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BEAM DIAGNOSTICS AND CONTROL FOR SLC*

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1. Introduction

Construction of the SLAC Linear Collider has posed some new problems in beam diagnostic device design. Typical beam sizes are small when compared with conventional storage rings, orbit tolerances are tighter and the pulsed nature of the machine means that signal to noise enhancement by averaging is not always possible. Thus the diagnostics must have high resolution, high absolute accuracy and must deliver data from a single pulse. In practice the required performance level depends on the function and dynamics of a given region in the collider.

For example, in the accelerator proper, performance may be limited by transverse phase space distortion due to wakefields. Since small (0.1 $\sigma_{x,y}$) launch fluctuations may cause unacceptable deterioration, the effects of these fluctuations must be monitored. This forces globally synchronized, parallel, read out schemes where data from each position sensor is received on a given pulse. In addition, in order to track down causes of pulse to pulse changes, device monitoring data from pulsed devices, such as klystrons, must be available for the given pulse.

Perhaps more challenging, the small dimensions of the beam ($\sigma_x, y \approx 0.1$ mm; $\sigma_z \approx 2$ mm) make accurate beam phase space measurements difficult. Since these parameters directly impact the luminosity, they must be carefully tuned. Online tuning is impossible due to the destructive nature of the devices used in making the measurements; high resolution phosphorescent screens (σ_x, y) and quartz Čerenkov radiators (σ_z). Measurements using the latter are especially cumbersome since they involve complex streak camera apparatus. No general, suitable, nondestructive beam size monitoring techniques have been found.

In this paper, we will review the major beam diagnostic systems and then discuss the global data acquisition schemes. Because space is limited each system will be described only in a very cursory fashion. More details may be found in the cited papers.

2. Beam Intensity

Beam intensity measurements are of primary concern in this extended transport line system since they can be used to find beam loss apertures. Interdevice calibration and absolute accuracy are therefore required to be within 1%. The intensity measurement system picks up beam current with a 50 KHz, 1 ms damping, resonant toroid circuit with a local preamplifier. Ferrite sizes range from about 1 inch inner diameter to 4in. The larger sizes of ferrite have faster damping times. A secondary winding is provided to allow injection of a known charge for calibration purposes. About 55 such devices are used throughout the SLC. Since the resonant period is long compared to the interbunch spacing these devices are not useful for multi-bunch, multi-flavor beams.

3. Beam Position

Beam position is detected almost exclusively with sets of four stripline electrodes. There are 1710 such electrode sets or one set every 5 m on average. The measurement errors that can be tolerated can be separated into two groups; resolution and absolute accuracy. Resolution refers specifically to the system noise, *i.e.*, the difference which would be observed when two successive measurements are made on identical beam pulses. Absolute error is the all encompassing error of the measurement when compared with ideal survey benchmarks.

The allowed errors are determined primarily from beam dynamics calculations. Limits on the resolution are derived from estimates of the allowed error on parameters which must be empirically adjusted such as the dispersion at the interaction point. The linac system is intended for use as a beam centering system primarily at relatively low beam currents ($5 \times 10^9 - 2 \times 10^{10}$). The arc tolerances are determined in part from estimates of the effects of improperly corrected orbits in the arc combined function magnets. In the final focus correction sections, performance limits are dictated by models of the intended optical correction procedures. Table I summarizes these limits.

Table I. Design Specifications for SLC BPM Systems.

Area	Electrode Diam. (inches)	Electrode Length (inches)	Dynamic Range (*no. e^-*)	Resolution (*midrange*)	Absolute Accuracy (*midrange*)
Injector	0.842	4.75	$5 \times 10^9 - 2.5 \times 10^{11}$	30 μm	100 μm
Damping Ring	1.057	1.094	$10^9 - 5 \times 10^{10}$	60 μm	200 μm
Linac	0.842	4.75	$5 \times 10^8 - 2.5 \times 10^{10}$	30 μm	100 μm
Positron Return	3.876	17.875	$10^9 - 5 \times 10^{10}$	250 μm	500 μm
Arc	0.56	1.78	$2 \times 10^9 - 10^{11}$	50 μm	100 μm
<u>Final Focus</u>					
Correction Section	1.73	5.9	$2 \times 10^9 - 10^{11}$	20 μm	50 μm
Interaction Region	1.87	48.62	$5 \times 10^9 - 5 \times 10^{10}$	20 μm	100 μm

Two beam position monitor (BPM) electronic systems have been developed, one for use in the linac, damping ring and $e+$ source and the other for use in the arcs. A third system is under development for use in the final focus interaction region. Since typical SLC bunches are very short, several millimeters at most, the signal produced at the connection to the vacuum chamber is a pair of very short ($\sigma_z c$), opposite polarity, high voltage (2 kV for 10^{10} particles), pulses. The dispersion and attenuation in the cable acts as a filter leaving the signal into the electronics a bipolar pulse with a length characteristic of the electrode length. In the signal processing electronics the signal is filtered further leaving a pulse with a characteristic time of 15 ns, the amplitude reduced to .1 V from the original 2 kV. This pulse is then amplified and the peak is digitized. The digitization time is determined by an internal trigger circuit. The use of the lowest practical frequency components facilitates the cable matching, both in timing (± .5 ns) and attenuation (.5%).

In the linac, where parallel read out is required, each set of electrodes is associated with a signal processing and digitizing CAMAC module. A gating signal is provided to each of these units from a programmable delay unit through a CAMAC upper backplane. The gate is a 67 ns long pulse stable in time with respect to the beam to ±1 ns. Its primary function is to select which bunch is to be digitized. In the full SLC operating mode, a positron bunch followed by two electron bunches appear in the accelerator, spaced by 59 ns. The gate is common to all ADC units in a given CAMAC crate thus requiring that the signal arrives at each unit at the same time. The cable sets are timed to within ±5 ns to achieve this. For about 2/3 of the linac, the positron return line position monitor signals are coupled into cables of some of the linac BPM's. The transit time through the source and down the return line make the time difference between the linac and return line signals from .5 μs to 13 μs.

In the arc, damping ring and positron target area, parallel read out is not required therefore a multiplexing scheme is used. A single width CAMAC unit has been built using PIN diodes which acts as a ten throw switch for these pulses. These devices have a 1 dB

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insertion loss and −50 dB cross channel coupling. Where they are used, the cable lengths from the electrodes are arranged so that the signal arrival times are staggered for different switch settings.

In the linac type electronics, hybrids are used to subtract the signals from opposing electrodes thus eliminating one channel; only three numbers are produced from which an x and a y posiiton are determined, two differences and a sum. Position is determined by dividing the pedestal subtracted difference data by the corresponding sum data. A calibration mode, in which the sum signal is directed into each of the three channels is used to compare the amplifier gains. A drawback of this procedure is that is requires real beam induced signals. However since it is a 'nulling' system, accurate knowledge of the beam displacement is not critical.

In the arc BPM system, this is more critical. The arc magnets pivot on one end as the other is positioned in x or y. The electrode set is mounted at the moving end in order to check its response.

To preserve low cross talk levels the high frequency components of the arc BPM system have been packaged in a separate, monolithic, machined aluminum package. This device delivers the filtered, amplified, waveforms, along with a sampling trigger, to the CAMAC based 12 bit ADC. Pairs of electrodes are summed making the BPM sensitive to either x or y. The signals are individually processed with the subtraction required for position information done in software. For calibration, a remotely controlled CAMAC pulse generator unit is used to inject pulses into the preamplifier. The pulse is evenly split and injected into the two parallel amplifier chains. Their gain ratios at a given digitizer attenuator setting are measured for three signal levels and fit to a line. Variations from flatness do not exceed 10^{-5} per ADC LSB.

The final focus interaction point BPM's serve as detectors of beam-beam deflection. As such they must have good resolution. In order to have good signal strength in a medium bandwidth and separate the the closely spaced (20 ns) incoming and outgoing beam pulses, the electrode set consists of four 1.3 m long round rods placed in an aluminum extrusion. Signal separation is achieved through the directionality of the electrode coupler (both ends are used) and by external gating from the timing system. The signals are integrated and sampled using a system similar to the arc system.

Figure 1 summarizes the resolution of the two BPM electronic systems over their dynamic range.

Electronic contributions to absolute accuracy include effects from mismatched cables, electronic multiplexers, passive adders and splitters. Mechanical contributions include effects from surveying and electrode calibration, used to determine the difference between the electrical and mechanical center of the assembly. This calibration is done by simulating the beam pulse and coupling it to the electrodes by sending it down a rod in the center of the BPM. Readings are made as the BPM is rotated in a fixture. Repeated measurements show the error in this procedure to be 25 μm. Cable tests are performed in a similar fashion,

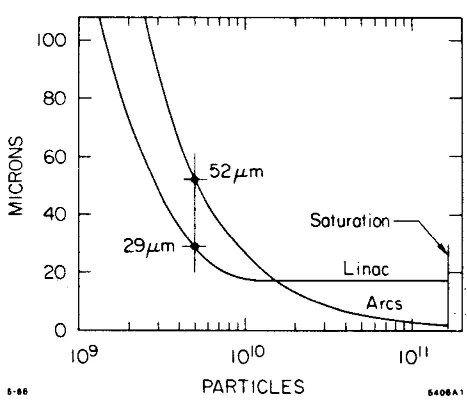

Fig. 1. Resolution for the two main BPM systems shown versus beam intensity.

putting a pulse through the cable and digitizing it with the standard electronics package. Errors from the cable tests contribute 10 μm to the overall absolute accuracy. Both mechanical and cable calibration data are compensated for in software.

4. Beam Profile

Phase space measurements are required both to check optics consistency and to estimate the emittance and bunch length. Eighty two profile monitors, equipped with television cameras, controllable iris (or filter wheel) and controlled illumination are used from the 50 MeV point to the beam dump. Table II summarizes some of the key units and their primary function.

Table II. Important SLC beam profile monitors and associated beam sizes.

Use	Region		Beam Size $\eta\,\Delta E/E$ (fullwidth)	Beam Size $\sigma_{x,y}$
Energy Spread Monitor				
	Injector	250 MeV	1 cm	
	Injector	1.2 GeV	5 mm	
	Linac–Arc	50 GeV	0.5 mm	
Emittance Measurement				
	Damping Ring Exit			200 μm
	Linac	50 GeV		70 μm
	Arc Rev. Bend			50 μm
	Final Focus			50 μm

Since the beam shape may become distorted, a full television image is very useful. A series of 8 units have been constructed for monitoring beam 'tail' growth and installed near the end of the linac. A pulsed magnet will direct selected pulses onto the screens which are slightly off axis. A flash digitizer circuit is used to compress the data by finding the peak amplitude of each horizontal line. Data from these devices are used to correct wakefield tail growth by controlling the initial linac launch.

Video from each profile monitor can be recorded and processed. A CAMAC based partial 'frame grabber' system allows flexible digitization of a portion of the image. A maximum number of 4 K 8 bit data points may be encoded at a minimum spacing of 512/picture width by 256/picture height. Limits on the performance of these devices arise when the beam is about the same size as the phosphor grains (5 μm). Resolution limits also arise from the camera tube and optics.

Accurate, nondestructive, beam size measurements on beams of this size are sometimes not possible. They are most useful for estimate of energy spread, in places where the beam aspect ratio is expected to be large and a projection is as useful as a full image. Two systems have been developed for this purpose. The first uses the quadrupole moment information available from the position monitor electrodes. If the four electrode signals are represented T, N, B, S then

$$\sigma_x^2 - \sigma_y^2 + x^2 - y^2 \propto \frac{(N+S)-(T+B)}{N+S+T+B}$$

Since the signal gives the square of the beam size, the resolution is degraded. The resolution expected for a 1 in BPM is about .3 mm in beam size, assuming the vertical beam size to be negligible. This system has been implemented using discrete hybrid packages to add and subtract the signals, standard linac type electronics is used for digitization.

The other nonintercepting beam width monitors used are synchrotron light monitors. These are used in both damping rings and in the linac to arc transition area. In the latter case, a vertical three pole wiggler is used to project synchrotron X-rays through a tungsten converter onto a fine grained phosphor screen. A set of horizontal lines from the camera viewing the image are processed by an analog adder which compresses them onto one line in order to enhance the signal. The data from this system are used to determine pulse to pulse energy spread corrections through a feedback computer.

In the final focus as well as the reverse bend region of the arcs, it is not possible to get a good estimate of the beam size with a phosphor screen. In these areas a prototype wire scanner system is being tested with a 7 μm carbon wire. Tests with a larger wire and a more diffuse beam have shown an adequate secondary emission signal.

5. Special Systems

Several special beam monitor systems are worthy of mention. The damping ring tune must be monitored remotely and since a new beam pulse is injected and extracted at the collider repetition rate a simple exciter/pickup system is not useful. The front end arc BPM system pre-amplifier is used to process the signal from a stripline monitor in a low dispersion region. An 'x' and 'y' signal are derived and digitized by a pair of 20 MHz transient recorders. When the recorder is started at injection time these signals show clear coherent oscillations and damping. The signal is best when the injected and stored orbit are substantially different.The data from the recorder are read into the main console computer for FFT processing.

Perhaps more innovative are the beamstrahlung monitor and the beam energy monitor. The beamstrahlung monitor functions somewhat as a luminosity monitor. A set of five photomultipliers are used on either side of the interaction point to generate an image projection of the photons emitted from one beam as it interacts with the other. The raw signals are digitized and processed in a dedicated microcomputer for mean, integral, and width. These results are available for the control system and are also displayed on a dedicated video monitor.

The energy monitor is not so much a beam diagnostic as it is an extension of the users apparatus. It's purpose is to provide a beam energy determination accurate to 0.01%. The proposed technique is to use a pair of three pole wigglers separated by a very accurately calibrated bend magnet just upstream of the beam dump. The synchrotron light produced in the wigglers is converted and directed on a phosphor screen with carefully placed markings. The space between the synchrotron light strips will be used to determine the energy.

6. Data Acquisition

There are three basic uses to which the data from these devices are put: 1) data processing by the central control system processors for automatic trajectory correction, stability checks or experiments, 2) input to beam feedback systems or 3) input to simple, rapidly updating, displays for use in tuning and monitoring. Each of these uses is facilitated by data paths whose design emphasizes the data buffer size/data rate tradeoffs important for those goals.

The global synchronization mentioned above is facilitated through a master pattern source that produces a 16 bit label at 360 Hz, *i.e.*, for each possible machine pulse. This code is split in two parts, 8 bits identify the user of the beam pulse and another 8 bits signifying that special action is to be taken, *e.g.*, acquire beam related data for this pulse. The code is distributed on a dedicated channel of the SLC broad-band communications cable to the remote computing nodes which in turn broadcast the code to their respective CAMAC systems and perform further special action if required. Selected CAMAC units are sensitive to this repetitive programming; most notably those controlling trigger pulses and those controlling klystrons.

The signal processing electronics is prepared for the upcoming measurement approximately 5 ms before beam time and is read out shortly after the beam pulse. The data is then corrected in the local micro computer and then reported back to the central system processor. This relatively simple system becomes substantially more complex when interleaved readings are requested. For position monitor data, users may use different attenuation and particle charge requiring the micro computer to keep indexed tables of conversion constants sorted on a per user basis. Figure 2 shows the display of the beam trajectory from the exit of the damping ring to the entrance of the final focus.

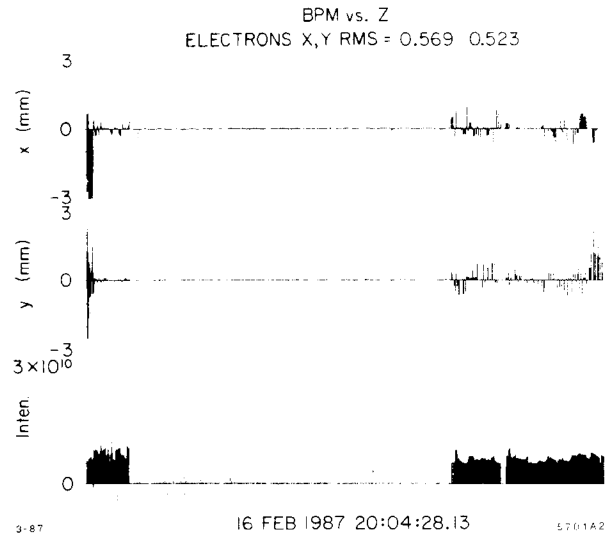

Fig. 2. Beam position and intensity online display. X, Y and intensity (derived from the sum of the electrode signals) are shown versus Z The damping ring to linac transport line is as the far left and the plot goes through the linac and another arc to the entrance of the final focus. No attempt is made to normalize the intensity readings.

In this complex machine chain, a simple, rapidly updating beam intensity display is needed to allow a quick asessment of the overall machine performance. The data displayed need not be very accurate and it is not needed from every monitor. In the full- blown operating mode, seven distinct bunches of electrons/positrons are present in the machine. It is not possible to acquire data from one machine pulse through a given signal processor, rather the bunches are selected by trigger timing.

The intensity display operates as a background process, using its own datalink rather than the SLC broadband cable. On those pulses for which no data is to be acquired for a specific use, a default code is broadcast which triggers the data processing path of the display system. Figure 3 shows the format of the display. The data are collected from the raw position monitor and beam intensity monitors, processed by the remote nodes and transmitted along a dedicated base band channel, in time multiplexed fashion to the display generating host. The update rate depends on the beam rate, but is about 1 Hz minimum.

The operator thus has at the console the ability to acquire data for the purposes of making simple experiments and the use

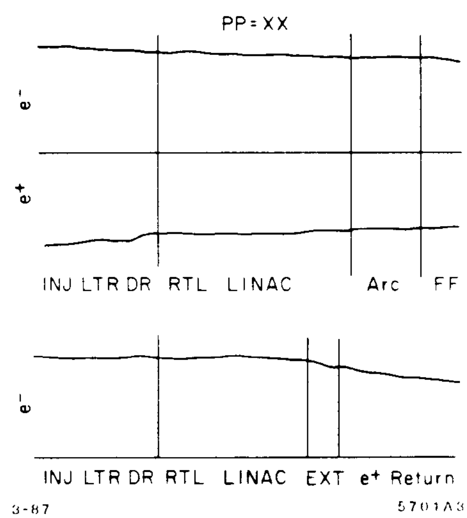

Fig. 3. Online, rapidly updating beam intensity display. The two bunches destined for collision are shown on arc top right. At the bottom right, the 'scavenger' electrons and return line positions are shown. On the left the electrons from the gun and the positions in the first linac sector are shown.

of a rapidly updating machine status display. However, in order to diagnose problems and for initial tune up, as well as for general monitoring, high bandwidth, full repetition rate signal displays are also needed. This is accomplished with remotely controlled oscilloscopes viewed by television cameras. All features of the oscillosope are remotely controlled and commercial high band width signal switches are used to multiplex signals from many different sources. The television signals are propagated to the console on the broad band cable.

Feedback systems may require special data acquisition protocols if the speed at which they are to operate is greater than that which can be reasonably serviced by a central processor. Any feedback loop requiring pulse to pulse data gathering and device control must have its own channels. This has been accomplished by establishing, for each of these loops, separate remote computing node, with signal processing and control hardware directly accessible. Examples of such loops are 1) energy and energy spread and 2) interaction point centering control loops.

These loops must average the last n pulses and determine the required correction accordingly. In order to improve their gain and protect them from erroneous data, other components of the control system, notably those controlling klystrons, must be able to tag a given pulse as bad and present this information to the feedback processor after minimum delay. A 'veto' system has been built for this purpose, using a dedicated base band communications channel, similar to the one used for the comfort display described above. Its inputs are the klystron controllers and the machine protection systems. In addition to warning the feedback systems of bad pulses, it also warns any remote node currently averaging data for transmission back to the central processors.

Acknowledgments

Many people from a wide range of disciplines have made significant contributions to this large system. The most important ones are listed as authors in the references below. Special thanks should go to the technical staff of the instrumentation and controls group of the electronics department.

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