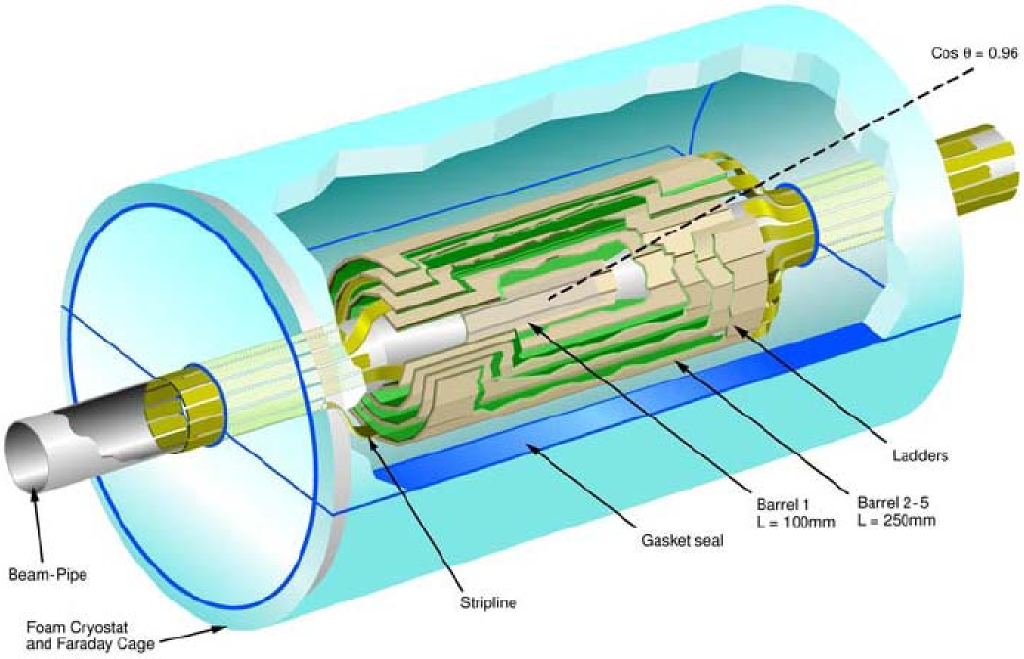
Linear Collider Flavour Identification

Bristol, Glasgow, Liverpool, Oxford, RAL

- Introduction to LCFI and the ILC
  - Physics at the ILC
  - LCFI physics studies
  - Sensor design and testing
  - Mechanical studies
- Proposed LCFI programme
  - Simulation and physics studies
  - Sensor development
  - Readout and drive electronics
  - External electronics
  - Integration and testing
  - Mechanical studies
  - Test-beam and electromagnetic interference studies

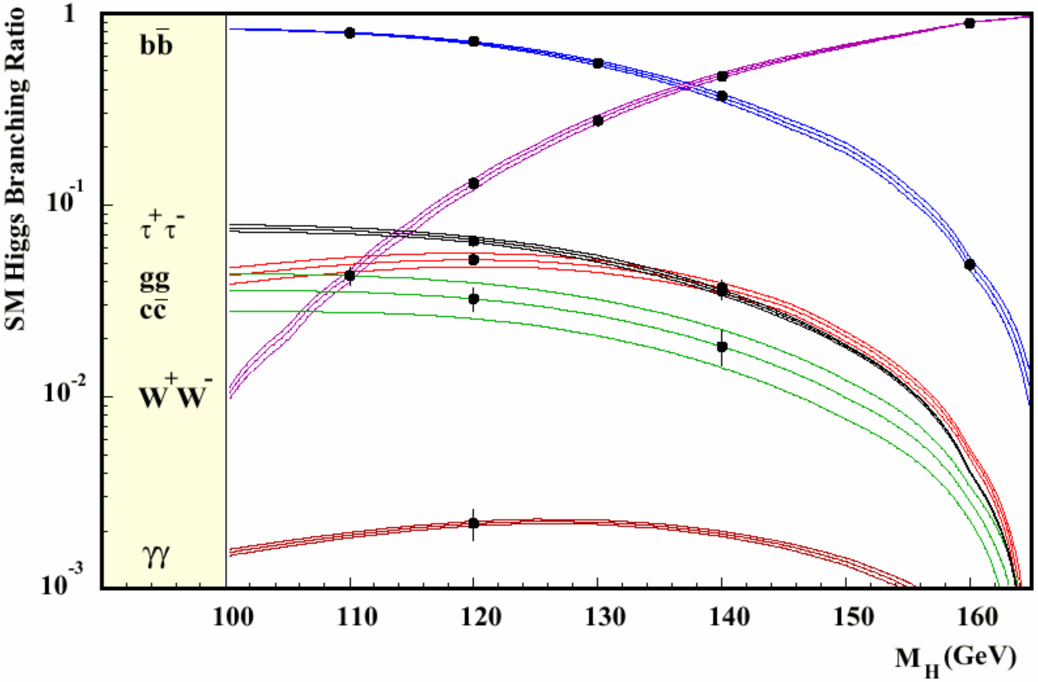


The International Linear Collider

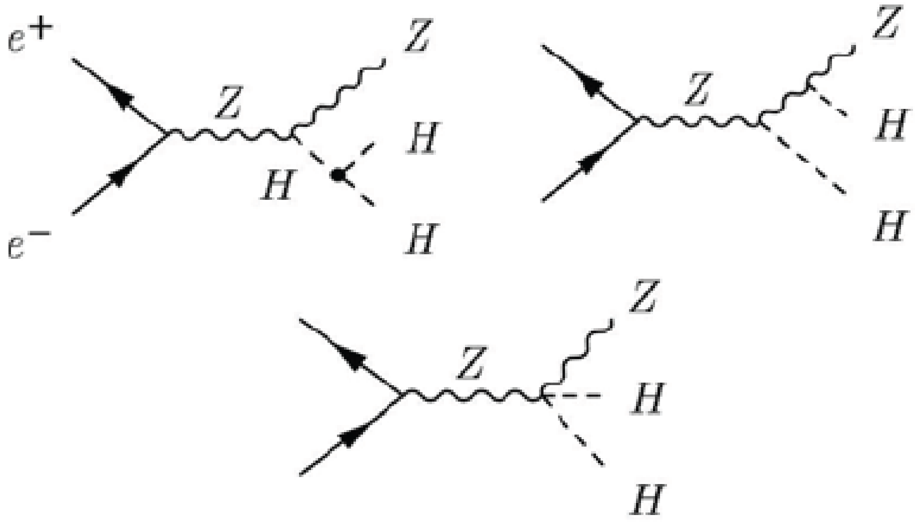
- Standard Model of particle physics is clearly incomplete.
- From 2007, LHC experiments will study pp collisions $\sqrt{s} = 14$ TeV giving large mass reach for discovery of new physics.
- Precision measurement (of masses, branching ratios etc.) complicated by hadronic environment.
- International consensus: e^+e^- LC operating at up to $\sqrt{s} \sim 1$ TeV needed in parallel with the LHC, i.e. start-up in next decade.
- Detailed case presented by LHC/LC Study Group: hep-ph/0410364.
- International Technology Review Panel recommended in August 2004 that superconducting technology be used for accelerating cavities.
- Global effort now underway to design SC ILC, director Barry Barish.
- Timeline defined by ILC Steering Group foresees formation of experimental collaborations in 2008 and writing of Technical Design Reports in 2009.
- Agreement that vertex detector technology be chosen following “ladder” tests in 2010.

Flavour and quark charge identification at the ILC

- Many of interesting measurements involve identification of heavy quarks.
- E.g. determination of branching ratios of Higgs boson.
- Are BRs compatible with the SM?



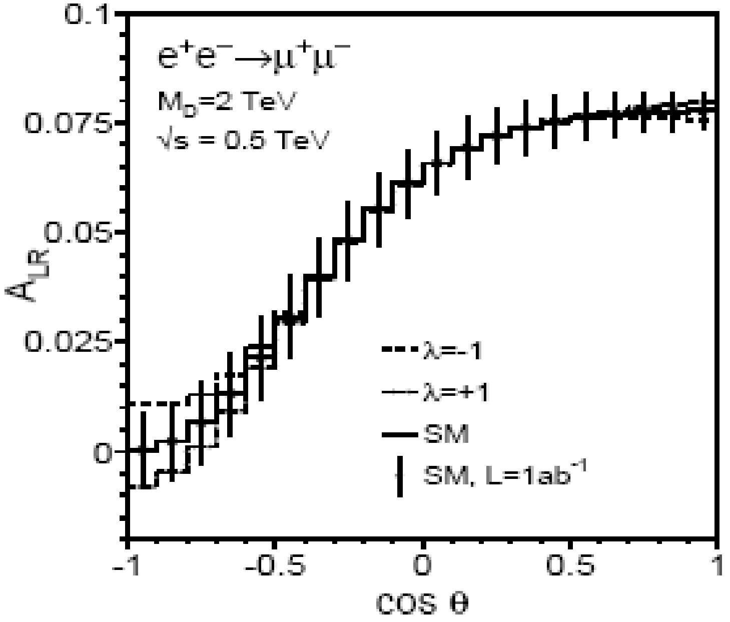
- Physics studies can also benefit from separation of b from $\bar{b}$ and c from $\bar{c}$.
- E.g. $e^+e^- \rightarrow HHZ$:



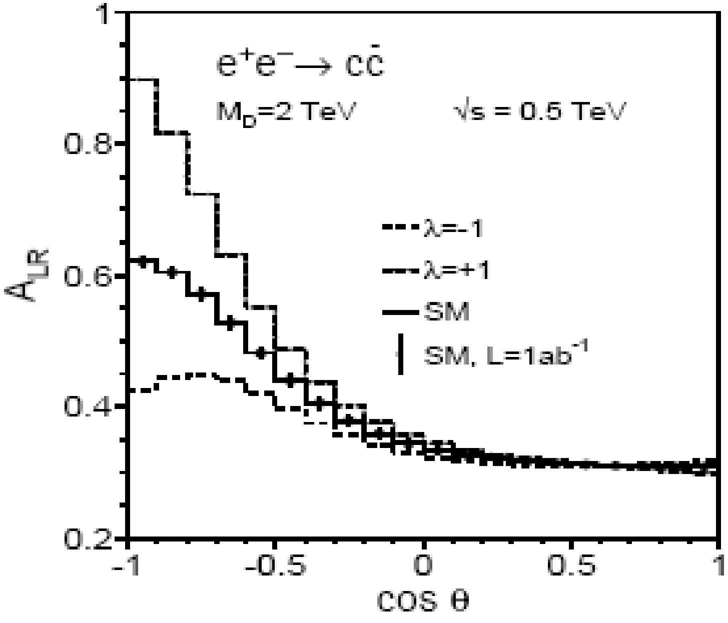
- Reduce combinatorial background.
- Allows determination of Higgs self-coupling.

Quark charge identification

- Increases sensitivity to new physics.
- E.g. effects of large extra dimensions on $e^+e^- \to f\bar{f}$.
- Study $A_{LR} = (\sigma_L - \sigma_R)/\sigma_{tot}$ as a function of $\cos\theta$.
- For muons, effects of ED not visible:



- Changes much more pronounced for c (and b) quarks:



- Requires efficient charge determination to large $\cos\theta$.

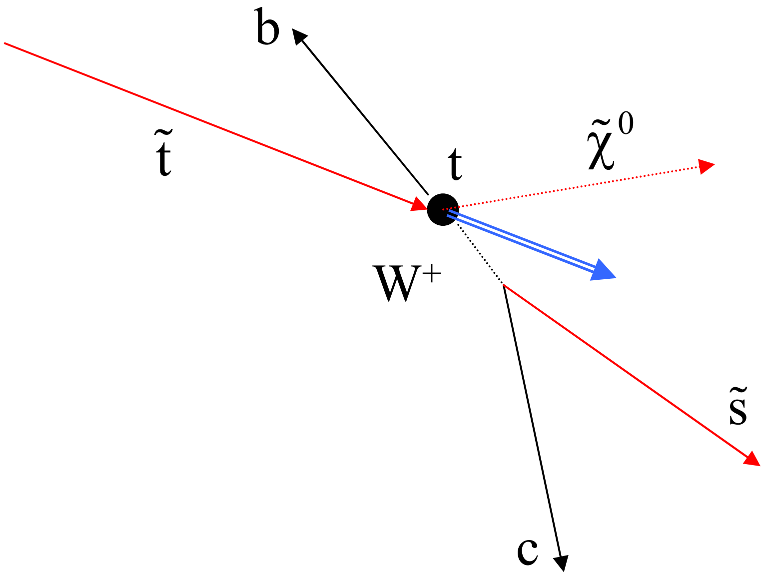
Quark charge identification

- Provides new tools for physics studies.
- E.g. measure top polarisation in decay $t \to W^+ b$

$$\begin{array}{l} t \to W^+ b \\ \quad\;\; \searrow \\ \qquad c\,\bar{s} \end{array}$$

- Top decays before hadronisation.
- Anti-strange jet has $1 - \cos\theta$ distribution w.r.t. top polarisation direction.
- Distinguish between t and $\bar{t}$ by tagging b and c jets.
- Determine quark charge for (at least) one of these jets.

- Example of physics made accessible using this technique:



- Determine $\tan\beta$ and tri-linear couplings A_t and A_b through measurements of top polarisation in $\tilde{b}$ and $\tilde{t}$ decays.

Vertex detector performance goals

- Average impact parameter, d_0, of B decay products ~ 300 μm, of charmed particles less than 100 μm.
- d_0 resolution given by convolution of point precision, multiple scattering, lever arm, and mechanical stability.
- Multiple scattering significant despite large √s at ILC as charged track momenta extend down to ~ 1 GeV.
- Resolve all tracks in dense jets.
- Cover largest possible solid angle: forward/backward events are of particular significance for studies with polarised beams.
- Stand-alone reconstruction desirable.
- In terms of impact parameter, require resolution in rϕ and rz:

$$\sigma = \sqrt{a^2 + \left(\frac{b}{p\sin^{\frac{3}{2}}\theta}\right)^2}$$

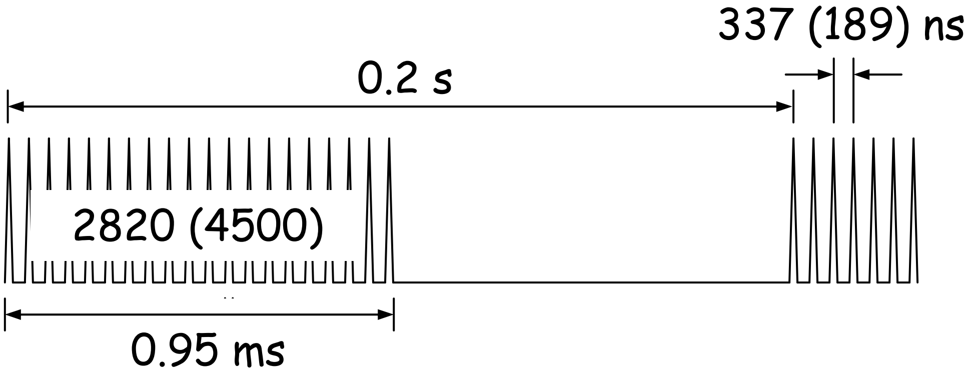
$$a < 5\,\mu\mathrm{m}\ (\text{point precision})$$

$$b < 10\,\mu\mathrm{m}\ (\text{multiple scattering}).$$

- Implies typically:
  - Pixels ~ 20 x 20 μm^2.
  - First measurement at r ~ 15 mm.
  - Five layers out to radius of about 60 mm, i.e. total ~ 10^9 pixels
  - Material ~ 0.1% X_0 per layer.
  - Detector covers $|\cos\theta| < 0.96$.

Constraints due to machine and detector

- Minimum beam pipe radius 14 mm.
- Pair background at this radius in ~ 4T field causes 0.03 (0.05) hits per BC and mm^2 at $\sqrt{s}$ = 500 (800) GeV.
- Bunch train structure:



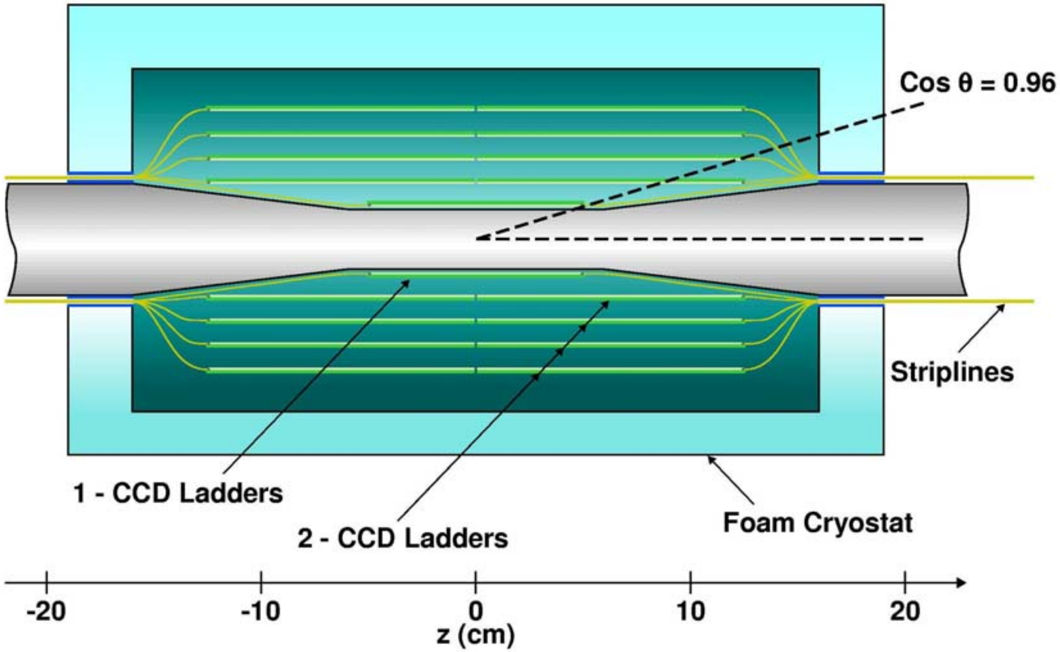
- For pixels of size 20 x 20 μm^2, implies readout or storage of signals ~ 20 times during bunch train to obtain occupancy less than ~ 0.3 (0.9) %.
- Must withstand:
  - Radiation dose due to pair background of ~ 20 krad p.a.
  - Annual dose of neutrons from beam and beamstrahlung dumps ~ 1 x 10^9 1 MeV equiv. n/cm^2.
- Must cope with operation in 4T field.
- Beam-related RF pickup and noise from other detectors may be an issue.

Constraints due to machine and detector

- ILC may be more hostile environment than storage ring.
- Nanometre beam spots and single pass operation mean invasive diagnostic tools essential, e.g. BPMs, with possible imperfections in shielding of cables, optical ports...
- Vertex detector is more vulnerable to pickup than other detectors due to:
  - Proximity to beampipe – Faraday cage ideals tend to be compromised.
  - Signals typically only ~ 1000 e^-, must be amplified electronically and read out.
- SLD vertex detector observed massive pickup and optical transmission was disrupted by every bunch: tens of μs needed for recovery.
- SLD CCD readout strategy:
  - During bunch train, signal charge is stored safely in buried channel.
  - When pickup has died down, charge transferred to output node and sensed as voltage on gate of output transistor.
- SLD still needed filter which suppressed noise by factor ~ 100.

Conceptual vertex detector design

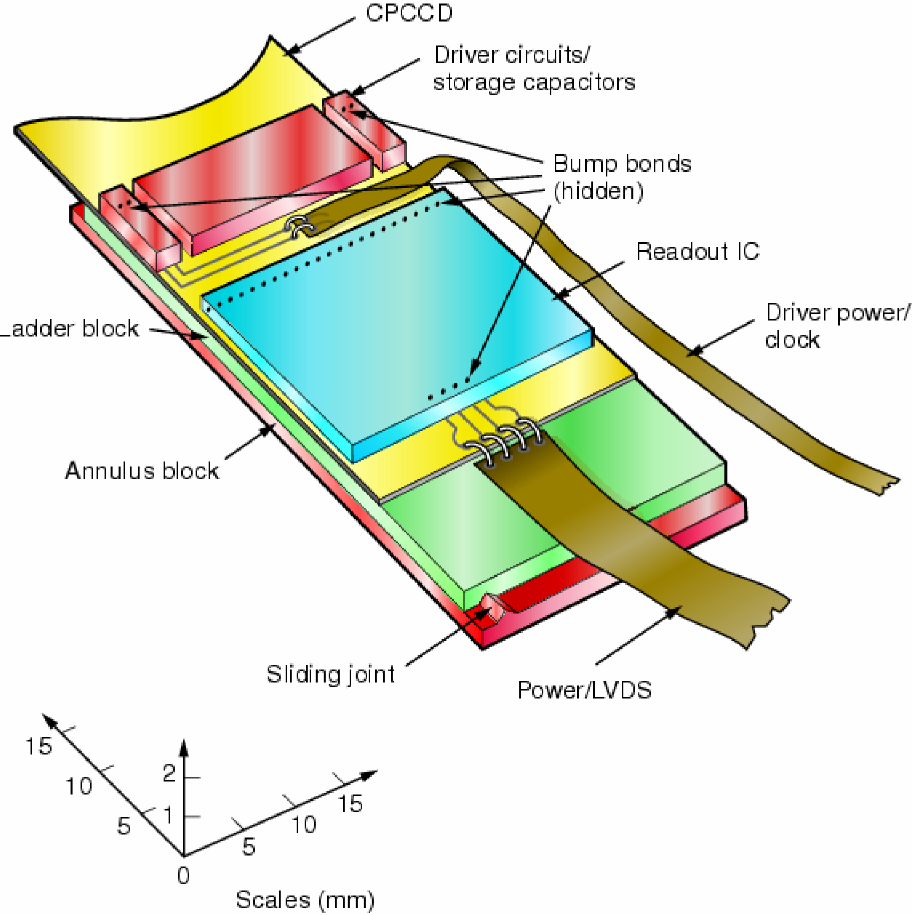
- Here using CCDs:



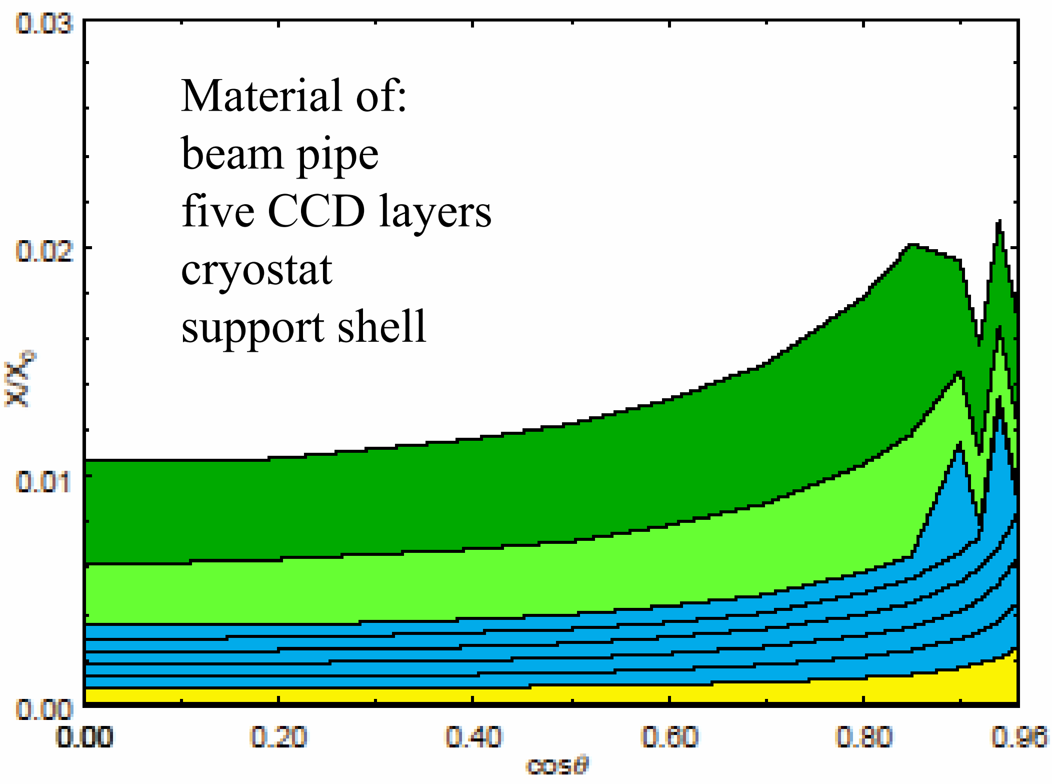
- VXD surrounded by ~ 2 mm thick Be support cylinder.
- Allows Be beam pipe to be of thickness of ~ 0.25 mm.
- Pixel size 20 x 20 μm^2, implies about 10^9 pixels in total.
- Standalone tracking using outer 4 layers.
- Hits in first layer improve extrapolation of tracks to IP.
- Readout and drive connections routed along BP.
- Important that access to vertex detector possible.

Conceptual detector design

- Amount of material in active region minimized by locating electronics only at ends of ladders.



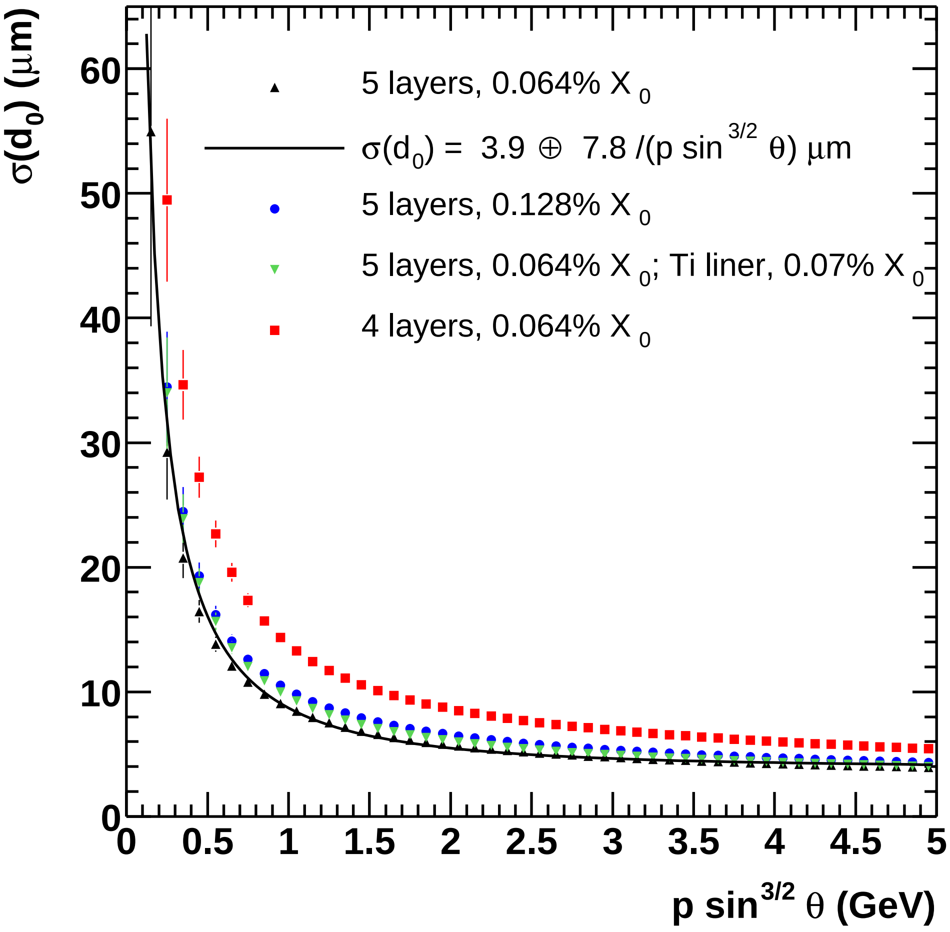
- Resulting material budget, assuming unsupported silicon sensors of thickness ~ 50 μm:



Vertex detector performance – impact parameter

- Performance of vertex detector investigated and optimised using Monte Carlo simulations.
- E.g. study effect on impact parameter resolution of variations in beam pipe radius, material budget and number of layers in vertex detector.
- Observe moderate effects due to increase in material budget, severe degradation due to increase in beam pipe radius.

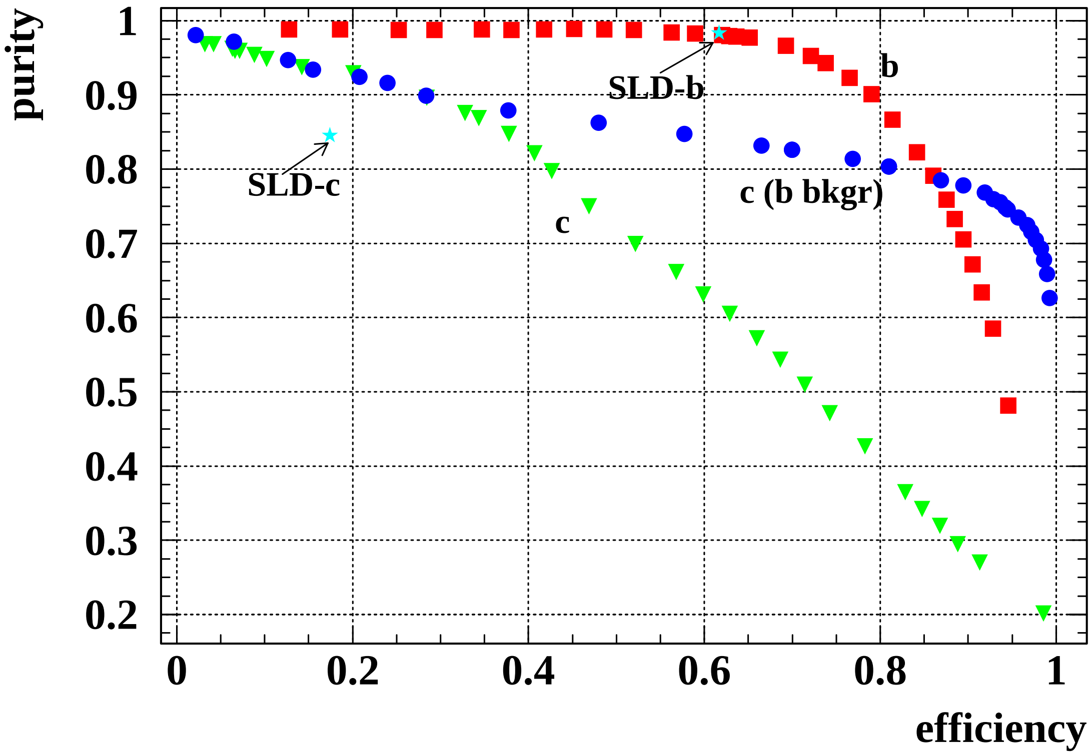
- Impact parameter resolution



Flavour identification performance

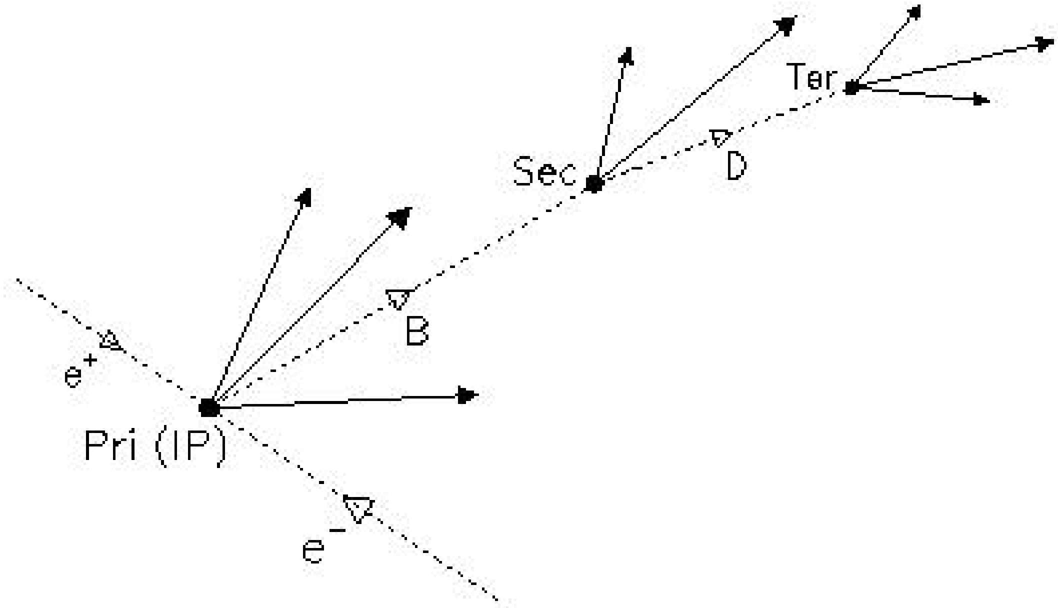
- Simulate flavour ID in $e^+e^- \to q\bar{q}$ events, here at Z^0 pole.
- Feed information on impact parameters and vertices identified using Zvtop algorithm into neural net.
- Modest improvement in beauty tagging efficiency/purity over that achieved at SLD.
- Improvement by factor 2 to 3 in charm tagging efficiency at high purity.
- Charm tag with low uds background interesting e.g. for Higgs BR measurements.

- Efficiency and purity of tagging of beauty and charm jets:



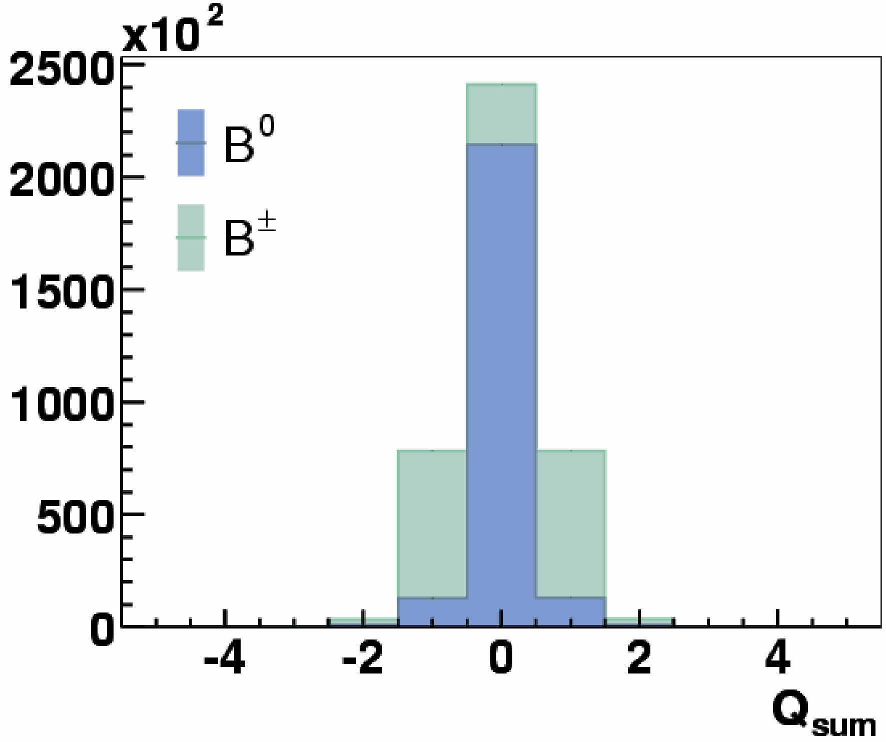
Quark charge identification performance

- Must assign all charged tracks to correct vertex.



- Multiple scattering critical, lowest track momenta ~ 1 GeV.

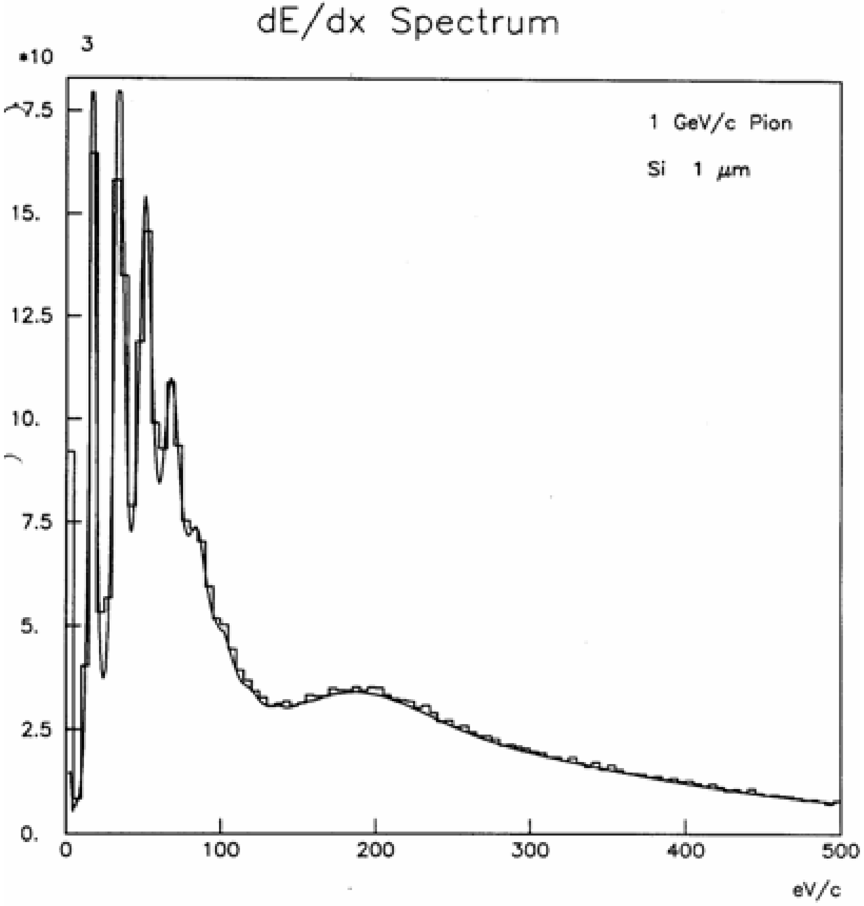
- Sum charges associated with b vertex:



- Quark charge identification for neutral B requires “dipole” algorithm.

Future physics performance studies

- Monte Carlo used so far is simplistic, must simulate all relevant effects from “MIPS to physics”.
- Need realistic simulation of processes leading to detection of tracks in the vertex detector, “MIPS to tracks”.
- E.g. must include:
  - Realistic dE/dx distribution in silicon and subsequent motion of charge in sensor.
  - Simulation of cluster finding and sparsification algorithms used in readout electronics.
  - Effects of backgrounds.
- Feedback to sensor/electronics design.
- dE/dx spectrum for 1 GeV pion in 1 μm of silicon:

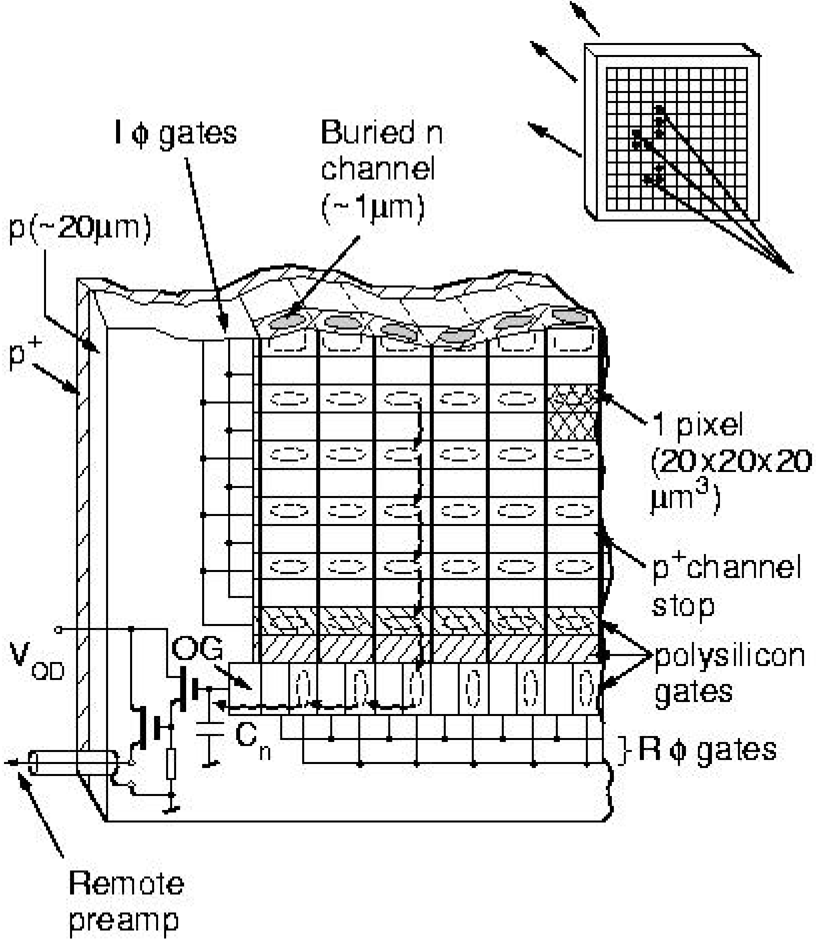


Future physics performance studies – tracks to vertex

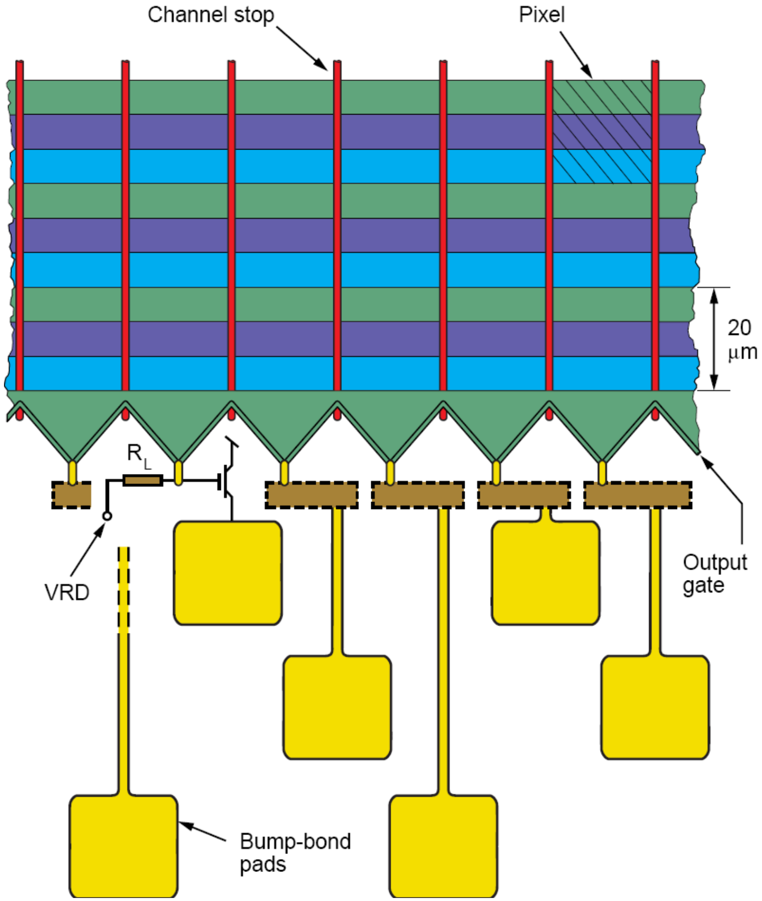
- Study factors affecting flavour identification and quark charge determination, “tracks to vertex”, including:
    - Optimise flavour ID and extend quark charge determination to B^0.
    - Examine effects of sensor failure.
    - Detector alignment procedures and effects of misalignments.
    - Polar angle dependence of flavour and charge identification.
- Provide feedback for mechanical design.
- May lead to design changes, e.g. additional layer, increased barrel length.
- With complete simulation, study physics processes for which vertex detector is crucial, for example:
    - Higgs branching fractions, requires flavour ID.
    - Higgs self-coupling, requires flavour and charge ID.
    - Charm and bottom asymmetries, requires flavour and charge ID.
    - Need to be prepared to react to discoveries at LHC.

Sensors for the vertex detector – CCDs

- Standard CCDs cannot achieve necessary readout speed

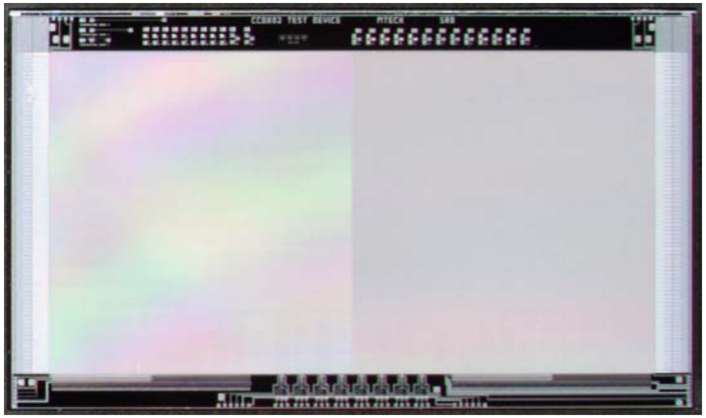


- LCFI developed Column Parallel CCD with e2v technologies.



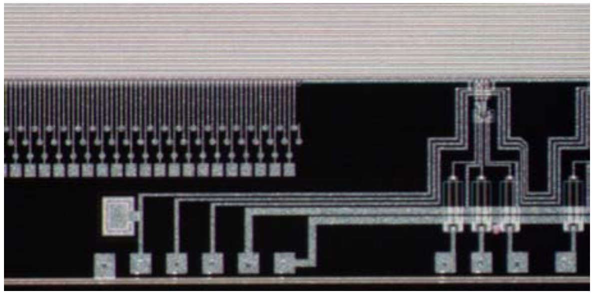
Sensors – CPCCD

- First of these, CPC1, manufactured by e2v.

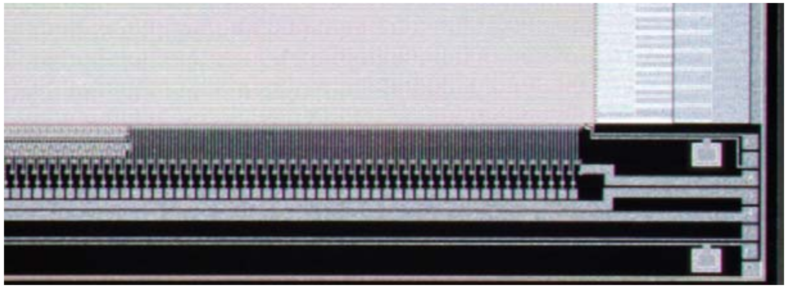


- Two phase, 400 (V) × 750 (H) pixels of size 20 × 20 μm^2.
- Metal strapping of clock gates.
- Two different gate shapes.
- Two different implant levels.

- Wire/bump bond connections to readout chip and external electronics.
  - Direct connections and 2-stage source followers:

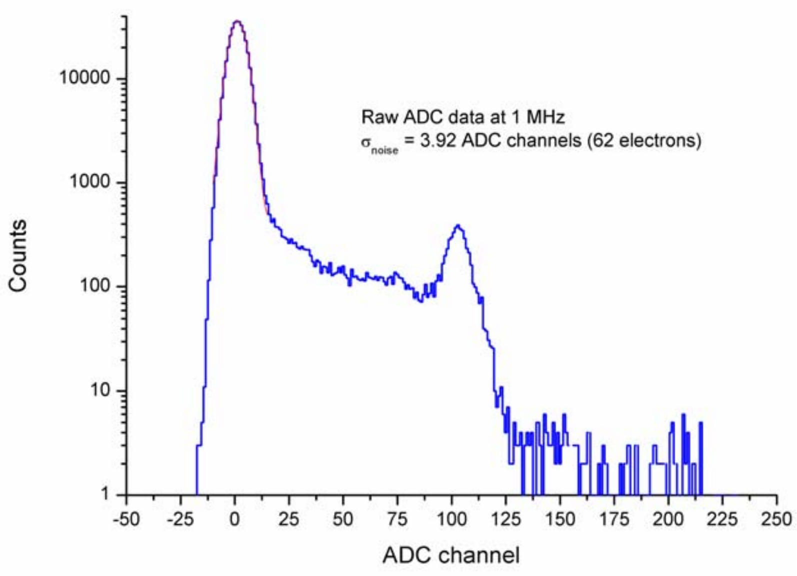


  - Direct connections and single stage source followers (20 µm pitch):



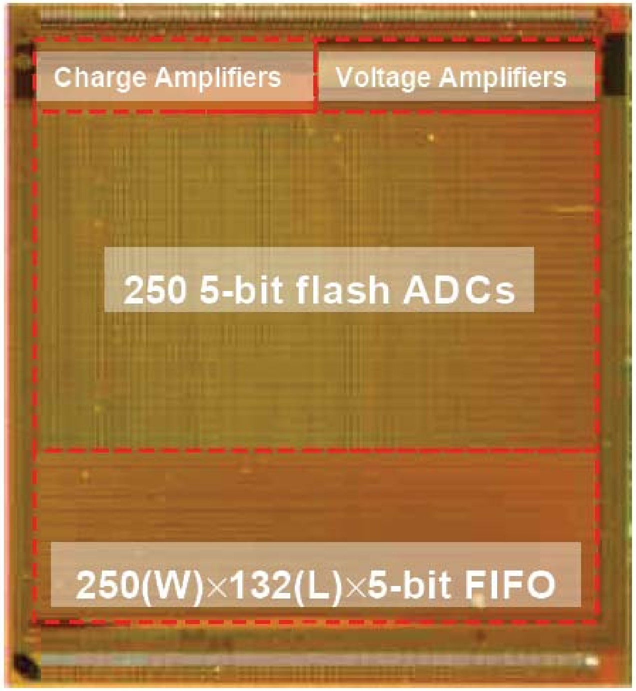
Sensors – CPC1 and CPR1

- Standalone CPC1 tests:
- Noise ~ 100 e⁻ (60 e⁻ after filter).
- Minimum clock potential ~1.9 V.



- Max clock frequency above 25 MHz (design 1 MHz).
- Limitation caused by asymm. clock signals due to single metal design.

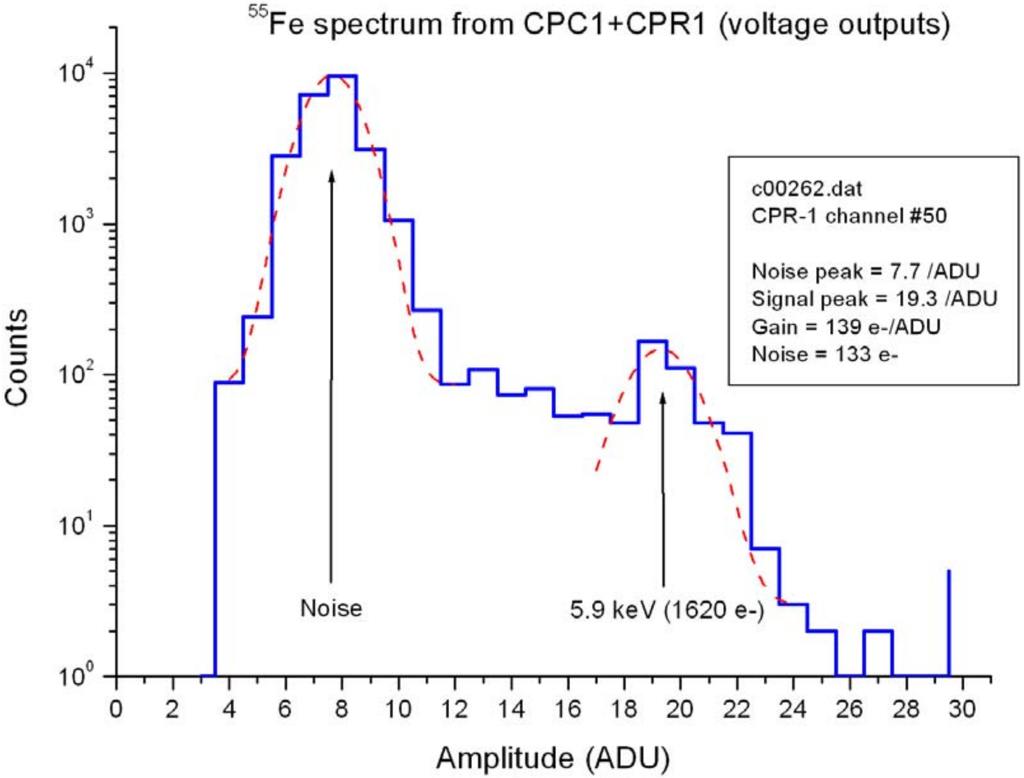
- Marry with CMOS CPCCD readout ASIC, CPR1 (RAL):



- IBM 0.25 µm process.
- 250 parallel channels, 20µm pitch.
- Designed for 50 MHz.

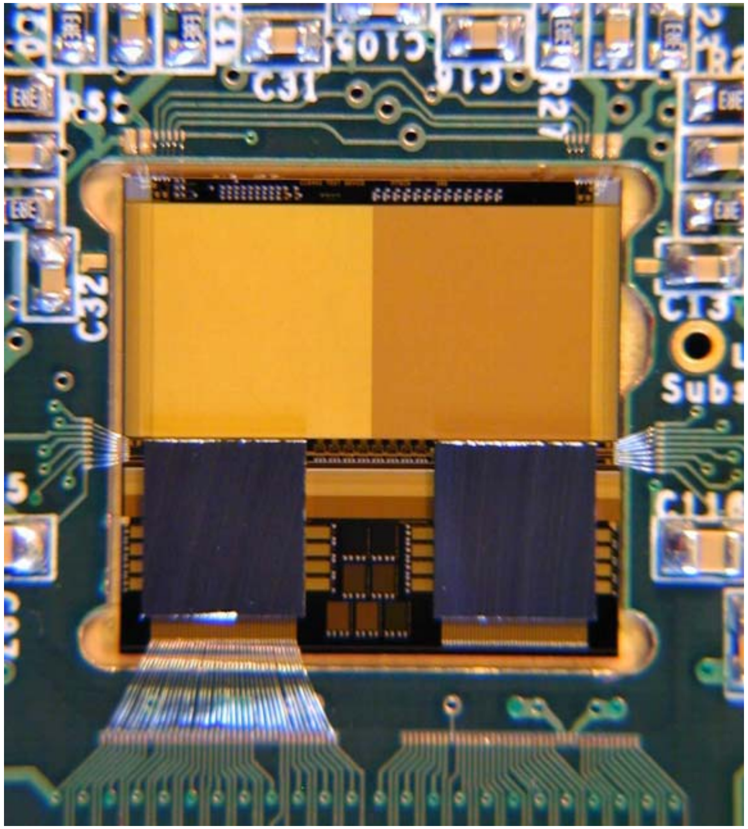
Sensors – CPC1 and CPR1

- Wire bonded CPC1 – CPR1 assembly.



- Total noise ~130 electrons.

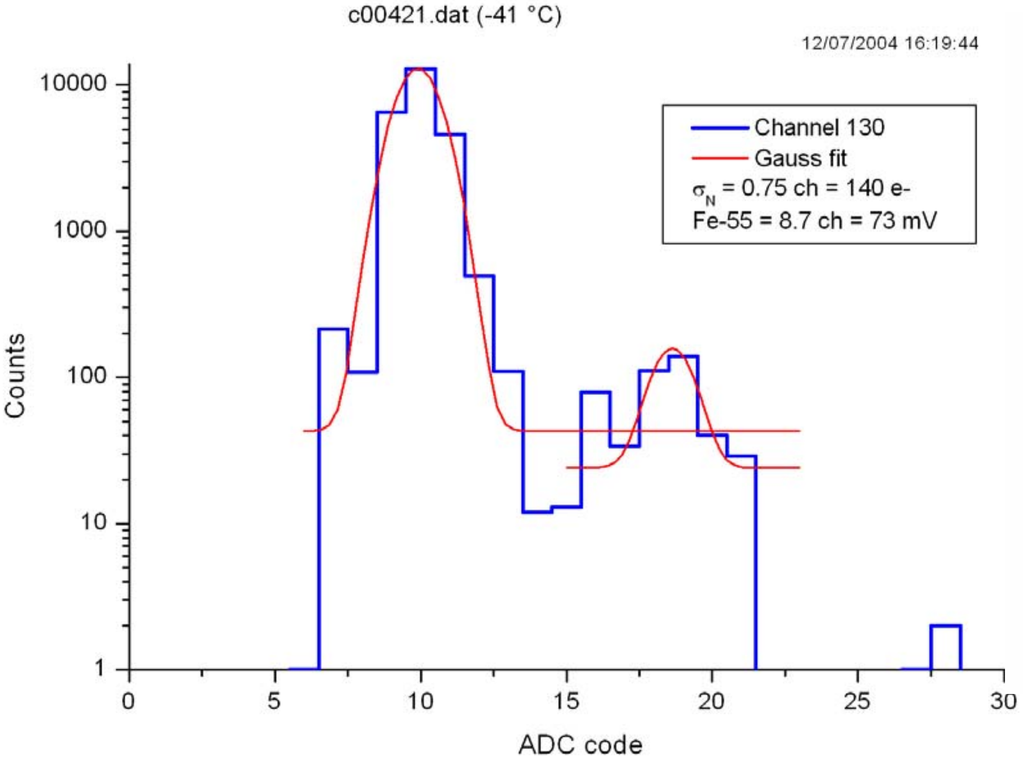
- Bump bonding done at VTT:



- First time e2v CCDs have been bump bonded.

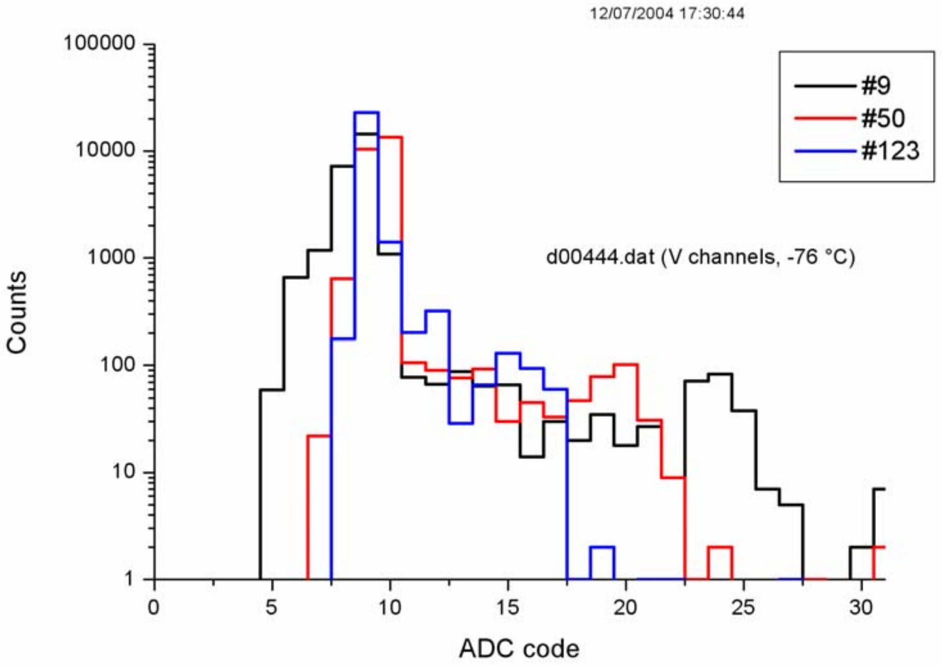
Sensors – CPC1 and CPR1

- CPR1 bump bonded to CPC1, charge channels:



- Observe ~ 70 mV signal, expected 80 mV, good agreement.

- Voltage channel gain decreases towards centre of chip.

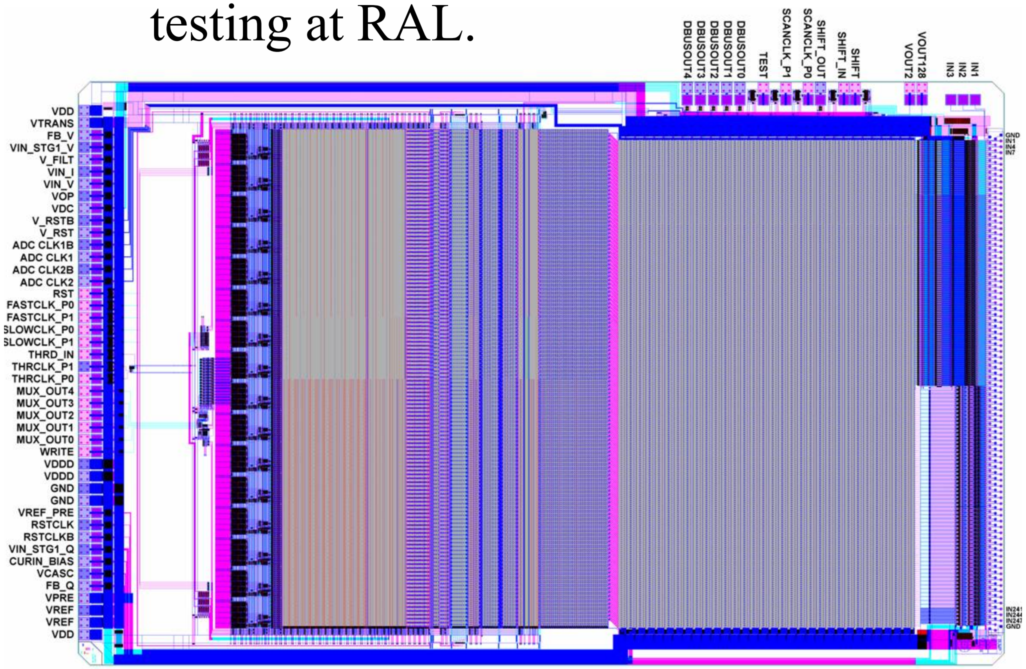


- Traced to timing problems in CPR1.

Sensors – CPC1 and CPR1

- Problems resolved in CPR2 design which also includes cluster finding logic and sparsified readout.
- Devices now delivered and awaiting testing at RAL.

- Bump bonding problems.

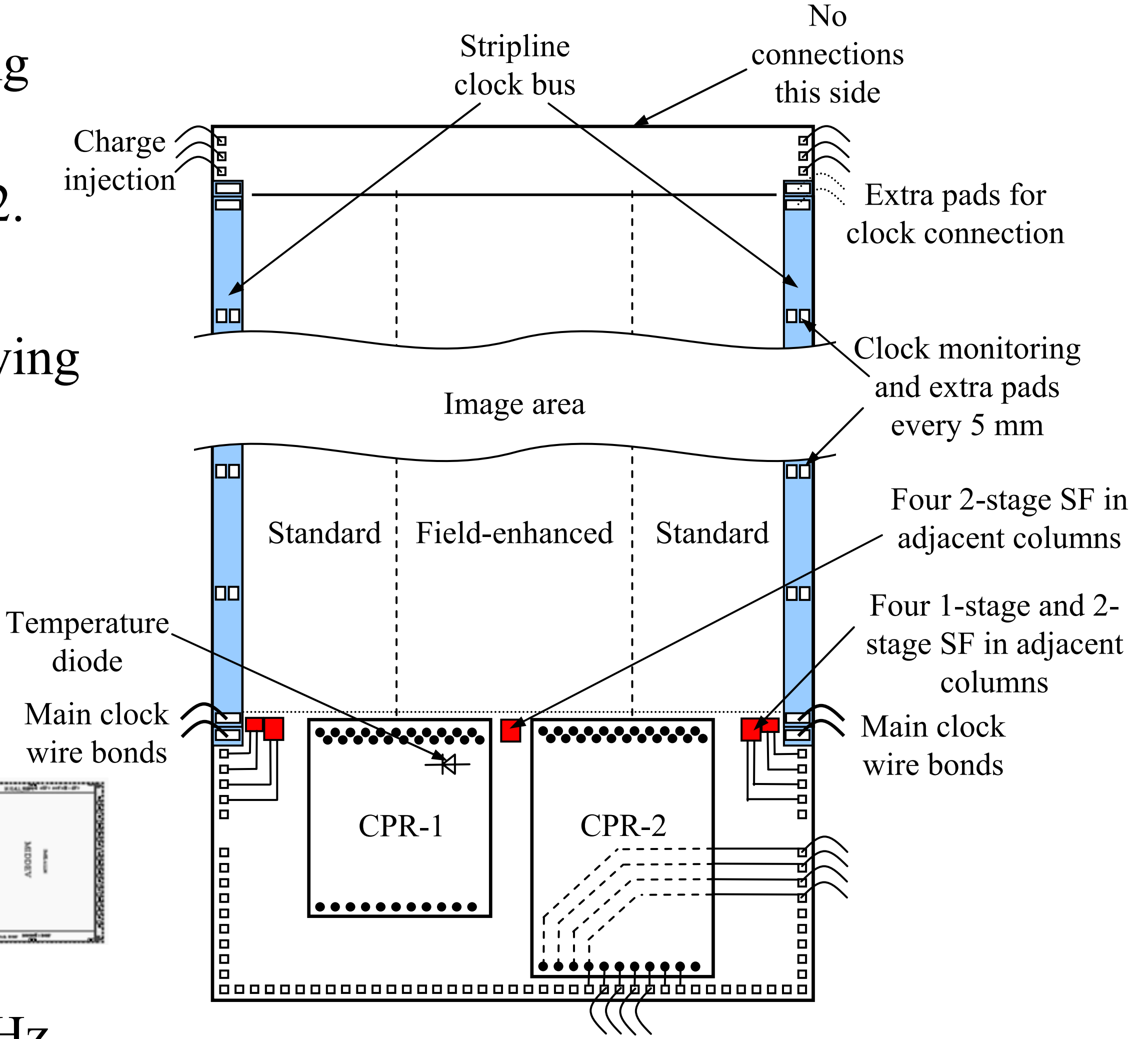


o/p | spars. MPX | clust. find | bin. conv. | 5-bit ADC | pre-amp

Sensors – CPCCD

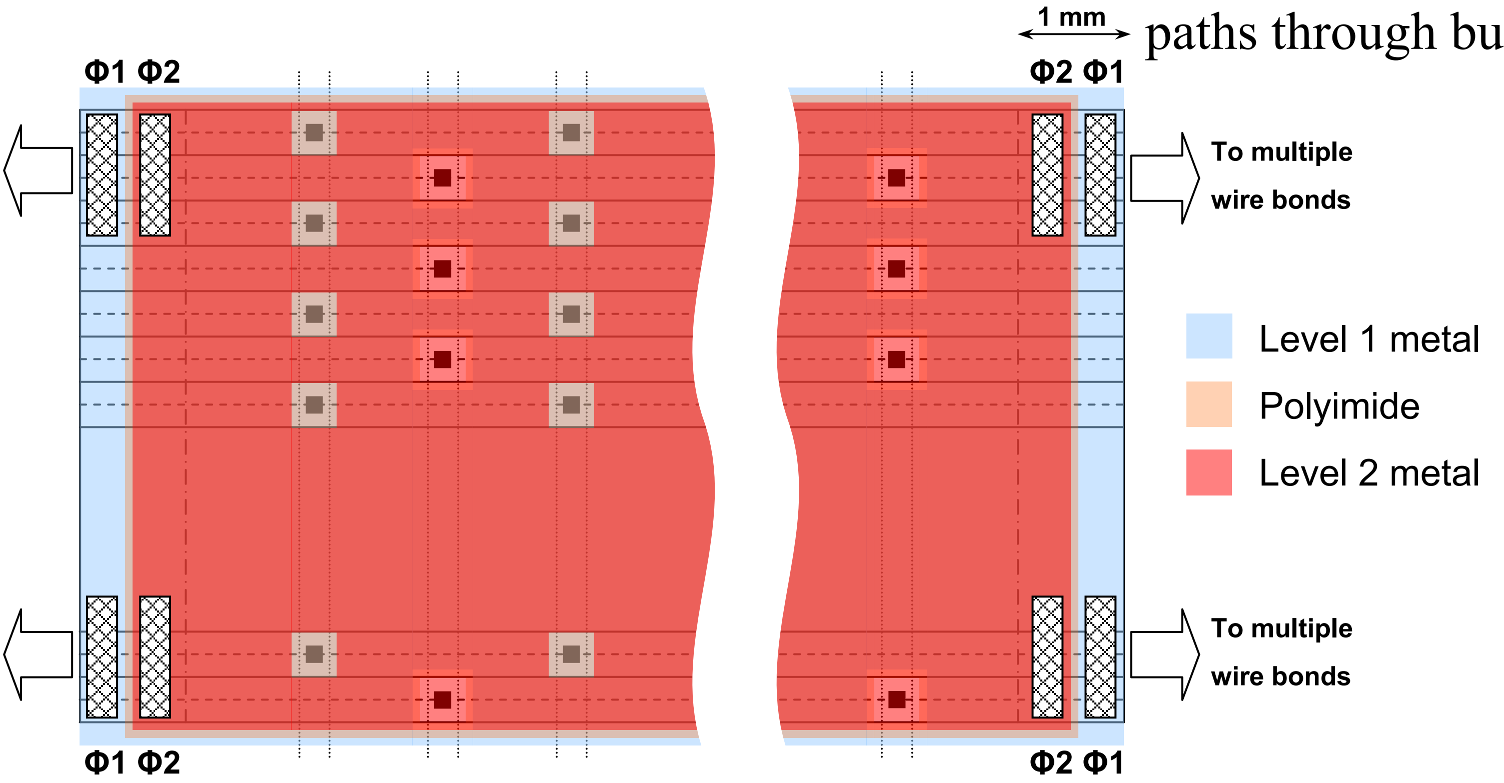
- Next generation, CPC2, now being manufactured.
- Compatible with CPR1 and CPR2.
- Two charge transport sections.
- Choice of epitaxial layers for varying depletion depth.
- Three chip sizes, includes:
- Large scale stitched devices, area 9.2 x 1.5 cm^2, close to ILC size, operate at few MHz.

- Smaller devices for tests to 50 MHz.



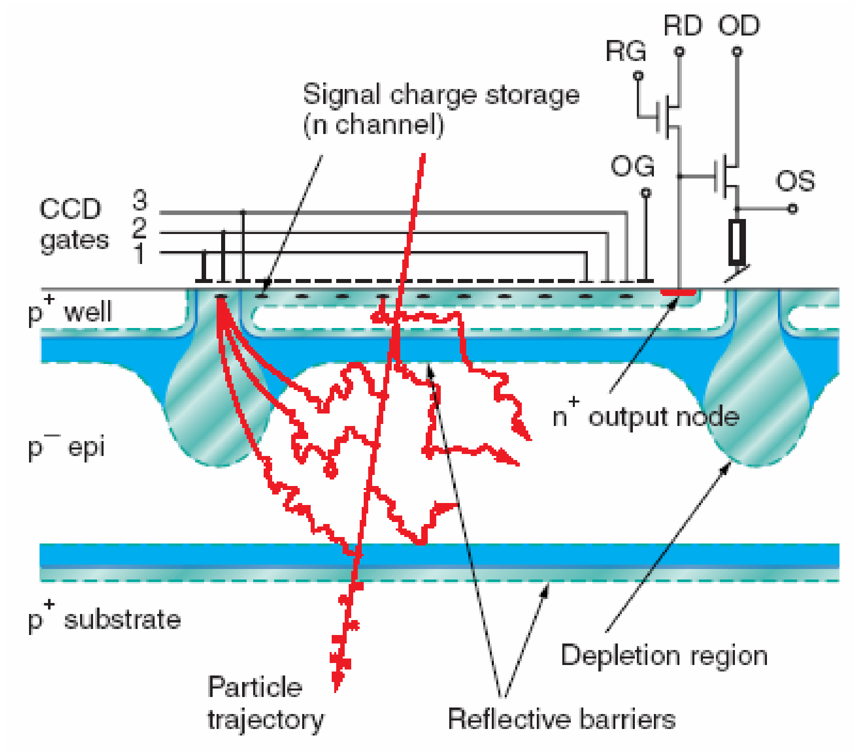
Sensors – CPCCD

- High-speed clock propagation, “busline free” CCD.
- Whole image area serves as distributed bus.
- Highest speed potential, 50 MHz achievable with suitable driver.
- Expect robust against pickup as signals “in silicon” until very short paths through bump bonds to CPR.



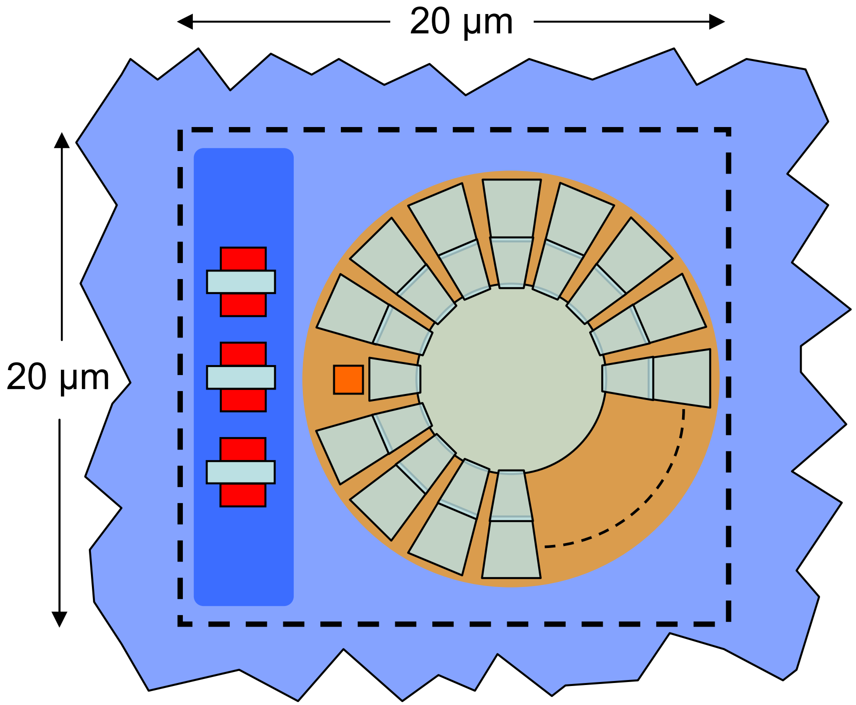
Sensors – ISIS

- In-situ storage image sensor.

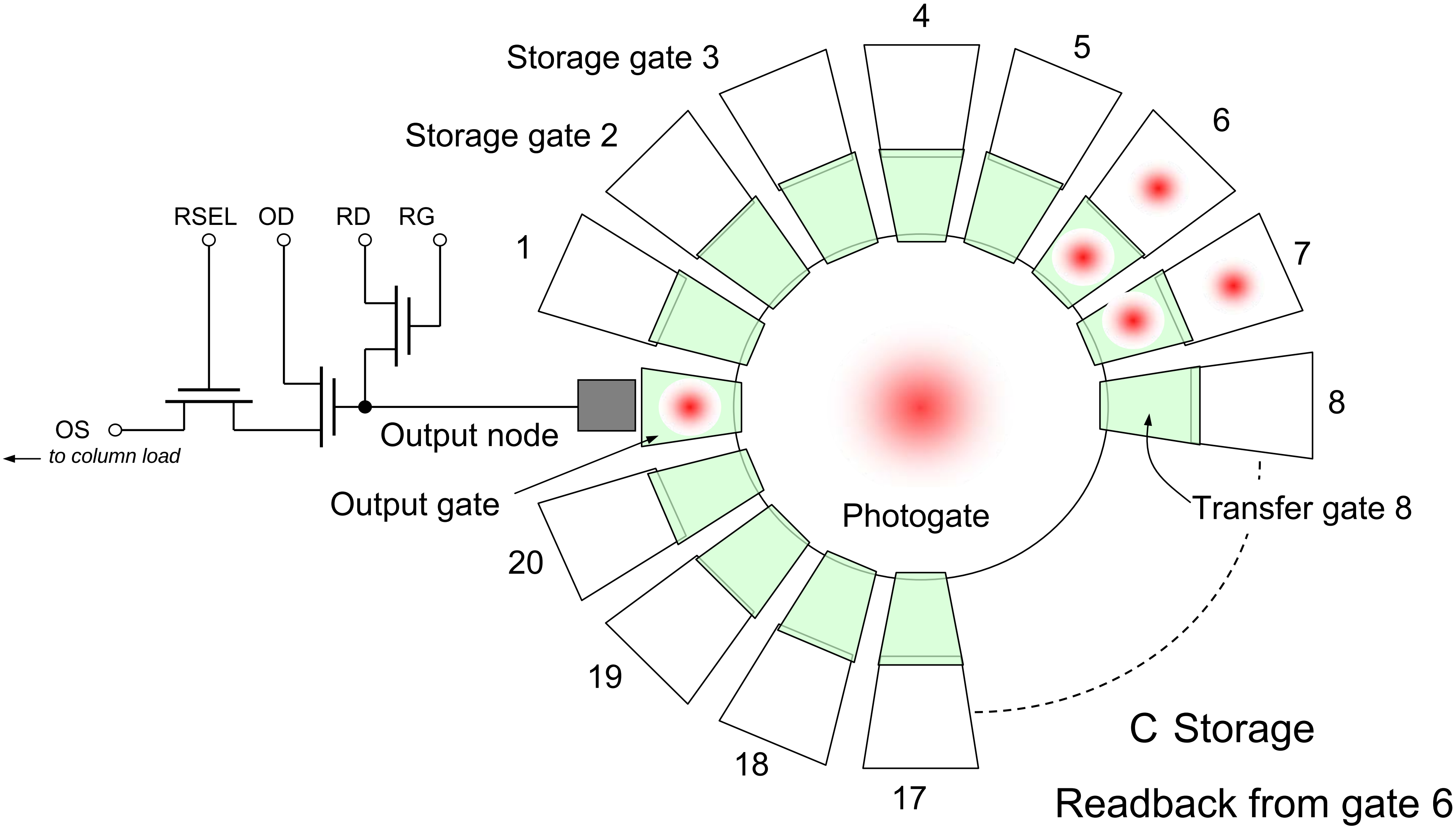


- Signal always buried in silicon until bunch train passed.
- Test device being built by e2v.

- “Revolver” variant of ISIS reduces number of charge transfers needed, increases radiation hardness and also flexibility of readout.



Sensors – ISIS

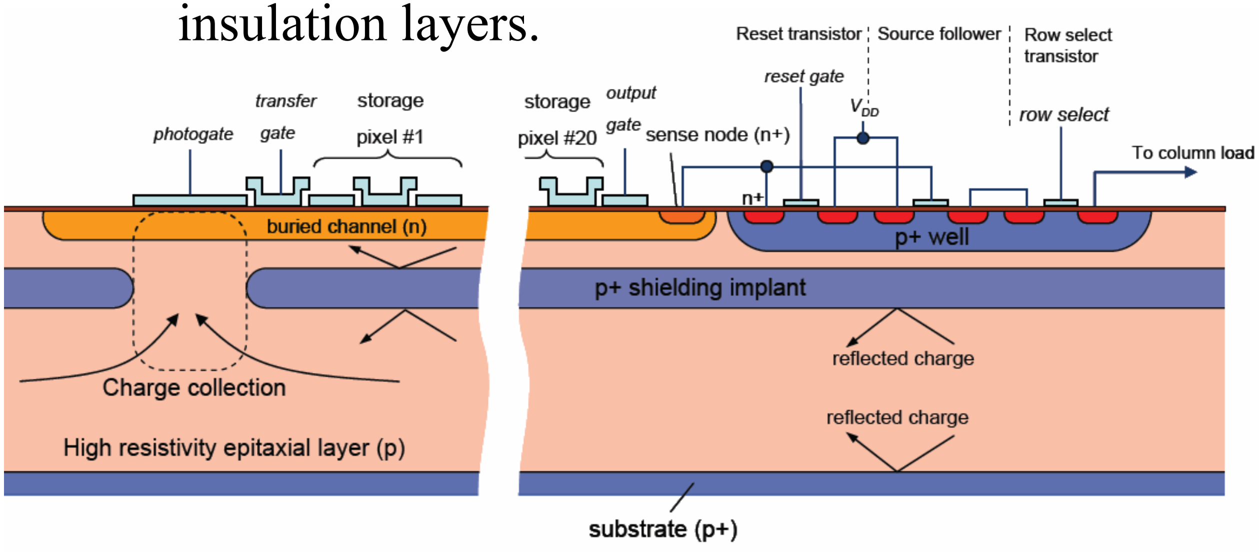


C Storage

Readback from gate 6

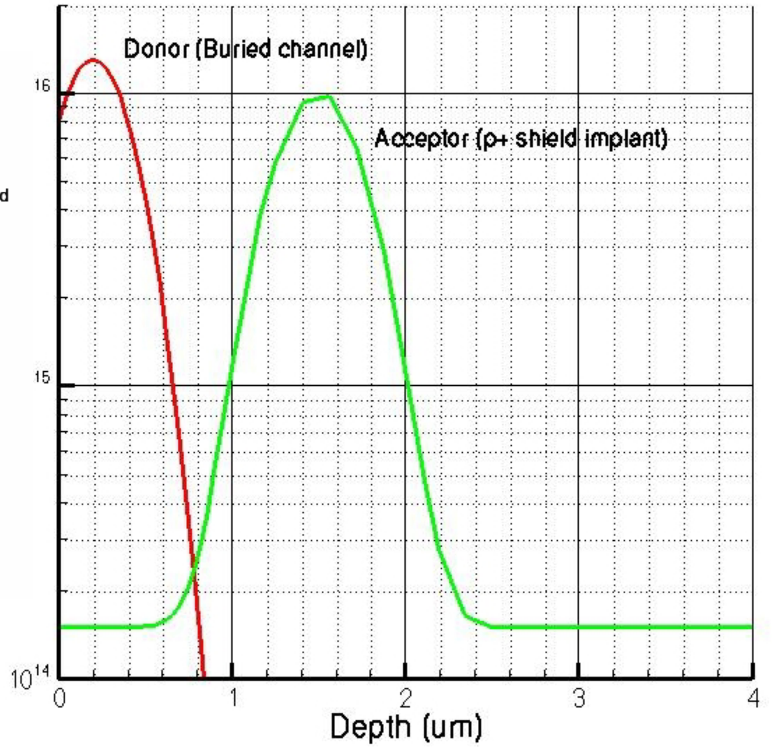
Sensors – ISIS

- Standard CMOS process doesn't allow construction of overlapping polysilicon gates and has thin SiO_2 insulation layers.



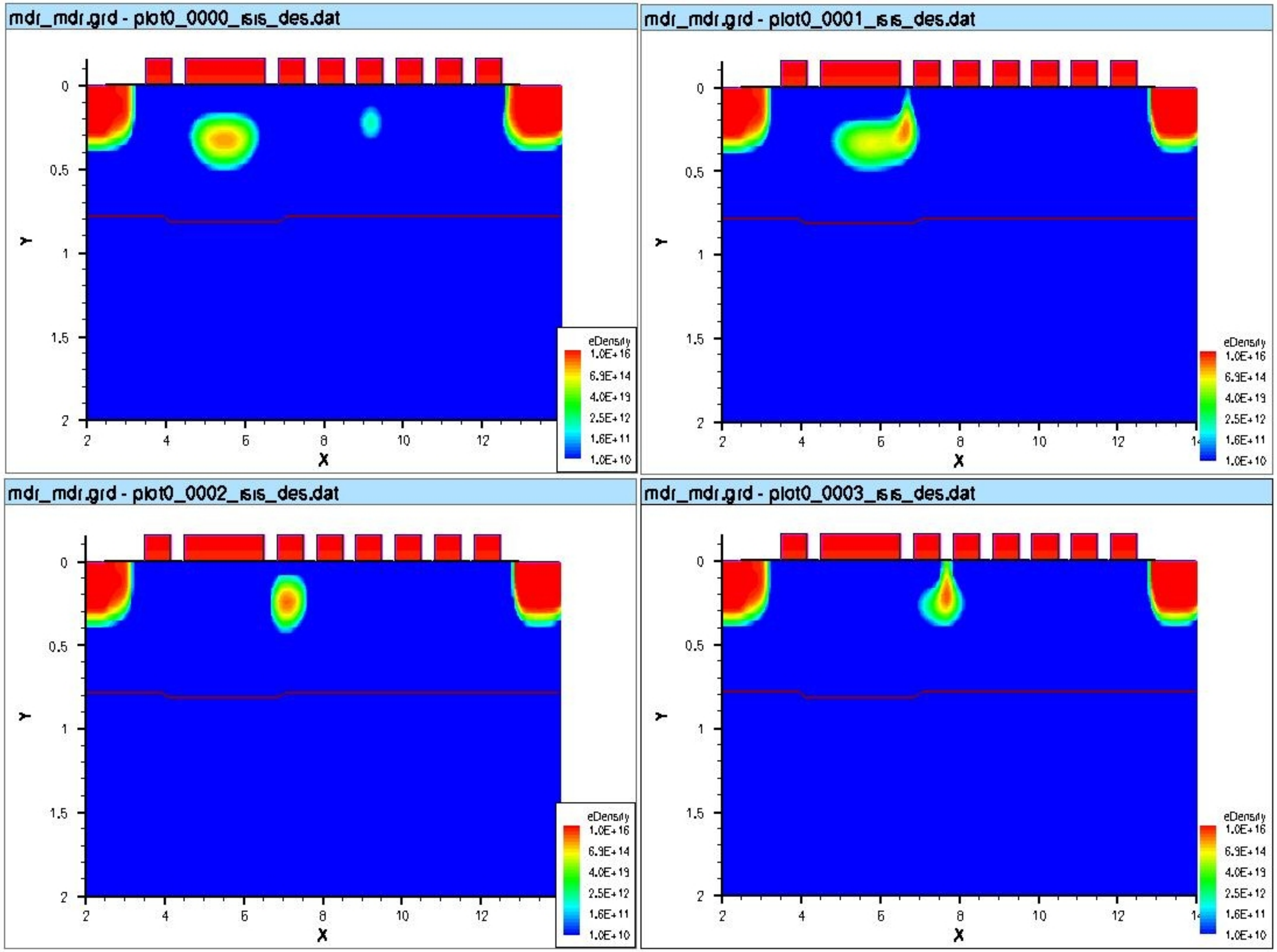
- Leads to problems with charge transfer in ISIS?
- Simulate using ISE-TCAD package.

- Modify dopant profiles to produce deeper buried channel:



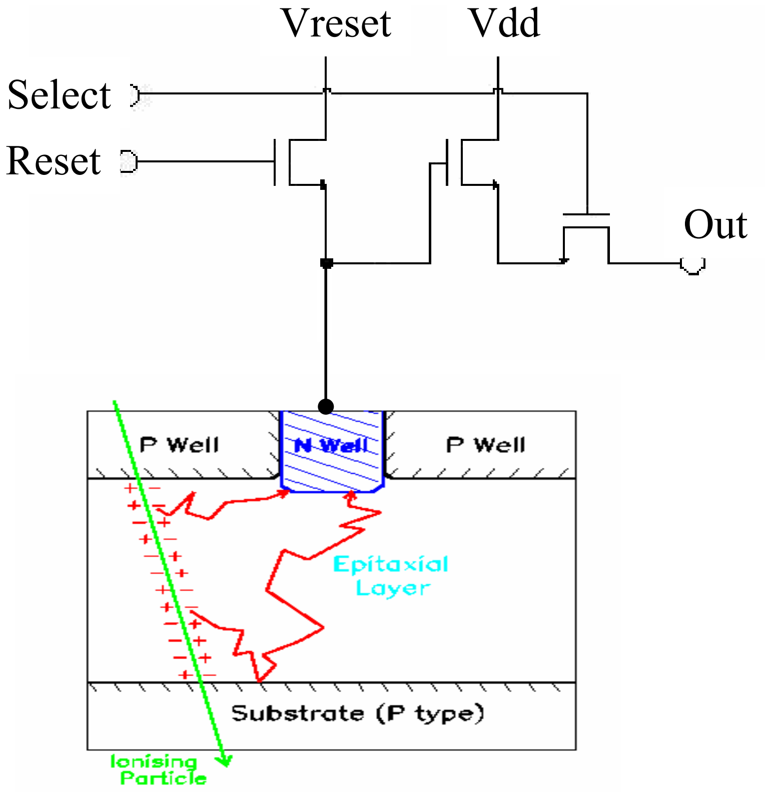
Sensors – ISIS

- Efficient charge transfer possible.
- Radiation hardness probably also enhanced by thin SiO_2 layer, less charge trapping occurs.

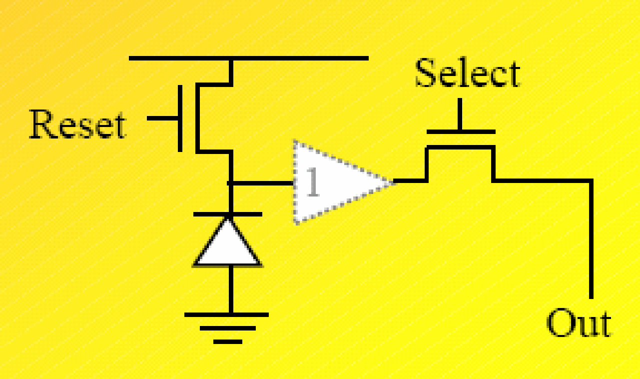


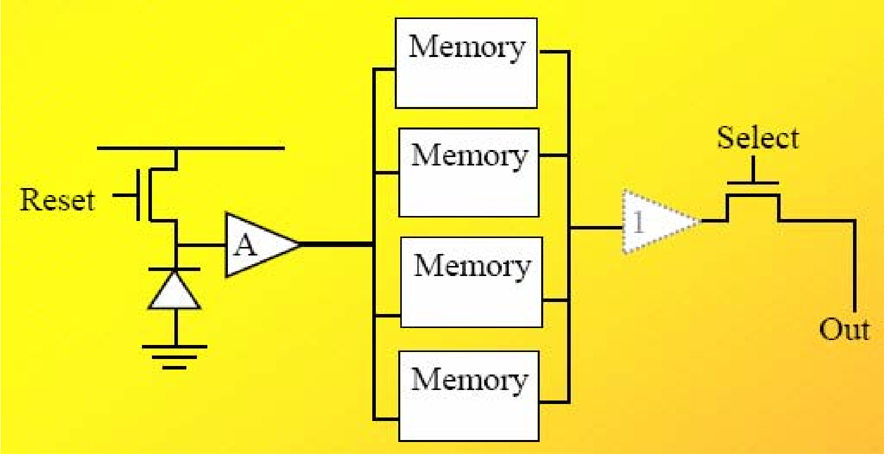
Sensors – FAPS

- Monolithic Active Pixel Sensors developed within UK, ongoing development for science by MI^3 collaboration.



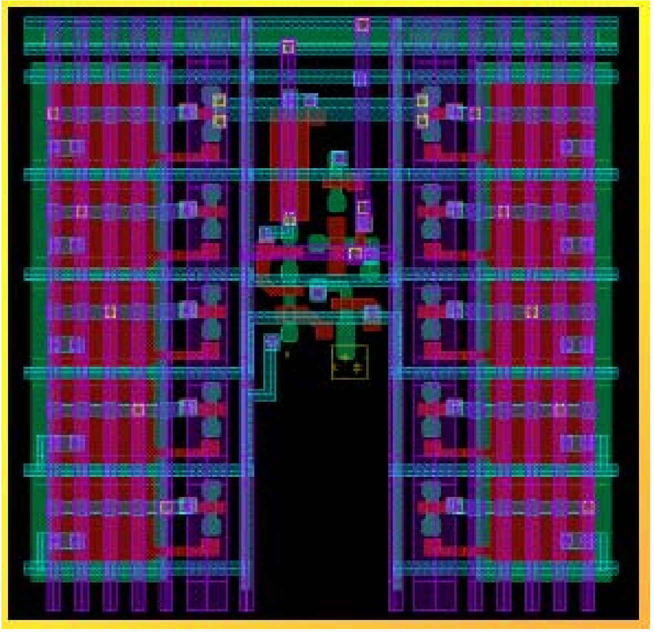
- Storage capacitors added to pixels to allow use at ILC, Flexible Active Pixel Sensors.



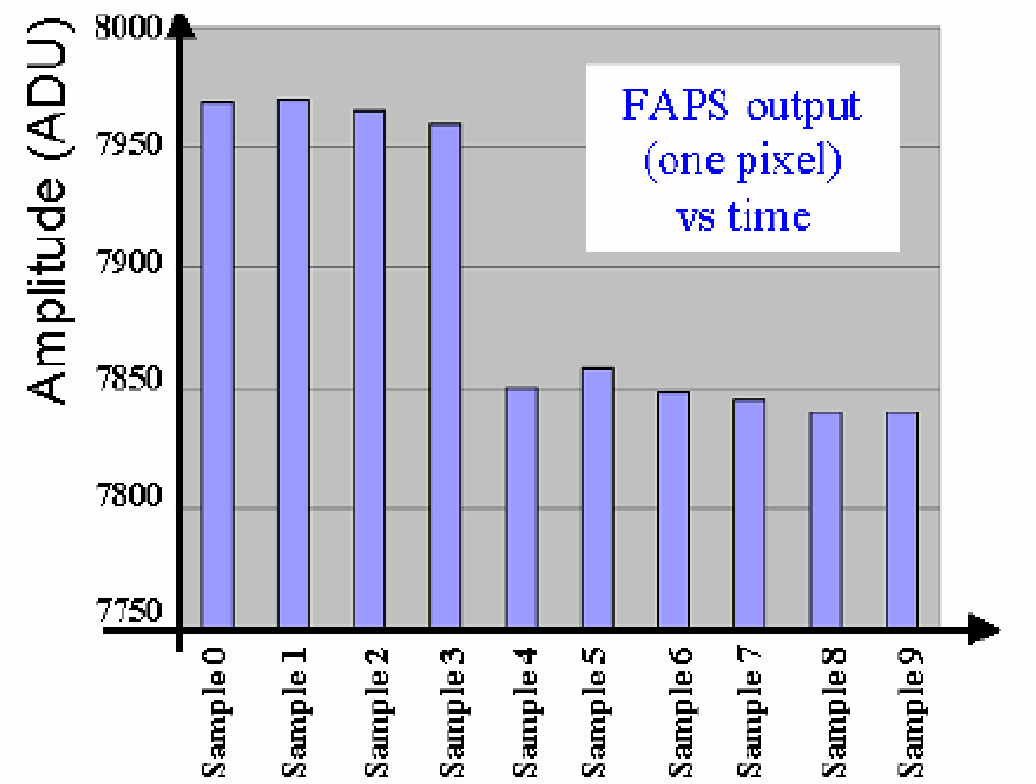


Sensors – FAPS

- Present design “proof of principle”.
- Pixels 20 x 20 μm^2, 3 metal layers, 10 storage cells.

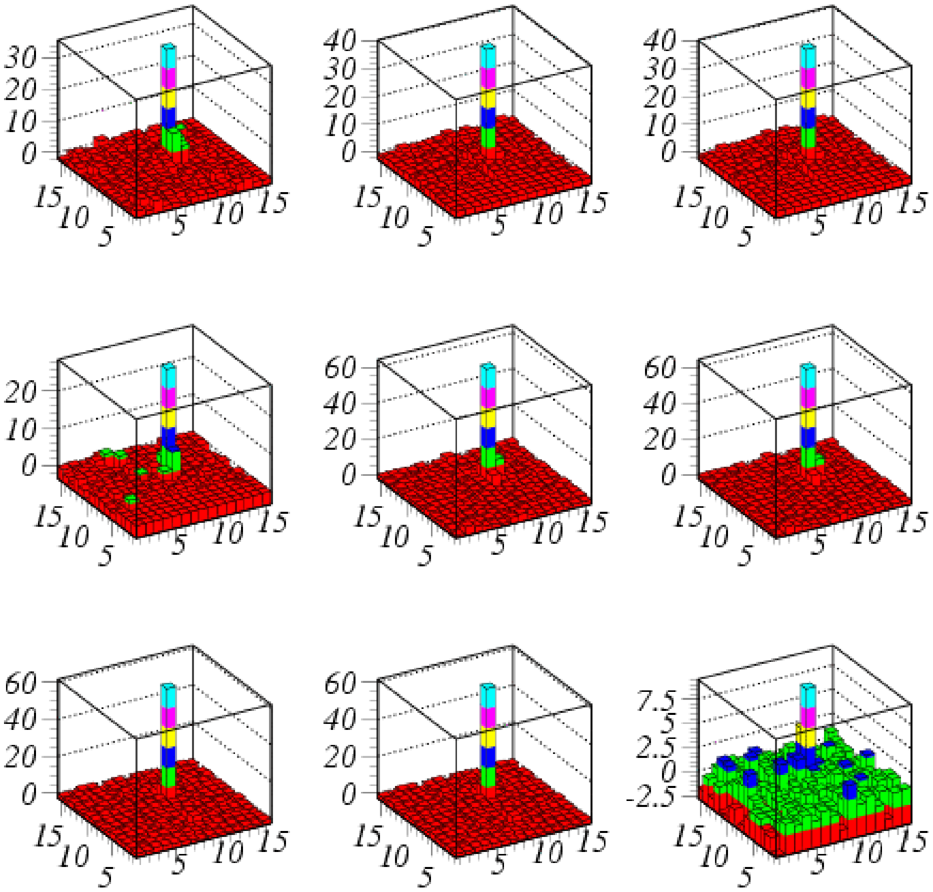


- Test of FAPS structure with LED:

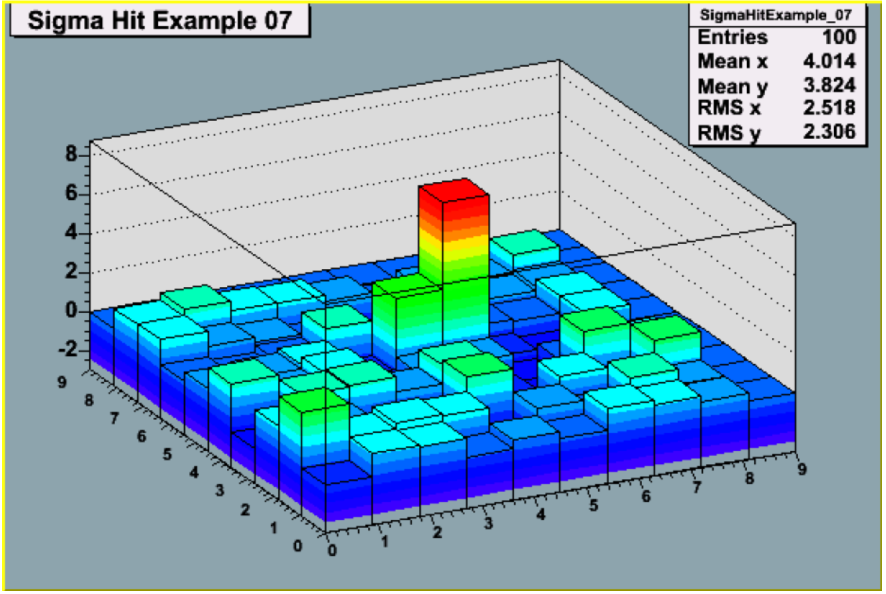


Sensors – FAPS

- ^{106}Ru β source tests, signal to noise ratio between 14 and 17.

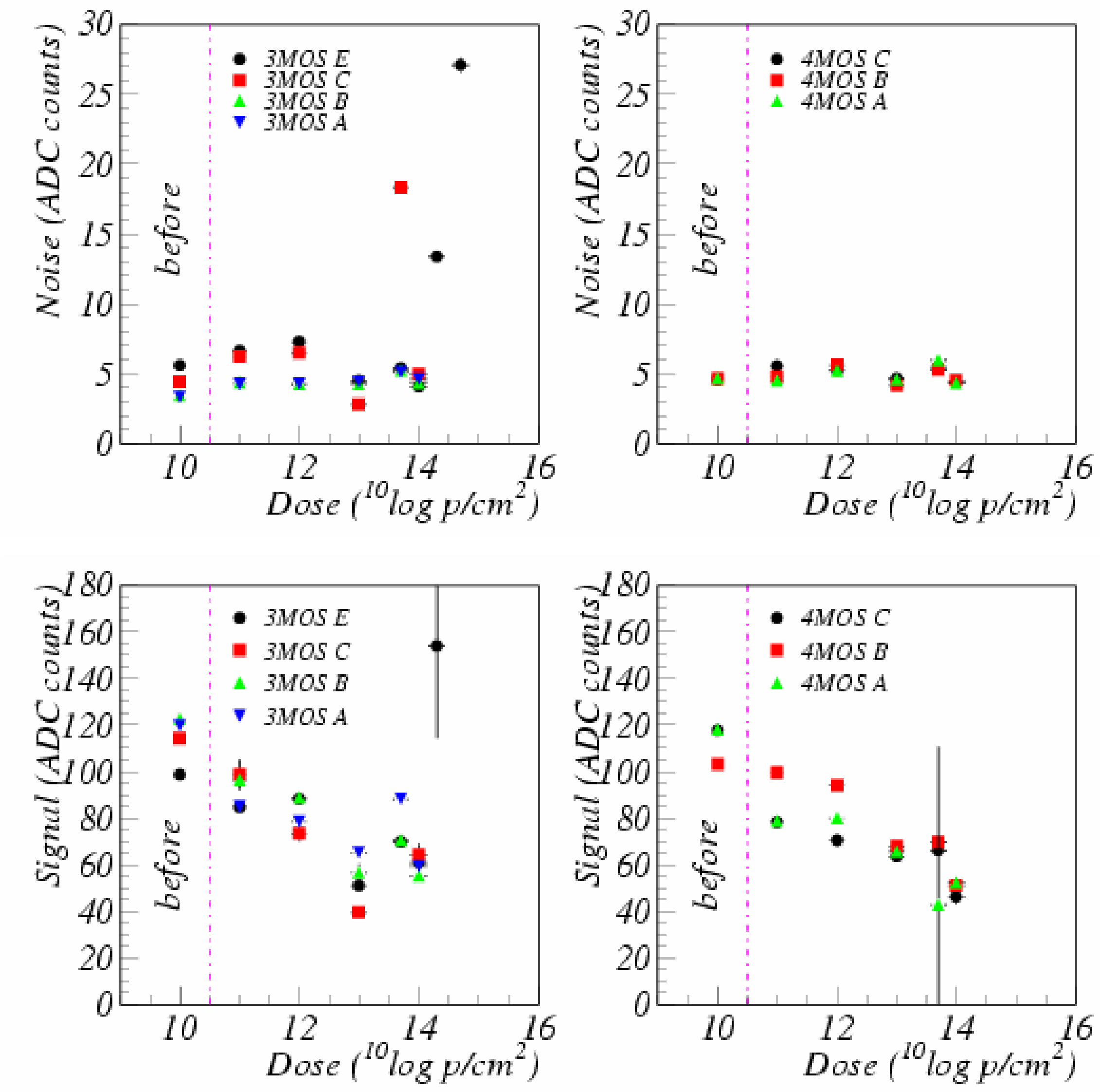


- FAPS and MAPS in test beam at DESY in February 2005.
- Data analysis ongoing, hits observed in MAPS and FAPS structures.



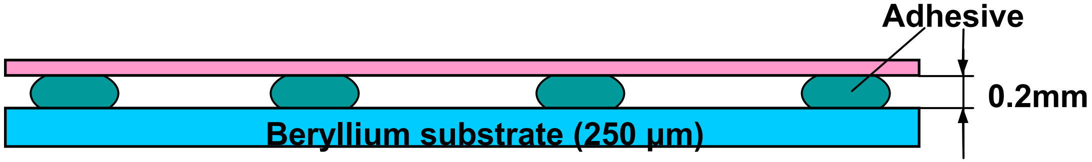
Sensors – FAPS

- MAPS demonstrated to be radiation hard.
- Signal decreases with dose, and noise increases slightly, but at doses well above those expected at the ILC.

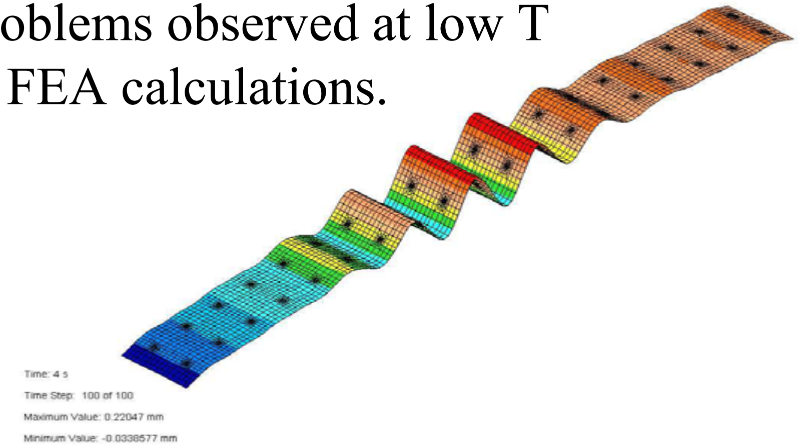


Mechanical considerations

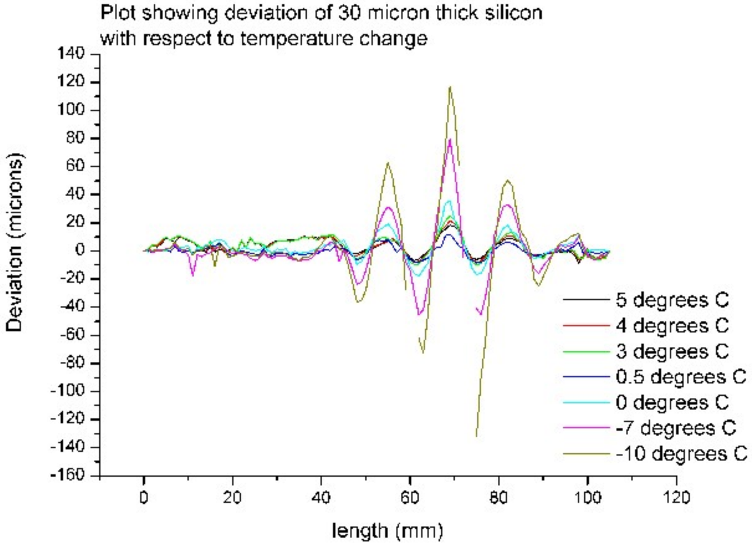
- Thin ladder design.
- Unsupported CCD option foundered due to stresses introduced when silicon is processed.
- “Stretching” maintained longitudinal stability, but provided insufficient lateral support.
- Re-visit using thin corrugated carbon fibre to provide lateral support.
- Supporting CCD on thin Be substrate studied:



- Problems observed at low T in FEA calculations.

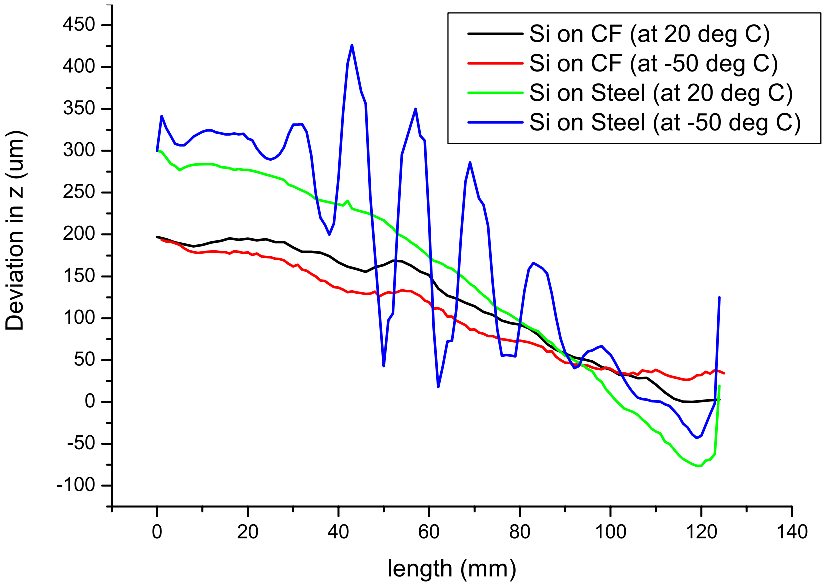


- Confirmed by measurements:

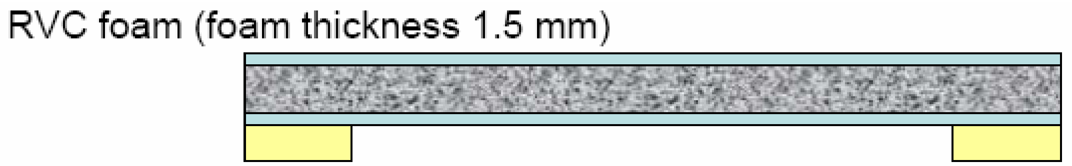


Mechanical considerations

- Importance of good matching coefficients of thermal expansion of silicon and substrate demonstrated in laboratory measurements:



- Now exploring use of silicon and reticulated vitreous carbon foam sandwich...



- ...and silicon carbide foam as support.

- These are extremely rigid and have very low mass.