New Developments for Si Detectors

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(on behalf of numerous very active research groups)

Outline

- ▶ **Why improving performances of existing technologies ?**
- ▶ **Performance issues**
- ▶ **Overview of (most of) on-going R&D activities:**
  - • **CCD**
  - • **Hybrid pixel detectors**
  - • **CMOS sensors**
  - • **DEPFET**
  - ○ **others (3-D, def.-engin., cryo., SoI, amorph. Si)**
- ▶ **Summary**

The Trends ... (1/2)

- ▶ need to increase $E_{Reaction} >$ new kin. thresholds ⇒
  - ○ final states with large nb of jets (typ. > 10)

    $f\bar{f} \rightarrow HA \rightarrow t\bar{t}t\bar{t} \rightarrow b\bar{b}b\bar{b}WWWW \Rightarrow \;\; \geq 12$ jets
  - ○ b, c, τ contained in most final states of interest
- ▶ unravelling Nature's mysteries is increasingly based on a detailed characterisation of (new) phenomena & particles

  → mandatory for disentangling numerous possible New Physics dynamics beyond any new observation: H, SUSY, Z', KK, ...

⇒ future Vertex detectors should allow reconstructing the flavour of EACH vertex in a POLY-JET environnement with very high efficiency and purity (charm !):

↬ pixels are mandatory in most applications demanding:
  - ○ to assign each track to its vertex origin
  - ○ to reconstruct vertex Q, M, E, chain ($2^{ry} \rightarrow 3^{ry}$)
  - ○ to reconstruct E_{flow}, $e^{\pm}_{conv.}$ vs P_{miss}, ...

⇒ **very granular, ultra-light, poly layer Vertex Detector, installed very close to the interaction region**

♡ **Flagship: Charged Coupled Devices (CCD)**

The Trends ... (2/2)

.... but Highest Lumi is needed ($\sigma\sim$ attobarns) ⇒

- ∘ harsh radiation → degrades detector performances
- ∘ high beam background → high occupancy

⇒ Detectors must be : a) radiation tolerant
b) fast (against occupancy)

▶ numerous applications demand a r.o. speed and a radiation hardness well above the performances (and potential ?) of CCDs ⇒ Hybrid Pixel Sensors

▶ HPSs are much faster and rad. tolerant but:

- ∘ they are much less granular (50 x 300 μm^2)
- ∘ they are much thicker ($\sim$ 300 μm)

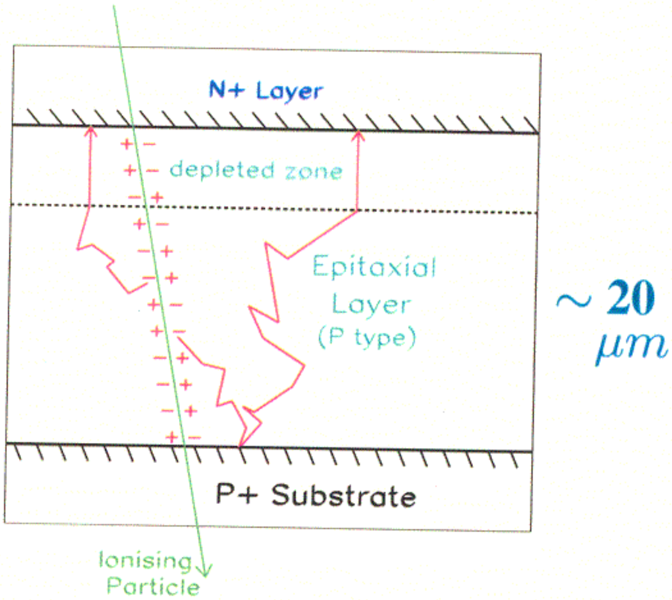
⇒ R&D aiming:

1) to combine performances of CCDs and HPSs
for F.L.C., B-Factories, H.I. Expts, Nuc.Phys. Expts
2) to win O(1-2) in speed and rad. tol. for SLHC, ...

R&D with Charged Coupled Devices

- ▶ widely used in commercial items and research
  - ⋆ baseline of TESLA Vx Det. (LCFI coll: 6 UK labs)
  - ⋆ also developed in Japan, US for F.L.C.

- ○ **signal generated in epitaxial layer (partially depleted)**
- ○ **e^- collected via diffusion and drift**
- ○ **signal charge clocked out through sensor material**



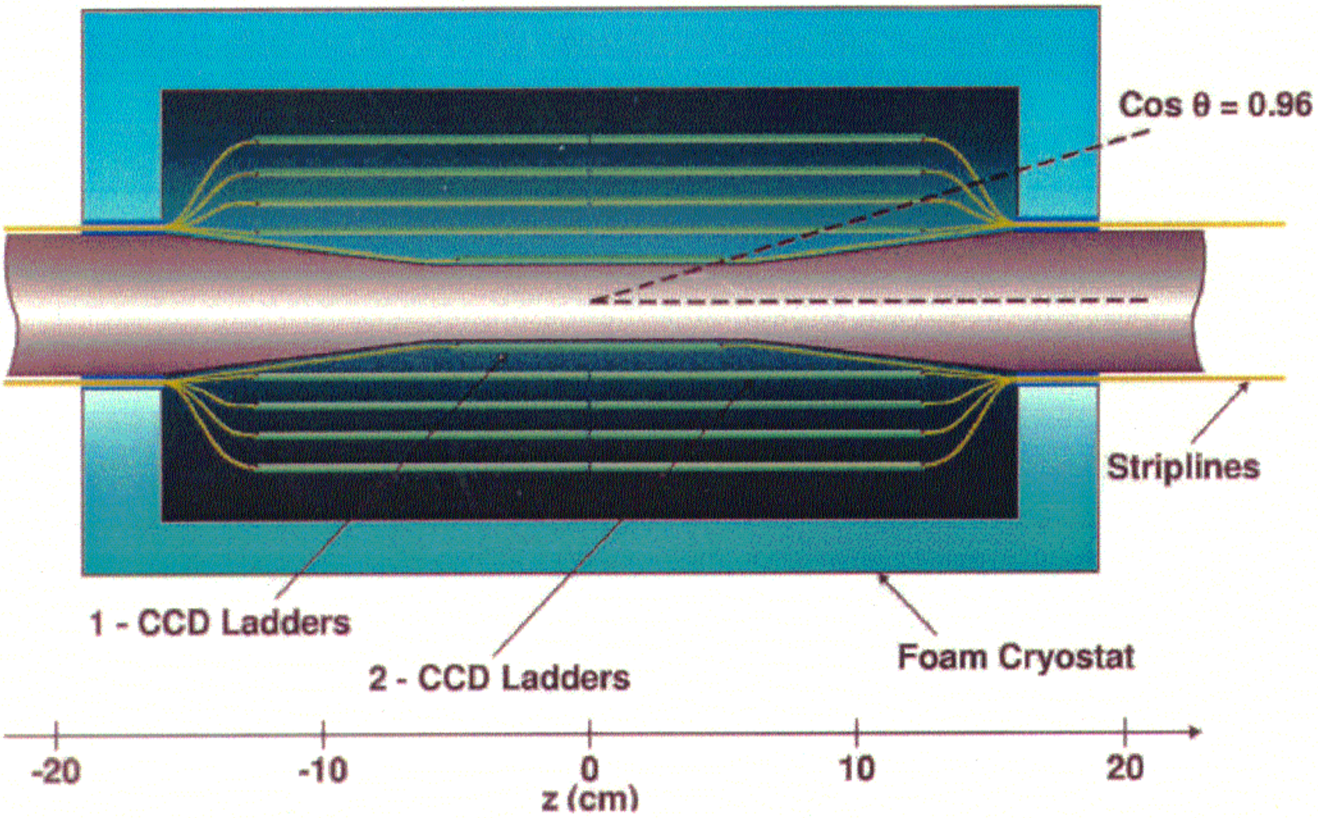
- ▶ best Vx detector ever built (SLD): 307 Mpix, 5 MHz/200 ms, 0.4 % X_0/layer, $\sigma_{i.p.} \sim 8 \oplus 33/p \cdot \sin\theta^{3/2}$ μm

- ▶ aim to increase r.o. frequency to 50 MHz $\Rightarrow t_{r.o.}^{col.paral.} \sim 50\ \mu s$:
  - ↪ sucessful test with commercial CCD58 (50 MHz, 3V)
  - ○ 1st C.P. CCD in prod, back in Oct. '02 → 50 MHz (?) , $20 \times 20\ \mu m^2$
  - ○ 1st C.P. r.o. chip being designed → back Fall '02
  - ○ demonstrate rad. tol. $\gtrsim$ 100 kRad, 10^{10} n/cm^2
  - ○ try high resistivity Si (full depletion) ⇒ fast (& n tol. ?)
  - ○ try 2-phase low voltage operation (10 V → $\leq$ 3 V)

- ▶ develop thinned (e.g. 60 μm) and (quasi)unsupported ladders
  - ↪ aim for $\leq$ 0.1 % X_0 (sensor + mech.sup. + cooling)

- TESLA: 5 layer Vx Det. ($r = 1.5, \ldots, 6$ cm)
- read-out $\lesssim 10^9$ pixels in a few $10^2\,\mu s$ (1st layer: $\lesssim 50\,\mu s$)
- $\lesssim 0.1\,\%\ X_0$ / layer
- stand a few 100 kRad and a few $10^{10}\,n/cm^2$

Conceptual Design



Konstantin Stefanov, RAL

→ demonstrate this for a complete ladder

☹ $\lesssim$ 2005 (?)

R&D with Hybrid Pixel Sensors

- pixel technology retained for LHC experiments:
  25 ns time stamping, sparse data scan, high hadron rad. tol.

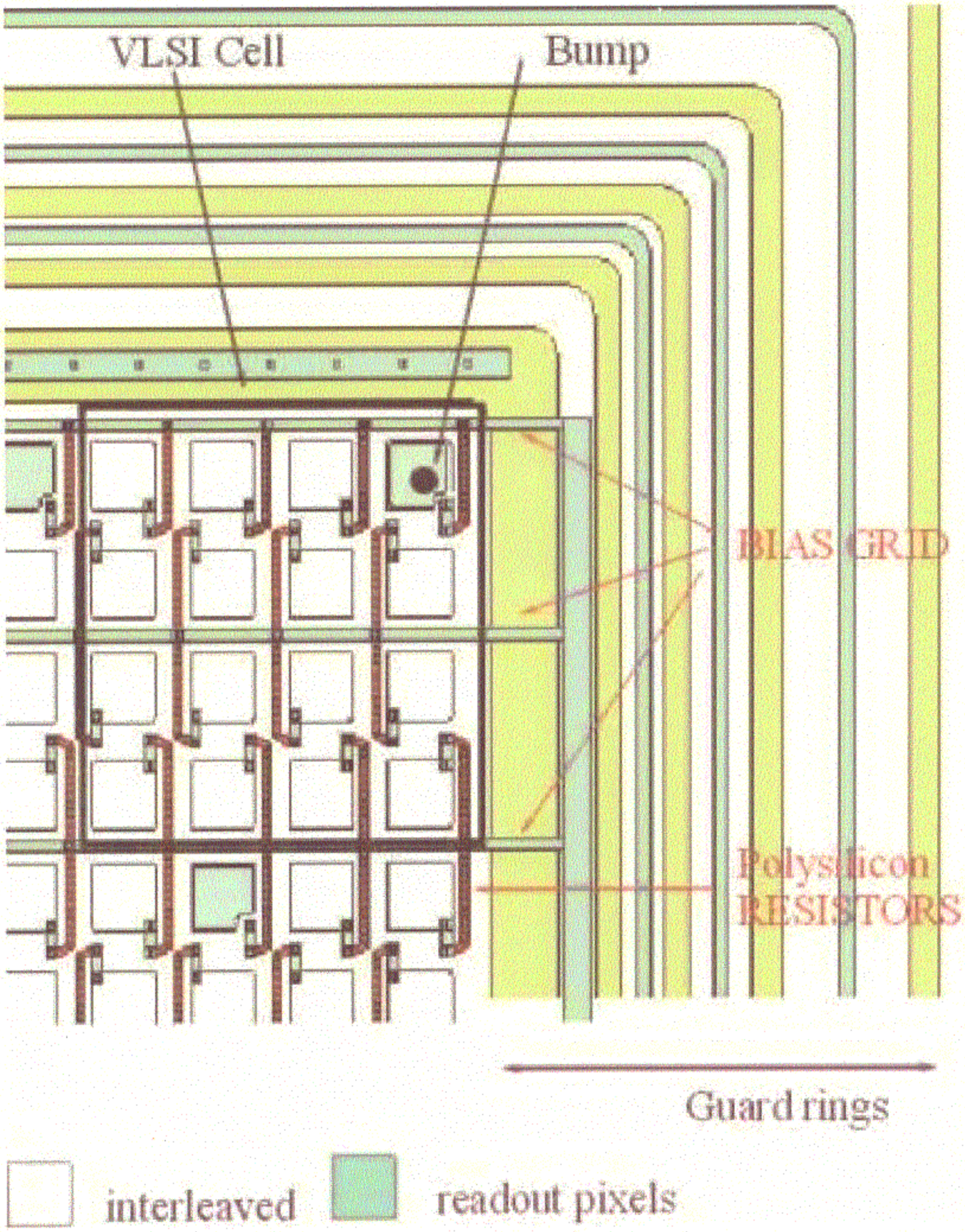
- objectives of present R&D: improve σ_{pt} (short term),
  radiation tolerance (medium term) and reduce thickness

- new layout adapting the concept of interleaved $\mu strips$
  to pixel geometry $\Rightarrow$ interleaved pixels (capacitive coupling)
  $\looparrowright$ $\sigma_{pt} \sim$ pixel pitch and N/S
  $\looparrowright$ C_{ip}/C_{bp} crucial issue $\longrightarrow$ source of charge loss

$\Rightarrow$ small prototypes with 200x200 and 300x300 μm^2 cells
fabricated with ≤ 3 interleaved pixels in each direction
(60/100 μm implant width/pitch, 200 μm r.o. pitch) :
$\hookrightarrow$ illumination with 80 μm wide laser spot:
$\sigma_{pt} \sim 6.5\ \mu m$, N/S $\sim$ 1/100, $Q_{loss} \leq 40$ %

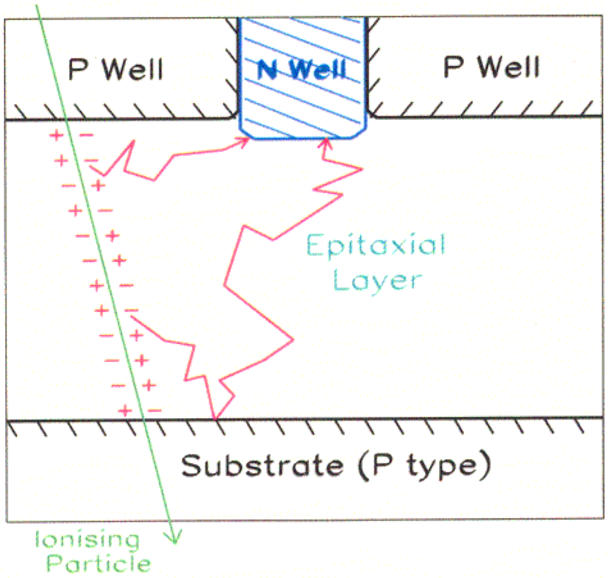
$\Rightarrow$ new test structure (25 μm implant pitch) being fabricated
$\hookrightarrow$ tests in Sept. 2002: expect $\sigma_{pt} \leq 3\ \mu m$
(Como, Cracow, Warsaw coll.)

Layout of the proposed Pixel sensor



Monolithic Active Pixel Sensors (MAPS)

- ▶ Originally developed for light imaging
  - ◇ standard low resistivity (1-10 Ω.cm) p-type Si
  - ◇ signal generated in epitaxial layer (low doping)
  - ◇ e^- diffuse thermally and get collected by n-wells
  - ◇ e^- reflected at epitaxy boundaries (high doping)



high doping

low doping

high doping

$\sim$ **10** μm

↬ high performance m.i.p. detection established: S/N $\sim$ 30, $\epsilon > 99$ %, $\sigma_{pt} \sim 1.5\ \mu m$, $\sigma_{2tr} < 30\ \mu m$, 10^{12} n/cm^2, $<$ 1 MRad

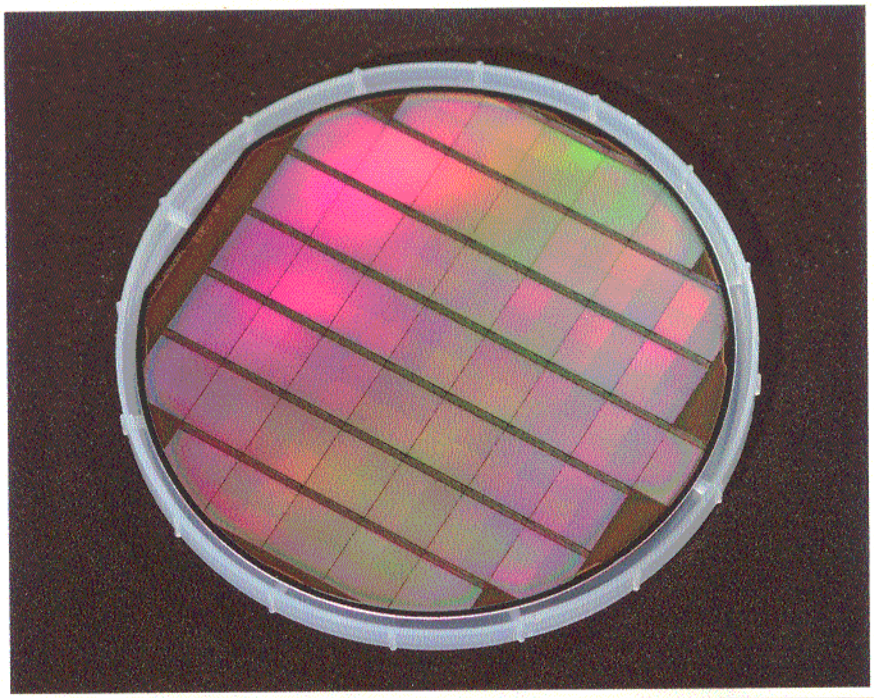
↬ low doping substrate and no epitaxy $\Rightarrow \sigma_{pt} \sim 4\ \mu m$

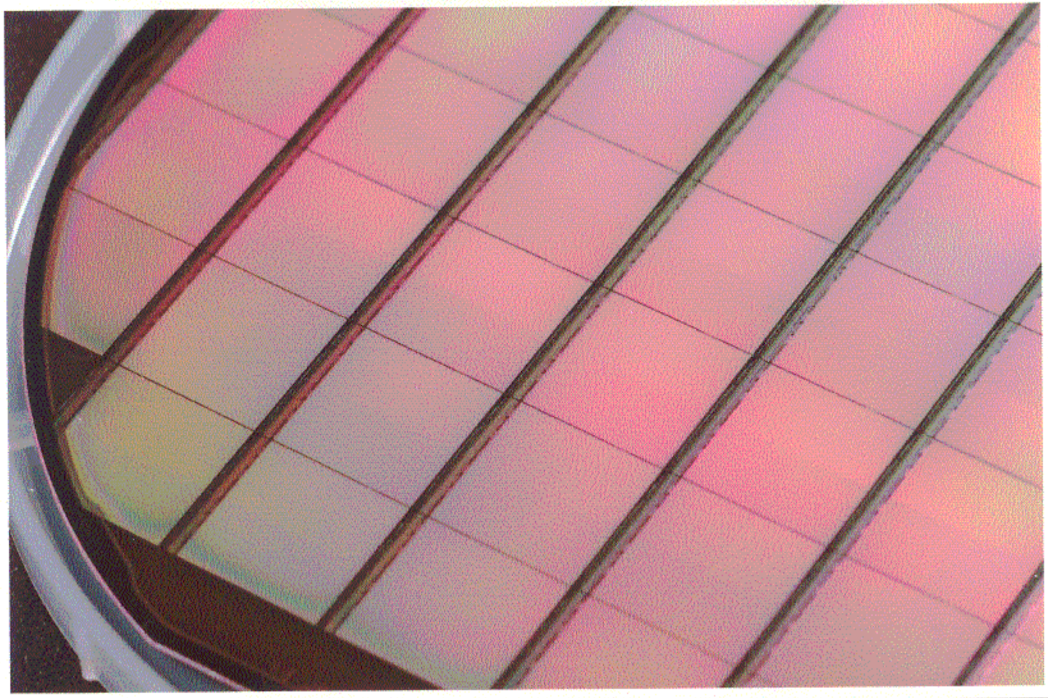
↬ large scale detector (10^6 pixels of 17x17 μm^2) works

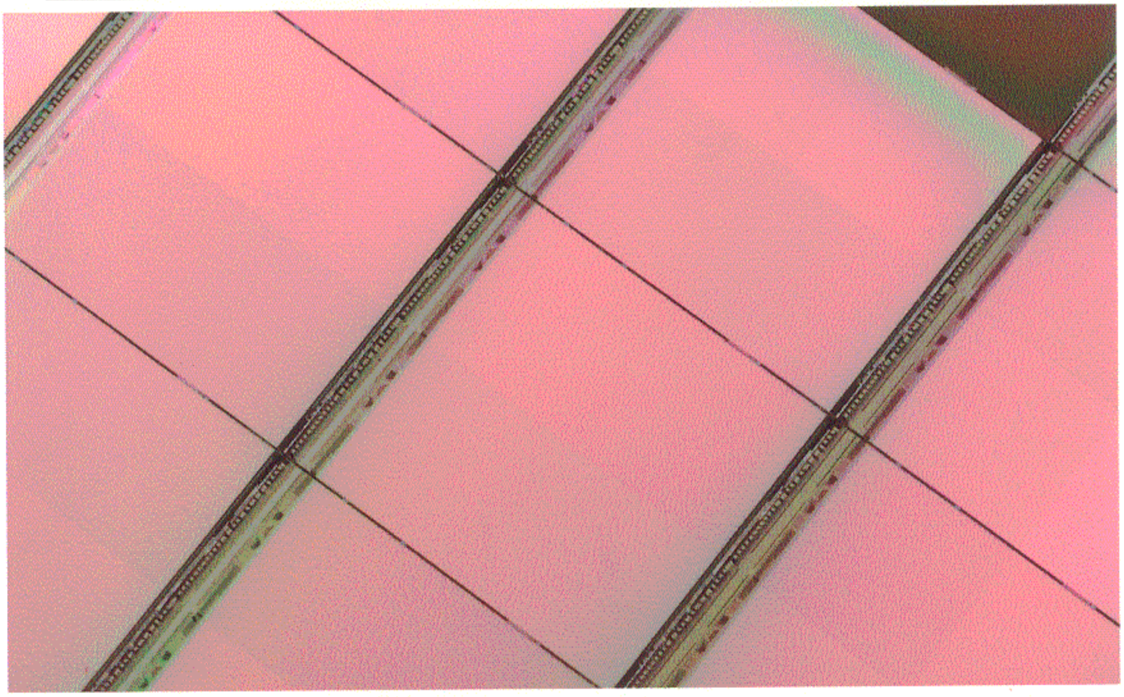
↬ prototype with CDS/pixel + discri/periphery fabricated

$\Rightarrow$ Goal: integrated (sparsif.), fast ($\leq$ 50 μs), thin ($\leq$ 50 μm),
more rad. tolerant (few MRad), large scale detector
in 2004-05 (coll. of 10 labs from F, UK, D, NL, CH)

◇ also developed at LBL-BNL (STAR) → small chip in 0.25 μm





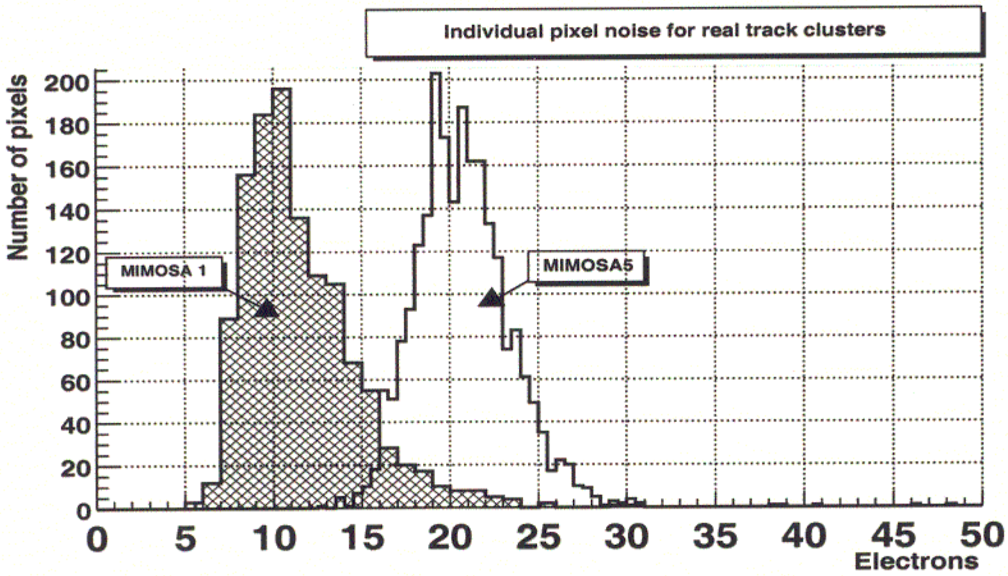


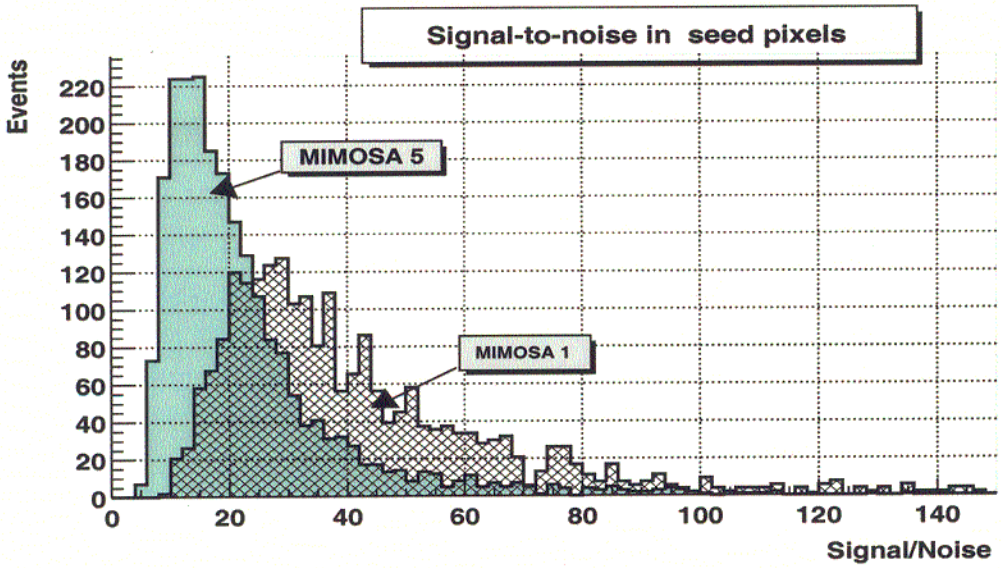
MIMOSA-5: 1st real scale prototype

▶ chip of 4 matrices of 512x512 (17x17 μm^2) pixels read-out in parallel (0.6 μm AMS process, 120 μm thick)

$\hookrightarrow$ exposed to 120 GeV/c π^- beam at CERN-SPS

- compared to small prototype (same process) of 64x64 pixels

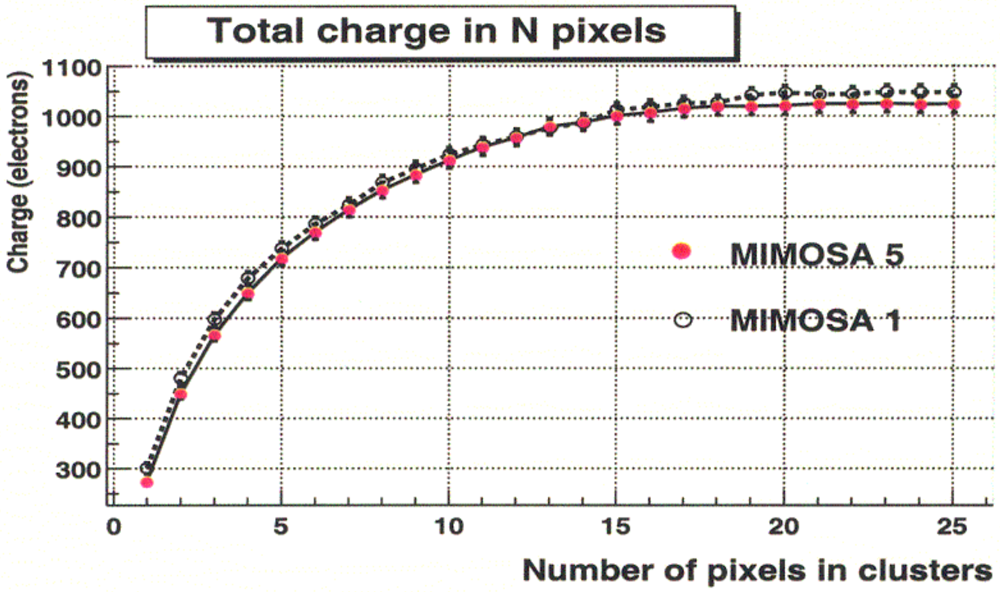


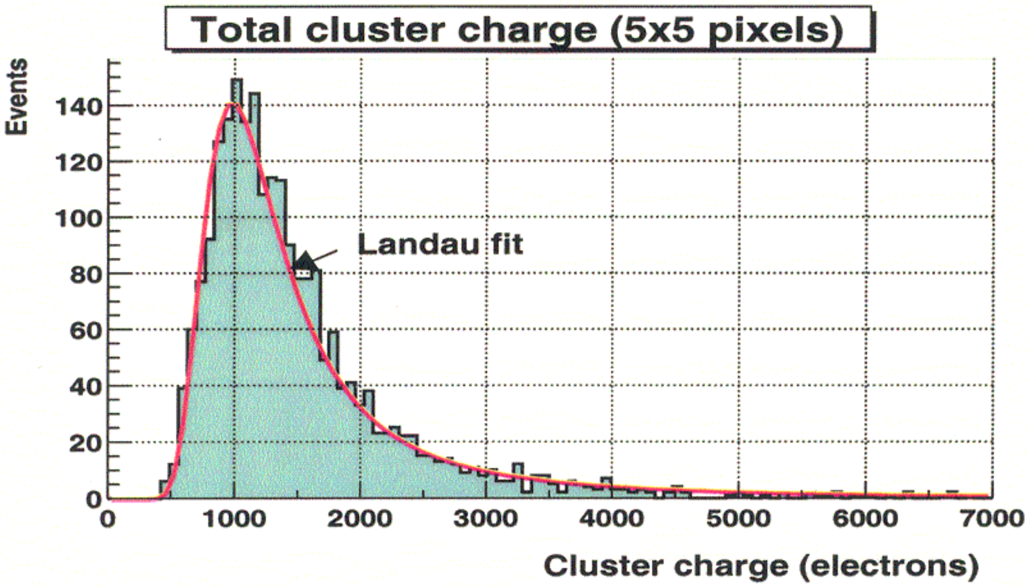


▶ preliminary result: det.eff. ~ 99.3 %, $\sigma_{pt} \sim 1.7\ \mu m$ (twice noise due to use of 2 source followers instead of 1)

MIMOSA-5: 1st real scale prototype (2)

- cluster charge: MIMOSA-5 vs MIMOSA-1
  (epitaxial layer thickness ~ 14 μm)

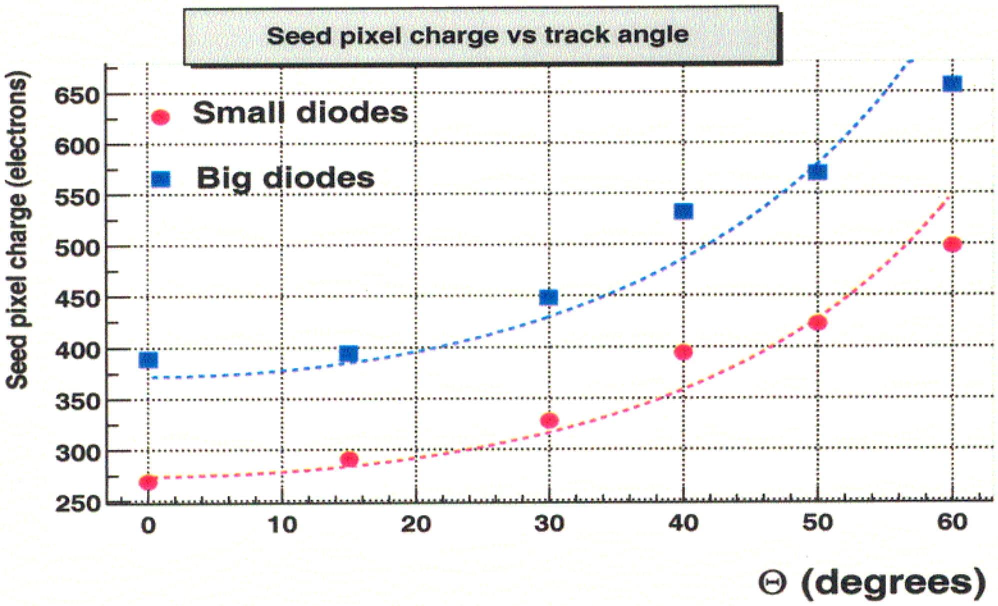


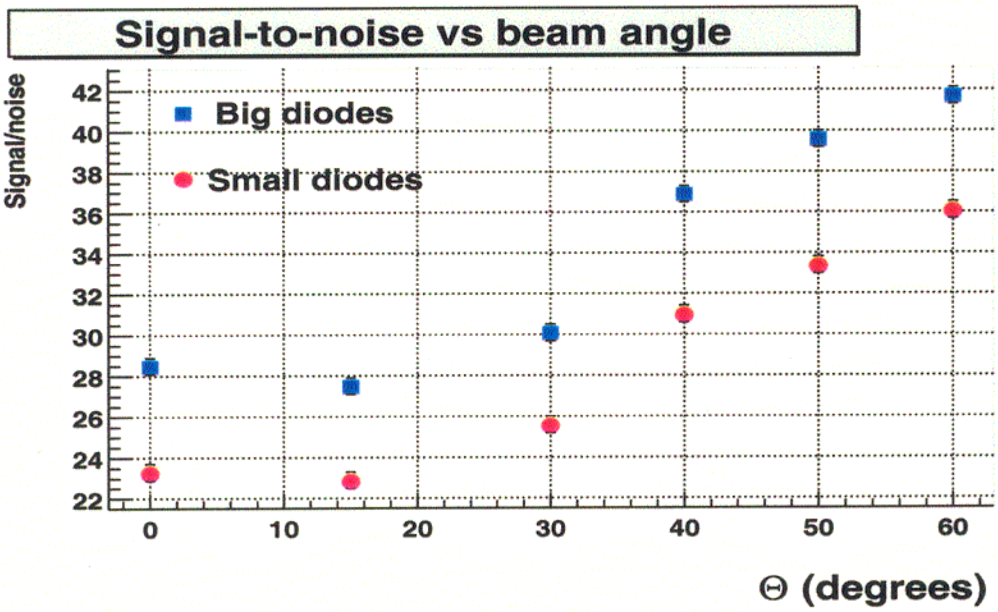


- identical characteristics:
  cluster multiplicity ~ 20, Landau peak ~ 1000 e^-

MIMOSA-5: 1st real scale prototype (3)

- ▶ response to inclined tracks (very preliminary)


Seed pixel charge vs track angle

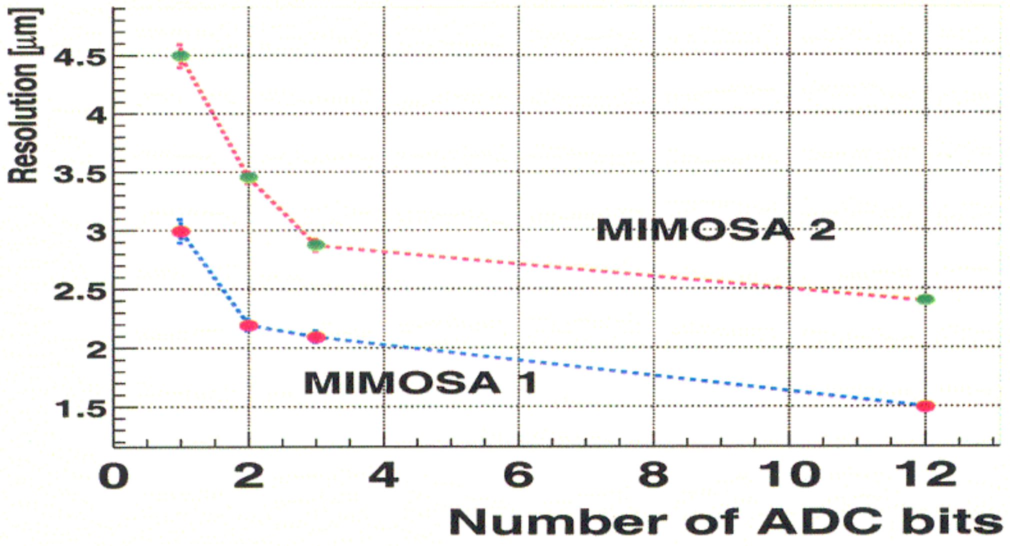

Signal-to-noise vs beam angle

- ▶ approximate cos θ behaviour (as expected)

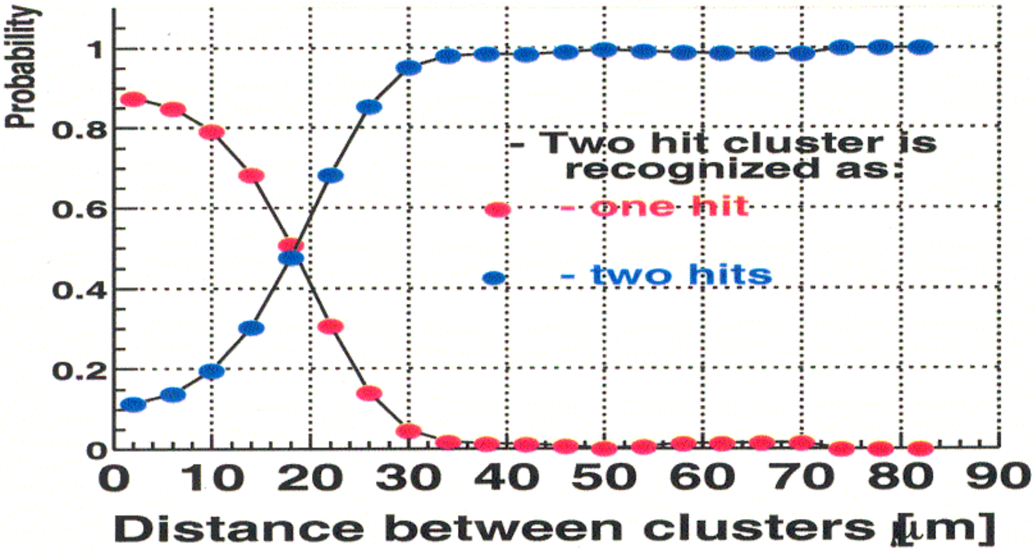
  still some features to understand ...

recent MIMOSA-1 results on track resolution

- spatial resolution as a function of ADC-bit encoding:
  $\sim 2\ \mu m$ for 3 bits ($\sim 3\ \mu m$ for 1 bit ...)



- double track resolution: excellent down to 30 μm distance



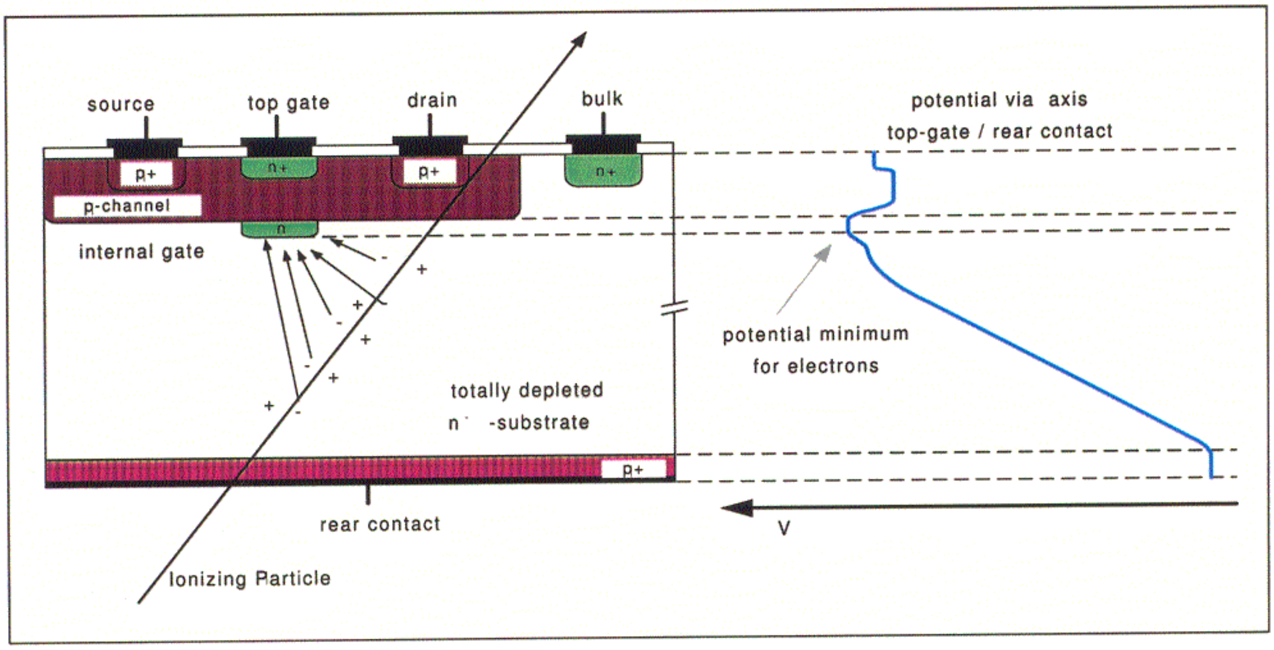
DEPleted Field Effect Transistors (DEPFET)

▶ **originally developed for X-ray imaging**

◇ detection based on JFET integrated into high resist. substrate

◇ signal generated in fully depleted (n^-) substrate (sidewards depletion ⇒ pot. mini. under JFET channel)

◇ signal collected in "internal gate" ⇒ modulate transistor current by inducing additional charges in p-channel



↬ 64x64 (50 x 50 μm^2) pixel prototype for biomedical imaging fabricated, tested: 40 e^- noise, $\sigma_{pt} \sim 10\ \mu m$, $t_{r.o.}^{frame} \sim 1$ ms

↬ thinning of 8 x 1 cm sensor to 50 μm achieved

↬ 1st r.o. chip with $\emptyset$ fabricated (0.25 μm TSMC)

⇒ aim for 25 x 25 μm^2 pixels, $\leq$ 50 μs r.o. time of multimillion pixel ladders, 50 μm thick sensors, steering and r.o. chips (coll. Bonn - MPI/Münich)

Other R&D Programmes (medium & long term)

▶ **3-D detector:** (Hawai, Glasgow)

↬ introduce electrodes (n, p) inside bulk

↬ short distance between electrodes

$\Rightarrow V_{bias} = 10$ V, $t_{coll} \sim$ few ns, $\sigma_{pt} \sim$ few μm

↬ successful tests with small proto (irrad. with 2.10^{15} n/cm^2)

▶ **Defect-engineered Si:**

↬ incorporate impurities/defects in Si bulk

$\Rightarrow$ enhance radiation tolerance

↬ e.g. Diffusion Oxygenated Float Zone (RD48)

$\rightarrow$ tolerance $>> 10^{14}$ had/cm^2 expected

▶ **Cryogenic detectors:**

↬ operation at 130 K motivated by factor 10 better rad. tol., factor 5 higher carrier mobility ($\Rightarrow$ short t_{coll}), ...

↬ still much to do ... → RD39

▶ **Silicon on Insulator (SoI):**

↬ consists in placing transistor's junctions on insulator (e.g. SiO_2) sensing vol. (high res. Si) underneath insulator (IET-Warsaw)

↬ monolithic, granular, fast, rad. tol., thin, but far from mature ...

▶ **Amorphous Si:**

↬ monolithic detector (granular, thin, very rad.tol., cheap) fabricated in hydrogenated amorphous Si

↬ severe material and technology issues to overcome

(LBL, LLR-France, IMT-Neuchatel, ...)

Summary

► Future physics programmes will require pixel vertex detectors with unprecedented performances (e.g.: tagging of b, c, τ jets in poly-jet final states)

$\hookrightarrow$ none of the existing technologies will allow to exploit the physics produced at a satisfactory level:

EITHER granular & thin OR fast & rad. hard

$\hookrightarrow$ very active R&D improving CCDs and HPSs, exploring new techno. (CMOS, DEPFET, 3-D, SoI, ...)

$\nearrow$ genuine rad. hard. (def-engin, cryo, amorph)

► F.L.C. $\rightsquigarrow$ CCD, HPS, CMOS, DEPFET (SoI ?)

$\gtrsim$ 2-3 years needed to see outreach of each techno.

$\hookrightarrow$ quite advanced vertex det. design (mat. budget) needed before optimal choice emergence

♡ within 1 decade, detectors responding in a few ns, with 1-2 μm resolution and standing fluences of $\sim 10^{16}$ may be mature enough to equip particle phys. expts

♡ several outcomes of these R&D lines will serve other research fields as well as areas of direct social interest