SiD ECal overview

R. Frey, University of Oregon

- Physics requirements
- Proposed technical solutions: silicon/tungsten
  - "traditional" Si diodes
  - MAPS
- LOI
- Opportunities for research

ECal requirements from physics

- Multi-jet final states
  - If no beam constraint possible (e.g. t-channel, $\nu\nu jj$, etc.)
  - Reduction of jet combinations (e.g. HHZ, ttH, tt, etc.)
- Tau id and analysis
- Tracking of MIPs
  - Especially for silicon tracker
  - PFA id of charged hadron; muon id
- Photons
  - Reconstruction in jets (resolution improvement)
  - Energy resolution for isolated photons (e.g. $h \rightarrow \gamma\gamma$)
  - Vertexing of photons (approx >1 cm)
- Bhabhas and Bhabha acollinearity
- Hermiticity
  - Missing energy
  - Forward veto of 2-photon events

Hadronic final states and PFA

<u>Complementarity with LHC:</u>

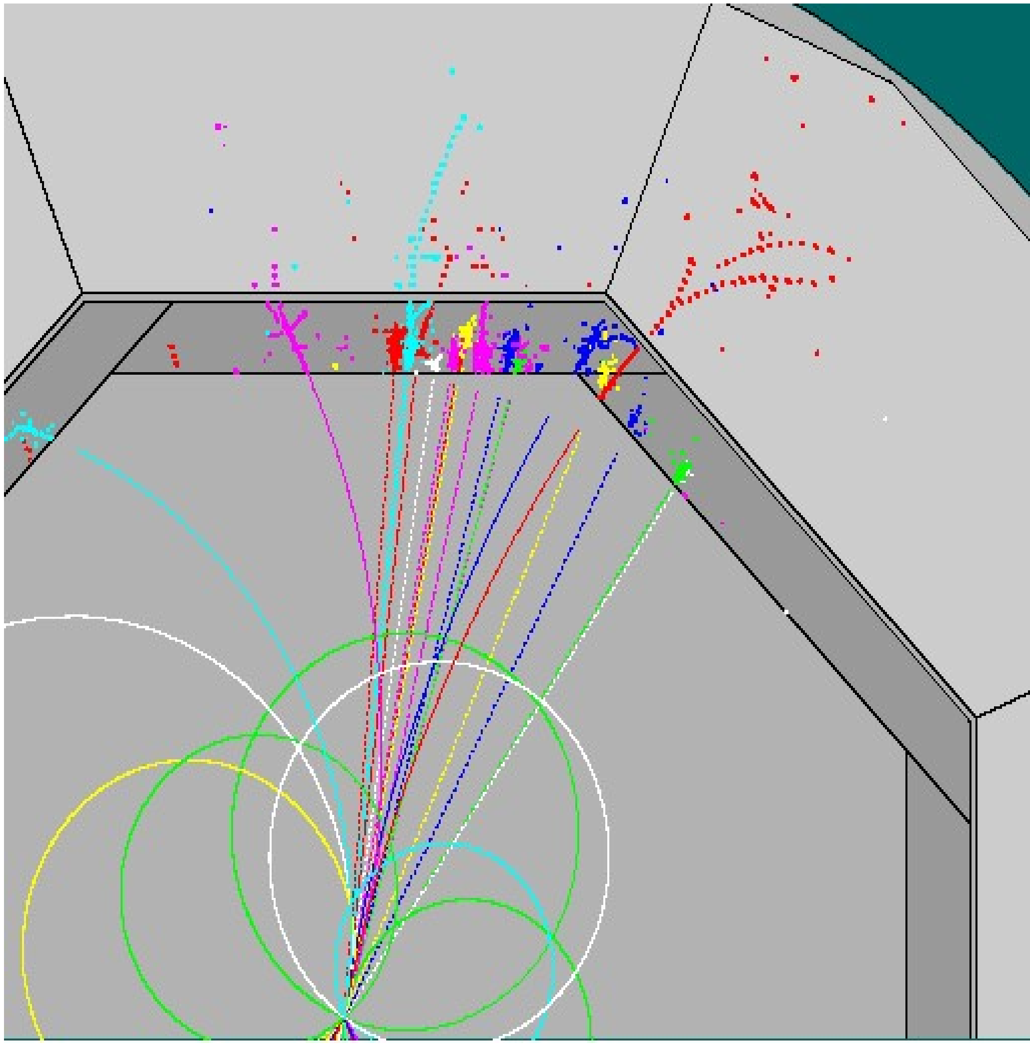
LC should strive to do physics with ***all*** final states.

and The New Physics may not provide nicely beam-constrained 2-jet hadronic final states.

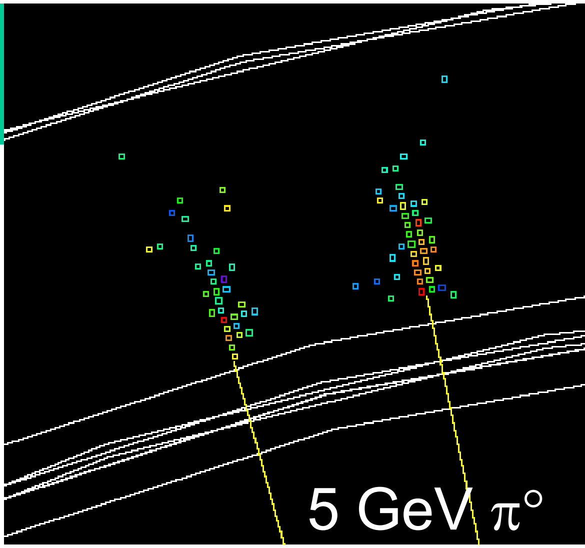
For PFA, need to provide photon measurement in a busy environment.

But, even with a beam-constrained final state, need to measure particle directions.

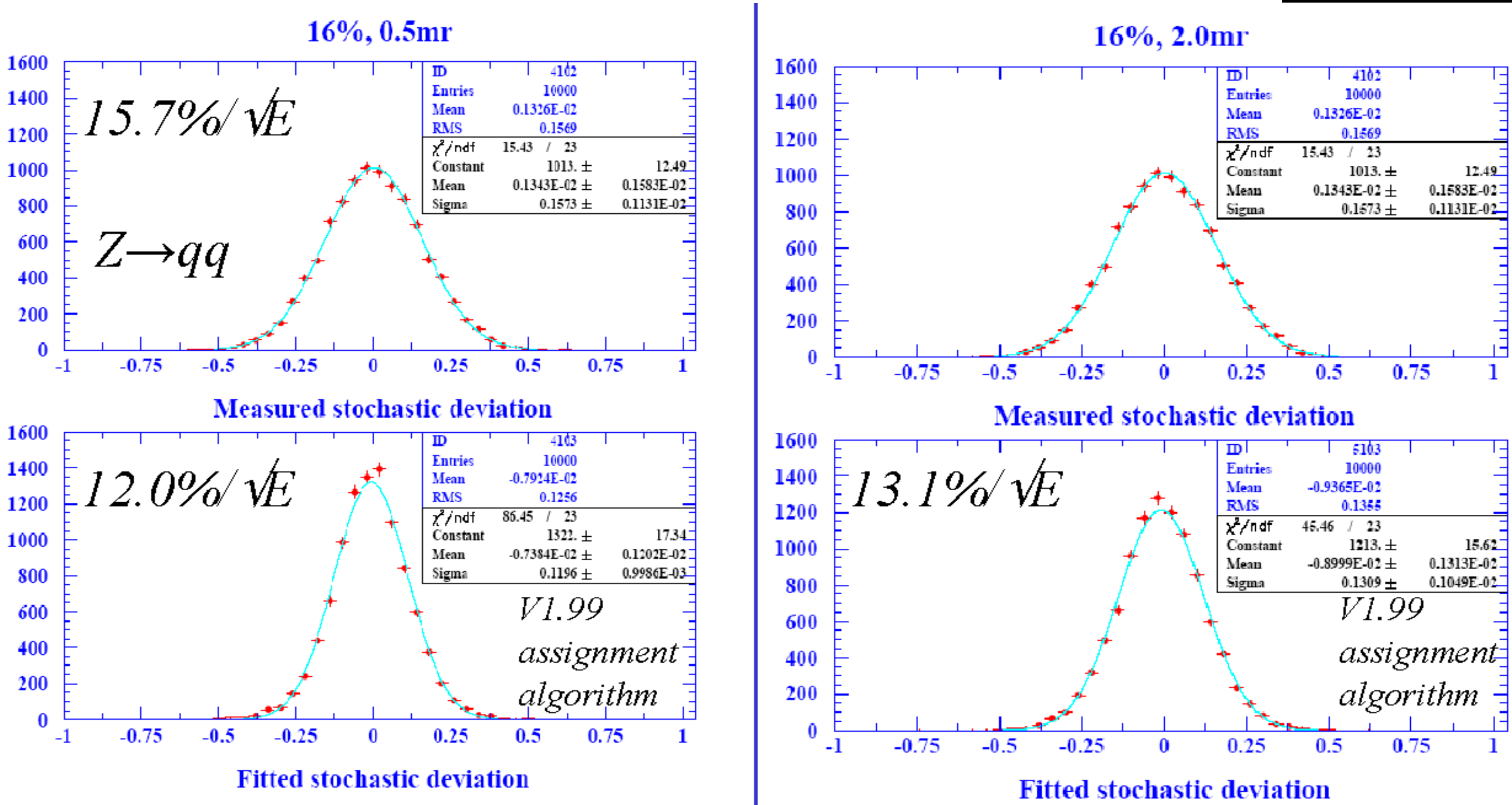
⇒ dense, highly segmented ECal (an “imaging calorimeter”)



as a bonus of the segmentation...



...improve resolution of jet EM component using π° mass constraint – Graham Wilson, Kansas



no constraint

with constraint

tau id and polarization

- Analysis of tau final states can provide crucial information on new physics
- Important & broad example: $e^+e^- \to \tilde{\tau}_1^+\tilde{\tau}_1^- \;,\; \tilde{\tau}_1^\pm \to \tilde{\chi}_1^0\tau^\pm$
- The SUSY model leaves fingerprint on tau polarization:

$$\tilde{\chi}_1 = N_{11}\widetilde{\mathrm{B}} + N_{12}\widetilde{\mathrm{W}} + N_{13}\widetilde{\mathrm{H}}_1 + N_{14}\widetilde{\mathrm{H}}_2$$

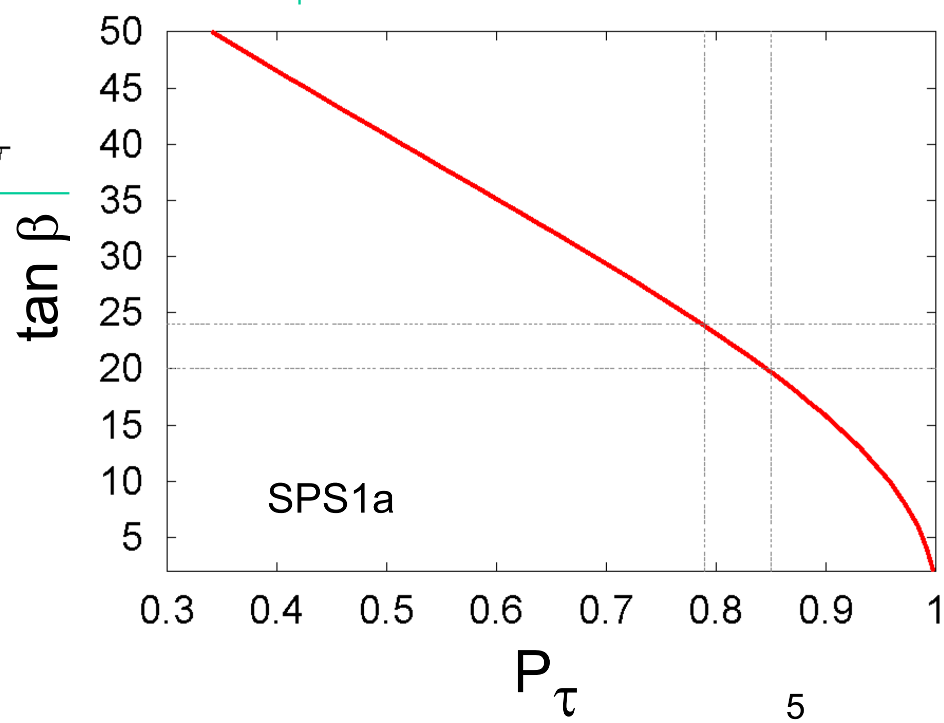
- mSUGRA: $\tilde{\chi}_1 \sim \widetilde{\mathrm{B}} \Rightarrow P_\tau \approx +1$
- non-universal SUGRA: $\tilde{\chi}_1 \sim \tilde{\mathrm{H}} \Rightarrow P_\tau \approx \cos^2\theta_\tau - \sin^2\theta_\tau$
- AMSB: $\tilde{\chi}_1 \sim \widetilde{\mathrm{W}} \Rightarrow P_\tau \approx -1$
- GMSB: $\tilde{\tau}_1^\pm \to \widetilde{\mathrm{G}}\tau^\pm \Rightarrow P_\tau \approx \sin^2\theta_\tau - \cos^2\theta_\tau$

References:

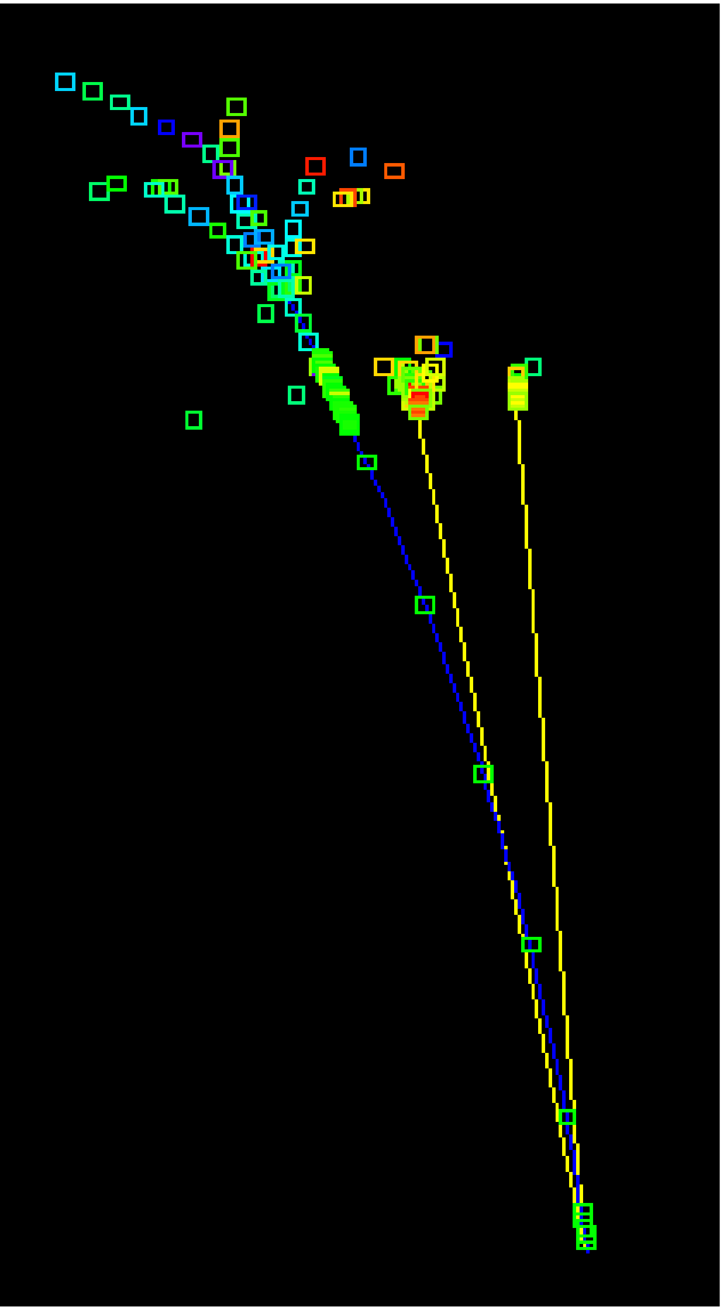
M. Nojiri, PRD 51 (1995)

E. Boos, et al, EPJC 30 (1993)

Godbole, Guchait, Roy, Phys Lett B (2005)



tau polarization (contd) - measurement



Separate the important decay modes:

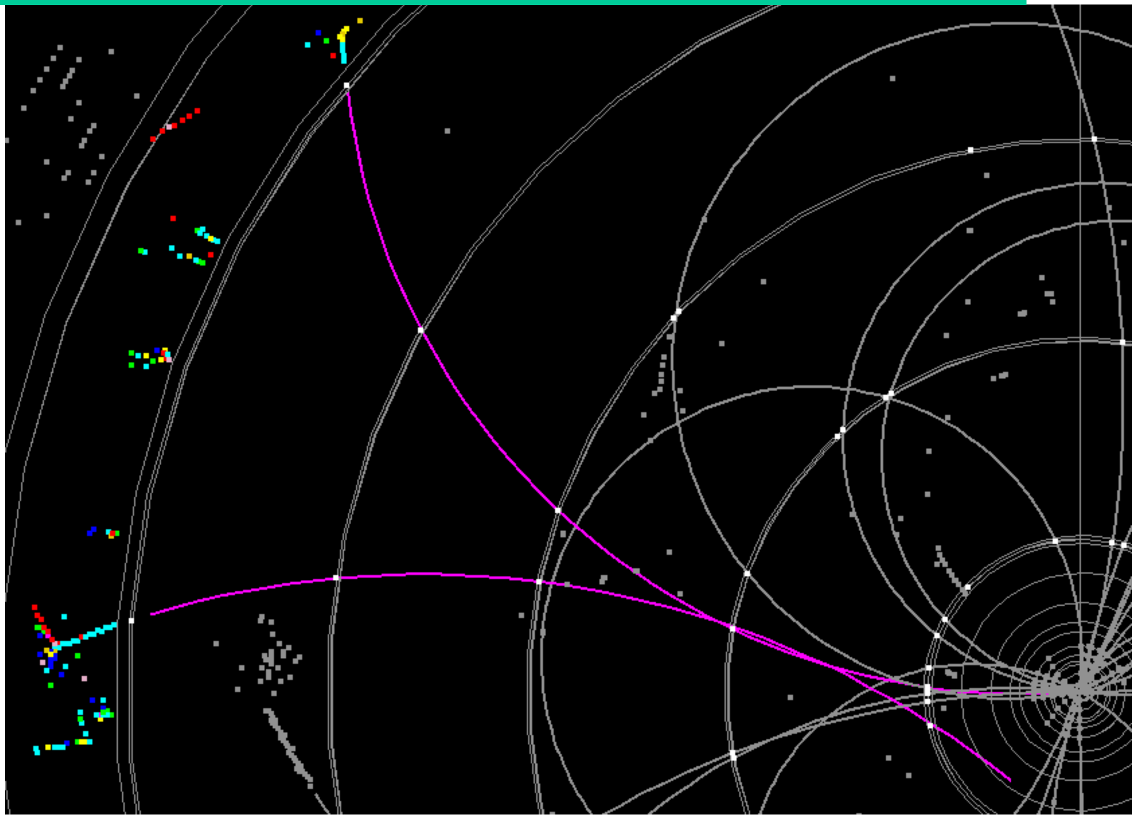
- $\tau^+ \rightarrow \rho^+\nu \quad (\pi^+\pi^o\nu)$
- $\tau^+ \rightarrow \pi^+\nu \quad (\pi^+\nu)$
- $\tau^+ \rightarrow a_1{}^+\nu \quad (\pi^+ \pi^+ \pi^- \nu, \;\; \pi^+\pi^o \pi^o \nu)$

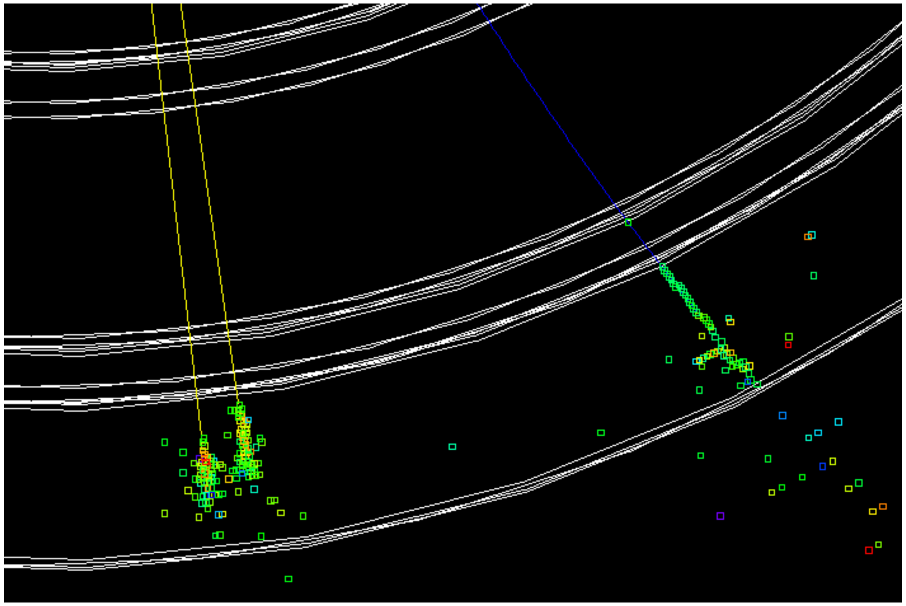
and measure the energy spectrum
as done at LEP (ALEPH best by ~2×)

An important tool to have in the box.

a MIP and photon tracker

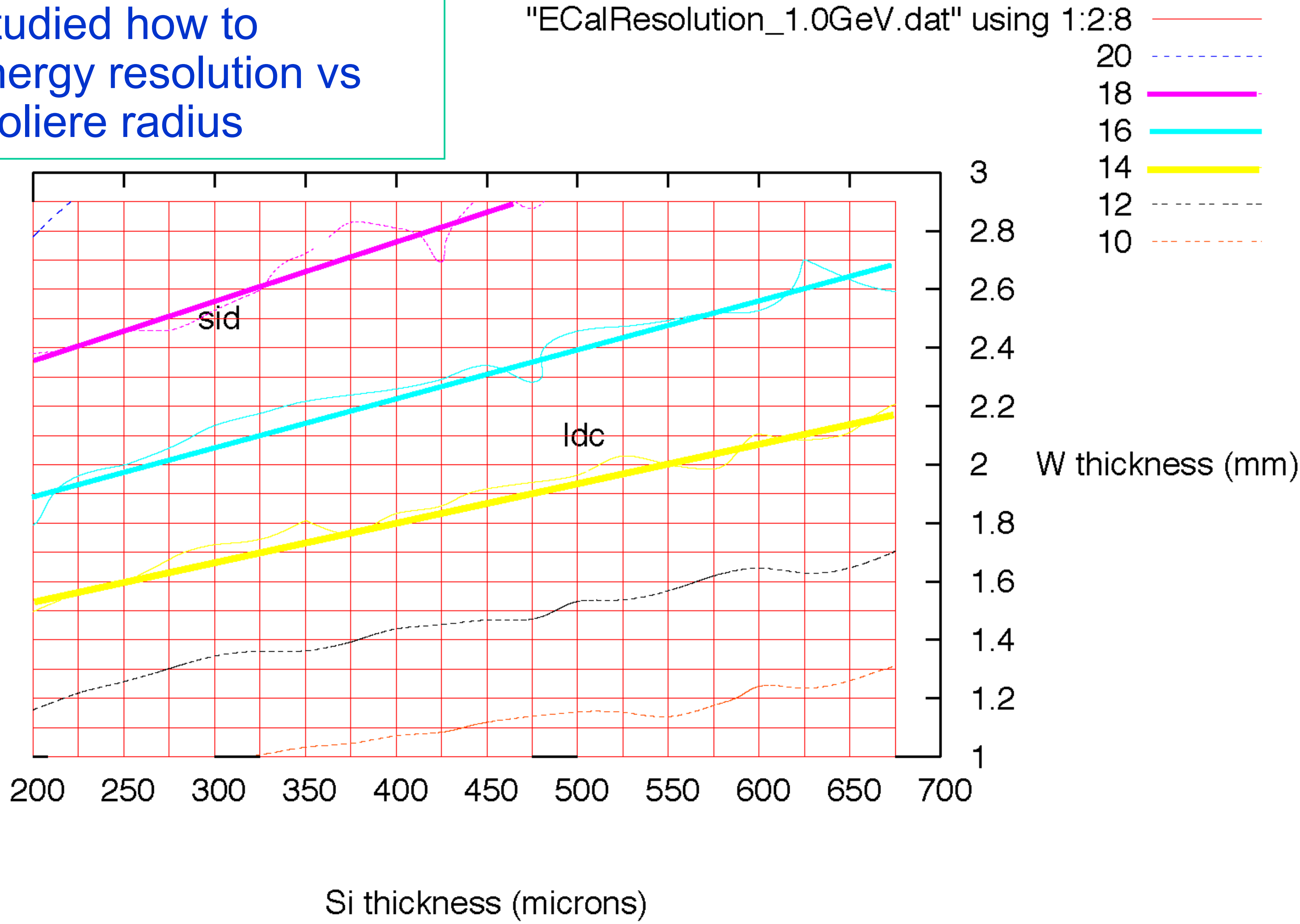
- Charged particle tracking, especially V0 recognition in silicon trackers
- charged hadrons and muons
- Photon vertexing
  - (e.g. GMSB SUSY)
- electron id in/near jets





Energy resolution

- No physics case has emerged for EM energy resolution better than ~0.15/√E
- We have studied how to optimize energy resolution vs cost and Moliere radius

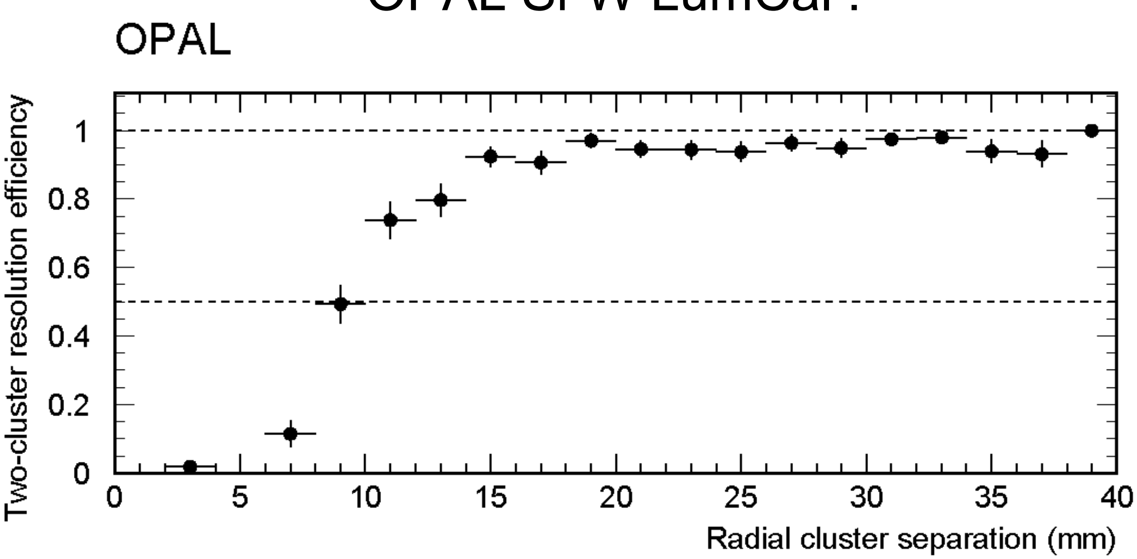


Noman Graf

Segmentation requirement

- The above require (or are neutral to) a highly segmented (in 3d) ECal
- In general, we wish to resolve individual photons in jets, tau decays, etc.
- The resolving power depends on Moliere radius and segmentation.
- We want segmentation significantly smaller than R_m – how *much* smaller is an open question

Two EM-shower separability in LEP data with the OPAL Si-W LumCal :



$$f_E \simeq \frac{R_{cal}}{\sqrt{R_M^2 + (4d_{pad})^2}}$$

$$d = 2.5\text{mm} \ , \ R_M \sim 17\text{mm}$$

Proposed technical solutions in SiD

A.) silicon/tungsten   B.) silicon/tungsten

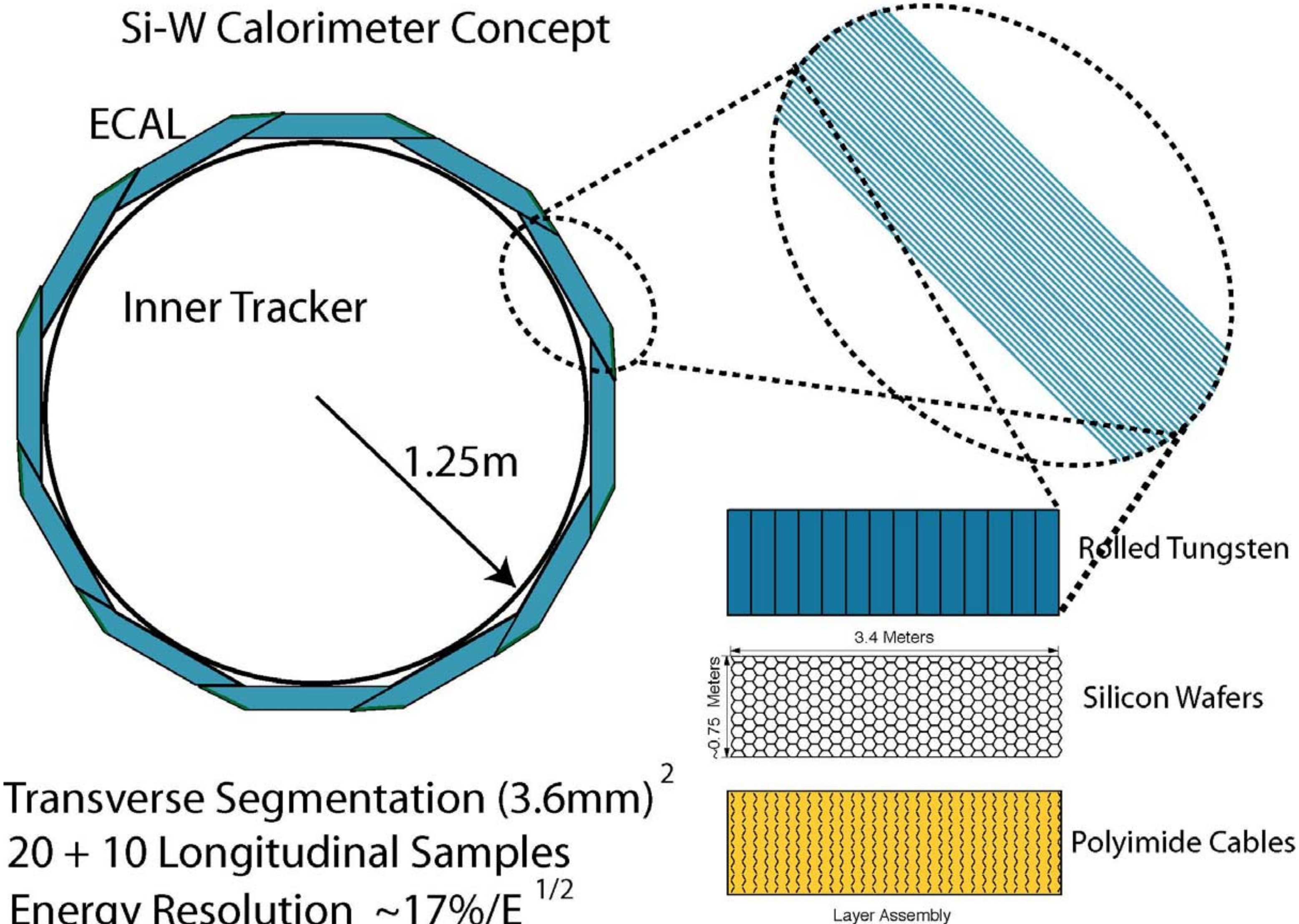
A) "traditional" silicon diodes with integrated readout

Transverse segmentation 3.5 mm   (Moliere radius ≈13 mm)

B) MAPS active CMOS pixels   (Terapixel option)

Transverse segmentation 0.05 mm   (Moliere radius ≈13 mm)

SiD Silicon-Tungsten ECal



Transverse Segmentation $(3.6\text{mm})^2$
20 + 10 Longitudinal Samples
Energy Resolution $\sim 17\%/E^{1/2}$

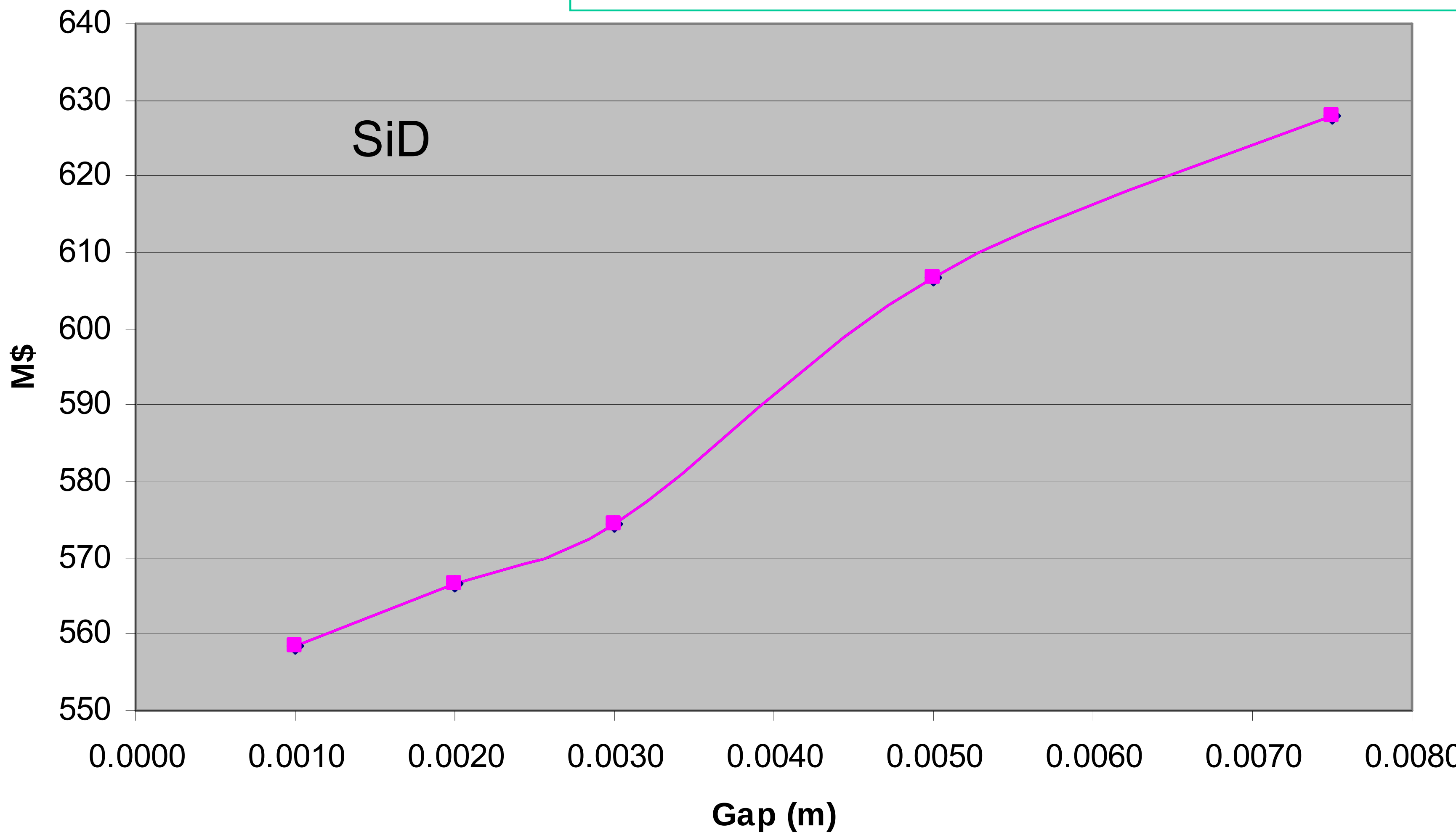
Baseline configuration:

- longitudinal: $(20 \times 5/7\ X_0) + (10 \times 10/7\ X_0) \Rightarrow 17\%/\text{sqrt}(E)$
- 1 mm readout gaps $\Rightarrow$ 13 mm effective Moliere radius

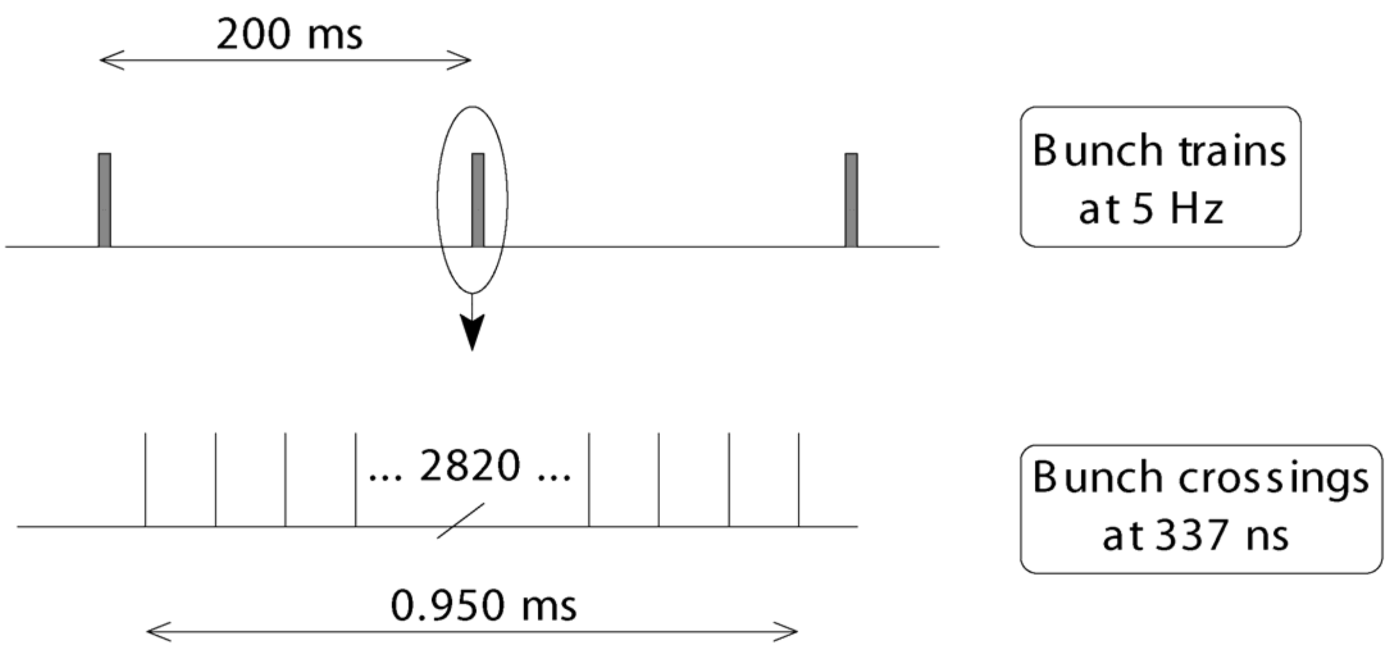
Generic consideration I: gap between layers

Config.	Radiation length	Molière Radius
100% W	3.5mm	9mm
92.5% W	3.9mm	10mm
+1mm gap	5.5mm	14mm

- Small gap maintains small Moliere radius
- Larger Rm ⇒ larger detector to maintain shower separability ⇒ cost !
- Small gap makes a cost-controlled compact detector practical



Generic consideration II: Power

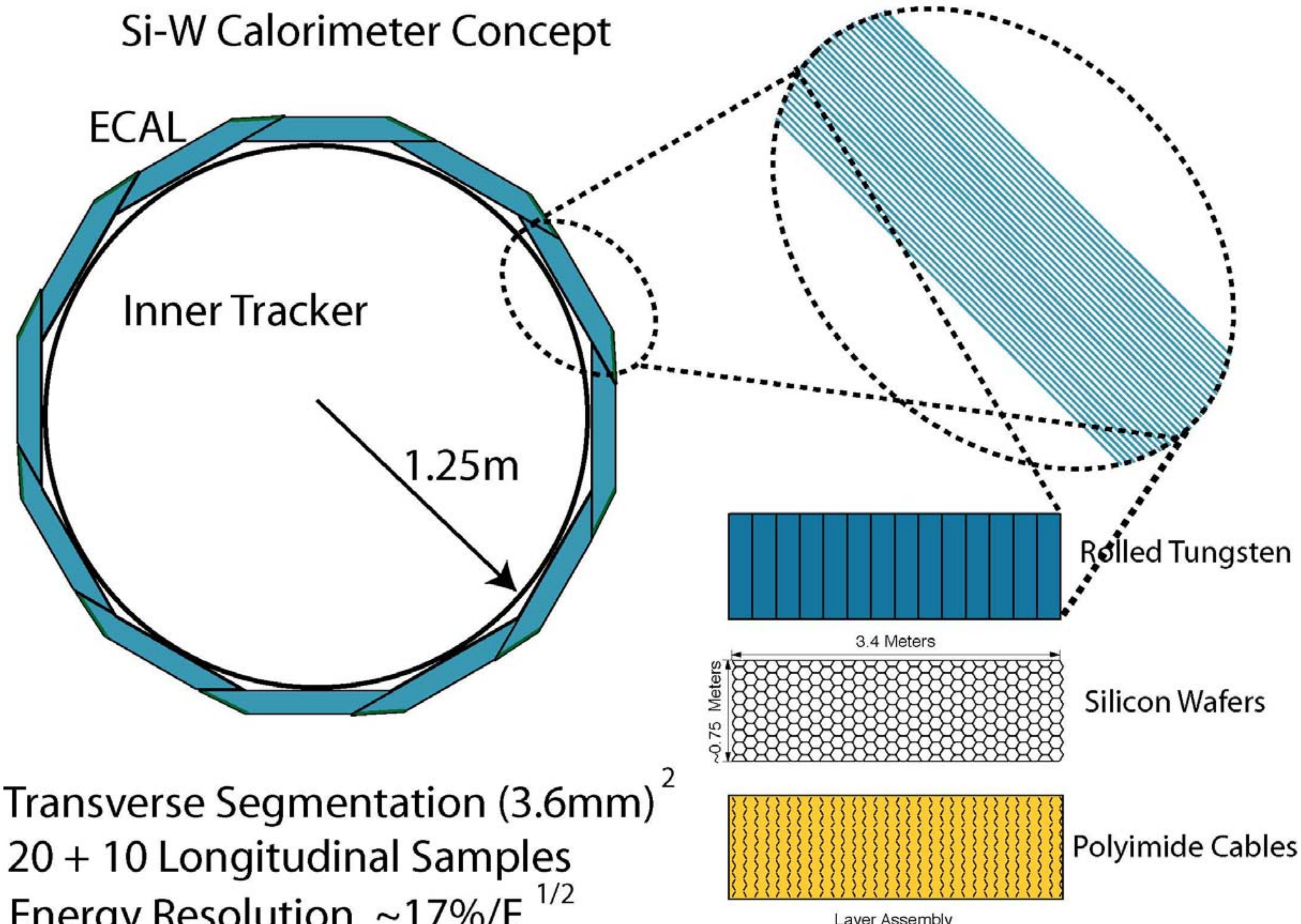


Turn off power between beam crossings.

⇒ Passive cooling (highly desirable!)

- for A), passive conduction of 20 mW to module end (≈75 cm) via the tungsten radiator results in a few °C temperature increase ⇒ OK !
- for B), this is an open question

A.) U.S. Silicon-Tungsten ECal
6” diode sensors with integrated electronics



Transverse Segmentation $(3.6mm)^2$
20 + 10 Longitudinal Samples
Energy Resolution $\sim 17\%/E^{1/2}$

<u>Baseline configuration:</u>

- transverse seg.: 13 mm^2 pixels
- longitudinal: $(20 \times 5/7\ X_0)$ $+ (10 \times 10/7\ X_0)$ $\Rightarrow$ 17%/sqrt(E)
- 1 mm readout gaps $\Rightarrow$ 13 mm effective Moliere radius

W/Si diode (A) R&D status overview**

- Require 1024-channel KPiX ASIC chips
  - Still evaluating 64-channel prototypes (KPiX-5 is latest)
  - Has been the critical-path item
- Silicon sensors
  - v1 evaluated successfully
  - v2 on order – expect to have 40 ~ Jan 08
- Bonding of KPiX to Si sensors
  - Trials in progress
- Tungsten
  - Have it
- Module mechanics and electromechanical
  - Serious work starting
- DAQ
  - Needs work
  - Compatibility with CALICE test beam DAQ

** See talks by M. Tripathi and T. Nelson in calorimeter session

U.S. Si/W ECal R&D Collaboration

M. Breidenbach, D. Freytag, N. Graf, R. Herbst, G. Haller, J. Jaros
Stanford Linear Accelerator Center

- KPiX readout chip
- downstream readout
- mechanical design and integration

J. Brau, R. Frey, D. Strom, undergraduates
U. Oregon

- detector development
- readout electronics

V. Radeka
Brookhaven National Lab

- readout electronics

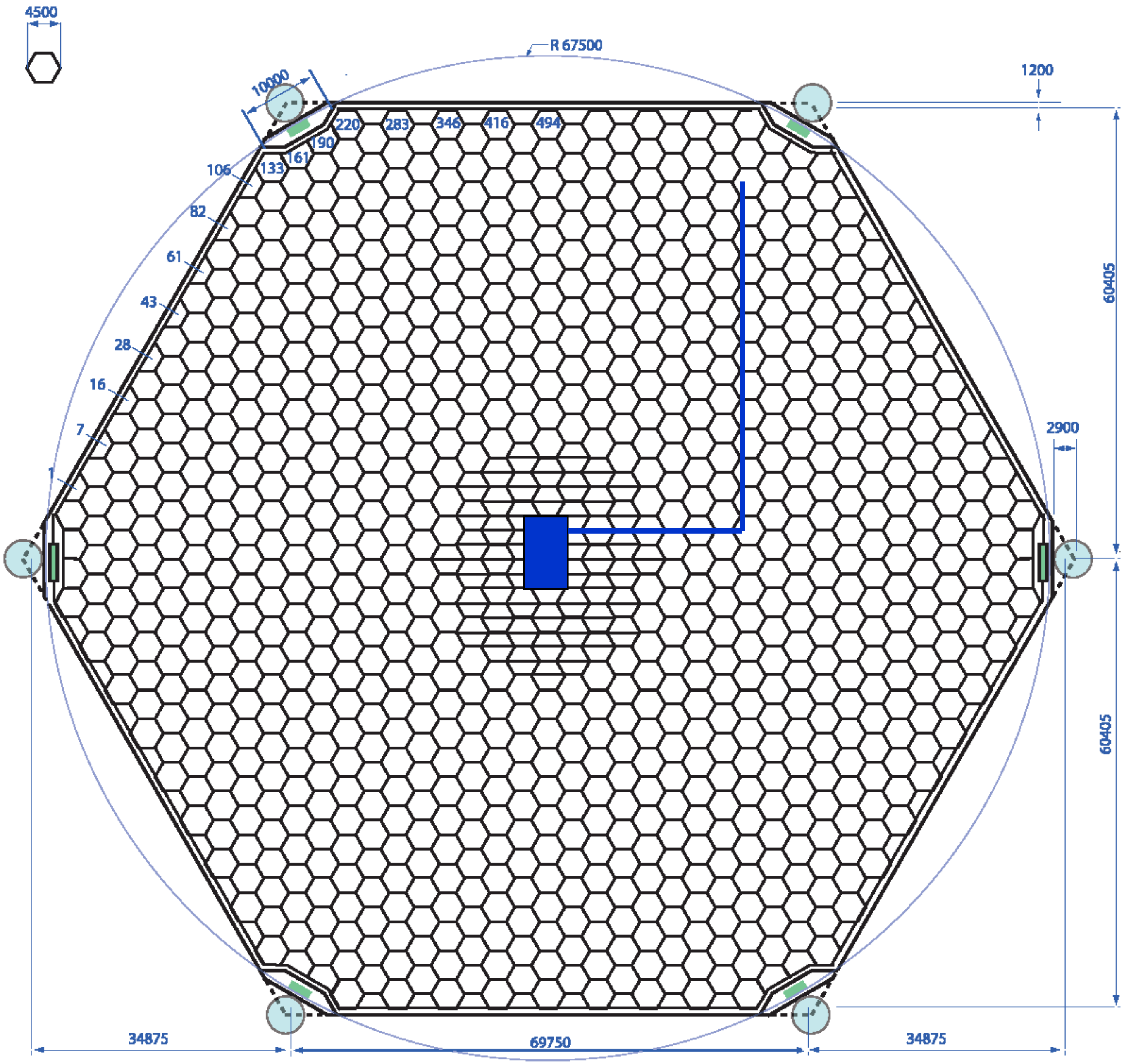
B. Holbrook, R. Lander, M. Tripathi
UC Davis

- cable development
- bump bonding

S. Adloff, F. Cadoux, J. Jacquemier, Y. Karyotakis
LAPP Annecy

- mechanical design and integration

v2 Si detector – for full-depth test module

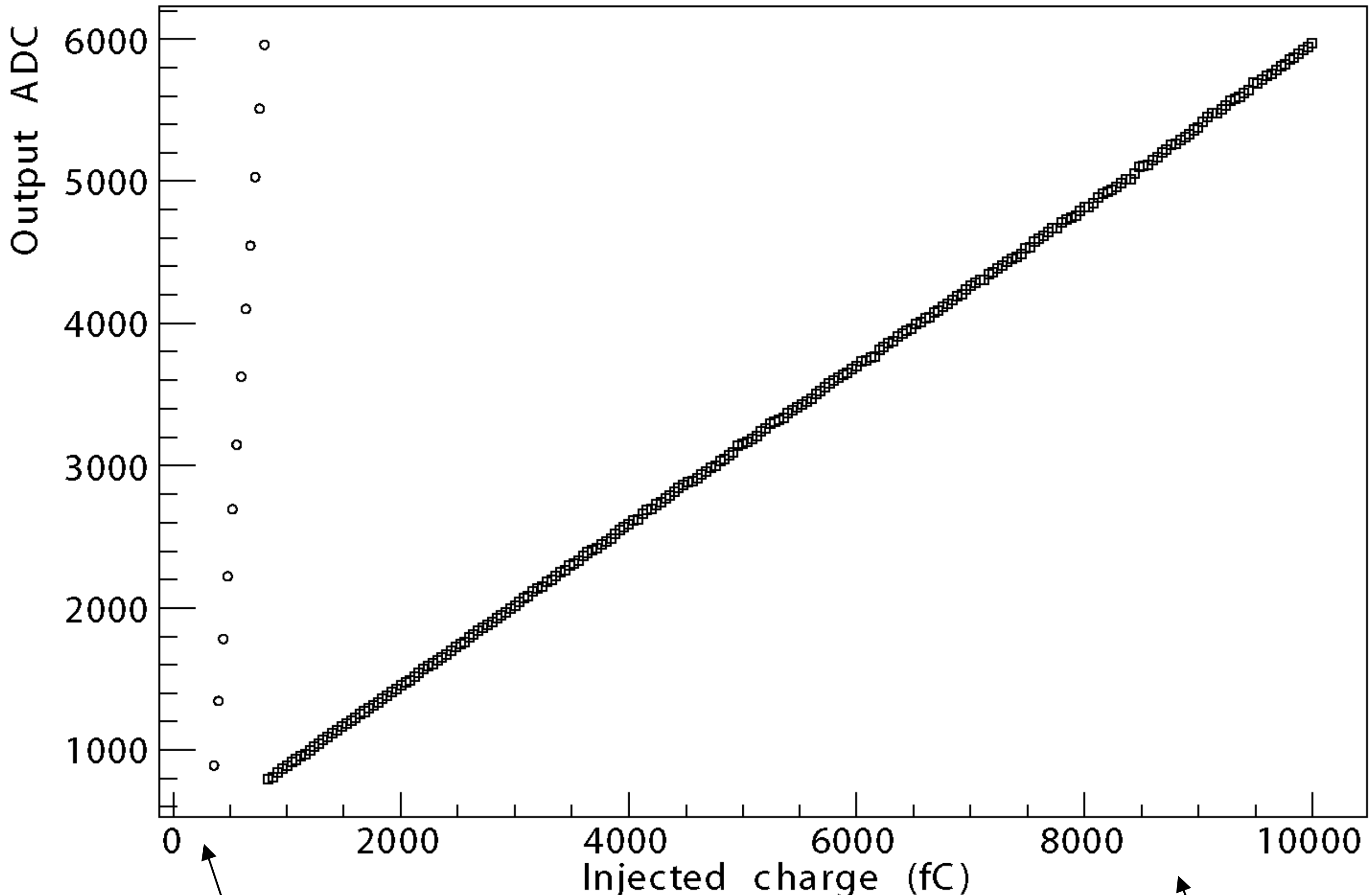


- 6 inch wafer
- 1024 13 mm^2 pixels
- improved trace layout near KPiX to reduce capacitance
- procurement in progress (it will take 6-12 months to complete the 40-wafer purchase – funding limited)

KPiX ASIC and sample trace

KPiX for Si/W

KPiX prototype on the test bench



1 MIP (4 fC)

Max signal: 500 GeV electron

DoE review (A)

The US effort is focused on silicon-tungsten calorimetry with KPiX (1k pixels per si sensor) readout of 1024 channels of few millimeter-sized hexagonal pixels. This program is well conceived with strong groups participating. There are many challenges to overcome, and there is a need to demonstrate solutions with beam and bench tests. The bump bonding techniques must be proven to be sufficiently robust. The layout and test of the signal traces to the KPiX must be shown to give adequate signal to noise. The KPiX design has not yet converged and demonstrated scalability to a fully operational 1024 channel chip. A calibration strategy using 241Am sources is defined, but as yet untested at the 1% channel-to-channel level using realistic readout electronics; exploration of alternate schemes would be useful. The planned tests of a module are crucial. The group is aware of all these issues, and the proof of concept for the Si-W calorimetry remains a high priority of the R&D program.

B.) MAPS (Terapixel) Si/W

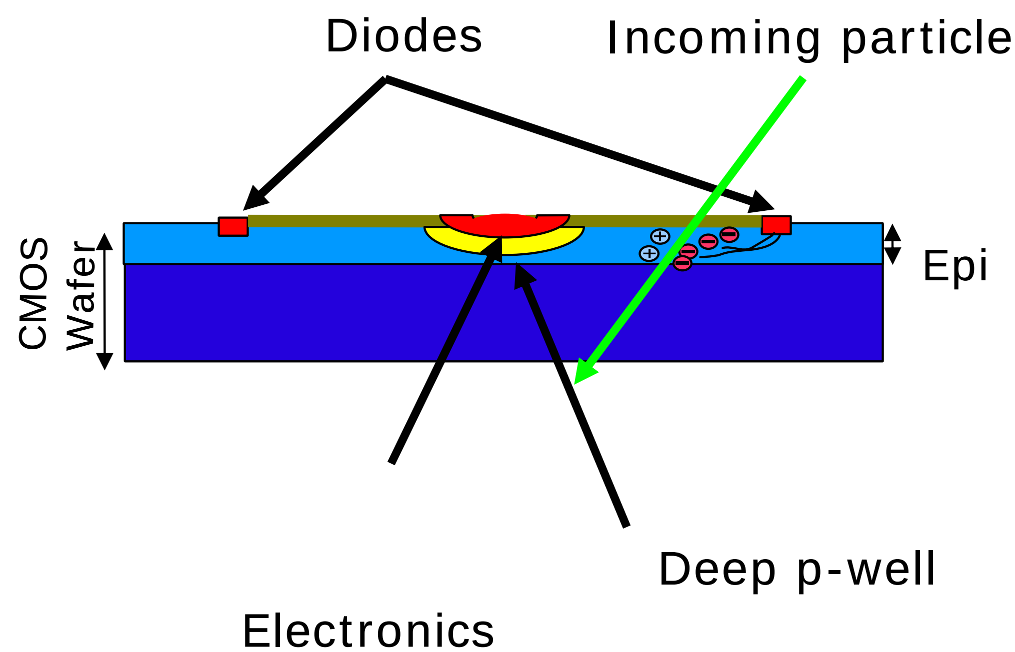
The MAPS ECAL

Y. Mikami, O. Miller, V. Rajovic, N.K. Watson, J.A. Wilson
University of Birmingham
J.A. Ballin, P.D. Dauncey, A.-M. Magnan, M. Noy
Imperial College London
J.P. Crooks, M. Stanitzki, K.D. Stefanov, R. Turchetta, M. Tyndel, E.G. Villani
Rutherford Appleton Laboratory

See M. Stanitzki talk in calorimeter session

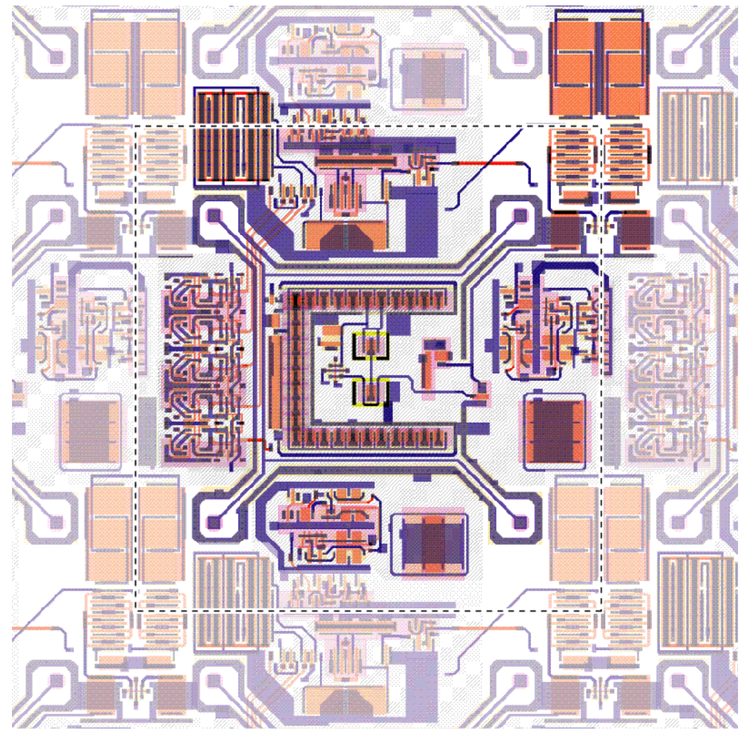
What are MAPS ?

- **M**onolithic **A**ctive **P**ixel **S**ensor
- Integration of Sensor and Readout Electronics
- Manufactured in Standard CMOS process
- Collects charge mainly by diffusion
- Development started in the mid-nineties, now a mature technology



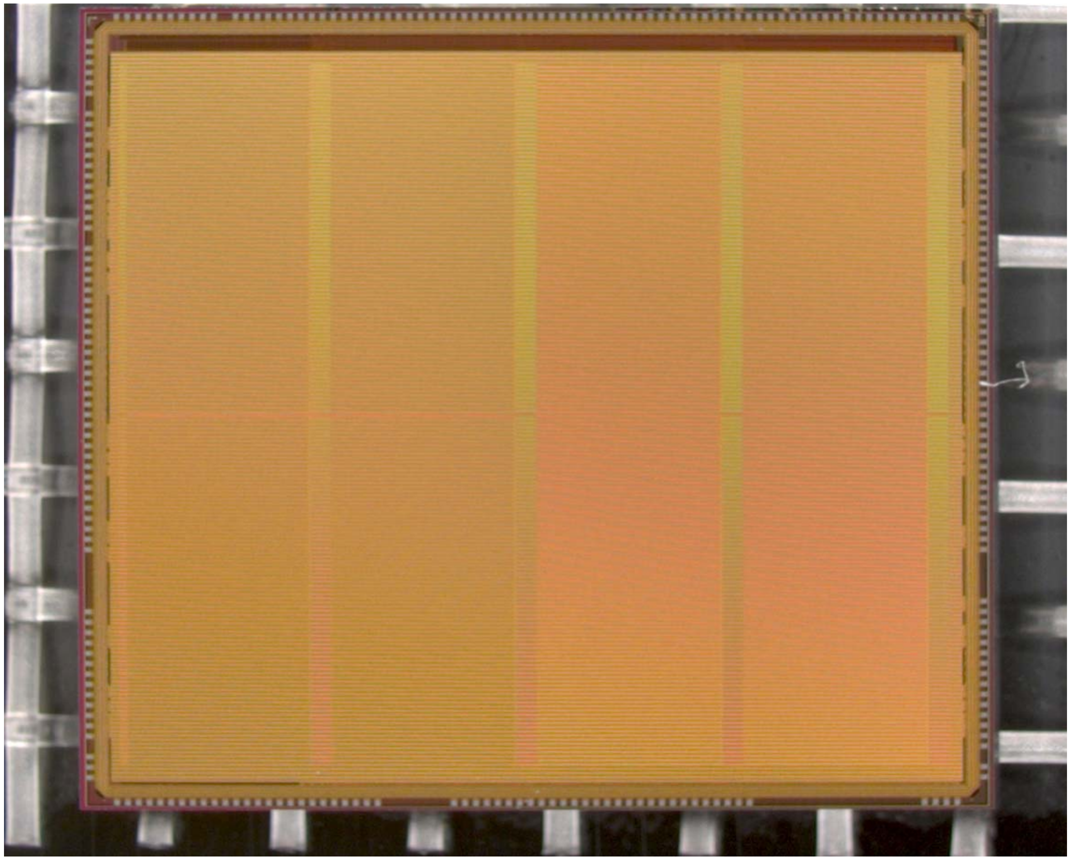
Sensor specifications

- 50x50 micron cell size
- Binary Readout (1 bit ADC realized as Comparator)
- 4 Diodes for Charge Collection
- Time Stamping with 13 bits (8192 bunches)
- Hit buffering for entire bunch train
- Capability to mask individual pixels
- Threshold adjustment for each pixel
- Usage of INMAPS (deep-p well) process



The ASIC1 sensor

- Received in late July
- 0.18 microns CMOS INMAPS Process
- 168x168 Pixels
- 8.2 million transistors
- Test structures
- A lot of bond pads



System issues

- A Tera-Pixel ECAL is challenging
- Benefits
  - No readout chips
  - CMOS is well-know and readily available
  - Ability to make thin layers
- Current sources of concern
  - Power consumption/Cooling
  - DAQ needs

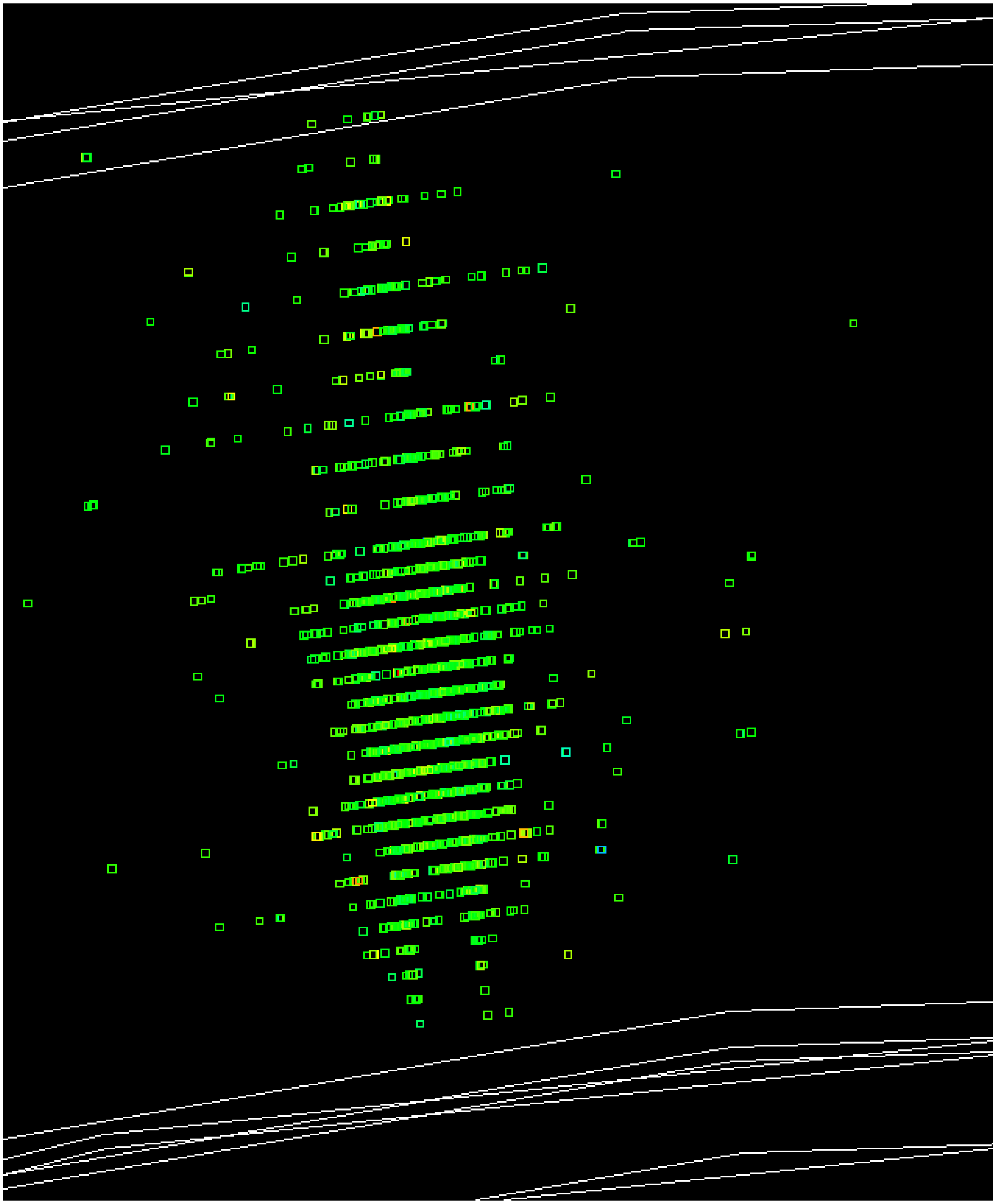
The path to the LOI

- Technology choice
  - MAPS terapixel still needs to be proven as a viable ECal technology
  - Si diode/W ECal technology is well established for relatively small calorimeters. But the integrated electronics needs to come together.
  - What does the physics say? Is there a physics case for segmentation<< R_m ? Perhaps. The case needs to be made and weighed against the risks.

  - Suggestion: Make Si diodes the default, but continue the R&D and studies for terapixel. Attempt to make an ECal mechanical structure which can accommodate either without important compromise.

- We need to do a lot of work to solidify and amplify the physics case for the LOI --- simulation studies at all levels.

Do we need < few mm segmentation?



- EM showers are narrower than R_m for the first radiation lengths.
- π° id and reconstruction are important, perhaps crucial:
  - Jet resolution
  - Tau id and analysis
  - Flavor tagging ??
- A few layers of MAPS ??
  - This avoids saturating the MAPS pixels at shower max.
- MAPS for the inner endcap? Forward tracking? ??

There is a lot to do...

- Si diode technical
  - Current focus on KPiX development
  - Starting serious look at mechanical issues
    - For SiD structure
    - For the test beam module
  - What goes on the other end of the cable from KPiX?
  - Procurement, layout, testing of a large number of sensors.
  - Test beam(s) !
    - e.g. DAQ and data analysis
- Terapixel technical
  - Reconstruction within org.lcsim framework

General needs:

- Sensor and electronics configuration for the inner endcap
- Simulation studies are badly needed
  - Especially to elucidate physics ⇔ segmentation

Some needed studies

- Longitudinal structure (baseline is a motivated guess)
  - What EM resolution is *required* ?
    - Particle flow (photon E res. shouldn't contribute on average)
    - Other indications? $h \to \gamma\gamma$?
  - Depth (containment) and numbers of layers (money, E resolution, pattern recognition of EM)
    - How much can the HCal help with EM resolution?
- Segmentation
  - gamma-gamma and $h^{\pm}$ –gamma separability; π° reconstruction
  - EM shower id
    - There has been progress. But we are still at an unsophisticated level relative to what has been accomplished, for example, at LEP.
- Physics/detector studies
  - jet/pflow processes [pushes seg. issue]
    - Without beam constraint (eg invisible decays)
    - Jet combinatorics in complicated finals states
  - Tau id and final-state reconstruction (polarization) [pushes seg. issue]
  - Photon tracking
  - Heavy quark id: electrons in jets, neutrino recon; exclusive B/D tags?

Summary

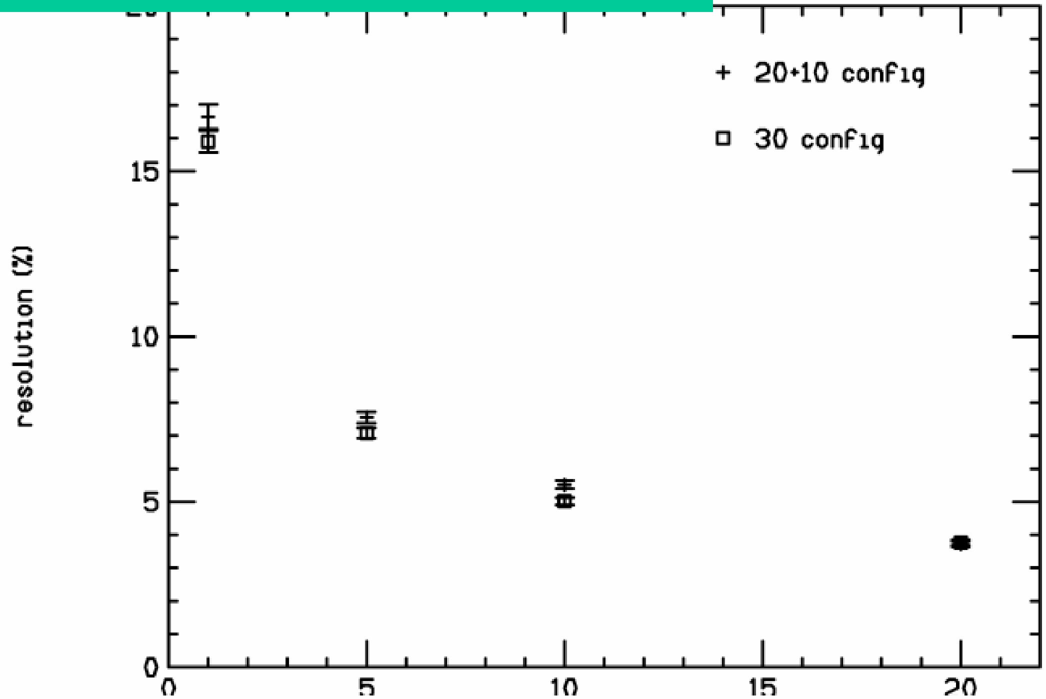
- The silicon/tungsten approach for the SiD ECal still looks good.
  - Baseline: Si diode sensors with integrated (KPiX) electronics
  - MAPS (terapixel)
- But there is a lot to do !
- Many important and basic simulation studies needed.... for the LOI and in general:
  - Detector related
  - Physics related
  - both

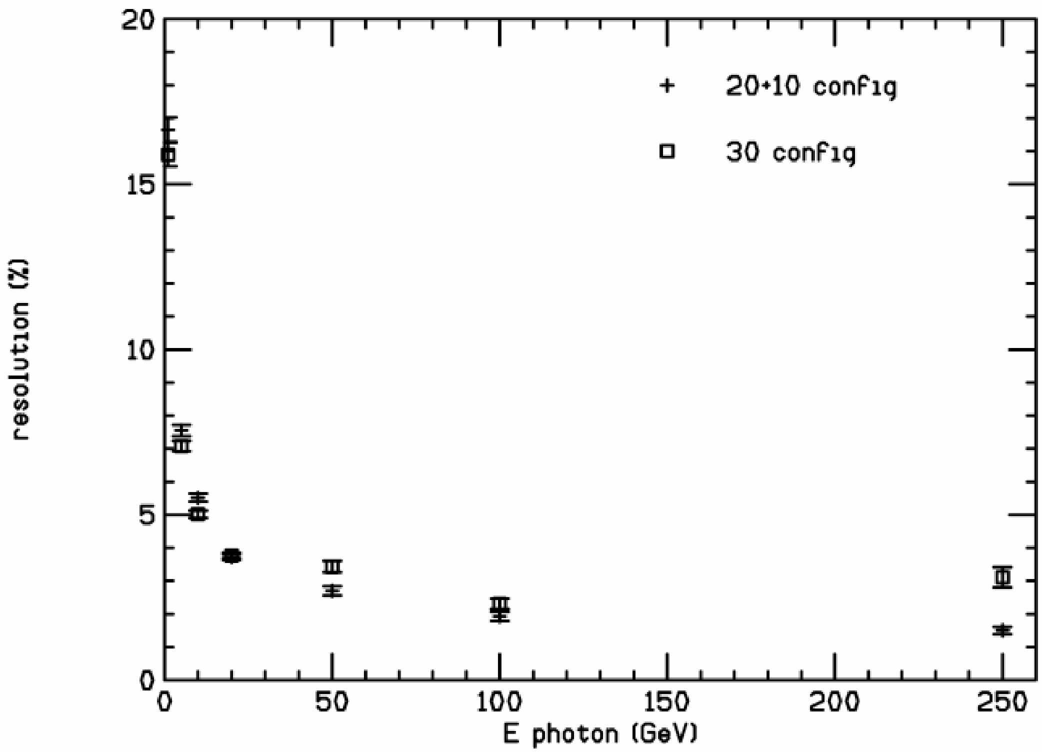
Extra stuff...

Longitudinal Sampling

Compare two tungsten configurations:

- 30 layers x 5/7 X_0
- (20 x 5/7 X_0) + (10 x 10/7 X_0)



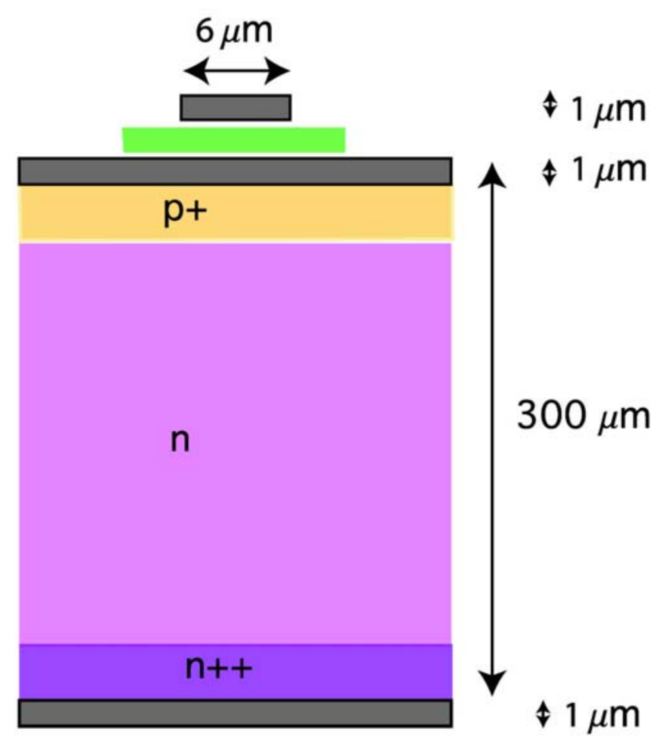


- Resolution is 17% / √E , nearly the same for low energy (photons in jets)
- Better for the 20+10 config. at the highest energies (leakage) ⇒ adopt as baseline

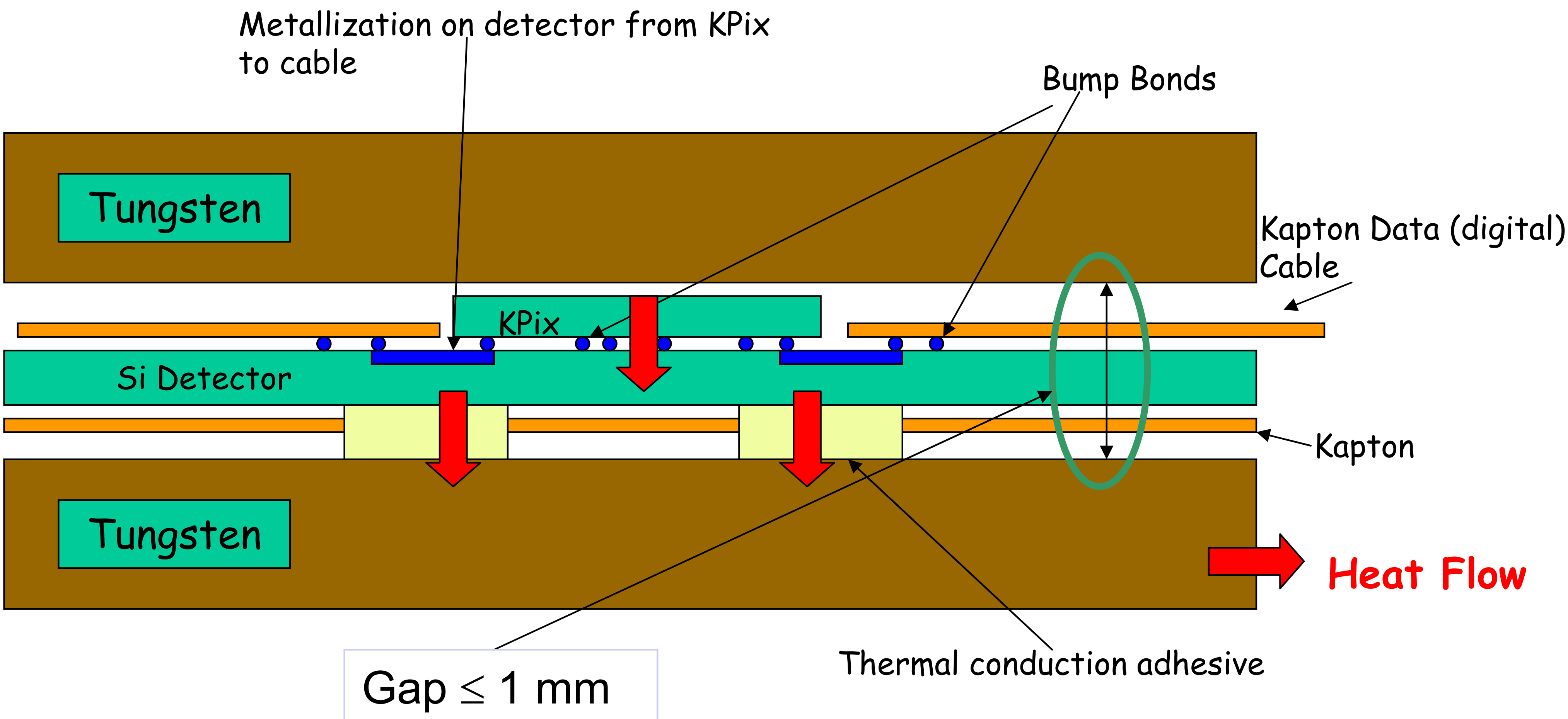
Electronics requirements

- Signals
  - <2000 e noise
  - Require MIPs with S/N > 7
  - Large dynamic range: Max. signal is ≈2500 MIPs (for 5mm pixels)
- Capacitance
  - Pixels: 5.7 pF
  - Traces: ~0.8 pF per pixel crossing
  - Crosstalk: 0.8 pF/Gain x Cin < 1%
- Resistance (traces)
  - 300 ohm max
- Power
  - If < 40 mW/wafer ⇒ allows passive cooling (as long as power is cycled off between bunch trains)
- Provide fully digitized, zero suppressed outputs of charge and bx time on one ASIC for every wafer.

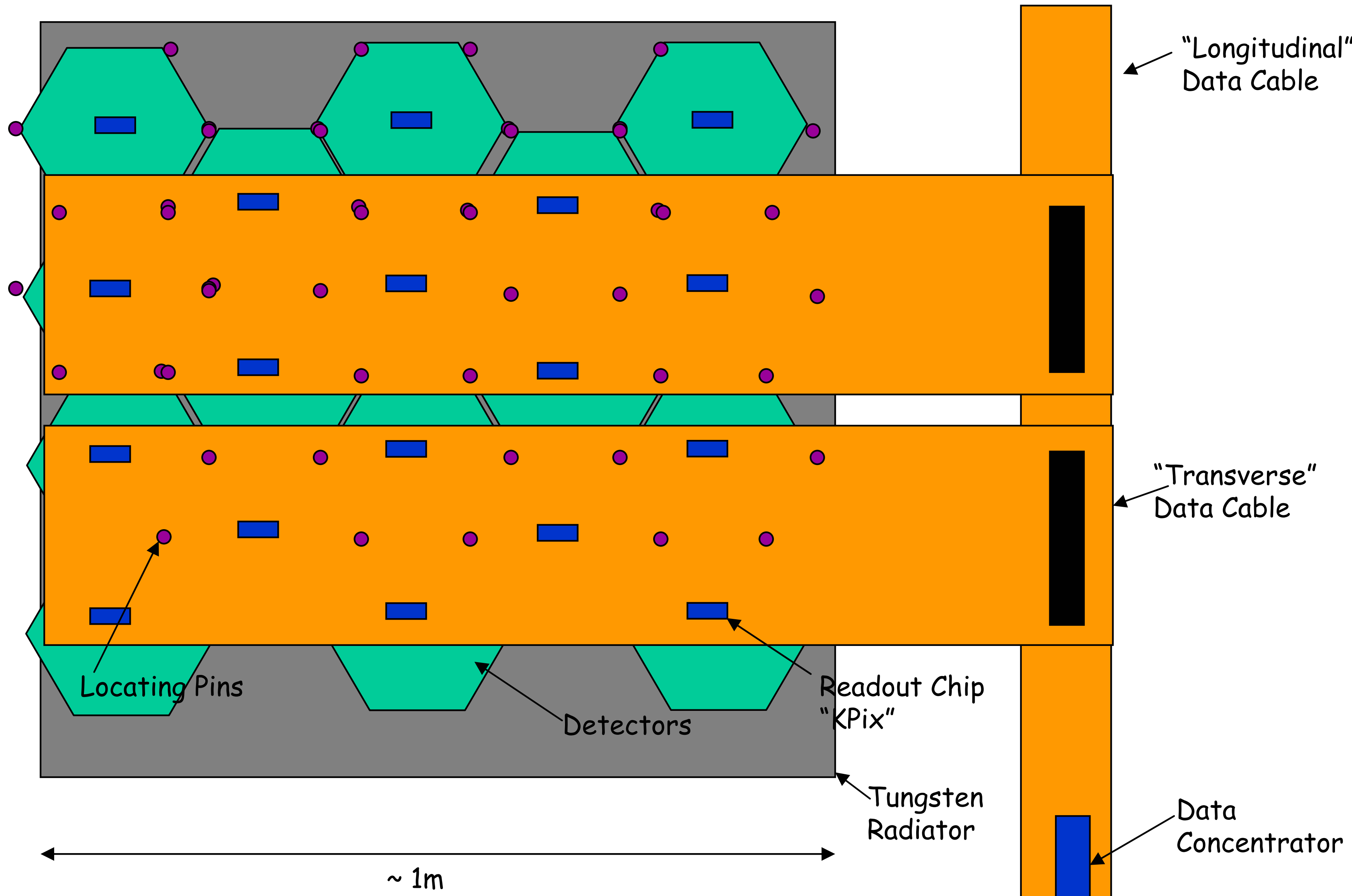
Use DC-coupled detectors: only two metal layers (cost)



readout gap cross section -- schematic

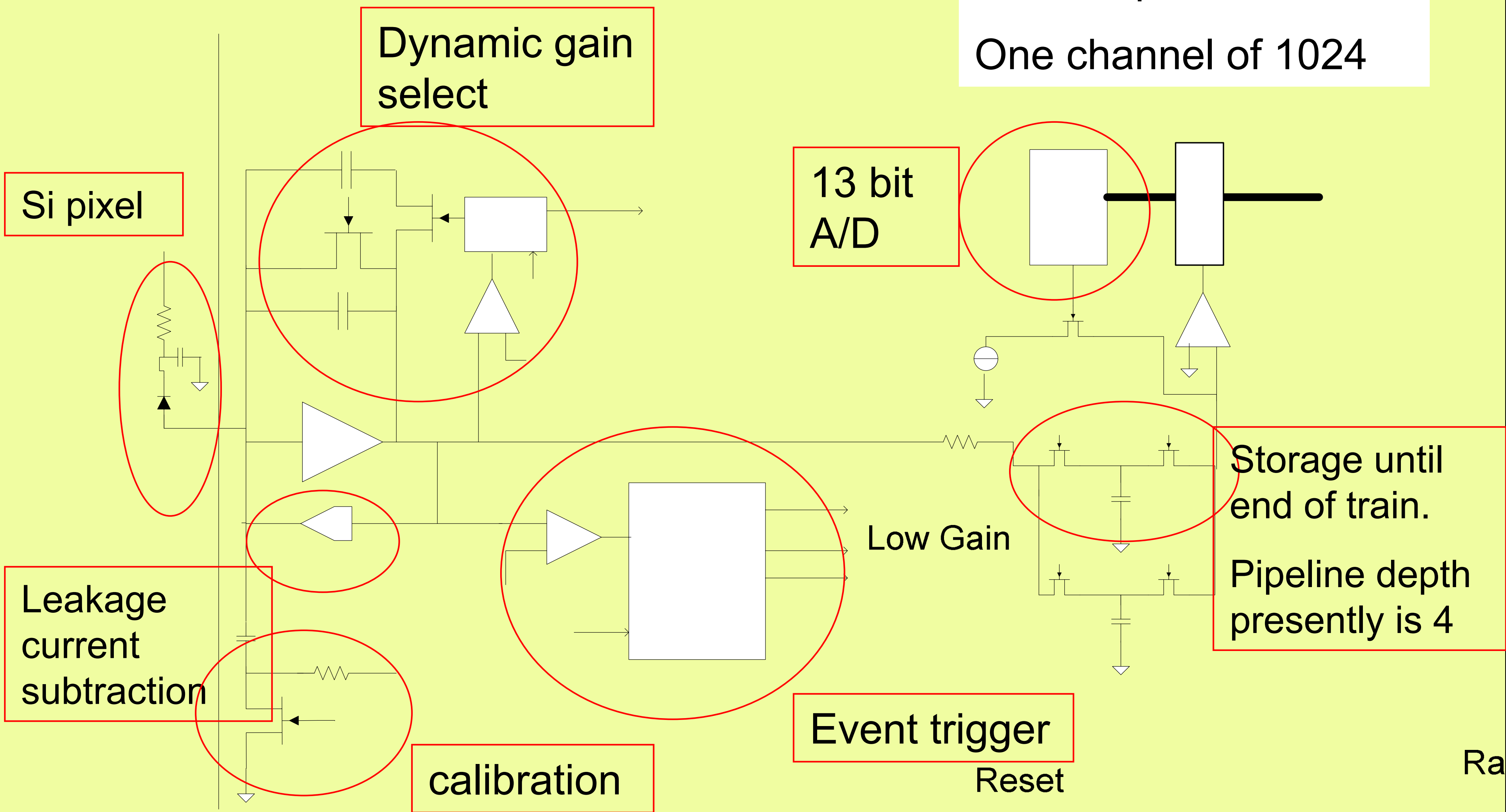


Conceptual Schematic – Not to scale

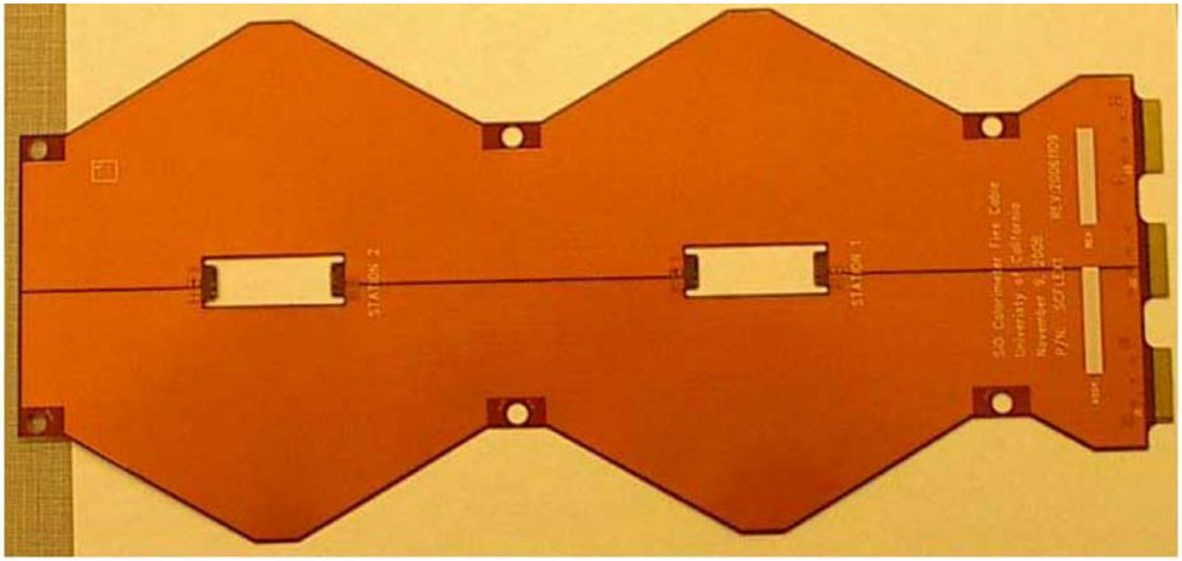


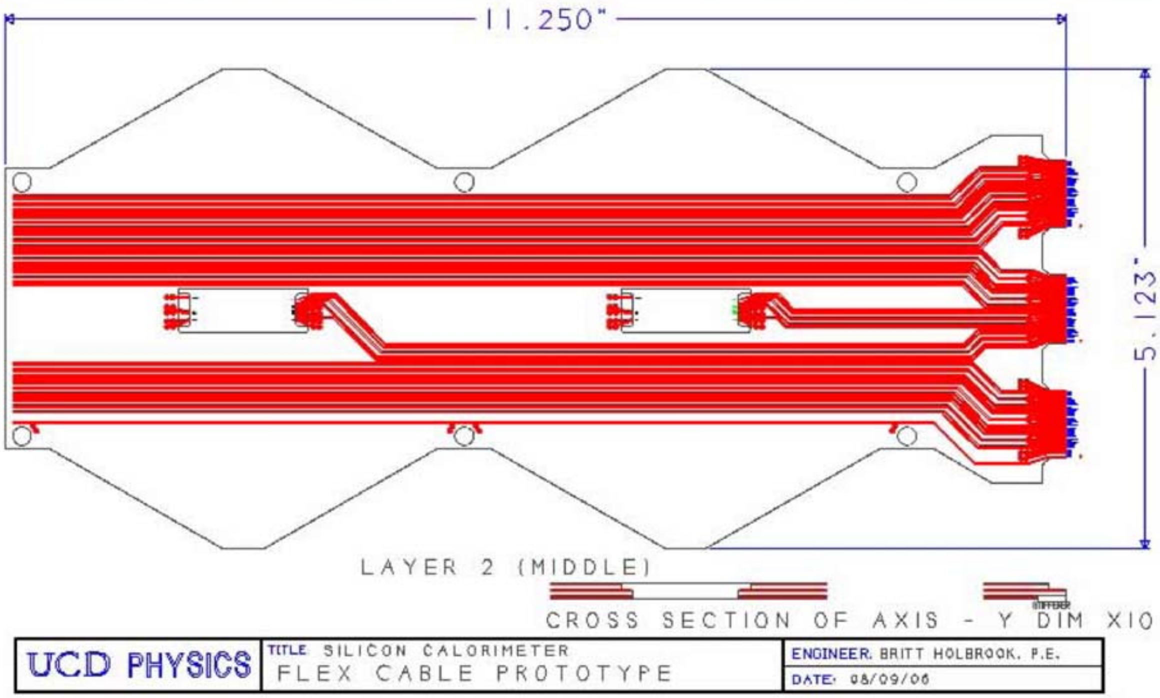
KPiX chip

One channel of 1024



Readout flex cable (digitized signals, power&control)





- First prototype:
  - 2 stations
  - Buried signal layer between power and ground
  - Wire bond connections
  - No problem for prototypes
- For ECal:
  - ~6 stations: should be OK
  - Would like to determine length limit for next round (vias and multi-layers difficult for ~1m)