SLAC-PUB-12613
June 2007

DISRUPTION OF PARTICLE DETECTOR ELECTRONICS BY BEAM GENERATED EMI

G. Bower SLAC, Menlo Park, CA 94025, U.S.A.
Y. Sugimoto, KEK, Ibaraki, Japan
N. Sinev, University of Oregon, Eugene, OR, 97403, U.S.A.
R. Arnold, M. Woods, SLAC, Menlo Park, CA 94025, U.S.A.

Abstract

The possibility that radio frequency beam generated electromagnetic interference (EMI) could disrupt the operation of particle detector electronics has been of some concern since the inception of short pulse electron colliders more than 30 years ago [1]. Some instances have been reported where this may have occurred but convincing evidence has not been available. This possibility is of concern for the International Linear Collider (ILC). We have conducted test beam studies demonstrating that electronics disruption does occur using the vertex detector electronics (VXD) from the SLD detector which took data at the SLC at SLAC. We present the results of those tests, and we describe the need for EMI standards for beam and detector instrumentation in the IR region at the ILC.

INTRODUCTION

We are investigating the disruption of electronics by accelerator beam generated electromagnetic interference (EMI) in the rf range. This is a progress report.

The studies are being conducted at SLAC’s End Station A (ESA) facility as part of an ILC test beam program focusing on prototypes of components for the Beam Delivery System at the ILC [2].

The beam generated EMI source is a 2” long ceramic insulator “gap” in a 2.5” diameter section of beam pipe. A 28.5 GeV electron beam from the SLAC Linac is delivered at 10Hz to ESA with bunch charges of 2-3 nC and bunch lengths of ~500 microns. The short bunch passing the much longer ceramic gap creates emitted rf radiation with power spectrum P given by

$$P(\omega) \sim Q^2 \exp(-\omega^2 \sigma^2 / c^2) \quad (1)$$

where Q is the bunch charge and σ is the bunch length.

Various antennas are used to measure the radiation. . The range of frequencies observed appears to go below 100MHz and above 100GHz. In the 0.1-1 GHz range the intensity is 35 V/m at one meter from the beam pipe

When the SLD detector was taking data at the SLAC linear collider (SLC) in the 1990s an electronics problem occurred. Although a work around was created, the cause was not understood and it was conjectured that it might have been due to beam generated EMI [1].

One of the electronics modules which experienced the problem was taken from the SLD vertex detector data readout system and is being exposed to EMI in the current project. The original electronics problem has been reproduced and the cause has been determined to be direct rf EMI radiation from the ceramic gap.

The basic experimental technique involves turning off the beam, accessing the beam line and making a specific arrangement of antennas, electronics, shielding, etc. The beam is restarted and signals from the antennas, the VXD electronics and machine/beam parameters such as current, phase relations, etc are observed and recorded. This cycle can normally be performed in less than an hour. Since most of the other projects prefer uninterrupted running a limited number of special shifts have been scheduled to allow these frequent accesses. The results presented here have been collected over three runs of less than a month each in April-May 2006, July 2006 and March 2007.

CHARACTERIZING THE RF EMI

The tools

No single tool was available to measure the full range of rf radiation emitted through the gap. A detailed characterization was obtained for a limited range using two movable antennas read out by coaxial cable to a digital scope.

The biconical antenna is factory calibrated for measuring the intensity of radiation in the frequency range 20-330 MHz. The log-periodic or “yagi” antenna is factory calibrated for the range 650-4000 MHz. Since we are not involved in precision measurements it is possible to make an adequate consistent extrapolation of both antenna calibrations in the gap between 330-650 MHz. The digital scope can read at up to 20 gigasamples per second. This rate combined with the sampling period gives the scope a good waveform readout up to 2.5 GHz and progressively degraded waveforms up to a theoretical maximum of 10 GHz. Thus, we are able to give an adequate EMI signal characterization in the range 20-4000 MHz, more than two orders of magnitude.

Another project [4] on the beam line to develop bunch length measurement techniques uses two high frequency diodes, one sensitive to ~20 GHz rf using a WR90 waveguide collector and the other sensitive to ~90 GHz rf using a WR10 waveguide collector. The diodes are located at an EMI emitting gap used for toroidal beam current measurements.

The beam line environment

The experimental area is about 50 meters of beam line enclosed in a concrete block tunnel roughly 4 meters wide and 4 meters high. The beam line is packed with

Contributed to Particle Accelerator Conference (PAC 07), 6/25/2007-6/29/2007, Albuquerque, NM, USA

Work supported in part by US Department of Energy contract DE-AC02-76SF00515

experimental equipment for the seven different ILC test beam projects. The beam pipe cross-section changes many times and there are a variety of projections inside the beam pipe such as collimators. There are also a number of non-conducting gaps along the beam line for devices such as toroids for current measurements.

EMI measured in the tunnel

Figure 1 shows a scope trace of the signals from the yagi and biconical antennas placed about 1.8 meters away from the 2” ceramic gap. The yagi signal appears to be about 750MHz and lasts for about 15 nanoseconds from its beginning until it attenuates about a factor of 10 from its peak value of about 35 V/m. The biconical signal appears to be roughly 75 MHz and lasts for about 120 nanoseconds from beginning until it attenuates about a factor of 10 from its peak value of 35 V/m. (Peak values are given normalized to a 1 m antenna-gap distance. The bunch charge was about 1.6x10^{10} electrons.)

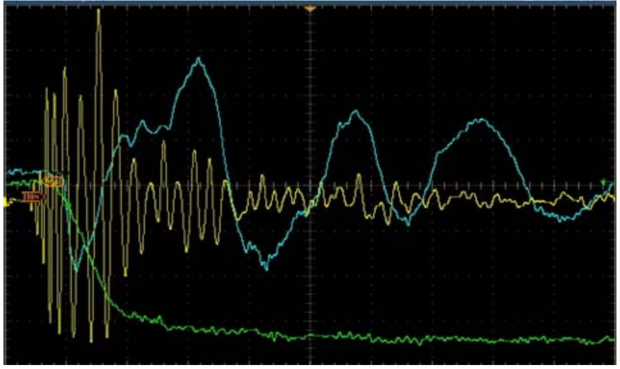

Figure 1: Signal traces from the run 3 gap location. The yagi antenna is the higher frequency trace, the biconical antenna is the lower frequency trace and the beam timing trigger signal is the step trace. The window is 50ns wide.

Both diode antennas also found signals in their response range demonstrating that beam induced EMI from a gap occurs at various frequencies at least in the range from ~100 MHz up to ~100 GHz.

During the first run the EMI signal from a beam current toroid gap was studied. The 2” ceramic gap was placed in different beam line locations for the second and third runs. The shape of the signal varied between locations. However, at a given location, the shape was essentially unchanged by variations in beam conditions (current, bunch length, and emittance). Even ragged poorly steered beams yielded essential the same shape pulse after pulse. This is illustrated in Figure 2 where we compare traces taken a few days apart with the yagi during run 1

We interpret this to mean that the shape of the signal is essentially a function of only the local beam pipe geometry. Since the bunch travels ~100 meters during the ~30 ns of the signal this is certainly the well understood phenomena of rf resonance inside a complicated structure [3].

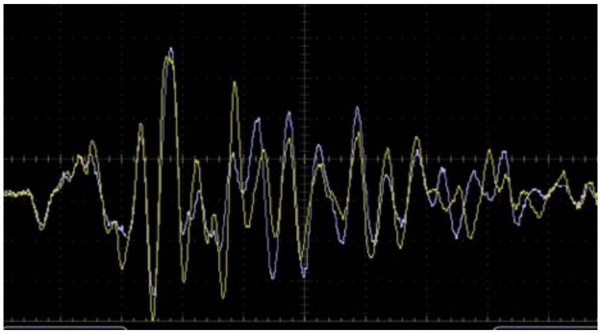

Figure 2: Overlain signal traces from the yagi antenna at the run 1 gap location. The two traces were taken days apart under different beam conditions. The window is 25 ns wide.

Having discussed the signal shape, we turn to the amplitude. The signal strength decreases with antenna distance from the gap. The decrease is slightly less than the expected inverse proportionality with distance. This is not understood at this time. It appears not to be a near field effect.

The amplitude of the signal seen on the biconical and yagi antennas is linearly dependent on the beam current. For example, in Figure 3 we have plotted the beam current versus the signal amplitude seen on the scope using the yagi antenna during run one. This result is expected from basic EM theory (1).

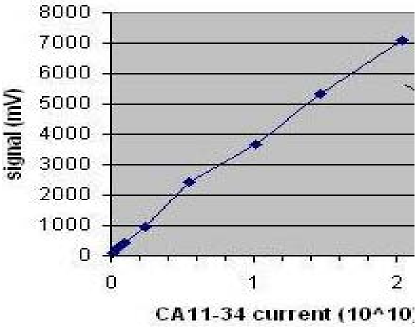

Figure 3: Beam current in units of 10^{10} electrons per pulse versus scope signal amplitude in mV for the yagi antenna. Data taken during run one.

According to theory the EMI signal should be forward directed. However, the wavelengths in the two antennas’ range are much larger than the gap and diffractive effects would tend in that case to produce a signal that is uniform in the polar angle formed by the beam pipe, the gap and the antenna location. A simple measurement with the yagi seemed to confirm this. (The anamolous 1/r result mentioned above may be due to a slight polar asymetry.) It would be interesting to make a polar angle sweep with the diode antennas. They should see the effect.

The signal amplitude measured on the biconical and yagi antennas is independent of the beam bunch length within the precision of the equipment. For the higher frequency horn antennas the signal strength is measured to be greater at the higher frequencies as the bunch length is decreased. This is expected from theory (1).

DISRUPTION OF ELECTRONICS

Electronics failure mode

The VXD electronics module is designed to read out data over an optical fiber. The fiber is also used to send commands and timing signals to the module. When the module is synchronized for data transfer over the fiber it asserts a ready signal. When initially installed at SLD it was found that the ready signal dropped for several microseconds when at least one of the two collider beams passed through the interaction region.

Due to the slow (120Hz) crossing frequency of SLC it was possible to work around this problem by delaying the VXD read out for 10 μs until ready was reasserted. The cause of this problem was not understood at the time.

The VXD module was placed next to an antenna at various locations around the gap in the tunnel. It was supported by the necessary power supplies and an optical fiber link to the communications board (initially placed outside the tunnel). The antenna provides a measurement of the lower rf frequncy signal strength at the module.

We were able to reproduce the original VXD failure mode. The ready signal drops on the order of 100 ns after the pulse crossed the gap. The rate of failure depended on the EMI signal strength which was controlled by changing the module's distance from the gap. The failure rate ranged from 100% (ready signal drops every beam pulse) to 0%. The failure rate as a function of signal strength observed on the antennas follows an S-curve.

Understanding the failure

At the time of the problem at SLC various explanations were put forward. Some of the possibilities were a ground fault effect, beam pipe image current entering the electronics, power source overloading as many detector components began to draw power at the same time and "airborne" EMI from a beam pipe gap directly affecting the module. It was not convenient at the time to explore these options and it was not necessary since a workaround was found.

We believe we have definitively established the cause to be direct rf radiation on the module. Two observations seem to establish this. First, as noted above the failure rate decreases as the module is moved away from the gap. Second, the module was placed inside a Faraday cage consisting of an aluminum foil enclosed box close enough to the gap that a high failure rate should be observed but while in the box the module did not fail.

At present the exact mechanism by which the EMI disrupts the electronics is not understood. Some initial tests have been performed exposing the module to steady rf signals in the 1-10 GHz range without any effect. This suggests that pulsing is important, our test signal is not strong enough or we are in the wrong frequency range (or some combination.).

We have some evidence that strongly suggests the cause is due to a higher frequency than in the test mentioned above. We wrapped a single layer of 5 mil aluminum foil around the gap and clamped both ends of the foil to the steel beam pipe on either side of the gap. With the gap completely covered and the module and antenna nearby, the module did not fail and if there was an rf signal emitted in the antennas' range it was below the tunnel background level in that area due to other distant gaps in the beam pipe.

We placed a single 1 cm by 1 cm hole in the foil cover. Once again, the antennas did not see a signal but this time the VXD module did fail. This strongly suggests that a frequency above the range detectable by the antennas/scope can cause the failure. We tried a 0.5 cm by 0.5 cm hole and the module did not fail. This may simply indicate that the smaller gap limited the EMI strength below what will cause the module to fail. However, if the hole is viewed as a radiator and its dimension are taken to be comparable to the wavelength of the radiation emitted, then it might suggest that rf somewhere around 30GHz is causing the failure.

CONCLUSIONS

We have presented a characterization of the rf EMI emmitted through beam line apertures by a short bunch length accelerator. We have demonstrated that this EMI is capable of disrupting the operation of the data collecting electronics of a high energy particle detector system. For the ILC we believe design, testing and shielding protocols will be required for both electronics and beam line elements. We will continue our studies aimed at this goal.

REFERENCES

[1] http://www-conf.slac.stanford.edu/mdi/sessions/beamrf.htm.

[2] M. Woods, et. al., "Test Beam Studies at SLAC End Station A, for the International Linear Collider", SLAC-PUB-11988.

[3] B. Zotter and S Kheifets, "Impedances and Wakes in High-Energy Particle Accelerators," World Scientific 2000.

[4] S. Molloy, et. al., "Picosecond Bunch length and Energy-z correlation measurements at SLAC's A-Line and End Station A," These proceedings, ID 1685.