Vertex Detectors - How to Overcome Electromagnetic Interference

C.J.S. Damerell
Rutherford Appleton Laboratory, Chilton, Didcot, Ox11 0QX, UK

Experience at SLD indicated that beam-induced electromagnetic interference (EMI) can disrupt the data from a vertex detector with hundreds of Megapixels and needing to be read out between bunch crossings. Naive calculations of skin depth suggest that beam-related RF should be well contained within the wall thickness of the beampipe, but in practice there may be numerous escape paths. The idea that one can protect the sensors by enclosing them in a Faraday cage is likely to fail, unless one invests in a quantity of screening material that would be most undesirable in the heart of a high performance tracking detector. However, a way is suggested of combining a number of strategies to ensure that the environment will be reasonably benign, and that the vertex detectors to be installed will be reasonably robust as regards EMI, so that peaceful coexistence between the ILC and its vertex detectors can be achieved.

1. INTRODUCTION AND SLD EXPERIENCE

In many respects, the ILC vertex detector (VXD) will be a logical extension of the technology established for the SLD vertex detector, which began with an R&D programme 20 years ago. Small pixels (~20 m square) will again provide good immunity to a high flux of background hits at small radius. Due to the increased detector area (approximately 5 layers instead of 3, for robust standalone track-finding, and longer barrels for improved polar angle coverage) the number of pixels will be increased by a modest factor (from 307 Mpixels at SLD to around 1 Gpixel at ILC). Due to the physics requirement of efficiently discriminating between *b*-quarks and their antiquarks [1] the inner layer radius needs to be reduced from 25 mm at SLD to 12-15 mm, and the layer thickness from ~0.4% X_0 to ~0.1% X_0. Fortunately, better control of machine backgrounds provided by the more elaborate beam delivery system is designed to establish the required background conditions at small radius, and ongoing mechanical engineering R&D is likely to deliver the necessary layer thickness with micron-level mechanical stability.

As at SLD, the readout of such a large number of channels will extend over many bunch crossings (BX); this is permitted due to the relatively low density of background hits per BX. In fact, the background hit density will be tolerable even with a sensitive time window of ~50 s, corresponding to ~150 BX. Such a readout time will permit a low-noise, low power readout matched to the requirements of gaseous cooling of the detector: liquid or evaporative cooling would be incompatible with the material budget imposed by the physics needs. There is a large number of detector technologies being designed to achieve the 50 s readout time [2], but none has yet been proven for sensors of the required active area (~10x1.5 cm^2 for the inner layer).

The fact that the readout will necessarily span many bunch crossings raises a serious potential problem. Each electron or positron bunch carries with it an image current on the inner surface of the beampipe as it flies through the Interaction Region (IR). If the beampipe consists of a continuous metal enclosure of sufficient thickness, the very high current (kAmps) would be confined by the skin effect so that no external signal would be generated. Unfortunately, the requirements for IR equipment (BPMs, kicker magnets for luminosity feedback, possible beam-size monitors, vacuum pumps etc) may create apertures through which RF radiation originating from the electromagnetic 'pancake' accompanying the beam bunch can escape. In addition, the IR enclosure (two conical regions either side of the IP) acts as a 'dumbbell' cavity in which wakefields are generated and decay slowly after the passage of each bunch [3].

This source of electromagnetic interference (EMI) is in principle present in every colliding beam machine, but certain features conspire to make a vertex detector using monolithic pixel sensors at a linear collider a risky combination. In order to maintain luminosity at a linear collider, a much more elaborate feedback system is required than at storage rings. Penetration of the beampipe by IR instrumentation provides apertures through which RF power can escape. However, the use of double- or triple-screened coax connectors and cables, and light fibres enclosed in metal pipes, can provide effective screening, as is also true at the remote ends of those cables and fibres. However, if standards are slightly relaxed, cover plates on boxes may offer thin gaps (slot antennas), power leads may be fed in through holes which allow RF to pour out, etc. In the case of SLC, each bunch crossing was accompanied by a large amplitude RF pulse (apparently a delta function, as seen by small antennas near the vertex detector) which was almost certainly generated by the primary RF 'pancake' rather than by residual wakefields, since these would have caused longer term ringing. Despite careful investigation, the source of this signal could not be established. Given the capability of a high frequency EM pulse to reflect off metal surfaces, this is not surprising. Observations many years ago at PEP [4] showed that such RF could fly around the experimental hall with very weak dependence on geometry, just as signals are received by a cellphone that does not have line-of-sight contact with the transmitter. A mis-assembled connector or a badly fitting cover on an electronics box could have been the source. This RF spike caused saturation of the vertex detector analogue front-end electronics and disruption of the phase-lock-loop used in the optical data link (GLink). Recovery took some tens of s, so the solution was to suspend the readout for ~100 s after each bunch crossing. The bunch crossing interval was 8.3 ms, so the increase in readout time was negligible. During readout, the so-far unread signals were held as charge in the CCD storage wells. Reading out the full event required ~20 BX, and the data quality (cluster size, spatial resolution) was preserved throughout this period. The reason why the pickup affected only the VXD front-end and not other SLD detectors may be related to the very small signals (~1000 e^-) hence sensitive analogue electronics required by comparison with the drift chambers and other SLD detectors.

SLD is so far the only experiment where a system of monolithic pixel detectors (CCDs) has been confronted with the EMI characteristics of a linear collider. Other detector systems have operated smoothly at SLD and at storage rings. We believe that the SLD experience may be a useful pointer to the future in which a linear collider and multi-Megapixel vertex detector will again need to operate harmoniously together.

2. SUSCEPTIBILITY OF VERTEX DETECTORS TO RF PICKUP

At first sight, it should be possible to shield or filter very high frequency RF radiation in the proximity of the detector. We discuss the issue of a Faraday cage in the next Section, and here consider RF radiation impinging on the detector elements. Most of the power from the primary electromagnetic pancake is in the frequency range of GHz and above, with the upper limit being given by the bunch length. Given that front-end shaping times are likely to be ~10 ns or longer, such frequencies are clearly dangerous. However, a typical monolithic pixel sensor (CCD, CMOS, DEPFET etc) consists of a thin electronic structure sandwiched between ground planes or planes of gate electrodes at well-defined potentials. Consideration of skin depth suggests that such high frequency radiation should be severely attenuated, so the circuitry within the sensor should be well protected. However, this assumption is frequently incorrect, for two main reasons [5]. Firstly, EMI may couple through the signal and power leads external to the sensor, and be carried to the circuitry within. To some extent, such sources of interference can be filtered on the sensor chip.

Secondly, the top and bottom ground planes do not constitute an electrical enclosure. They would normally be linked together by a number of connections, typically using the bulk silicon substrate, but at high frequencies the inductive components in these links would cause the top and bottom plates to perform rather independently of one another - see Fig 1. Currents induced on the outer surface of a plate would necessarily also flow on the underside, and hence couple to the circuitry within. The excitation of surface or crawling waves in such structures is well-studied - see Fig 2. The most efficient way for RF to couple to a sensor structure is generally along the edges, so that the ground planes become the boundaries of a waveguide [7]. The internal circuitry modifies the resonant frequencies, so quantitative simulations are virtually impossible. However, there are standard test procedures for measuring the response of ICs to external RF radiation, and such procedures are likely to be valuable in the ILC environment, as discussed in Section 4.

While a front-end source follower with a shaping time of say 50 ns may be relatively immune to such pickup, this may be far from true of other parts of the analogue circuit. For example, in the FAPS or CAP option, the signal is distributed over an internal busline to which a number of voltage storage circuits, consisting of capacitors, are each connected by a switch. These provide a string of sample-and-hold circuits triggered sequentially during the bunch train. Due to the need to fit ~20 of these circuits in each pixel, they must be physically small (hence extremely low capacitance) and due to the impossibility of integrating high value resistors (multi-M) in a small area of an IC, the RC shaping time of these circuits is extremely short, typically in the ps range. Hence, any fluctuations picked up on the internal busline when a switch opens and closes will be sampled and held on top of the signal, thereby injecting noise onto the stored voltage which is to be measured after the bunch train. A similar problem would be faced by a standard CCD readout, due to the very small node capacitance (some fF) to which the signal is transferred for voltage sensing.

In view of the SLD experience, some ILC vertex detector collaborations are working on architectures which promise to be robust with respect to EMI. Several (CCD, DEPFET) collect the signal charge in a buried channel within the pixel. Despite the small magnitude of this charge (~1000 e^-) it is extremely robust as long as it is stored in the bulk silicon. This signal could in principle be disrupted by pickup on the gate electrodes, but these have huge capacitance and would need to fluctuate by ~1 V in order to dislodge the charge from its potential well. These figures contrast by typically a factor 10^6 with the combined effect of the tiny node capacitance used for voltage sensing, and the small voltage fluctuation on that node (much less than 1 mV) which would destroy the min-I signal measurement.

The safest procedure would thus be to store the signal charges in the bulk through the bunch train, delaying the charge-to-voltage conversion till the quiet inter-train period. However, assuming pixels of size around 20 m, this would lead to an unacceptably high density of background hits. There are at least two possible approaches. One (under investigation by the FPCCD collaboration [8]) aims for much smaller pixels, and uses cluster shape information to reduce background from spiraling electrons. Another approach (under investigation by the LCFI Collaboration [9]) involves multiple wells for storage of charge (not voltage) within each pixel, with the signal charge being held in this array of storage wells for about 20 time slices during the train. This approach builds on the In Situ Image Storage (ISIS) technology developed for fast burst optical imaging [10]. None of these architectures is yet proven for the ILC conditions, and there is as much room for surprises regarding resistance to EMI as there is to ionising radiation; for both these complex phenomena, simulations alone are unlikely to be conclusive.

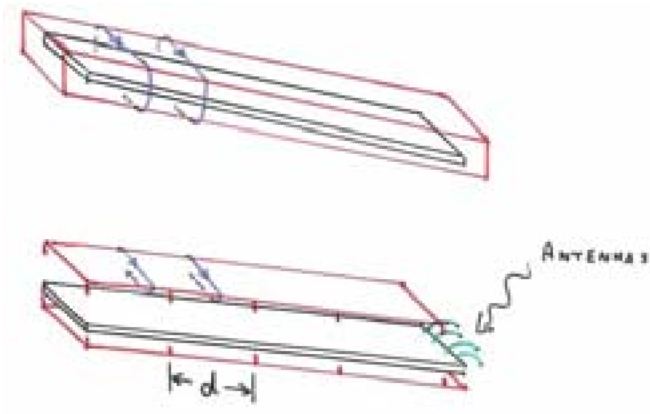

Fig 1. Sketch of a typical monolithic sensor assembly. Far from providing an electrical enclosure (top sketch), currents induced by RF radiation will typically flow independently on each ground plate, thereby inducing fields in the interior of the chip.

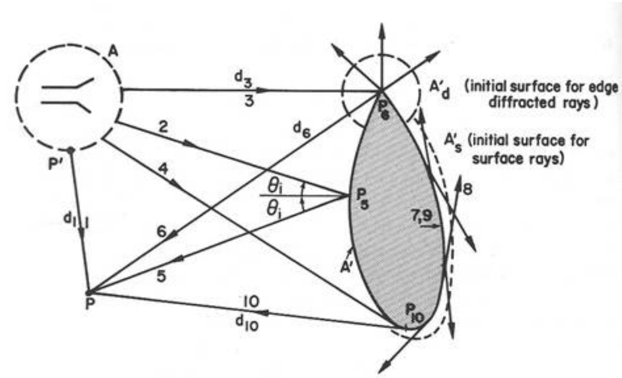

Fig 2 From [6]. Radiation impinging on a conducting surface of size comparable to the wavelength undergoes a variety of diffraction processes (inducing crawling and surface waves) so that the concept of RF 'shadowing' is valid only for relatively large surfaces.

3. THE FARADAY CAGE - REAL OR ILLUSORY PROTECTION?

The SLD Faraday cage (F-cage) [11] was designed carefully, apart from (with hindsight) at least one major weakness. It consisted firstly of a thin beryllium tube concentric with and just outside the beampipe, electrically insulated from it. It was perforated with fine holes, and when the volume between the pipes was slightly pressurised with cold nitrogen gas, it delivered the distributed cooling that maintained the working temperature of the detector. This 'gas shell' was connected by small springs to the two semi-circular sections of the F-cage/cryostat endplates each end, and these were similarly connected to the two semi-cylindrical sections comprising the barrel enclosure. These F-cage sections were thin aluminium sheets (with non-oxidisable conductive plating in the regions for spring contact) bonded to the inner surfaces of the foam cryostat. When the cryostat was tightly closed, all 7 sections of the F-cage made excellent electrical contact with one another.

The system was first tested without beam, with excellent results. The combination of the F-cage and the iron of the SLD magnet provided the cleanest electrical environment ever experienced in the CCD detector studies, including fixed target experiments and test lab conditions. All this changed when the beam was switched on, when the previously mentioned disruption due to the beam-induced EMI was encountered. With hindsight, having the F-cage sections make contact via springs was insufficient. There remained a number of very narrow disconnected slits between the sections, allowing high frequency RF radiation to penetrate unimpeded through large effective apertures (slot antennas) in the enclosure. In addition, numerous low-mass copper-kapton flex circuits emerged from the cryostat through ring-shaped slits in the endplates, which would also have created large-area entry paths for RF radiation to penetrate.

In future, such problems could certainly be solved, but at considerable expense in material budget. There exist effective screening meshes which could ensure full contact round the seams between the 6 sections of the F-cage. Instead of routing striplines out through slits, they could be made into properly screened multi-core twisted pair cables, with many good quality double-screened connectors fitted to the ends of the cryostat. However, the vertex detector, being the innermost tracking detector, runs the greatest risk of degrading the overall detector performance due to photon conversions and secondary interactions, whether these occur in the sensors, in the local electronics or in the F-cage/cryostat. By following the SLD principles, the overall VXD-related material budget, in the worst region of polar angle, would be 2% X_0, as described in the TESLA TDR [12]. If a truly effective F-cage system were obligatory, the material budget in this region would need to be at least 10 times greater, with a corresponding reduction in physics capability of the overall detector. Such a retrograde step should be avoided if at all possible.

Marvin Johnson of Fermilab has asserted that most Faraday cages used in HEP detector systems are little better than dust covers. While this may be true, it is also true that most detectors in most experiments are usable, despite their inferior screening. It is to be hoped that the same minimalist approach to the vertex detector F-cage will also be successful at the ILC, but in view of the SLD experience, one should not count on it.

4. THE WAY FORWARD - A SUGGESTION

We suggest that all VXD sensor prototypes should be characterised experimentally regarding their sensitivity to external RF, both injected along their cables and in the form of radiation. In cases where early prototypes perform badly, this may, encourage the development of new ideas, leading to more robust architectures. The sensitivity figures for different architectures should prove useful, along with all the other performance parameters, when the overall experiment collaborations choose their vertex detector options,. With luck, one of the EMI-robust architectures will also be in the forefront regarding the critical tracking performance requirements.

Next, we presume that each of the ILC IRs will be commissioned with the detector in a 'garage' location. This procedure was followed at SLC, and the requirements for special beamsize monitors etc make this virtually obligatory at the ILC. This will provide a marvellous opportunity for vigilant evaluation of RF leakage from the IR, with its associated instrumentation and electronics boxes. It will for example be possible to track down and repair slightly mis-assembled connectors which would be impossible to locate and diagnose with the detector in place.

Putting together the information from the detector evaluation with the observations from the operating ILC, it will be clear whether the 'lightweight' F-cage is likely to work. If so, all will be well. However, given the possibility of a mismatch, it is suggested to have on standby a truly effective F-cage assembly. If necessary, one would install this around the detector, guaranteeing a working vertex detector, albeit with reduced physics capability for particle flow due to the massive F-cage. In these circumstances, one would expect a strenuous effort to construct a more EMI-resistant vertex detector, to be installed after the first period of ILC operation.

Regarding the SLD experience, it claimed by our SLC colleagues that all reasonable precautions were taken to prevent the escape of RF. So where did those spikes come from? It is possible that they were associated with beamline equipment some distance from the IR (vacuum pumps, for example) but it could also be that some part of the complex IR assembly was imperfect. This could be tested by installing the R20 module (the inner 2 m of SLD beampipe, BPMs etc, equipped with the original cables and electronics) in a SLAC test beam. Studies of RF escaping from this assembly could be revealing, particularly if some 'standard' part of the system such as an electronics box proved to be deficient in a way that might otherwise be perpetuated at ILC.

There has been some discussion of attempting to simulate the entire chain from escape of radiated RF, injection via cables or radiation into the F-cage, and on into the internal sensor electronics. Expert advice is that such a simulation would be impossibly complicated. The most that could be done would be to simulate specific parts of the system, for example to improve the design of a chip that had been found vulnerable in a particular frequency range. It is clear that the way to make progress with such a complex problem must be largely experimental. It is expected that the ILC vertex detector community, working closely with the MDI people at ILC, will find a way to guide the overall ILC/vertex detector assembly to a future of peaceful coexistence.

Acknowledgments

I would like to thank the many experts who took the time to educate me in this area, where it became clear to me that inter-disciplinary experience is valuable. I should particularly mention Marty Breidenbach, Steve Smith, Mike Sullivan, Tor Raubenheimer, Peter Tenenbaum, and Jerry VaVra of SLAC, Jim Eastwood, John Hardwick and Mike Hook of Culham Electromagnetics and Lightning, John Bradford, John Eastment, Brian Ellison and Richard Stephenson of RAL, Ulrich Koetz of DESY, Colin Perry of Oxford U, and Sherwood Parker of Hawaii U.

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