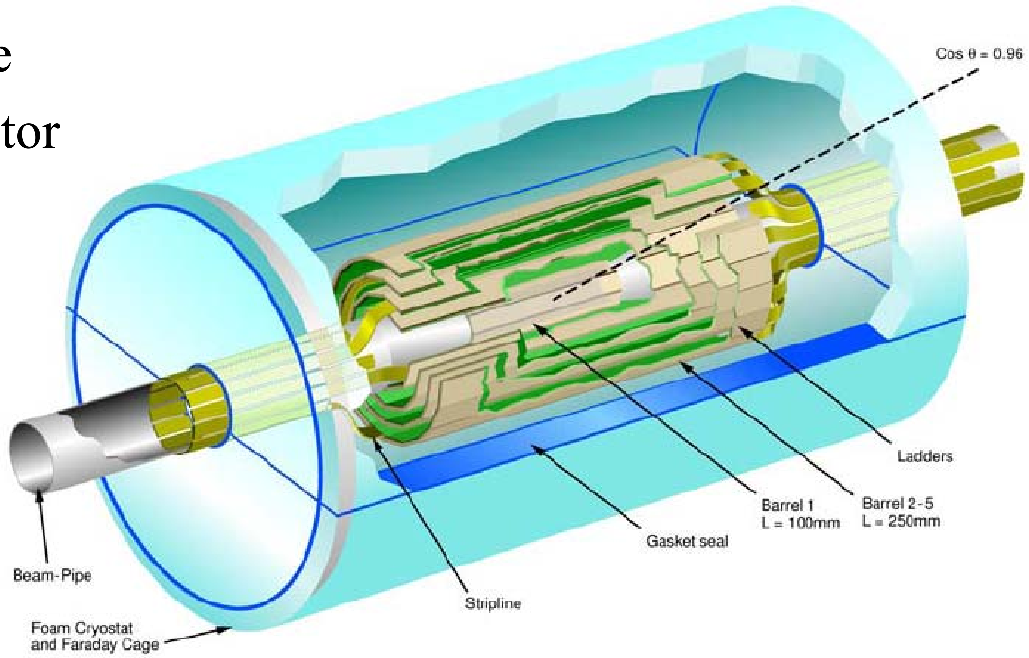
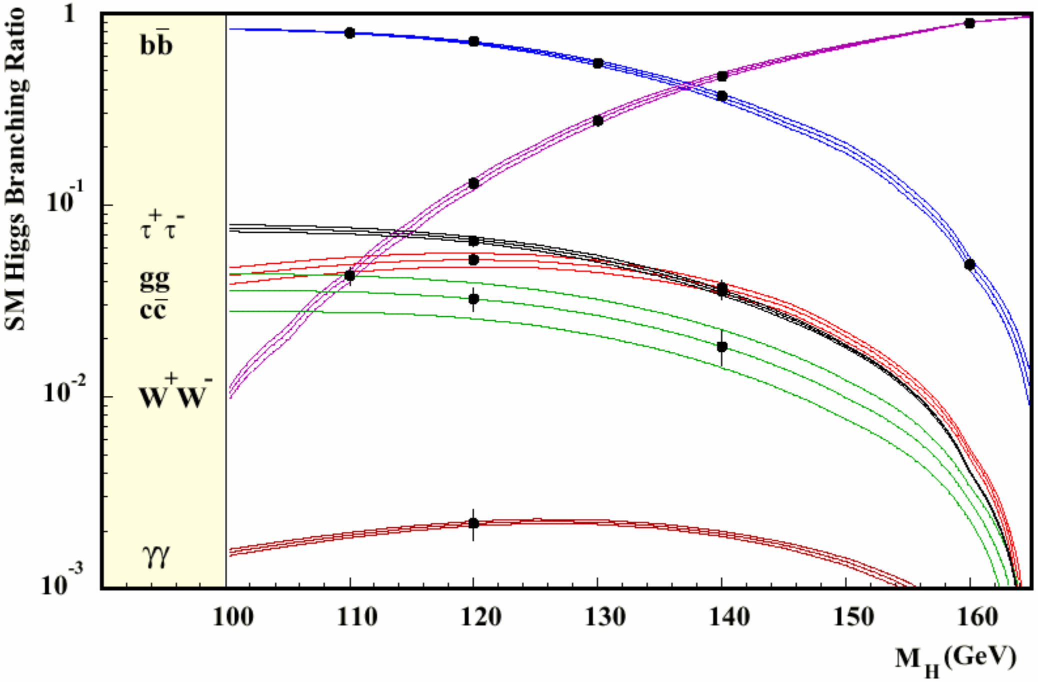
Linear Collider Flavour Identification

- Physics at the ILC:
  - Quark flavour and charge identification
  - Required vertex detector performance
  - Constraints due to machine and detector
- Vertex detector design
  - Conceptual design for ILC
  - Vertex detector performance
- Sensor design and testing
  - Charge Coupled Devices
  - Column Parallel CCDs
  - Storage sensors
- Mechanical and thermal studies
- Summary

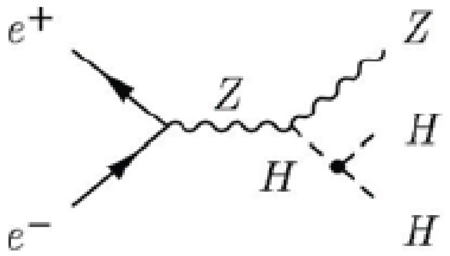


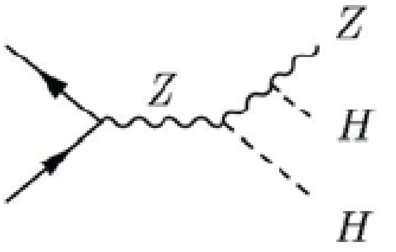
Flavour and quark charge identification at the ILC

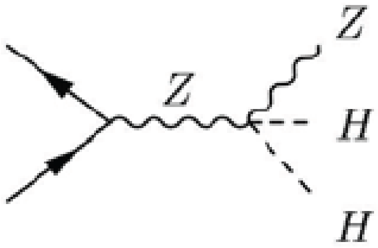
- Many of interesting measurements at ILC involve identification of heavy quarks.
- E.g. determination of branching ratios of Higgs boson.
- Are BRs compatible with the SM?



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



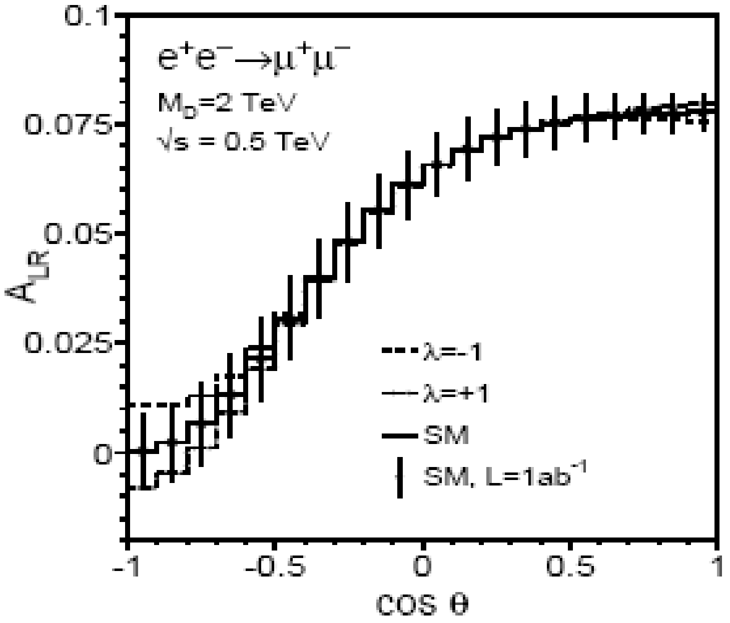




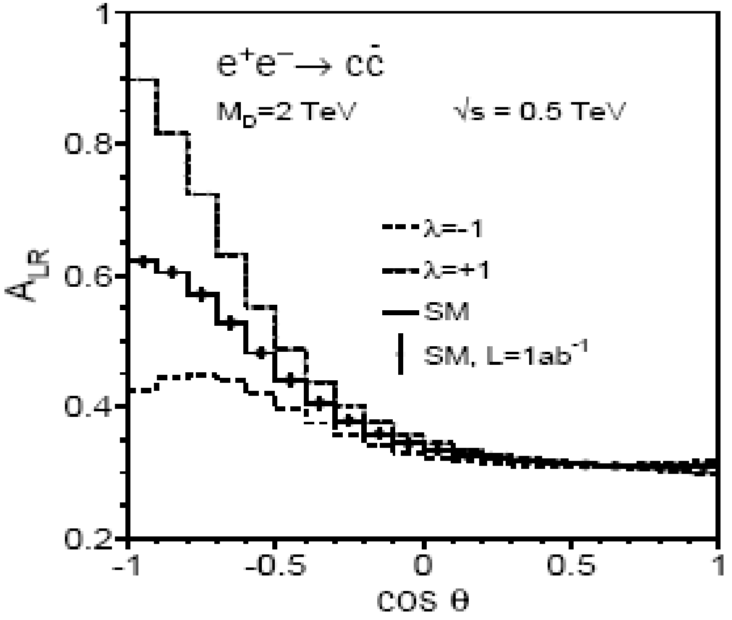
- Reduce combinatorial background.
- Study of this process allows determination of Higgs self-coupling.

Quark charge identification

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



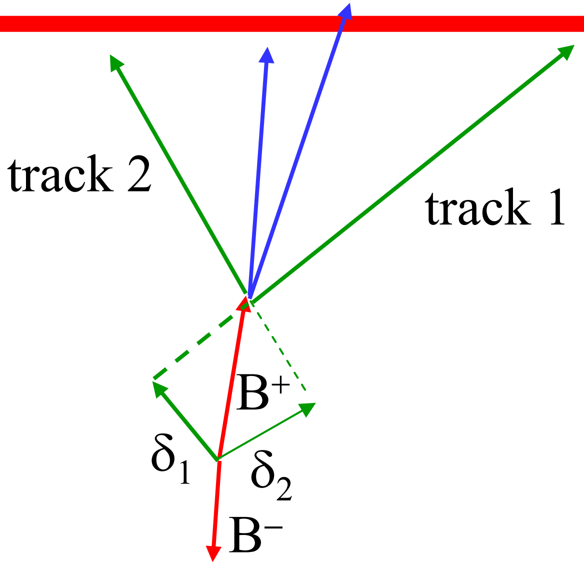
- Changes much more pronounced for c (and b) quarks:



- Requires efficient charge determination out to large cos θ.

Vertex detector performance goals

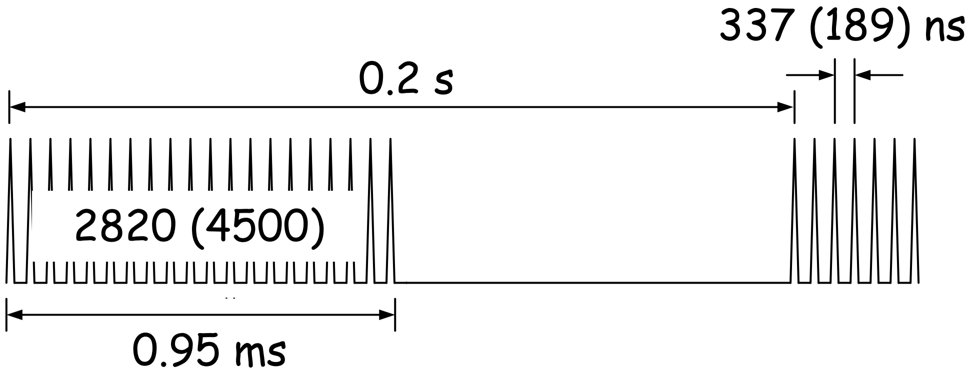
- Average impact parameter δ of B decay products ~ 300 μm, of charmed particles less than 100 μm.
- δ resolution given by convolution of point precision, multiple scattering, lever arm and mechanical stability.
- Multiple scattering significant despite large √s at ILC: charged track momenta extend below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



- Implies typically:
  - Pixels ~ 20 x 20 μm^2.
  - Hit resolution better than 5 μm.
  - 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 θ| < 0.96.

Constraints due to machine and detector

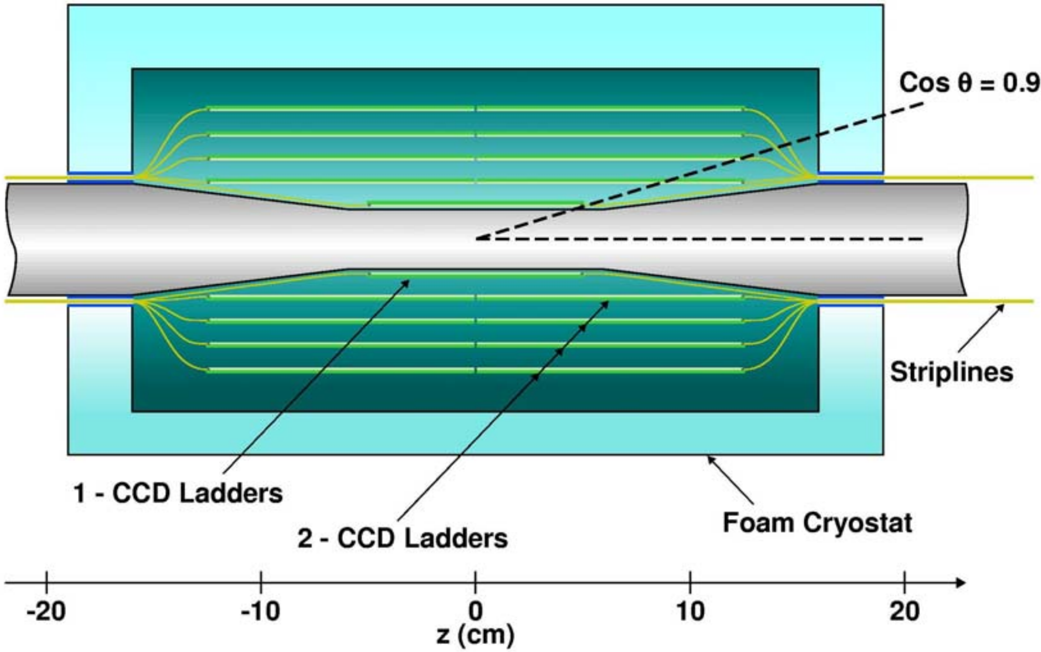
- Minimum beam pipe radius ~ 14 mm.
- Pair background at this radius in ~ 4T field causes ~ 0.03 (0.05) hits per BC and mm^2 at $\sqrt{s} = 500\ (800)$ GeV.
- Bunch train structure:



- For 10^9 pixels of size 20 x 20 $\mu\mathrm{m}^2$, implies readout or storage of signals ~ 20 times during bunch train to obtain occupancy less than ~ 0.3 (0.9) %.
- Must withstand:
  - Radiation dose of ~ 50 krad p.a.
  - Annual dose of neutrons from beam and beamstrahlung dumps ~ 1 x 10^9 1 MeV equiv. $\mathrm{n/cm}^2$.
- Must cope with operation in magnetic field of up to 5 T.
- Must be robust against beam-related RF pickup and noise from other detectors.

Conceptual vertex detector design

- Here using CCDs:

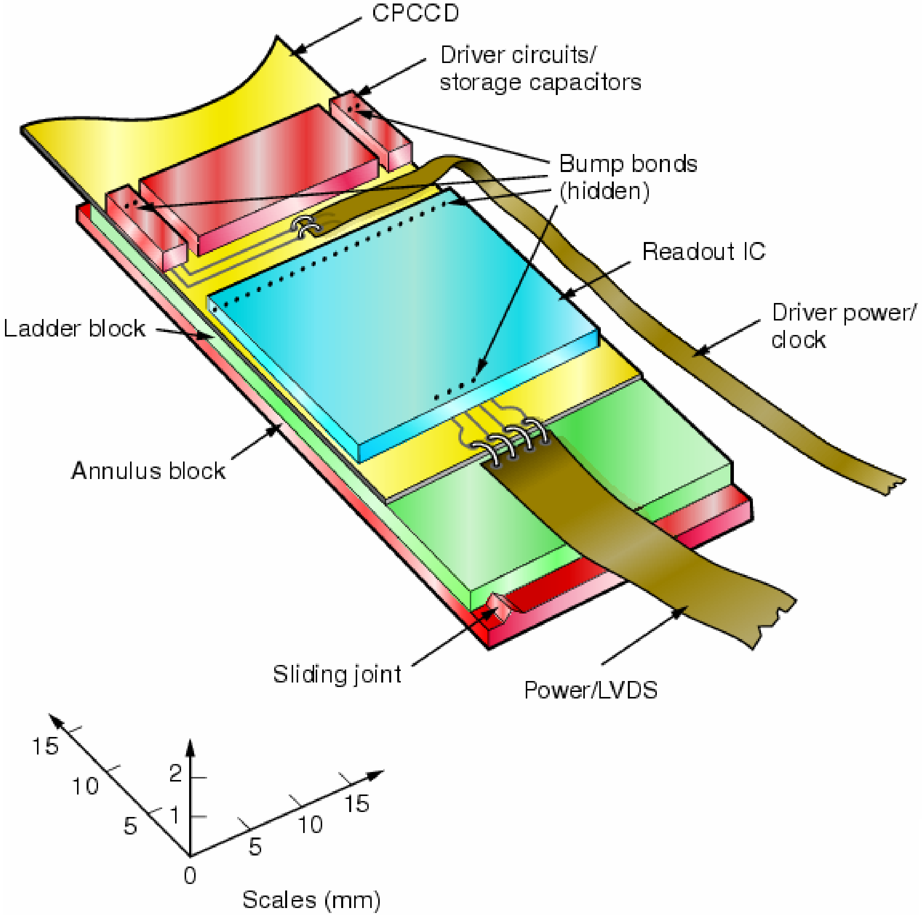


- VXD surrounded by ~ 2 mm thick Be support cylinder.
- Allows Be beam pipe to be ~ 0.4 mm thick.

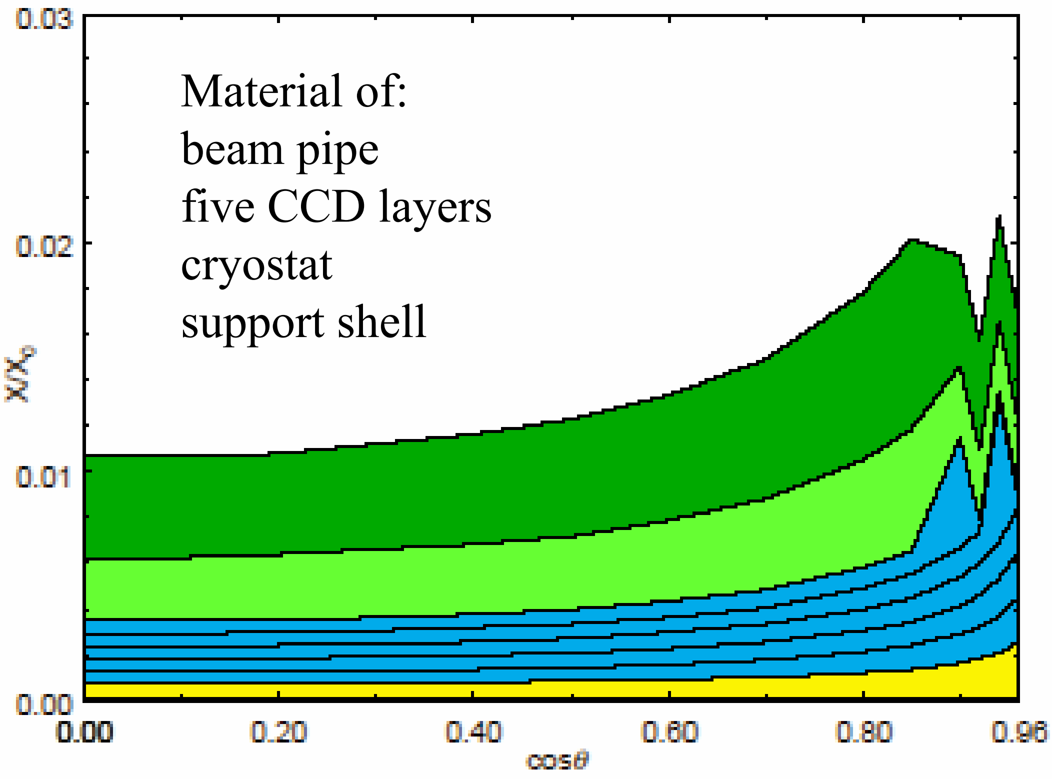
- Pixel size 20 x 20 μm^2, implies about 10^9 pixels in total.
- Standalone tracking using outer 4 layers.
- Hits in first layer improve extrapolation of tracks to IP.
- Readout and drive connections routed along BP.
- Important that access to vertex detector possible.

Conceptual detector design

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



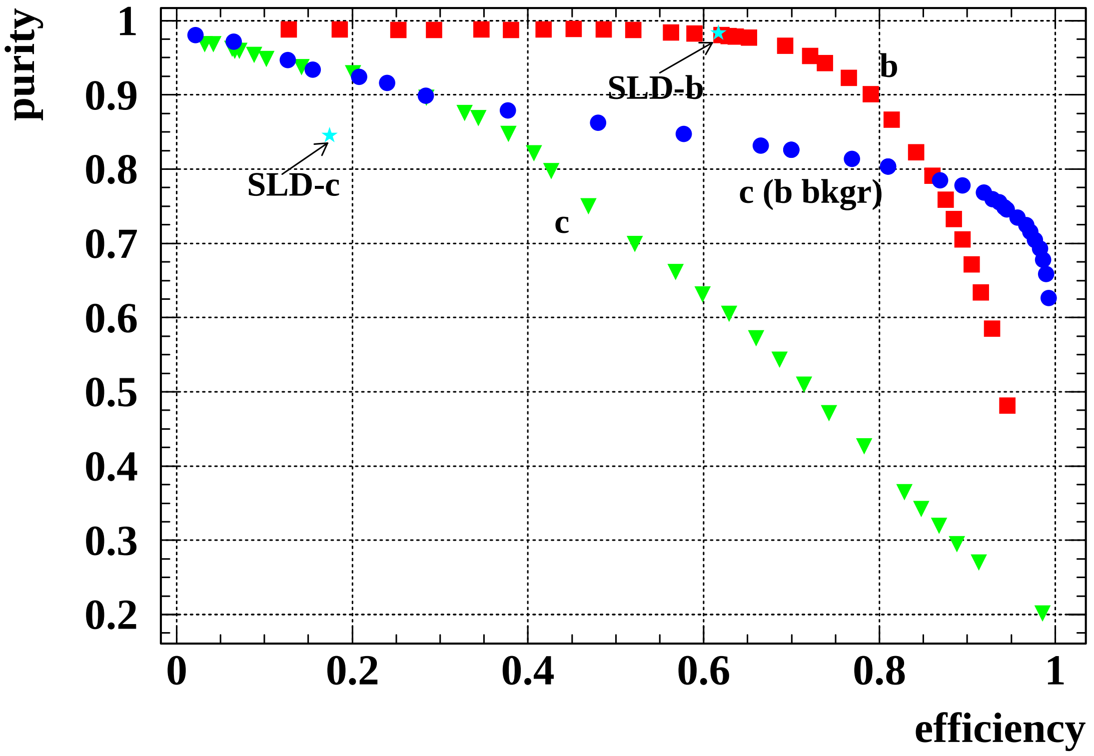
- Resulting material budget, assuming unsupported silicon sensors of thickness ~ 50 μm:



Flavour identification performance

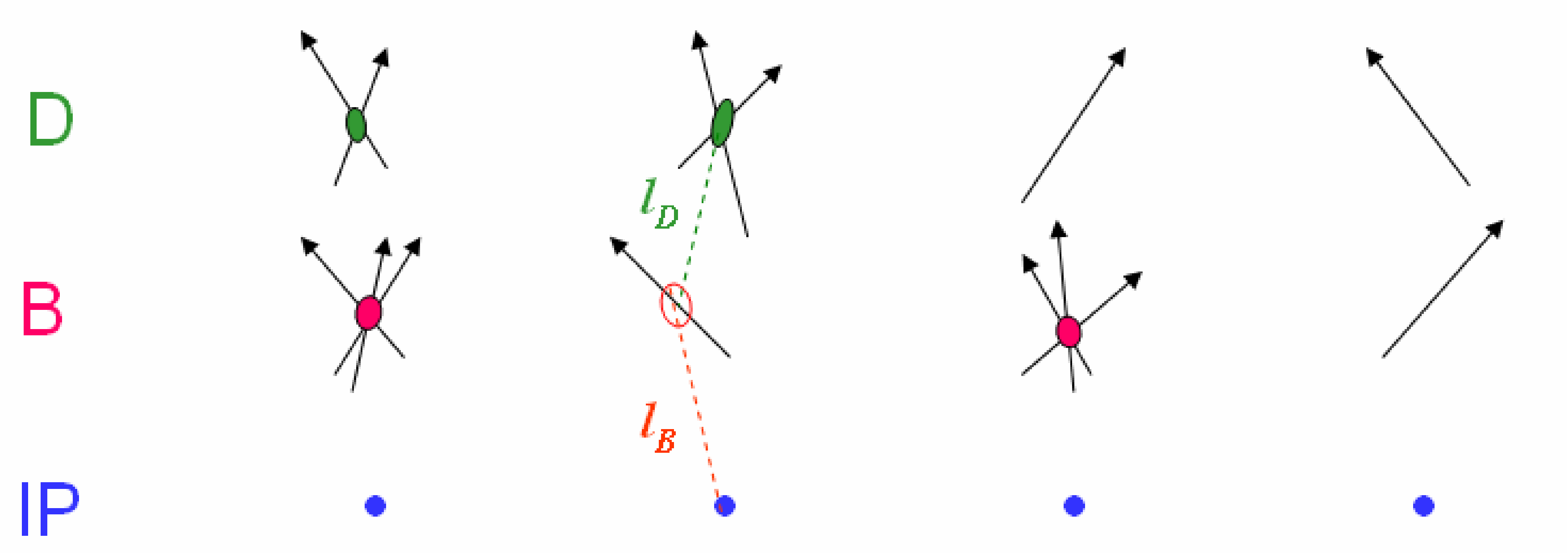
- Simulate flavour ID in $e^+e^- \rightarrow q\bar{q}$ events, here at Z^0 pole.
- Feed information on impact parameters and vertices identified using Zvtop algorithm into neural net.
- Modest improvement in beauty tagging efficiency/purity over that achieved at SLD.
- Improvement by factor 2 to 3 in 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:



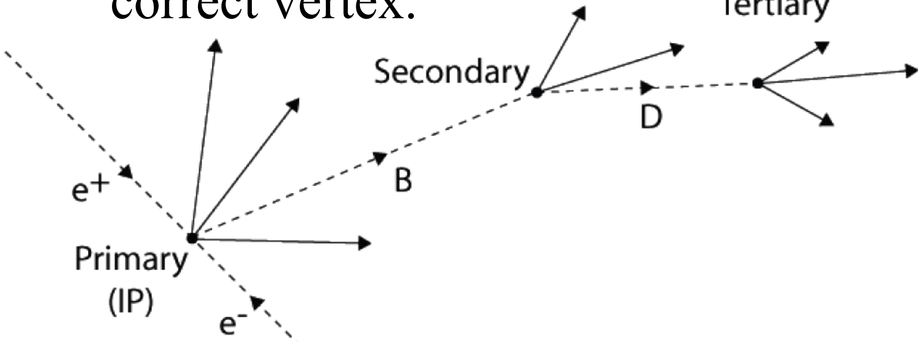
Improving flavour identification

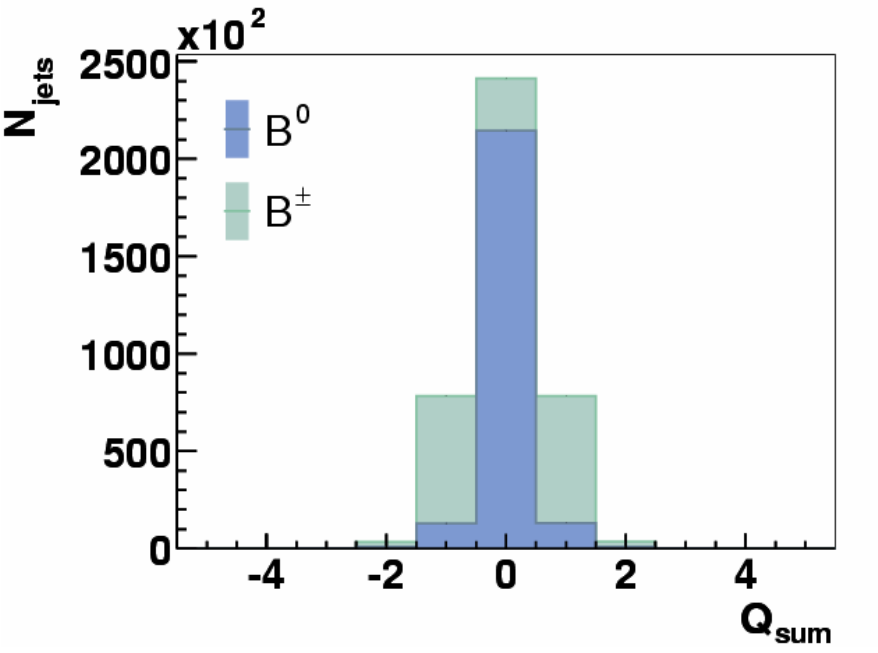
- Increase efficiency of b identification through implementation of Zvkin “ghost track” algorithm.
- Identify b-jets in which secondary and/or tertiary vertex one pronged.
- Use fact that IP, B- and D-decay vertices approx. on straight line due to boost of B hadron
- Further flavour ID improvements possible by incorporating additional information.



Quark charge identification performance

- Must assign all charged tracks to correct vertex.

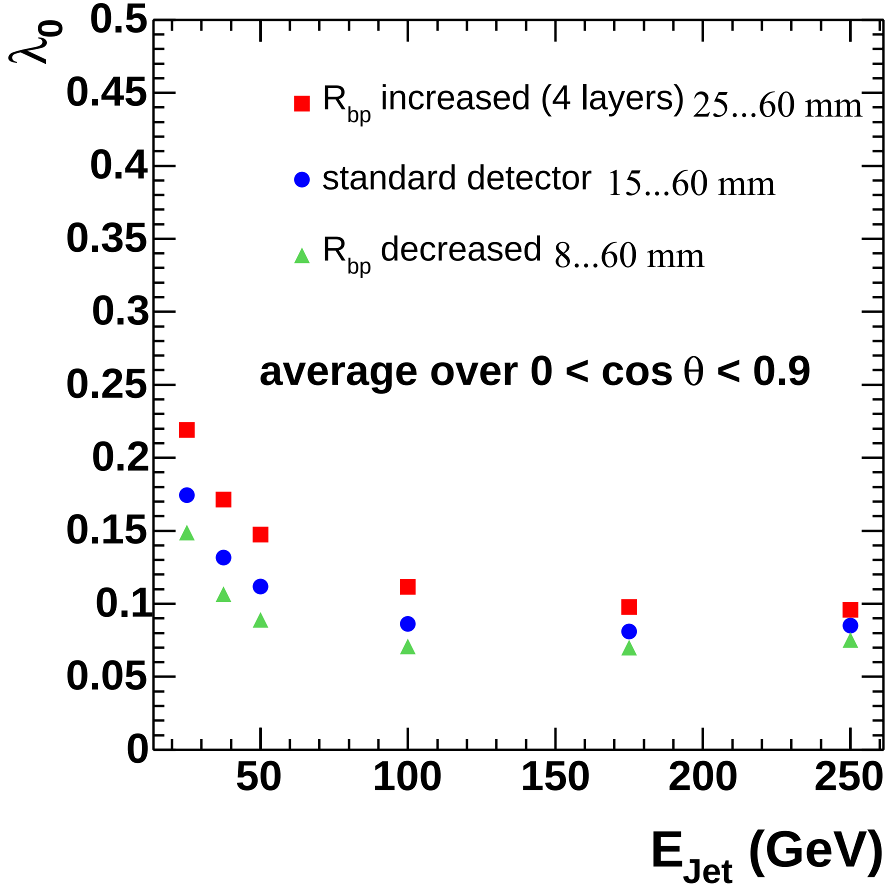




- Multiple scattering critical, lowest track momenta below 1 GeV.
- Probability of incorrectly identifying vertex charge small for neutral and charged Bs.
- For ~ 40% of cases in which b produces charged hadron, get quark charge from B vertex charge.
- Quark charge identification for neutral B requires “dipole” algorithm.
- (See Sonja Hillert’s talk at the Vienna ECFA meeting for more detail on this!)

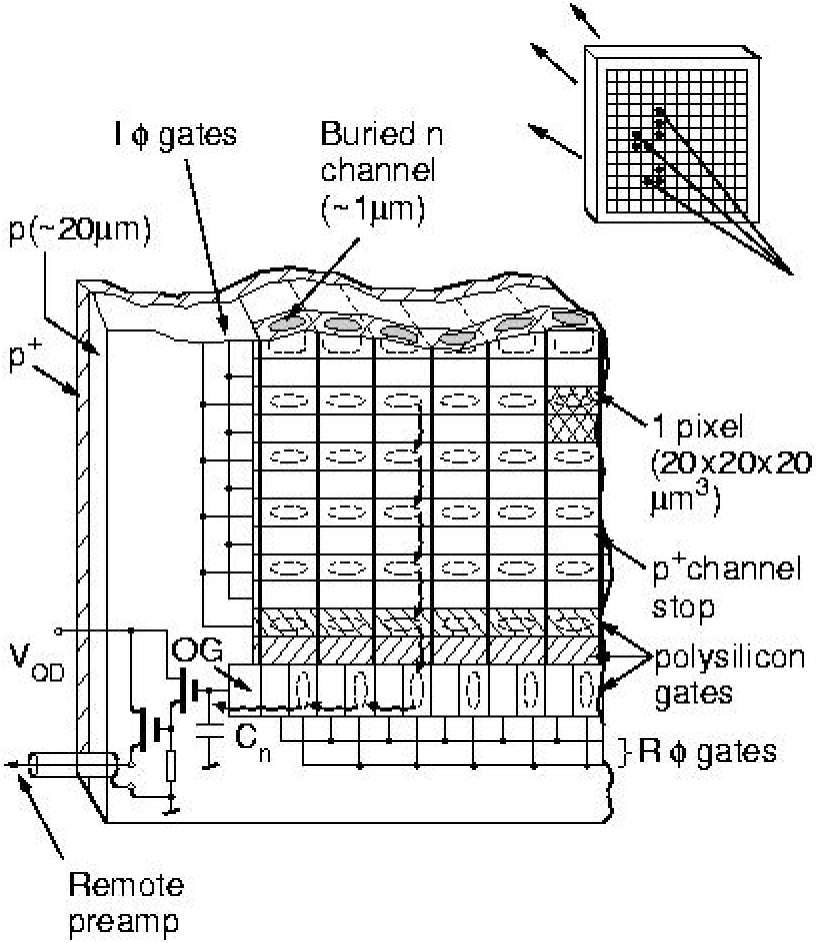
Quark charge identification performance

- Quantify performance in terms of λ_0, probability of reconstructing neutral B hadron as charged.
- Investigate effects of changing detector inner radius.
- Larger BP radius implies thicker BP:
  - R_{BP} = 14 mm, t = 0.4 mm.
  - R_{BP} = 25 mm, t = 1.0 mm.
- Significant loss of performance with increasing R_{BP}.
- Can quantify in terms of effective luminosity loss.
- For E_{Jet} = 25 GeV and R_{BP} = 25 mm, must inc. lumi. by factor ~1.7 w.r.t R_{BP} = 15 mm to get same error.
- λ_0 for different detector configurations:

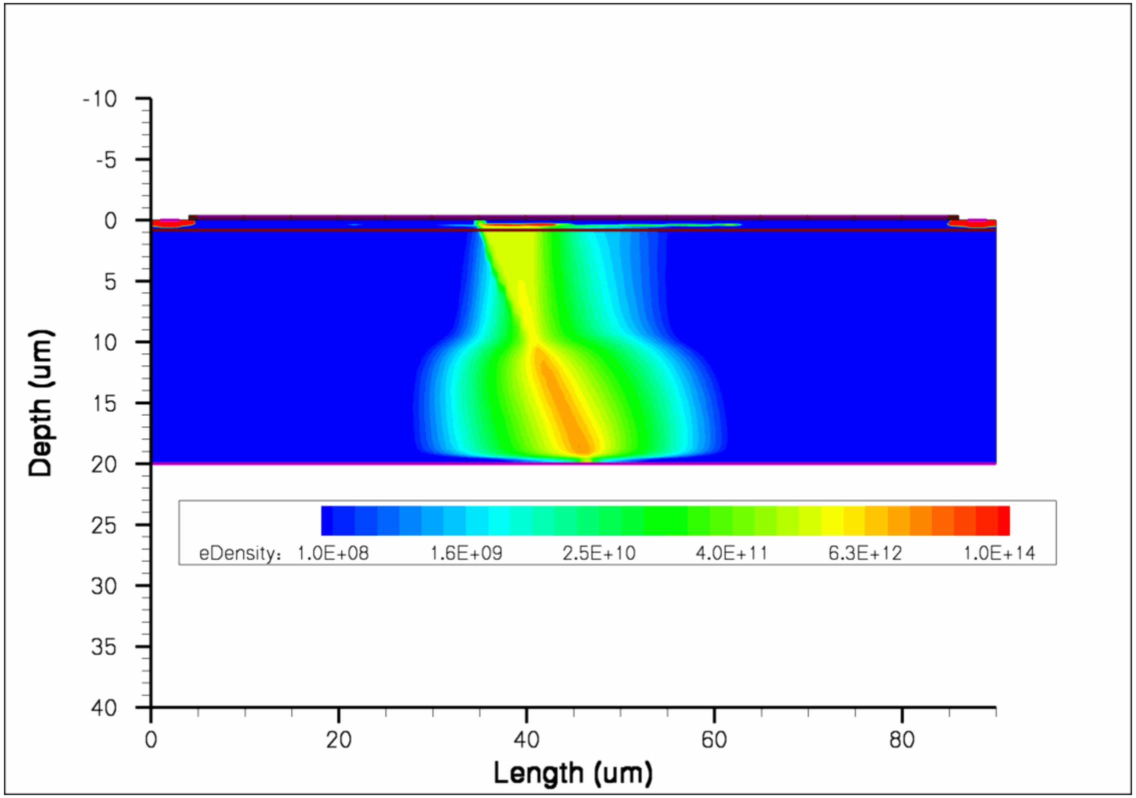


Sensors for the vertex detector – CCDs

- Conventional CCD:

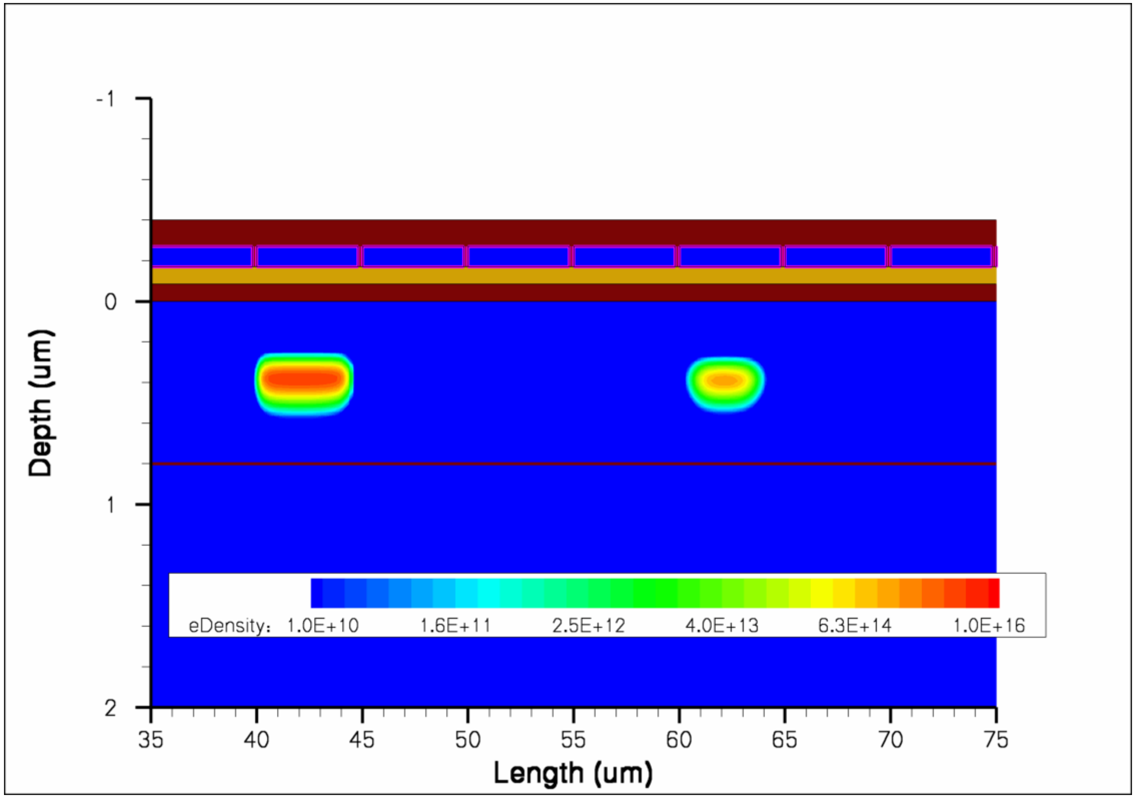


- Charge collection in two-phase CCD, 20 μm epitaxial layer, 100 Ω.cm (~ 10 μm depleted), pixels 20 x 20 μm^2.

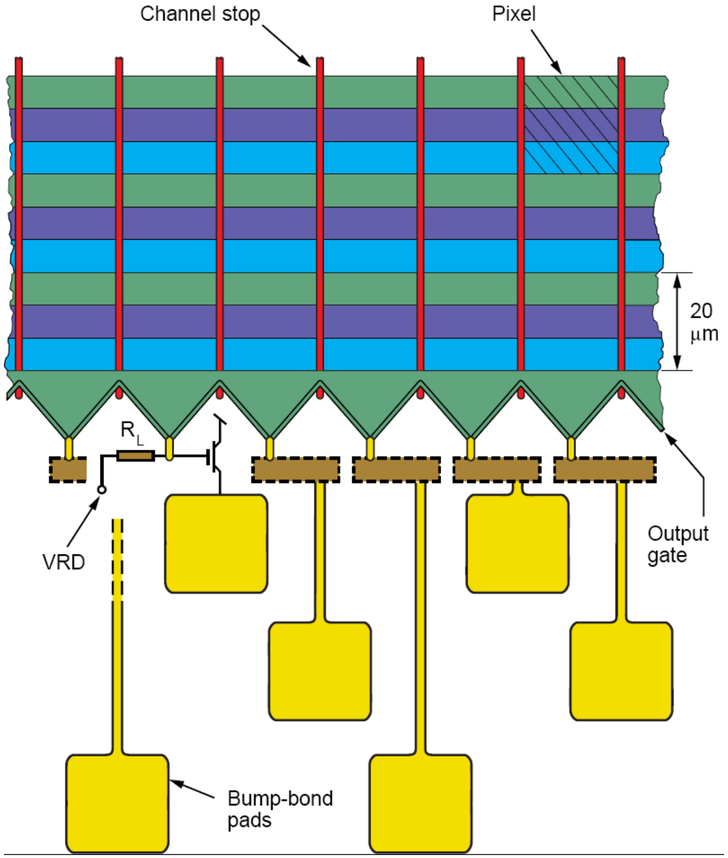


Sensors – CCDs

- Charge transfer in two-phase CCD, gate potentials change from + to –2 V (and vice versa) in 10 ns:

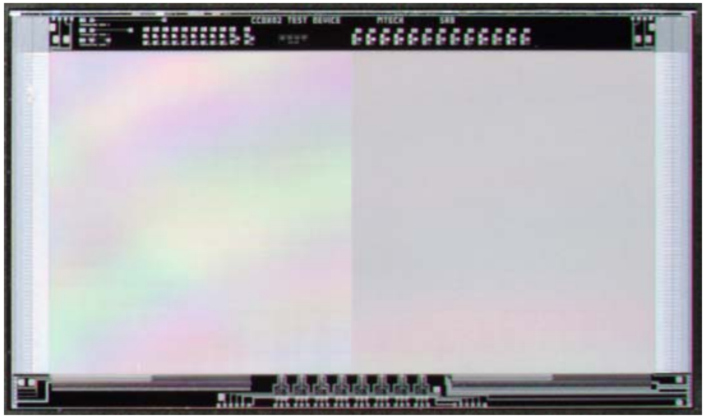


- Conventional CCD too slow for ILC.
- LCFI developing Column Parallel architecture with e2v technologies.



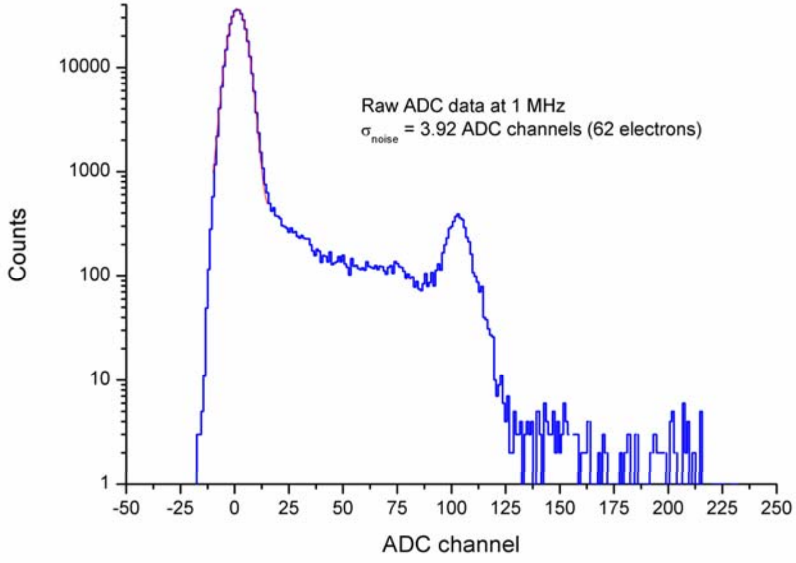
Sensors – CPCCD

- First of these, CPC1, manufactured by e2v.



- Two phase, 400 (V) × 750 (H) pixels of size 20 × 20 μm².
- Metal strapping of clock gates.
- Two different implant levels.
- Two-stage and one-stage source follower and direct (charge) outputs.

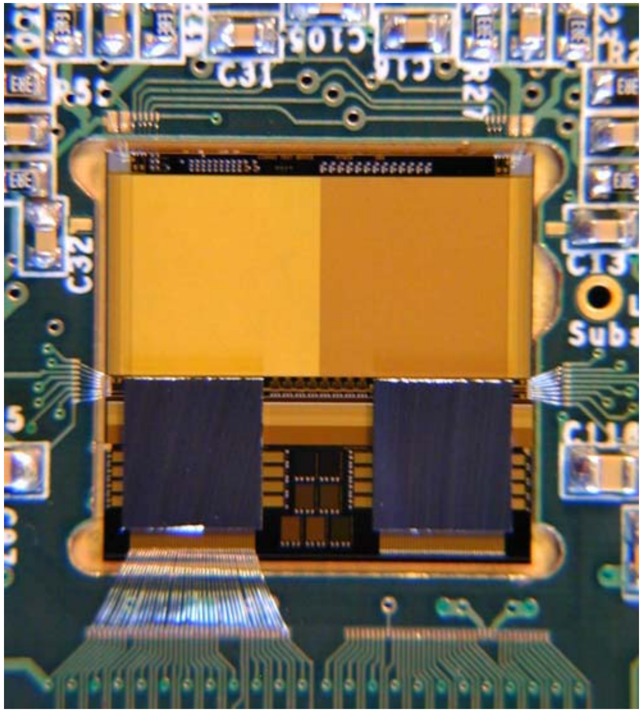
- Standalone CPC1 tests:
- Noise ~ 100 e⁻ (60 e⁻ after filter).
- Minimum clock potential ~1.9 V.



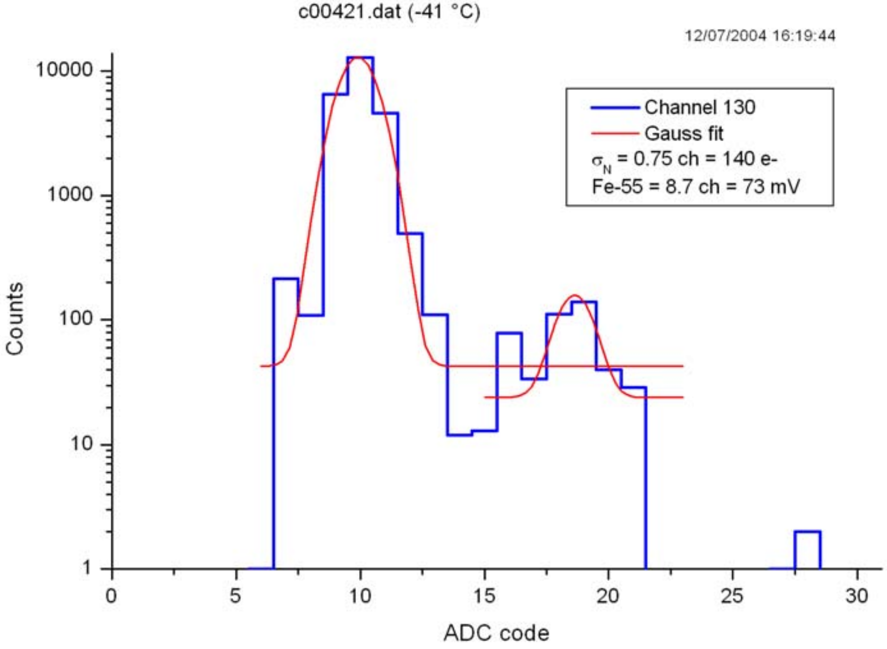
- Max clock frequency above 25 MHz (design 1 MHz).

Sensors and readout – CPC1 and CPR1

- Bump-bond to CMOS CPCCD readout ASIC, CPR1 (RAL).
- IBM 0.25 µm process.
- 250 parallel channels, 20 µm pitch.
- Designed for 50 MHz.



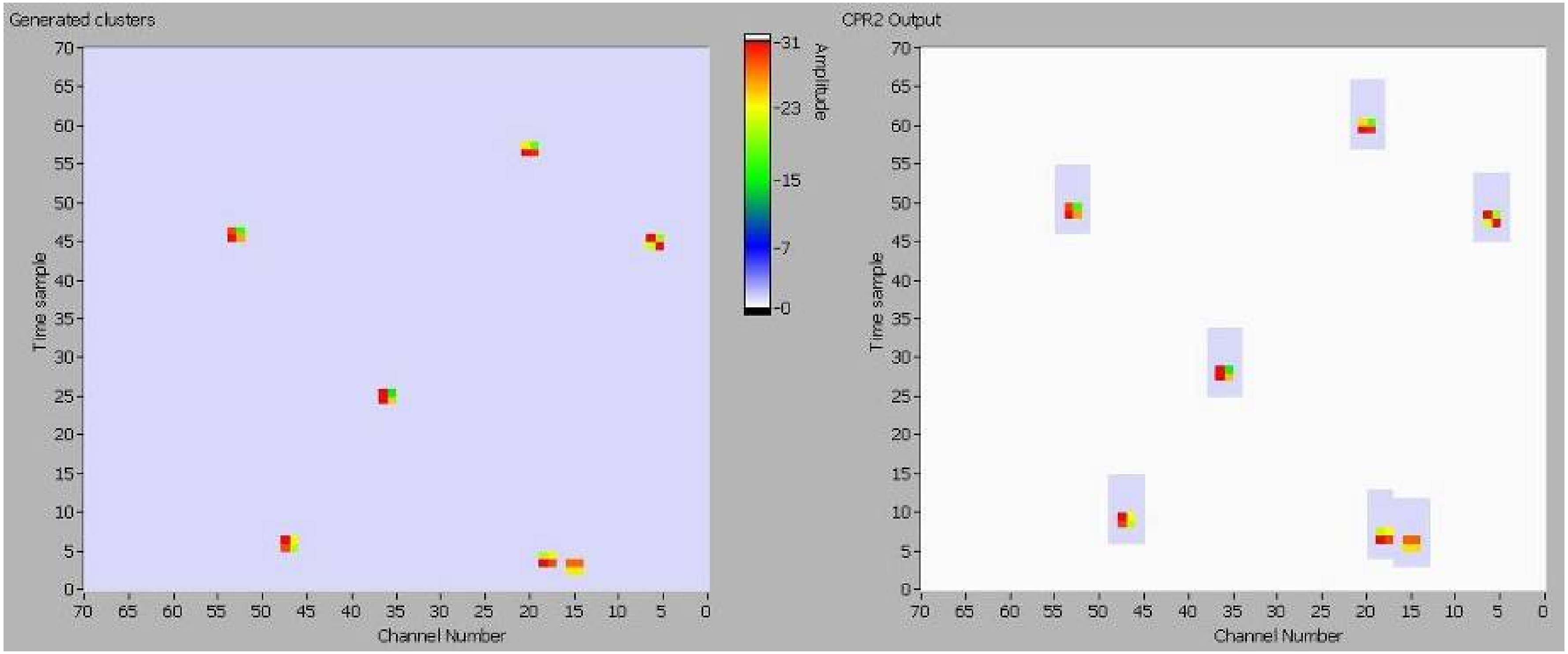
- Bump-bonding done at VTT.
- Yield ~ 30%: mechanical damage during compression?
- Signal from charge channels:



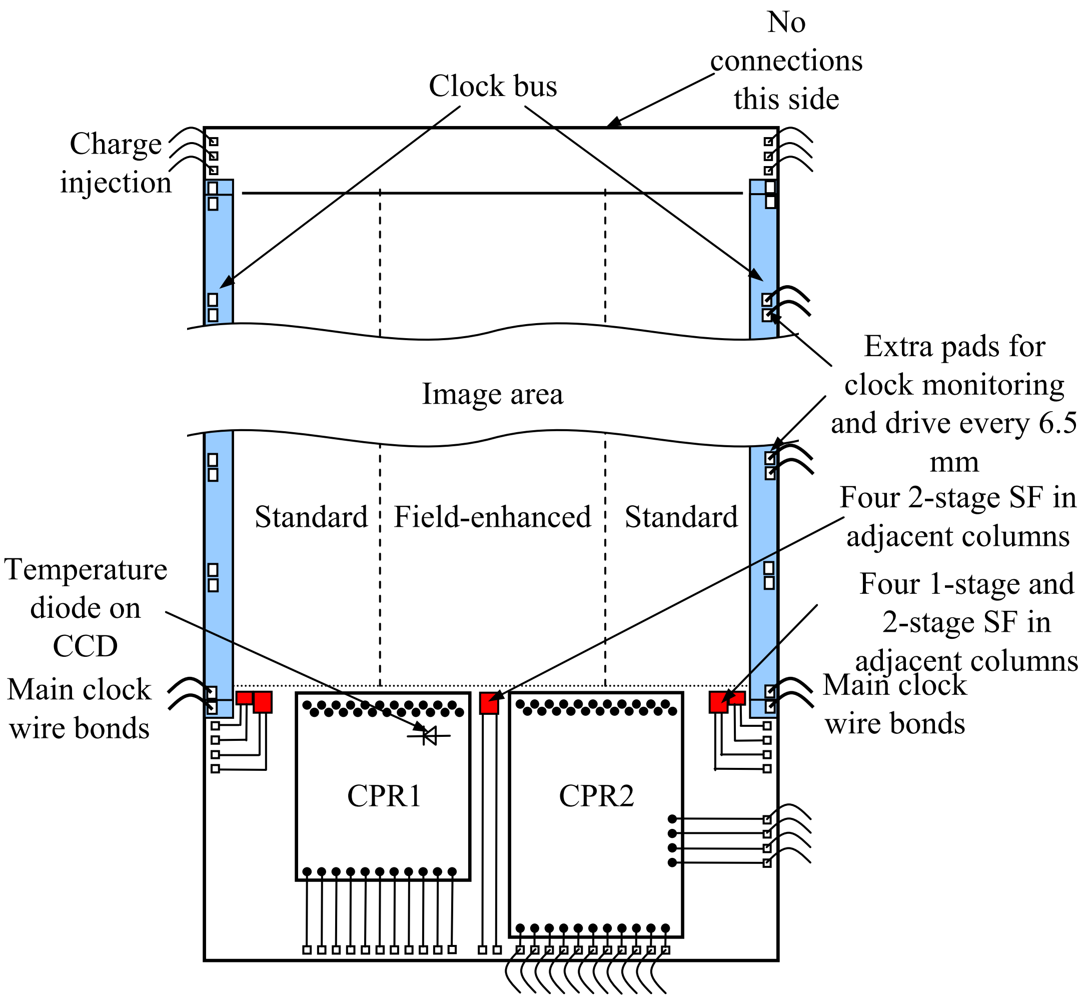
- Observe ~ 70 mV, expected 80 mV signal, good agreement.

Next generation readout chip – CPR2

- 6 × 9.5 mm², 0.25 µm CMOS (IBM), “features” of CPR1 fixed.
- Includes cluster finding logic and sparse data circuitry.
- Test clusters in:
- Sparsified data out:



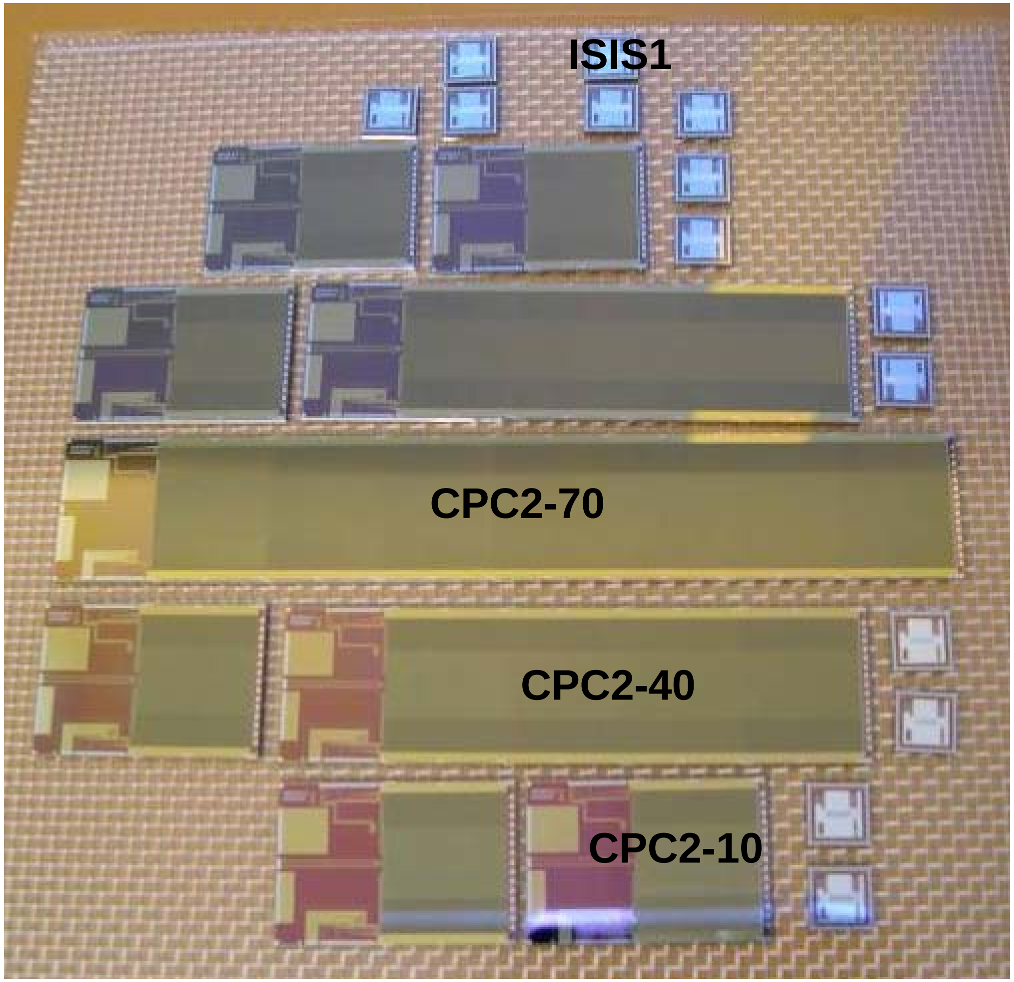
Next generation CPCCD – CPC2



- Three different chip sizes:
  - CPC2-70: 92 × 15 mm^2 image area.
  - CPC2-40: 53 × 15 mm^2.
  - CPC2-10: 13 × 15 mm^2.
- Compatible with CPR1 and CPR2
- Two charge transport sections.
- Choice of epitaxial layers giving different depletion depths: 100 Ω cm (25 μm thick) and 1.5 kΩ cm (50 μm thick)
- Design allows few MHz operation for CPC2-70.
- Hope to achieve 50 MHz with small CPC2s.

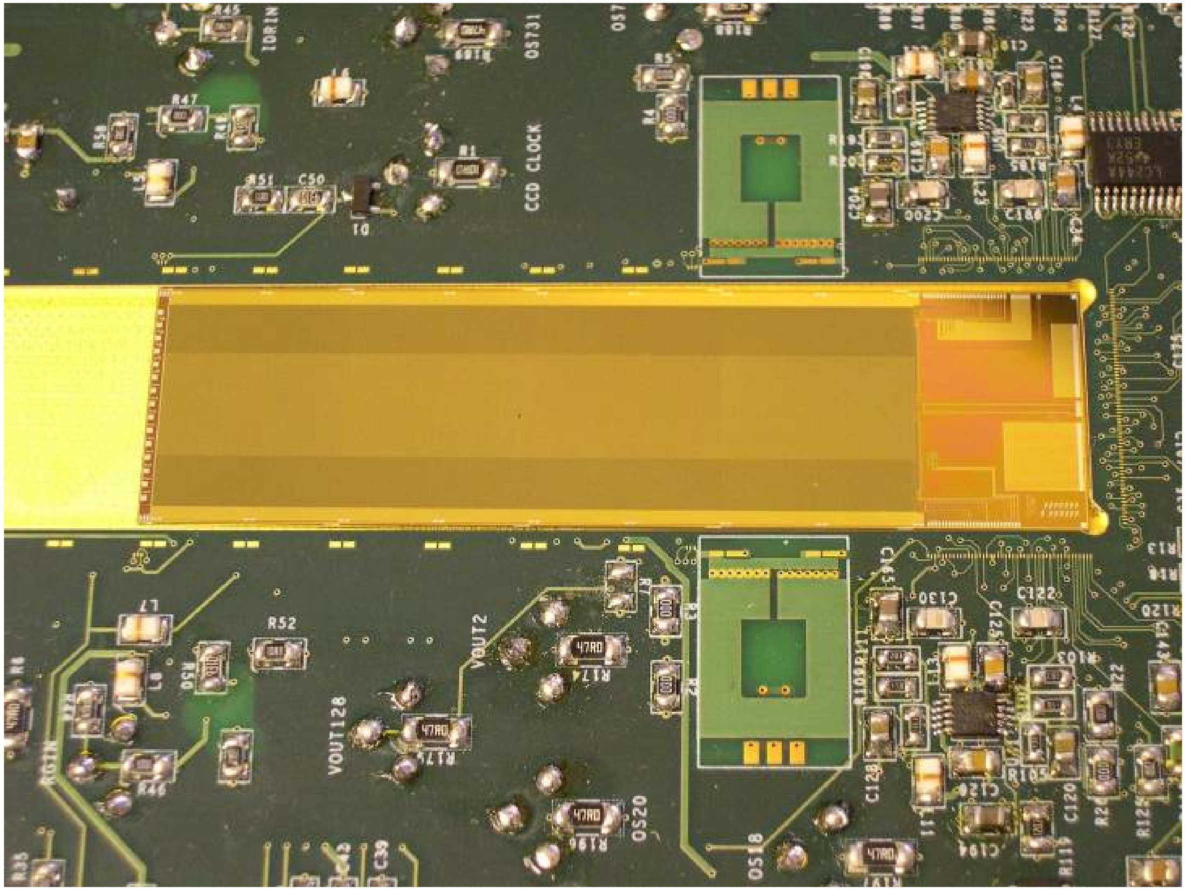
Next generation CPCCD – CPC2

- Manufactured by e2v on 5” wafers.
- One CPC2-70: 105 × 17 mm^2 total chip size.
- Two CPC2-40s per wafer.
- Six CPC2-10s per wafer.
- Fourteen In-situ Storage Image Sensors (ISIS1).
- Three wafers delivered so far.



Next generation CPCCD – CPC2

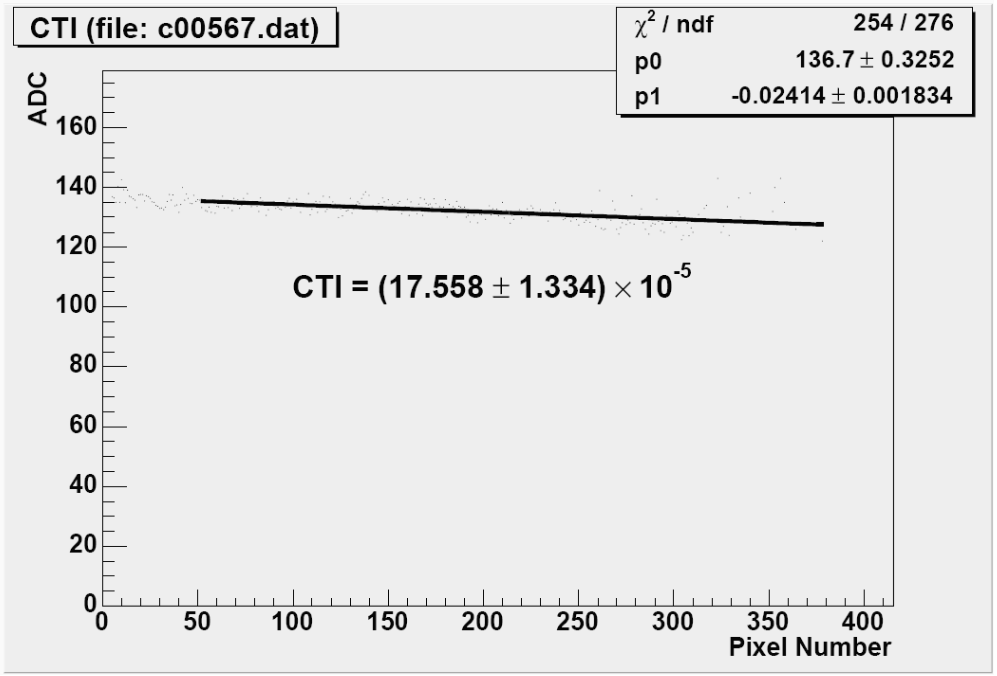
- CPC2-40 on motherboard awaiting testing: let the fun begin!



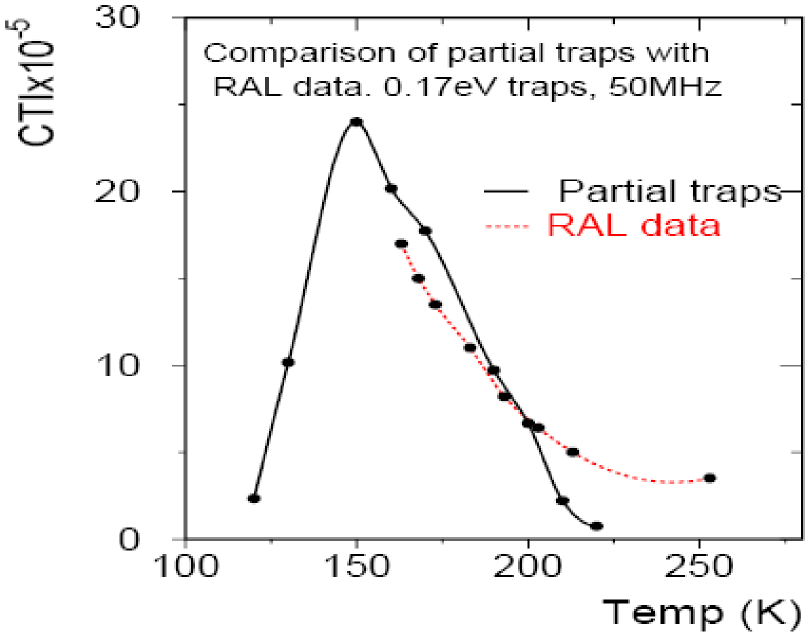
- (See Konstantin Stefanov’s talk at Vertex05 for more details!)

CCD radiation hardness tests

- Study CTI in CCD58 before and after irradiation (^{90}Sr 30 krad).
- Measure decrease in charge from ^{55}Fe X-rays as func. of number of pixels through which charge transferred.



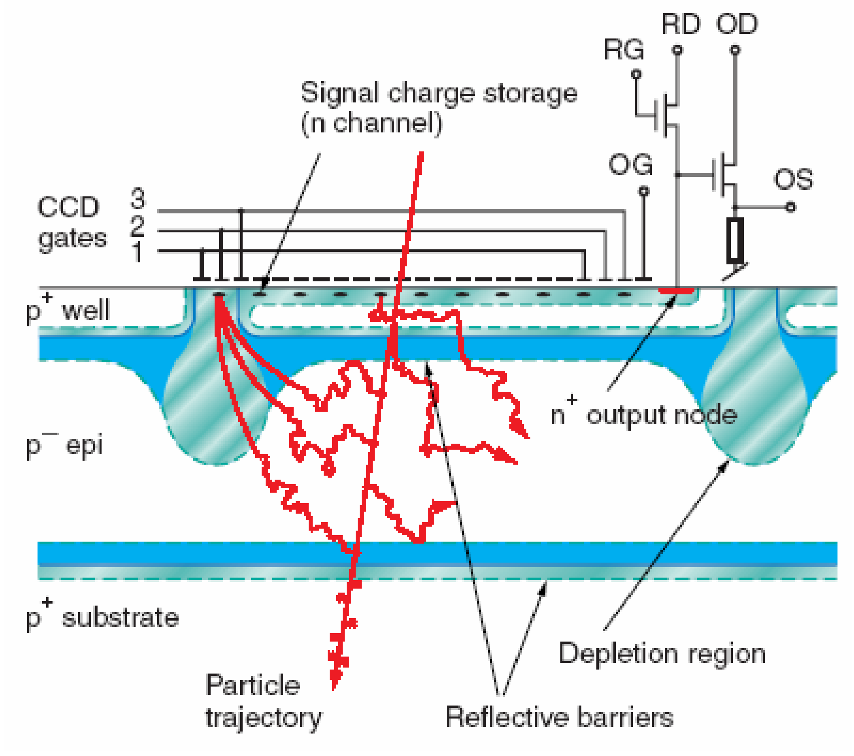
- Compare data with simulations performed using ISE-TCAD.



- Extend to CPCCD.

Sensors – ISIS

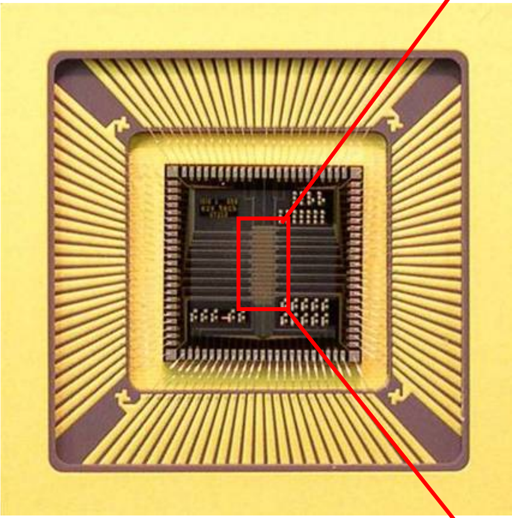
- In-situ Storage Image Sensor.

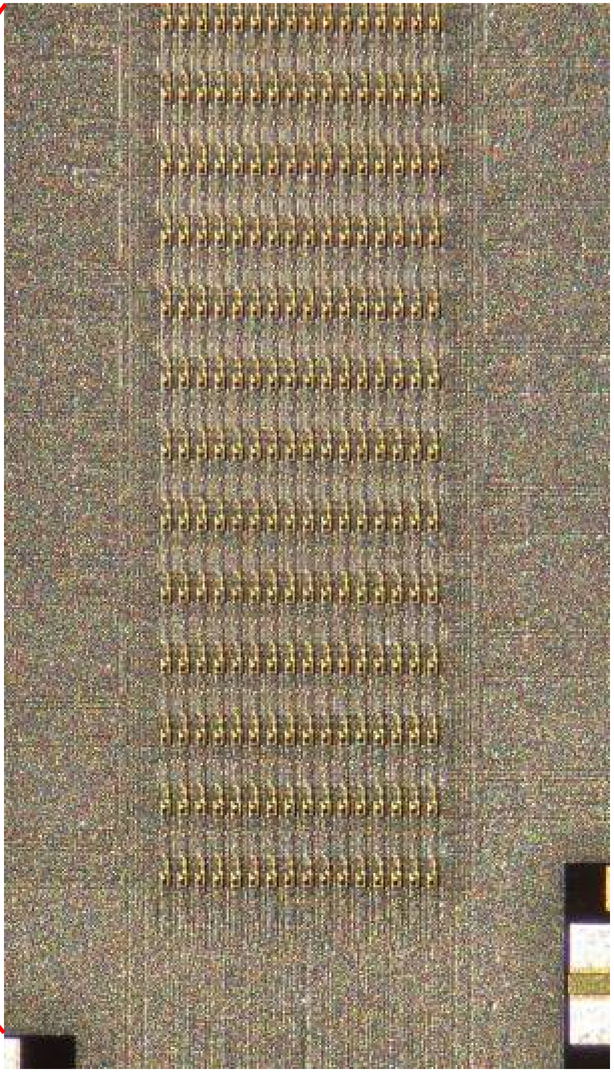


- Signal collected on photogate then transferred to CCD register in pixel 20 times during bunch train.
- Beam-related RF pickup is concern for all sensors converting charge to voltage during bunch train.
- ISIS eliminates this source of EMI:
- Readout in 200 ms quiet period between bunch trains.
- Column parallel readout at ~ 1 MHz sufficient to read out before arrival of next bunch train.
- Signal charge always buried in silicon until bunch train has passed.
- Approx. 100 times more radiation tolerant than CCDs.
- Easier to drive than CPCCD because of low clock frequency.

Sensors – ISIS1

- “Proof of principle” device designed by e2V technologies.
- Array of 16 ×16 pixels with CCD storage register (5 cells) in each pixel.
- ISIS1 in 100-pin PGA carrier →

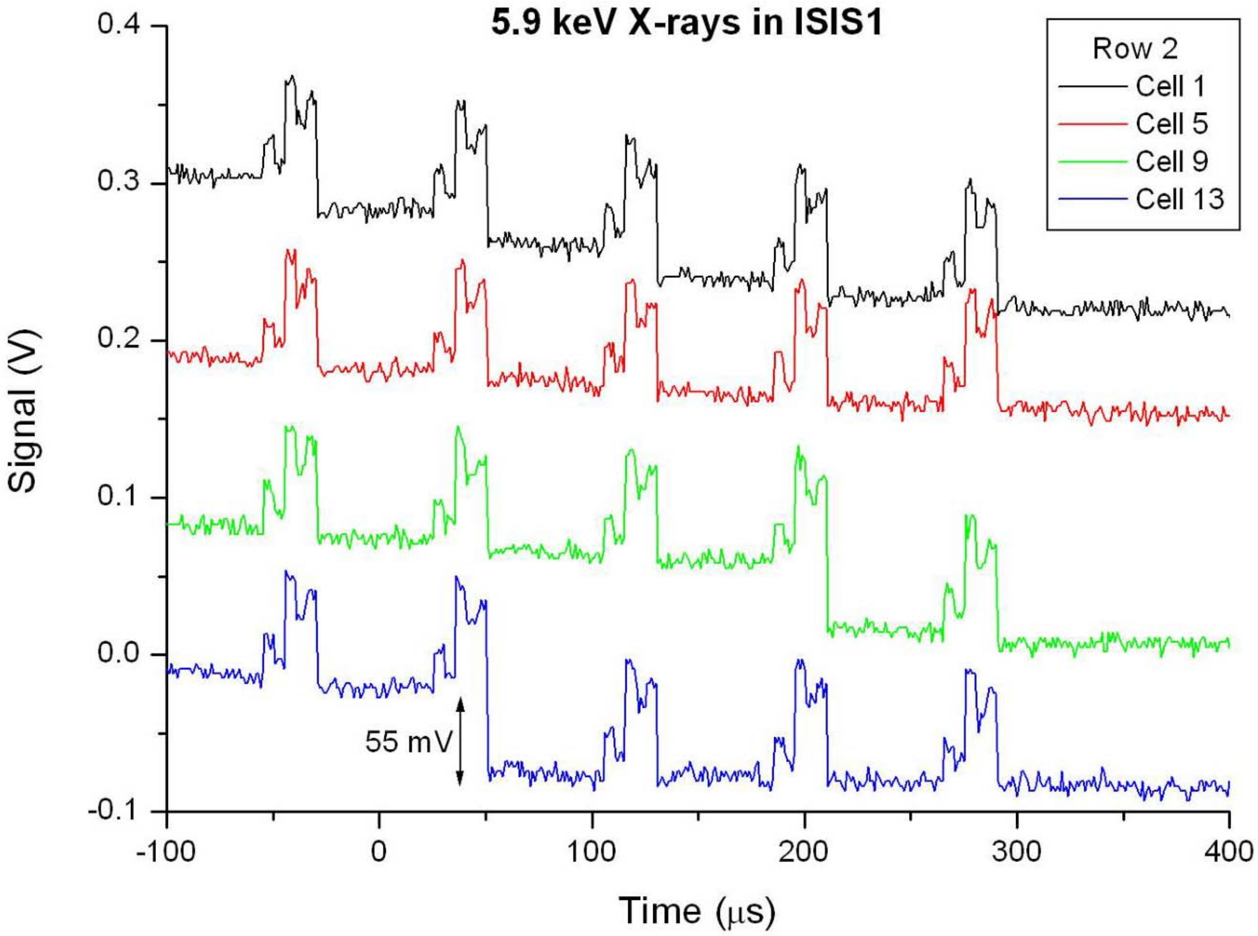




- Pixel pitch 40 × 160 μm^2, no edge logic (pure CCD process).
- Size ≈ 6.5 × 6.5 mm^2.

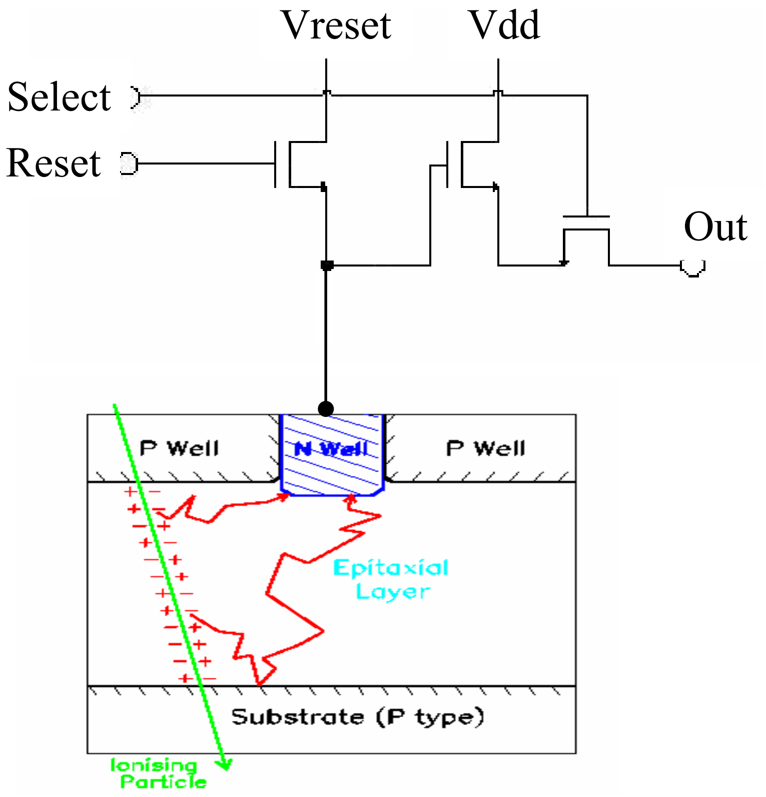
First X-ray signals from ISIS1

- Observe “steps” with correct amplitude: 3 μV/e⁻ × 1620 e⁻ × gain (10) = 49 mV.

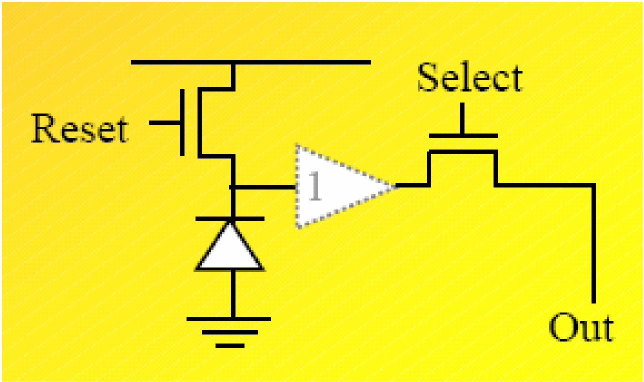


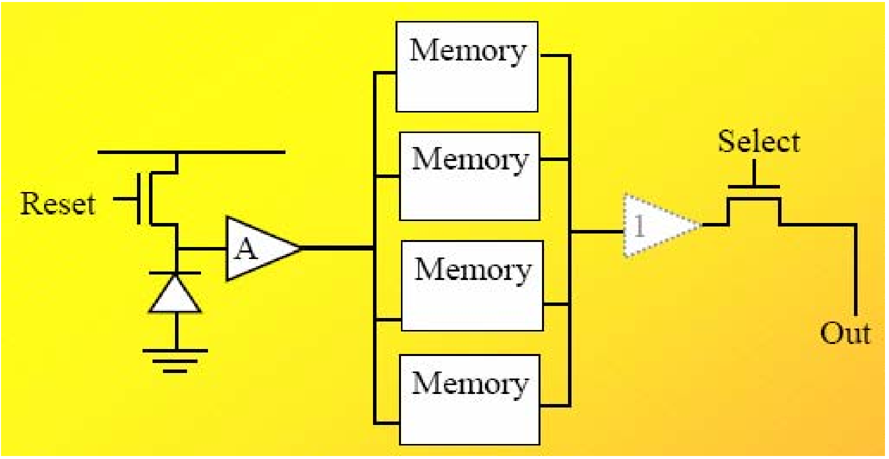
Sensors – FAPS

- Monolithic Active Pixel Sensors also under investigation for ILC.
- Ongoing development for scientific applications by MI3 collaboration.



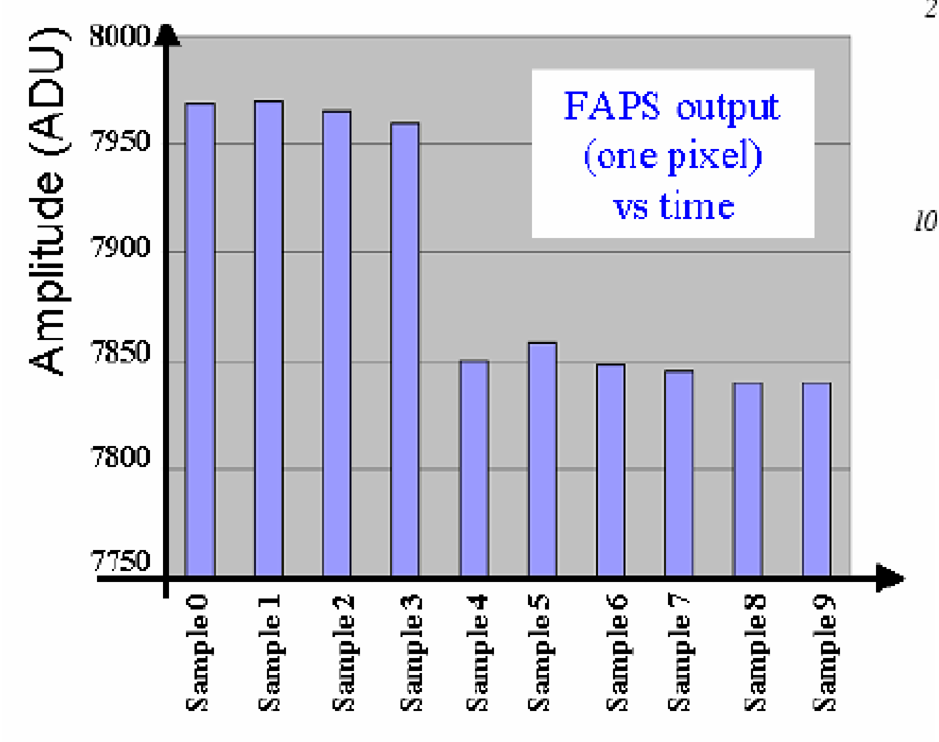
- Storage capacitors added to pixels for use at ILC: Flexible Active Pixel Sensors.



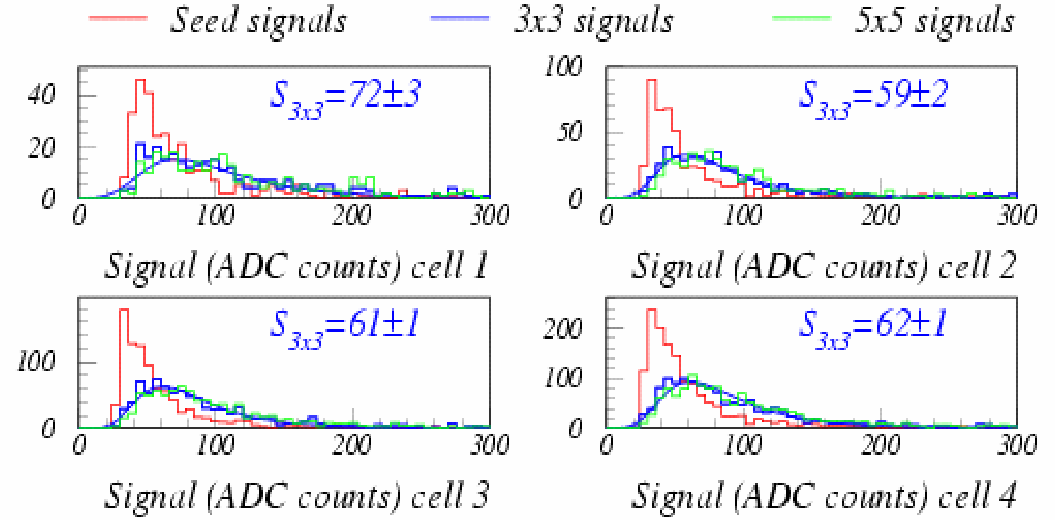


Sensors – FAPS

- Present design “proof of principle”.
- Pixels 20 x 20 µm^2, 3 metal layers, 10 storage cells.
- Test of FAPS structure with LED:



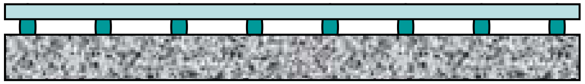
- ^{106}Ru β source tests:



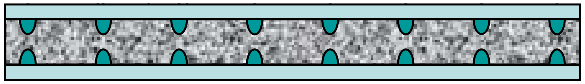
- Signal to noise ratio ~ 14.

Mechanical and thermal studies

- “Stretched” sensor studies revealed thickness of ~ 50 μm Si needed.
- Beryllium results poor: bad match of thermal expansion with Si.
- Look at silicon “floating” on silicon carbide...



- ...and silicon/carbon-foam (reticulated vitreous carbon)



- Both use “Nusil” silicone to attach the silicon to the substrate.

Ladder	Material	X/Xo
Silicon on SiC foam (~ 8% density)	Silicon (25 μm), SiC foam (1.5mm); silicone adhesive (~ 300 μm in tiny pads)	0.16% (~ 0.26% at glue pad locations)
Silicon-RVC foam sandwich (~ 3% density)	Silicon (25 μm) ×2; RVC foam (1.5mm); silicone adhesive (~100 μm in tiny pads) × 2	0.08% (~ 0.14% at glue pad locations)

- Thermal considerations:
- CPCCD drive will exploit LC duty cycle of 0.5% to achieve low average power consumption: cool using N_2 gas.
- Investigations of efficacy of cooling starting using quarter vertex detector thermal test rig.

Summary

- LCFI studying many aspects of quark flavour and charge identification at the ILC, including:
  - Algorithms for flavour/charge ID.
  - Optimum vertex detector design.
  - Sensors.
  - Mechanical and thermal effects.
- Many opportunities in all these areas, some examples:
- Physics:
  - Move from fast MC (SGV) to full simulation.
  - Develop pattern recognition in VXD, move to full reconstruction.
  - Study benchmark reactions.
- Sensors:
  - Device simulation: effects of B field.
  - Effects of increased background, halo muons... on readout.
  - Sensor testing and design.
- The vertex detector is small, but the amount of work that must be done to make sure we have the best possible system is not!