MASTER

INSTRUMENTATION,
COMPUTER CONTROL
AND
ELECTRONIC SYSTEMS
FOR THE SLAC
BEAM SWITCHYARD

Edited by D.A.G. Neet

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Technical Report

Prepared Under

Contract AT(04-3) - 400

for the USAEC

San Francisco Operations Office

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FOREWORD

This report is intended primarily to provide the Switchyard Operations Group with adequate functional descriptions of the various switchyard systems. However, since there may be a wider interest in these subjects, we have made an effort to include information of a more general nature also.

In order to limit the length of the text we have included many photographs and tables. Reference is made to several existing publications and SLAC internal reports either for more detailed discussions or for backup reading.

The work described in this report is the joint effort of the Beam Switchyard Instrumentation Group over the last three years. The contribution of each of the engineers is:

J. Cole	-	Electronics for protection systems
R. Coombes	-	Design and testing of beam instrumentation
H. Dijkhuizen	-	Interlock system and control room layout
R. Gurney	-	Mechanical design of instruments
J. Hall	-	Electronics for spectrum and SEM monitors
M. Hu	-	Computer system, interlock signal scanner, and Slit/Collimator control
D. Mills	-	Mechanical design of instruments
D. Olsen	-	Electronics for beam current and position monitors
R. Scholl	-	Computer system, magnet control system, and magnetic measurements

The work was supported by many valuable contributions of the following members: C. Appleby, R. Bortle, D. Clark, L. Lawler, C. McLucas, A. Naeslund, A. Spencer, and L. Via, and by several other individuals.

The following work was due to members in other groups:

D. Farkas/H. Hogg	-	Design and construction of microwave cavities and associated detector electronics
S. Howry	-	Computer programming
W. Basinger	-	Coordination of mechanical fabrication
R. Shelton	-	Coordination of electronic circuit fabrication
T. Constant	-	Cable system and control room installation

Dirk A. G. Neet

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I. GENERAL DESCRIPTION OF INSTRUMENTATION FOR THE BEAM SWITCHYARD

The function of the Beam Switchyard (BSY) is to energy-analyze the electron beam from the Stanford two-mile accelerator and to deliver either electron, positron, or photon beams to the End Stations for various experiments. The components of the beam transport systems in the Switchyard are shown schematically in Fig. 1. These components are located in the lower part of a double tunnel, a typical cross section of which is shown in Fig. 2. For a general description of the Beam Switchyard, we refer to Ref. 1 and 2.

In the following paragraphs the functions of the various components shown in Fig. 1 are discussed with emphasis on instrumentation.

A. Undelected Beam Area and Tune-Up Dump

The accelerator produces up to 360 beam pulses per second. The size and position of the beam pulses are defined at the beginning of the Switchyard by collimator C-1. The pulsed magnets (PM-1 to PM-5) deflect the beam pulses through an angle of 0.5 degrees (8.8 milliradian) into either the A-beam or the B-beam energy analyzing system. The distribution pattern for A- and B-beam pulses is completely flexible and beam energy and current can be different for each beam. The polarity of the magnets in the analyzing system can be reversed if positrons are produced by the accelerator. The beam pulses can also proceed undeflected through the pulsed magnets (central beam) in which case they are absorbed at the present time in a temporary 50-kW central beam dump D-2. A permanent 50-kW tune-up dump D-10 has been provided between the central beam and the A-beam. This tune-up dump is 16.6 inches wide and absorbs electrons deflected between 1.58 and 7.5 milliradians.

We will now describe the function of various components in the area outlined above (see Fig. 1). The two-megawatt collimator C-1 (Ref. 3) consists of a horizontal and a vertical pair of jaws each 16 feet long. It is backed up by a 40-kW collimator C-0 of more conventional design. The characteristics of the beam in front of the collimator are checked by a current transformer I-1, a microwave position monitor P-1, and a Cerenkov

540-46-A

FIG. 1--Layout of Beam Switchyard components.

540-3-0

Fig. 2- SWITCHYARD TUNNEL
INSTRUMENTATION AREA

light profile monitor PR-1. The current absorbed in the collimator can be monitored by measuring the signal difference between current transformer I-1 and current transformer I-2 located after the collimators. Because the collimators are very critical devices, secondary emission foils have been mounted on the front end and at the rear end of the collimator jaws in order to measure the portion of the beam absorbed in each jaw and to assist in checking up on jaw alignment.

The angle of the beam with respect to the center line of the collimator is very critical and can be studied by comparing the signals from position monitors P-1 and P-2. P-2 is located in front of the central beam dump D-2 one hundred meters downstream of P-1. The beam can be steered through the collimator by two pairs of pulsed steering coils AP 1-2 and AP 3-4. The first pair AP 1-2, located 30 meters in front of C-1, is used to center the beam on the collimator; the second pair AP 3-4, located immediately before C-1, can be used to correct the beam angle with respect to the 16-foot-long jaws. The effect of the collimator on the beam and the divergence of the beam can be observed by comparing the two Cerenkov light profile monitors PR-1 and PR-2.

The switching magnet consists of five identical one-meter-long pulsed magnets (PM-1 to PM-5) and is backed up by two dc magnets (B-1 and B-2). The protection collimators (PC) between magnets protect the magnet coils and the ceramic vacuum chambers of the pulsed magnets against radiation and thermal damage due to beam interception in this region. The vertical pulsed magnet AP-5 in front of B-1 applies a vertical correction to the beam path in order to compensate for the horizontal component of the earth magnetic field.

Crude beam energy measurements can be made by deflecting the beam into the center of the tune-up dump D-10. A spectrum monitor S-10, consisting of a row of 38 secondary emission foils, is located in front of D-10 for this purpose. The beam should be centered on the six foils with high energy resolution ($0.9\% \Delta E/E$), the center of which is at a deflection angle of 5.7 milliradians.

B. The A-Beam Analyzing Channel

The optics of the beam analyzing channel has been described in Ref. 4.

The magnetic components in beam channel A consist of a quadrupole pair Q-10, Q-11, the 12-degree energy defining magnets B-10 to B-13, a symmetry quadrupole Q-12 in front of the energy defining slit SL-10, the second 12-degree bending magnets B-14 to B-17, and a quadrupole pair Q-13, Q-14 at the end.

The instrumentation in front of Q-10 consists of a current transformer I-10, a microwave position monitor P-19, and a multiple zinc sulfide screen profile monitor PR-10. A similar set of monitors is placed at the end of the analyzing channel. Current transformer I-13 and profile monitor PR-13 are placed after Q-14. Because of the limited aperture of the microwave position monitors (2 inches i.d.), P-12 was placed before Q-13 where the maximum possible beam envelope is 1.4 times smaller than after the quadrupole pair.

A synchrotron light observation station P(S)10 is installed after the first bending magnet B-10. This is provided as an attractive nonintercepting visual technique to monitor the beam spot through Q-10, Q-11 and the first part of B-10. An optical target OT-10 in front of B-10 serves to align the mirror system associated with the synchrotron light station. Another synchrotron light observation station in the second group of bending magnets was eliminated for budgetary reasons.

A 0.1% $\Delta P/P$ resolution spectrum analyzer S-11 is placed in the beam in front of Q-12 rather than directly in front of the analyzing slit in order to keep it away from back-scattered radiation from the slit. Profile monitor PR-11 at the same location is a 10-inch-wide zinc sulfide flap screen which is provided to check the vertical position of the beam plane in front of the analyzing slit. One may notice in Fig. 1 that bending magnet B-13 is displaced a few meters downstream. The purpose of this displacement is to give clearance for a future 6-degree, low intensity, parasitic photon beam which may be obtained by placing a thin radiator between B-11 and B-12.

Several protection collimators (shown in Fig. 1) are placed at carefully selected locations to protect instrumentation and magnet coils from stray radiation and from the intercepting electrons due to the low energy tail of the beam.

C. Beam Line Section After the Analyzing Channel

The beam is normally focused at infinity by Q-13, Q-14. Steering magnets A-10, A-11 and a quadrupole pair Q-20, Q-21 farther downstream are provided to bring the beam focused on a target, usually in the End Station.

A photon beam can be produced by placing a radiator TC-20 in the beam. When this is done, the electrons and other charged particles are deflected by dumping magnets B-23 to B-26 into a 2-MW underground dump D-11 (Ref. 3). The integrated charge on radiator TC-20 can be measured by I-16, and the current going into the dump by I-15. A four-quadrant foil secondary emission monitor is mounted in the same housing as I-15 and provides information for centering the beam on the entrance window of the dump.

The exact direction of the photon beam is established by observing the electron beam position on profile monitor PR-14 located in front of the radiator and the center of the aperture in the 40-kW collimator C-10. Both are aligned with high precision. Bending magnet B-28 may be used to produce a photon beam at a small angle. Sweeping magnet B-29 clears the photon beam from charged particles. Quadrupole magnets Q-23, Q-24 are required for specific experiments in End Station A.

The beam paths A' and A'' shown in Fig. 1 have been provided for future expansion. The magnetic components marked with an asterisk in Fig. 1 show one of the possible future developments in this area. They represent another analyzing channel that could be used to re-analyze the beam after it has passed through a photon radiator placed in this case after A''. This would be a more efficient use of the electron beam than dumping it in D-11.

D. The B-Beam Analyzing Channel

The B-beam analyzing channel is identical to the A-beam channel except that the energy resolution is two times lower. Two bending magnets are used at each 6-degree deflection point, but a third magnet can be added at each point (B-31, B-34) if higher electron energies become available at a later time. The instrumentation in this channel is identical to the instrumentation described for channel A.

At the end of analyzing channel B, a pulsed magnet PM-30 enables the B-beam to be divided into three separate beams B, B', and B'' serving three experiments. The beam is deflected ± 0.2 degrees in this magnet, corresponding to a separation of approximately 8 cm at the dc magnetic slit B-36 (Ref. 5) located 24 meters downstream. The magnetic slit increases the deflection angle to 1 or 2 degrees. The beam has to be properly centered on the positive and negative magnetic field plateaus at the two sides of the slit. A multiple 10-inch-wide zinc sulfide screen monitor PR-34, located in front of B-36, is used for this purpose.

E. The Central Beam

The central beam is not developed at this time, but structural provisions are made to locate a high power target in the area near D-2 and to split off a 10-degree beam further downstream, as shown in Fig. 1. A study is underway for the initial construction of a K-meson beam in this area.

II. GENERAL DESIGN CONSIDERATIONS

Several unusual factors have influenced the design of the instrumentation and control system for the Beam Switchyard.

A. Access and Cable Routine

The Y-shaped beam layout resulted in a complicated housing structure with many access and cable routing problems. It was decided to use the underground double-tunnel structure shown in Fig. 2, which has the advantages of improved access and reduced radiation exposure in the upper tunnel when the shielding floor is in place. The price for this is that the routing for cables and pipes becomes more complicated in that they have to be taken through cable chases in the wall between the upper and lower tunnel in order to avoid interference with the rails for the tool car (Fig. 2).

Since access by personnel into the lower tunnel is not permissible after induced radioactivity is built up, instruments and connections have to be designed in such a way that servicing and replacement can be done from the upper level, about 10 feet above the instruments. The instruments have been designed with many features that reflect this requirement (Ref. 6), and a number of simple hooks and long arm tools have been made to assist in this work.

B. Radiation and Nitric Acid Exposure

The extreme radiation exposure, the induced radioactivity and the production of corroding gases (Ref. 7) present many design difficulties. A general discussion on these problems is given in Ref. 8.

Table I shows a list of construction materials and selected components used for the instruments in the radiation environment and nitric acid atmosphere in the Switchyard.

C. Instrument Access and Interchangeability

The beam monitors and other instruments in the Switchyard are designed to allow interchangeability and replacement of working parts from the upper tunnel with minimum effort and disturbance.

TABLE I

RADIATION-RESISTANT COMPONENTS FOR THE SWITCHYARD

Components	Description	Threshold Exposure (ergs/gram)
12 pin plugs	SLAC design; Al_2O_3 insulation, gold-plated contacts, chrome-plated housing*	10^{14}
Type-N coaxial plug	Special construction with Al_2O_3 insulation, gold-plated contacts, and body*	10^{14}
Wire	1. Al_2O_3 coated wire (Permaluster)	10^{14}
	2. Ceramic beads	10^{14}
	3. Mica asbestos insulation (Micatemp)	10^{13}
Coaxial cable	1. Commercial RG 81-u (50-ohm) with MgO insulated in copper tubing..	10^{14}
	2. Special MgO insulated cables in stainless steel* tubing	
	3. Specially ordered equivalents of RG 58/214/22 with S994 fiberglass insulation	$10^{12} - 10^{13}$
Viewing windows	Non-browning Corning - 7940 fused silica 100% pure	10^{12}
Plane and spherical mirrors	Front surface mirror. Several $1/4\lambda$ dielectric layers on the surface will make it nitric acid proof.	
Vacuum feedthroughs	Al_2O_3	10^{14}
Vacuum seals	Indium or metal	10^{14}
Drive motors	Standard type. Made by SLAC as plug-in units	10^9
Water connectors	All metal, fast-disconnect	10^{13}
Micro-switches	Ceramic body, gold-plated contacts*	10^{14}
Position pickup	Standard Encoder. (Easy replacement mounting). LVDT transducer with ceramic insulation.	5×10^9 10^{13}
Magnet coils	Alumina-filled epoxy (see Ref. 9)	5×10^{12}
Paints	High temperature paint* (Sperex VHT)	10^{13}
Lubrication	1. Dry lubrication. Diconite is a thin film of tungsten applied by special process.	10^{14}
	2. Molydisulfide (MoS_2)	10^{11}
	3. Shell VRT oil	$5 \cdot 10^{11}$

* Required because of nitric acid atmosphere.

A module design was adopted with a standard 18-inch flange-to-flange length. The instruments along the beam line are mounted in groups on a common support where they are interconnected by a bellows section (see Fig. 3). An alternate design would have been to place the instruments in a large vacuum tank with large flanged mounting holes on the top. Instruments would then be mounted by means of vacuum couplings to these flanges. This scheme would have saved many flanges, but was rejected because of inflexibility.

D. Instrument Support and Alignment

The individual instruments are all pre-aligned (precision ± 0.5 mm) in the shop and installed on precision rails on an adjustable instrument support. Figure 3 shows instrument support IS-11 carrying I-10, PR-10, and P-10 during the installation activities in the lower tunnel. The picture shows one of the bellow sections between two instruments and the feet by which the instruments are clamped to the rails on the support.

The support is adjustable over a large stroke (± 3 inches) in order to compensate for possible structural changes in the building — for example, as a result of earthquakes.

The support can be adjusted from the upper tunnel by a plug-in drive device through holes in the shielding floor. The alignment can be checked through holes in the shielding floor by optical alignment using precision balls fixed to the support.

Alignment balls are also mounted on the housing of each individual instrument. These balls are needed to mount the feet to the proper height during pre-alignment and serve to check the alignment of individual instruments after installation, if desired.

E. Control Room (see Fig. 4)

Initially it was attempted to integrate the controls for the Switchyard with those of the linear accelerator proper. However, the extra cost as a result of the rather long distance to the accelerator control room, and the fact that the Switchyard can largely be operated as an independent area, resulted in a separate Switchyard control room.

The control room building (Data Assembly Building) also houses most of the magnet power supplies for the Switchyard as well as two reference

FIG. 3--Instrumentation stand.

FIG. 4--Control room.

magnets (see Section IX).

The Y-shape structure of the Switchyard building makes it difficult to find a good central location for this building. A long narrow building in the center of the Switchyard on top of the 32 feet of earth shielding looked initially attractive but had many disadvantages. It was discarded because of the more favorable construction schedule for the existing location on the south slope of the earth shield (see Fig. 5). The cable distances with the building at this location are slightly longer than for a building on top of the earth shielding.

F. Location of Electronics

Because of the limited access into the upper housing of the Switchyard and for reasons of maintenance, it was decided not to locate any electronic circuits in the tunnel, and to centralize it as much as possible in the control room building.

Obviously compromises had to be made for some of the circuits, such as TV cameras, and also for the detector diodes associated with the microwave position monitors. Most of these circuits are located in alcoves specially built for this purpose in the wall (Figs. 2 and 23) or in corners hidden from direct radiation.

A different compromise was made with the local preamplifiers for the current transformers and the integrator and scanner circuits for the tune-up spectrum monitor. These circuits are located in weather-proof boxes just outside the earth shielding in the service areas (see Fig. 5). The cables from the service area to the monitors are routed into the housing through a cable duct in the earth shielding.

540-47-A

FIG. 5--Switchyard building structure.

III. BEAM CURRENT MONITORING

A. Current Monitors

Current transformers are chosen for measuring the beam pulse current at various locations throughout the Switchyard. A toroidal transformer can be considered by approximation as a current source supplying a pulse current I/N into the cable with impedance Z . The output voltage on the cable is thus:

$$V = \frac{I}{N} \cdot Z \quad (1)$$

where I is the beam pulse current and N is the number of windings.

Relation (1) is approximately true for a current pulse as long as

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

where L_T = inductance of the transformer

t_p = beam pulse length ($\pm 2\mu\text{sec}$)

The time constant of the transformer is

$$\frac{L_T}{Z} = \frac{\mu\mu_o N^2 \cdot A}{2\pi r \cdot Z} \text{ Sec.} \quad (2)$$

so that the droop is

$$D = \frac{2\pi r \cdot Z}{\mu\mu_o N^2 \cdot A} \cdot t_p \cdot 100\% \quad (3)$$

where A = cross section of core

r = mean radius of core

μ = initial permeability

It is desirable to have a large output voltage V and a small droop D , so it is necessary to compromise on Z and N . The cable impedance Z was chosen at 95 ohms and the number of windings at $N = 48$. This results in an output voltage $V = 2$ volts/amp. An extra single turn winding has been provided for calibration purposes.

The droop can be made smaller by choosing μ as high as available and A as large as practical.

The permeability μ of supermalloy is very high (9000), but according to literature this value decreases after a radiation exposure of the order of 2×10^{10} ergs/gram. Ferrite has a lower μ and does not change this property for levels up to 10^{11} ergs/gram. We therefore chose to use commercially available ferrite rings with a permeability $\mu = 3600$ and dimensions shown in Table II. When the core information shown in Table II is used in Eq. 3 we find a droop of 0.8%.

The 3-inch beam aperture current intensity monitor assembly as shown in Fig. 6 incorporates two toroids. One toroid is used in the current monitoring system. The other is used in the precise integrator system (Section III. C) or serves as a spare. Construction details of the monitor are shown in Fig. 7. The core consists of a stack of four 1/2 inch-thick ferrite rings between rounded aluminum end plates, tightly bound together with a double layer wrapping of fiberglass tape. The sides of the rings should be ground flat to avoid breaking when they are clamped. The signal and calibration windings (standard 16g copper wire, mica and fiberglass insulated) are wound over this wrapping and are overlaid with a similar wrapping of tape. 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 vacuum housing is closed by a weld which may be opened and re-welded a few times before the housing needs to be replaced. 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 inches is needed in front of beam dump D-11 and in front of beam dump east (not shown in Fig. 1). The core data for this transformer are shown in Table II and the construction is very similar to the 3-inch transformer. The 6-inch transformer is built into one housing with the 4-quadrant secondary emission

TABLE II
DATA ON BEAM CURRENT MONITOR

Description	
3-INCH-APERTURE CURRENT TRANSFORMER	
Core	Four Rings: 6" o.d., 3.675" i.d., each 1/2" thick
Core Material	M _n -Z _n Ferrite; Ceramag 24 (Stackpole carbon Comp.)
Beam Aperture	3 inches
Initial Permeability	3600 (measured value) Catalog value = 2500
Radiation Threshold	$>2.10^{11}$ ergs/gram
Number of Turns	48 for output signal; 1 for calibration input
Windings	Fibreglass insulated, stranded copper wire
Cables	Output signal 95 Ω twinaxial (T-95 and RG/22/u) Calibration signal 50 Ω coaxial (B-50 and RG/63u)
Shielding	Transformer; Aluminum can insulated from vacuum housing Cables; copper shield up to pre-amplifier
Inductance	24 mH
Sensitivity	2 mV/mA
Noise Level	100 μ V (equivalent input noise of system)
Droop	0.8% (2- μ sec-long beam pulse)
Rise Time	Transformer proper: 10 nsec. On scope in control room: 30 nsec
6-INCH APERTURE CURRENT TRANSFORMER	
<u>Same as 3-inch transformer with the following exceptions:</u>	
Core	Three rings: 10" o.d., 7-1/2" i.d., each 1/2" thick
Beam Aperture	6.35 inches
Droop	Approximately 2-1/2%
Feedthrough	Stainless steel MgO cables welded into housing

FIG. 6--Beam current monitor.

540-16-B

FIG. 7 --CONSTRUCTION OF CURRENT TRANSFORMER
(CROSS SECTION OF ONE HALF)

monitor (sec. VII). The assembly of these two monitors (Fig. 26) is called the dump monitor.

B. Beam Current Monitor Electronics

There are three readout systems (Ref. 9) associated with the beam current transformers. 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 measure the beam peak current. The second readout system displays average beam current (μA) on a meter. The principal justification for this type of display is that average current is a linear measure of average power, and by observing these meters the operator can get a feel for both the current and power loss in the Switchyard. The third readout is an integrator system which reads average current and total charge with higher precision. This system is discussed in Section III. C. The characteristics of the three readout systems are summarized in Table III. A block diagram of the current monitoring system is shown in Fig. 8.

The local pre-amplifier (BCM Local Electronics Chassis) is located in a weather-proof box (local electronics box), placed as close as possible to the current transformer but outside the Switchyard shielding so that it is accessible during operation. The pre-amplifier has a gain of 25 and a balanced input and output. The purpose of the pre-amplifier is to minimize the effect of noise pickup in the long cable runs to the control room. The cable from the toroidal current transformer to the pre-amplifier is totally shielded by a combination of flexible bronze tubes and copper pipes. The minimum thickness of this shield is 1/32 inch.

Twinaxial cable (Rg/22/u) is used to minimize noise pickup over the long transmission distances (400 feet to 1000 feet) after the pre-amplifier. An effort was made to keep the system completely balanced. The frequency response of all the amplifiers in one channel from the current transformer to the oscilloscope is approximately 20Mc. This corresponds to a 10-90% rise time of 17nsec. The limiting element is the twinaxial cable. The frequency response of the cables will be equalized, but for the longer cable lengths practical considerations limit the amount of equalization. For the 1000-foot length the rise time might be as long as 50nsec. The total linearity

TABLE III
CHARACTERISTICS OF CURRENT MONITOR READOUT

Description	
<u>1. Dynamic Pulse Readout</u>	
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 μ A peak current, signal/noise = 1 Max. 100 mA peak current
Electrons-Positrons	Polarity of scope signal reverses. Change polarity of comparator on control chassis
<u>2. Average Current Readout</u>	
Display	4-inch scale meter
Precision	2%
Range	0.03 μ A to 100 μ A full scale
Electrons-Positrons	Use polarity switch on front panel
<u>3. Integration Circuit</u>	
Display	Digital (Nixie tubes)
Precision	0.3% relative, 1% absolute
Range	0.001 μ A and 100 μ A
Readouts	Total charge over any time period; (manual start/stop) Q/sec measured over 0.1, 1, 10 sec (μ A) Q/pulse average over 10, 100 beam pulses (Coulomb)
Electrons-Positrons	Polarity switch on front panel

FIG. 8 --BEAM CURRENT MONITORING SYSTEM

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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. 8 serves three purposes: (1) to adjust the gain of each transformer channel to 50mV/mA; (2) to provide five separate buffered outputs; and (3) to provide equalization for the twinax cable frequency response. The input to the amplifier is balanced (differential); the outputs are single ended and are designed to feed a 95-ohm load. The five buffered outputs are 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, I-2, I-3, I-10, and I-30 are processed by the linear-Q circuit (Ref. 13) in the Sector Electronics. This circuit integrates the video signal and sends a signal which is proportional to the charge per pulse to the Central Control Room.

4. Differential current interlock circuits.
5. Other purposes: The analyzed beam current signals from I-13 and I-33 are combined with other signals in the display of the spectrum analyzer.

The transformer 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). Only channel 1 on the oscilloscope can be used for calibration. The calibration pulse is delayed 100 μ s with respect to the beam pulse in order to allow calibration during beam operation. The control chassis is also used to calibrate the switched gain amplifiers in the transformer selection chassis. The absolute accuracy of the calibration system should be better than 3%.

1. Video Display System

The basic criterion of the video display is to observe on an oscilloscope simultaneously the output signal of any two transformers along one beam, e.g., either I-10 and I-13 or I-10 and I-15, etc. It is also possible to display simultaneously the signal of transformers in two different beams.

The control chassis shown in Fig. 8 (BCM Video Signal Control) contains 36 transformer selection switches, 18 for oscilloscope channel 1 and 18 for channel 2, in such a way that any transformer 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 controls on the comparator circuit are calibrated in terms of beam current.

The actual switches for the transformer selection and two amplifiers with a gain $\times 2$, $\times 20$, and $\times 200$ are mounted in a separate chassis (BCM Video Selector Chassis). The purpose of these amplifiers is to present a high enough voltage to the oscilloscope, to make the output voltage a decimal function of the beam current, (0.1 volt /mA, 1.0 volt /mA, 10 volt /mA) and to provide a filter to reduce the high frequency noise.

The current transformers in the common beam area (I_1 and I_2) pick up the signals from each of the three interlaced beams A, B, and C. These signals are separated on the oscilloscope by triggering the oscilloscope with the $-1.5\text{-}\mu\text{sec}$ synchronization pulses for that particular beam. (The $-1.5\text{-}\mu\text{sec}$ pulses arrive $1.5\text{ }\mu\text{sec}$ before the beam pulse).

2. Average Current Display

The average beam current display consists of three chassis, each of which contains eight separate meter displays. Each chassis is separately synchronized by a $-1.5\text{-}\mu\text{sec}$ synchronization pulse. The chassis has a front panel switch which allows the selection of two synchronization pulses. With this arrangement it is possible to display the current from two interlaced beams on the same meter by switching over the synchronization switch.

The maximum zero offset on the meters is due to system noise, and dc drift is less than 10% of the most sensitive reading ($0.003\mu\text{A}$). The precision is about 2%.

C. Beam Current Integrator (See also Ref. 10)

The purpose of the integrator (see Fig. 9) 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, B, or C beam (I-13, I-33, I-3). A local integrator circuit for I-3 is not installed at the present time.

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FIG. 9 -- BEAM CURRENT INTEGRATOR SYSTEM

The integrated current can be displayed on two digital readouts. One display consists of a four-digit nixie readout followed by five mechanical digits. This reading 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 either in terms of μA or alternately in average charge per pulse. The average is taken over 0.1 sec, 1 sec, 10 sec, 10 pulses or 100 pulses.

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:

$$V_{\text{out}} = \frac{I \cdot t_p}{N \cdot C} \quad (4)$$

where C is the integrating capacitor.

After the integration period t_p , the capacitor and transformer inductance L_T produce a damped oscillation, as shown in Fig. 9.

The integrator is followed by an amplifier with a fixed gain of about 30 and a switched gain amplifier with a gain ranging between $\times 1$ and $\times 10,000$. The 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 three inputs (I-13, I-33, I-3) go to a separate amplifier to compensate 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. 9). 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 bi-polar 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. It is expected that the instrument is typically useful to better than 10^{-9} amperes average beam current.

An integrator calibration system introduces a high value of current through the calibration winding of the transformer. This current is averaged on a capacitor and the charge is then measured accurately by a digital voltmeter. The reading of the digital voltmeter provides the calibration figure for the integrator.

IV. BEAM POSITION MONITORING

A. Position Monitors

Both electromagnetic and electrostatic principles were considered for beam position detection in the Switchyard. However, because of their radiation resistance and good sensitivity, microwave cavities were chosen as more satisfactory.

A difficulty with cavities operating at the 2856-MHz frequency (linear accelerator frequency) is the size of the aperture that can be allowed without losing the Q-value. To overcome this problem, a resonant ring microwave monitor was proposed. A prototype of this monitor gave good results with an aperture 4 inches wide and 1.5 inches high.

Experiments were made with the three cavity position monitors used on the accelerator but with a much larger aperture (2 inches). It was found that reasonable results could be obtained by spacing the cavities four inches and by connecting them with a 2-inch-aperture pipe. This 4-inch-long section reduces energy leakage from the cavity through the aperture, which prevents coupling and results in a better Q value. Further work on this cavity resulted in the 2-inch-aperture microwave cavity position monitor shown in Fig. 10. The three cavities consist of (1) a TM_{010} cylindrical cavity, which provides beam current intensity information (Ref. 11); and (2) two rectangular cavities (Ref. 12) which are excited by the beam in the TM_{120} and TM_{210} modes, respectively, and which provide beam X and Y displacement information. The cavity assembly is aligned so that the common axis of the cavity assembly coincides with the theoretical beam orbit.

The output of the intensity cavity is proportional to the square of the beam current and is independent of beam position; the output of the position cavities is proportional to the square of the beam current and to the square of the beam displacement in one of the two transverse directions and is independent of displacement in the other direction. The phase of the rf power output of the position cavities changes 180° as the beam crosses the cavity center line. The parameters of the cavities are shown in Table IV.

FIG. 10--Microwave position monitor.

TABLE IV

PARAMETERS OF MICROWAVE CAVITIES

	INTENSITY	POSITION
Sensitivity	80mW/mA ²	0.170mW/mA ² mm ²
Loaded Q	1200	600
Unloaded Q	5000	3000
Resonant Frequency	2856.0 ± 0.3 MHz	2856.0 ± 0.6 MHz
Operating Temperature	90°F	90°F
Temperature Detuning	-0.002%/°C	-0.002%/°C
Rise Time	175nsec	85nsec
Cavity Inside Dimensions	r = 3.5430 inches h = 1.100 inches	3.1800 × 4.4455 × × 2.001 inches
Output Connector	Special Quick-Disconnect	Same
Cable to Detector Electronics	500-ohm styroflex cable, air dielectric with polystyrene spiral as spacer	Same

Figure 10 shows special fast-disconnect coaxial plugs through which the signals are taken out of the cavities to the detector diodes through about 15 feet of styroflex cable. The plugs are placed on an extension pipe away from the cavities in order to keep insulation materials away from the higher radiation exposure close to beam center.

The cavities are constructed with a water circuit in order to temperature-stabilize them. At present the water circuit is not used, because the monitor is essentially used as a beam centering device. To keep the cavity output voltage constant to within $\pm 1.5\%$ it is necessary to stabilize the cavity temperature to within $\pm 5^\circ\text{C}$.

A thermometer at each end of the cavity is provided to check possible beam interception by the cavity as a result of possible errors in alignment. For some of the cavities in the BSY the alignment of the small 2-inch aperture is very critical with respect to the gaps of associated protection collimators.

B. Microwave Position Monitor Electronics

The microwave position monitor electronics is divided into two parts. One part is the microwave detector circuit, which is located in the alcoves inside the tunnel (see Fig. 2); the other part is located in the control room. This location of the microwave electronics was unavoidable, since short cables are essential to limit power loss and phase variations in the cables. The microwave detector electronics converts the pulsed rf signals from the three cavities into video signals whose amplitude gives the beam position and beam intensity information.

Each position cavity signal is combined with half the signal of the intensity cavity in a hybrid ring. The rf output of the hybrid rings is converted into video pulses by either thermionic or crystal diode detectors. The detector signals are transmitted via 125-ohm coaxial cables from the (blue) detector chassis in the alcove to the control room where the signals are processed and displayed.

The microwave detector electronics is shown in Fig. 11. The power input into the hybrid in terms of parameters from the beam intensity and

Beam Position Signals To Balancing Circuit In Control Room

FIG.11 -- MICROWAVE DETECTOR ELECTRONICS

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beam position cavities, respectively, are:

$$P_i = K_i^2 I^2 = (K_i I)^2 \quad (5)$$

$$P_x = K_x^2 I^2 X^2 = (K_x I \cdot X)^2 \quad (6)$$

The constants K_i^2 and K_x^2 include the cavity response and all attenuation from the cavity output to hybrid input.

The phase shifter is adjusted so that the hybrid is in the amplitude sensing mode. In this mode the hybrid response (the two power outputs in terms of the two power inputs) is as follows:

$$P_a = \frac{1}{2} P_i \left[1 + \left(\frac{P_x}{P_i} \right)^{\frac{1}{2}} \right]^2 \quad (7)$$

$$P_b = \frac{1}{2} P_i \left[1 - \left(\frac{P_x}{P_i} \right)^{\frac{1}{2}} \right]^2 \quad (8)$$

The terminal of the hybrid at which P_a and P_b appear can be interchanged if the relative phase of the input signals is shifted 180 degrees.

Let us define:

$$\nu = \left(\frac{1}{2} \cdot P_i \right)^{\frac{1}{2}} = \frac{1}{\sqrt{2}} K_i I \quad (9)$$

$$\text{and } \mu = \left(\frac{P_x}{P_i} \right)^{\frac{1}{2}} = \frac{K_x}{K_i} \cdot X \quad (10)$$

Then Eqs. (7) and (8) become:

$$P_a = \nu^2 (1 + \mu)^2$$

$$P_b = \nu^2 (1 - \mu)^2$$

The detector response (voltage output in terms of power input) is given by:

$$V = K_n \cdot P^{n/2} \quad (11)$$

so that:

$$V_a = K_a \nu^n (1 + \mu)^n \quad (12)$$

$$V_b = K_b \nu^n (1 - \mu)^n \quad (13)$$

where $1 < n < 2$. The detector is linear if $n = 1$; a square law curve if $n = 2$; and a quasi-linear curve if n is close to 1. In order to extend the useful range of the position monitor in the lower currents, two types of detectors have been used. The thermionic detectors can be used for beam pulse currents of 0.2 milliamps and higher. They are normal glass-metal diodes which are estimated to stand up to a radiation exposure of 5×10^{10} ergs/gram, without damage. This level should not be reached in the alcove for several years.

The crystal diodes are added to cover currents as low as 0.01 milli-amp. Tunnel diodes are used because of their greater sensitivity, lower output impedance, and better radiation resistance (5×10^9 ergs/gram) than other semiconductor detectors. The tunnel diodes are square law detectors and the thermionic diodes are square law at low power and quasi-linear at higher power. The transition point is approximately at 10 milliwatts into the diode.

The output signals obtained after electronic processing are:

$$V_d = V_a - V_b \text{ (video display)} \quad (14)$$

$$V_s = V_a + V_b \quad (15)$$

$$V_d/V_s \text{ (normalized display)} \quad (16)$$

The output power from the cavities is adjusted such that $\mu < 1$ for all values of X . The output signals for the three possible values of n can be derived as a function of beam parameters. The relations assume that the

diodes are balanced, e.g., $K_a = K_b$. These constants are also a function of input power and therefore vary in the three cases below:

Linear ($n = 1$)

$$V_d = 2 K_a \nu \mu = K_1 \cdot I \cdot x \quad (17)$$

$$V_s = 2 K_a \nu = K_2 I,$$

where K_1 and K_2 are new constants.

$$V_d/V_s = \mu \quad (18)$$

Quasi-Linear ($n = 1 + \epsilon$)

$$V_d = K_3 I^{(1 + \epsilon)} X \quad (19)$$

$$V_s = K_4 I^{(1 + \epsilon)}$$

$$\frac{V_d}{V_s} = (1 + \epsilon) \mu \quad (20)$$

Square Law ($n = 2$)

$$V_d = K_5 I^2 X \quad (21)$$

$$V_s = K_6 I^2$$

$$V_d/V_s = \frac{2\mu}{1 + \mu} \quad (22)$$

In the Beam Switchyard the constants for the cavities are matched to within 20% and are nominally:

$$K_x^2 = 0.1 \text{mW/mA}^2 \cdot \text{mm}^2$$

$$K_i^2 = 0.8 \text{mW/mA}^2$$

The thermionic diodes never operate in the linear region, as the minimum value of n is about 1.15. Typical values for K_3 and K_5 in terms of the voltage coming out of the detector are:

$$K_3 = 36 \text{mV/mA}^{1.15} \cdot \text{mm (thermionic diode)}$$

$$K_5 = 2 \text{mV/mA}^2 \cdot \text{mm (crystal diode)}$$

The calibration curves shown in Fig. 12 are based on measurements taken on position monitors P_1 and P_2 during the beam test run in June 1966. They are taken with a gain setting equal to 1. The curves depend on the system gain which can be adjusted internally. The complete beam position monitoring system is shown in Fig. 13.

The microwave position monitor has two display systems (Ref. 9): 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. 13, the X and Y position signals of any two monitors may be viewed simultaneously on the Type 551 oscilloscope. In this display, the Y signal is delayed by $4\mu\text{sec}$ and combined with the X signal so that both are displayed on the same trace of the oscilloscope.

The video signal distribution circuit (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 $I_0 x$; two position signals proportional

FIG.12--MICROWAVE POSITION MONITOR CALIBRATION

FIG.13 --BEAM POSITION MONITORING SYSTEM

to $I_0 y$; and one current signal I_0 (I_0 = beam peak current measured in current 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_0 is changed.

The output to the video system may be range-switched through relative gains of 0.1, 1, 10. This is provided for reasons of noise and operator convenience.

The control chassis (BPM Video Signal Control) selects the cavities that are displayed on the scope, provides control for the balancing procedure, and controls such functions as phase adjustment and diode switching in the (blue) microwave detector chassis.

The chassis marked microwave detector control in Fig. 13 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 at the accelerator (Ref. 13). The inputs to these circuits are the video position signals $I_0 x$, $I_0 y$, and I_0 signal. The output produces three pulses, each 500- μ sec 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. This system is working properly for currents above 0.5mA.

V. SYNCHROTRON LIGHT OBSERVATION STATION

Electrons radiate electromagnetic radiation when deflected in a magnetic field. For most of the magnets in the Switchyard, the wavelength of this radiation covers the visual spectrum. This phenomenon has been used after bending magnets B-10 and B-30 as a non-intercepting means of visual observation of the beam spot (Ref. 14).

The radiation covers a wide frequency spectrum which depends on the bending radius in the magnet and which shifts towards shorter wavelengths with the third power of the beam energy:

$$\lambda_c = 5.59 \cdot R \cdot \left(\frac{1}{E} \right)^3 \quad (23)$$

where

λ_c = shortest wavelength radiated ($\text{\AA}$)

E = electron energy (GeV)

R = bending radius (meters)

Bending magnet B-10 has a bending radius $R = 57$ meters, and radiates therefore in the visual spectrum if the beam energy $E = \left(\frac{5.59 \cdot 57}{5000} \right)^{1/3} = 0.4$ GeV or higher.

The photons are emitted in a narrow cone along the direction in which the electrons move. The number of photons emitted per second for each microamp of beam current is

$$N_\phi = 2.4 \cdot 10^{12} \cdot \frac{L}{R^{2/3}} \text{ photons/sec} \cdot \mu\text{A} \quad (24)$$

where L = the length over which the electrons travel in the magnetic field.

The optics system is arranged to look at the first 1-foot-long path in bending magnet B-10 (Fig. 14). The light produced by this section is 4.9×10^{10} photon/sec $\cdot \mu\text{A}$. For orientation purposes, we assume a beam spot size in B-10 of 1 cm by 2 cm and a demagnification from the beam to the vidicon tube cathode of 1/100. The optics use four front surface aluminized mirrors (reflectivity = 85%), one polished metal mirror (reflectivity = 50%), and one 3/8 inch quartz window (transmission 95%). All these factors together give

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FIG.14--SYNCHROTRON LIGHT OBSERVATION

an effective light level on the photo cathode of approximately 6.4×10^{11} photons/cm² sec ($1\mu\text{A}$).

A vidicon tube shows reasonable pictures for 0.1 foot candle = 4×10^{11} photons/cm² sec on the photo cathode. The synchrotron light monitor therefore can be used with a vidicon TV camera for beam currents of about $1\mu\text{A}$ or higher.

The range can be extended to about $10^{-2} \mu\text{A}$ if the vidicon camera is replaced by an orthocon camera. Provisions are made for the delicate orthocon TV camera in an accessible and radiation-free hut on top of the Switchyard shielding. The light can be observed from this point through the penetration and mirror optics shown in Fig. 14.

The special V-shaped vacuum chamber located after B-10 is shown in Fig. 15. The mirror inside this chamber 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 cross wires fixed inside the V-shaped chamber (see Fig. 14).

The visible light as well as the shorter wavelength part of the synchrotron radiation, which represents about 21 watts at maximum beam power, is intercepted by the mirror. The mirror should therefore consist of a thin polished metal plate. At the present time we have installed a front surface quartz mirror. This mirror should be replaced by a metal one as soon as beam power increases to a high level.

The mirror is attached to the vertical circular section of the vacuum chamber. This section can be removed easily by means of the 12-inch fast-disconnect vacuum flange. The quartz viewing window is mounted at the top of the removable section in order to keep it away from radiation.

At the present time only station P(S)10 after magnet B-10 in the A-beam is completely equipped. Station P(S)30 in the B-beam consists of a blanked off V-shaped vacuum chamber, which will be equipped with a mirror when the usefulness of this beam observation method has been demonstrated in the A-beam.

FIG. 15--Synchrotron light pick-up station.

VI. BEAM PROFILE MONITORING

A. Beam Profile Monitors

The use of conventional zinc sulfide screens and Cerenkov light from a gas cell were selected for beam profile observation in the Switchyard. Several other techniques were explored but were found to be less suitable.

The two-mile linear accelerator proper uses the Cerenkov light from a quartz plate for beam profile observation. Also a small electrical probe has been developed which sweeps through the beam and displays the current intensity throughout the beam spot on an oscilloscope (Ref. 15).

B. Zinc Sulfide Screen Profile Monitors

Zinc sulfide screens are widely used in high energy physics. They are easy to make and have good sensitivity, but have the disadvantage of losing luminescence after exposure to an integrated beam current of $10 \mu\text{A hr/cm}^2$.

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 disc with its axis of rotation tilted 45 degrees with respect to the beam, the film roll principle (which has now been developed by Experimental Group A at SLAC), and others.

The mechanism finally adopted for the Switchyard is a carousel with 48 independent screens shown in Fig. 16. The 48 screen arms hang on balls in the slotted rim of a 10-inch wheel. The screen frames can be raised into the beam by the blade lift mechanism. The u-shape of the screen frame ensures that the beam is intercepted only by the 2-mil-thick, zinc-sulfide-coated aluminum foil. The index drive mechanism rotates the wheel 7.5 degrees so that a new screen comes into the lift position. When all the screens have been used, the carousel is lifted out of the housing. Each screen frame can then be lifted out of a slotted rim for replacement.

FIG. 16--ZnS screen changer lifted out of vacuum housing.

Figure 17 shows the foils mounted inside the vacuum housing of profile monitor PR-30 with screen number 39 raised into the beam path. The picture shows the position reference marks which are fixed inside the housing. These reference marks are positioned with respect to the beam with a tolerance of 1 millimeter. The reference marks and the screen can be illuminated from outside the housing.

The image of the beam spot on the screen is brought outside the housing via a front surface mirror inside a light pipe and a vacuum window at the upper end of this pipe. The optics is described in more detail in Section VI. D. The adjustable mirror on top of the vertical light pipe and the drive motors shown in Fig. 18 stick up into a wide slot in the 2-foot-thick concrete shielding floor. This location provides shielding from radiation in the lower tunnel and easy access.

Figure 18 shows various other details designed to make remote replacement possible: a fast disconnect plug, two plug-in type drive motors, assembly guide rods, a 12-inch fast-disconnect vacuum flange, and lift eyes.

Two types of the multi-screen profile monitors described above have been built: one is for a 6-inch beam pipe (4-inch-wide screen) and the other is for a 12-inch beam pipe (8-inch-wide screen). The difference between the two types is in the angle of the screen with respect to the beam (see Table V). The carousel is identical for both types for reasons of interchangeability.

The 12-inch monitor is used at location PR-34 and was also intended for locations PR-11 and PR-31 in the analyzed beam. However, because the last two monitors are not expected to be used frequently, it was decided to construct a less expensive single-flap screen for these locations (see Fig. 19). The screen in this monitor can also be replaced relatively easily because of a specially designed vacuum clamp.

The technique of zinc sulfide coating on the many foils for the Switchyard was developed by W. Schulz at SLAC. The spraying is done in a small ventilation chamber in which the foils are heated to about 80°C. The spraying liquid consists of 15% Sylvania P-4 phosphor, 3% glycerin, 3% sodium silicate, and 79% H₂O (all by weight). The ZnS is sprayed in a few layers to obtain better stability. It has been established experimentally

FIG. 17--Detail of multi-screen ZnS monitor.

FIG. 18--Complete multi-screen ZnS monitor.

FIG. 19--10-inch flap screen ZnS monitor.

that no light output is gained by using a grain size finer than 10 microns, and that maximum light output is obtained with a 4-mil-thick layer. Thicker layers produce light flares and distort the spot at higher beam currents. The first screens installed in the profile monitors are sprayed alternately with 1-mil-thick and 4-mil-thick layers. The 1-mil thick screens are provided to reduce beam scattering and will be used at higher beam currents. Table V shows the characteristics of this monitor and compares it with the Cerenkov light profile monitor.

C. Cerenkov Light Profile Monitor

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 monitor for the Switchyard (Ref. 16) we observe the Cerenkov light produced when the electrons pass through a gas at atmospheric pressure. The number of Cerenkov photons produced in a gas is:

$$N_{\phi} = 900(n\beta - 1) \text{ photons per cm} \quad (25)$$

where $\beta = v/c$ and n = index of refraction.

The photons are emitted at an angle

$$\theta = \cos^{-1} \frac{1}{\beta n} \quad (26)$$

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 equal to $\ell \sin \alpha$, where ℓ is the effective length of the gas cell.

✓ The construction of the Cerenkov profile monitor is shown schematically in Fig. 20. ✓ The inner gas cell operates slightly above atmospheric gas pressure. As a gas filling we have used at different times argon and helium. Argon produces eight times more light, but helium reduces the distortion as well as the beam scattering. A comparison between the two gases is made below:

TABLE V

COMPARISON OF BEAM PROFILE MONITOR CHARACTERISTICS

	CERENKOV CELL	ZnS SCREEN MONITOR WITH 48 SCREENS
Sensitivity	(Helium) 10^{-9} amp/cm ² (Argon) 3×10^{-10} amp/cm ²	10^{-9} amp/cm ²
Spot Definition	1 millimeter	1 millimeter
Maximum Aperture	3-inch diameter	8 inches wide 2 inches high
Material in Beam	2 aluminum windows, 3 mils thick; 1 aluminum mirror, 1 mil thick; 20 cm gas at atmospheric pressure	2-mil aluminum foil at 45 degrees
Coating	1-mil-thick graphite (Aquadag) reference mark on one window	1-mil and 4-mils-thick zinc sulfide (10-micron grain size, Sylvania P-402)
Total Material in Beam	6×10^{-3} radiation length (argon) 2.42×10^{-3} radiation length (helium)	4.8×10^{-3} radiation length
Mechanical	Cell moves into the beam by applying air pressure to a small cylinder; moves out of the beam by gravity	Screen is selected and moved into and out of the beam by electric motors
Expected Life	Mirror $> 1.5 \times 10^4$ $\mu\text{A hr/cm}^2$. The reference mark may fade before this	Each screen good for $10 \mu\text{A hr/cm}^2$
Remarks	Gas flows through the cell when the cell is in the beam	Carousel with used screens can be replaced easily

FIG. 20 -- PRINCIPLE OF CERENKOV LIGHT MONITOR

Gas	n	$N_{\phi}/\text{electron}$	θ	α	$\ell \sin \alpha$
		$\ell = 12 \text{ cm}$		(mr)	Distortion
Argon	1.000 281	3.	$1^{\circ} 22'$	48	0.21mm
Helium	1.000 036	0.39	$30'$	17	0.08mm

The gas cell is built in a tubular hammerhead configuration and has 3-mil-thick hard aluminum beam entrance and exit windows. The light cone is reflected vertically by a mirror placed in the beam at 45 degrees. The mirror consists of a 1-mil-thick mechanically and chemically polished aluminum foil stretched over a ring using the drum head 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 counter-weight (see Fig. 21) moves the cell out of the beam when the air pressure is released.

The gas flows at a rate of about 1cc/sec through the cell when it is placed in the beam. The cell has four position reference marks (1/16-inch pins) which protrude into the cell from the four sides. In addition, there is a reference cross on the inside of the entrance beam window marked by a black field. The black field is obtained by spraying the sandblasted foil with a mixture of 15% graphite, 10% ammonium hydroxide, and 75% distilled water (Schulz). The reference cross is marked at the foil which is heated to about 70°C during spraying. The reference marks can be illuminated with a lamp mounted outside the silica viewing window.

Table V shows the characteristics of the Cerenkov profile monitor.

D. Optics and TV System

The optical system for observation of the light from the zinc sulfide screens, the Cerenkov cells, and the synchrotron light station is described below. The television cameras use RCA 7735A vidicon tubes with non-browning faceplates. The faceplate has a fairly sharp spectral sensitivity curve with a peak at 5500Å. The other optical components in the system are chosen wherever possible to match this wavelength.

FIG. 21--Cerenkov light profile monitor.

The light is focused on the vidicon tube with a reflector telescope using front surface aluminized mirrors (see Figs. 20 and 22). The advantage of the telescope is that the mirrors are better resistant to radiation than non-browning lenses (which are, in addition, more expensive). A TV camera-telescope assembly mounted with a ball mount in an alcove is shown in Fig. 23. The ball mount allows adjustment in all directions.

Light from the beam profile spot in the monitors passes through a radiation-resistant vacuum window (Corning pure fused silica, code 7940) and is directed into the telescope mirror by a remotely adjustable front surface mirror. The mirror can be tilted from the control room through small angles in two directions by electric motors driving cams. The cams are contoured to give two speeds. The front surface aluminized mirrors are unaffected by radiation but are very sensitive to nitric acid corrosion. A mirror covered with several $1/4\text{-}\lambda$ thick layers of titanium dioxide and magnesium fluoride was tested and found to be both nitric acid and radiation resistant. A commercial mirror of this type (Liberty mirror No. 90-500) has been installed at location PR-2 for further testing.

The telescopes are designed to give an overall magnification on the 17-inch T.V. monitor between one and two times the actual beam size. The spherical mirrors vary in focal length between 10 and 20 inches for the different monitors in the Switchyard. The telescope is constructed in such a way that it will accept any 4-1/4-inch-diameter mirror in this range. Coarse focusing is provided by means of a thumbscrew on the telescope; fine focusing is provided by remote control of the position of the vidicon tube inside the TV camera.

E. Beam Profile Monitor Control and TV Camera Selection

Control circuits are needed to move a Cerenkov cell or a zinc sulfide screen into or out of the beam, to select new screens, to adjust the illumination of the reference marks and to adjust the angle of the mirrors.

The profile monitor selector system shown in Fig. 24 is built to multiplex these controls for all of the profile monitors in two parallel channels.

The camera-profile monitor selector panel has a pushbutton for each monitor, which actuates a corresponding multicontact relay. The profile

FIG. 22--Telescope.

FIG. 23--Telescope and microwave detector in alcove.

540-30-B

FIG. 24 --PROFILE MONITOR SELECTION

monitor relay chassis has one such relay for each monitor. Thirteen of the relays are suitable for switching the controls of a zinc sulfide monitor, and seven are suitable for Cerenkov light monitor control.

Each channel is associated with two different control panels, one to operate zinc sulfide monitors and one to operate Cerenkov monitors.

The illumination controls are the same for both monitors, and there is only one panel to serve both channels.

The actuating circuit for the selection of a relay is routed via the corresponding relay in the other circuit to make sure that a monitor can be operated only by the controls of one channel at a time. The reason for this is to safeguard the equipment from damage as a result of dual control.

The TV video signal selector is controlled via a contact of the profile monitor relays. The TV signal for the selected profile monitor is therefore automatically switched to the TV monitor associated with the channel being used.

A panel with several lamps shows for each monitor whether either a cell or a screen is moved into or out of the beam and transmits this information to the signal scanner (Section XI. B). In this way, the scanner prints out when and how long a profile monitor was in the beam. The lamp panel also produces a beam suppression signal during the short period that the flange of the Cerenkov cell is passing through the beam. Another signal from this panel opens the gas valve that allows gas through the cell when it is moved into the beam.

VII. SECONDARY EMISSION FOIL MONITORS

A. Secondary Emission (SEM) Devices

Low energy (< 30 eV) secondary electrons are emitted from the surface of a foil when it is traversed by high energy charged particles. Since secondary emission monitors do not show saturation effects at higher currents (Ref. 17) they are attractive linear current sensors for the high current expected in the Switchyard.

Secondary emission foils have been used in various monitors performing different functions in the Switchyard:

- a. In the spectrum analyzer and spectrum monitor (see Section VIII)
- b. To monitor the portion of the beam current which is intercepted by the jaws of the collimator and slits.
- c. To provide beam centering information in front of the high power dumps (4-quadrant SEM).
- d. To provide signals for the equipment protection system. These signals are derived from the foils mentioned under b. and c. and from foils in front of the walls of the tune-up dump (see Section VIII. A).

Aluminum foils are used in all applications because of the low density, good mechanical strength, and high thermal conductivity of this material.

The secondary emission coefficient of aluminum is about 4%. This coefficient is fairly independent of the primary electron energy, but is somewhat variable because of the unstable surface conditions of aluminum. Gold plating of the foils will result in more stable secondary emission and a higher secondary emission coefficient. In our application the absolute calibration is not very important so that we have avoided the complication of gold plating.

B. Sem Foils On Slits And Collimators

SEM foils are mounted on the front and back of each jaw of the high power slit (SL-10) and collimator (C-1) and also on the front of the high-Z slit (SL-31) as a result of the fact that the high power slit (SL-30) in the B-beam will not be installed until later. The signals from the foils at the front end are proportional to the amount of beam current intercepted by the jaws. On the slits these signals are used as a rough

indication of the drift in the energy spectrum (Section VIII. C). The foils at the front end of each jaw are also used for protection purposes.

The foils mounted on the rear end of the jaws produce a large signal if the beam hits toward the end of the 16-foot-long jaw. Since the front and rear end of the jaws can be moved independently, these signals can be used for jaw angle adjustment. The radiation levels in the collimator areas will be extremely high (10^{15} ergs/gram), and a great effort has been made to obtain a good radiation-resistant construction.

As an example, Fig. 25 shows the SEM foils mounted on the front end of SL-10. These SEM assemblies consist of a stack of three emitter foils (0.005 inch-thick aluminum) sandwiched between four high voltage collector electrodes. In the case of the collimator, where beam excursion is limited to a circular area slightly more than 1 inch, the collector electrodes are made of 1/8 inch-thick aluminum and are set back from the aperture so that they cannot intercept the beam. On the slits, the analyzed beam also passes partly through the collector electrodes, which in this case are made of 0.005 inch-thick aluminum foil. The emitter and collector assemblies are mounted on the jaws using ceramic insulators with indium washers to increase heat conductivity.

Electrical connections inside the vacuum housings are made with unsealed multi-conductor magnesium-oxide-insulated cables. The motion of the jaws is permitted by looping the cables inside the vacuum tank. A special 6-inch flange assembly with a MgO cable pigtail and electrical connectors was designed to bring the signals out of the vacuum housing and into the upper tunnel of the Switchyard housing. The ends of the stainless-steel-jacketed MgO cables are sealed with quartz-loaded epoxy in a potting box in the upper housing. Standard coaxial cables are used from this point on to the control room.

As far as the thermal protection of the jaws is concerned, the important measurement is not beam current, but beam current density. Various ways to measure current density at these high beam current intensities were investigated rather unsuccessfully. E. Seppi at SLAC introduced the principle that the conductance of a thin dielectric layer changes when traversed by an electron beam. This idea was developed into a modification of the simple SEM foils, which makes it possible to measure beam current

FIG. 25--SEM foils on slit SL-10.

density with an area resolution of about 2mm^2 . Two of the three SEM emitter foils on the front of the jaws of SL-10 (see Fig. 25) and C-1 have been modified in this way.

The modification involves coating the aluminum foil with a 10-micron-thick ceramic layer (by anodization) and the vacuum deposition of a series of thin metallic strips on top of the ceramic. The gold strips ($1/8$ inch-wide) are separated by gaps of about 0.030 inch and are arranged horizontally and vertically on consecutive foils to form a hodoscope. A voltage is applied to the aluminum foil and a signal taken from each of the gold strips. Because of the experimental nature of this conduction monitor, the foil can still be used as a SEM foil by shorting the metallic strips to the aluminum baseplate. This can be done in the upper tunnel.

C. Beam Centering Four-Quadrant SEM

The beam to be disposed of in the underground dump is characterized by an intense halo as a result of multiple scattering in the photon target, which may be 0.01 radiation length thick.

A four-quadrant SEM monitor with an aperture of three inches was designed (see Fig. 26) in order to monitor the halo. The signal from each foil can be displayed separately on an oscilloscope to provide information to center the beam properly on the dump. The beam must be carefully centered on the 6-inch-diameter dump window, because only a 3-inch-diameter area in the center can safely accept a very high current density.

Each quadrant consists of two emitting foils in parallel to increase the output signal. The emitter foils are made of 5-mil-thick aluminum, which is spot-welded to a frame. The frame is supported on a stainless steel rod using alumina insulation. Electrical leakage across the ceramics from the high voltage (200 volts) collector electrode to the foil is prevented by an intermediate ground. It was mentioned earlier (Section III. A) that this monitor shares the vacuum housing with the 6.35-inch current monitor. The signal leads for the SEM and the current monitor consist of stainless-steel-jacketed, magnesium-oxide-insulated cables. The jackets of these cables are welded into a small flange on the vacuum housing. The cables pass via wall chases to the upper tunnel of the Switchyard housing, where they are sealed with quartz-loaded epoxy and connected to standard Rg-58 cables.

FIG. 26--Dump monitor (4 quadrant SEM monitor and 6.35-inch current transformer).

D. SEM Electronics

The SEM electronics provides two output signals, one for analytical purposes and the other for interlock purposes. The electronics is shown schematically in Fig. 27. Each SEM foil is connected via a low leakage coaxial cable to an integrating circuit with a fixed time constant (200 msec). The integrated voltage signal is monitored by a variable threshold level detector (+20mV to +2.5 volts) built into the integrator. The outputs of all the detectors are connected into one OR gate and are used as an interlock signal to shut off the beam in case of excessive current interception by any of the foils connected to this output.

The output voltage from the integrating circuit can also be selected for display on an oscilloscope. The timing circuit is arranged in such a way that any four pairs of foil signals may be displayed on a dual trace oscilloscope. In this way the four signals from either the four-quadrant SEM foils or from the foils on the front and rear of a slit can be observed simultaneously. The minimum signal level that can be detected out of the integrator is 2mV.

540-32-B

FIG.27--SEM ELECTRONICS

VIII. BEAM SPECTRUM INSTRUMENTATION

The energy spectrum is measured in the analyzed A-beam and B-beam with identical spectrum analyzers S-11 and S-31. A crude spectrum measurement can be made with a spectrum monitor S-10 located in front of the tune-up dump. All of these devices use the principle of secondary emission discussed in Section VII. The main characteristics are listed in Table VI.

A. The Tune-Up Spectrum Monitor

The tune-up spectrum monitor consists of a row of SEM foils mounted in a wide vacuum chamber in front of the tune-up dump (see Fig. 28). The tune-up dump and the tune-up spectrum monitor were made as wide as possible to provide maximum energy acceptance during accelerator tuning. In order to mount the foils into the vacuum chamber with standard 12-inch fast-disconnect flanges, the monitor is split into two halves. The half carrying the higher resolution foils is shown in Fig. 29. The emission foils are spot-welded to nickel tabs which are brazed to metallized areas on two sides of a rectangular ceramic bar. The foils are supported at the top only, and are made of 5-mil-thick aluminum, folded slightly to give increased mechanical strength. Each foil is connected by a signal lead to the multi-pin vacuum feedthrough in the upper flange. The six narrow foils in the center give an energy resolution of 0.85%. The secondary electrons are collected by two cylindrical collector electrodes (at + 100 volt), one placed on each side of the foils.

The stack of SEM foils to the left of Fig. 29 is not part of the spectrum monitor. This stack, SEM-11(A), is aligned to be in front of the wall of the tune-up dump. It provides a beam interlock signal if a beam should hit accidentally at that point. The other half of the spectrum monitor is constructed in the same way and carries the lower resolution foils (see Fig. 28).

The tune-up dump spectrum monitor electronics is shown in Fig. 30. Each of the 38 individual foils is connected to an integrator in the local electronics box. The low leakage coaxial cable between the foil and this circuit is part of the integrating capacitor. The discharge time constant and integrating capacitor of each integrator are remotely adjustable in discrete steps.

540-13-B

Fig.28-TUNE-UP SPECTRUM MONITOR AND DUMP

FIG. 29--Tune-up spectrum monitor.

FIG.30--TUNE-UP SPECTRUM MONITOR SYSTEM

540-6-B

A short discharge time constant gives faster integrator response. The smallest integrating capacitor gives highest sensitivity. All 38 channels are switched simultaneously.

The scanner sequentially samples the voltage on each integrator, and amplifies the output signal (gain 1 to 20). The spectrum signal is then displayed on the Type 565 oscilloscope and is also transmitted to the accelerator control room. The controls for the integrators and scanner can be operated in the Switchyard and in the accelerator control room.

A special output is available (not shown in Fig. 30) from one of the narrow foils for plotting the spectrum on a recorder versus the current in the deflection magnet. To obtain a spectrum using this procedure, one has to sweep the beam across the narrow foil.

B. The Spectrum Analyzer

The construction principle of the spectrum analyzer (Ref. 18, 19, 20) is shown in Fig. 31, and Fig. 32 is a photograph of the completed instrument.

The secondary emission foils are supported by two foil holders each carrying six foils. The foil holder consists of an aluminum C-frame which supports the spring loaded 1-mil-thick aluminum foils (Fig. 33). The foils were made thin to avoid heat absorption (cooling is by radiation) and to reduce beam scattering. The foils near the center have the highest resolution and are 6mm wide (see Table VI). The foils which monitor the tails of the spectrum have been chosen wider in order to save the cost of the electronics associated with each foil and also to improve the signal-to-noise ratio of the signals on these foils.

The foils are insulated from the C-frame by small ceramic tube inserts (see Fig. 33). Each foil is nickel-plated at the ends in order to spot-weld a support pin to it. The shielded signal wire is in turn spot-welded to each of the support pins.

The secondary electrons are collected by two C-shaped collector electrodes (at + 100 volts) mounted on each side of the C-frames.

All electrical connections on top of the C-frame are shielded by a cover plate (see Fig. 32) which also prevents deposition of any material on the ceramic tube insulators, which might cause leakage.

540-15-A

FIG.31-- SPECTRUM ANALYZER SCHEMATIC

FIG. 32--Spectrum analyzer.

FIG. 33--SEM foils for spectrum analyzer.

540A4I

TABLE VI
DATA ON SPECTRUM INSTRUMENTATION

Spectrum Monitor S-10	
1. <u>Data on Foils</u>	Material Aluminum foils 5 mils thick High Resolution Side 22 foils covering $\alpha = 4.0$ to 7.5 mr deflection Low Resolution Side 16 foils covering $\alpha = 1.58$ to 4.0 mr deflection SEM-11 A and B SEM protection foils (see Section XII)
2. <u>Signal Integrator</u>	Time Constants 1/3 sec, 1 sec, 3 sec Signal Attenuation $100\times (1\mu F)$, $10\times(0.1\mu F)$, $1\times(0.01\mu F)$
3. <u>Signal Scanner</u> (SLAC design)	38 channels (expandable to 100) Noise level 3 millivolts Trigger Rate 60 cps synchronized with beam Scan Time 270 μ sec/channel
4. <u>Minimum Current</u>	1.5nA at S/N = 3
5. <u>Display</u>	Tektronix 565 oscilloscope
Spectrum Analyzers S-11, S-31	
1. <u>Data on Foils</u>	Width mm 40 24 12 12 6 6 6 6 12 12 24 48 S-11 $\Delta P/P$ % .8 .4 .2 .2 .1 .1 .1 .1 .2 .2 .4 .8 S-31 $\Delta P/P$ % .16 .8 .4 .4 .2 .2 .2 .2 .2 .2 .8 1.6 Maximum opening between foils 6 inches Material Aluminum 1 mil thick
2. <u>Average Spectrum Display</u>	See details 2, 3, 4, of spectrum monitor Scanner I 12 foils from S-11 + current signal from I-13 Scanner I 12 foils from S-31 + current signal from I-31 Scan Time 70 μ sec/channel
3. <u>Video Spectrum Display</u>	Any combination of four out of the 26 video signals can be displayed on a Tektronix 551 scope Response Time 30 nonaseconds
4. <u>Sampled Spectrum Display</u>	Texas Instr. scanner with 13 channels Noise Level 20 millivolts Synchronization Every beam pulse
5. <u>Sample Circuit</u>	Sample Width 100 nsec; sample can be taken at any point of beam pulse length: (0-2.2 μ sec)

The foils are normally closed when the analyzer is used, but the two foil holders can be retracted sideways. The retraction mechanism moves the two foil arms at an equal distance from the beam center line. When the analyzer is not used in the beam, the foils should be retracted to an opening equal to the gap used for the slit. Beam scattering is avoided in this position, but the foil can still monitor the spectrum tails intercepted by the slit.

The essential part of the instrument is supported by a housing connected to the upper part of a horizontal 12-inch fast-disconnect vacuum flange and can be lifted out of the lower vacuum housing.

The foil arms are pivoted inside the top of the housing. Their motion is synchronized by a drive screw with right-hand thread on one side and left-hand thread on the other. In order to avoid damage, it is essential that the foil arms are closed before the instrument is lifted out of the lower vacuum housing. The electric drive motors plug in with a multi-jaw coupling. The plug in motor is non-radiation-resistant and protrudes two feet into the shielding floor for radiation shielding.

A calibrated linear voltage dependent transformer (LVDT) is connected to one of the drive arms to read the position of the foils remotely. Mechanical stops are mounted on the drive screw. Microswitches stop the drive motor just before the foil arm hits the stops.

Control and position readout wires go through a 13-pin electrical quick-disconnect connector. Signal wires from the foils go through a vacuum header and are carried to the upper tunnel by a pigtail made of radiation-resistant twinaxial cable.

The spectrum analyzer electronics system is shown in Fig. 34. 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 located after the slit (I-13, I-33). 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. Each of the 12 emission foils and the current monitor signal are connected to a video amplifier (gain $\times 1 - \times 300$).

FIG. 34--SPECTRUM ANALYZER SYSTEM

The 13 signals are split after the video amplifiers. One set goes to integrators for the average spectrum display. This system uses the same electronics as described for the spectrum monitor. The other set goes to 13 mixing amplifiers (gain $\times 10$), which combine the A and B beam signals into one output. The mixed video signals are connected to 13 triggered sample-and-hold circuits. The sampling time of these circuits is 100 nsec and the sample time can be taken at any instant during the video pulses by proper timing. The outputs of the sample-and-hold circuits are scanned and displayed on an oscilloscope at the beam pulse repetition frequency. The oscilloscope display represents a sampled spectrum of 100-nsec-long portion of the beam pulse.

Normally the sample-and-hold circuits are reset before each new beam pulse, and give a pulse-to-pulse beam spectrum. An alternate mode of operation is to average the 100-nsec-long sample over many beam pulses.

It is also possible to increase the sample time from 100nsec to the full beam pulse length. This allows a display of the normal beam spectrum on a pulse-to-pulse basis.

Although the sampled spectrum system has very good analytical capability, it was felt desirable to retain the spectrum information available in the video pulses proper. For this reason, output signals from the mixing amplifiers were routed into a video signal selector which can select any combination of four signals for display on the Type 551 oscilloscope (see Fig. 33). Signals from beam A or beam B can be selected by choosing the proper trigger signal on the oscilloscope.

Operating characteristics of the spectrum analyzer are summarized in Table VI.

C. Spectrum Drift Indicator Electronics

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

The signals for the spectrum drift indicator are derived from the two SEM foils on the front end of the slits (Section VII. A) and the current transformer 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 towards higher or lower energy and the transmitted current.

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

IX. MAGNETIC MEASUREMENT INSTRUMENTS

This section describes magnetic measurement instruments which are a permanent part of the already installed magnets (Ref. 21). They are used for checking and calibration purposes but not for current control. Three types of magnetic measurements can be made on the magnets: nuclear magnetic resonance (NMR); remnant (zero-current) field (R); and dynamic integration from flux loops (F). Table VII shows a list of all the magnets in the Switchyard. The last column shows the type of measurement that can be done in each magnet.

A. Nuclear Magnetic Resonance

NMR probes are placed in the energy-defining magnets, B10-13 and B30-32, and in the reference magnets. (Two reference magnets B100 and B300 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 (Ref. 22) marginal oscillator, and offers no unusual design features. The probe itself consists of a quartz tube with a volume of 0.03cm^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: H^1 at 4.2577 Mc/kg and Li^7 at 0.23487 Mc/kg. This double resonance technique allows us to cover a wider field range without range switching in the electronics. No sweep coils are provided because the dimensions of the probe were made as small as possible (3/8 inch 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-cps 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 feet.

B. Remnant Field Measurement

Detection of the zero-current field in certain critical magnets (see Table VII) is accomplished by a gated magnetometer, or second-harmonic detector, placed in the flux to be measured. The small magnetic cores in the magnetometer are driven into saturation in alternate directions by a

TABLE VII

DATA ON REGULATION AND MAGNETIC MEASUREMENTS FOR BSY MAGNETS

Magnet (see Fig. 1)	Description	Regu- lation	Control	Measurement		
				Current †	Magnetic‡	
Central Beam						
1. Ap-1/Ap-4	Pulsed Steering	± 1.0%	M	Current trans- former and peak reading digital voltmeter	- (none)	
2. Ap-5	Vert. Pulsed Steering	± 1.0%	C(DAC)		- (none)	
3. B1/B2	DC Emergency 0.25°	± 0.1%	C(DAC)		Shunt, DVM	F, R
4. PM-1/PM-5	Pulsed 0.1°	± 0.1%	C(DAC)		Current trans- former and peak reading digital voltmeter	F, Gated Integrator
A-Beam						
5. A-16	DC Vert. Steering	± 0.2%	M		- (none)	
6. Q10/Q14	DC Quadrupoles	± 0.1%	C(DAC)	Shunt, DVM	F	
7. B10-B13	30 DC Deflection	± 0.01%	C(S.S)	Shunt, DVM	F, R, NMR	
8. B14-B17	DC Deflection	± 0.01%	C(S.S)	Shunt, DVM	F, R	
9. B-100	DC Ref. Magnet	± 0.01%	C(S.S)	Shunt, DVM	F, FC, NMR, R	
10. A10/A11	DC Steering	± 0.2%	M	Shunt, DVM	- (none)	
11. Q20/Q21	DC Quadrupoles	± 0.1%	C(DAC)	Shunt, DVM	F	
12. B28	Sweep Magnet	± 0.1%	C(DAC)	Shunt, DVM	R, F	
13. B23/B26	Dumping	± 2.5%	C(DAC)	Transducer, DVM	R, F	
14. B29	Sweep Magnet	± 0.1%	M	Shunt, DVM	R, F	
15. A400/A404	End Station Steering	± 0.2%	M	Shunt, DVM	- (none)	
16. Q400/Q404	End Station Quads	± 0.1%	C(DAC)	Shunt, DVM	F	
B-Beam						
17. A-36	DC Vert. Steering	± 0.2%	M	Shunt, DVM	- (none)	
18. Q30/34	DC Quadrupoles	± 0.2%	M[C(DAC)]*	Shunt, DVM	F	
19. B30/B32	3° Deflection	± 0.01%	M[C(S.S)]*	Shunt, DVM	F, R, NMR	
20. B33/35	3° Deflection	± 0.01%	M[C(S.S)]*	Shunt, DVM	F, R, NMR	
21. B-300	Ref. Magnet	± 0.01%	M[C(S.S)]*	Shunt, DVM	R, FC, NMR, F	
22. A30/31	DC Steering	± 0.2%	M	Shunt, DVM	- (none)	
23. B38	0.2° DC Deflection	± 0.1%	M	Shunt, DVM	- (none)	
24. P30*	Pulsed 0.2°	± 0.2%	M[C(DAC)]*	Current trans- former and peak digital volt - meter	R, F, with gated inte- grator	
25. B36	Magnetic Slit	± 0.1%	M[C(DAC)]*	Shunt, DVM	R, F	

TABLE VII - continued

Legend:

- * = not provided at this time.
- M = manual control of potentiometer with dc motor.
- C(DAC) = computer control via digital-to-analog converter.
- C(S.S) = computer control via slo-syn.
- F = flux loop and field integrator.
- R = remanent field probe.
- FC = flip coil $\int Bdl$ meas.
- † = computer measurement of current, where applicable, is identical to manual method shown.
- ‡ = the only computer measurements related to magnetic fields are:
 - (a) output of gated integrators on P1/P5 and P30.
 - (b) output of flip coil integrators on B100/B300.

The flip coil integrators are not read manually.

coil wound around them. A secondary coil picks up the gated signal, which is at the second harmonic of the driving frequency and proportional to the gated flux. This signal is processed by a high gain amplifier, a filter, and a synchronous detector. The output signal is displayed on a panel meter. The advantage of this system is that the magnetometer probe unit is entirely passive and therefore could be built more easily with radiation-resistant materials. Fields of about 0.05 gauss are easily detectable with 1000 feet of cable between the probe and the electronics.

C. Flux Loop Measurements

A simple integrator system has been provided to allow crude field measurements of the dc magnets. The purpose of the measurements is to allow detection remotely of possible shorts or other changes in the magnet coils. The field coils or flux loops consist of several turns of magnesium-oxide-insulated wire around the return yokes of the magnets. These coils can be connected by a selection switch to a stable dc integrator. The system is used as follows: The magnet is turned on to a measured current value and the integrator capacitor is reset. The magnet is then turned off, and the resulting output from the integrator is read by a digital voltmeter. The system measures magnet characteristics to better than 1%.

A special rotating flux coil is used in the reference magnets B100 and B300. This coil is rotated 180° in the gap of these magnets, and the integrated output voltage is connected to a voltage-to-frequency converter. Because the coil is made longer than the magnet and long enough to include most of the fringing fields, it measures $\int Bdl$ to better than 0.02%. Short term (1 hour) measurements typically show r.m.s. deviations of 5 parts in 10^5 . The rotating flux coil output is used by the computer to set the energy acceptance of the Beam Switchyard.

The stationary flux loops on the pulsed magnets PM-1 to PM-5 are used to integrate the magnetic field in these magnets every beam pulse (Fig. 42). The output is used not only to measure the field, but also to interlock the beam in the event of misfiring of the pulsed magnet modulator (see XII. E).

X. CONTROLS FOR MAGNETS, SLITS AND COLLIMATORS

A. Magnet Control and Readback

Control of the more than 50 magnets in the Beam Switchyard (see also Ref. 23) is accomplished by three distinct systems: (a) conventional manual control; (b) computer-assisted manual control; and (c) full computer control. The latter two systems are used in conjunction during normal circumstances. The first type of control is used when the computer system is inoperable for maintenance, and for those magnets over which the computer has no control (steering in all beams and, at the present time, the magnets along B-beam which are not yet equipped with digital-to-analog converters). A list of all the magnets in the Switchyard, showing the precision of control required and types of controls available, is given in Table VII. Figure 35 is a block diagram showing the three control systems for a typical magnet power supply.

1. Manual Control

All of the magnet power supplies have an internal reference voltage and a potentiometer to allow local control of the output current. It is by driving this potentiometer remotely with a motor that manual control is achieved. The mechanical details of mounting of the motor drive and the type of motor (dc or stepping) vary from supply to supply, but the controls themselves are uniform, consisting of a double action lever switch (non-locking) for increasing or decreasing the magnet current and a three-position toggle switch (center-off) to allow fast or slow motor speeds. Where dc motors are used, the speed is controlled by decreasing the duty cycle of a full voltage square wave applied to the motor. The slow speed position of the toggle switch allows adjustment of any magnet in steps of about 0.03%.

The operator can read the magnet currents on a digital voltmeter. The input to the voltmeter is switched by a relay scanner which is operated manually.

2. Computer-Assisted Control

Although the language of the computer programming system (see Section XI. C) is quite flexible, small adjustments and corrections to magnet settings are most easily obtained by an operator using lever switches or a potentiometer

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FIG. 35--MAGNET CONTROL SYSTEM

adjustment. To allow this type of control while the computer is operating, two manual control panels have been included in the computer system. The panels are identical and consist of 24 pushbuttons, one lever switch (two-position, non-locking), 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 interrupt signals are sent to the computer is determined by the "speed" control. Each interrupt causes the computer to inspect the pushbuttons and to increment or decrement the magnets selected depending upon the position of the lever switch.

It is possible to depress one to twenty-four pushbuttons at the same time. This feature is useful in adjusting a quadrupole pair or a group of magnets simultaneously and in the same proportion. The size of the increment (or decrement) is determined by an instruction typed on the console typewriter and may be different for each magnet (see Section XI. C.)

3. Computer Control

Full computer control is accomplished through the use of the 925 System program language on the typewriter, as described in Section XI. C. Only the electronic details will be described in this section. A magnet is controlled by providing the power supply with a stable reference voltage, adjustable by the computer. For most magnets, this voltage (10 volts) is produced by a highly stable ($\pm 0.01\%$ /24 hours) digital-to-analog converter, which operates by selecting resistors in a binary resistor ladder with mercury-wetted reed relays. The present system includes 18 such converters, with provisions to extend this number to 64.

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 8 three-meter-long magnets to deflect the beam 24 degrees in the analyzing system. These magnets are electrically connected in series, along with the reference magnet (which is placed in the control room building for measurement purposes). In order to insure accurate tracking of magnetic fields, the current in these magnets must be changed at a relatively slow rate, $3/4\%$ per second.

The digital-to-analog converters mentioned above inherently produce transients which far exceed this rate. Therefore, these magnets are

controlled by a reference voltage from a multi-turn helipot driven by a digital stepping motor. The mechanical nature of such a system precludes transients larger than about 0.003% in amplitude.

Readback of magnet current is accomplished by two methods. In the case of dc magnets, the currents are measured by shunts 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%. The operator can select the signal he wants to read out by typing an instruction (see XI. C) or by using the manual readback system described above.

The currents through the pulsed magnets are read through a solid-state differential multiplexer and a fast analog-to-digital converter. The signals in this channel are read with an accuracy of about 0.1%.

B. Slit/Collimator Position Control and Readback (Ref. 24, 25)

1. Control Requirements

The various slits and collimators used in the Switchyard are listed in Table VIII. The opening in these devices has to be controlled accurately from the control room. The slits and the collimators are enclosed in vacuum tanks. The movements 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. The motors, the magnetic clutches, and position readout devices are located in the upper tunnel of the Switchyard housing to minimize radiation damage.

There are two types of controls: One type controls the open-close position of the gap between the jaws inside the tanks, the other type controls the up-down or the left-right position of the slit or collimator tanks itself. The last control is necessary in order to extend the life of the 8-inch-high jaws by changing the beam interaction area. The jaws can be controlled at variable speeds, the tanks only at one speed.

The 16-foot-long jaws of the high power (2MW) collimator C-1 and high power slits SL-10/SL-30 require two independent drive mechanisms one at the front end and one at the rear end of the jaws. 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

TABLE VIII

DATA ON SLIT AND COLLIMATOR POSITION CONTROL

Name	Designation	Type	Speed	Number of Encoders	Number of Potentiometers	Number of Mechanical Counters	Travel of each Jaw (inches)	Readback Precision (inches)
High-Z Collimator		Hor. Vert.	slow/fast	2	2	2	3	0.0020
High-Z Slits	SL-11	Single	slow/fast	1	1	1	3	0.0029
	SL-31	Single	slow/fast					
High Power Slits	SL-10	Front Rear	slow/fast	2	2	2	3	0.0029
	SL-30	Front Rear	slow/fast	2	2	2	3	0.0029
High Power Coll.	C1-H	Front Rear	slow/fast	2	2	2	0.75	0.0007
	C1-V	Front Rear	slow/fast	2	2	2	0.75	0.0007
Photon Collimator	C-10	Hor. Vert.	slow/fast	2	2	2	3	0.0029
Photon Coll. (Tank)	C10(T)	up-down left-right	slow	2	2	2	3	0.0029
High Power Slits (Tank control)	SL-10(T)	up-down	slow	none	1	1	7	0.05
	SL-30(T)	up-down	slow	none	1	1	7	0.05
High Power Coll. (Tank control)	C1-H(T)	up-down	slow	none	1	1	7	0.05
	C1-V(T)	left-right	slow	none	1	1	7	0.05

of shaft encoders. In addition, potentiometers are provided to back up the encoders and to give a crude jaw position signal for readout in the accelerator control room. The position calibration of the shaft encoders and the potentiometers is obtained by mechanical counters connected to the drive shafts.

2. Control System Design

The position control and position readback system for the slits and collimators is shown in Fig. 36 and consists of the following units:

- (a) Slit and Collimator Position Controller
- (b) Shaft Encoder Multiplexer
- (c) Position Readout I and II
- (d) Position Feedback Multiplexer
- (e) Motor/Clutch Selector
- (f) Slit/Collimator Computer Control
- (g) Motor/Clutch ON/OFF Feedback

The central unit from an operations point of view is the Slit and Collimator Position Controller, the frontpanel of which is shown in Fig. 37. 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 (Section XI) samples the position of the slit or the collimator selected by the operator. In this mode the operator is not able to make another selection until the computer has had a chance to store the previous setting into its memory. In the computer control mode, the operator can select to 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 mode, if three minutes have elapsed since the last change was made by the operator.

FIG. 36 --CONTROL OF SLITS AND COLLIMATORS

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FIG. 37--Slit and collimator control panel.

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The Shaft Encoder Multiplexer contains 16 input channels and 2 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, 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 while six 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 Slits/Collimators Computer Control unit receives a control command directly from the computer. After it receives the command, the control word is decoded. First it selects the requested slit or collimator, then it waits for an acknowledge signal from the slit or collimator. If that signal returns, it proceeds to send the next control command to turn on a speed clutch; then it waits for an acknowledge signal from that speed clutch. If that signal returns, it proceeds to send a signal to turn on the motor. If the motor is turned on, the S/C computer control sends a signal to the computer indicating that everything is set, and that the computer can proceed to sample the position feedback multiplexer. No matter what signal the S/C computer control sends out, it always waits to receive a return acknowledged signal from the clutches or the motors. If no signal returns within one-half second, the S/C computer control will send a malfunction interrupt to the computer and the computer will in turn inform the operator by printing "S/C malfunction" on the typewriter.

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

XI. COMPUTER SYSTEM

A. General Description

The control computer system used in the Switchyard is designed to improve efficiency in beam operation and to allow greater flexibility and better stability in the requested beam parameters (Ref. 26, 27).

The computer is an SDS 925 machine with 24-bit parallel arithmetic and a 4096-word core memory with an access speed of $1.75 \mu\text{sec}$ (it is planned to expand the memory to 8000 words). The computer system performs at the time of this writing most of the functions described below:

- (1) Controls all magnets, slits, and collimators along the beam line, with the exception of some of the steering magnets;
- (2) Sets up, measures, and maintains the $\int B dl$ in the analyzing magnets (see Section IX C);
- (3) Produces upon command a set of punched cards which, when read into the computer at a later time, will reproduce the conditions existing at the time the cards were punched;
- (4) Monitors 1008 two-state interlock and status signals and prints a record of all changes in those signals with a resolution of $1/360$ second. The system can be expanded in the future to handle other desirable functions.

A block diagram of the computer system is shown in Fig. 38. The standard peripheral equipment purchased with the machine consists of a 10-cps teletypewriter, a 200-card/minute photoelectric card reader, and a 100-card/minute IBM 523 summary card punch. These are shown in Fig. 38 connected to the memory communication channel, and provide most of the operator - machine communication. Other peripheral devices have been designed for magnet control, slit/collimator control, and status monitoring; these are shown in Fig. 38 connected to the input connector of the 925 and have been described in some detail in Section X. The interlock and status signal scanner is described in Section B below. A link to a larger machine, the SDS 9300 in End Station A, is being built to allow closer communications between the experimenter and the Beam Switchyard. This link allows fully buffered transfer of instructions and data at a maximum rate of about 50×10^3 computer words per second.

FIG. 38--SWITCHYARD COMPUTER SYSTEM

B. Interlock and Status Signal Scanner

1. General

The function of the scanner is to read, every beam pulse (2.8 milliseconds), the 1008 two-state interlock and status signals originating in all areas of the Switchyard. The computer scans these signals, detects changes in them, identifies them, and prints the changes out on a printer. The time required by the computer for scanning, detecting, and identifying the signals is $320\ \mu\text{sec}$. Additional computer time is needed for printing if changes occur.

The scanner is essentially a digital multiplexing system controlled by the SDS-925 computer; It transfers the 1008 input signals to its output, 16 input signals at a time. Along with each group of 16 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.

The computer is capable, in principle, of effecting each transfer in one memory cycle ($1.75\ \mu\text{sec}$), but in practice the speed of the system is limited by wiring capacity and propagation time through the scanner circuitry. Thus scanner delays are adjusted to slow the transfer rate to one every two memory cycles, or $3.5\ \mu\text{sec}$.

2. Principle of Operation

A block diagram of the scanner is shown in Fig. 39 and the hardware in Fig. 40. The system consists of 1008 signal gates, arranged in 63 channels of 16 bits. The gates in one channel (word) to be enabled at any given time are controlled by the action of two elements: the 6-bit binary up-counter and the address decoders. When the computer is ready to begin the series of transfers, it sends a start signal (EOM), which resets the counter to zero. This action produces a signal at the output of the "O" address decoder, which enables the "O" group (first word) of gates, and starts the delay circuits mentioned above. The first delay allows the wiring capacity of the scanner to charge up. At the end of this delay ($1.6\ \mu\text{sec}$) the second delay begins, and a signal is produced which strobes the 16 data bits and the 6 address bits into a 22-bit register, where the parity is computed. During the second delay

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FIG.39--COMPUTER INTERLOCK-AND STATUS SIGNAL SCANNER

FIG. 40--Two state signal scanner.

(1 μ sec) the parity circuits are settled and at the end of the delay the ready signal ($\overline{Rt}$) is presented to the computer and the data (22 bits + parity) is accepted by the computer. The 925 then sends a next input signal, which increments the 6-bit counter by one, which in turn activates the "1" address decoder, enables the "1" group (second word) of gates, and the cycle begins again. This sequence of operations continues until the number of transfers required by the computer is completed. (The transfers are initiated by "Pin" signals; 63 pin signals are needed to read in all 1008 status signals, but this number can be reduced by the program if less than 1008 signals are connected to the scanner.) The computer then sends an operation complete ($\overline{RTi}$) signal, which resets the binary counter and disconnects the scanner from the input circuits of the computer.

Once the computer has gathered the data, it proceeds to analyze them. The computer is programmed to compare the old data (2.8 msec old) with the new data. It compares them word by word. If there is no difference between the two, it proceeds to compare to the next word. However, if there is a difference, the program starts to compare the two words bit by bit. If there is no difference in the first bit, the next bit is compared, until it finds the bit with the difference, and then records the word number and the bit number in the memory. The program also detects whether the change was from a normal state to an abnormal state (fault), or vice versa (normal). Once the computer has done the recording, it proceeds to compare the other bits until it has finished all bits in that word, then it proceeds to the next word. This process goes on until all 63 words are compared and the changes recorded. The analysis of interlock status data takes approximately 70 to 400 μ sec depending on whether or not errors are detected. There is a limit set to the number of changes the computer can detect and store every 2.8 msec; this limit is set to be 30 at the present time, but can be increased if desired.

The computer will print the changes stored in the memory out on a low priority basis. A coded format rather than English words was adopted for printout, mainly because of limited space in the core memory but also to

increase the printing speed. The printing format is as follows:

<u>GROUP</u>	<u>BIT</u>	<u>STATE</u>	<u>MIN</u>	<u>SEC</u>	<u>BEAM PULSE</u>
07	12	+	15	31	267

The group (63 groups) and bit numbers are in octal code (base 8 number system). The group number refers to a certain group of signals; the bit represents an individual interlock signal. The + sign indicates a change from fault to normal, the - sign a change from normal to fault. The time is printed to the nearest beam pulse with each interlock or status printout. The computer is also programmed to print out the date and the time every hour (or at any other interval requested in the program). This printing format reads:

<u>MONTH</u>	<u>DAY</u>	<u>HOURL</u>	<u>MIN</u>	
8	11	09	30	---

The three dashes at the end indicate that the date and time are printed, and not an interlock or a status signal.

C. Computer Program

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 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 IX.

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

Repeatable Instructions - clauses may be added

STEP <elt> BY <no.> ;
 STEP FLC ;
 CARDS ;
 OUTPUT <elt> ;
 OUTPUT BOX1 ;
 OUTPUT BOX2 ;
 RECORD <elt> ;
 SEND <string> ;
 TIME ;
 CLOCK ;
 DATE <string> ;

TABLE IX

LIST OF COMPUTER INSTRUCTIONS

Clauses

EVERY <time> }
 AT <time> } - time clauses
 UNTIL <time> }
 TO <destination> - destination clauses
 <label> : - label clause

'Once only' instructions - clauses are ignored

KILL <label> ;
 SET <elt> = <no.> ;
 TUNE <elt> = <no.> ;
 TUNE ALL = <no.> ;

<time> format examples

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

<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	Q10	Q21	ABEND	COV	C10V
PM2A	Q11	B23	FLC	C1H	T10H
PM3A	Q12	B1	SL10	C1HR	T10V
PM4A	Q13	B29	SL0R	C1V	SL30
PM5A	Q14	A400	SL11	C1VR	S30R
AP5	Q20	Q401	COH	C10H	SL31

In case of confusion, e.g., if two instructions appear before the semicolon, the computer takes the last one. If there is no meaningful instruction between semicolons, the computer types out

ERR

and the instruction should be repeated.

1. Repeatable Instructions

STEP <elt> BY <no> ;
(elt = element)	- causes specified magnet power supply to increase its current by the specified fraction of its present value.
STEP FLC ;	- starts the flip coil on a single flip, which takes about 10 seconds 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 '✓' (8-7 punch on cards).
OUTPUT <elt> ;	- causes current of specified magnet (or width of specified slit) to be packaged as output.
RECORD <elt> ;	- causes current 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.
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 specified time of day.

2. Clauses

Clauses may be added to the repeatable instructions to give them flexibility. The clauses that may be used in the program are given below.

Time Clauses

Each of the repeatable 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 time clauses. (They can appear, in any order, anywhere before the final semi-colon.)

EVERY <time>

AT <time>

UNTIL <time>

Destination Clause

TO <integer>

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

OUTPUT

RECORD

SEND

TIME

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

<u>Integer</u>	<u>Destination</u>
1	no destination (i. e. , ignore the output)
2	typewriter
3	card punch

For example,

AT (9:05:00 SEC) EVERY (30SEC) UNTIL (9:20:00SEC) STEP B1 BY . 10;

AT (9:05:20 SEC) EVERY (30SEC) UNTIL (9:20:20 SEC) OUTPUT B1 TO 3;

causes the current in B1 to be punched on cards every 30 seconds, but 20 seconds behind the execution time of the magnet current step instruction.

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.

For example,

LABL : EVERY (1 MIN) OUTPUT B1 ;

causes B1 current to be printed on the typewriter every minute indefinitely.

3. 'Once Only' 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. 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) $\leftarrow$ (1+(scale factor))(old current).

Examples:

KILL LABL ;	- kills the instruction given in examples in label clause section.
SET B1 = 4.5 ;	- sets the current in magnet B1 so that the design momentum of beam through the Switchyard is 4.5 GeV/c.
SET SL10 = 2.0 ;	- sets slit width of SL10 to 2cm.
TUNE ALL BY 0.01 ;	- loads scale factor of 1 percent for all elements connected to TUNE box.

4. List of Elements

The magnets, slits and collimators controlled by the computer at the present time are listed in Table LX. The location of this component (elements) is shown in Fig. 1. The name 'ABEND' in this list refers to the A-beam analyzing magnets B10 to B17 and B100 in series.

XII. EQUIPMENT PROTECTION IN THE SWITCHYARD

A. General

The average power of the electron beams in the Switchyard may eventually be as high as 2.2 megawatts. The handling of such beams is a delicate operation, and errors may easily result in thermal damage of vacuum components, magnets, instruments and other parts. In addition to the thermal damage, damage may be caused by excessive exposure to the radiation from the many beam-absorbing devices in the Switchyard.

A rather complex equipment protection system has been built in order to prevent such damage to the greatest possible extent. This protection system described in Ref. 29, consists of several protection collimators placed at carefully selected locations along the beams (Fig. 1) and various detectors that will immediately sense intolerable beam loss anywhere along the beam line. The protection collimators shadow groups of instruments, magnet coils and vacuum components from direct interaction with the beam and from stray radiation. A pair of ionization chambers hanging on the protection collimators (Fig. 41) produce a signal which is calibrated against the beam power absorbed in the collimator.

The detectors include a long ion chamber, (Ref. 30, 31), various individual ion chambers, thermometers placed at critical locations on the vacuum chamber and in all cooling water circuits, secondary emission foil signals, a pulsed magnet interlock circuit, and differential current interlock circuits. An out-of-limit signal from each of these devices will either shut off the beam or give warning to the operator. Details of the detecting devices are discussed in the following sections.

B. Ionization Chamber Interlocks

1. General

A few beam pulses at maximum beam power may damage a vacuum chamber or a protection collimator. Because thermal sensors are too slow to detect instantaneous local temperature changes, ionization chambers, which respond quickly to such changes, have been used. Ionization chambers have the advantage of being simple in construction, easy to make radiation resistant, and of operating physically independently of the equipment to be

FIG. 41--Protection collimator with ion chambers.

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. 41) consist of a number of parallel aluminum plates with 1/4-inch spacing connected alternately to a signal lead and a high voltage lead (300 volts). The welded stainless steel housing contains helium (or argon) 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. 41, the charge collected by the chamber is of the order of 10^{-10} coulomb per joule 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 shown in Fig. 41 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 section in the vacuum pipe. These coaxial chambers consist of lengths of "Andrews Heliax" 1-5/8 inch coaxial cable filled with helium (or argon). A positive high voltage is applied to the inner conductor, and the charge is collected from the inner conductor through a capacitor.

2. Gas Flow System (Ref. 32)

A gas flow system continuously delivers to the ionization chambers a small flow of gas slightly above atmospheric pressure. Argon was used for the initial beam run, but because of the too great sensitivity, the system will operate with helium in the future.

The gas is supplied by a double bank of 12 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 (see Section VI. C).

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.

3. Ionization Chamber Detector Circuits

The pulsed current produced in the ion 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; 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 stage. 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 20kW. The trip level at this power absorption level is reached in 100 milliseconds. When the protection collimator is hit by a beam carrying the full 2-megawatt beam power, the trip level will be reached about 100 times faster (1 millisecond), so that the beam will be switched off before the accelerator can send the next beam pulse (beam pulses are spaced at 2.7 milliseconds).

The output signals from the integrating circuits are terminated in a plug on the backside of each detector circuit. These signals will be connected to a patch panel for digital readout. This patch panel system is not ready at the present time, but a selected number of these signals were displayed on meters during the initial beam tests in June 1966. The signals are extremely useful for beam steering purposes.

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

Some of the ion chambers located near the collimators and dumps are not 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 they are associated.

C. Thermal Protection

1. General

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 (Rosemount 118G) 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/gram. The sensors are spot-welded to small copper pads which are mounted in many cases against the vacuum chambers with a bayonet fitting that allows easy replacement. In other cases the sensors are an integral part of the device, such as those on magnet chambers.

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 (Rosemount 104FB) is screwed into the well. These devices have basically the same element as the surface sensor, a 100-ohm platinum resistance wire, ceramic insulated, in this case 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 (Rosemount 104P). Because these are used as direct devices with no thermal wells, the electrical connections are made through fiberglass insulated cables.

2. Temperature Detector Circuits

The two basic temperature detector interlock circuits are an absolute circuit (measuring temperature at various locations on vacuum chambers, etc.) and a differential circuit (comparing inlet and outlet temperature 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 $2 \text{ mV}/^{\circ}\text{C}$. The bridge circuits are not yet compensated for the differences in cable length between the detector and the thermometers. Until this is done, the absolute accuracy is not better than about 5°C .

The trip circuit uses a commercial differential detector called "magsense meter monitor." 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 kilohms, 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. Among other things this facility may be useful in checking on the alignment of some of the relatively narrow passages in the vacuum chamber.

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 shut-off, but can also be started manually or on a programmed basis.

D. Secondary Emission Foil Signals

Most of the SEM foil devices described in Section VII are used for beam monitoring. Some of the foils, however, are provided for monitoring and protection, and a few are used for equipment protection only. The protection foils are SEM-11 in front of dump D-10 used to protect the side walls of this dump, and SEM-30 used to protect the low power jaws of slit SL-31 which will be used for relatively high beam currents until the high power slit SL-30 in the B-beam is installed at a later time.

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

E. Pulsed Magnet Interlock

A special interlock circuit has been built for the pulsed magnets. This circuit holds the beam pulse if the magnetic field has not reached the proper value shortly before beam injection. A block diagram of the circuit is shown in Fig. 42.

When the modulators for the pulsed magnets receive a trigger signal (approximately $416 \mu\text{sec}$ 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 $203\text{-}\mu\text{sec}$ delay circuit. Triggers are injected into the start circuit to prevent an output if the modulators fire too early or too late. The $203\text{-}\mu\text{sec}$ delay in turn actuates a gate generator, which produces a $10\text{-}\mu\text{sec}$ gate $213 \mu\text{secs}$ before beam time.

While the delay is in progress, the gated integrator is producing a signal which is proportional to the $\int Bdl$ 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-beam. 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.

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

540-33-B

FIG. 42 --PULSED MAGNET INTERLOCK

The defeat circuits shown in Fig. 42 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.

F. Differential Current Interlock

This circuit provides protection against unanticipated beam deflection errors and backs 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 will be operative at higher beam currents only; at low currents it will be switched off automatically.

Rather than using a signal from a second transformer, the circuit may operate with a signal from other reference sources, such as a dc signal or a signal from an ionization chamber.

G. Overall Beam Interlock Circuit

The Beam Switchyard interlock system (Ref. 33) protects the equipment in the Beam Switchyard and in the primary beams in the end stations against malfunctioning and damage by the beam. The interlock system is divided into groups, but in such a way that an interlock in one beam does not switch off the other two beams. Three of the groups are formed by the equipment in the A-beam, B-beam and the C-beam. The fourth group is formed by equipment in the area common to the three beams.

Before any beam pulse is injected into the accelerator, the interlock system has to send a "permissive pulse" to the injector gun. The permissive pulse circuit cannot be considered a foolproof interlock, because it actually only "holds" the beam if the permissive pulse is not generated; the klystrons still do accelerate any stray electron. The fast acting (50- μ sec) permissive pulse is therefore backed up by a slower interlock (response about 1 milli-second) which prevents acceleration (Ref. 34). In the common beam area a tone interrupt circuit is used for this purpose, while in the A-, B-, and

C-beams, relays are used to interrupt the accelerator trigger generator.

The permissive pulse generator is triggered for every beam pulse if proper conditions do exist. For example, let us examine in Fig. 43 the conditions required to send a beam pulse to End Station A: AND-Gate A_1 requests three O.K. signals. One signal comes from AND-Gate A_2 , which checks in the common beam area all signals coming from ion chambers, secondary emission foils, thermometers, differential current circuits, and various relays. These signals also feed into the slower back-up interlock circuit. The second signal for A_1 comes from a group of relays that require to interrupt only a few beam pulses and consequently do not feed into the backup interlock circuit. (An example is the microswitches that have to interrupt the beam for a few seconds while the Cerenkov cell is moved into the beam.) The third signal for A_1 comes from an OR-Gate O_1 , which requests an O.K. signal from either the A, B, or C-beam.

Now follow the gates for beam A. Gate A_9 demands a signal from the pulsed magnet circuit and from AND-Gate A_6 . Gate A_6 requests the presence of the A-beam pre-trigger pulse and checks via Gate A_3 in the A-beam and in End Station A the status of the signals coming from the various sources listed above for the common beam.

Most of the detector chassis contain 10 individual detector circuits. The signals of the 10 circuits are gated into one AND-Gate so that only one signal from each chassis is fed into the interlock summary and logic circuit.

The overall interlock chassis has a lamp display for the status in each group and a reset button for each beam. All individual signals are taken from the cross-connect frame and are shown on lamp panels. A fault status is indicated by an orange lamp.

In contrast to most industrial systems, where all detectors are latching, the changes of state in this interlock system are memorized by the computer interlock and status signal scanner which records all changes in a coded format (see Section XI B). The lamp indicators can be used in case of computer trouble.

In order to keep flexibility in the interlock system, all signal carrying wires have been routed via a cross-connect frame.

FIG. 43--OVERALL BEAM INTERLOCK DIAGRAM

XIII. BEAM SWITCHYARD CONTROL ROOM

The control room (Fig. 4) is equipped to operate the electron beams in the Switchyard and their extensions into the End Stations.

The 20- by 50-foot control room has a computer floor, with a 16-inch space under the removable tiles for cable distribution. The cables enter this space via a 3- by 3-foot underground cable duct or via cable drops along the walls from an overhead cable tray.

The floor plan of the electronic equipment racks is shown in Fig. 44. It was necessary to add racks outside the control room (numbers 40-51 and 70-73) to accommodate some back-up electronics and the equipment for interaction with the End Stations and accelerator control room. These racks can be relocated later in a planned expansion of the control room building which will provide more than double the rack floor space.

Racks 3 to 9 have been modified to serve as an operations console and contain the essential controls and all beam observation and beam analyzing equipment.

The computer control console, typewriter, and card reader are now separated from the operations console. A second typewriter on the operations console has been planned, which will operate in parallel to the first one. This will improve the integration of the conventional controls and the computer controls.

FIG. 44 SWITCHYARD CONTROL ROOM LAYOUT

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