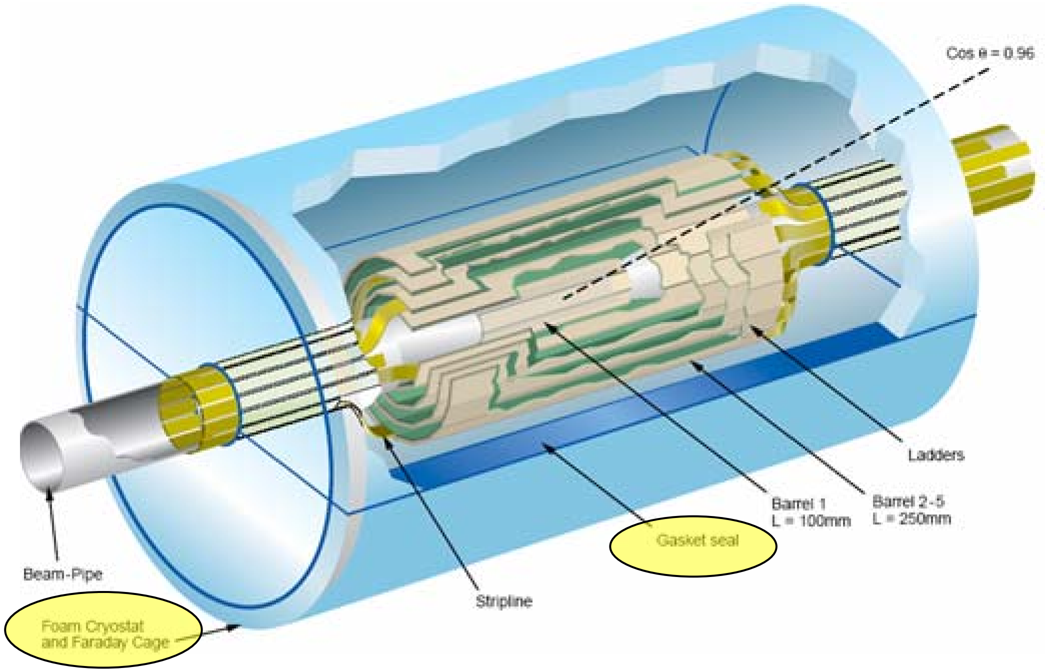
Vertex Detectors – How to Overcome Electromagnetic Interference

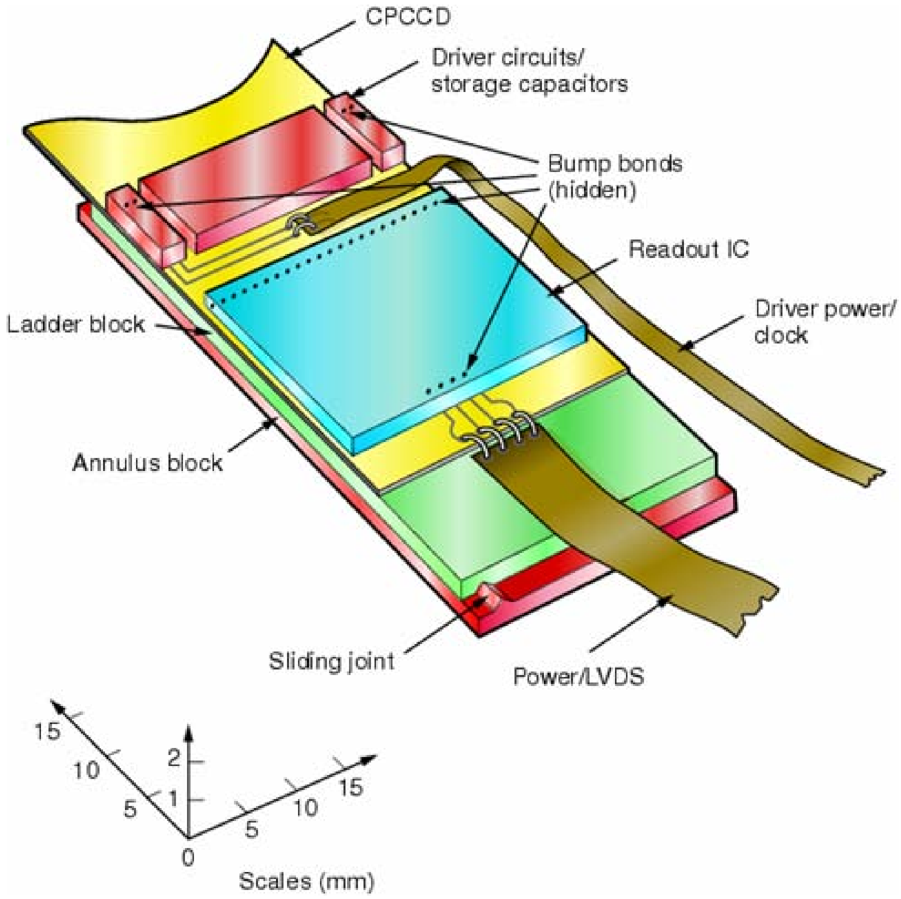
Chris Damerell
Rutherford Appleton Lab

- ***How to avoid being blown away by pickup, jangling around in 10^9 pixels with only hundreds of electrons signal in each?***
- **An unprecedented challenge in particle physics experiments, though we can learn some lessons from SLD**
- **Previous experience of beam-related pickup**
- **RF sources in the ILC interaction region – can the EM radiation leak into the experimental enclosure?**
- **Susceptibility of ICs (eg vertex detector sensors)**
- **The Faraday cage – saviour of EMI-sensitive detectors, *or not*?**
- **The way forward – a few suggestions**

Generic long-barrel detector
(TESLA TDR, and LDC baseline)



- **Thin copper/kapton striplines bring power in, and carry sparsified (digital) data to local opto-couplers, hopefully inside the Faraday cage**
- **Single optical fibres each end, carry data out of the detector**
- **By many standards, should be relatively easy to screen from RF interference, but this was also true at SLD.** ***Note the 6 components of the Faraday cage …***



- **For ISIS and other non-CCD options, driver circuit is eliminated**
- **Readout chip *may* be eliminated – depends on compatibility between sensor technology and 'standard CMOS' used for this chip, which may be a 0.13 μm or below**
- **In any case, material budget beyond ladder sensitive areas is probably dominated by the mechanical support system, as at SLD, in view of the mechanical stability requirements for these ultra-thin ladders**

Beam-related pickup – previous experience

- ***Sherwood Parker at SPEAR***
  - **Beam-related (totally clean when RF on but beam off)**
  - ***Not from the expected cause* – penetration through central section of beampipe. When thickness was reduced, pickup was slightly reduced**
  - ***Not the expected 1/r falloff*. When probes fell off beampipe, pickup increased slightly**
  - **RF was encountered 'all over the hall', like microwaves received by cellphones, or light in a darkened room, from a small hole in a black blind**
  - **Source (thin-walled bellows? some electrical discontinuity in beampipe assembly?) was never found**
- ***Ulrich Koetz at TASSO***
  - **CDC totally disabled after a shutdown**
  - **Switched off, opened up, and found a missing terminating connector on a BPM signal port**
- ***SLD***
  - **Pre-beam, we congratulated ourselves on our good Faraday cage, and the effective shielding provided by the hermetic magnet iron**
  - **Beam-pickup sent VXD2 front-end electronics into saturation for some μs after each bunch crossing**
  - **With upgrade detector (VXD3) there was the further problem of disrupting the PLL of the electro-optical converters**
  - **Problem 'solved' by delaying readout for about 20 μs – not an option at ILC!**
  - **Could have been a mild version of the TASSO problem (badly assembled connector, …)**

- ***XMM (highly successful X-ray telescope with ESA)***
  - **Detailed calibration and testing of all components for EMC**
  - **Vast documentation, every detail cross-checked and signed off**
  - **However, after all that, David Lumb mentioned that in orbit, two of their CCDs intermittently pick up above-threshold noise in groups of 4 adjacent rows**
  - **No idea whatsoever as to the cause**

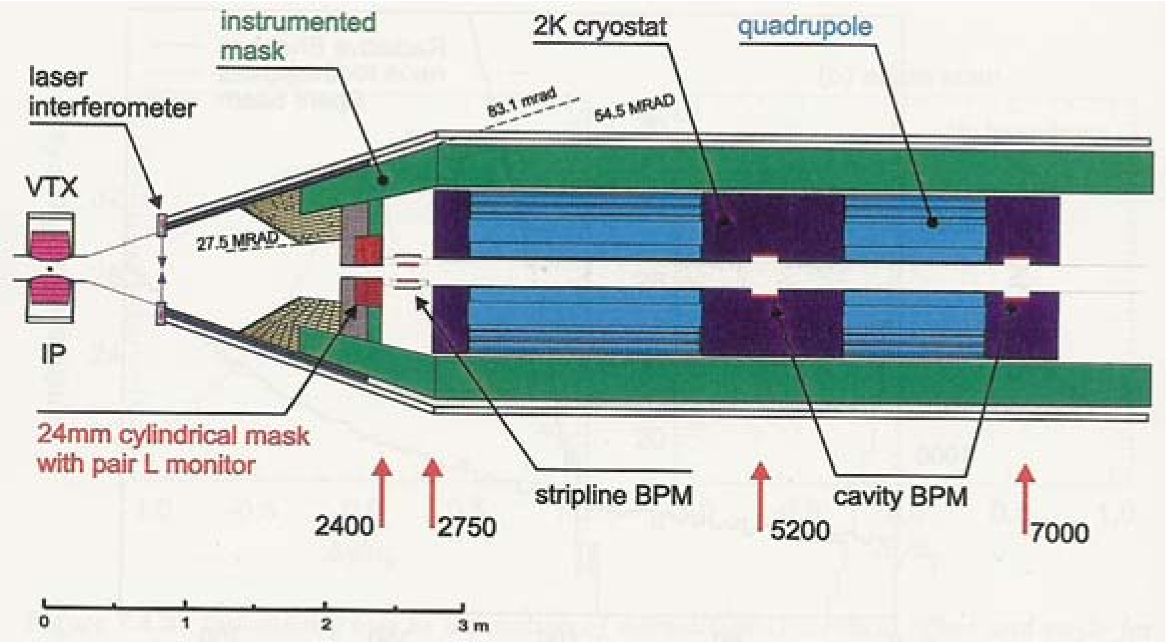
- ***OPAL***
  - ***Didn't they offer a prize for discovering the source of some intermittent pickup in their detectors? Never claimed …***

- ***CDF***
  - ***Layer 00 problems …***

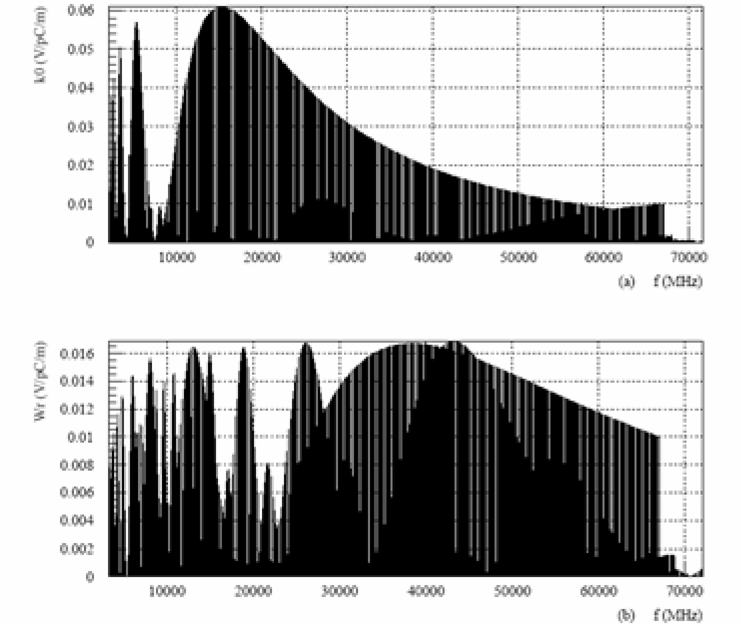
- ***TR detector at TTF (Manfred Tonutti)***
  - **Massive wakefield leakage through a small ceramic plug**
  - **Major effort needed to de-sensitise their readout electronics**

- ***Conclusion***
  - **Need to be vigilant – don't be complacent about these problems**

RF sources in the ILC interaction region; can the EM radiation leak out?



- ❑ ***Beam-related***
  - **2 types of wakefields, resistive-wall and geometrical. Mostly the latter in the IR, due to the drastic changes of radius encountered**
  - **Vacuum chamber looks like a dumbell, cutoff frequencies around 500 MHz**
  - **Effective Q is quite low, damping times typically 3 μs at 3 GHz, so ringing will build up to some steady state through the bunch train**



Monopole radiation (above) and dipole (below)

Both TE and TM modes are excited for each.

Fcy range plotted is 0-70 GHz

Peak amplitudes 0.06 and 0.016 V/m per pC respectively

Bunch charge is approx 3.2 nC

Jie Gao, LAL Orsay, LCC – 0025 08/09/99

How can this RF power leak out?

welded assemblies are pretty close to perfect

there is potential to escape due to insufficient skin depths, but entirely negligible except at very lowest frequencies (thin bellows can be a weak spot) Skin depth for beryllium is 3-1 μm for frequencies 1-10 GHz.

***BUT* high fcy RF can escape through tiny apertures:**

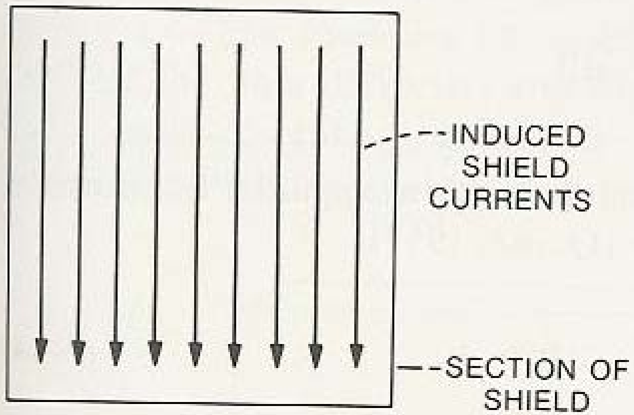
BNC connectors are EXCLUDED. Need UHF screw-type connectors

Single, even double-screened coax may not suffice (may need to contain cables in rigid pipe)

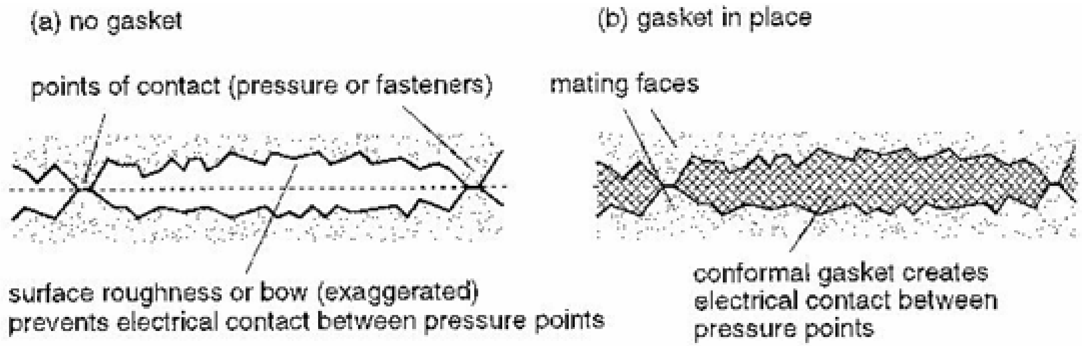
Vac seals may be inadequate: metal seals, well made are OK; O-ring seals definitely not

Leakage may originate from remote end of a cable or light fibre, eg via a hole for a power lead, in the box to which it is connected

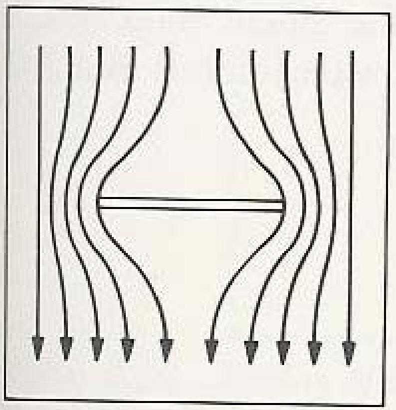
beware of *slot aerials* introduced by intermittent contact of lids etc



(A)



- A welded joint comprises an excellent conformal gasket
- Anything less needs to be checked carefully after assembly. Lack of cleanliness is all it takes
- Minimum length for significant leakage is approx $\lambda/100$, , ie 0.3 mm at 10 GHz



(C)

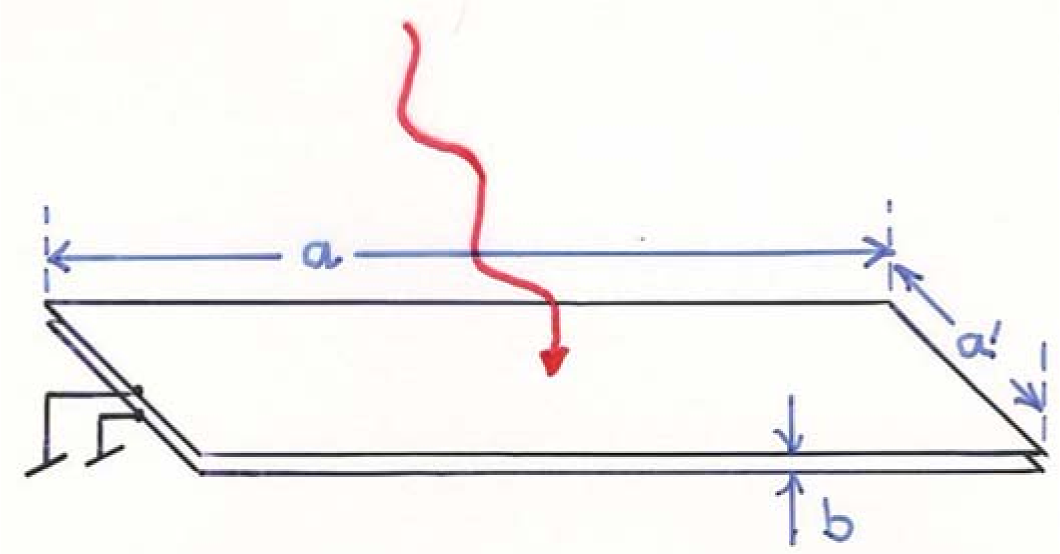
Typical slot antenna

Other sources of RF radiation

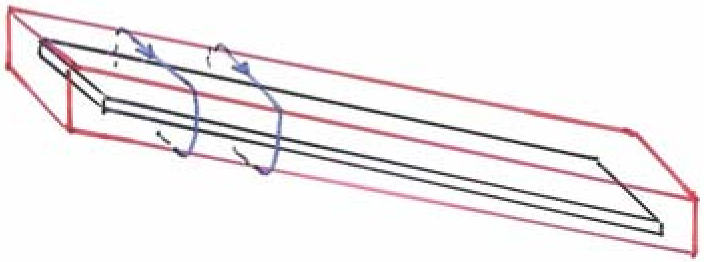
- Dangers are by no means confined to the beams, during the bunch train
- Sources such as kicker magnet supplies, feedback systems, and readout from other detectors may also contribute
- Environmental testing should take place with these systems operational and beam on

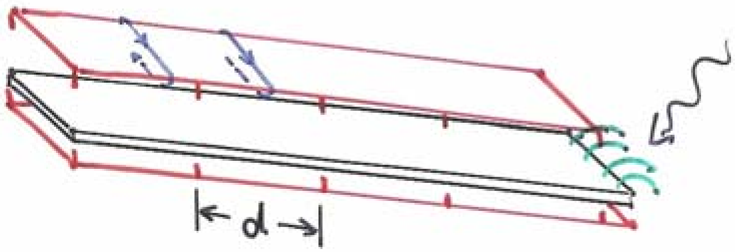
Susceptibility of integrated circuits (eg vertex detector sensors)

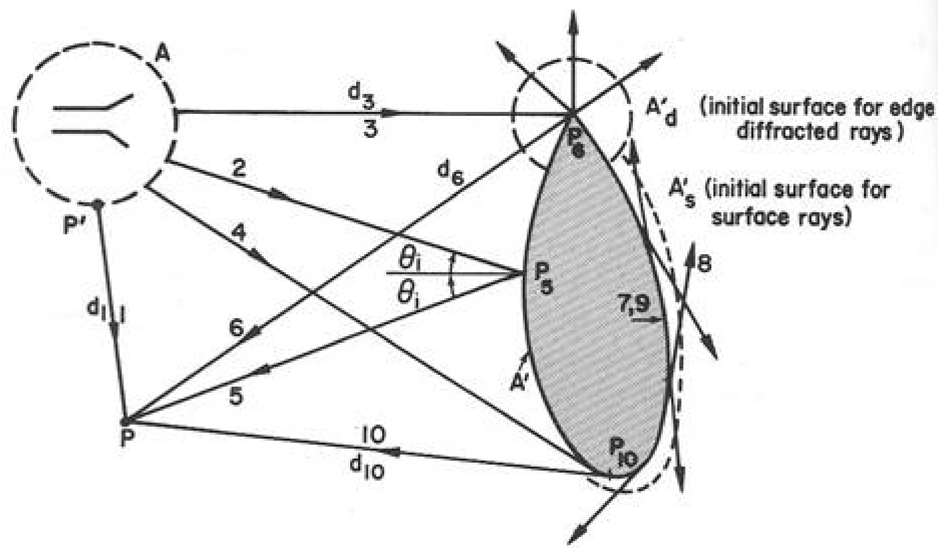
- Accept that RF power can leak out
- Ignore (for now) the widely believed capability of a Faraday cage to isolate the detector (return to this question later)
- RF power in the GHz range and above, sometimes claimed to be 'easily shielded' because of the tiny skin depths involved



- Is this valid? 'Radio darkness' *is* experienced behind large satellite dishes, in cases where the wavelength is much shorter than the dish dimensions
- But for smaller (conducting) obstacles, diffraction effects are important (as in optical systems, where a bright spot is found behind a small opaque disk)
- Need to solve Maxwell's equations
- Those 'ground planes' are effectively floating, due to parasitic inductances, at frequencies of 1 GHz and above

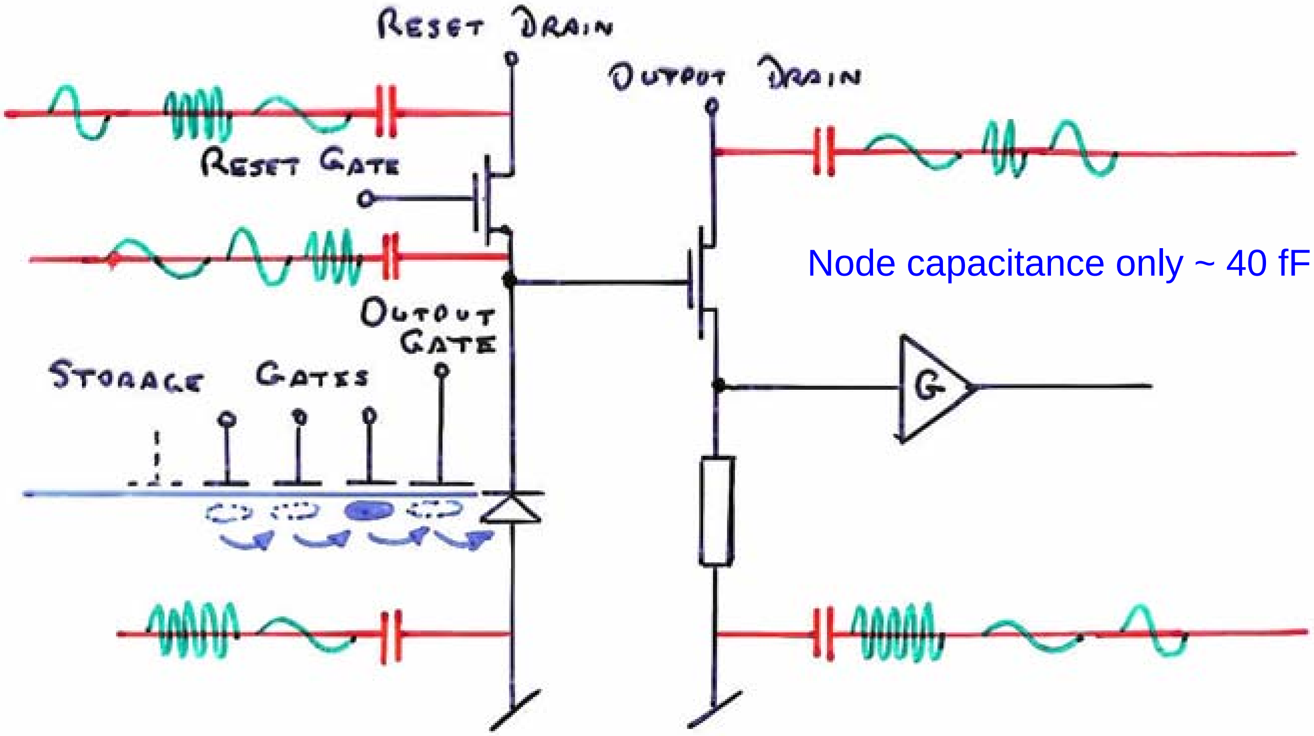






- **For an integrated cct in an RF bath of ~ GHz radiation, most severe internal radiation will (probably) arise from external radiation couling in to the effective waveguide provided by the two ground planes**
- **Cutoff wavelength λ_c = 2*a* or 2*a*' (typically around 1 GHz for ILC vertex detector sensors). HOMs at $\lambda_c/2$, $\lambda_c/3$ etc**
- **Assembly thickness *b* and internal dielectric (mainly silicon) determines the characteristic impedance, and hence the degree of mismatch to the incident radiation**
- **In practice, EM radiation will couple in quite effectively, also from the wire bonds, if any.**
- **Internal components (notably metal traces) detune the waveguide resonances to an unpredictable degree, typically shifting them downwards in frequency**

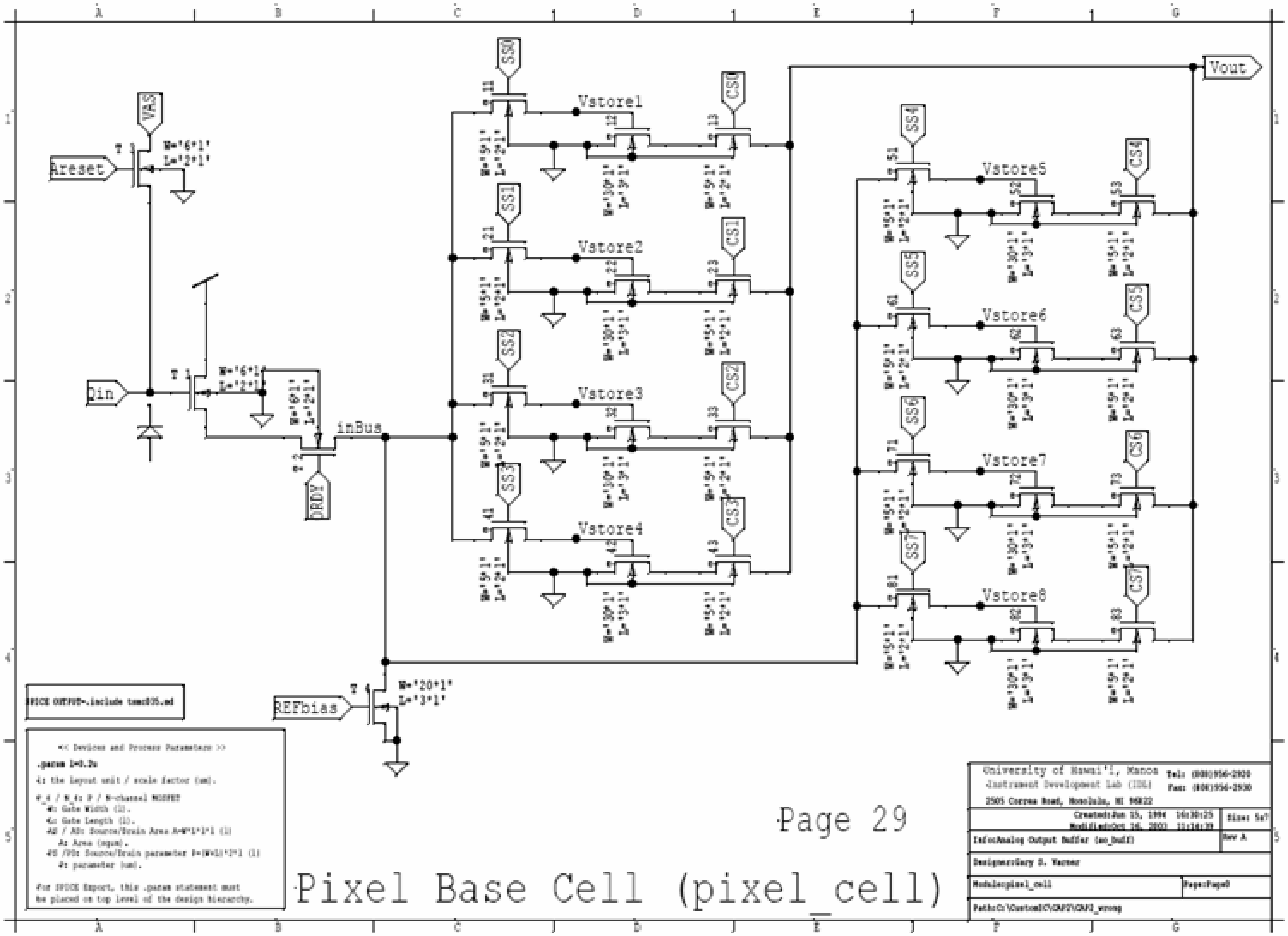
Reality, during the bunch train?



Node capacitance only ~ 40 fF, so highly sensitive

From SLD experience, signal charges stored in buried channel are virtually immune to disturbance by pickup. They were transferred in turn to the output node and sensed as voltages between bunches, when the RF had completely died away

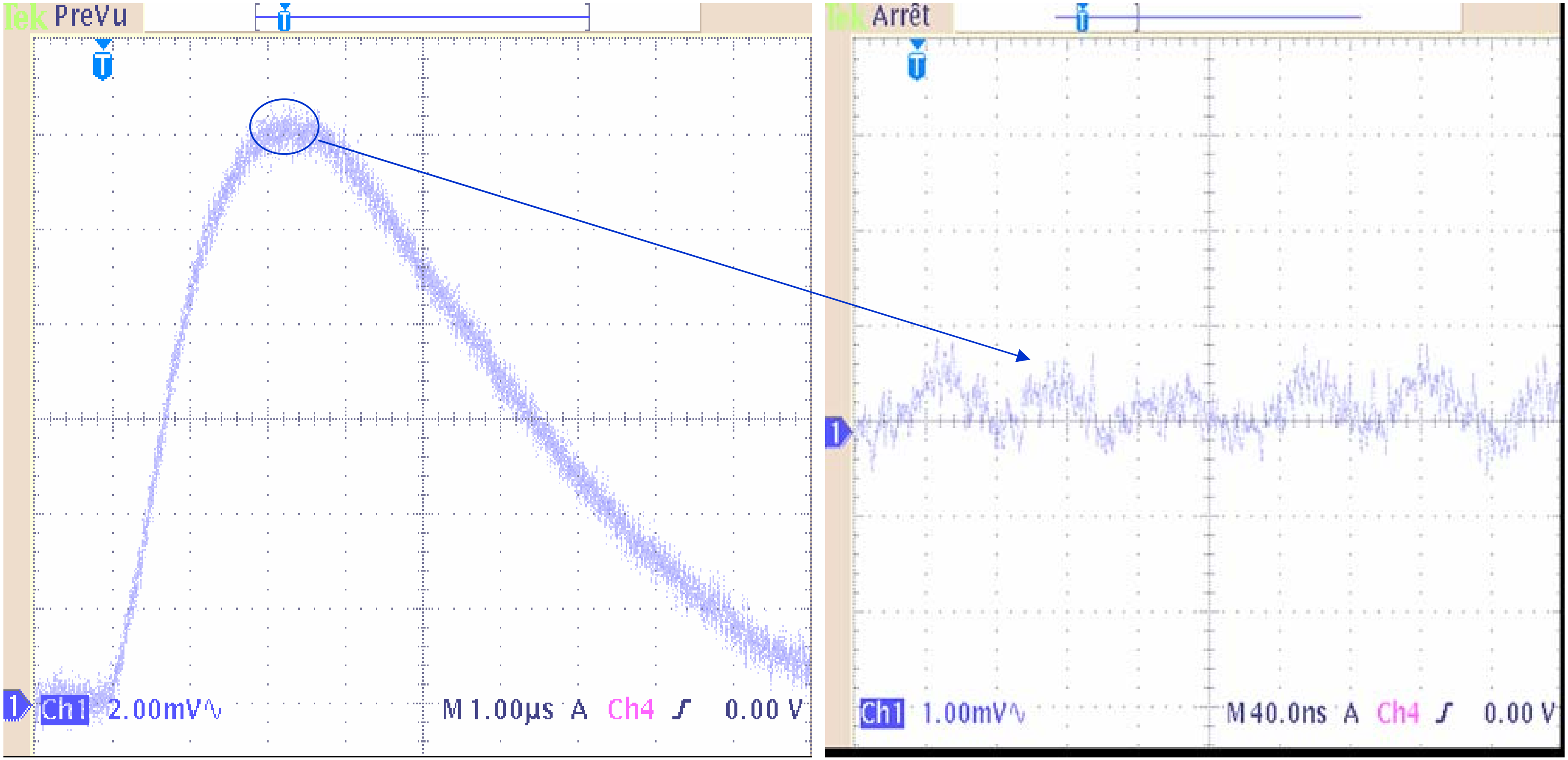
Could this also be done at ILC?



- CAP (Gary Varner), AKA FAPS (Renato Turchetta), AKA multi-cell sensor (Marc Winter)
- Shaping time for pickup on the busline conecting the 8 cell inputs is given by RC ~ 55 ps
- 'Lack of high value series resistors is fundamental to current CMOS' (Jan Kaplan et al, MIC group, CERN)
- Many ICs intended for < 1 MHz operation run into problems due to multi-GHz internal speed capability

This has been and continues to be a major challenge for LCFI readout chip development (CPR-0, CPR-1 and CPR-2)

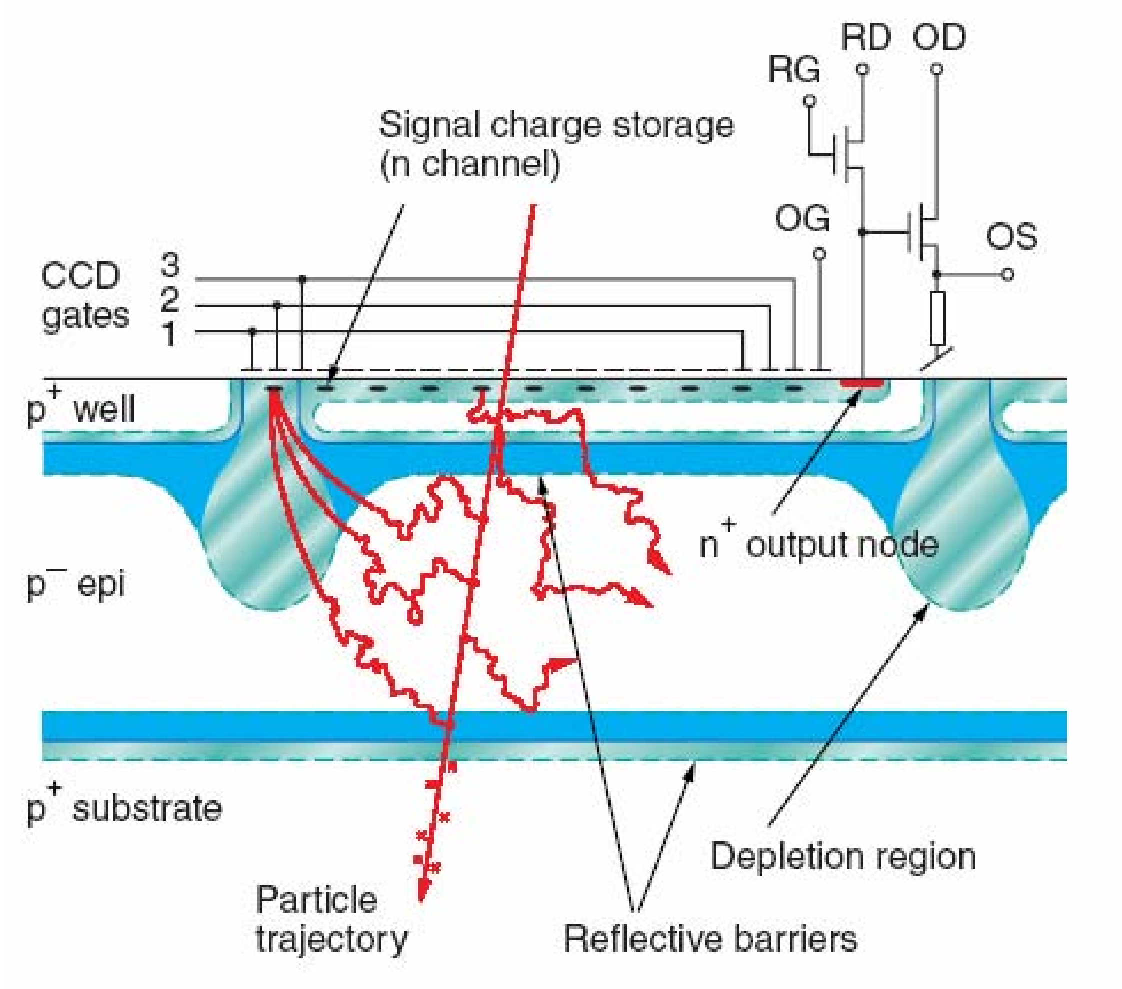
Nice example showed in a recent SiD meeting by Jean-Francois Genat of LPNHE Paris:



0.18 µm readout chip for a silicon tracker
8 MHz oscillations at the shaper output

The ISIS (Image sensor with in-situ storage)

An attempt to devise a sensor with as high EMI immunity as possible



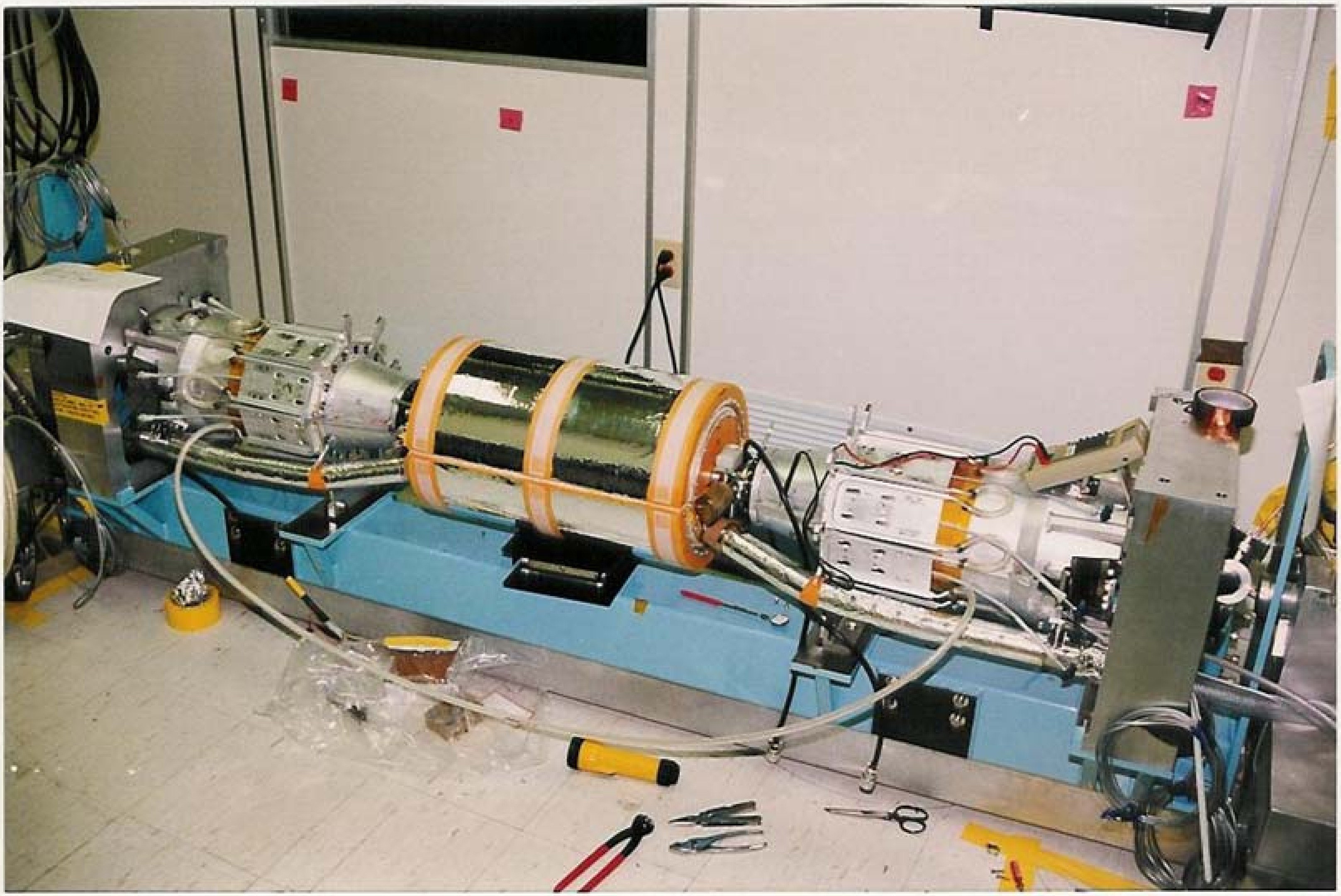
- **charge collection to photogate from ~20 mm silicon, as in a conventional CCD**
- **signal charge shifted into storage register every 50ms, to provide required time slicing**
- **string of signal charges is stored during bunch train in a buried channel, avoiding charge-voltage conversion**
- **totally noise-free charge storage, ready for readout in 200 ms of calm conditions between trains**

The Faraday cage – saviour of EMI-sensitive detectors, *or not?*

A practical implementation (of which we were quite proud) in SLD, 1996

Gas shell, electrically isolated from beampipe, connected by springs to the 4 sections of F-cage endplate …

2 halves of barrel F-cage complete the assembly

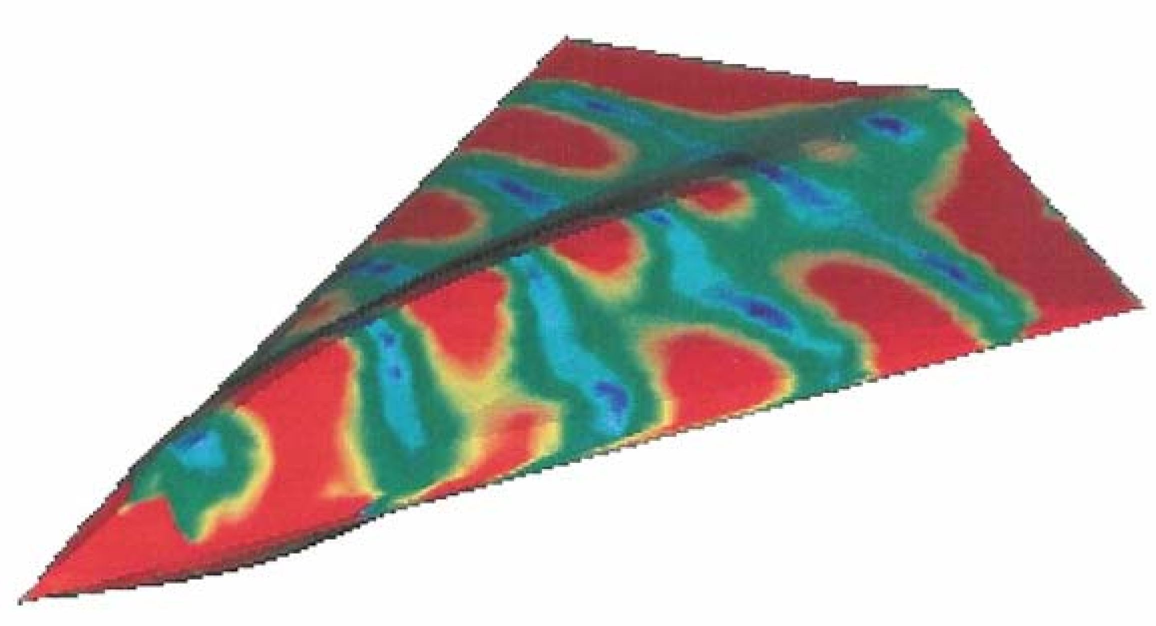


Marvin Johnson (Fermilab) 'Most detector Faraday cages are little more than dust covers'.

Was the SLD box any better than that? With the advantage of hindsight, maybe not …

- ***The problem***
  - **On the scale of 0.3 mm, most detector F-cages are riddled with slot aerials and other apertures through which the RF sails unimpeded**
  - **Even professional systems need serious commissioning – the case of the surprise with the cellphone**
  - **Once inside the enclosure, high frequency radiation bounces off the metal walls repeatedly, creating an isotropic radiation bath, able to excite the waveguides provided by the sensors**

- ***The 'solution'***
  - **UHF bulkhead connectors**
  - **Wide conducting gasket seals to avoid small discontinuities in the contact areas between parts of the F-cage – ideally a welded vessel**
  - **Double screened coax cables, maybe installed in rigid pipe welded to the (thick) ends of the F-cage**
  - **Absorptive coating (foam, plastic, often in form of paint) on interior of F-cage. There are a number of commercial products, developed for defence and other industries. 1 mm thickness provides ~10 dB attenuation for 1-10 GHz**



- ***But, you really don't want to do that …***
  - **Particularly not for the vertex detector, where the material budget is of paramount importance**
  - **Hope instead that a combination of vigilant control of RF sources, and most robust possible sensor design, will produce a happy marriage**

The way forward (a suggestion)

- ***Sensor development***
  - **Follow standard industrial procedures to characterise response of sensors to external RF, injected by cables and in form of radiation**
  - **Use these results in feedback to the sensor development (just as studies of ionising radiation effects are used to develop sufficiently rad-hard sensors)**
  - **Once collaborations come to select their preferred vertex detector option, use these results, along with the other performance parameters, to reach a wise decision**

- ***ILC Commissioning***
  - **Can this be carried out in a relatively open environment (within a blockhouse free of the detector, as was done at SLC)?**
  - **If so, should be possible to include in the machine commissioning a vigilant evaluation of all RF leakage, and fix problems such as badly made connectors, loosely screwed cover plates, dirty gaskets on BPM monitor boxes, whatever**

- ***Detector Installation***
  - **Decide in light of these measurements whether it is safe to use the lightweight F-cage**
  - **If not, one will start with a sub-standard detector, but one which can at least be read out**
  - **Construct and eventually install an upgrade detector using a technology having better EMI-immunity (which may not have been ready in time for startup)**

- ***The SLD mystery***
  - **Is it worth solving? I think so –could provide valuable guidance**
  - **It doesn't require much effort – R20 module is available and could be installed in the ESA test beam**
  - **If not done, who knows if a similar oversight will recur at ILC, with possibly expensive consequences?**

- ***Things not to invest in (?)***
  - ***System Simulations.*** **Sophisticated FE code exists, but is useful only for studying individual components of the system.**
  - ***Typical Commercial EMC consultants.*** **Experience suggests that they are not well qualified to advise on the typical HEP scenario – small signals embedded in high power environments. However, there exist some wonderful specialist companies serving the aerospace and defence markets, dealing with very similar problems to ours**

- ***Sincere thanks (to many patient experts)***

  - ***Aachen U*** **Manfred Tonutti**
  - ***Culham Electromagnetics and Lightning*** **Jim Eastwood, John Hardwick, Mike Hook**
  - ***DESY*** **Ulie Koetz**
  - ***Fermilab*** **Marvin Johnson**
  - ***Hawaii U*** **Sherwood Parker**
  - ***LEPSI*** ***Wojciech Dulinski***
  - ***Oxford U*** **Colin Perry**
  - ***RAL*** ***John Bradford,*** **John Eastment, Brian Ellison, Richard Stephenson,**
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