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Design and Performance of the Beam Loss Monitor System for the Advanced Photon Source*

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Abstract

The design of the beam loss monitor system for the Argonne National Laboratory Advanced Photon Source is based on using a number of air dielectric coaxial cables as long ionization chambers. The coaxial cables are multiplexed into a high sensitivity DC current-to-voltage converter, which provides an output proportional to the average loss rate over the length of the multiplexed cable. Losses of sufficient amplitude generate measurable voltage pulses on the coaxial cable at a location near the loss point. Multiplexed pulse timing circuits determine the location of the losses by measuring the time at which these voltage pulses arrive at the beginning of the coaxial cable. The loss monitor system has been tested on the SPEAR accelerator at SSRL and was demonstrated to be as sensitive as the DCCT. Preliminary performance data from the APS injector show that the sensitivities of the current-to-voltage converter circuit are about ten picoamperes of loss monitor signal per picocoulomb per second beam loss rate. The corresponding pulse sensitivity is about 28 μV pulse amplitude in the coaxial cable per picocoulomb of loss. Both these sensitivities are at 300-MeV beam energies. The loss monitor has proven useful in initial commissioning of the injector. Further data will be available as accelerator construction and commissioning continue.

INTRODUCTION

Knowledge of beam loss rates and the approximate location of beam losses has been found to be an important diagnostic tool during commissioning and operation of many accelerator systems. This information is used to determine the cause of catastrophic beam loss events and to improve beam steering and control. The Advanced Photon Source (APS) system designers anticipated that such information would be critical during the initial commissioning and optimization of the APS accelerator(1). Therefore, the APS loss monitor system was designed to provide relative measurements of loss rates and an indication of the location of loss events throughout the accelerator. Large losses can be located more precisely than small losses. The system has no personnel safety function, but was found to be an economical method of providing data on potential radiation hot spots, especially in the rf/extraction building.

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SYSTEM DESIGN

The APS loss monitor system is similar in many ways to loss monitor systems in use at Brookhaven(2,3,4,5) and SLAC(6,7,8), and has been described in more detail earlier(9). The system is based on a 7/8-inch air dielectric coaxial cable used as an ionization chamber. Five hundred volts DC is applied to the center conductor of the cable. The cable shield is grounded. An ionization gas consisting of a mixture of 95% argon and 5% carbon dioxide at 8 psig is passed through the cable. The average current flowing through the ionization gas is measured. This average current is proportional to the average beam loss rate along the cable. The cable is laid parallel and as close as feasible to the vacuum chamber (subject to mechanical constraints) to maximize the system sensitivity.

When accelerator conditions generate a large, localized beam loss, a correspondingly large, localized ionization is produced in the coaxial cable ionization chamber. The position of the ions in the coaxial cable and, therefore, the location of the beam loss is determined by measuring the time between the arrival of a beam bunch at the beginning of a coaxial cable ionization chamber and the arrival of the resulting voltage pulse at the same end of the cable.

Up to seven coaxial cable ionization chambers are multiplexed into a single electronics package. The package is shown in block diagram form in Fig. 1. The DC-coupled current-to-voltage amplifier and input multiplexor are floating on the output of the 500-V power supply. This is necessary so that the high voltage can be applied to the cable center conductor rather than to the outer shield, which could be perceived as a personnel safety hazard. The current-to-

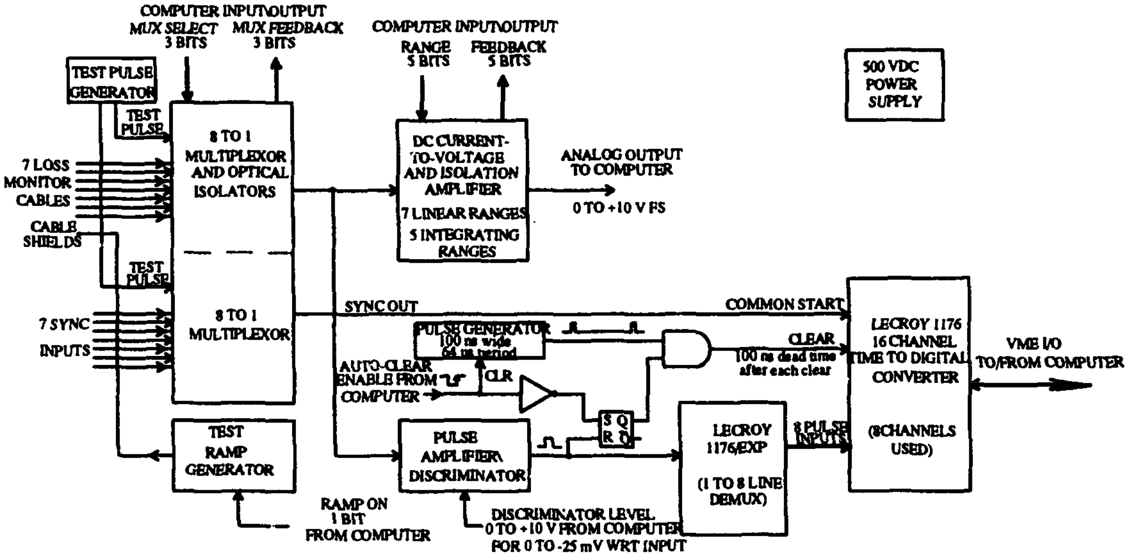


Figure 1: Block Diagram of the APS Loss Monitor System

voltage amplifier consists of a field-effect transistor input (low leakage) operational amplifier with seven linear feedback ranges and five integrating feedback ranges, plus one integration reset range (see Fig. 2). These ranges are selected by low leakage reed relays. With careful design and layout, including the use of Teflon printed circuit board materials, input currents as low as 10 pA are easily measured. The linear ranges are well suited for operating conditions and locations where particle bunches repeatedly pass the coaxial ionization chamber with a repetition frequency of 60 Hz or higher. Under these conditions the time-averaged ionization current is continuously available at the output of the beam loss monitor in the form of a DC voltage.

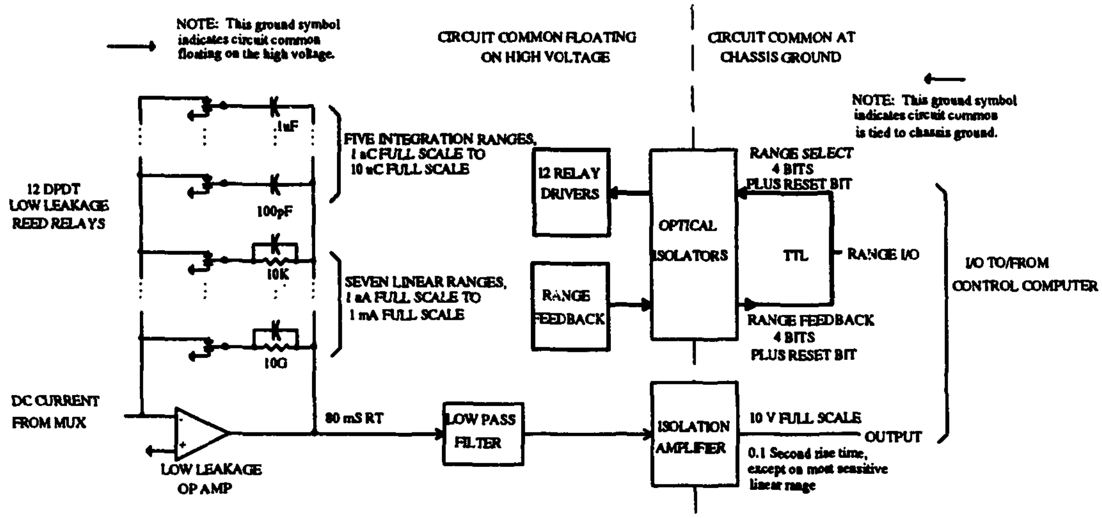


Figure 2: DC Coupled Current-to-Voltage Converter

Other accelerator subsystems, such as the transport line from the positron accumulator ring to the synchrotron, normally experience repetitive particle bunches at a 2-Hz rate. If the linear ranges were used for these subsystems, the resulting output signal would be a pulse that the control system would have to rapidly sample and integrate or peak detect to obtain a signal proportional to the beam loss rate. To simplify the measurement under such conditions, five integrating ranges have been added to the DC-coupled current amplifier. The 1-mA linear range is also used as an integration reset range to discharge the selected integration capacitor.

The amplifier/discriminator circuit contains the high frequency pulse amplifier and discriminator needed to convert the low amplitude pulses from the coaxial ionization chamber into the logic level signals required by the time-to-digital converter. Since only the fast-rising edges of signal pulses are of interest, these circuits include components that implement high-pass filters to reduce response to slower noise signals. The discriminator threshold voltage is set by the control computer.

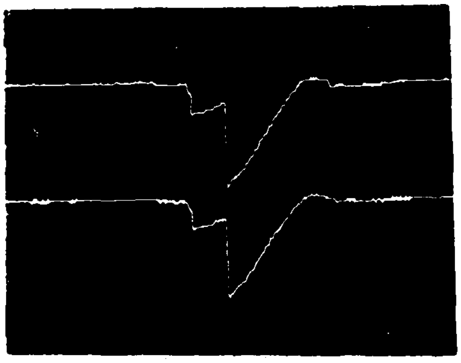
Pulse timing nominally begins when a particle bunch passes one end of the coaxial ionization chamber, generating a timing synchronization signal. The required reference signal is derived from the nearest convenient beam position monitor. During the timing interval the times of arrival of all pulses on the coaxial ionization chamber are recorded. Each pulse represents a localized beam loss at a position easily calculated from the recorded time interval. Four cables are used in the synchrotron and twenty cables without pulse timing are used in the storage ring to avoid potential pulse timing ambiguities caused by the existence of multiple particle bunches.

TEST RESULTS

Tests of the loss monitor concept were conducted in the SPEAR accelerator at the Stanford Synchrotron Radiation Laboratory (SSRL) in February 1993. Three loss monitor cables were installed parallel to the vacuum chamber beginning at the storage ring injection point and running downstream for 100 feet. One cable was installed outside and above the ring, one outside and below the ring, and one inside and below the ring. Each cable was nominally 25 inches from the vacuum chamber, subject to mechanical constraints that sometimes required significant deviations from the nominal. During these tests, the accelerator operators maneuvered the stored and injected charge with the intent of producing stable losses of known amplitudes in known locations. All measurements were made at 2.28 GeV using 100% argon gas in the cables.

DC signal sensitivities measured for the three cables ranged from 4.2 to 7.7 picoamperes of loss monitor signal per picocoulomb per second beam loss rate. This factor of two difference in sensitivity is considered to be inconsequential. Therefore cable locations in the APS were determined primarily by mechanical considerations. This DC signal sensitivity is about equal to the sensitivity obtainable from the SPEAR direct-coupled current transformer (DCCT). Both can measure loss rates with lifetimes in the 8- to 10-hour range. However, the DCCT requires averaging times of about 20 seconds at low loss rates to remove noise and cannot determine the location of the loss. The loss monitor prototype was able to measure the loss rates with an averaging time of about 1/3 second and could localize the loss to the length of the coaxial cable.

Pulse signal sensitivities in the three SSRL cables with 100% argon gas fill were measured to be 71 to 110 microvolts pulse amplitude in the coaxial cable per picocoulomb of loss. Measurements in the APS linac test stand at 50 MeV showed that pulse amplitudes in 95% argon, 5% carbon dioxide fill gas were six times larger than comparable pulse amplitudes measured in 100% argon. The pulse technique at SSRL with 100% argon did not have enough sensitivity to be useful during stored beam mode, even when lifetimes dropped to less than one minute. It was, however, very useful during injection, showing that the injected charge bunches in SPEAR are frequently lost over several circuits of the storage ring rather than all at once at injection. Figure 3 shows an oscilloscope trace of pulse signals on two of the three loss monitor cables during normal injection. Note that some of the injected charge is lost during initial injection but the majority of the charge makes one pass around the storage ring before being lost near the injection point.



Vert: 2 mV/div Horiz: 1 uS/div

Figure 3

As of this writing, the loss monitor system has been used successfully in support of the commissioning of the APS injector components, including the low energy transport lines, positron accumulator ring, and booster synchrotron. Figure 4 shows early data taken to verify proper operation of the loss monitor. It is a strip chart made of the analog signal obtained with the beam hitting an inserted screen. At the middle of the trace, the screen was removed. The resulting reduction in loss monitor signal verified that the signal was valid and that the loss monitor was functioning as intended.

Vert: nanoampers Horiz: seconds

Figure 4

Accelerator operations to date have not allowed much quantitative data to be collected on the performance of the loss monitor. This is because the accelerator pulse repetition rate has been in the 2- to 10-Hz range rather than the designed 60-Hz rate. At these frequencies the DC output from the loss monitor contains a large ripple at the pulse repetition rate. This ripple is aliased by the 6-Hz data sampling rate, making data interpretation nearly impossible. The loss monitor integrating ranges are intended for low pulse repetition rates, but the controlling software for the integrating ranges does not yet exist. However, much useful information has been derived from relative loss rate indications. These relative indications have been a significant tool in early commissioning. More quantitative data will be collected in the future as accelerator operating conditions allow.

One quantitative measurement of the DC current sensitivity was made by intentionally directing a 300-MeV, 10-mA, 30-ns wide, 10-Hz repetition rate electron beam from the linac into the beam dump at the last linac dipole. This

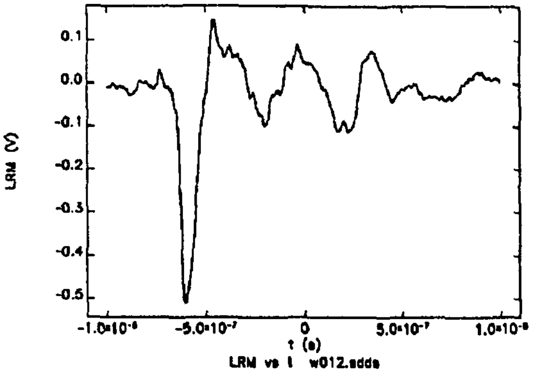


Figure 5

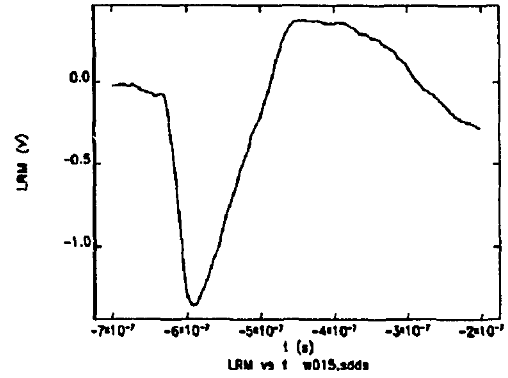


Figure 6

resulted in a charge loss rate from the beam of 3000 pC/s. The measured ionization current in the loss monitor cable was 30 nA, for a loss monitor sensitivity of 10 picoamperes of loss monitor signal per picocoulomb per second beam loss rate. Of course, this sensitivity varies with beam energy, mass between the loss point and the loss monitor cable (shielding and showering effects), and other causes.

Figure 5 shows the voltage output from the pulse amplifier and high pass filter circuits in response to a localized loss signal generated from a 300-MeV, 450-pC electron bunch 30 ns long. The amplifier has a high frequency gain of 40. The fast falling edge of the waveform contains the timing information for determining the location of the loss, and was observed to move relative to beam timing as the loss location was changed. The amplitude of the pulse was used to calculate a sensitivity of 28 μV pulse amplitude at the coaxial cable per picocoulomb of loss at 300 MeV. The lower frequency ringing shown on the trace is because the coaxial cable is not terminated at low frequencies because of the use of DC-blocking capacitors in series with the 50-Ω terminating resistors. This ringing contains no information and can be ignored.

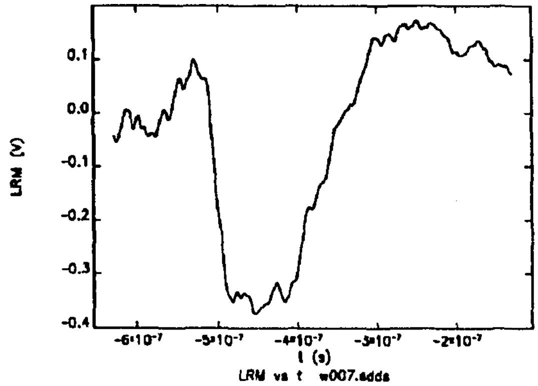


Figure 7

Figures 6 and 7 show two loss events on a faster time base. Figure 6 appears to be from a localized loss event, while Fig. 7 appears to be from a more spatially diffuse loss event. Note that bunch lengths for both Fig. 6 and 7 were 30 ns, limiting the spatial resolution to no better than about 15 feet.

CONCLUSION

Tests of a prototype loss monitor system at SSRL have verified that the concept will work and that signal sensitivities will be within usable ranges. The loss monitor system has been installed and operated in the APS injector. It has proven valuable in initial commissioning of the injector, and some quantitative data has been collected. Further quantitative testing awaits more prototypic operating conditions and the completion of the control and data acquisition software.

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