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

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PRELIMINARY DESIGN OF THE BEAM LOSS MONITOR SYSTEM FOR THE ADVANCED PHOTON SOURCE*

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Abstract

The preliminary design of the beam loss monitor for the ANL Advanced Photon Source is based on the use of an air dielectric coaxial cable as a long ionization chamber. Each coaxial cable section uses a high sensitivity DC current-to-voltage converter with both linear and integrating ranges. Pulse timing circuits determine the positions of individual losses by measuring the time at which the resulting voltage pulses arrive at the beginning of the coaxial ionization chamber. A possible timing ambiguity can be removed by correlating the particle bunch timing with the resulting voltage pulse timing. Measurements have shown that pulse rise times less than 15 nanoseconds can be obtained, so that determining loss locations to better than 7 feet may be possible. Best performance may be obtained when 500 VDC is applied to a 50-ohm, 7/8-inch air dielectric coaxial cable filled with approximately 8 psig of a 95% argon, 5% carbon dioxide gas mixture. Cable lengths will be between 100 and 300 feet long, depending on the part of the accelerator being monitored.

Introduction

The APS loss monitor system provides a relative measurement of beam loss rates in the APS accelerator[1]. This is done by measuring the high energy photons given off by the accelerated particles as they collide with the vacuum chamber wall, residual gas molecules, or some other obstruction.

The loss monitor system is based on the use of an Andrew Corporation model HJ5RN-50 7/8-inch air dielectric coaxial cable used as an ionization chamber. It is similar in many ways to loss monitor systems in use at Brookhaven[2,3,4,5,6] and SLAC[7,8,9,10]. Five hundred volts DC will be applied to the center conductor of the cable, and the cable shield will be grounded. An ionization gas consisting of a mixture of 95% argon and 5% carbon dioxide at 8 psig will be slowly passed through the cable. The average current flowing from the center conductor through the ionization gas to the cable shield will be measured. This average current is proportional to the total rate at which ion pairs are generated in the cable and, therefore, to the average beam loss rate along the cable. The cable will be laid parallel to the vacuum chamber (subject to mechanical constraints) to maximize the

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fraction of the high energy photons generated by beam particle losses that pass through the coaxial cable and generate ion pairs in it. Coaxial cable ionization chambers will be placed along the entire length of each of the major machine components.

When beam bunches encounter conditions that produce a large, localized beam loss, the resulting high energy photon emissions will produce a corresponding large, localized ionization in the coaxial cable ionization chamber. The location of the ionization in the cable will be related to the location of the associated beam loss. The position of the ionization in the coaxial cable will be 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.

Each coaxial cable ionization chamber will have an associated electronics package. The package is shown in block diagram form in Figure 1. A DC-coupled current amplifier is used to measure the total ionization current flowing through the coaxial cable. This circuit has a slow response and therefore time averages fast current pulses. For this reason, it is unable to localize a loss within the associated coaxial ionization chamber. It is, however, very sensitive to losses that may be too small or too diffuse in time or space to generate a measurable pulse in the coaxial cable. An amplifier/discriminator circuit and a time-to-digital converter are used to determine the position of a localized ionization event, provided that the resulting voltage pulse is large enough to be detected. These circuits are discussed in more detail in the sections below.

The DC-coupled current amplifier is floating on the output of the high voltage 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. Most leakage currents from the amplifier to ground are outside the measurement path and do not decrease measurement sensitivity. The amplifier/discriminator circuit need only be capacitively coupled to the center conductor of the coaxial ionization chamber and, therefore, will not be floated on the high voltage.

The section of the coaxial cable that is sensitive to ionizing radiation must be located next to the vacuum chamber. A section of foam-filled coaxial cable (which is insensitive to gamma radiation) is used to conduct the DC ionization current and voltage pulses from the vacuum chamber to the electronics package. The far end of the air dielectric cable and the end of the foam dielectric cable at the electronics package are connected to terminating resistors through blocking capacitors.

DC-Coupled Current Amplifier

The DC-coupled current amplifier consists of an FET input (low leakage) operational amplifier with eight linear feedback ranges and five integrating feedback ranges, plus one integration reset range (see Figure 2). These ranges are selected by low leakage reed relays to reduce the leakage currents below that obtainable with

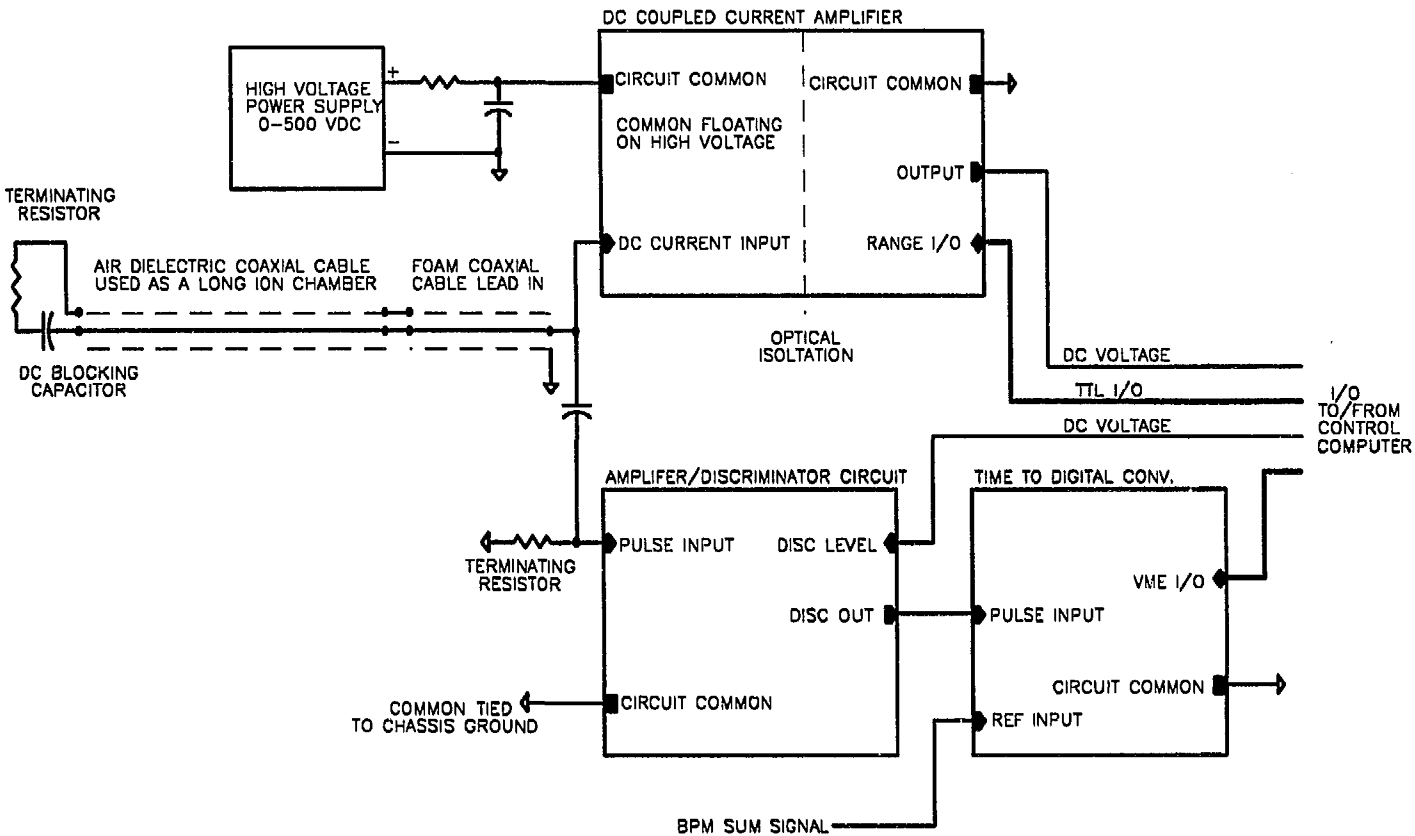


FIGURE 1: BLOCK DIAGRAM OF THE APS LOSS MONITOR SYSTEM

active electronic switches. With careful design and layout, input currents as low as 10 pA, and possibly as low as 1 pA, will be measurable.

When a linear range is selected, the DC-coupled current amplifier acts as a frequency-limited current-to-voltage converter. The eight ranges will be 1 milliampere full scale to 100 picoamperes full scale, in decade steps. The signal rise time (0-63%) at the output will be 100 milliseconds, except possibly on the most sensitive range. These 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 Hertz or higher. Under these conditions the time-averaged ionization current is continuously available at the output of the beam loss monitor. The control system does not require any special timing or peak detection logic to read the output signal.

Other accelerator subsystems, such as the transport line from the PAR to the synchrotron, do not experience repetitive particle bunches at a 60 Hz or higher rate. If linear ranges were used for these subsystems, the resulting output signal would be a pulse which 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. These integrating ranges are 10 microcoulombs full scale to 1 nanocoulomb full scale, in decade steps. An integration reset range is also provided to discharge the selected integration capacitor.

All digital I/O signals will be coupled between earth ground and the local ground (floating on the high voltage) by optical isolators. The analog output signal will be coupled to earth ground through an isolation amplifier. Power to the DC current amplifier will be provided by an internally isolated DC power supply module or by a conventional DC power supply module fed from an isolation transformer.

Amplifier/Discriminator Circuit

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. The discriminator threshold voltage is set by the control computer. The control computer adjusts the threshold as needed to minimize response to noise on the cable, and to allow rudimentary measurement of pulse amplitudes.

PAR and Synchrotron Timing

In the PAR and synchrotron, only one particle bunch can be in the ring at a time, simplifying the timing. In these rings, timing begins when a particle bunch passes one end of the coaxial ionization chamber, generating a reference signal. The required reference signal can most easily be derived from the beam position monitor, provided that the coaxial ionization chamber can be located such that it always

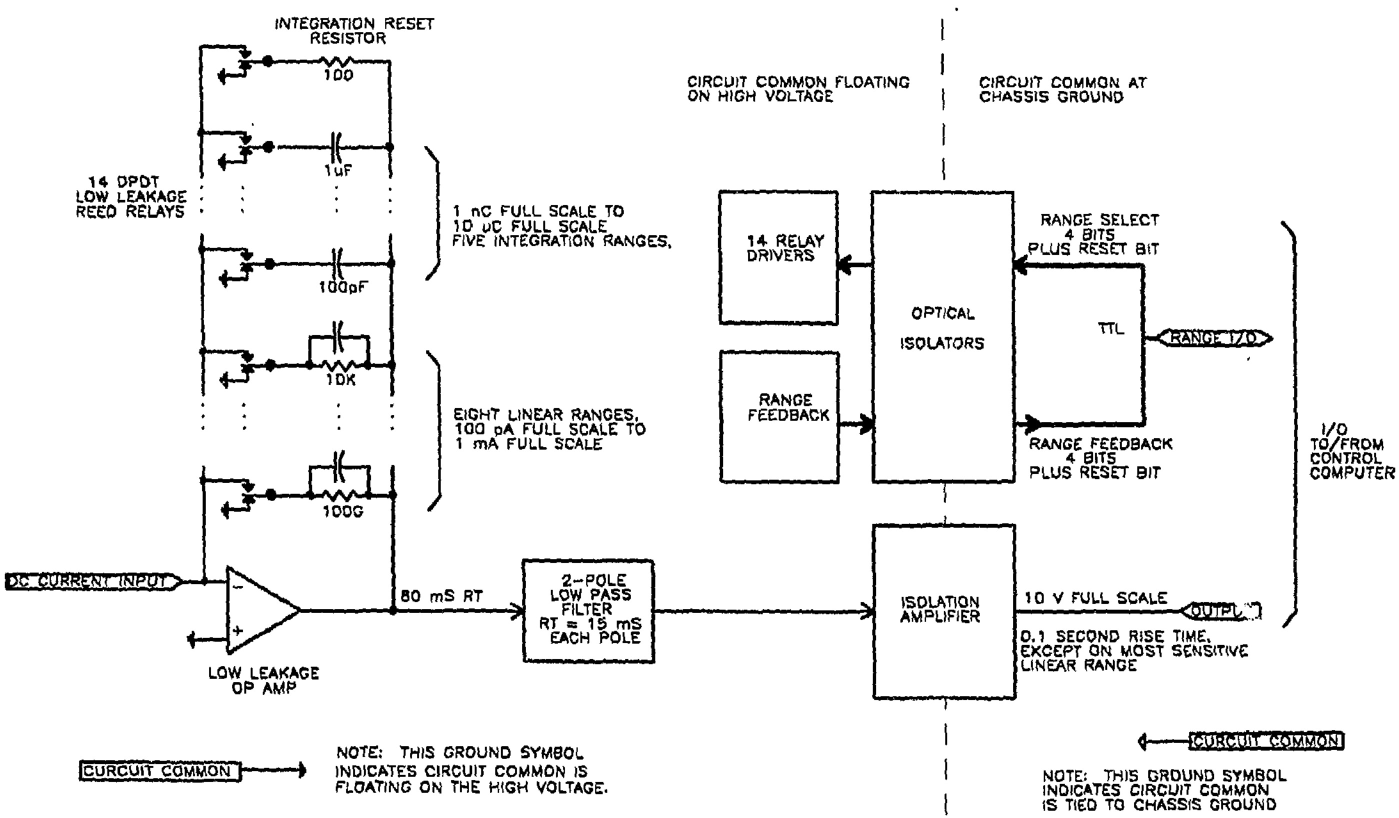


FIGURE 2: DC COUPLED CURRENT–TO–VOLTAGE CONVERTER

begins at a set of beam position monitor buttons. Timing ends after an interval equal to the time required for a particle bunch to travel through the vacuum chamber plus the time required for any resulting loss pulses generated at the far end of the coaxial ionization chamber to propagate back to the beginning of the cable. This round trip travel time is approximately 2 nanoseconds per foot of coaxial cable, since both the particle bunch and the electrical pulse propagate at approximately the speed of light. During this 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.

If a second particle bunch enters the section of vacuum chamber paralleling a coaxial ionization chamber during the timing interval, timing ambiguities arise which make it impossible to determine whether a given pulse on the coaxial cable was caused by the first particle bunch at a location near the end of the cable or by the second particle bunch at a location near the beginning of the cable. For example, assume that a 100 foot long coaxial ionization chamber is in use, and that two particle bunches are present in the vacuum chamber, separated by 160 nanoseconds. A pulse is detected from the beginning of the coaxial ionization chamber 180 nanoseconds after the first particle bunch passes the beginning of the cable. This pulse could have been generated by the first bunch at a loss located about 90 feet down the cable (180 nanoseconds round trip travel time) or by the second bunch at a loss located about 10 feet down the cable (180-160=20 nanoseconds round trip travel time). For this reason, a single coaxial ionization chamber cannot be used to cover the entire circumference of a ring, no matter how small, without introducing position ambiguities.

The above analysis ignores the reduced pulse propagation velocity in the coaxial cable. Since the pulse propagation velocity in the cable is 91.6% of the speed of light, the PAR and synchrotron will retain a small amount of ambiguity near the beginning and end of the coaxial ionization chambers if only two cables are used. For example, in the PAR it will be impossible to determine if a loss detected in one of the coaxial ionization cables was located in the first 2.5 feet of the cable or in the last 2.5 feet. The corresponding ambiguity for the synchrotron if only two coaxial ionization chambers are used is 27 feet. Therefore, the use of only two cables in the PAR may be acceptable, but this would appear to be unacceptable in the synchrotron. There will be no location ambiguity for losses located elsewhere in either ring, or anywhere in either ring if three or more cables are used in each.

Storage Ring Timing

In the storage ring, multiple particle bunches will be in the machine at the same time, possibly separated by only 20 nanoseconds, making the use of many short cables (10 feet long or shorter) and the timing method described above impractical. Under the correct circumstances loss locations can still be unambiguously determined, but at the cost of more data collection equipment and more data processing. This is done by simultaneously recording the timing of the particle bunches as they pass the beginning of the coaxial ionization chamber and the voltage pulses propagating back to the beginning of the cable. The control computer then calculates a correlation between these two data sets. The timing associated with each loss position is just the timing delay required to make the particle bunch timing correlate with the coaxial cable signals.

Figure 3 shows an example of the pulse timing to be expected in the storage ring in a way that makes it clear why the correlation works. This figure assumes that two losses are located at 15 and 40 feet downstream from the beginning of the coaxial cable (round trip travel times of 30 and 80 nanoseconds, respectively). Three particle bunches are also assumed, the second and third following the first by 40 and 60 nanoseconds, respectively. Trace A shows the bunch timing. Trace B shows the coaxial cable pulses generated by the first bunch (at t = 0) when it encounters the two losses at 15 and 40 feet down the cable. Similarly, traces C and D show the coaxial cable pulses generated by the second and third bunches when they encounter the two losses. Note that these traces are identical to trace B, accept that they are delayed by the delay of the associated bunch. Trace E shows the actual signal observed on the coaxial cable, which is the sum of the pulses generated by all three particle bunches.

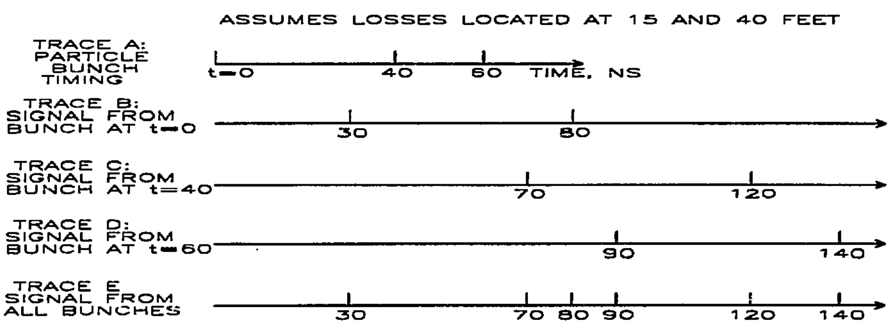


FIGURE 3: TIMING OF PULSES FROM THE COAXIAL CABLE IONIZATION CHAMBER FOR THE STORAGE RING

Calculating the correlation of the particle bunch timing (trace A) and the signal from the coaxial cable (trace E) is equivalent to overlaying trace A on trace E, offsetting trace A to the right, and observing the amount of offset required to make every pulse in trace A match up with a pulse in trace E. The resulting offset times are merely the round trip travel times associated with the loss locations.

The analysis above assumes that any pulses on the coaxial cable generated by particle bunches preceding t = 0 have had time to propagate to the beginning of the coaxial cable before t = 0. This assumption simplifies the timing diagrams, but is not essential to the conclusions. If pulses remain on the cable at t = 0 from previous particle bunches, trace E would contain the additional pulses, but the correlation results would be the same.

It is possible for this correlation technique to produce false time delays that are not associated with a loss location. These false time delays will be produced by the correlation calculation when the output pulse pattern from the coaxial cable just happens to correlate with the particle bunch pattern, even though they are not related by a loss. This is most likely to happen if the particle bunch timing (trace A) is uniform over the round trip travel time of the particle bunch and resulting voltage pulse. For example, if particle bunches are evenly spaced at 20 nanoseconds apart during and preceding the data collection interval, a single loss with a round trip travel time of 50 nanoseconds will produce a pulse stream out of the coaxial cable consisting of one pulse every 20 nanoseconds, offset by 10 nanoseconds from the particle bunch timing. The correlation calculation would show delays of 10, 30, 50, etc., and would appear to show a large number of loss locations.

This ambiguity only exists when the collected data shows that the particle bunch pattern repeats during every possible time interval of duration equal to the round trip travel time. The ambiguity can be minimized by collecting data for as long an interval as possible, so that short-term repetitions of the bunch pattern are likely to be broken up and show some identifying, non-repeating structure. The presence in the collected data of only one non-repeating bunch pattern over a time interval equal to the round trip travel time will be enough to allow the correlation calculation to unambiguously determine the loss location. However, if the storage ring is fully loaded with equally spaced bunches, it will be impossible to determine the location of the losses, unless the bunches are separated by at least the round trip travel time.

Pulse Timing Hardware

The timing data will be collected by a LeCroy model 1176 time-to-digital converter and a LeCroy 1176/EXP2 expander, or something equivalent. The 1176 is a VME module that communicates with the control computer through the VME bus. The 1176/EXP2 occupies a VME slot, but does not communicate over the VME backplane. The 1176 and 1176/EXP2 combination can record the arrival time of ECL pulses (from the amplifier/discriminator) with a resolution of 1 nanosecond and a dead time following each pulse of only 2 to 3 nanoseconds. Each of two identical channels can record and store the arrival times of up to 128 pulses. The data collection interval can be set from 1.024 microseconds to 65.536 microseconds, in binary steps, allowing long data collection intervals to be used to minimize location ambiguity in the storage ring. Simultaneous data collection on both channels begins upon receipt of the first START pulse following a computer reset of the 1176 module. This computer reset can be treated as an ARM signal, allowing synchronization of the collection of timing data with machine operating conditions.

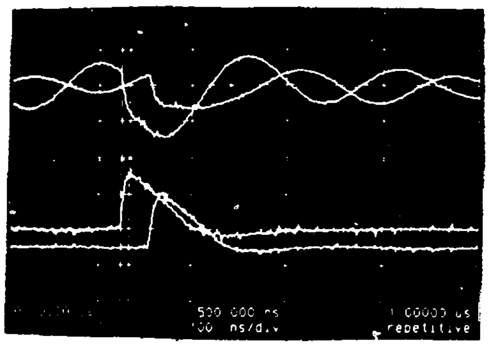
One 1176 and 1176/EXP2 combination will be used for each coaxial ionization chamber in the storage ring. The BPM sum signal will be fed to the START input and one of the channel inputs. The other channel input will come from the coaxial cable by way of the amplifier/discriminator circuit. Therefore, the particle bunch timing will be recorded in one channel and the return pulse timing from the coaxial cable will be recorded in the other channel. The control computer will read out the timing data, calculate the correlation, and determine the location of any losses.

One 1176 and 1176/EXP2 combination can be used for two coaxial ionization chambers in the PAR and synchrotron. This is because it is sufficient to feed one BPM sum signal to the module START input. No particle bunch timing pattern need be recorded since there is only one particle bunch in the ring at a time. The bunch arrival time at the beginning of the second coaxial cable is not recorded directly, but is calculated from the time of arrival at the beginning of the first cable and the known distance between them. This allows the two channels of the 1176 and 1176/EXP2 to be used to collect data from two adjacent coaxial ionization chambers.

One channel of one 1176 and 1176/EXP2 combination will also be used for each linear transport line. The second channel will not be used.

Test Results

Preliminary tests were conducted in a 50 MeV linac test stand to determine the feasibility of the loss monitor concept and to fix some of the design parameters. These tests were designed to study the effects of coaxial cable type, high voltage value, and ionization gas composition and pressure on DC current output and voltage pulse rise time and amplitude. Best results were obtained with a 95% argon, 5% carbon dioxide gas mixture at 7-8 psig with 500 VDC applied to a 7/8-inch, 50-ohm air dielectric coaxial cable. Leakage currents in this coaxial cable were measured and determined to be negligible. Figure 4 shows the pulse waveform obtained under these conditions. The top two traces are the voltage pulse plus modulator noise at the near end of the coaxial cable. One trace was taken with +500 VDC applied and the other with -500 VDC applied. One of the bottom two traces shows the voltage pulse after most of the noise was removed by subtracting the two top traces. The other bottom trace is similar, except that it is the voltage pulse observed on the far end of the cable. The pulse rise time was measured to be about 15 nanoseconds. Since the linac bunch width was also 15 nanoseconds, the loss monitor rise time must be less than 15 nanoseconds. This will allow the position of losses to be determined to better than 7 feet.



100 nsec per division, 20 mV per division

Figure 4: Loss Monitor Waveform

Conclusions

The preliminary design of the beam loss monitor for the APS transport lines and rings using air dielectric coaxial cable as a long ionization chamber is complete. Both DC current measurements and pulse timing measurements are planned.

Limiting the length of the coaxial cable in the rings and collecting bunch timing data will eliminate most, but not all, of the timing ambiguities. This will be verified by conducting tests in the PAR and injector synchrotron during or soon after commissioning. DC current measurements are planned initially for the storage ring with an upgrade to pulse timing measurements dependent on the verification of the results in the PAR and synchrotron, and on the availability of funding.

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