magnet systems use shunts that have a calibration of about 1.2 V at rated current; this higher voltage shunt allows precision current measurements to be made even below 10% of rated output current. They are water cooled for rated currents greater than 100 A.

The regulation system on each power supply system is required to maintain the output current within specified tolerances even when a $2\frac{1}{2}\%$ line voltage transient is experienced. Fast response against line voltage transients was specified to prevent the high-energy electrons from hitting objects in the BSY. Even a single beam pulse wrongly steered can produce enough radiation relative to normal levels to cause the protection circuits in the BSY to trip and result in lost beam time of several minutes.

The SCR's or diodes used in the main dc power circuits were required to have a peak-reverse-voltage rating of $2\frac{1}{2}$ times the normally expected circuit voltages. The number of units used in parallel for the specified current had to be sufficient to allow normal operation with one device disconnected in each leg of the rectifier circuit without exceeding the manufacturer's ratings.

Transistor banks were required to have fast acting fuses for each power transistor and diode isolation on the bases to allow normal operation with up to 10% of the transistors not functioning or shorted.

Motor-driven reversing switches were required on all of the BSY power supplies to allow easy changing of the magnet polarity for handling either an electron or a positron beam. These switches also permit easy degaussing of the magnets.

Reverse diodes were installed across the dc circuits ahead of the reversing switches to protect each of the systems against open circuits from blown fuses in the SCR or transistor circuits. A 10-μF capacitor is connected across the magnet terminals to protect the magnet against voltage transients when the reversing switches operate at currents less than 10 A.

Magnet impedances

The mechanical construction of the magnets used in the BSY is described in Chapter 18. Except for the pulsed magnets, the iron yokes or return paths of these magnets are solid (not laminated); therefore, the inductance of the magnet will vary as a function of frequency. Table 19-8 shows the calculated low-frequency inductance (frequency less than 0.001 Hz). In general the lag in ac current versus the ac voltage applied to a magnet will not exceed 70° for frequencies less than about 2000 Hz, and the impedance will be less than one-tenth of that calculated using the low-frequency inductance for frequencies > 5 Hz, because of the lossy nature of the solid iron cores.[11]

The location of the energizing coils of these magnets relative to the gap is such that the percent field variation is about equal to the percent current variation for frequencies less than 5 Hz and is only about a factor of 10 down at the ripple frequencies of 360 Hz.

Dump magnet power system

Four magnets (B- 23, -24, -25, and -26) are connected in series and powered from a single power supply to direct either the electrons or positrons being guided through the A bending system into a water-cooled dump. This dump is used during photon beam experiments and for other special cases to prevent the primary beam from entering the end station A experimental areas.

The power supply is fed from a 480-V, three-phase power line and consists of two three-phase bridge rectifiers using SCR's with separate *LC* filters (20-Hz cutoff), connected in series to provide the rated output with twelve-phase ripple. A single plate transformer is used with a delta primary and water-cooled Y and delta secondary windings.

The power supply uses a transductor as the current sensing element in the slow loop portion of the current regulation system. A voltage feedback loop sensing ahead of the main *LC* filters (20 Hz cutoff) is combined with the slow current loop to give a fast response against sudden line voltage changes.

Table 19-8 Calculated magnet inductances[a]

Magnet system	*Calculated inductance (H)*	*Time constant (sec)*
1. A dump magnets (4 in series)	0.36	1.0
2. A bending magnets (9 in series)	1.5	1.8
3. 8-cm quads	0.04	0.5
4. 18.5-cm quads	0.05	0.4
5. B-1 and B-2 in series	0.17	1.7
6. B-beam magnetic slit (B-36 or B-37)	0.03	0.009

[a] Frequencies less than 0.001 Hz.

The variable phase triggers for control of the SCR's are Schmidt triggers derived from comparison of a variable dc voltage and a well-filtered sine wave from the 60-Hz ac line voltage.

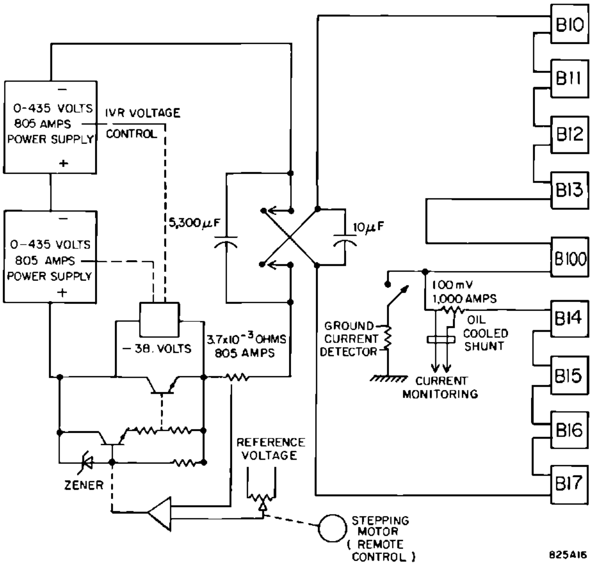
The A bending magnet power system

The A bending magnet system used to guide the accelerated particles through the BSY to the end station A experimental hall consists of eight of the 3° bending magnets in the switchyard and one reference magnet of the same design, located in the Data Assembly Building (DAB). These nine magnets are connected in series with the power supply to guarantee that all the magnets have an identical history of variations of current. (See Fig. 19-18.)

Earlier investigations of the reproducibility of a magnetic field of similar magnets[12] has shown that they will track if the rate of change of current through all of the magnets is held the same.

The dc power for this magnet system consists of two 350-kW (435-V, 805-A) power supplies connected in series with a transistor bank to provide a regulation of $\pm 0.01\,\%$. The transistor bank uses 328 transistors connected in parallel to handle a maximum of 805 A. The bank has a maximum rating of 53 kW but normally operates at 31 kW (38 V drop). The voltages from the two 350-kW power supplies furnishing the main dc power for this system have their output voltages controlled with induction voltage regulators by a slow loop servo system that senses the voltage across the series transistor bank; the regulation system maintains approximately 38 V dc across the series

Figure 19-18 End station A bending magnet—power supply system.



transistors and maintains the current in the bending magnets within ±0.01% from 40 to 100% rated current.

The dynamic range of control is from about 10 to 805 A. The current is controlled from the DAB control room with a stepping motor drive on a multiturn potentiometer that always changes the current in the magnet at a rate of 6 A/sec. This rate was chosen as about the optimum regarding convenience and reproducibility of the field versus current in the magnet.

The B bending magnet power system

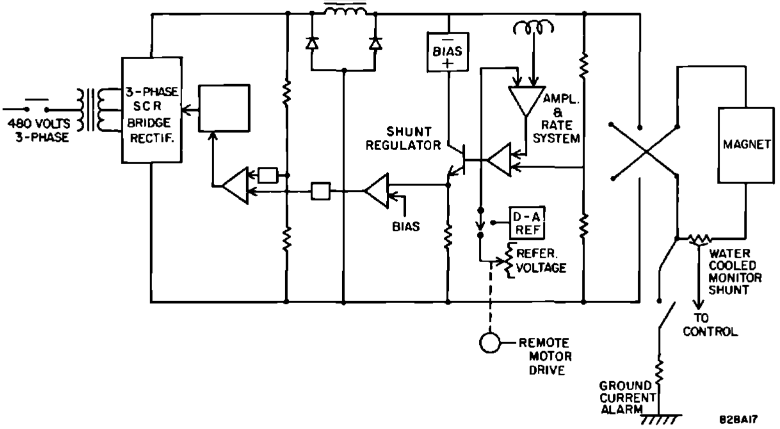
The B bending magnet system uses components similar to the A bending system except that only one 350-kW power supply is required to drive four bending magnets in the switchyard and one reference magnet in the DAB. The transistor bank for the B side is rated for 35-kW and operates at a normal voltage drop of 27 V.

Quadrupole and other miscellaneous magnet power supplies

Quadrupole power supplies rated at 27.5 and 55 kW have been provided. They energize magnets of similar impedances but allow for the fact that the beam optics does not require maximum power to be available for all of the magnets. Power supplies of these ratings are also used to energize other magnets, such as the emergency magnets B-1 and -2, the B-beam switching magnets B-36 and -37, and the B-beam pulsed magnet B-38 when the latter is energized with dc (not pulsed) power.

The regulation system of these power supplies is a current-stabilized, voltage-regulated, three-phase bridge, SCR system. The voltage-regulated system is current-stabilized through a slow loop using a transductor as the current sensing element. The voltage regulation part of the system comprises

Figure 19-19 The 27.5- and 55.3-kW quadrupole power supplies.



two loops: (1) an SCR regulation system and (2) a shunt transistor bank carrying about 10% of the rated power supply current to extend the frequency response range above the limit of about 10 Hz for the SCR loop (see Fig. 19-19).

The current in these power supplies can be adjusted from the control room by either a dc motor driving a multiturn potentiometer or by the use of a digital-to-analog converter. The regulation loop amplifiers have a built-in rate-limiting system that forces the current to change slowly regardless of the size of step required by the digital-to-analog converter. This rate limiter helps prevent overshooting of the current when making step changes in current with the digital-to-analog converter. The ±0.1% accuracy required for these magnets can be attained using only the current vs field relationships obtained during magnetic measurement.

Steering magnets

The power supplies for the steering magnets must be easily controlled from a positive current to a negative current with as little perturbation as possible at the zero current point. Some of the magnets steer in the vertical plane and others steer in the horizontal plane.

Reversing control is accomplished with reversing switches automatically actuated when the stepping motor-driven multiturn potentiometer used for current control approaches its zero position.

This type of control allowed for the minimum size of required power supply. A lever-type switch is used for the control of the current setting for these steering magnets.

The reversing switch position and current setting potentiometer controls are coordinated so that the position of the potentiometer control handle indicates the direction in which the beam will be steered regardless of the magnitude or sign of the current in the steering magnet. Thus, a left position of a control handle may mean an increase in current in the normal position of the reversing switch, but it would cause the current to decrease if the reversing switch were in the reverse position.

All these power supplies are regulated with series transistor banks to give good control and stability over a dynamic range of 100 to 1 in current.

Some of the power supplies use a narrow range regulator with a motor-driven variable transformer controlled to keep the regulator in range; other units have a fixed power supply voltage with a series transistor bank that can absorb the total voltage when required to operate at low magnet currents.

Acknowledgments

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magnitude in the time required. B. de Raad supplied most of the criteria, calculations, and preliminary development of the monitoring instruments in addition to several very valuable suggestions on electronics techniques. H. Dijkhuizen and J. Cole designed and developed most of the original interlock circuits for machine protection.

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