

# Detectors at Lepton Colliders

Michael Kagan, Caterina Vernieri,  
Marty Breidenbach, Ariel Schwartzman, Su Dong

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It will take at least 5 years of fully supported (100-150M\$) hard work to produce a TDR for a construction start.

- Significant work on a TDR requires rebuilding the collaboration; difficult before the ILC is approved.
- A middle ground might be significant support for the detectors coincident with the pre-lab initiation

Availability of serious R&D support	starting point
Collaboration re-formation	~1 year
TDR	~5 years
Detector Construction	-7 (optimistic) -10 (more realistic) years, primarily dependent of funding levels

*SiD had 36 U.S. institutions that signed the LOI (out of 77 total).*

*The U.S. activity is now only SLAC, FNAL, ANL, PNNL and UTA, UCSC, UCD, and UofO. The national lab activity is almost gone as DOE has almost stopped ILC detector R&D.*

# Cost scale (2016)

- The SiD construction cost estimate from the DBD is:
  - Base M&S 315 M\$
  - Contingency M&S 127 M\$
  - Engineering 186 Man-Years
  - Technical 532 Man-Years
- Magnet (162M\$) and EMCal (183M) are driving cost of the SiD detector.

WBS	Description	M&S	M&S Cont	Labor	Labor Cont	Total
1.1.1	Beamline Systems	\$ 3,680,000	\$ 1,423,000	\$ 1,525,864	\$ 508,692	\$ 7,137,556
1.1.2	VXD	\$ 2,797,000	\$ 2,035,000	\$ 2,200,359	\$ 802,325	\$ 7,834,684
1.1.3	Tracker	\$17,743,797	\$ 6,866,105	\$ 9,359,577	\$ 3,712,232	\$37,681,712
1.1.4	EMCal	\$99,927,619	\$39,966,048	\$31,946,627	\$11,177,819	\$ 183,018,113
1.1.5	Hcal	\$51,607,707	\$ 20,110,325	\$ 5,626,083	\$ 1,969,129	\$79,313,244
1.1.6	Muon Sys	\$ 8,299,900	\$ 2,904,965	\$ 2,502,565	\$ 860,550	\$14,567,980
1.1.7	Electronics	\$ 4,899,887	\$ 1,649,911	\$ 9,688,085	\$ 1,598,125	\$17,836,008
1.1.8	Magnet	\$ 114,801,030	\$ 39,452,437	\$ 5,642,201	\$ 1,920,276	\$ 161,815,944
1.1.9	Installation	\$ 4,102,800	\$ 1,082,070	\$ 4,746,050	\$ 1,677,383	\$ 11,608,303
1.1.10	Management	\$ 921,000	\$ 171,700	\$ 9,120,454	\$ 2,236,359	\$12,449,513
Totals (M\$)		\$ 308.8	\$ 115.7	\$ 82.4	\$ 26.5	\$ 533.3

# Ongoing e+e- conversations in the US

IDT: International Development Team

A new group has been formed in the US with the goals of:

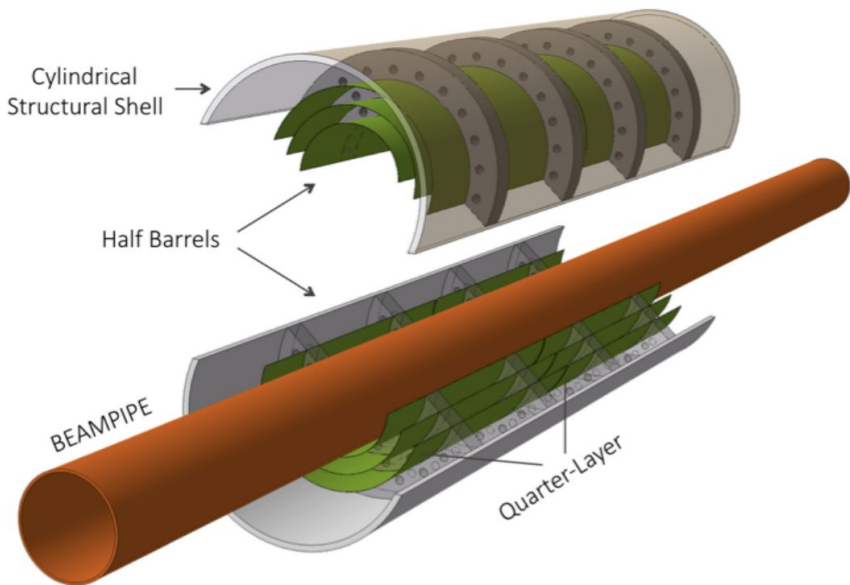
- Increase US involvement: get new people involved, integrate into existing efforts, connect them with others doing similar R&D
- Recruit and educate new young scientists
- Evaluate benchmarks and needs for e+e- detector (ILC but also other future opportunities that are on the table)
- Coordinate ongoing R&D efforts in the US (not many so far)

ICL R&D meeting in the Fall (Japan) is an opportunity to discuss efforts

- Ideally any old/new SLAC involvement should be ready to join that conversation.

- Young scientists in the US seem quite confused as to how to get involved, let alone lead new efforts for ILC
  - IDT seems to be the place to help get connected, but not a clear picture of “how to move forward”
  - Not clear if a coherent effort is building, or if this is mainly serving to get people connected and “in the know”
  - Since there is no money available, seem to suggest simulation studies
- More clear: A conversation is starting in the US → SLAC should be involved
  - We should engage in IDT meetings and discussions
  - Leadership role in this community where possible in future
  - Contribute with even small R&D efforts in near-term

# ALICE: Bent MAPS for Run 4



**Bending Si wafers + circuits is possible**

*Charlie is in touch with them and he can tell us more about a possible involvement there.*

Recent ultra-thin wafer-scale silicon technologies allow:

Sensor thickness = 20-40  $\mu\text{m}$  - 0.02-0.04%  $X_0$

Sensors arranged with a perfectly cylindrical shape a sensors thinned to  $\sim 30\mu\text{m}$  can be curved to a radius of 10-20mm (ALICE-PUBLIC-2018-013)

# SLAC Potential Steps Forward

- MAPS R&D
  - Going to be a major piece of future detectors
  - Device R&D needed. Knowledge building needed. Need money to build lab.
  - Device simulation studies may be a good path to get started
  - Marty has an existing effort at SLAC: It is a promising way to grow engagement into tracker discussions for e+e-
    - Timing info has not been proven to be necessary so far : no dedicated R&D
- Simulation studies
  - Physics impact / System level studies of detector design
    - Valentina/Ariel/Su Dong/Caterina: started some work for SnowMass
- Get involved in construction of near-term systems
  - ALICE Bent MAPS vertexing system (interesting possible detector for ILC)
  - EIC LGADS potentially a stepping stone towards future lepton colliders.

# Backup



We will have to evaluate best match between current resources and ILC/C3 detector needs in the next couple of years

- Important to start now if we want to have a leading role in the future
- Tracker seems to be a natural choice, but other opportunities too
- The way we engage for ILC and C3 might be somewhat different.
  - C3 could be aiming for on site as a host lab and more ambitious coverage would be natural and important.

Depending on the \$\$\$ available we could start ramping up with allocated engineering time to follow up on :

- MAPS R&D / Solenoid / VTX detector dedicated technology

# R&D ideas for e+e-

Item	Benefits	Duration (years)	R&D Cost (M\$)	Cost Benefits (M\$) -if R&D successful
Superconducting Cable Improvements	Lower conductor cost, reduce coil by one layer, reduce steel thickness	4	6	50
Eliminate Detector Integrated Dipole (DID)	Lower coil cost, radius, and risk	1	0.1	25
MAP Development	lower cost, lower risk, better performance	4	5	~5
Tungsten Manufacturing Process	lower cost	3	3	~10
Note: There is very substantial R&D that must be done to make the detector possible, and is necessary to make the existing cost estimate plausible!				

- Solenoid : room for improvements over the CMS technology
- Tracker MAPS - (Historically FNAL with some SLAC involvement)
  - On going R&D @SLAC with US-Japan, Japan-US funds
  - Recent new submission at Desy
  - Note that although the vertex detector will be based on a different technology, it will be likely a responsibility of the same institute
- Calorimeter MAPS - historically an area where SLAC had been leading
  - A prototype is under test
- HCAL : Desy lead

# ILC vs C3 optimizations

Bunch spacing is different but detector R&D would not be significantly impacted

- ILC~300ns versus C3~3.3 ns

C3 has the potential to go higher in center of mass energy (up to 3 TeV)

- Detector optimization for high energy might lead to different choices
- Beyond 2-3 TeV the beam dynamics at the IP gets challenging

## IBL

- 3D Sensor design and optimization
- DAQ
- electrical services
- Detector QA

## ITK

- Pixel vertex detector assembly and testing
- Data transmission
- DAQ

Timing : HGTD (fast timing) ASIC readout chip design

Currently evolving towards 4d Tracking effort

## TDAQ

- Luminosity, Beamspot, Trigger algorithms

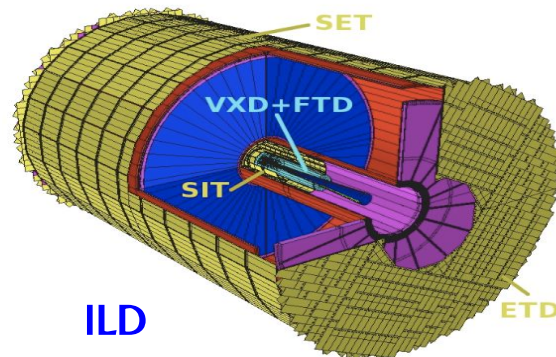
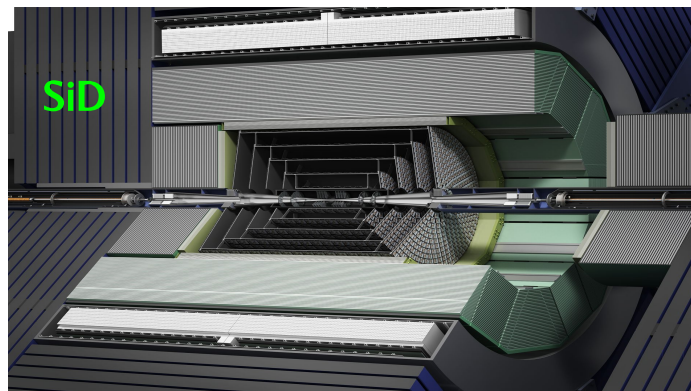
A natural progression from ATLAS to a lepton collider would be a focus on vertex and tracker detectors

- Note that most of the requirements assume a Particle Flow approach - but this could also be re-visited
- Calorimeter granularity
  - Need factor  $\sim 200$  better than LHC
- Pixel size
  - Need factor  $\sim 20$  smaller than LHC
- Material budget, central tracking
  - Need factor  $\sim 10$  less than LHC
- Material budget, forward tracking
  - Need factor  $\sim >100$  less than LHC

Requirements for Timing, Data rate and Radiation hardness are very modest compared to LHC

- Required radiation tolerance from the beam related background affects mostly the innermost layer.
- 1 kGy and  $10^{11} n_{eq}/cm^2$  per year, assuming neutrons backscattered from beam dump are shielded well enough

# Introduction



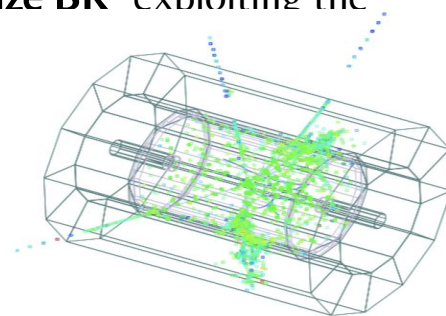
- Future lepton colliders target unprecedented precision on physics  $\leftrightarrow$  extremely high precision detectors
- Silicon strip and pixel detectors are **key** for precision charged particle tracking, secondary vertexing, and as input to Particle Flow reconstruction - which is assumed as baseline
- Minimizing material budget is vital  $\rightarrow$  Exciting Si pixel & strip technologies in development

# Detectors at ILC

Two detector designs developed with complementary features **that maximize  $BR^2$**  exploiting the beam-time-structure :

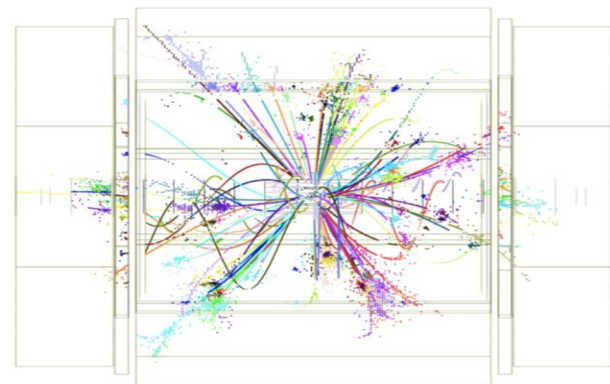
**SiD** is a compact, cost-constrained detector

- 5 T solenoid magnetic field with with  $R_{\text{ECAL}}=1.27$  m
- All-silicon tracking system
- Highly granular calorimeter optimized for particle flow analysis



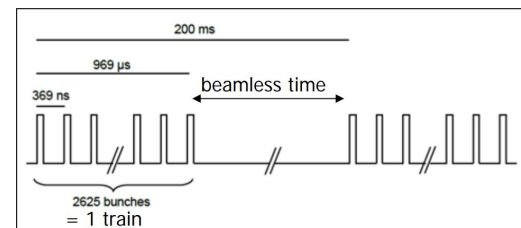
**ILD** is a large detector

- Time Projection Chamber (TPC) providing continuous tracking for  $e^+e^-$  and  $dE/dx$  capability, V0 reconstruction
- 3.5 T (4 T) magnet with  $R_{\text{ECAL}}=1.85\text{m}$  (1.46 m) for ILD-L (S)
- Highly granular calorimeter, with minimal material between the inner and outer calorimeter.



# Physics Drivers → Detector Design Requirements

- Requirements on single point resolution of sensors, location of innermost layer, and overall detector occupancy
  - **Very small pixels** for excellent IP resolution and minimal pattern recognition ambiguity
  - **Minimal material** as close to the interaction point as possible:
    - Goal  $<0.3\% X_0$  per layer (ideally  $0.1\% X_0$ ) for vertex detector and  $<1\% X_0$  per layer for Si-tracker
  - **Low power** to eliminate need for active cooling
- ILC timing structure: Fraction of a percent duty cycle
  - **Power pulsing possible**, significantly reduce heat load
    - Factor of 50-100 power saving for FE analog power
  - Si vertexing & tracking detectors **don't need active cooling**
    - Significant lowers mass budget
  - **Triggerless readout** possible

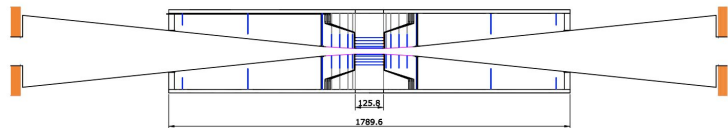


1 ms long bunch trains at 5 Hz

2820 bunches per train

308ns spacing (ILC TDR)

- Compact, cost constrained detector
  - 5 T solenoid B-field with  $R_{\text{ECAL}} = 1.27 \text{ m}$
  - All silicon pixel + strips tracking system
  - Highly granular calorimeter optimized for PFLOW
  
- Pixel Vertex detector
  - 1 kGy and  $10^{11} \text{ n}_{\text{eq}}/\text{cm}^2$  per year
  - **Pixel hit resolution** better than  $5 \mu\text{m}$  in barrel
    - Better if charge sharing is used
  - Less than **0.3%  $X_0$**  per pixel layer
    - air cooling  $\rightarrow$  low-mass sensor
  - Single bunch time resolution
    - Low capacitance and high S/N allows for acceptable power dissipation for sin (300-700 ns)
  
- Strip Tracker:
  - Silicon micro-strips, double metal layers
  - 0.1-0.15%  $X_0$  in the central region



20x20  $\mu\text{m}$  pixels in the central region  
 50x50  $\mu\text{m}$  for the forward tracker disks

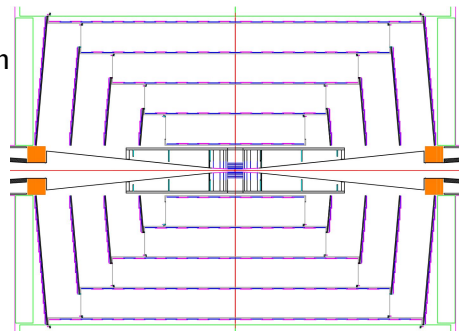
Barrel	R	$z_{\text{max}}$
Layer 1	14	63
Layer 2	22	63
Layer 3	35	63
Layer 4	48	63
Layer 5	60	63

Disk	$R_{\text{inner}}$	$R_{\text{outer}}$	$z_{\text{center}}$
Disk 1	14	71	72
Disk 2	16	71	92
Disk 3	18	71	123
Disk 4	20	71	172

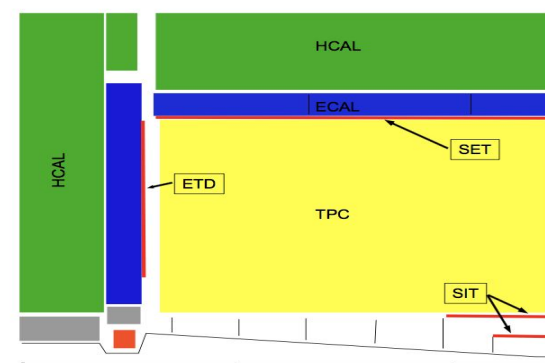
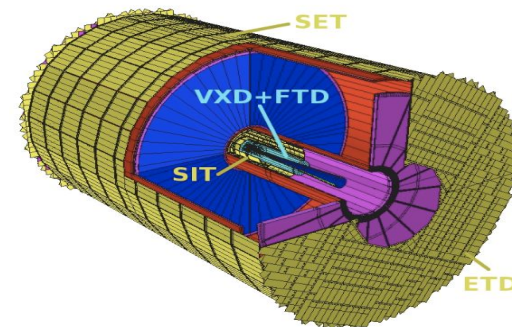
  

Forward Disk	$R_{\text{inner}}$	$R_{\text{outer}}$	$z_{\text{center}}$
Disk 1	28	166	207
Disk 2	76	166	541
Disk 3	117	166	832



# ILD in a nutshell

- Question if all-silicon tracking is too massive  **TPC-based** design
  - Large number of hits for a robust pattern recognition
- Tracker = pixel vertex detector + Si-strip detectors + TPC
  - VTX has long barrel approach
    - 17x17 $\mu\text{m}$  pixel in 1<sup>st</sup> layer  spatial resolution <3  $\mu\text{m}$
  - Si-strips: High precision space points outside the TPC system
    - Redundancy in regions b/w main tracker and calorimeters
- Large volume time projection chamber (TPC) w/ 224 points per track.
  - Optimized for 3D point resolution and minimum material in field cage and end-plate (<0.25%  $X_0$ )
    - T2K (Ar-CF<sub>4</sub>(3%)-isobutane(2%)) gas
    - Drift length of 2m in 3.5T field
  - Resolution goal:  $\sigma_{\text{point}}$  in  $r\phi$  <100  $\mu\text{m}$  (60  $\mu\text{m}$ ) full drift (zero drift)
  - Momentum resolution of  $\sim 10^{-4}$  GeV<sup>-1</sup> with TPC alone
  - **dE/dx based particle identification, 5% resolution**



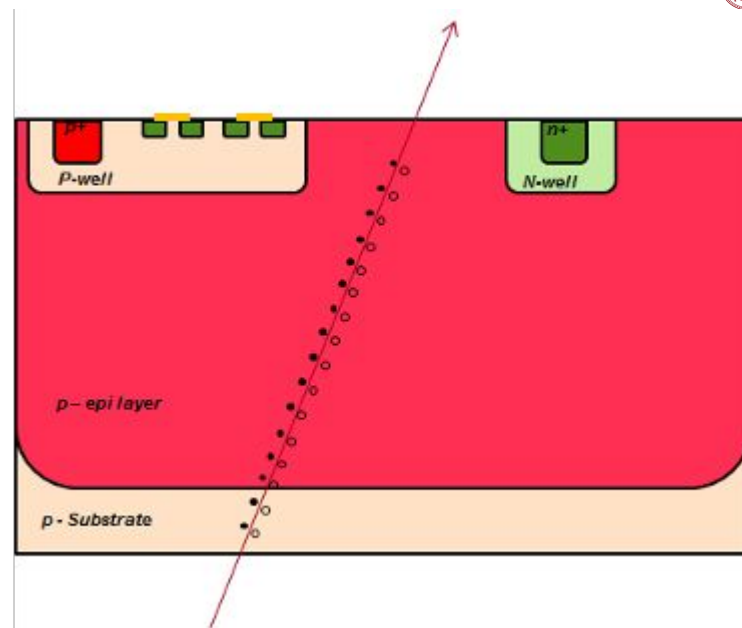
# Sensor technology overview

- Sensor's contribution to the total material budget of vertex detector is 15-30%
- To meet the physics performance sensors will have to be less than 75  $\mu\text{m}$  thick with  $\sim 5$   $\mu\text{m}$  hit resolution (17-25 $\mu\text{m}$  pitch) and low power consumption:
  - continuous r/o during the train with power cycling
  - delayed after the train  $\rightarrow$  either  $\sim 5\mu\text{m}$  pitch for occupancy or in-pixel time-stamping
- Several possible choices for the VTX detector:
  - Monolithic Active Pixels (MAPS)
    - CMOS Pixel Sensors (CPS)
    - Fully Depleted on High Resistivity Substrate (DNwel sensing)
    - Fully Depleted SOI technologies
  - Depleted Field Effect Transistors (DEPFET)
  - Fine pixel Charged Coupled Devices (CCD)
  - 3D integration

The general landscape is also changing rapidly with advances in microelectronics

# MAPS for SiD tracker detector

- Monolithic technologies have the potential for providing higher granularity, thinner, intelligent detectors at lower overall cost.
- Significantly lower material budget: sensor and readout electronics are integrated on the same chip
  - Eliminate the need for bump bonding and can be thinned to less than 100 $\mu\text{m}$
- Smaller pixel size, not limited by bump bonding
- Lower costs - can be implemented in standard commercial CMOS technologies
- Over the past decade, SiD has developed a first generation of sensors, readout with KPiX – which is the baseline approach.





- SLAC has developed a Monolithic version of kPix (kPixM) class of devices both for the tracker and the E-calorimeter:

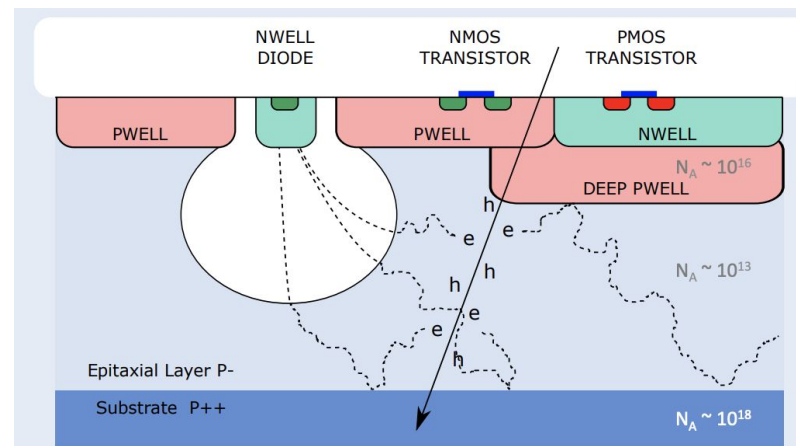
- kPixM-Trk has pixels of  $50\mu\text{m} \times 500\mu\text{m}$  size arranged in a  $2400 \times 200$  matrix.
  - A position resolution of  $<14\ \mu\text{m}$  is expected
- To be useful for a collider detector, the area of MAP sensors will be  $O(100)\text{m}^2$

#### KPiX Track module:

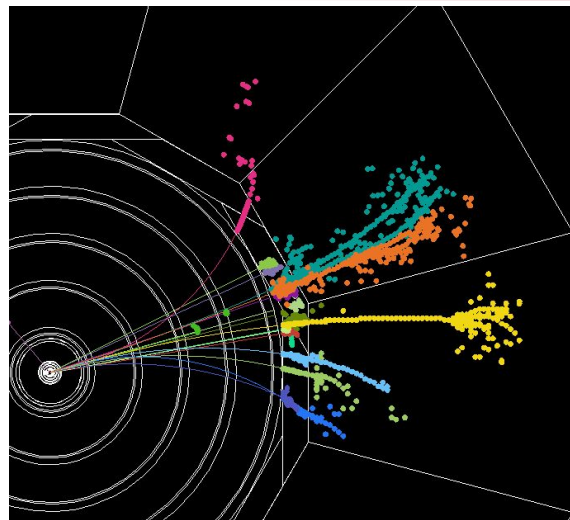
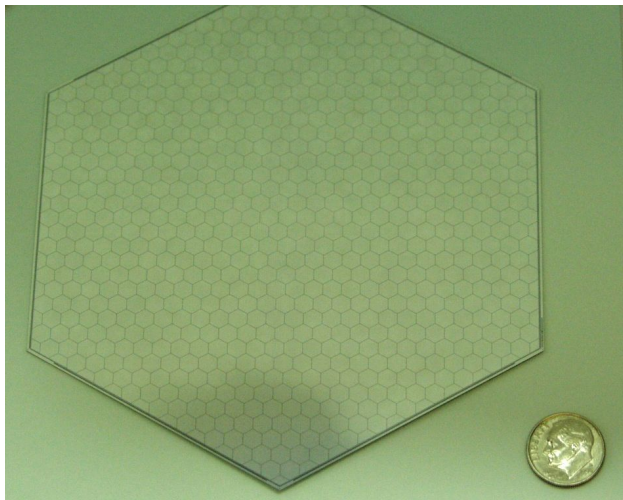
- 25/50  $\mu\text{m}$  strip pitch
- Two KPiX chips per sensor
- low mass readout cable services two chips and is also bump bonded to the face of the sensors

# CMOS in HEP

- CMOS-MAPS originally conceived by the HEP mainly in the ILC framework (since 2000)
  - **STAR HEAVY** Flavour Tracker @ RHIC(2014):
  - With the current tracker upgrade **ALICE** redefined the new state-of-the art in CMOS MAPS technology and its applications in HEP
- ALice Pixel DEtector (ALPIDE) employs CMOS Pixel sensor used in imaging process
  - Full CMOS circuitry within active area
  - Sensor thickness = 20-40  $\mu\text{m}$  (0.02-0.04%  $X_0$ )
- The used technology offers further opportunities: smaller feature size, **bending** that directly impact the key measurements that highly rely on precise vertexing and low material budget



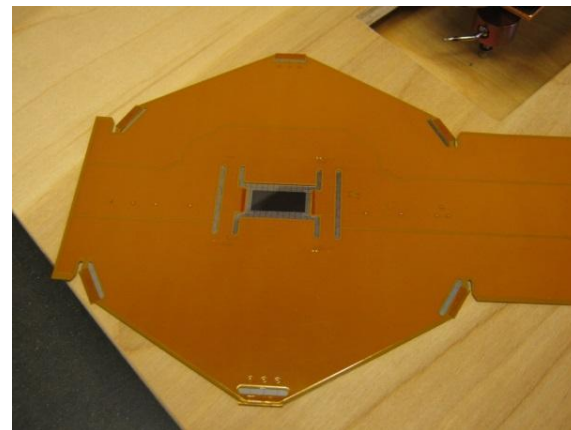
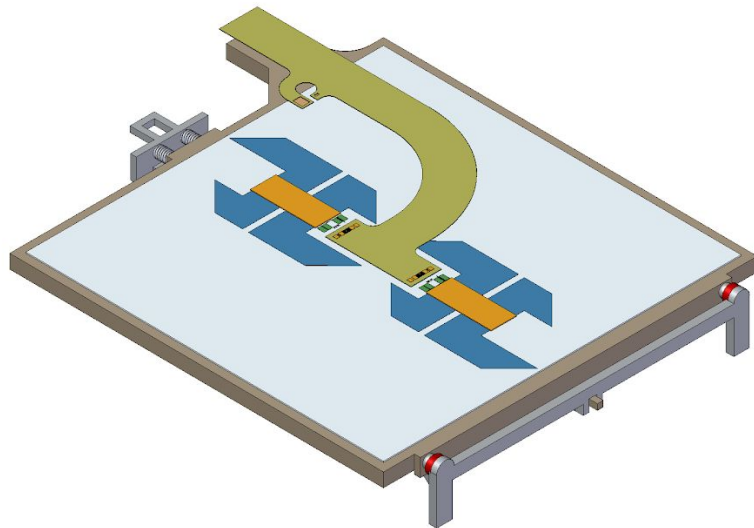
- SiD ECAL
  - “Imaging” calorimeter utilizing 30 layers of Si with 5 mm pixels.



Particle flow significantly improves jets resolution by reducing contribution of hadron calorimeter resolution.

Pandora simulation:  $\Delta E/E \sim 3\text{-}4\%$

# Baseline Sensor Module



- Hamamatsu high resistivity sensors with bump bonded SOC KPiX.
  - Sensors are expensive, lots of handling
  - KPiX tailored to ILC
- Perfect solution 25 years ago.
- It's time to develop Collider Detector MAP's

- Environment is benign.  $\sim 0$  hit rate, 100 kRads lifetime dose.
- Tracker: 67 m<sup>2</sup> sensor area
- EMCal: 1200 m<sup>2</sup> sensor area
- C3 (Cool Copper Collider) 120 Hz Train rate, 75 bunches spaced by 3.3 ns.
- ILC 5 Hx Train rate, 1312 bunches spaced by 554 ns.