SLAC–PUB–5521
March 1991
(A)

-SURVEY OF BEAM INSTRUMENTATION USED IN SLC*

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ABSTRACT

A survey of beam instruments used at SLAC in the SLC machine is presented. The basic utility and operation of each device is briefly described.

The various beam instruments [1] used at the Stanford Linear Collider (SLC), [2,3] can be classified by the function they perform. Beam intensity, position and size are typical of the parameters of beam which are measured. Each type of parameter is important for adjusting or tuning the machine in order to achieve optimum performance.

BEAM INTENSITY

Beam Intensity is measured at SLC to about 1% accuracy using toroid transformer pickups at a ceramic gap in the metal beam pipe. Most of the toroids are made as part of a resonate LC circuit with a local preamplifier to give good sensitivity to beam charge. A sample and hold circuit is gated on the desired machine pulse and the charge read out via a custom CAMAC module. The closely spaced bunches in the SLC are not resolved in time and the readout gives the difference between positron and electron bunches. For that reason, the toroids are used mostly where or when only one beam pulse is present.

Another device commonly used is a gap pickup. This monitor sends a part of the wall image current down a cable to an oscilloscope or to a charge integrator. The connection and back termination of the cable to the vacuum pipe is critical to get a clean signal with an accurate representation of the beam. Gap monitors are used mostly at the electron injector [4] where the beam pulse length is long, on the order of several nanoseconds.

BEAM LOSS MONITORS

Beam losses are monitored at SLC in order to optimize transmission and to give warnings of levels of beam loss which could cause damage to equipment. With beam sizes as small as 100 μ, and intensities of 5×10^{10} particles, the possibility for melting or cracking of machine components is severe.

Liter-sized gas ion chambers are most commonly used to protect equipment. They are spatially located outside the beam pipe and near the device to be protected, typically a collimator, beam dump [5,6] or septum magnet. The integrated or average signal is read out to the control computer. Threshold levels are set in hardware to turn off or reduce the repetition rate of the machine automatically. Calibration is

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* Work supported by Department of Energy contract DE–AC03–76SF00515.

Presented at the Workshop on Advanced Beam Instrumentation (ABI) KEK,
Isukuba, Japan, April 22–24, 1991

made by running a known but safe beam power and intercepting it in the device being protected. The chambers are usually filled and flushed with He gas. In locations where high sensitivity is desired such as in the Final Focus, [7] Argon gas is used. There the readout is calibrated in terms of radiation dose, (R/hr) to give a quantitative measure of losses. This monitoring is used extensively to avoid backgrounds in the interaction point detector.

For a long time, the SLAC LINAC has used a long cable as an ion chamber to record the distributed losses along its 3 km length. With the construction of SLC, and additional beam transports, many additional systems [8,9] have been added. Nitrogen gas is used to fill a gas dielectric cable whose center conductor is biased at several hundred volts. When a loss occurs, signals propagate in each direction down the cable. The temporal distribution readout from the up beam end gives the spatial distribution of losses along the cable. (For convenience, usually the down beam end of the cable is viewed in the control room and the up beam end AC shorted through a capacitor to reflect the signal.) For machine protection from losses, hardware thresholds are used to cause turn off and/or cause reduced repetition rate operation of the machine.

BEAM POSITION MONITORS

For the SLC machine, measurement and control of the beam position is the most important beam control function. Not only is position control needed to efficiently transport beams without loss, it is essential to avoid beam induced wake fields in the accelerator disk loaded wave guide. The wake fields act back on the beam and cause phase space correlations and distortion which effectively results in enlargement of the beam emittance. This results in larger beam spots and beam divergence in the final focus and hence reduced luminosity and possibly increased detector back grounds. Beam position measurements also perform a vital role in a number of diagnostic checks of the machine such as checking quadrupole focusing strengths and alignment. [10-16]

The beam position monitors (BPM) at SLC [17] are strip lines inside the beam vacuum pipe, coupled out to 50 ohm cables with vacuum coax SMA connections. The strips vary in length from a few centimeters in the Damping Ring to over 40 cm in the Positron Return Line system. Most locations incorporate 4 strips for horizontal and vertical position; some use only 2 strips in case only one dimension is needed. The strips are sometimes rotated 45 degrees to avoid their being hit by synchrotron radiation. The BPM's are located along the beam line at least every 90 degrees in betatron phase to provide adequate determination of the beam trajectory. In the LINAC there are over 270 4-strip monitors.

The signals from four strips are read out with a CAMAC module. Hybrids in the module subtract signals from opposing strips and a sample/hold and digitizer provide difference amplitude read back. A sum signal is used for self gating of the module, and is also digitized for normalization of the difference signal. A gate from the control timing system also gates the signal. In the LINAC electron and positron beams are separated by 60 ns; either beam can be read out independent of the other. Multiplexing of signals is done in most of the systems to reduce module cost. However, the LINAC system is not multiplexed so the full trajectory can be obtained in a single beam pulse. This is useful when searching for the cause of pulse-to-pulse beam jitter.

For the LINAC BPM's which have a radius of 12 mm, typical accuracy is 100 μ; the precision and short term reproducibility is about 25 μ.

BEAM PROFILE MONITORS

Beam size monitoring is important for SLC in order to know the emittance of the beam. Several monitor devices are used. The emittance [18,19] is measured with three or more successive screens separated by known beam transport elements, or by a single screen and taking data scanning a focusing quadrupole up-beam. In addition to transverse beam emittance, the energy spread is measured at locations where the dispersive size of the beam dominates the beam profile.

Until recently, the most common beam profile monitor at SLAC [21] utilized a fluorescent screen optically coupled to a commercial TV camera. There are advantages and disadvantages to this type of monitor. On the plus side, it is a relatively simple device with inexpensive readout and display hardware available. Digitizers are even commercially available for analysis. At SLC a CAMAC synchronization and timing module coupled to a CAMAC digitizer is used to input a video frame into the computer. There curve fitting and emittance calculations are done. Some of the disadvantages found with this type of monitor are sensitivity to radiation damage of the screen, camera and optics, and the disturbance of the beam down-beam of the screen. These disadvantages have led to modifications to the video system and to the development Wire Scan monitors for use at SLC.

Near the end of the LINAC where beam profile monitoring is most important, a new system has been installed which samples a beam pulse every second. This is done with pulsed magnets which deflect a single beam pulse onto a fluorescent screen. To avoid radiation damage to the video camera it is located outside the radiation shielding and the light is transmitted to it with lenses and mirrors. A video frame grabber is used to store the picture for view. Intensity is digitized and a false-color representation supplied to the control room operators. Eight screens are used to obtain good resolution in each transverse plane for both particles (electrons and positrons) at two locations along the beam line approximately 90 degrees apart in betatron phase advance.

The Wire Scan monitor is a relatively simple device conceptually. A thin wire is moved through the beam and its interaction with the beam detected. This is basically a sampling technic extending over a number of beam pulses. It is therefore subject to error if the beam is not stable. In the SLC design the wire is attached to a fork which is driven in the beam vacuum using a bellows, a linear stage and a stepping motor drive. The motion is calibrated with a linear variable displacement transformer (LVDT) readout and stepping motor counts are used to determine the location at each beam passing. The fork usually holds three wires at relative angles of 0, 45, and 90 degrees in order to obtain horizontal, vertical and skew projections of the transverse beam profile. Some care was necessary to avoid vibration of the wire caused by the discrete stepping of the motor. A set of high resolution wires have been used at the final focus [24,25] to determine beam sizes down to 2 μ. In that application, the beam is scanned across the wire with magnets rather than moving the wire.

Several methods have been used to detect the interaction of the beam with the wire. Secondary emission from the wire has been used, but for most applications at SLAC, the field of the beam is so great that it presents a noise signal which adversely affects the accuracy of the measurement. Instead, a scintillator seen by a photomultiplier tube has been successfully used to detect the beam wire scattering. Considerable care is required to obtain a linear response in this case so as not to bias the size measurement. An ion chamber has also been used successfully to detect the beam-wire interactions. Because each beam, spaced apart by only 60 ns, must be measured, a small drift fast ion chamber was developed. The readout is from a gated ADC CAMAC module.

At present 21 wire scanners are installed in SLC with another 9 or more being planned for future installation. During colliding beam operation emittances are measured in several locations every 15 minutes. This can be done while the experiment continues data collection.

Synchrotron radiation is used to monitor beam size in each of the SLC damping rings and the energy spectrum at the end of the LINAC. The light from the damping rings is simply imaged on to a video camera and viewed in the control room. It is commonly used to note the relative horizontal to vertical beam size and determine if the ring horizontal and vertical tunes are coupled as desired. The energy monitor at the end of the LINAC [22,23] has the feature of not disturbing the beam and provides continous monitoring of the energy spectrum. Synchrotron radiation is made by vertical bend magnets in a chicane geometry. Down-beam, after an horizontal bend magnet has deflected the electron beam out of the path of the synchrotron x-rays, a phosphor is located and viewed by a video camera. This device is used extensively to fine tune the LINAC RF phase, thereby controlling the energy spread of each beam.

A variant of the strip line beam position monitor has been utilized to measure a coarse resolution beam profile in the case of a beam much bigger in one dimension than the other. The vacuum chamber in this case is rectangular with a 6 to 1 aspect ratio. A series of 6 strips along the long sides of the chamber give a coarse measure of the beam profile. The read out in this device is split into the usual BPM module for position information and to a system of combiners and delays which provide a real time scope picture.

BEAM–BEAM SCAN

The ultimate beam size monitor for SLC is the head-on collision of the 47 GeV electron beam with the 47 GeV positron beam. While the rate of events gives a measure of the average beam size a faster method is needed to tune the parameters of the machine. This is accomplished by scanning the transverse position of one beam and measuring with sensitive BPMs the deflection of the other on a series of beam pulses [26-28]. When the beams are far apart, little deflection occurs. As the scan brings the beams close to collision, the electromagnetic fields seen by each beam due to the other increase to a maximum. When the beams collide head-on, the net coherent force averages to zero for the beam and no deflection is detected on the BPMs. As the beam is scanned across the range of interaction, an S-shaped curve is obtained. Fitting the curve determines the quadrature sum of the electron and positron beams sizes. Nearly all the tuning of the the SLC Final Focus system relies on this technique.

When the SLC beams collide, particles are accelerated sufficiently by the electromagnetic field of the oncoming beam to radiate photons of high energy in the range of

10 to 20 MeV. These photons are detected in a Cerenkov counter behind a lead converter [30-35]. The detector is located after a bend magnet so the direct beam is not intercepted. Synchrotron radiation from the bend magnet could present a background signal. The threshold of Cerenkov detector is high enough to avoid this background.

LONGITUDINAL BUNCH LENGTH

The longitudinal phase space of the SLC beams typically occupy a 0.5% in energy and 1 to 1.5 mm longitudinally. Often there are considerable correlations between energy and distance along the beam path. The bunch length is manipulated in the transport lines from the damping rings to the LINAC, reducing it from 6 mm to about 1 mm. In the positron system the energy spread of the beam is reduced in the transport to the damping ring [36], essentially to match the longitudinal beam phase space to the ring acceptance. Control of bunch length is also of interest in the electron injector where a 600 mm bunch is reduced to several mm with three RF systems and in the positron system where a beam is collected with a spread in velocities. In a LINAC [37,38] a bunch which is too long will result in an enlarged energy spread downstream. Monitoring the bunch length is important because it allows tuning the smaller portions of the system.

A beam pickup RF cavity which resonates at 9 GHz is used in the positron and injector systems to obtain a signal dependent on the beams bunch length. When a single beam passes through the cavity it excites the cavity and causes it to resonate more or less depending on the frequency components present in the beam pulse. For a given charge the cavity will be excited to a greater amplitude if the pulse is short (high frequency components) than if it is long. The resonate frequency was chosen for sensitivity to beam pulse lengths around 5 mm. The cavity is coupled to a rectangular wave guide to transmit the signal out of the radiation area. The signal is passed through a filter and variable attenuator and then is detected in a crystal. The output of the crystal is viewed on an oscilloscope and digitized for monitoring by the control computer. The Q of the cavity is low in order to couple out a large signal in a short time allowing pulses 60 ns apart to be separately resolved. This device can be calibrated if care is taken in the linearity of the detector and normalization to total charge. In practice at SLC, it has been most useful as an empirical tuning aid giving a signal which increases with intensity and decreased bunch length.

At several locations in the electron source, the positron source [39] and in the early part of the LINAC, Cherenkov radiation from a thin plate of quartz was used with a streak camera to determine the bunch length of the beam. The resolution of the camera was about 2 ps, although verification of that was difficult to confirm in actual measurements. The camera was located several tens of meters from the radiator so it could be located out of the radiation area. The optical light was transmitted with an array of lenses. Results from this technique were useful during the early commissioning of the machine when tuning a localized portion of SLC was necessary.

ACKNOWLEDGEMENTS

The detectors mentioned in this report are the work of a large number of people. The reader is directed to the references for additional information and appropriate credits.

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