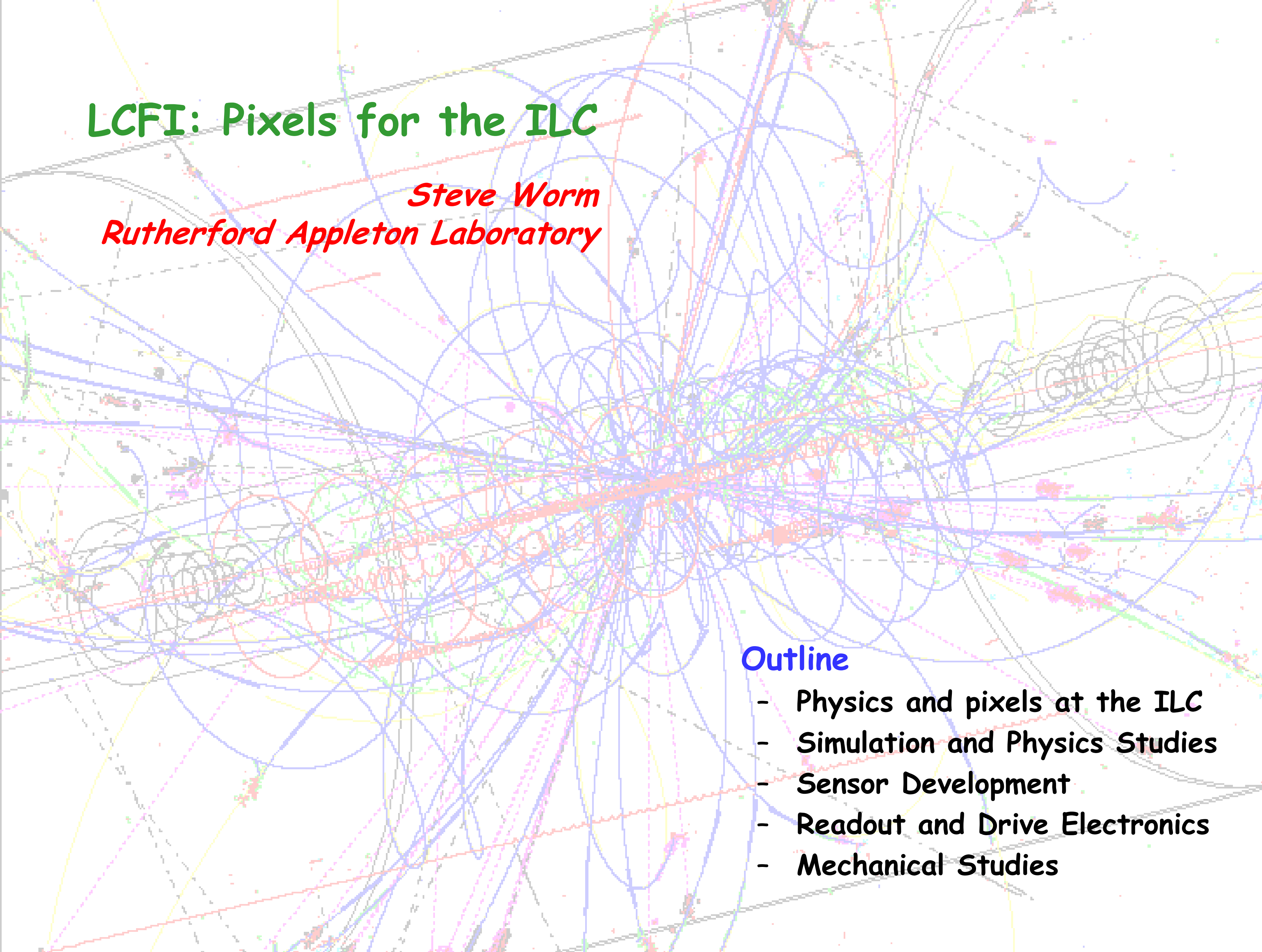


LCFI: Pixels for the ILC

Steve Worm
Rutherford Appleton Laboratory

Outline

- Physics and pixels at the ILC
- Simulation and Physics Studies
- Sensor Development
- Readout and Drive Electronics
- Mechanical Studies

Linear Collider Flavour Identification

LCFI Collaboration

P Allport[3], D Bailey[1], C Buttar[2], D Cussans[1], C J S Damerell[3], N De Groot[4], J Fopma[5], B Foster[5], S Galagedera[6], A R Gillman[6], J Goldstein[6], T J Greenshaw[3], R Halsall[6], B Hawes[5], K Hayrapetyan[3], H Heath[1], S Hillert[5], D Jackson[5,6], E L Johnson[6], A J Lintern[6], P Murray[6], A Nichols[6], A Nomerotski[5], V O'Shea[2], C Parkes[2], C Perry[5], K D Stefanov[6], P Sutcliffe[3], S L Thomas[6], R Turchetta[6], M Tyndel[6], J Velthuis[3], G Villani[6], T Wijnen[4], S Worm[6], S Yang[5]

1. Bristol University
2. Glasgow University
3. Liverpool University
4. Nijmegen University
5. Oxford University
6. Rutherford Appleton Laboratory

UNIVERSITY of GLASGOW

EHEF K.U. NIJMEGEN

University of BRISTOL

PPd CCLRC

THE UNIVERSITY of LIVERPOOL

The International Linear Collider

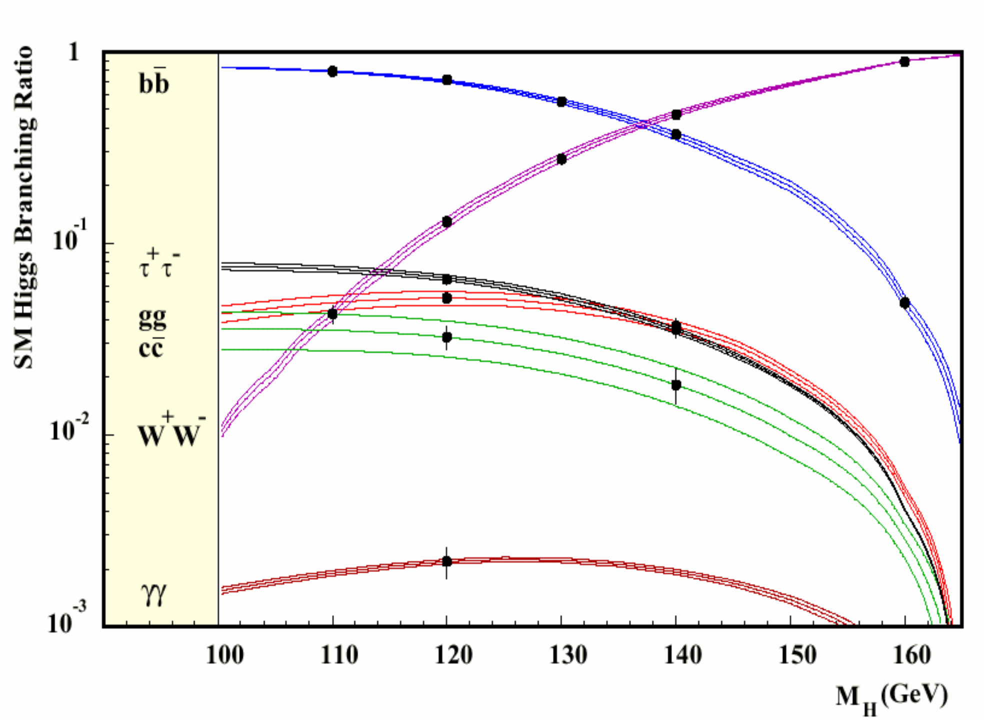
- The way forward…
  - Standard model is an incomplete picture of nature.
  - LHC experiments will study pp collisions $\sqrt{s}$ = 14 TeV giving large mass reach for discovery of new physics.
  - Precision measurements (masses, BRs, etc) are greatly complicated by the hadronic environment.
  - International 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.

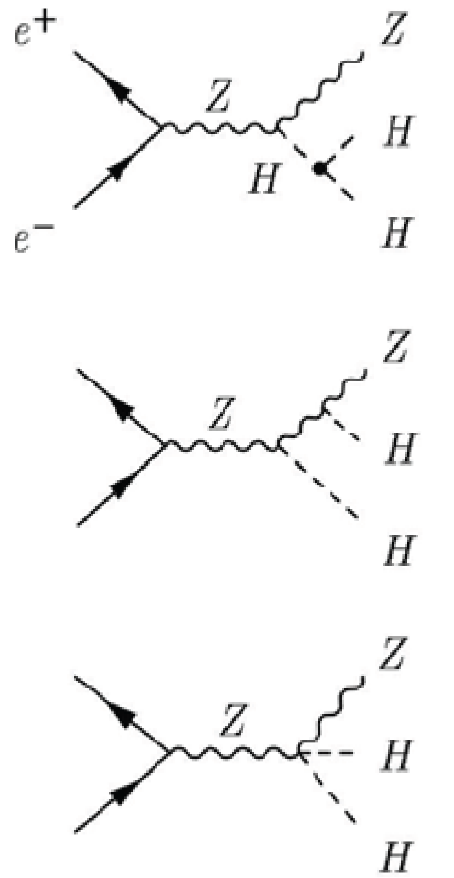
- Timeline and recent events
  - Superconducting RF technology selected for accelerating cavities.
  - Global effort now underway to design ILC, director Barry Barish.
  - Current timeline: Formation of experimental collaborations in 2008 and writing of Technical Design Reports in 2009.
  - Pixel vertex detector technology chosen following module tests in 2010.

Flavour and Quark Charge Identification at the ILC

- Understanding the new physics will require identifying heavy quarks.
  - Higgs Branching ratios; are they as expected in the Standard Model?
  - Separation of b from $\bar{b}$, and c from $\bar{c}$ will be important, eg. $e^+e^- \rightarrow HHZ$
  - Leads to reduced combinatorial background.
  - Allows determination of Higgs self-coupling.

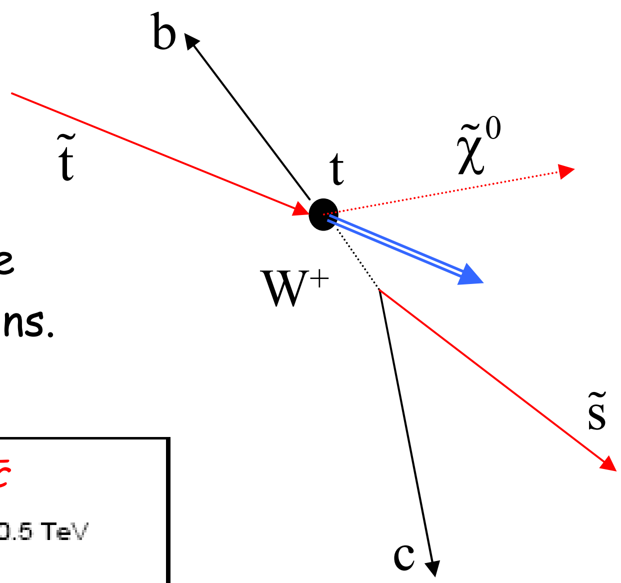
Not just b/c tagging, but also determine quark charge



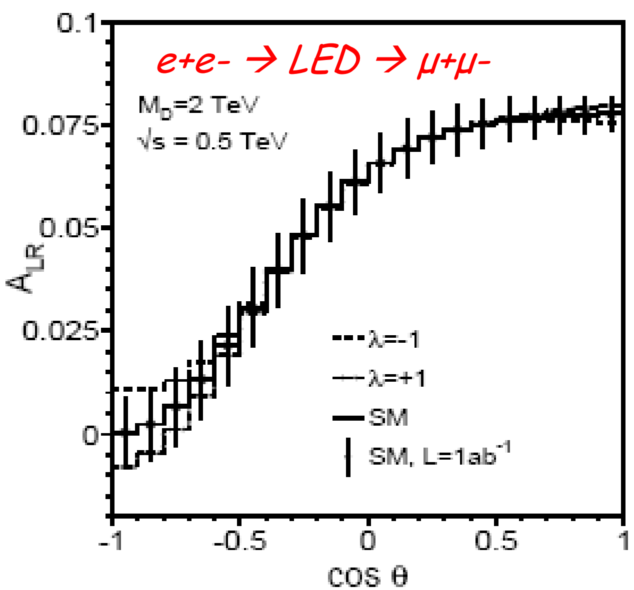


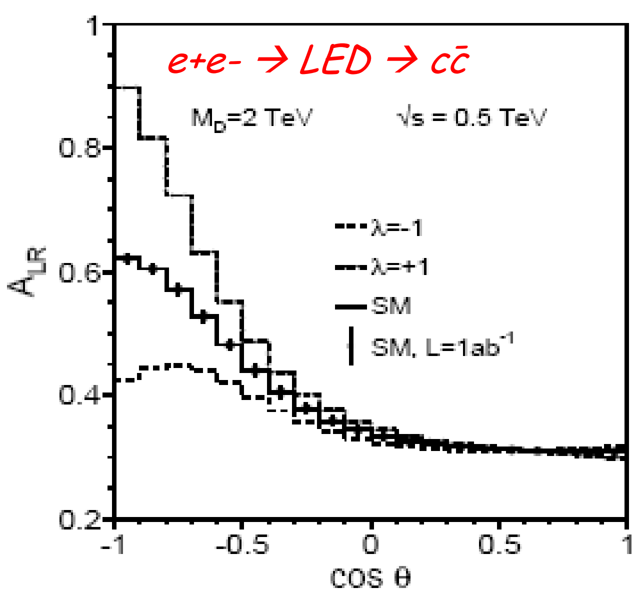
Quark Charge Identification

- Provides a new tool for physics studies
  - Allows study of polarisation in top decays, e.g. $t \rightarrow bW^{+} \rightarrow b(c\bar{s})$
  - Determine $\tan\beta$ and tri-linear couplings A_t and A_b through measurements of top polarisation in sbottom and stop decays.



- Gives increased sensitivity to physics studies
  - Large Extra Dimensions; $e+e- \rightarrow f\bar{f}$. LED not visible in $A_{LR} = (\sigma_L - \sigma_R)/\sigma_{tot}$ as a function of $\cos\theta$ for muons.





Vertex Detector Performance Goals

- Physics environment:
  - 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 $\sqrt{s}$, as charged track momenta extend down to ~ 1 GeV.
  - Resolve all tracks in dense jets.
  - Cover largest possible solid angle: forward/backward events are important.
  - Stand-alone reconstruction desirable.

- In terms of impact parameter, require resolution in rφ and rz:

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

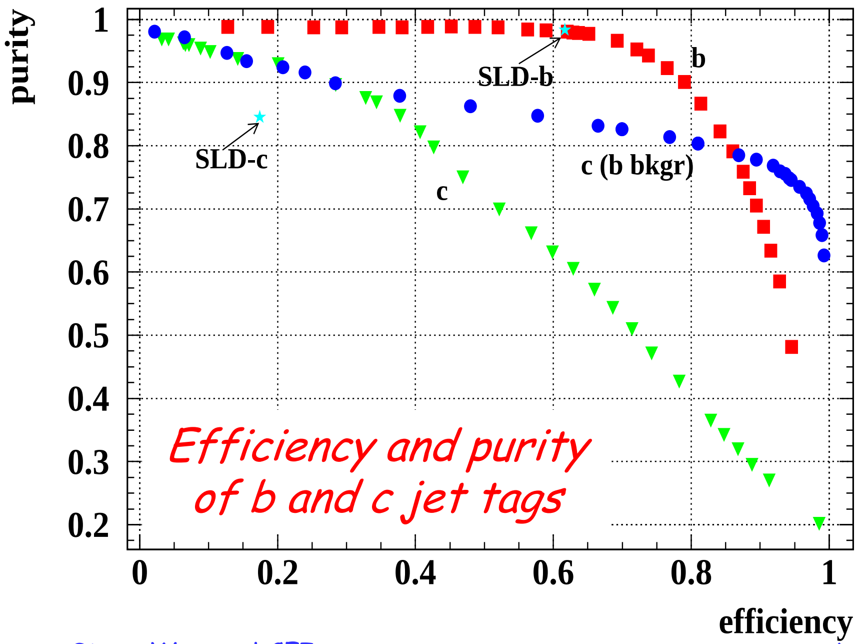
$$a < 5\,\mu\text{m}\,(\text{point precision})$$

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

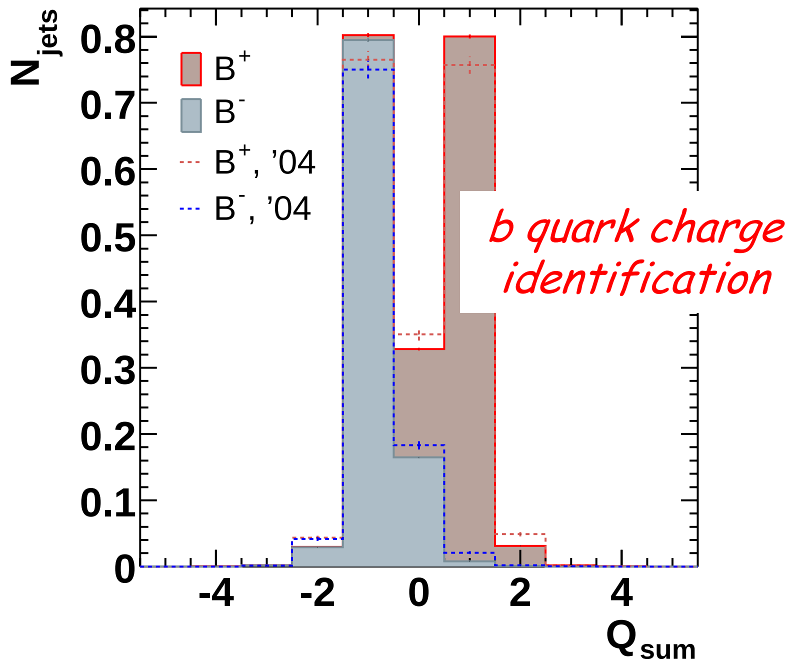
- Implies typically:
  - Pixels ~ 20 x 20 μm^2.
  - First measurement at r ~ 15 mm.
  - Five layers out to radius of about 60 mm, i.e. total ~ 10^9 pixels
  - Material ~ 0.1% X_0 per layer.
  - Detector covers |cos θ| < 0.96.

LCFI Physics Studies

- Identification of b/c quarks
  - ZVTOP algorithm plus neural net
  - Modest improvement in b tagging over that achieved at SLD.
  - Improvement by factor 2 to 3 in charm tagging efficiency.
  - Charm tag interesting e.g. for Higgs BR measurements.



- Identification of quark charge
  - Must assign all charged tracks to correct vertex.
  - Multiple scattering critical, lowest track momenta ~1 GeV.
  - Sum charges associated with b vertex:



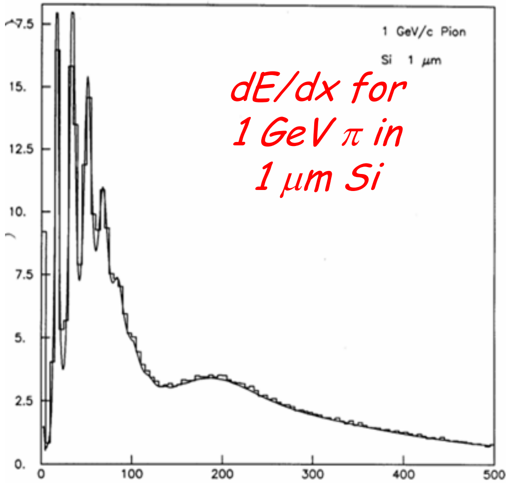
Physics Studies: From MIPS to Physics

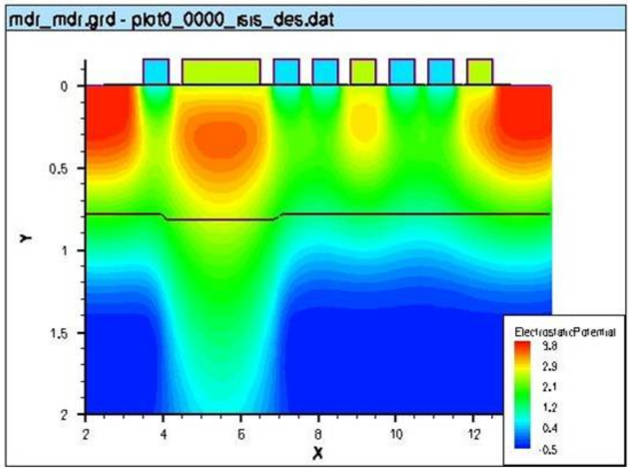
Charge deposition, clustering, sparsification, track fitting → *Vertexing, track attachment, topological dependence* → *Impact on physics quantities, individual physics channels*

The sensors we study are *new devices*; we need to model how they work.

- We will need to develop understanding of:
  - Charge generation, propagation, and collection in new sensor types
  - Cluster finding, sparsification, fitting to tracks
  - Background effects and environment

→ Provides feedback to sensor and electronics design



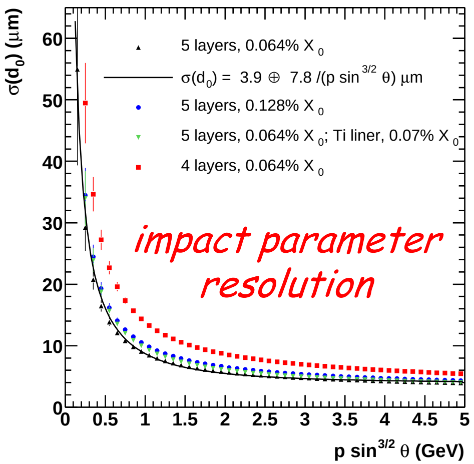


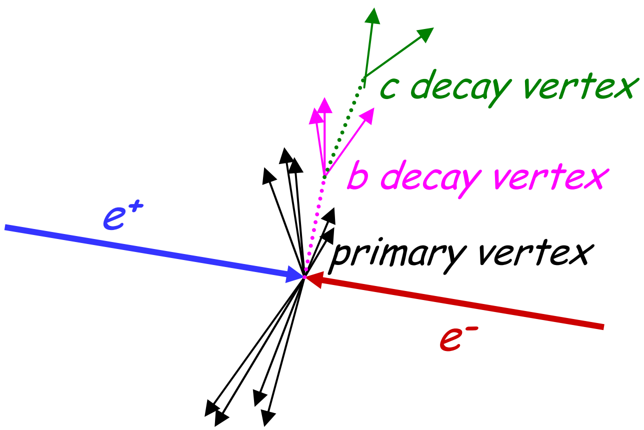
Physics Studies: From MIPS to Physics

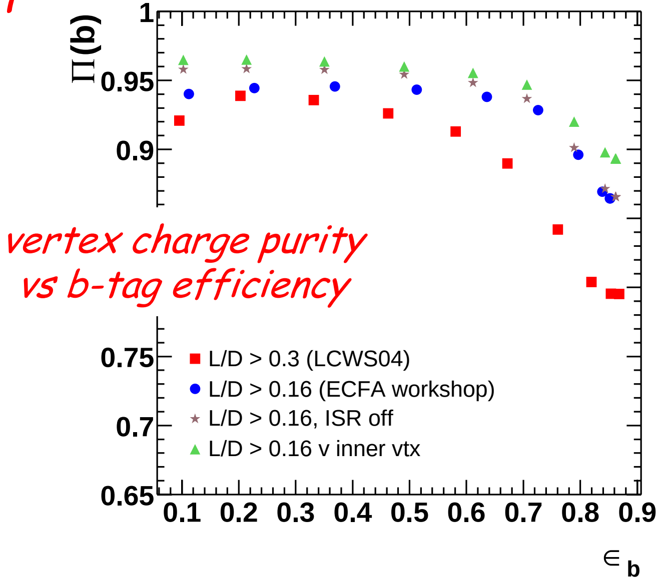
Charge deposition, clustering, sparsification, track fitting → ***Vertexing, track attachment, topological dependence*** → *Impact on physics quantities, individual physics channels*

- Study factors affecting flavour identification and quark charge
  - Optimise flavour ID and extend quark charge determination to B^0.
  - Examine effects of individual sensor failures.
  - Detector alignment procedures and effects of misalignments.
  - Polar angle dependence of flavour and charge identification.

→ *Provides feedback to mechanical design; can shape overall detector design, e.g. additional layers, increased detector length*





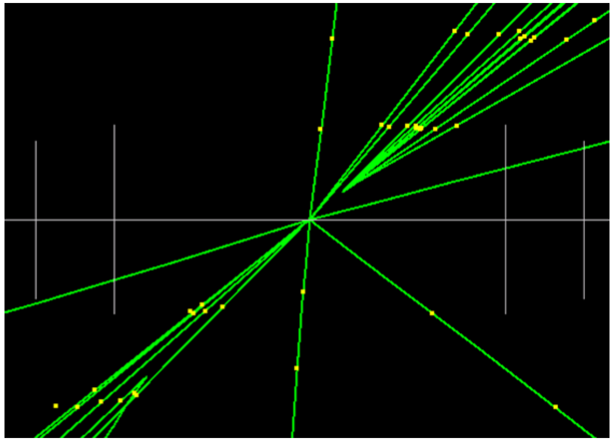


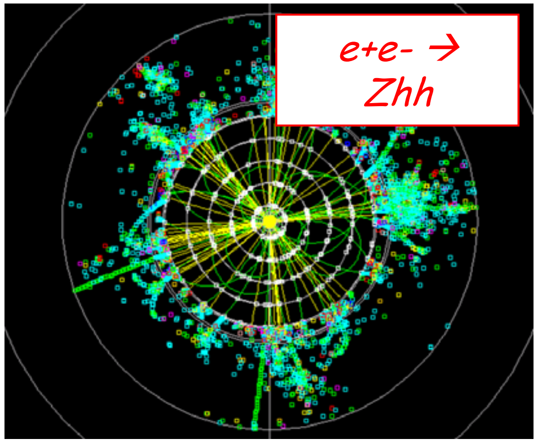
Physics Studies: From MIPS to Physics

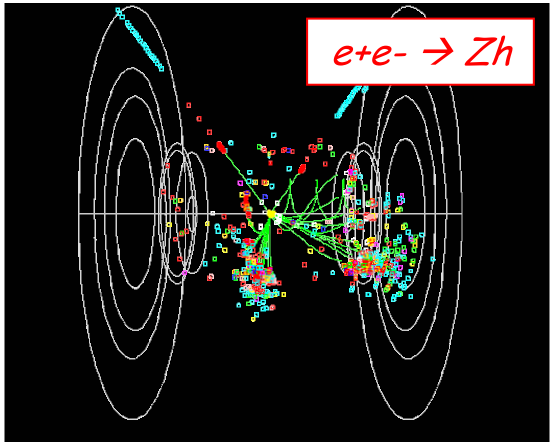
Charge deposition, clustering, sparsification, track fitting → *Vertexing, track attachment, topological dependence* → *Impact on physics quantities, individual physics channels*

- 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.

→ Plan to be prepared to react to discoveries at the LHC, and to show detector impact on physics.



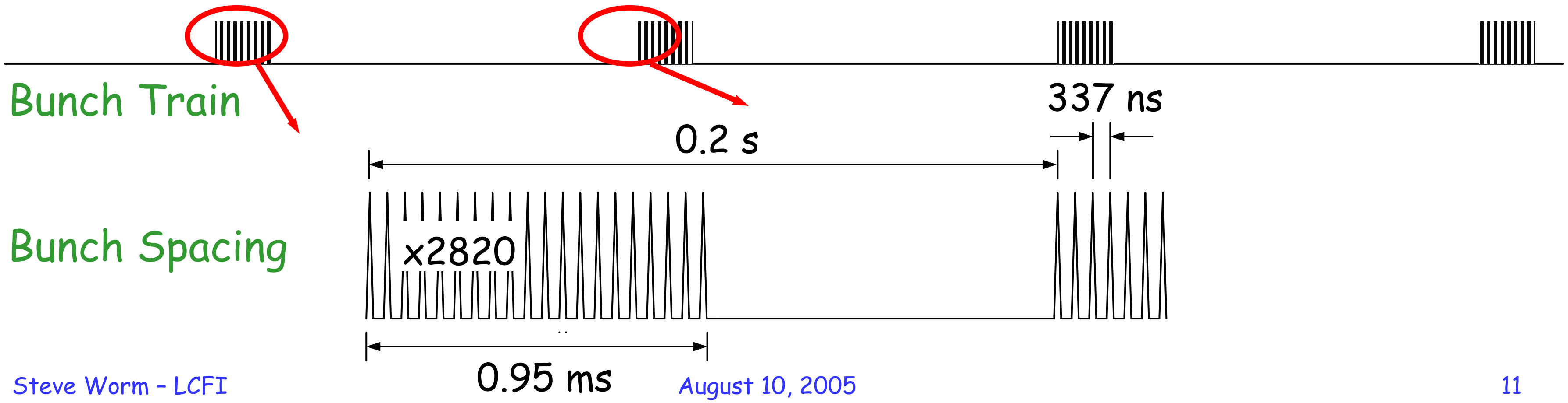




Tracking and Timing Features at the Linear Collider

What sort of tracking and vertexing is needed for the Linear Collider?

- Vertex detectors for the Linear Collider will be *precision* devices
  - Need very thin, low mass detectors
  - No need for extreme radiation tolerance
  - Need high precision vertexing → eg ~20 μm pixels
  - Can not simply recycle technologies used in LHC or elsewhere
- High pixelization and readout implications
  - 10^9 pixels: must break long bunch trains into small bites (2820/20 = 141)
  - Read out detector many (ie 20) times during a train → susceptible to pickup
  - …or store info for each bite and read out during long inter-train spaces



Sensors for the ILC vertex detector

ILC long bunch trains, ~10^9 pixels, relatively low occupancy

Read out *during* the bunch train:

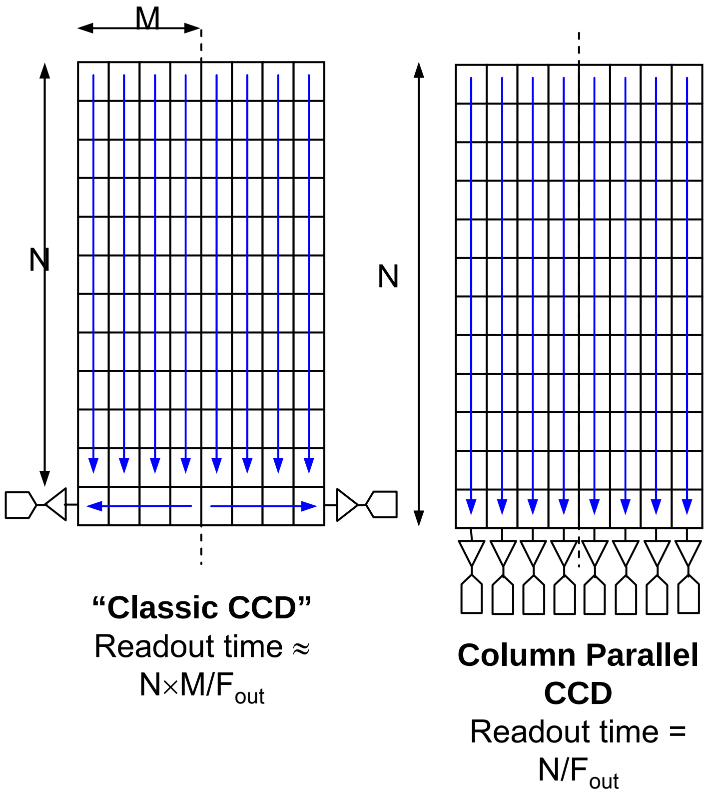
- Fast CCDs
  - Development well underway
  - Need to be fast (50 MHz)
  - Need to increase speed, size
  - Miniaturise drive electronics

Read out in the *gaps*:

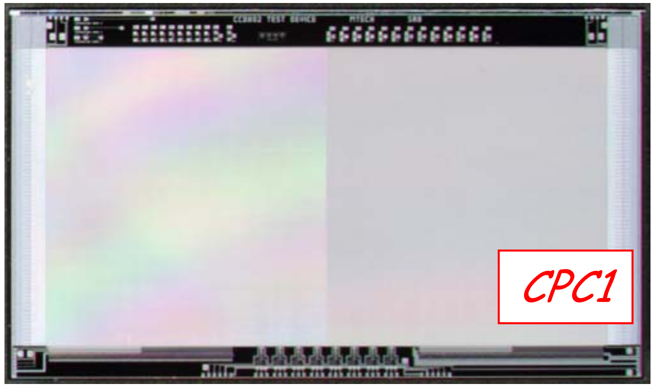
- Storage sensors
  - Store the hit information, readout between bunch trains (exploit beam structure)
  - Readout speed requirements reduced (~1MHz)
  - Two sensor types under study; ISIS and FAPS

Sensors: Column-Parallel CCDs

- Fast Column-Parallel CCD's (CPCCD)
  - CCD technology proven at SLD, but LC sensors must be faster, more rad-hard
  - Readout in parallel addresses speed concerns
  - CPCCD's feature small pixels, can be thinned, large area, and are *fast*



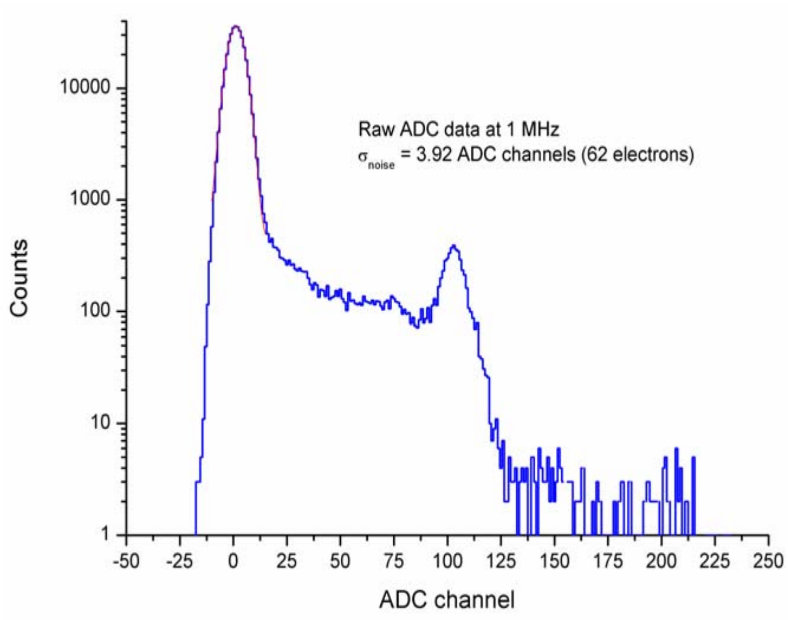
- CPC1 design features (e2v technologies):
  - Two phase, 400 (V) × 750 (H) pixels of size 20 × 20 μm^2
  - Metal strapped clock gates
  - Different gate shapes and implant levels
  - Single and double-stage source-followers



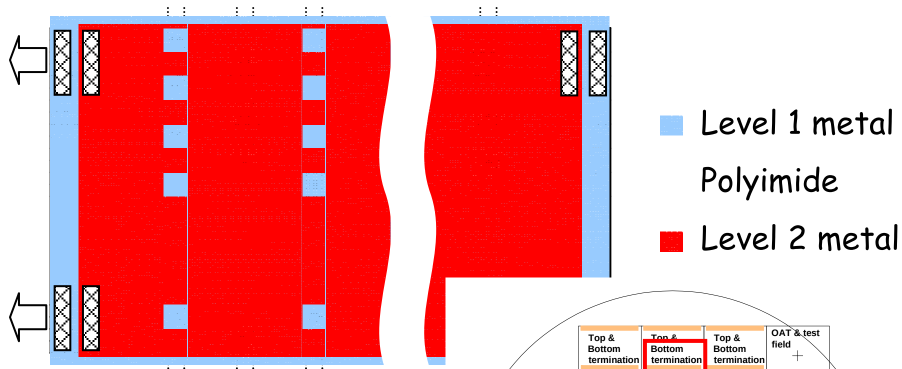
Column-Parallel CCDs: Recent Results

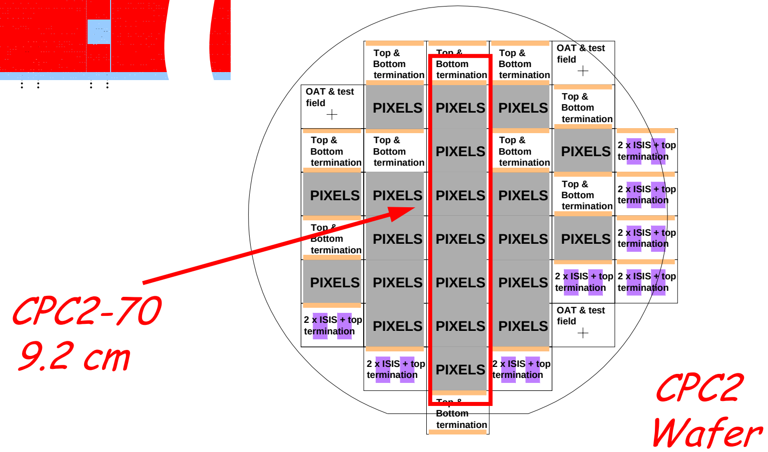
- First-generation tests (CPC1):
  - Noise ~100 e⁻ (60 e⁻ after filter).
  - Minimum clock potential ~1.9 V.
  - Max clock frequency above 25 MHz (design 1 MHz).
  - Limitation caused by clock skew

Extremely successful!



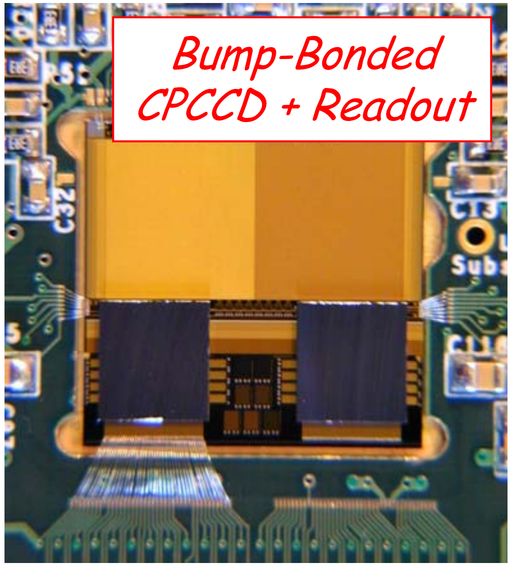
- Next generation in production (CPC2):
  - Busline free design (two-level metal)
  - Large area 'stitched' sensor, choice of epi layers for varying depletion depth
  - Range of device sizes for test of clock propagation (up to 50 MHz)
  - Large chips are nearly the right size

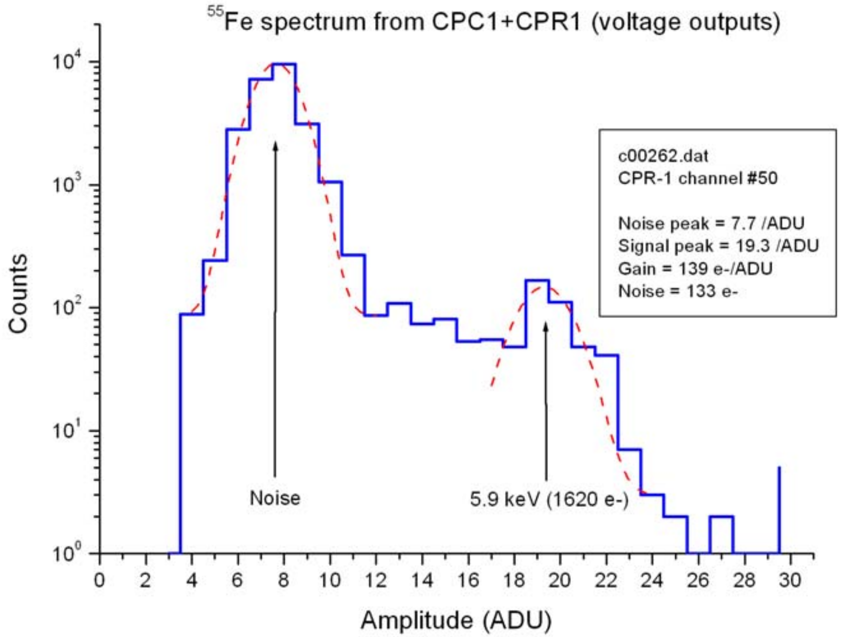


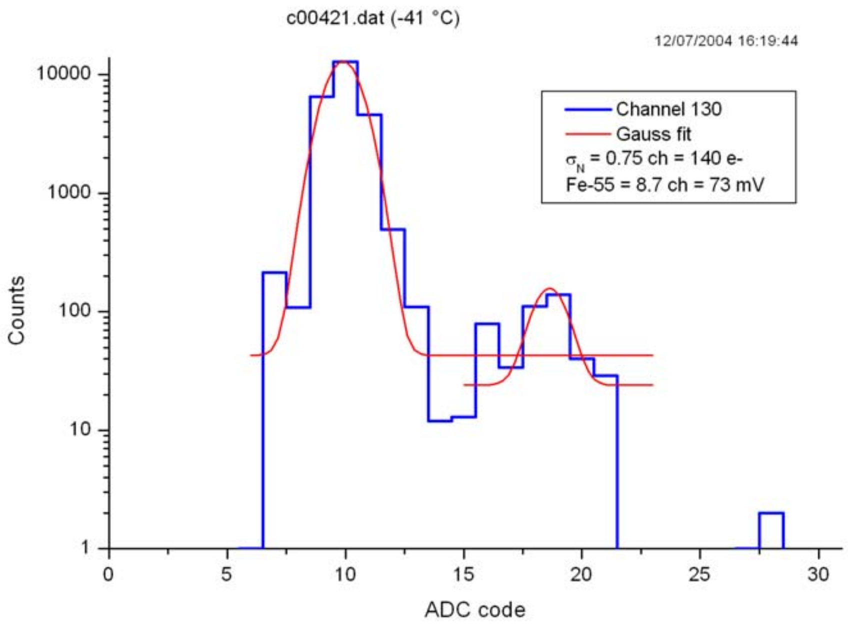


Column-Parallel CCDs: Recent Results

- Wire and bump bonded Column-Parallel CCD and readout chip (CPR1)
  - Source tests with ^{55}Fe
  - Noise ~130 e-
- Bump-bonding CCDs
  - Bonded at VTT (with some teething pains)
  - First time e2v CCDs bump bonded



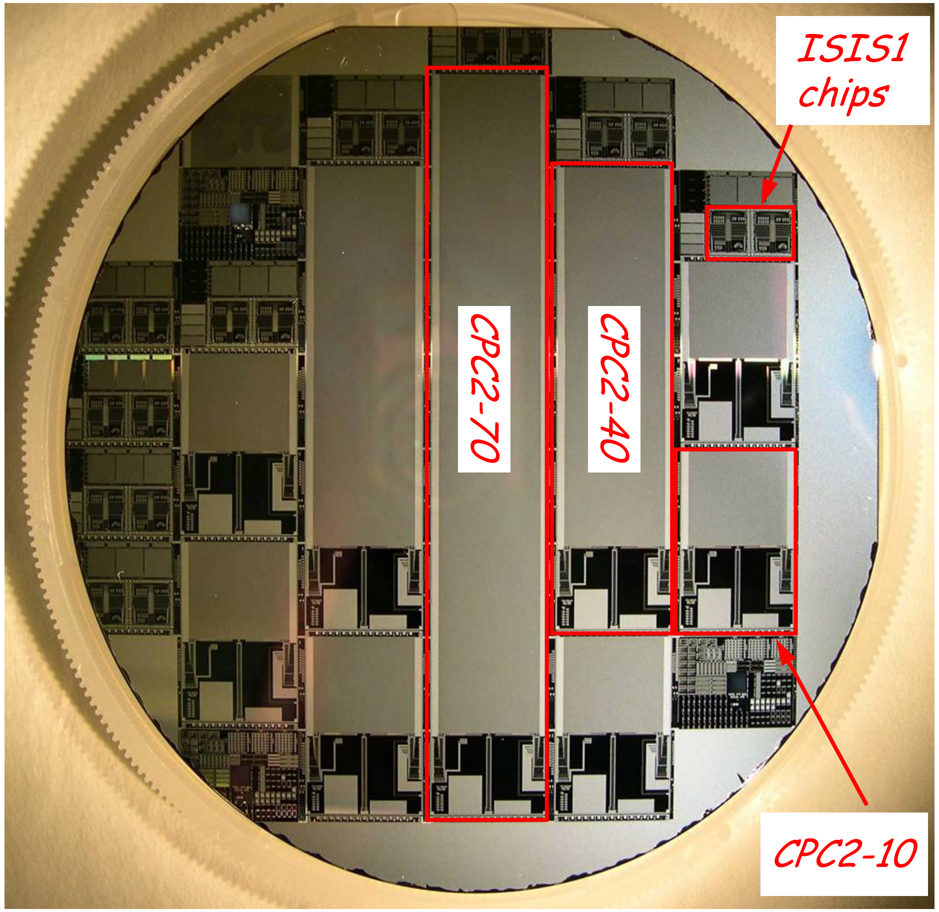




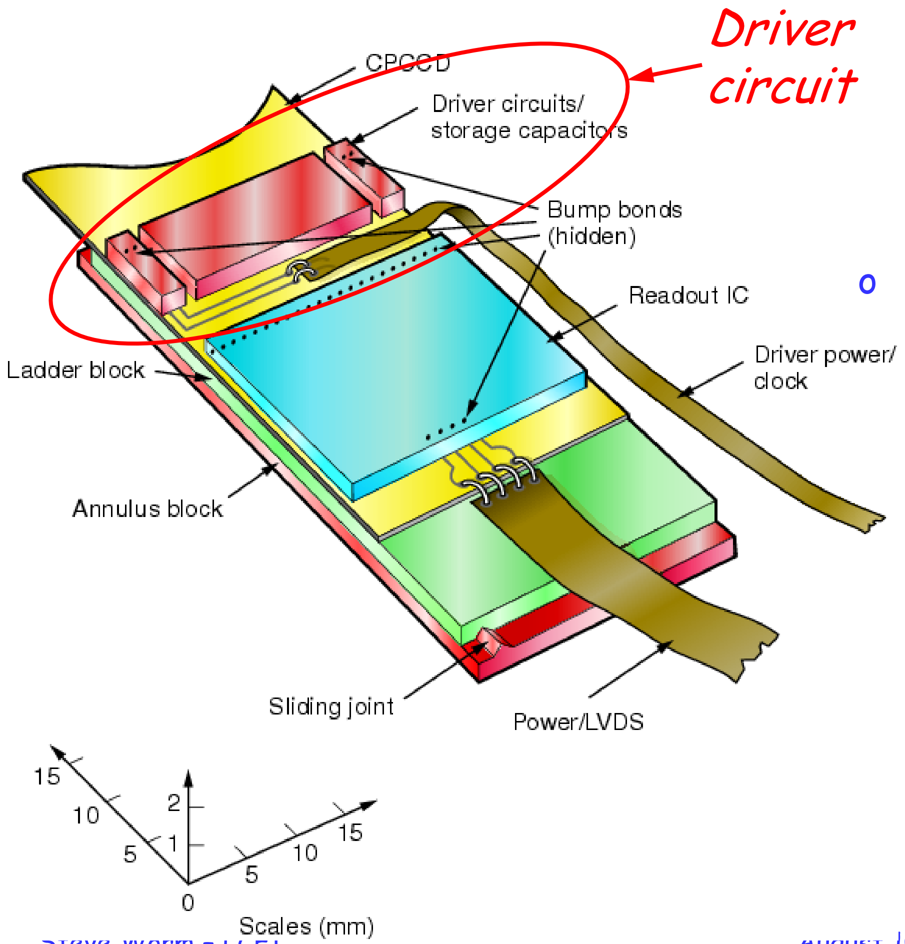
CPC2/ISIS1 Wafer

- Currently in manufacture at e2v technologies
- Three different Column-parallel CCD sizes:
  - CPC2-70: 92 mm x 15 mm image area
  - CPC2-40: 53 mm long
  - CPC2-10: 13 mm long
- Features include:
  - Two charge transport regions
  - Choice of epi layers for different depletion depth: 0.1 to 1.0 kΩcm (25-50 μm)
  - Largest size sensor designed for few MHz operation

Ready for delivery in August.



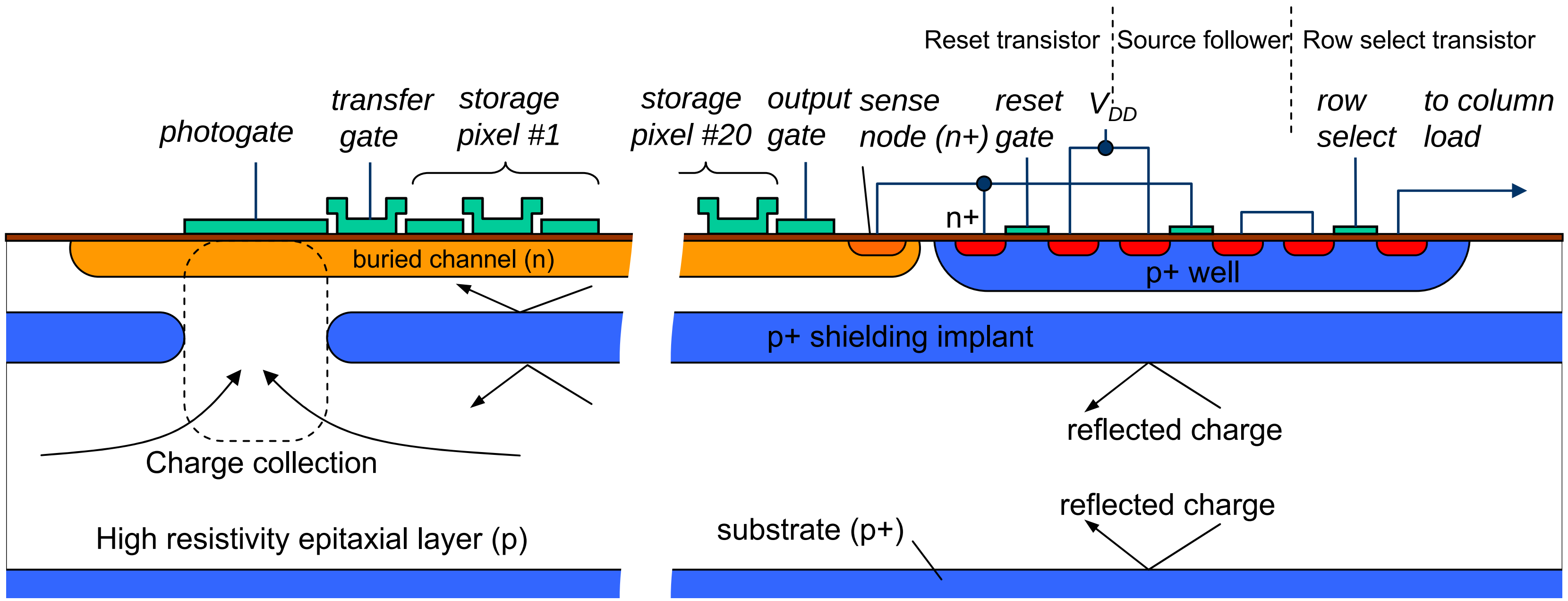
Driver Design Issues for CPCCD



- High Current
  - Problem supplying ~10A to driver IC (thick wires)
  - Solution may be capacitive storage (charged at low rate between bunch trains, discharged at high rate when CCD is clocked during bunch train)
- Waveform shape and timing
  - The driver IC will provide a high degree of control over the waveform
  - Shape and timing of CCD clock could be fine tuned to match readout IC timing
  - Adjustable clock drive voltage (aim to minimise power, without degrading charge transfer efficiency)

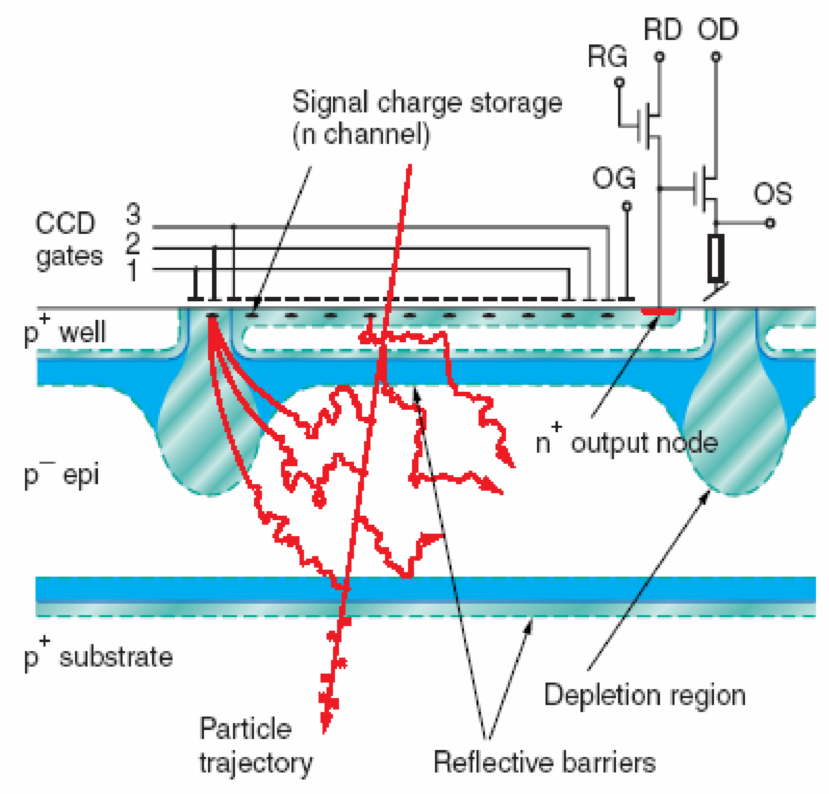
Storage Sensors - ISIS

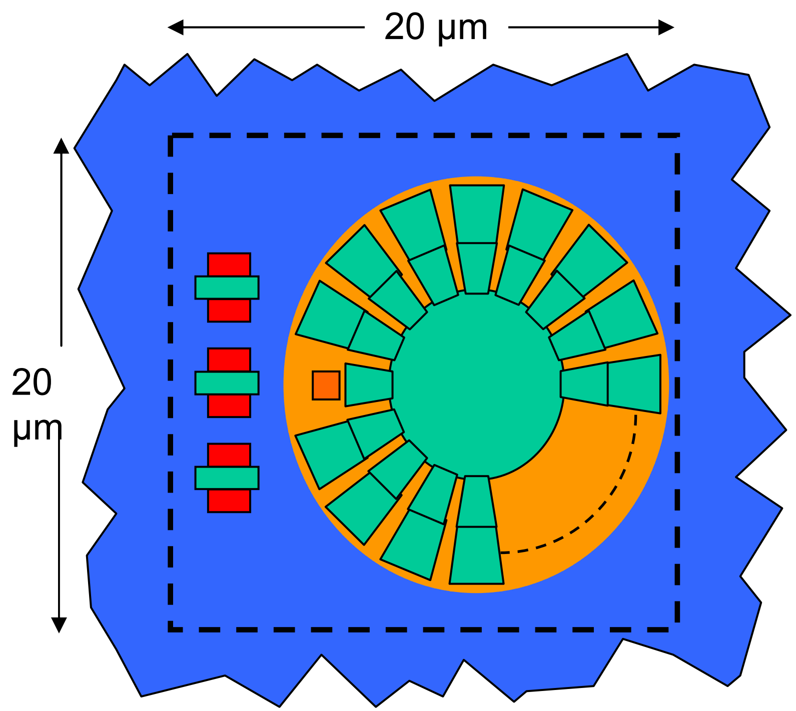
- In-situ storage image sensor (ISIS) details:
  - CCD-like charge storage cells in CMOS technology
  - Processed on sensitive epi layer
  - p+ shielding implant forms reflective barrier (deep implant)
  - Overlapping poly gates not likely in CMOS, may not be needed
- Basic structure of one pixel shown below:



Storage Sensors: ISIS

- "Linear" variant of ISIS
  - Linear array of ~20 storage cells in each pixel
  - Test device being built by e2v

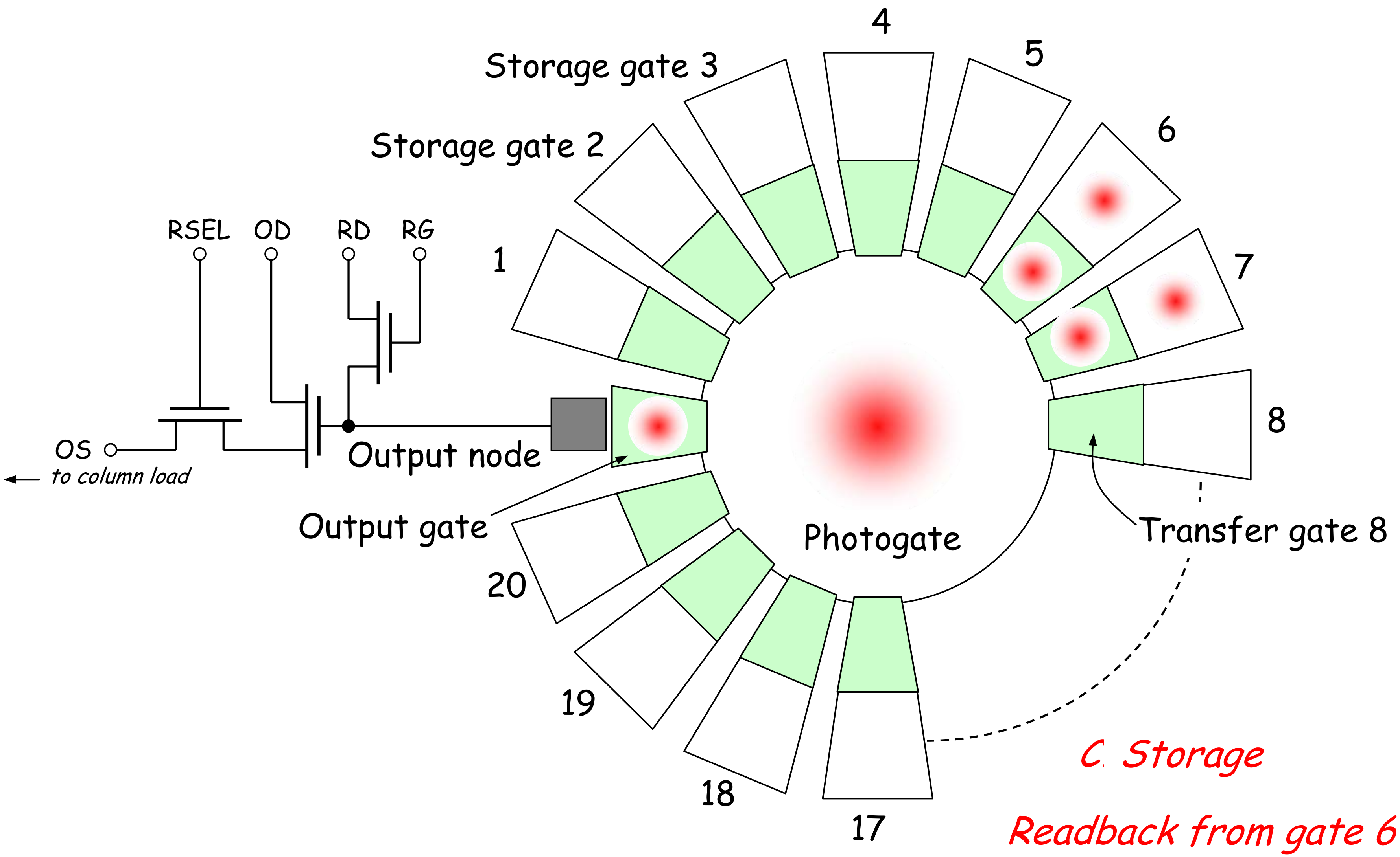




- "Revolver" variant of ISIS
  - Reduces number of charge transfers
  - Increases radiation hardness and flexibility

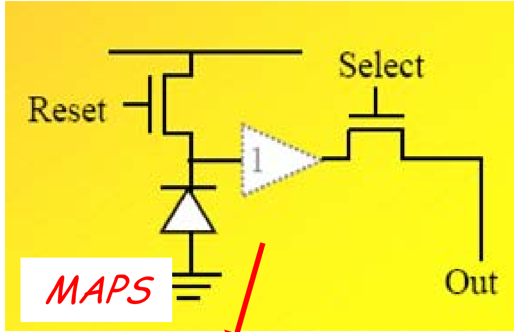
→ *No shortage of good ideas*

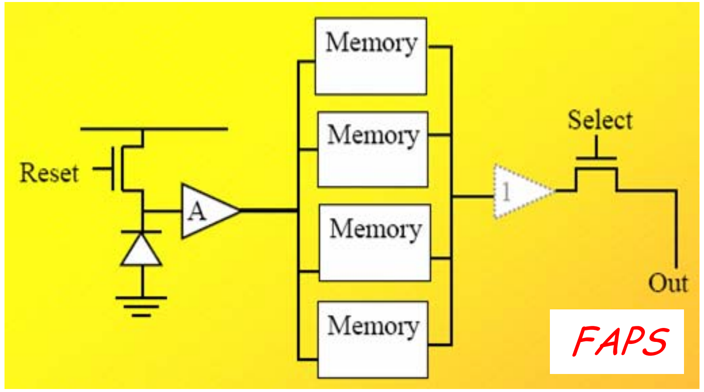
Storage Sensors: ISIS

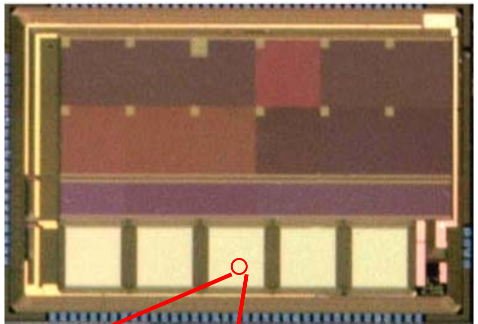


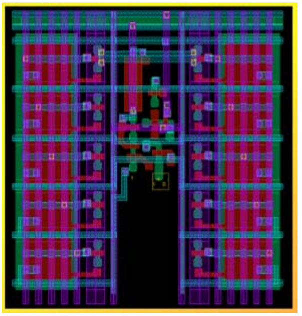
Storage Sensors: FAPS

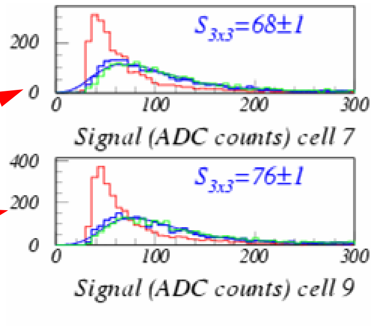
- **FAPS architecture**
  - Flexible active pixel sensors
  - Adds pixel *storage* to MAPS
  - Present design "proof of principle" test structure
  - Pixels 20x20 μm^2, 3 metal layers, 10 storage cells







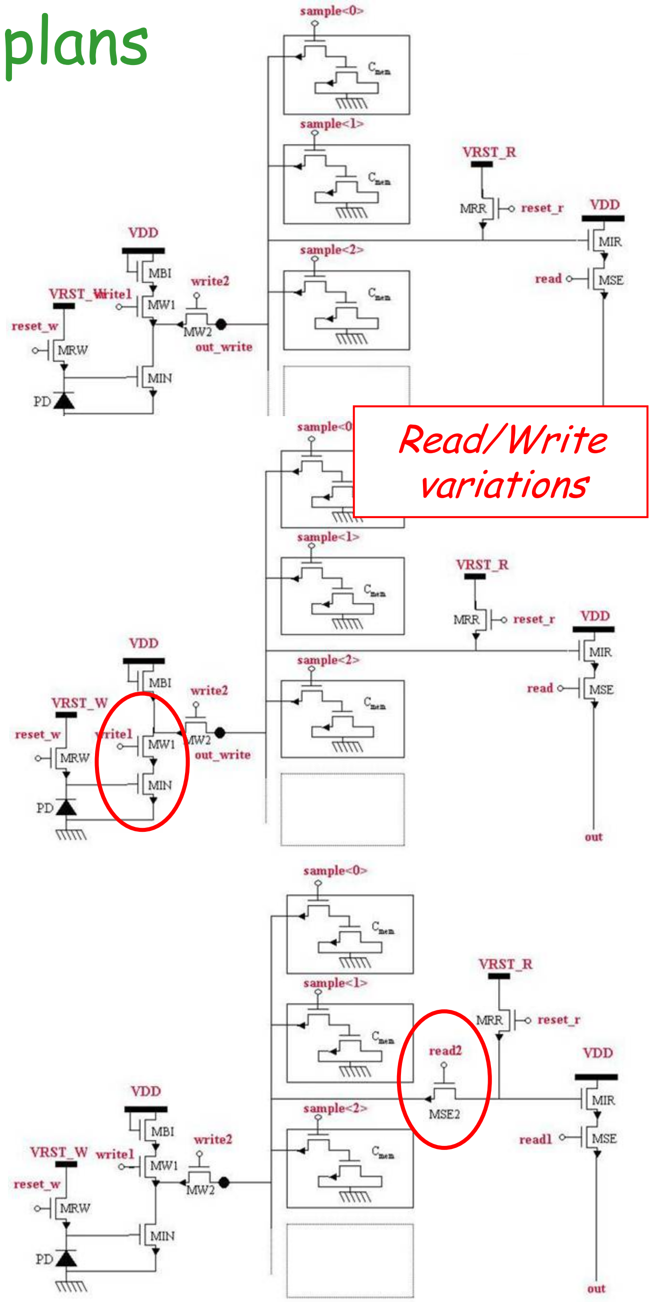


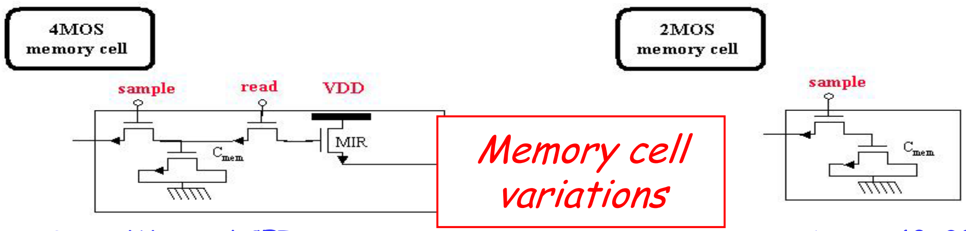


- **Results with initial design:**
  - ^{106}Ru β source tests: Signal to noise ratio between 14 and 17.
  - MAPS shown to tolerate high radiation doses.

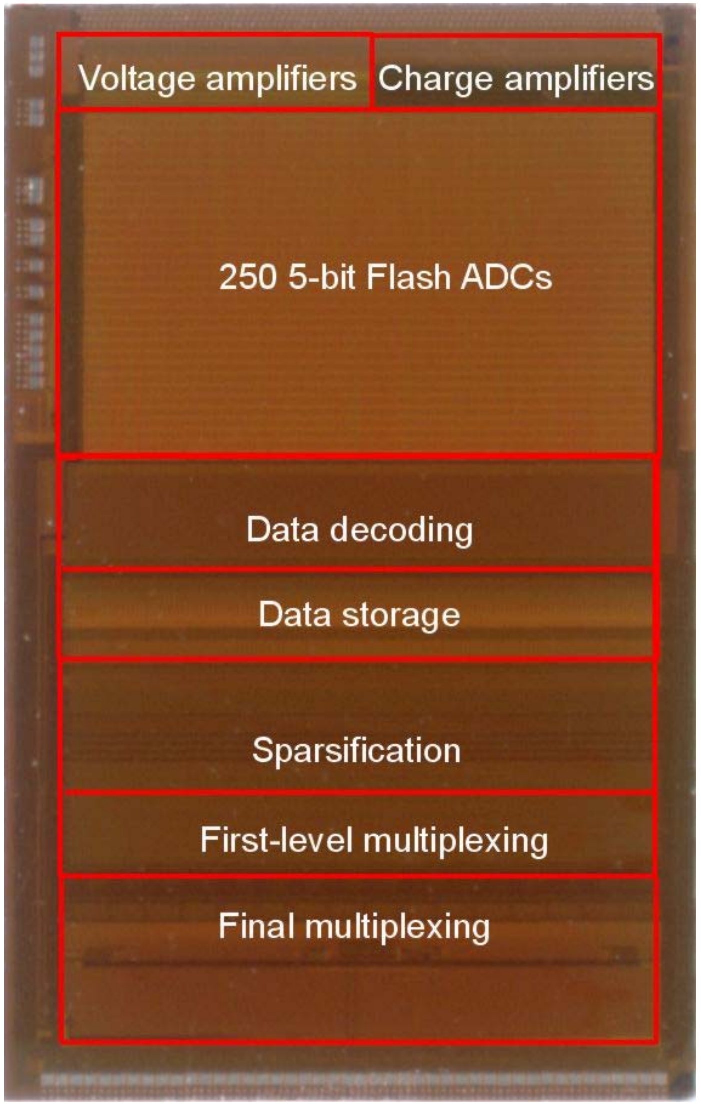
Storage Sensors: FAPS plans

- Next step: Parametric test sensor
  - 64x64 identical pixels (at least)
  - Variants of write and read amplifiers and in storage cells
- Will evaluate pixels in terms of
  - Noise
  - Signal
  - Radiation hardness
  - Readout speed
- Optimisation is between
  - size of the pixel
  - readout speed
  - maximum amount of time available for readout
  - charge leakage





Readout Electronics: CPR2 Readout Chip

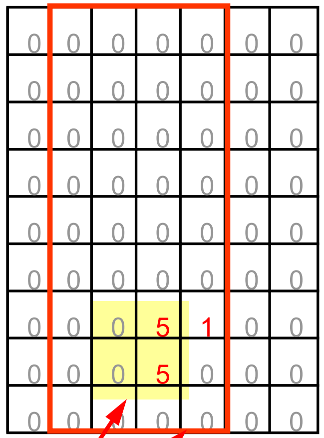


- Designed to match the Column Parallel CCD (CPC2)
  - 20μm pitch, maximum rate of 50MHz
  - 5-bit ADC, on-chip cluster finding
  - Charge and voltage inputs
- New features for the CPR2 include
  - Cluster Finding logic, Sparse read-out
  - Better uniformity and linearity
  - Reduced sensitivity to clock timing
  - Variety of test modes possible
  - 9.5 mm x 6 mm die size, IBM 0.25μm
  - Recently delivered, testing beginning

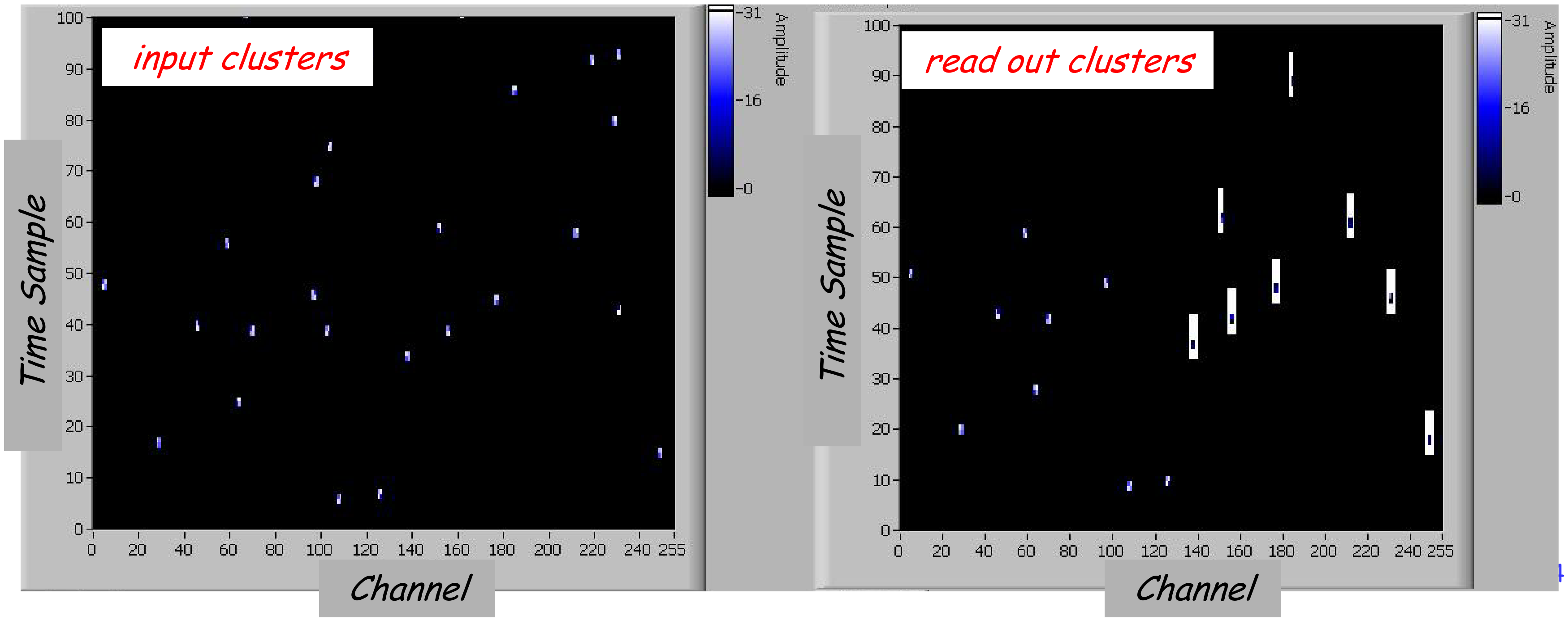
→ *Major piece needed for a full module*

CPR2 Readout Chip: Initial Tests

- First tests with CPR2 readout chip
  - Tested with injected digital patterns (not testing analog yet)
  - 2 x 2 clustering threshold, 4 x 9 readout
  - *Works(!)* …but not perfect yet
  - Some problems at boundary channels and with timing
  - Will adjust timing, continue tests

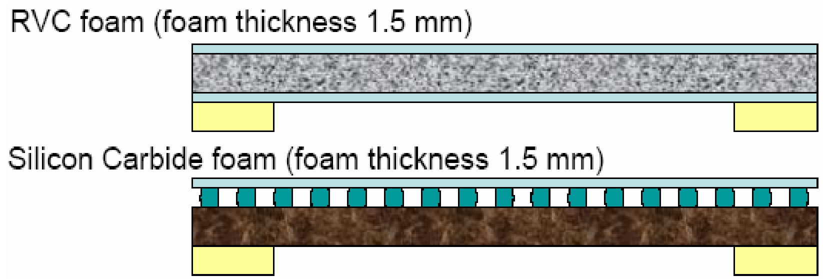


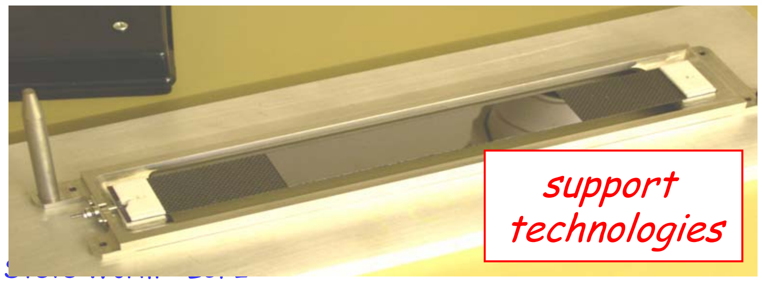
channels above threshold (2 x 2)
readout cluster (4 x 9)

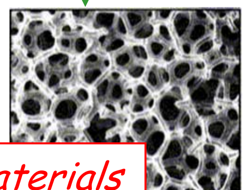


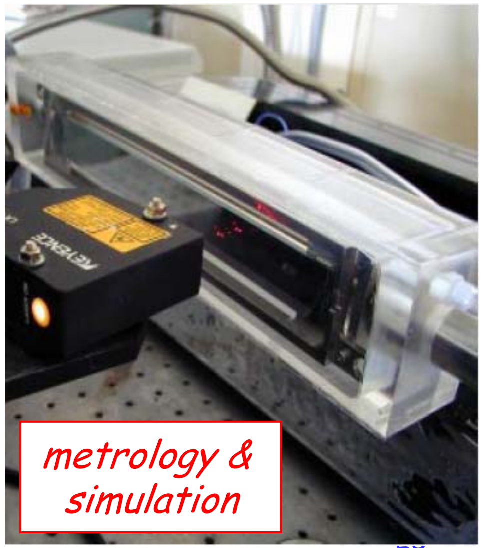
Vertex Detector Mechanical Studies

- Thin Ladder (module) construction Goals are ambitious;
  - 0.1 % X/X_0 → Thinned silicon sensor, ultra-light support
  - Uniformity over active area
  - Wire or Bump bondable, robust under thermal cycling
- Mechanical development timeline
  - Develop support technologies, fixturing, production techniques (mid 2007)
  - In parallel, global design and cooling studies, mounting, power, etc
  - Natural evolution into baseline detector design



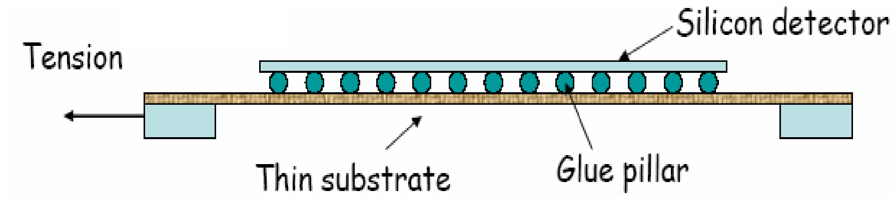


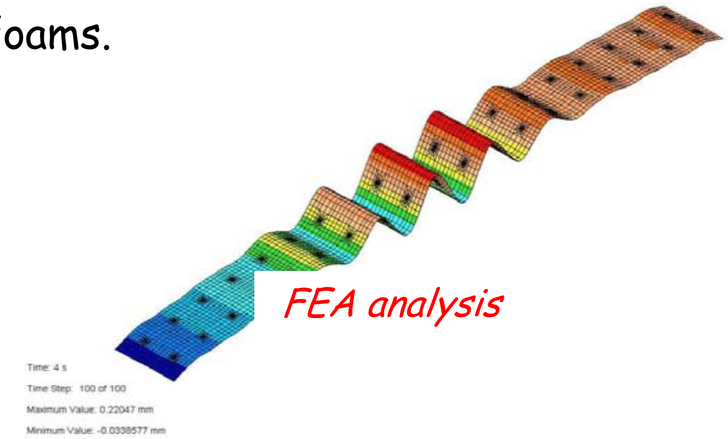




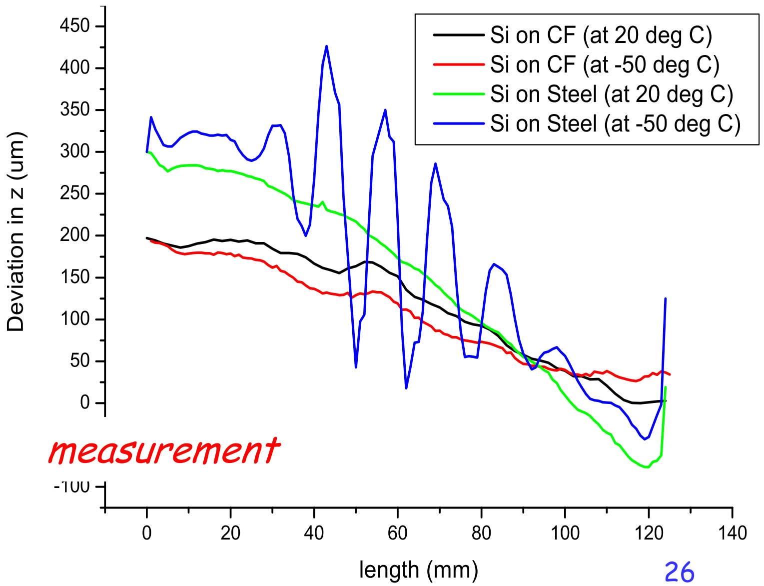
Mechanical Studies: Support Structures

- Thin Ladder Mechanical Considerations
  - Stresses introduced in processing imply "unsupported" Si > 50μm.
  - "Stretching" maintained longitudinal stability, but insufficient lateral support.
  - Re-visit using thin corrugated carbon fibre to provide lateral support.
- Measurement and Stress Analysis
  - Supporting CCD on thin substrate studied at low temperatures.
  - Simulation (FEA) provides good guide.
  - Under study: sandwiched structure with foams.





FEA analysis

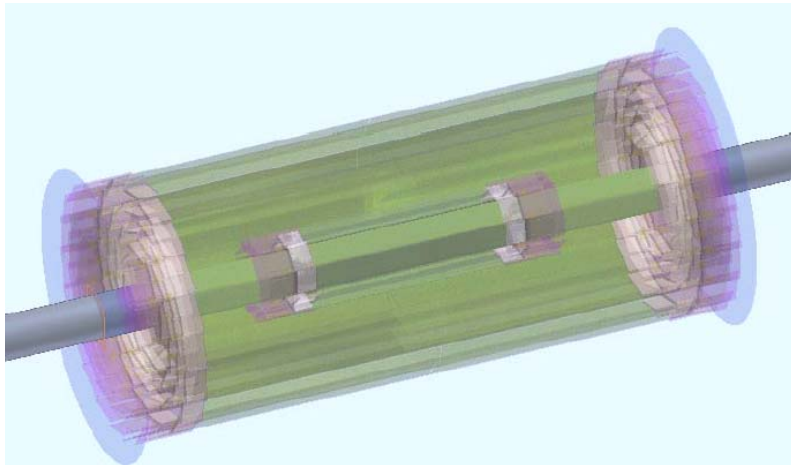


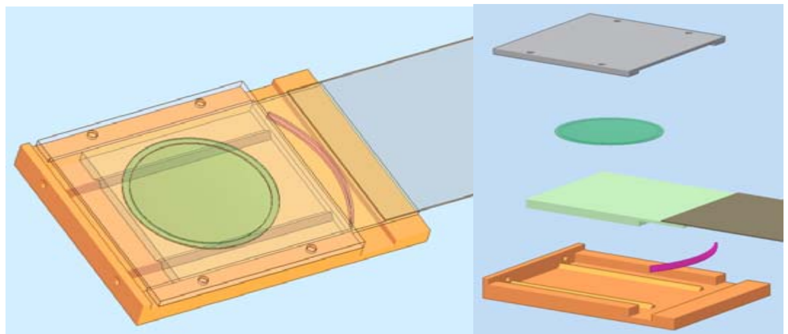
measurement

Vertex Detector Global and Thermal Studies

- Mounting schemes, layout, services, cooling etc
  - Must all be shown to be compatible with candidate technology
  - Large dependence on decisions in other work (e.g. sensors, electronics)
  - Thermal test stand under construction

- Many mechanical challenges ahead
  - How to hold the ladders
  - Full detector layout
  - Thermal studies
  - How to cool the ladders
  - Stress analysis for candidate ladder support

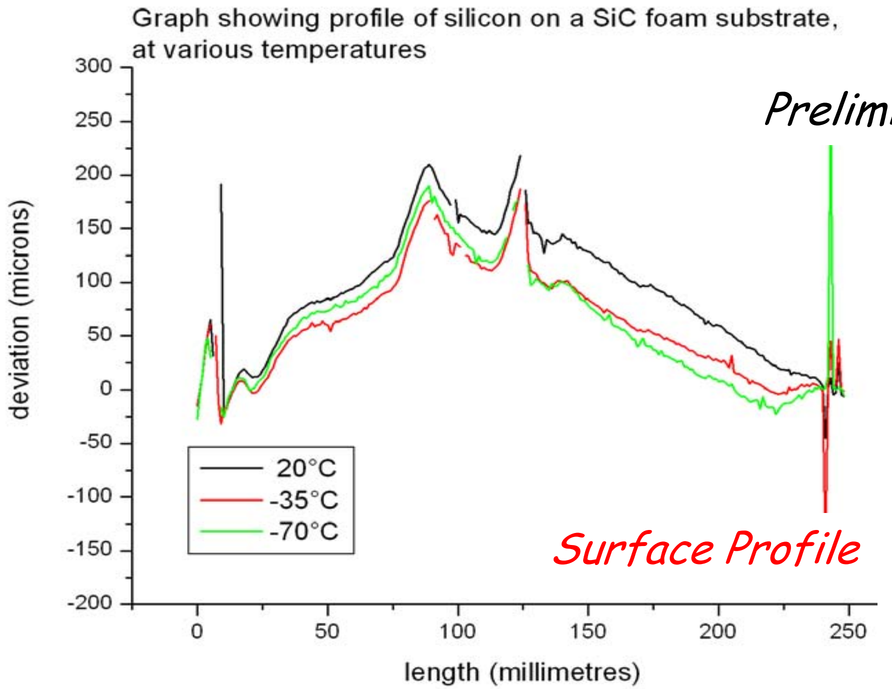




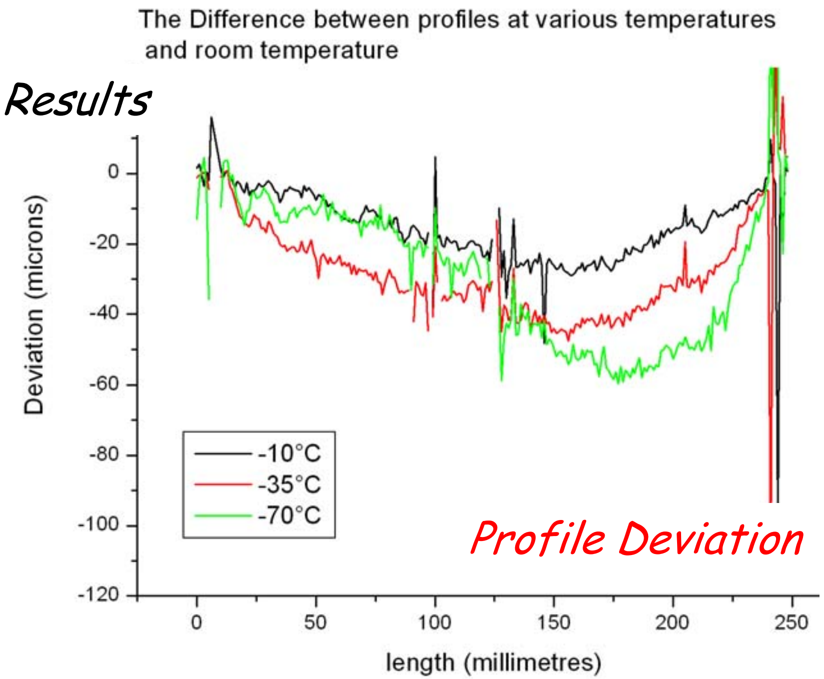
→ Many interesting mechanical challenges

Mechanical R&D: Foams

- Foam structures and prototyping
  - Investigating silicon foam and silicon carbide foam (good CTE match)
  - Foams are extremely rigid and also light weight (3-10% the normal density)
  - As they are so light, can be made more thick
  - The co-efficient of thermal expansion is a close match to silicon
- *First results: very promising!*
  - Silicon 20 micron thick on SiC foam → ~40 μm deviation in ΔT = 90 °C



Preliminary Results



Conclusions

LCFI: Balanced programme of physics, sensors, readout, mechanical, testing.

Much work shown, but much more remaining to be done!