Silicon-Tunsgten Calorimetry

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Silicon Sensors

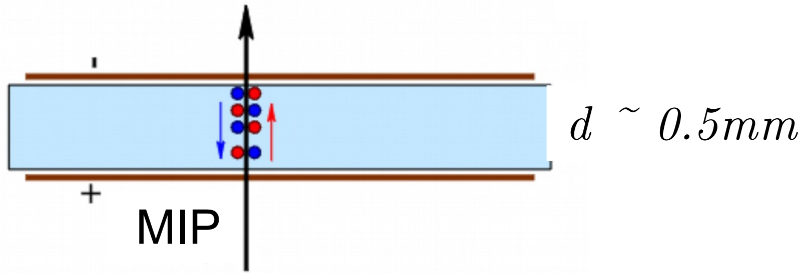
Semi-Conductor Sensors

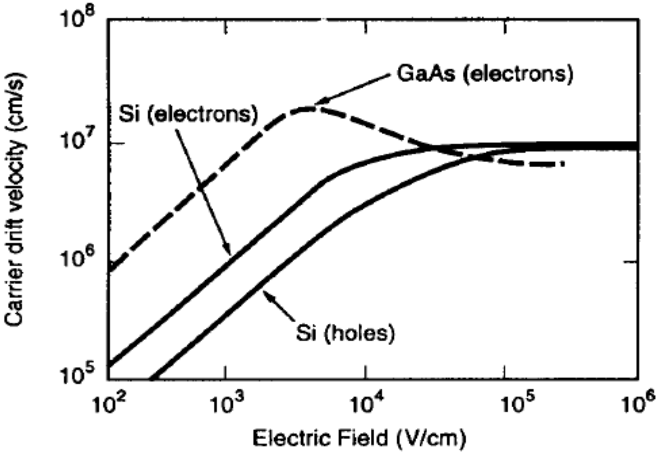
Many types

- Si, Ge, GaAs, ...
  (Diamond, Sapphire)

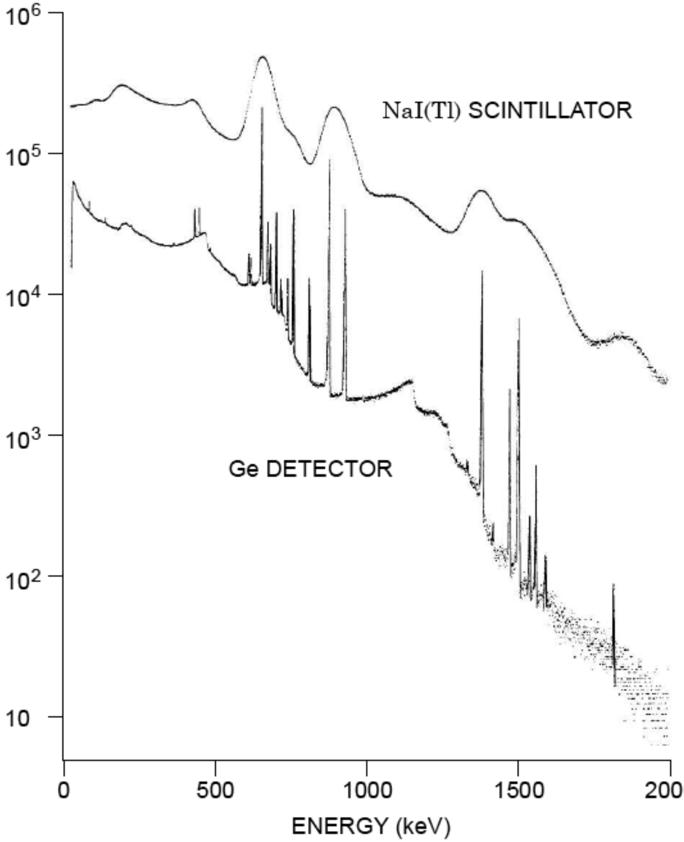
Principle

- Collection of ionisation charges by a high electric field
  - Drift $V_d = E\mu$, μ = mobility
  - A few 100's V





Carrier drift velocity as a function of electric field



J.Cl. Philippot, IEEE Trans. Nucl. Sci. **NS-17/3** (1970) 446

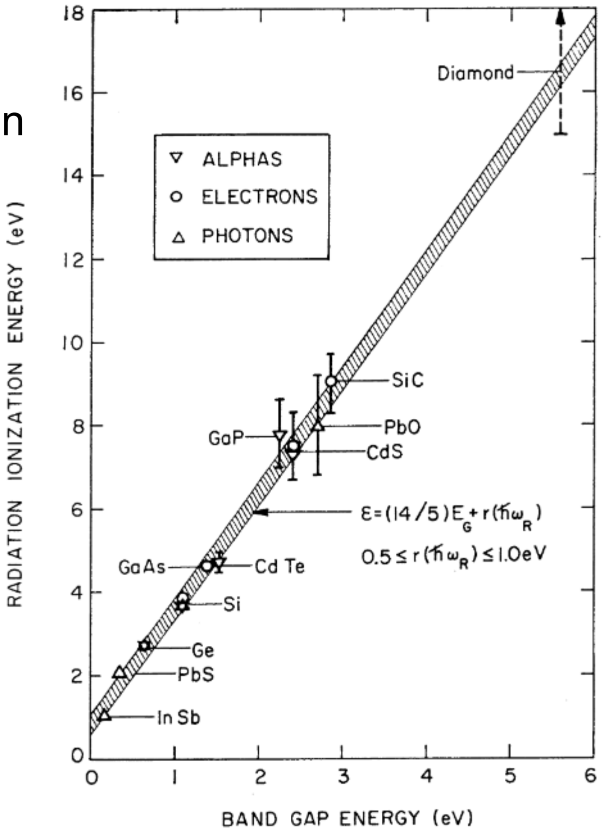
Carrier Statistics

Sensitivity

- Very high sensitivity:
  - Many information carrier:
    N = E/w mean energy to create 1 e-h pair $w_{\text{e-h}}$ ~ 3.6 eV → ~100 e-h/µm (Silicon)
- Fano Factor = 0.12 due to binomial statistics σ(E)/E = 2.35 ΔN/N = 2.35√Fw/E
  Resolution ×3 wrt raw Poissonian fluctuations
- Important for
  - Energy measurement
  - Signal-to-background ratio (trigger), data reduction, power dissipation

Ionization in gases ~30 eV
Ionization in semiconductors 1 – 5 eV
Scintillation ~10 – 1000 eV
Phonons meV
Breakup of Cooper Pairs meV

$E_{\text{ionisation}}$ ~ 3× E_{gap}
- E+p conservation
- phonons



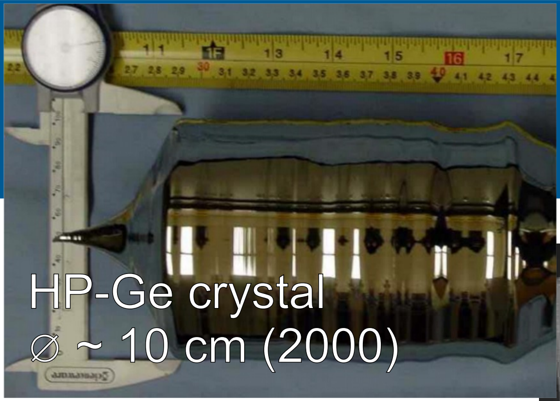
A. Klein, J. Applied Physics 39 (1968) 2029

Some candidates

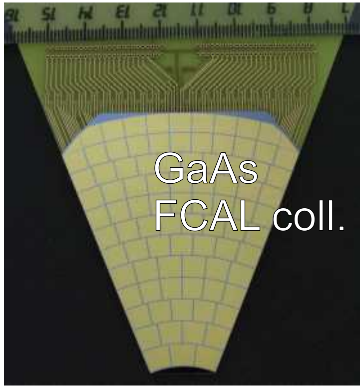
Material	Z	Bandgap [eV]	Mobility [cm^2/Vs]		Density g/cm^3
			electrons	holes	
Si	14	1.1	1350	480	2.3
Ge	32	0.7	3800	1800	5.3
Diamond	6	5.5	1800	1200	3.5
GaAs	31-33	1.5	8600	400	5.4
AlSb	13-51	1.6	200	700	4.3
GaSe	31-34	2.0	60	250	4.6
CdSe	48-34	1.7	50	50	
CdS	48-16	2.4	300	15	4.8
InP	49-15	1.4	4800	150	
ZnTe	30-52	2.3	350	110	
WSe_2	74-34	1.4	100	80	
BiI_3	83-53	1.7	680	20	
Bi_2S_3	83-16	1.3	1100	200	6.7
Cs_3Sb	55-51	1.6	500	10	
PbI_2	82-53	2.6	8	2	6.2
HgI_2	89-53	2.1	100	4	6.3
CdTe	48-52	1.5	1100	100	6.1
CdZnTe	48-30-52	1.5-2.4			

For layers

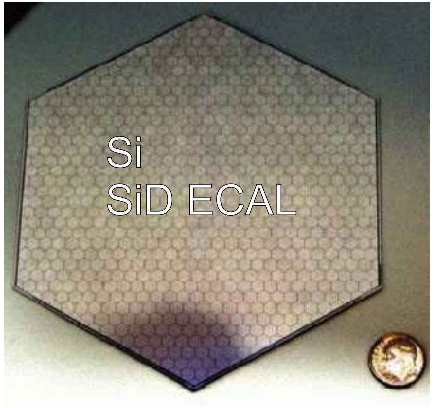
- Small dead Space


HP-Ge crystal
∅ ~ 10 cm (2000)


Si
FCAL coll.


GaAs
FCAL coll.


Si
CALICE/ILD ECAL


Si
SiD ECAL

Pros & Cons of Semi-Cond in calorimeters

High Signal (~×10 wrt gaseous det for same deposit)

High Charge collection (HV)

- Insensitive to magnetic field

Intrinsic Stability

Fast O(1–10ns)

Granularity O(1–100μm)

- High Precision

Low resistivity fine for Calo's (less expensive)

Large support from industry for Silicon

- Processes, R&D

Cost

- with high variations

Fragility

Radiation damages

- In some cases

No intrinsic amplification

- Low noise readout electronics needed

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Deposited Energy for electrons in Si

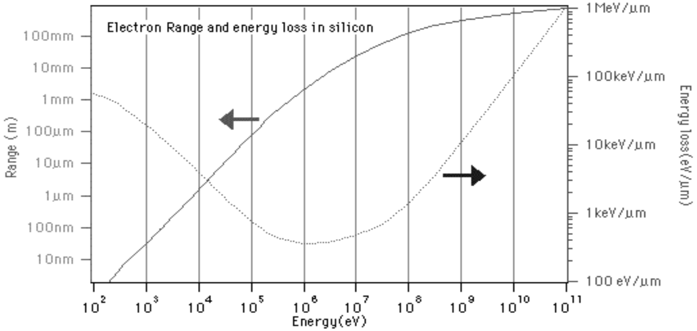
For minimum ionising particle (γ ~ 3.5)

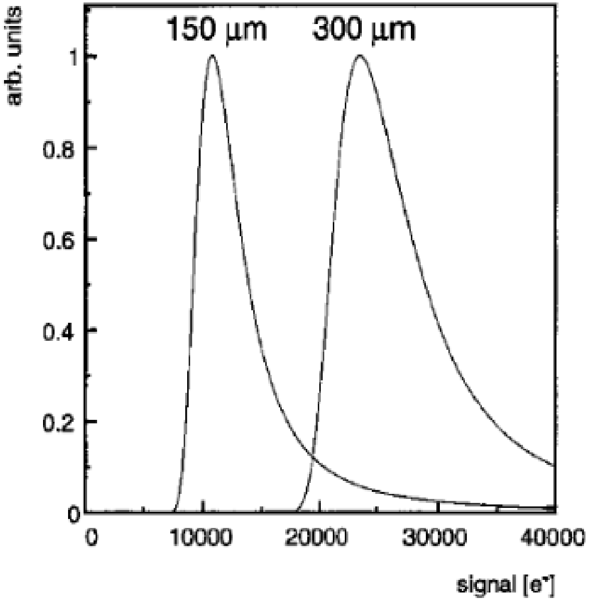
$$\mathrm{d}E/\mathrm{d}x = 39\ \mathrm{keV}/100\ \mathrm{\mu m}$$

$N_{\text{e-h}} = E_{\text{dep}}/3.6\mathrm{eV} =$ ~30,000 e-h pairs for 300 µm (100/µm, 80 in peak)

- Laudau stat N_{peak} ~ 24,000 e-h pairs ~ 4 fC; [free charges ~ 4.5×10^{8}]

  ⇒ depletion & amplification needed





Landau distribution (calculated) for a 300µm and a 150µm thick silicon detector.

Charge carriers

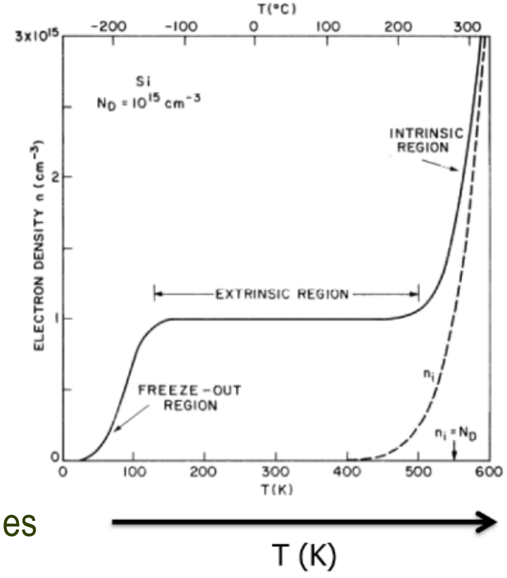
Intrinsic

- $n = p = n_i$
- $E_f = E_i = (E_c+E_v)/2 + kT \ln(N_v/N_c)$
  - Fermi level close to middle of Valence-Conduction gap.
  - kT = 0.026eV @ room temp.
  - $n_i \sim T^{3/2} \exp(-E_g / 2kT) \sim 1.5\ 10^{10}$ for Si (10^{-12} atoms ionised)
  - Current density → ρ = 230kΩ cm

$$\boxed{n_i = \sqrt{N_C N_V} \cdot \exp\left(-\frac{E_g}{2kT}\right) \propto T^{\frac{3}{2}} \cdot \exp\left(-\frac{E_g}{2kT}\right)}$$

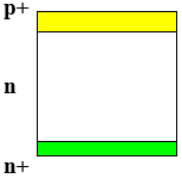
Doped

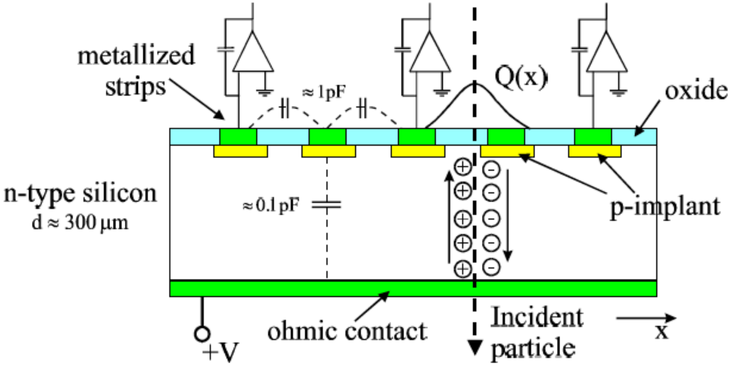
- n = P, As (tri-valent)
- p = B (pentavalent)
- Concentrations
  - $10^{12} - 10^{18}$ / cm³ >> n_i
- Effects:
  - changes free charges / holes
  - Diffusion length, resistivity
  - Mobility $v = \mu E$
  - Stabilize working temperature

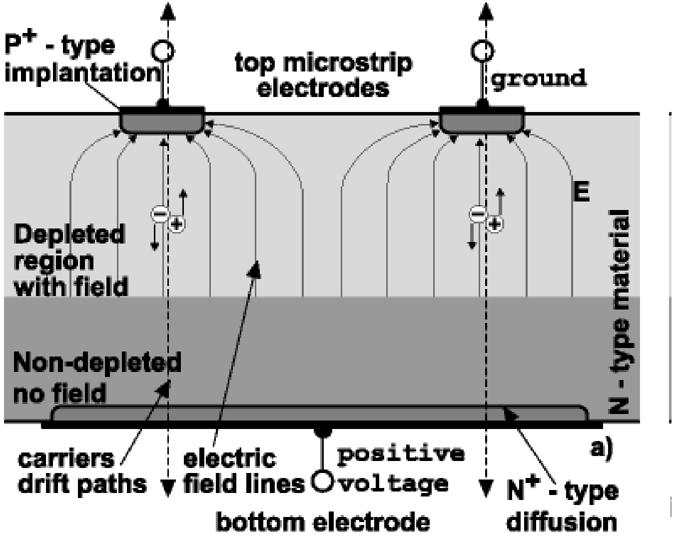


Source: S.M. Sze, *Semiconductor Devices*, J. Wiley & Sons, 1985

PIN diode (reversed)







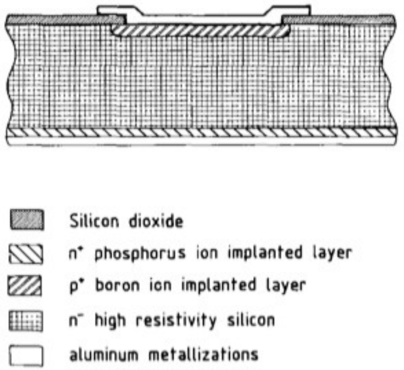


Fig. 12. Full p–i–n structure of a silicon detector.

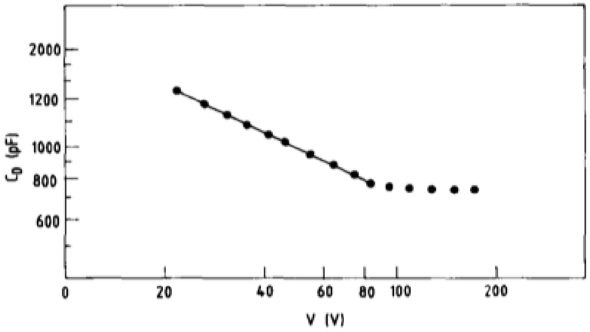


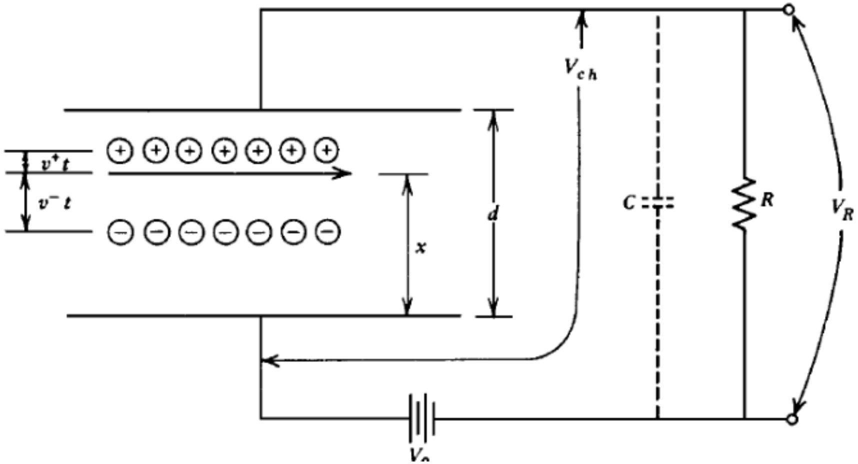
Fig. 14. Detector capacitance vs reverse bias voltage for a 28 cm^2 trapezoidal detector. The continuous line represents the best fit of eq. (4) to the data.

Depleted thickness

$$W \approx \left[\frac{2\epsilon_r\epsilon_0}{q} \left(\frac{N_A + N_D}{N_A N_D} \right) (V_{bi} - V) \right]^{\frac{1}{2}}$$

Nuclear Instruments and Methods in Physics Research A263 (1988) 84-93

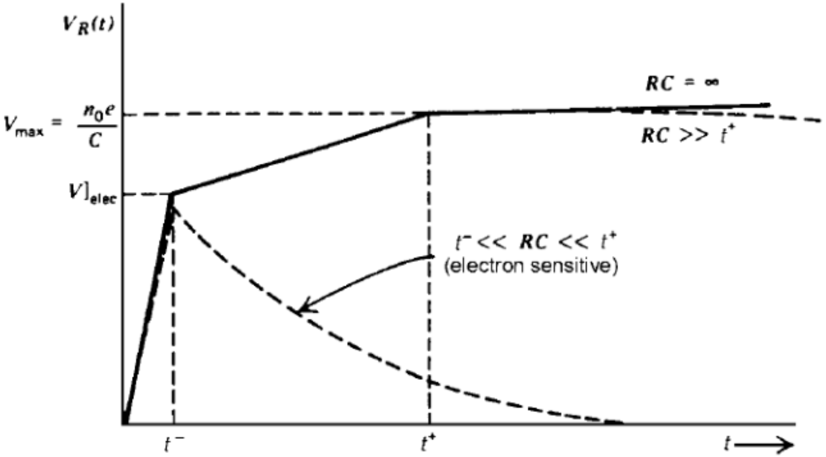
Signal shape



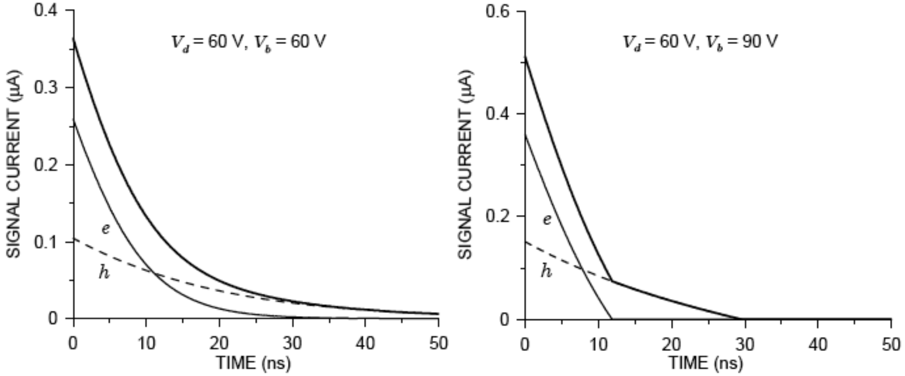
Current induced by charge movement

$$U = \frac{1}{2}CV^2$$

$$i(x) = \frac{q}{V_0}E(x)v(x),$$



300 µm thick silicon detector



Noise

Expressed in ENC (Equivalent Noise Charge)

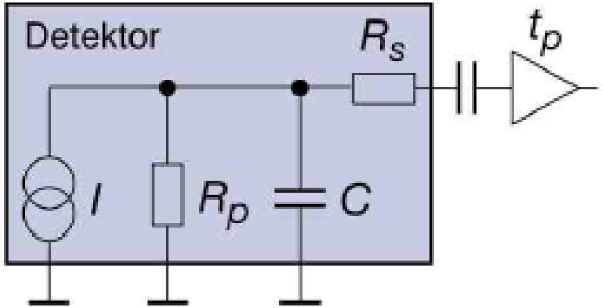
- Typically a 10–1000 e⁻
  - Not always Gaussian

Many inputs:

- Irradiation
- Readout speed
- Leakage Current: $ENC_I \propto \sqrt{I}$
- Thermal Noise: $ENC_I \propto \sqrt{(k_B T/R)}$
- Capacitive noise: $ENC_C \propto C_d$

Noises add quadratically

$$ENC = \sqrt{ENC_C^2 + ENC_I^2 + ENC_{Rp}^2 + ENC_{Rs}^2}$$



Alternate circuit diagram of a silicon detector.

A Brief History of Silicon-Tungsten Calorimeters

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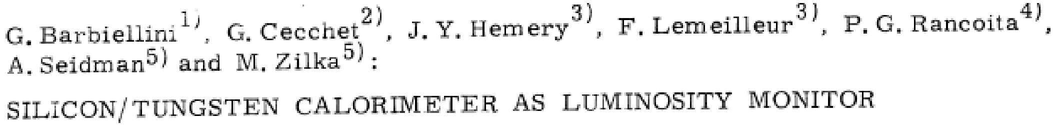
Beam & luminosity Monitors

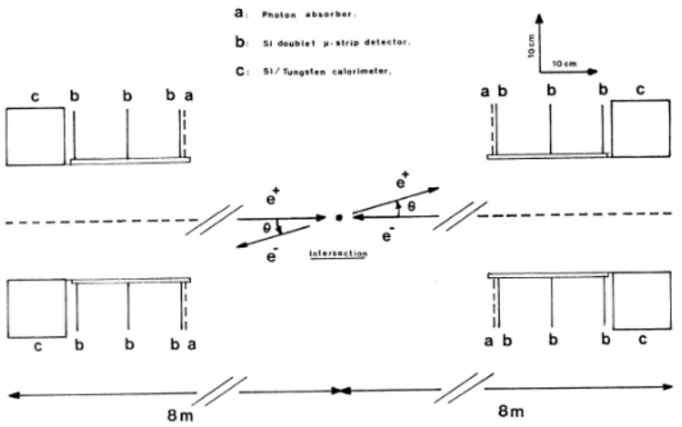
First applications of Silicon Sampling Calorimeters (to my knowledge): 1984

- Small EM calorimeters around beam tubes to detect Bhabha electrons $e^+e^- \rightarrow e^+e^-$
  - Very precise positioning
  - Fast return for beam positioning & lumi tuning
  - Perfect for 1st applications
- SICAPO (Si CAlorimeter & POlarimeter) collaboration
  - Prototypes os Si/W & Si/U calorimeters (1986)
  - In view of LEP



G. Barbiellini1), G. Cecchet2), J. Y. Hemery3), F. Lemeilleur3), P. G. Rancoita4), A. Seidman5) and M. Zilka5):

SILICON/TUNGSTEN CALORIMETER AS LUMINOSITY MONITOR



Beam & Lumi: LEP experiments

PICASSO collaboration

- ⇒ 4 detector for each LEP experiment
  - Pad = 5×5 cm², 300µm at $6X_0 + n \times 2X_0$

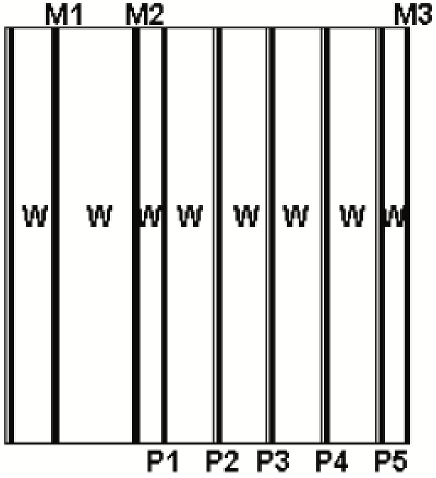
OPAL–Si/W,

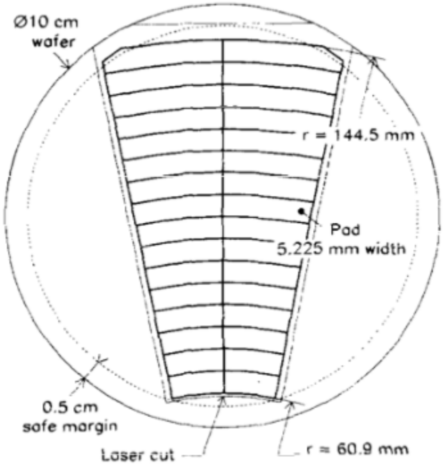
DELPHI–VSAT

- Square design

ALEPH–SiCAL,

- 300µm (Canberra)
- Round around beam pipe:





M1,2,3 = Silicon strip detectors
P1–5 = Si Pad det

Beam & Lumi : SLD

SLD detector at SLAC Linear Collide (SLC) : 1991

- 300μm Si + 90% W alloy, 17.5X_0
- LMSAT : 23 layers, 300μm & MASC: 10 layers, 300μm
  - Sampling 0.86 X_0 & 1.74 X_0
  - 2 longitudinal sections × ~ 1×1 cm² cells
- Readout by ribbon cables
- $\sigma(E)/E = 20\%/\sqrt{E}$

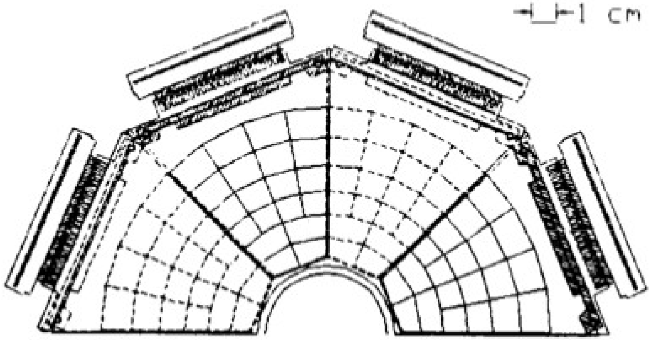
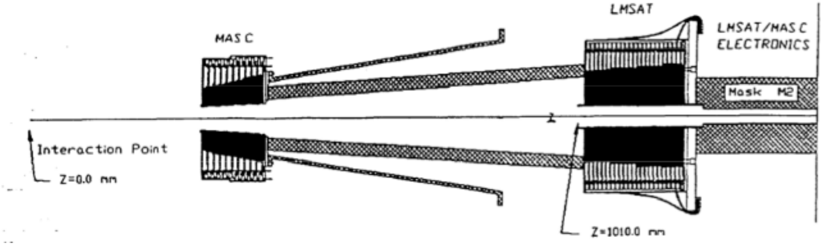


Figure 2. Front face of one LMSAT module as seen from the IP. Detectors shown with dashed lines have their ground planes facing away from the IP.



FCAL Collaboration: LumiCal & BeamCAL

LumiCal :

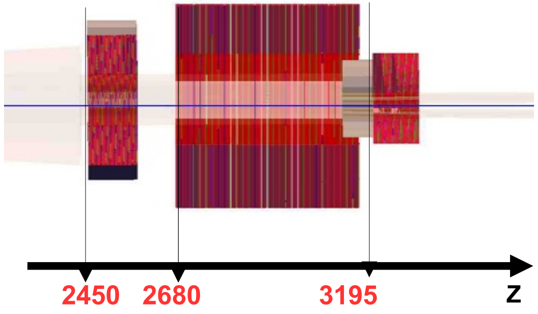
- Precise integrated luminosity measurements (Bhabha events)
- Extend calorimetric coverage to small polar angles. Important for physics analysis

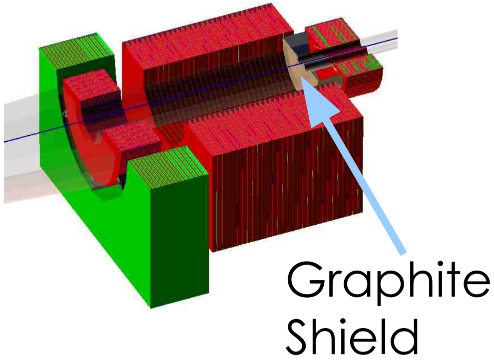
LHCal :

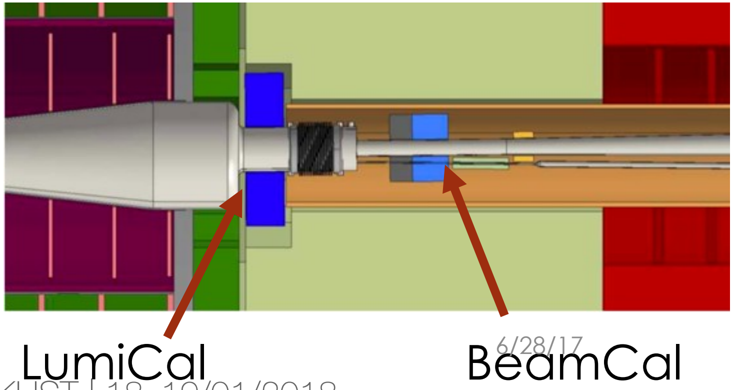
- Extend the hadronic calorimeter coverage
- 29 layers of 16mm thickness. Absorber : tungsten or iron

BeamCal :

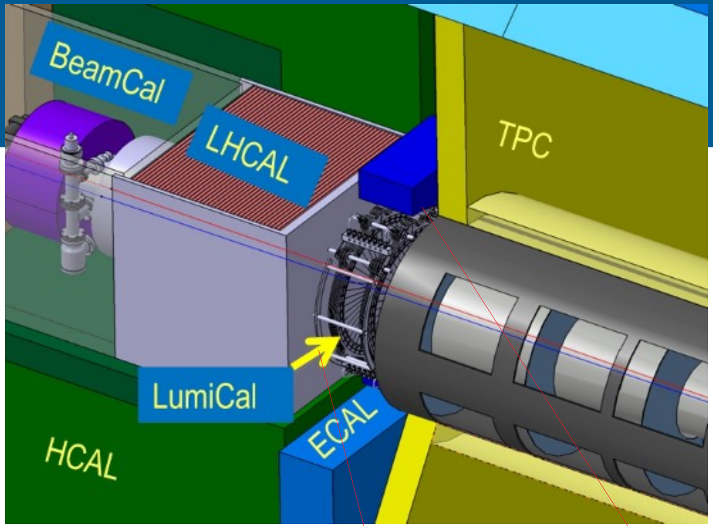
- Measure instant Luminosity. Feedback for beamtuning
  - providing supplementary beam diagnostics information extracted from the pattern of incoherent-pair energy depositions
- tagging of high energy electrons to suppress backgrounds to potential BSM process
  - shielding of the accelerator components from the beam-induced background
- Sampling calorimeter based on tungsten plates
  - 30 layers for ILC, 40 layers for CLIC
- Due to large dose, rad hard sensors (GaAs, Diamond, Sapphire)







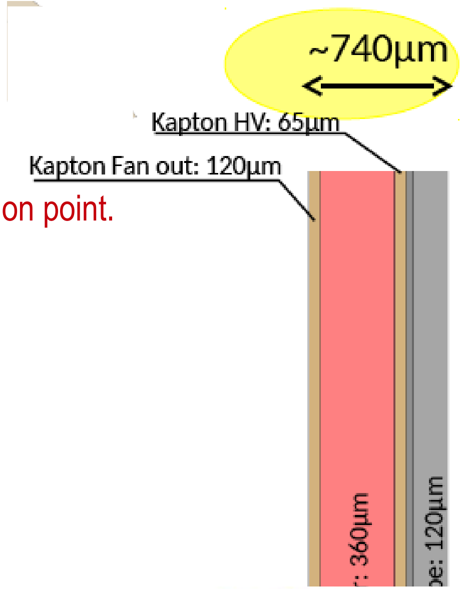
FCAL collaboration: LumiCal

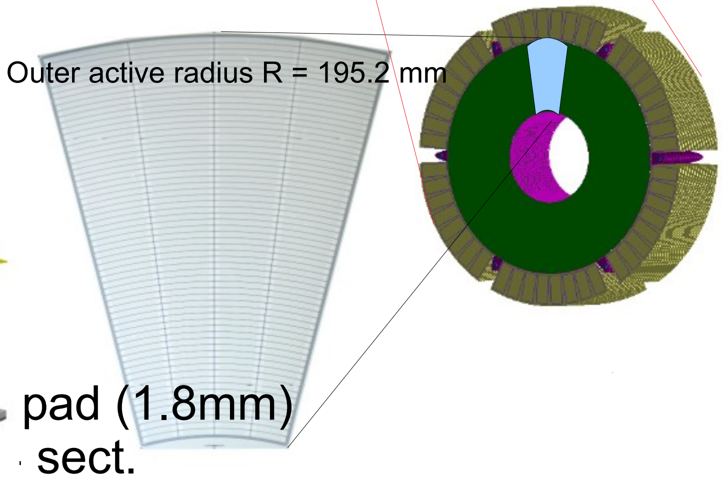


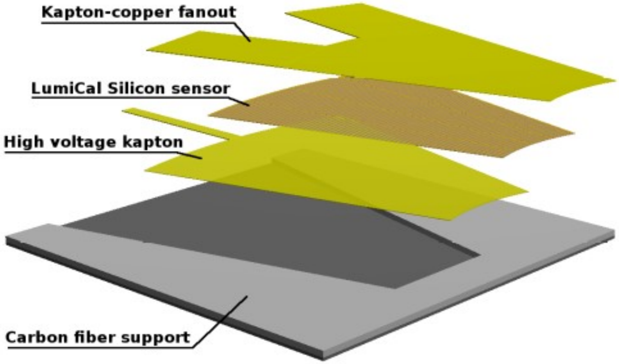
Bhabha measurement

Sampling ECAL

- symmetrically on both sides at ~2.5m from the interaction point.
- 30 layers of 3.5 mm thick tungsten plates ($1X_0$)
- 320 µm Si (p+ implants in n-type bulk)
  - DC coupling to readout
  - through Kapton foils glued on wafer
- Ultra-thin design: R_M=12mm expected
  - Bhabha + γγ background







Digital-ECAL: ALICE-FOCAL

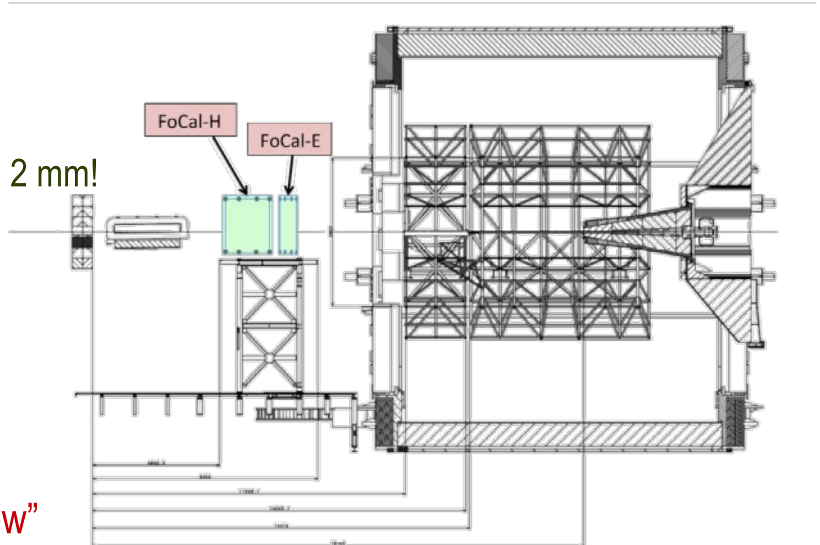
Mat from T. Peitzmann, Gert-Jan Nooren

Use photons to measure PDF saturation in proton/nucleus

- High π_0's background
  - two-photon separation from π_0 decay (p_T = 10 GeV/c, y = 4.5, α = 0.5) is d = 2 mm!

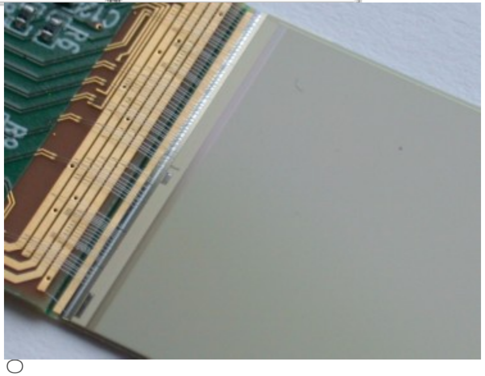
Ultra-granular ECAL for γ and π_0 measurement

- Ideally: at $z \approx$ 7m (outside solenoid magnet), $3.3 < \eta < 5.3$
  - space to add hadronic calorimeter
  - under internal discussion, possible installation in LS3
- advantage in ALICE: forward region not instrumented, "unobstructed view"

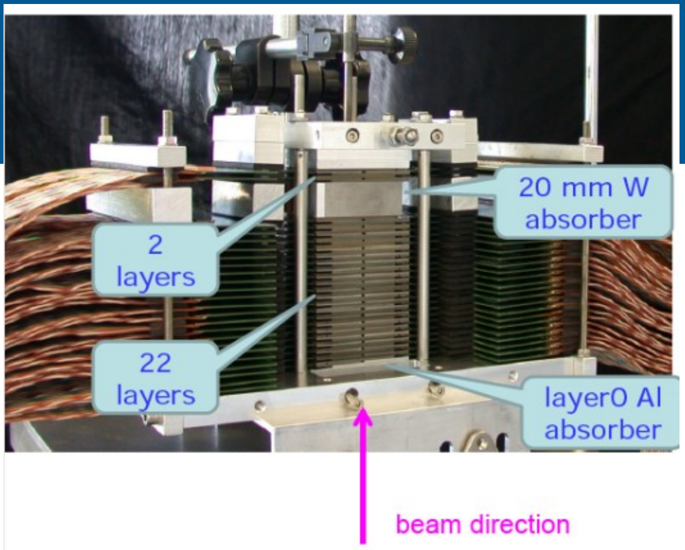


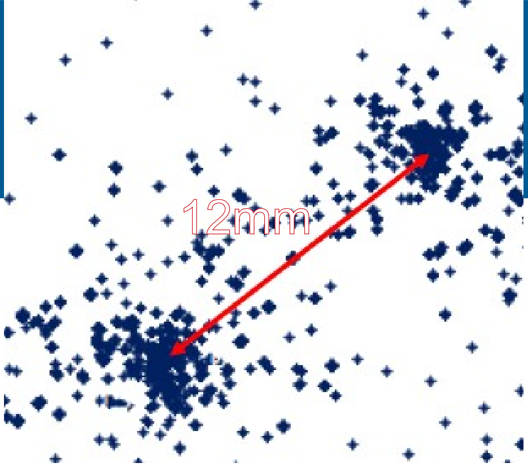
MAPs (Monolithic Active Pixel Sensor) in calorimeter ⇒ test of concept in prototype

- PHASE2/MIMOSA23 sensor (VTX)
  - 30 μm pixels: max. occupancy 1111/mm²
  - 642 μs integration time ⇒ beam tests
  - 15 μm active layer ⇒ very small sampling fraction



DECAL: FOCAL





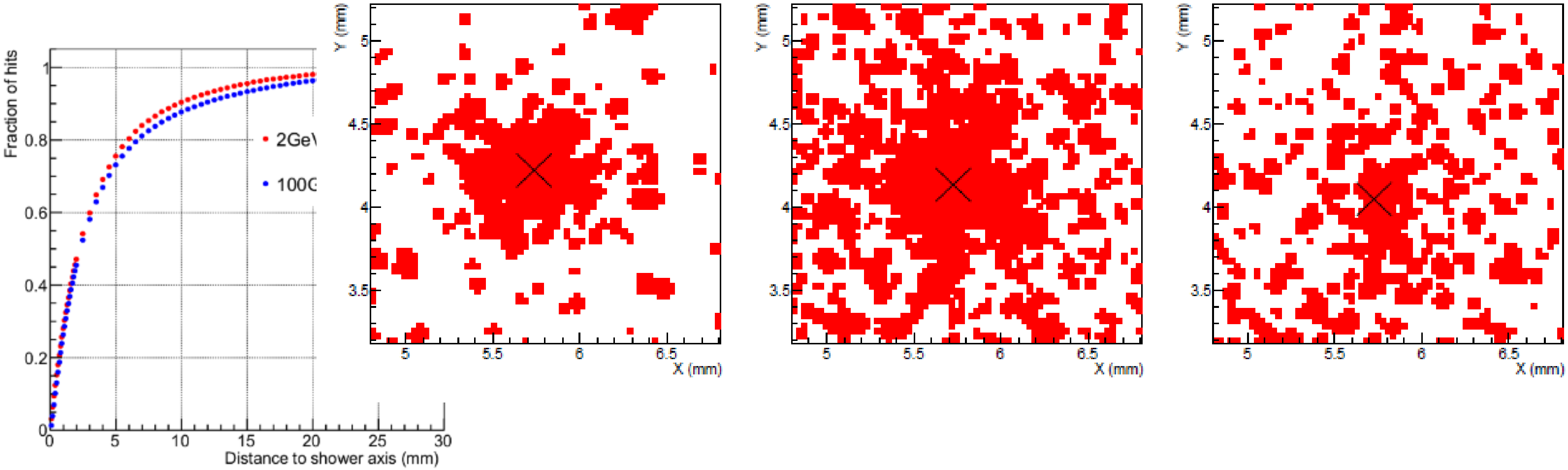
Prototype:

- 24 layers × 4 sensors
  - 39 M pixels =, full readout
- 28 X_0

Digital calorimetry

- E ∝ cluster size
  - Mips † ⇒ Symmetri
- Saturation effects

$R_M = 11\text{mm}$



Balloons & Space experiments

Possibility to work in vaccum + Large range of working temperature

Experiments γ-astronomy by photon to pair conversion in W + tracking in Si (Strips)

- AGILE: launch 2007
  - 13 trays. 10 first trays with W layers and 24 silicon microstrip plane layer - of 9.5 × 9.5 cm 2 area, 121 μm pitch and 421 μm
  - X-ray imager (for imaging in the range 18-60 keV) is a coded-mask system made of a silicon detector plane and a thin tungsten mask.
- **Fermi-LAT (next slide)**

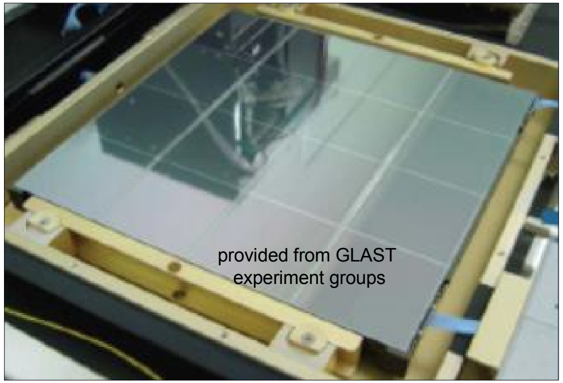
Cosmic Ray studies

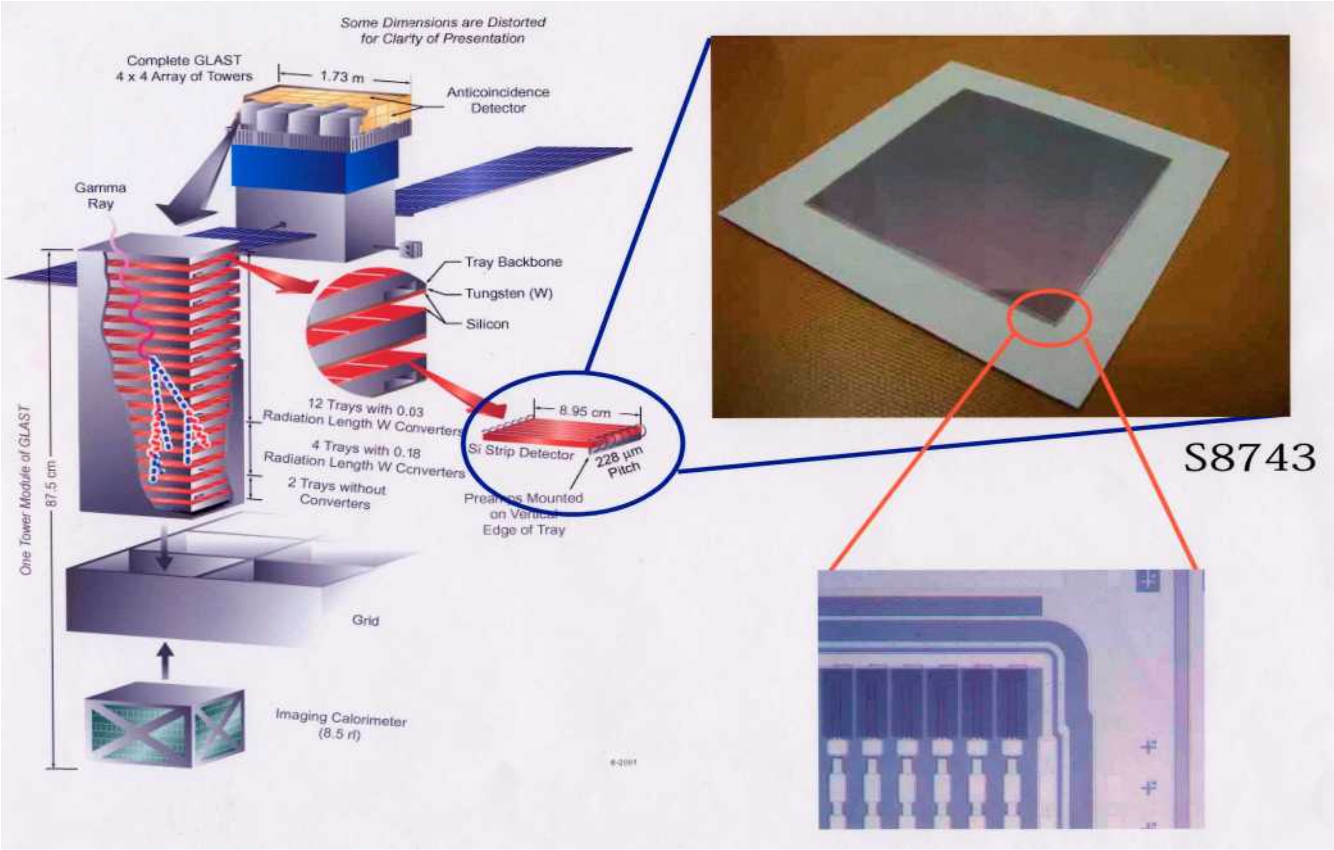
- NINA (New Instrument for Nuclear Analysis): 1997
  - Space telescope: 16 pairs of silicon sensitive planes x-y readout planes.
    - Sensors: 60 × 60 mm² × 380 μm and is divided into 16 strips of 3.6 mm pitch.
  - Stopping by N_2 gas at 1 atm.
- Nucleon: ???
- **PAMELA (2007):**

Fermi (GLAST) – almost a calorimeter

Pair conversion telescope

- Launch in 2008
- Si/W : 410 µm × 89.5×89.5 mm²
- 16 towers ⇒ 37×37 cm² active area
- 70 m² of strip silicon (228 µm pitch), 9216 Wafers, 880k channels


provided from GLAST experiment groups



PAMELA

Satellite

- Launched June 2006
- Cosmics rays (e±, p, pbar, light *N*), DM
  - 50 meV – 100's GeV

SiW-calorimeter

- 22 Tungsten plates of 0.26 cm (16.3 X_0 and 0.6 λ)
  - 0,74X_0 per plane
- 44 silicon layers, of 3×3 Wafers
  - 80 × 80 × 0.380 mm^3
  - Interleaved x and y strips
  - and segmented into 32 strips, (96 strips/plane)

+ tails catcher (Scint.) + Si Tracker (perm. 0.43T)

Si(W)-ECAL in Large Experiments

no realisation (yet!) but many projects nearing realisation

SSC proposal (~1984), LHC : no

e^+e^- colliders: ILC ⇒ CLIC, CEPC, FCC-ee: 2028-30 ?

- **SiD full SiW-ECAL**
  - Design & prototype
- **ILD: full SiW-ECAL**
  - ILC , CEPC, CLIC options
  - CALICE collaboration
    - Physical prototype
    - Technological prototype

Challenges :
- large numbers of ch.
- integration
- cooling
- uniformity

Heavy Ion experiments (only as projects)

- PHENIX, AFTER, ALICE
  - Tagging of many photons

See presentation from Huaqiao Zhang

CMS-HGCAL prototype: 2026 ?

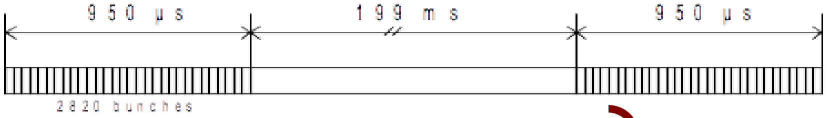
- Large area PAD detectors
- Very Precise Timing → 5D calorimetry

(ATLAS-HGTD)

Current Studies

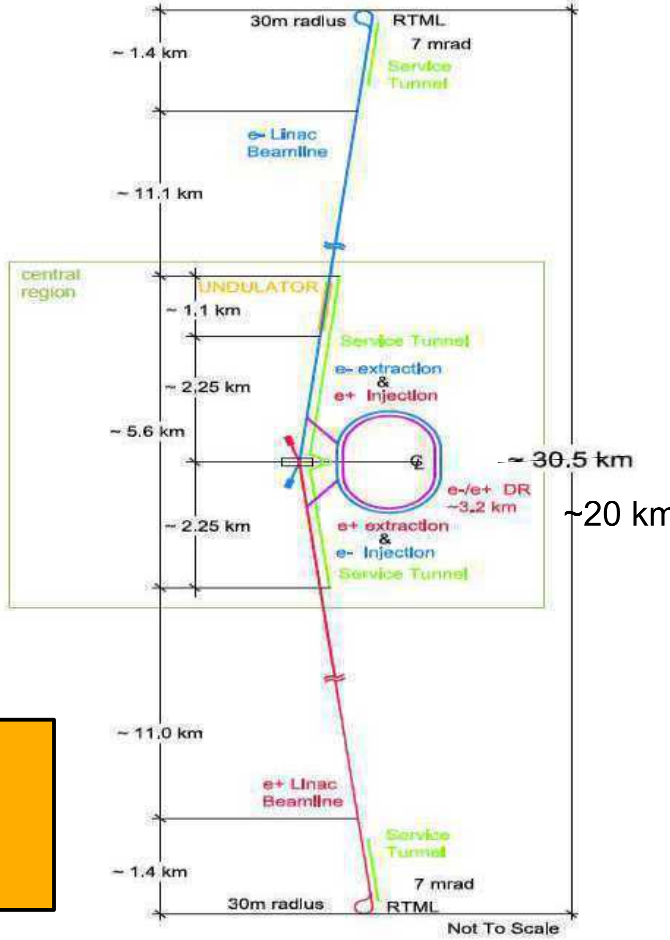
ILC parameters

Max. Center-of-mass energy	**250**–500 (90)	GeV
Peak Luminosity	0,8–3x10^{34}	1/cm^{2}s
Beam Current	5.8	mA
Repetition rate	5 **(10)**	Hz
Average accelerating gradient	31.5	MV/m
Beam pulse length	0.95	ms
Total Site Length	31	km
Total AC Power Consumption	120-300	MW



- Time between collisions : 350–700 ns
- Trains of 1300–2700 Bunches
- Low detector occupancy
- Low bgd : $e^+e^- \to qq \sim 0.1$ / BC
  $\to \gamma\gamma \to X \sim 200$ / BX

- High B field
- Trigger-less
- Power Pulsing (≤1%)
- Differed readout



Constrains on detectors:

Basis: sep of H ⟶ WW/ZZ ⟶ 4j

- σ_Z/M_Z ~= σ_W/M_W ~= 2.7% ⊕ $2.75\sigma_{sep}$

⇒ σ_E/E (jets) < 3.8%

- Sign ~ S/√B ~ $(\text{resol})^{-1/2}$
  60%/√E ⟶ 30%/√E ⇔ +~40% L

Large TPC

- Precision and low X_0 budget
- Pattern recognition

High precision on Si trackers

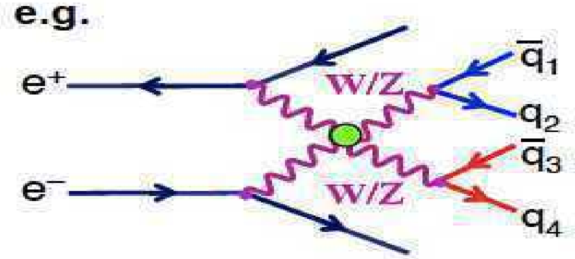
- Tagging of beauty and charm

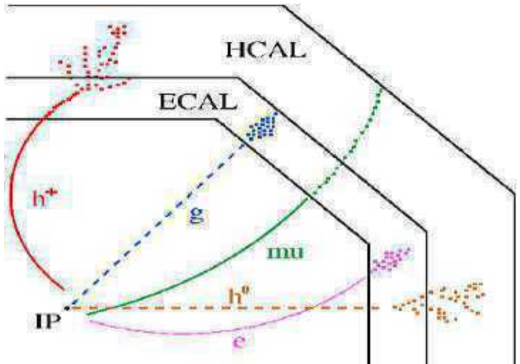
Large acceptance

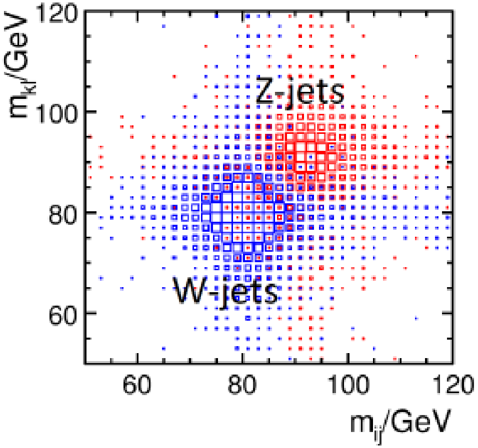
Fwd Calorimetry:

- lumi, veto, beam monitoring

Imaging Calorimetry







Photons in jets

Tau physics (γ vs π_0)

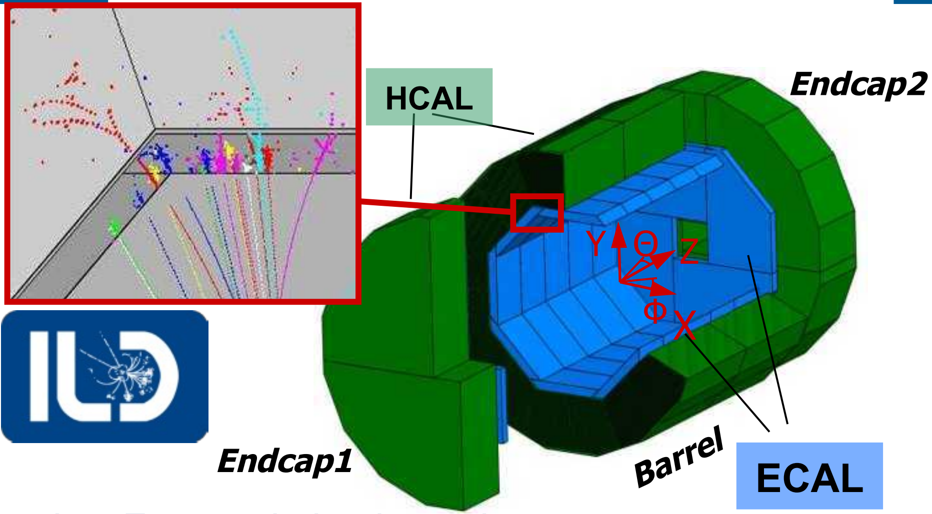
1/3 of IA in ECAL

Particle Flow Algorithms :

- Jets = 65% charged Tracks + 25% γ ECAL + 10% h^0 CALO's
- TPC $\delta p/p \sim 5\cdot10^{-5}$; VTX $\sigma_{x,y,z} \sim 10$ µm

H. Videau and J. C. Brient, “Calorimetry optimised for jets,” in Proc. 10th International Conference on Calorimetry in High Energy Physics (CALOR 2002), Pasadena, California. March, 2002.

An Ultra-Granular SiW-ECAL for experiments



Particle Flow optimised calorimetry

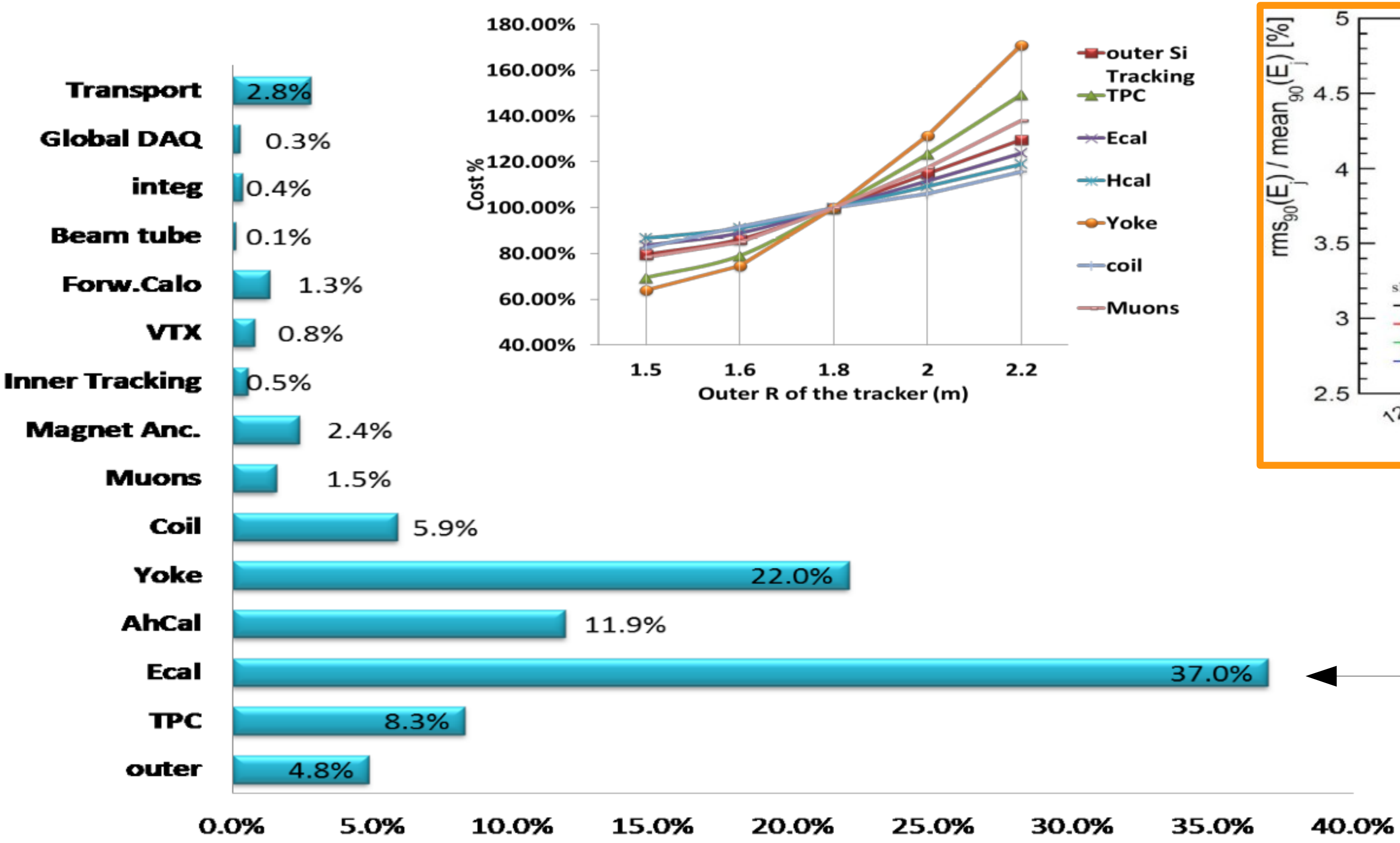
- Standard requirements
  - Hermeticity, Resolution, Uniformity & Stability (*E*, *(θ,φ)*, *t*)
- PFlow requirements:
  - Extremely high granularity
  - Compacity (density)

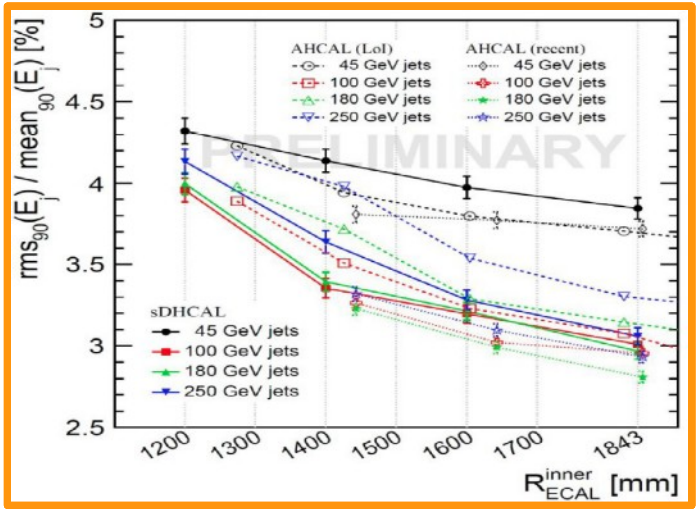
SiW+CFRC baseline choice for future Lepton Colliders:

- Tungsten as absorber material
  - X_0 = 3.5 mm, R_M = 9 mm, λ_I = 96 mm
  - **Narrow showers**
  - **Assures compact design**
- Silicon as active material
  - **Support compact design**
  - **Allows for ~any pixelisation**
  - **Robust technology**
  - **Excellent signal/noise ratio: ≥10**
  - **Intrinsic stability (vs environment, aging)**
  - **Albeit expensive…**
- Tungsten–Carbon alveolar structure
  - **Minimal structural dead-spaces**
  - **Scalability**

Cost Structure of ILD

For ILD see presentation from Imad



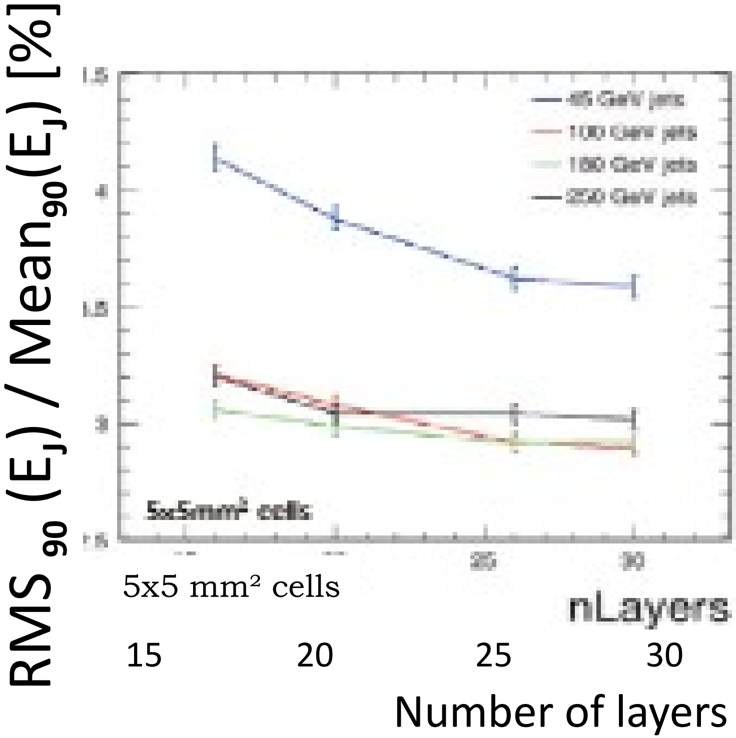


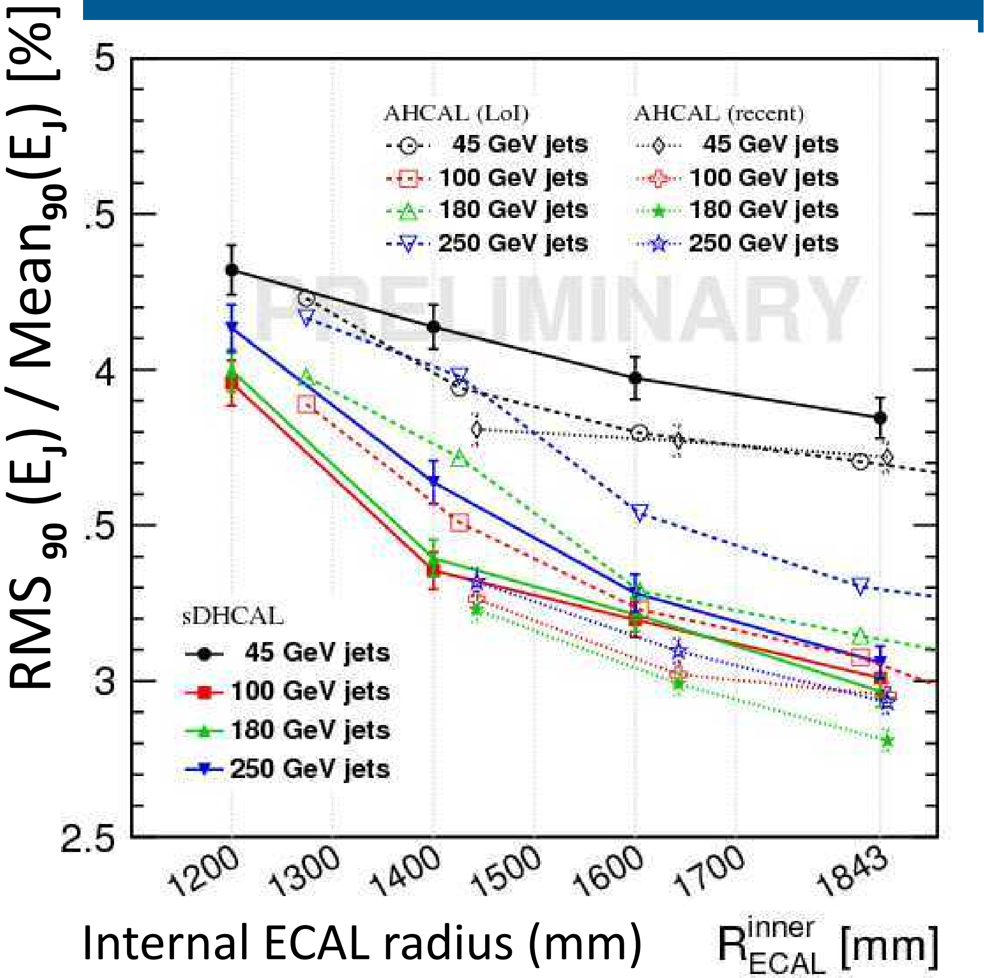
◀

Full Silicon
option

Parameter optimisations

A new feeling , **AFTER** the staging proposal





Vincent.Boudry@in2p3.fr

Reduced number of Layers

Going from 30 to 22 layers

- Reduction of cost; (small) reduction of R_M ; increase of Energy resolution
  - “better separation at the expanse of the intrinsic resolution”

Increasing the Si thickness to 725µm, if really feasible (next slide)

Energy resolution σ(E)/E:

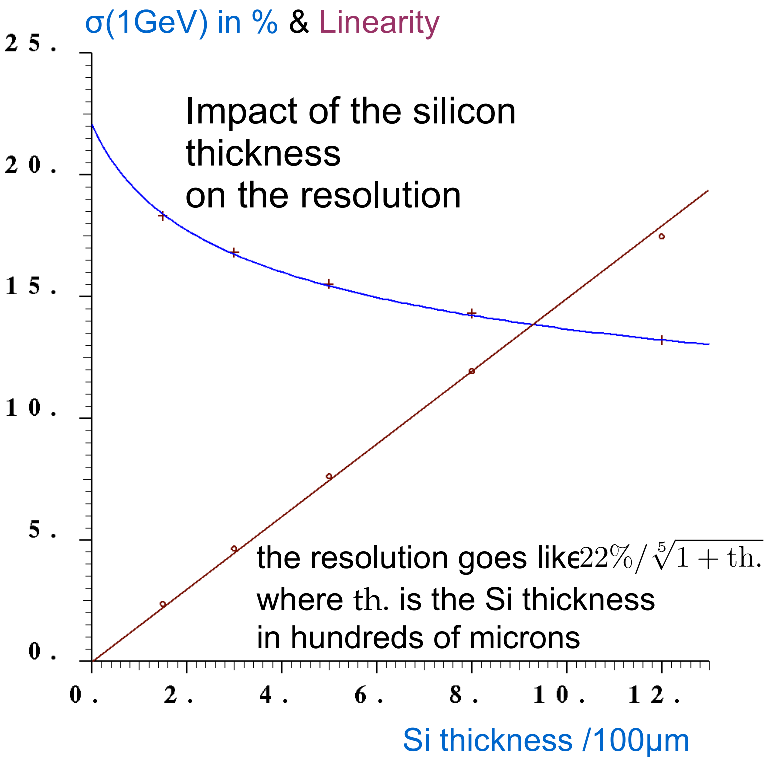
- for 22 layers w.r.t. 30: +16.8%
- with 725µm w.r.t 500µm : –6.1%

ECal thickness = 190.1 mm (close to 185 mm of DBD).

- 22 layers = 14 layers with 2.8mm thickness
  + 8 layers with 5.6mm shared between structure and slabs.

Study needed on separation, resolution and efficiency performances at low energy.

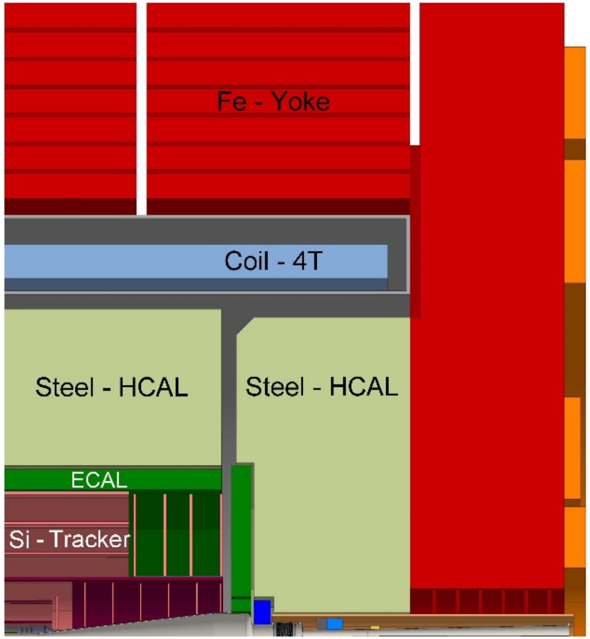
- JER : $\sigma(E_J)/E_J$ +10% for 20 layers (500 µm).



Impact of the silicon thickness on the resolution

the resolution goes like $22\%/\sqrt[5]{1+\text{th.}}$
where th. is the Si thickness
in hundreds of microns

CLIC calorimeters



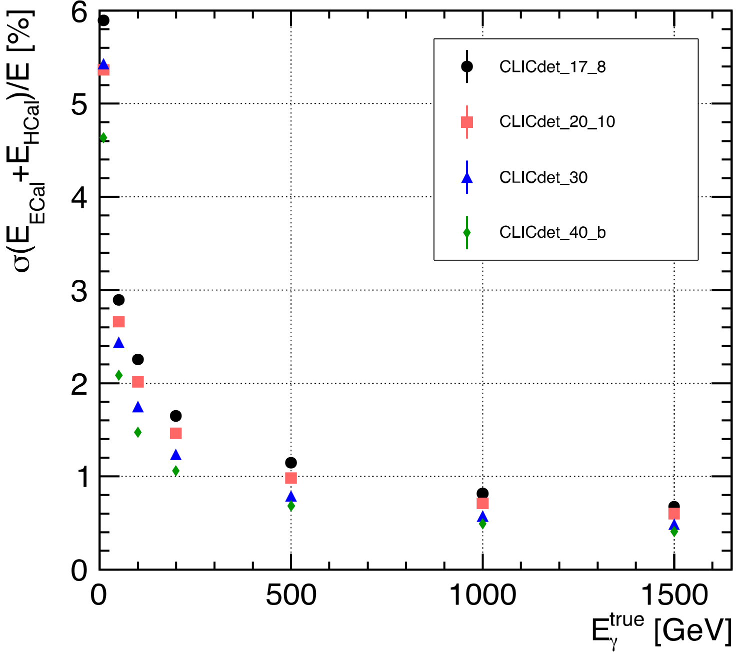
ECAL Optimization:

40 layers uniform fine sampling silicon-tungsten plates

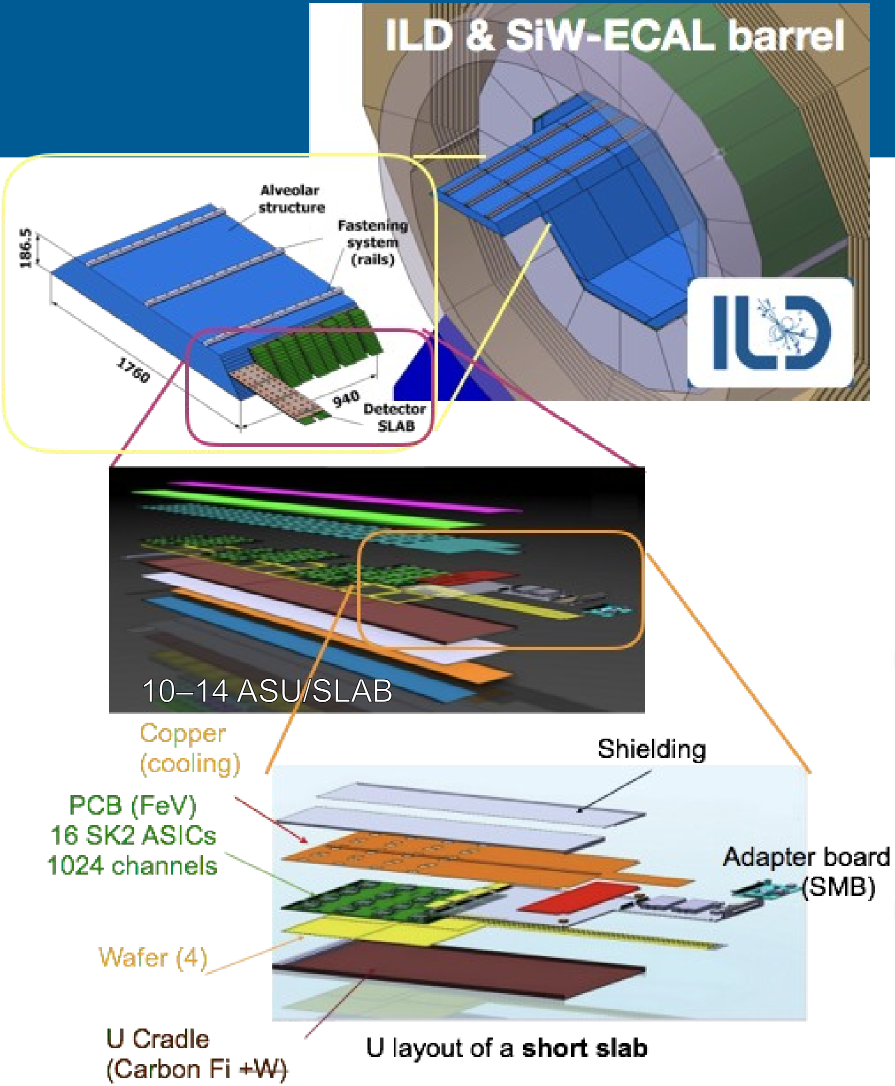
(1.9 mm W, 5x5 mm^2 silicon cells)

22 X_0 (1 λ_i) total thickness

Energy Resolution for central high energy photons



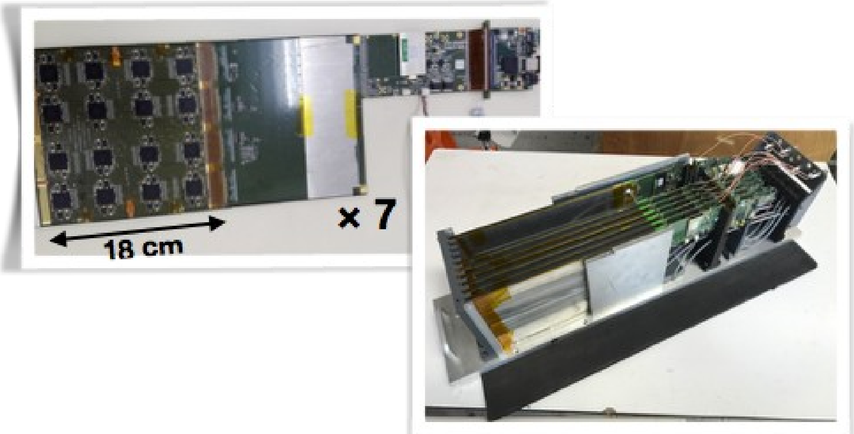
Large Scale Building



ILD SiW-ECAL	Prototyped*
~10,000 SLAB's	~0.1
100,000 ASU's	~20
400,000 Wafers	~350
1,600,000 ASIC's	~1000
100,000,000 channels	~20000

* incl. Physical Prototype

+ Mechanics , Cooling, Integration, ...



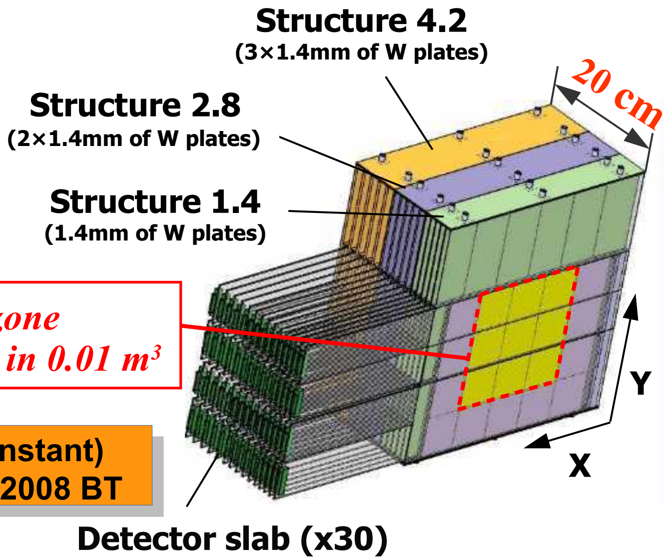
CALICE SiW ECAL: Physics & Technological prototypes

Physics prototype: 2005–2011

PFA proof of concept with comparison to MC (PandoraPFA etc.)

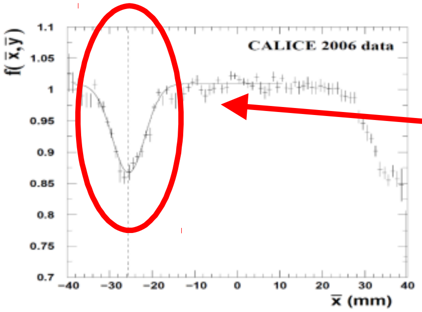
Electronics outside

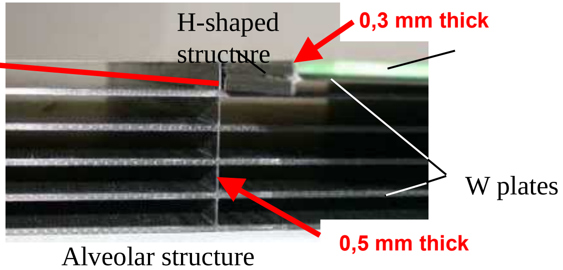
- 1 × 1 cm² pixels



Active zone
~10000 pixels in 0.01 m³

16.5%(stochastic) 1–2% (constant) with 1–45 GeV e^-/e^+ at 2006/2008 BT





Technological prototype

Embedded electronics

- SKIROC2 analog/digital ASICs
  - auto-triggered, zero suppr., PP
- pixels 5×5mm²

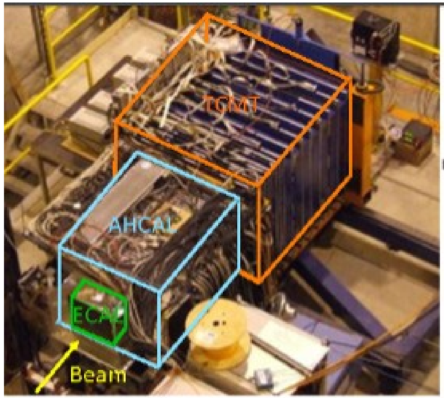
Performances: photon reconstruction confusion studies

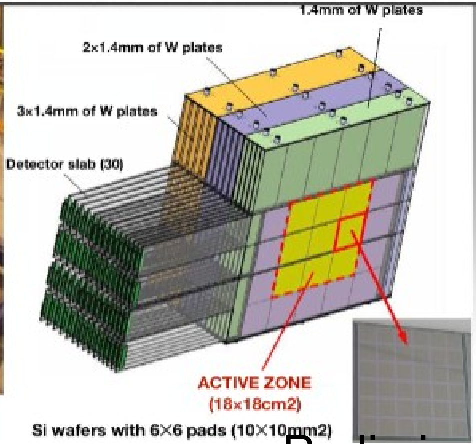
“raw performances”

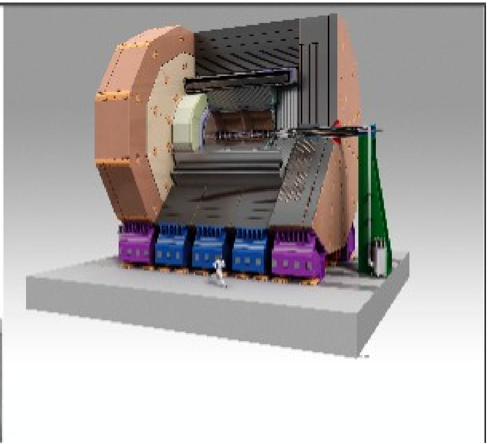
- Efficiency vs separation distance
- EM vs EM (e / γ)
- EM vs π

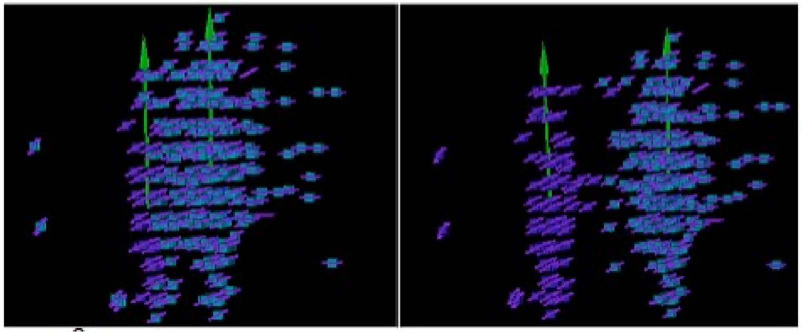
Using Particle Flow Algorithms

- PandoraPFA, Arbor, GARLIC

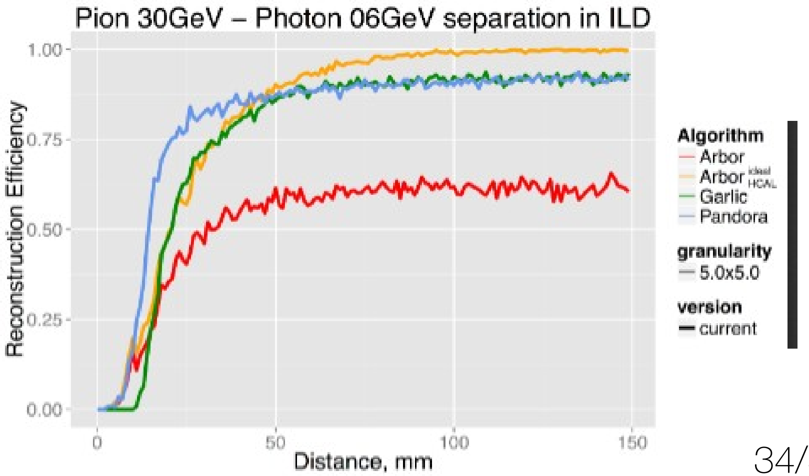




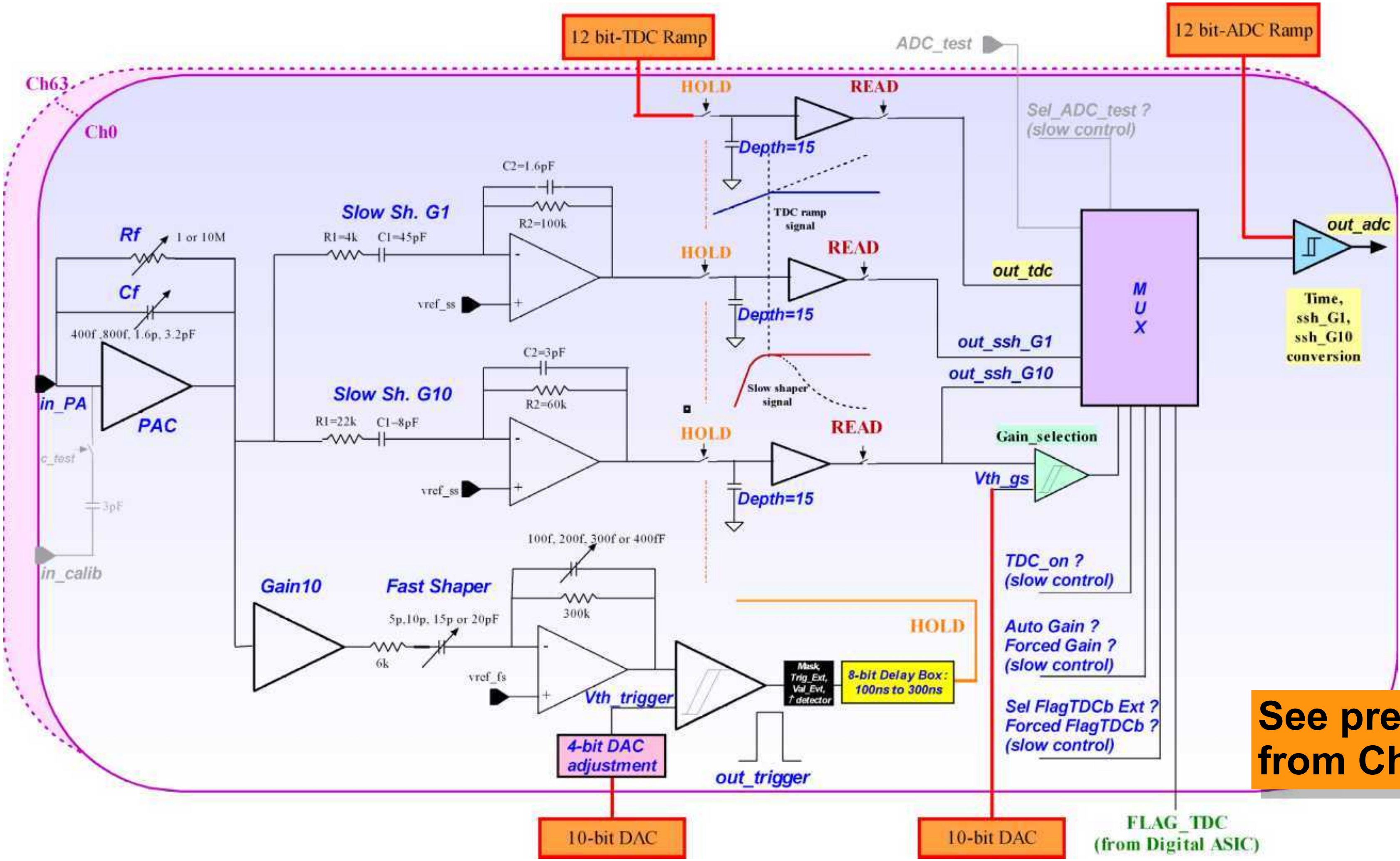




Preliminary



SKIROC2 / 2A Analogue core



Similar to
SiD Kpix

- 64 channels
- Preamp
  + 2 (auto)Gains
  + TDC
- Auto-triggered
- 15 memory
- Low consumption
- Power-pulsed

- Not final chip
  (full 0-suppr.)
- Not suitable
  for CEPC

See presentation from Ch. De la Taille

callier@omega.in2p3.fr

ILD Building blocks: SLAB's & ASU's

R&D for "mass production" and QA

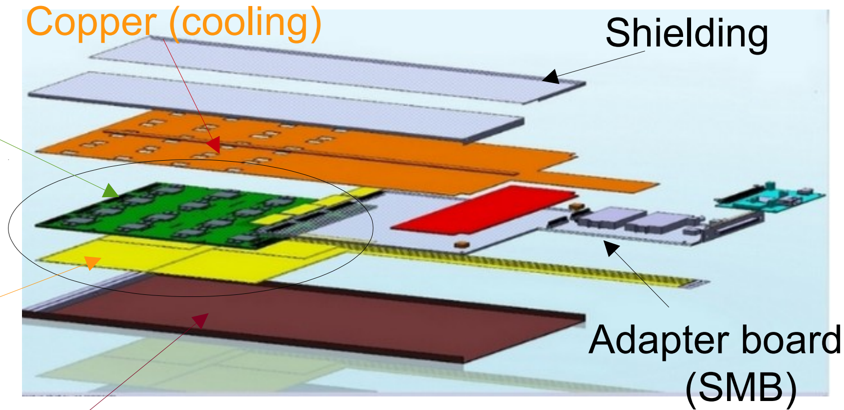
- Quality tests & preparation of large production
- Modularity → ASU & SLABs
- Choice of square wafers
    - (≠ from hex: SiD, CMS HGCAL)

Numbers (R_{ECAL} = 1,8 m, $|Z_{Endcaps}|$=2,35m)
(likely to be reduced by 30–40%)

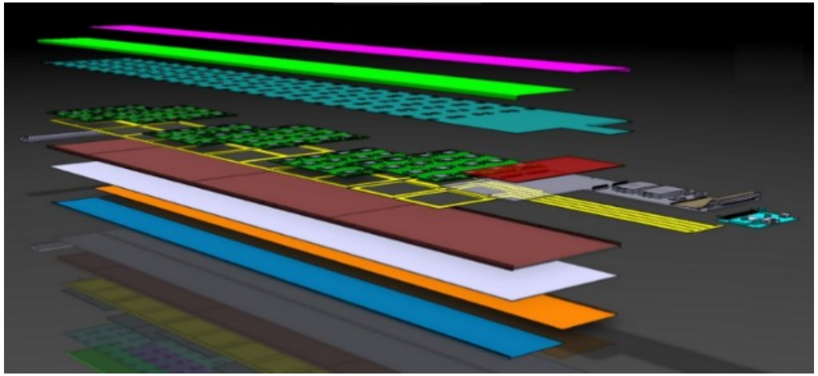
- Barrel modules: 40 (as of today all identical)
- Endcap Modules: 24 (3 types)
- ASUs = ~75,000
    - Wafers ~ 300,000 (2500 m²)
    - VFE chips ~ 1,200,000
    - Channels: 77Mch
- Slabs = 6000 (B) + 3600 (EC) = 9600
    - ≠ lengths and endings

Tests of producibility

Tests of feasability



U layout of a **short slab**



U layout of a **long slab**

Beam Test of Technological prototype: 7 SLAB's

MIP scan

- Positrons of 3 GeV
- Grid of 9x9 points separated by 2 cm

Data used for pedestal subtraction and energy calibration:

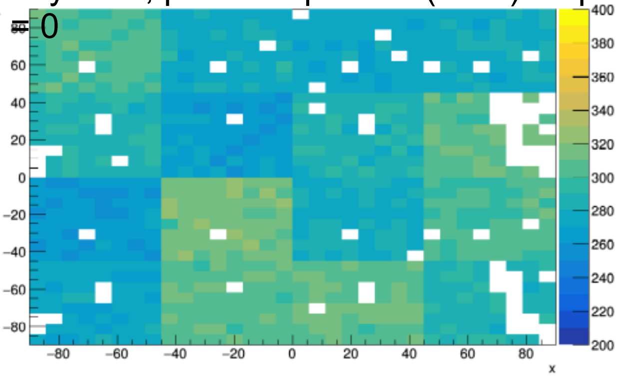
- Pedestal correction done chip/channel/sca wis
- Energy calibration done chip/channel wise

Fit the 98% of available channels.
Channel dispersion of 5%.

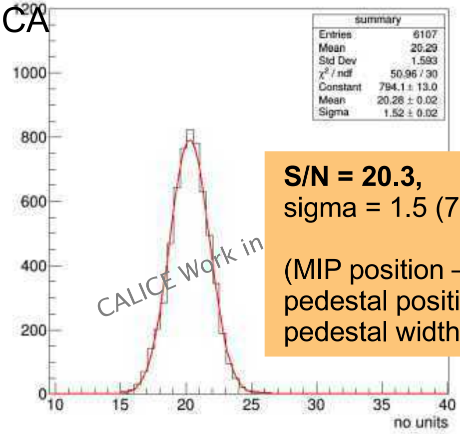
Also 45 degrees inclination run:
MIP value scaling as expected
→ good thresholds choices.

Trigger @ ~1/3 of MIP

Layer #6, pedestal postion (ADC) map for SCA = 0

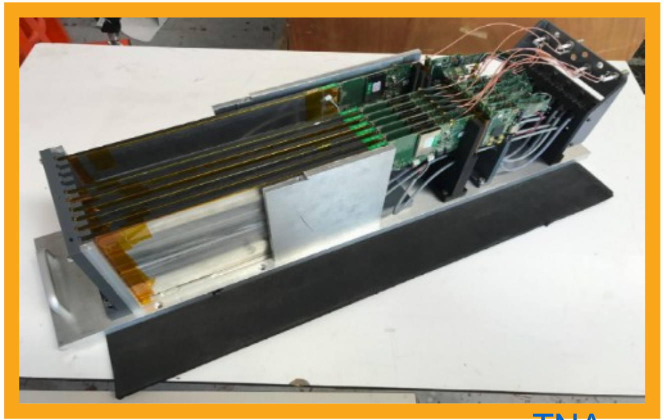


S_N summary (all slabs)

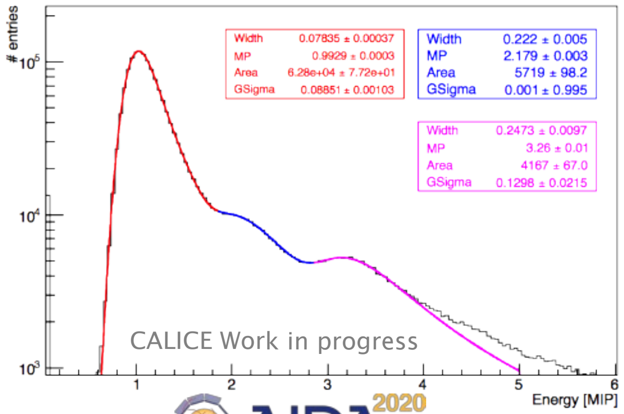


S/N = 20.3,
sigma = 1.5 (7.4 %)

(MIP position – pedestal position) / pedestal width



Single cell energy distribution for 3 GeV e^+ beam w/o absorber

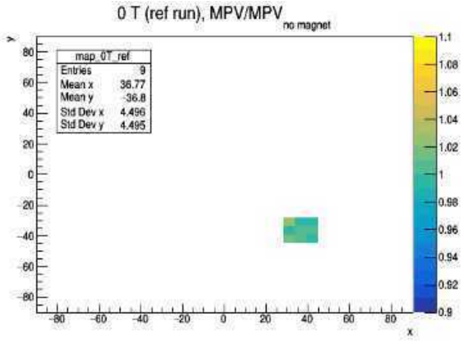


TNA support + WP14

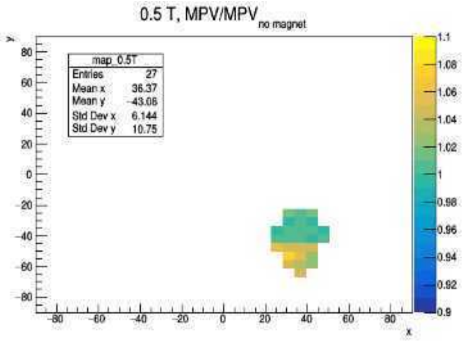
Test in B field

Magnetic field tests

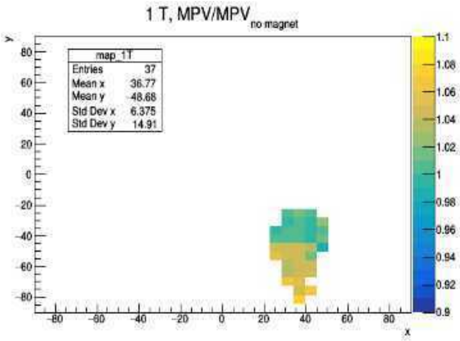
- Single Slab (21, first layer in the full stack)
- (Magnetic field from 0, 0.5, 1 T) ⊗ (With and without beam)
  - Same configuration than in the other beam area.
- Not evident failure/loss of performance during visual inspection on the web cam & online monitor.
- ~20 hours of data in total



0 T (ref run), $\mathrm{MPV}/\mathrm{MPV}_{\text{no magnet}}$



0.5 T, $\mathrm{MPV}/\mathrm{MPV}_{\text{no magnet}}$



1 T, $\mathrm{MPV}/\mathrm{MPV}_{\text{no magnet}}$

TNA support + WP14

Test of ‘Long Slabs’

Scale to support electronics

- 2+6+4 ASUs = ~3.2 m
- Total access to upper and lower parts
  - Baby wafers (4×4 pixels) on the bottom

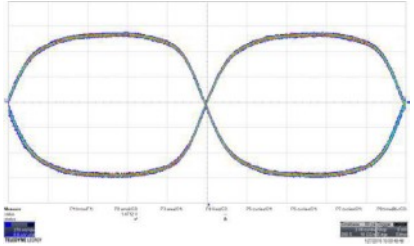
Mechanical characteristics

- Movable: table and to beam test
- Rotatably along long axis (for beam test)
  Rigidity : ≤ ~1 mm per ASU
- No electrical contacts scale / cards

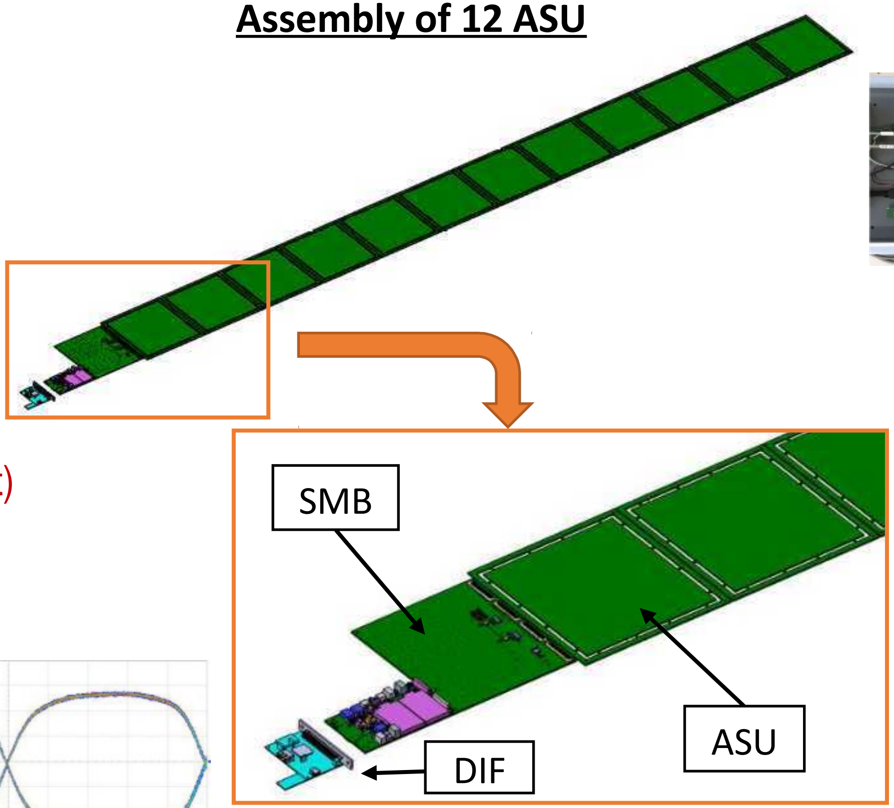
Shielding

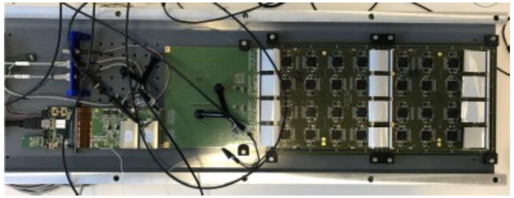
- vs Light and CEM

⇒ **Power & Signal Integrity**



Assembly of 12 ASU



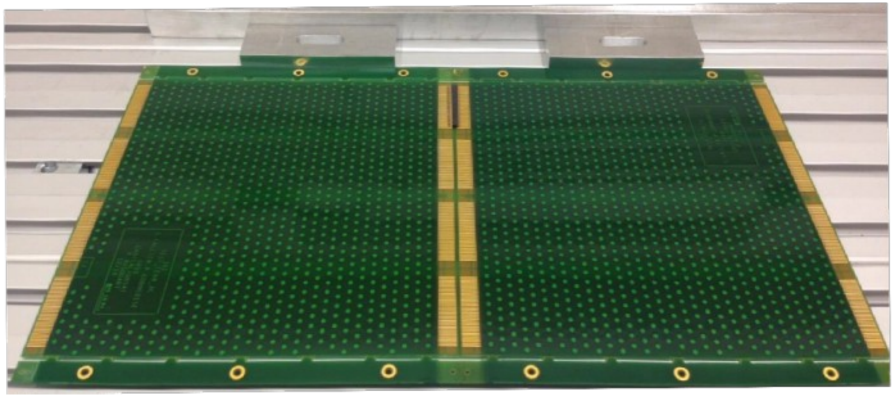


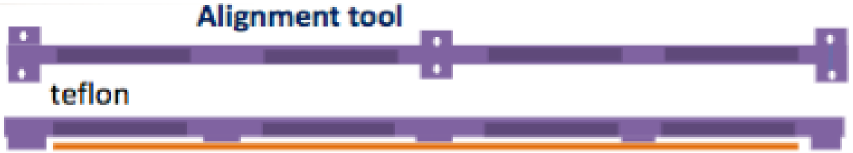
Mechanical Assembly for SLABs

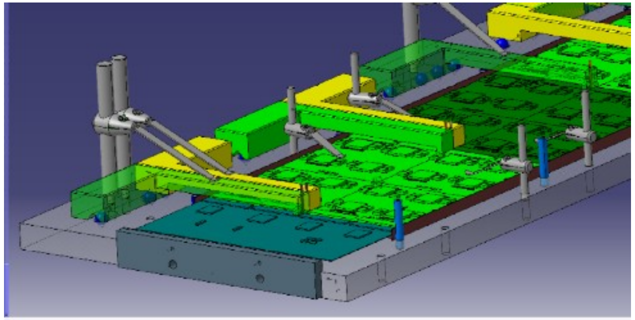
Fragile Wafers

Medium precision of PCB's

⇒ Assembly benches





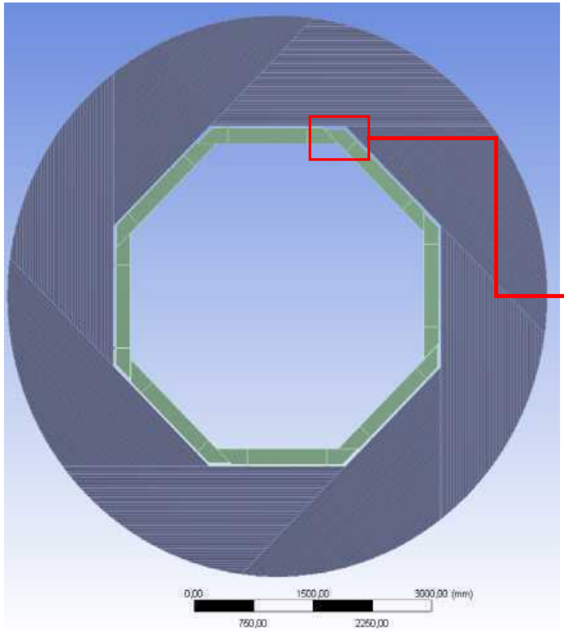


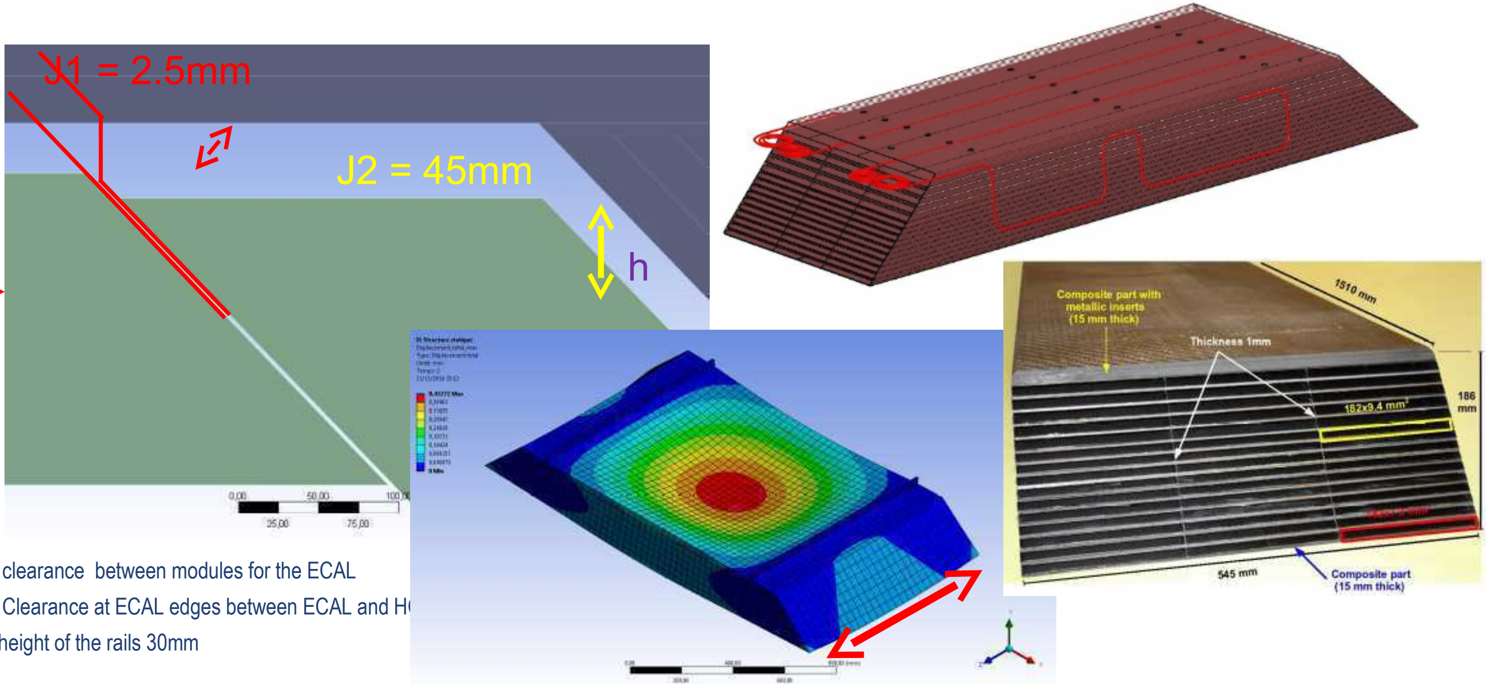
Connections to be handled by industry

- Dedicated Kaptons ✘
- → connectors

Embedded ultra-thin super-capacitors

Thermo-mechanical simulations

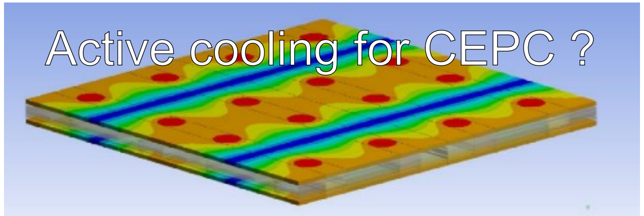


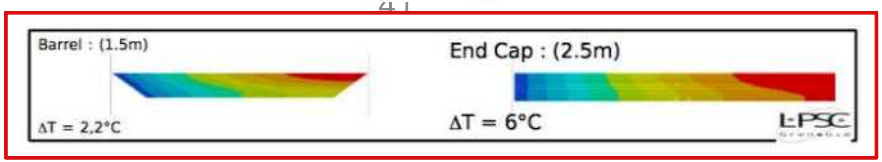


J1 = clearance between modules for the ECAL

J2 = Clearance at ECAL edges between ECAL and H

h = height of the rails 30mm

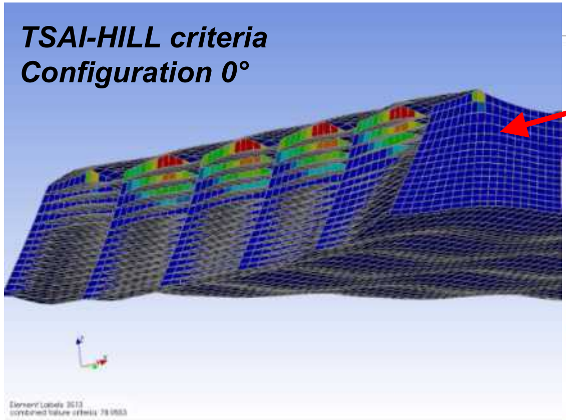

Active cooling for CEPC ?

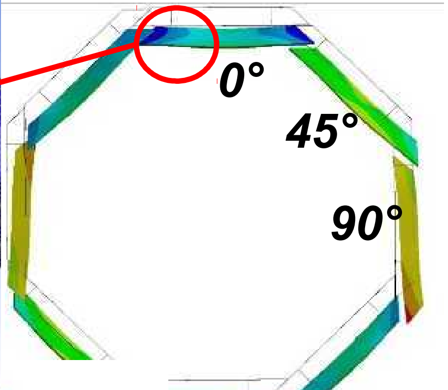


H. Videau, M. Anduze, T. Pierre-Émile
+ LPSC (D. Grondin, J. Giraud)

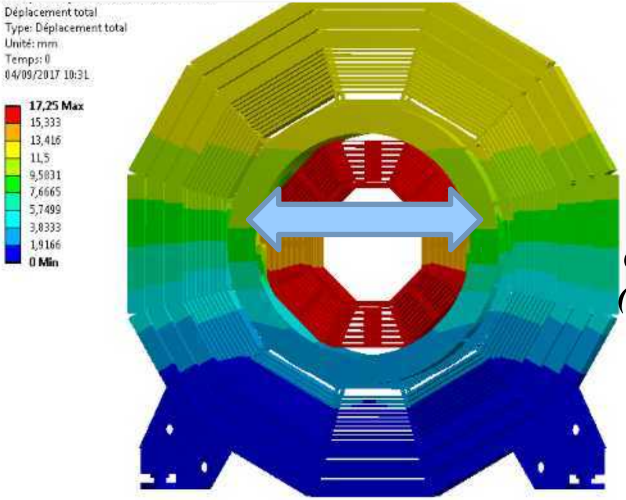
Mechanical simulations

- ❑ All dimensions of the ILD prototype are defined according to FEA results in static and dynamic (earthquake) conditions and for all positions of final modules in the barrel (8 cases)
- ❑ Study of deformations and limit stresses analysis using composite criteria (TSAI-HILL)
  Max stresses are located on the top ribs, a strong effort is needed to define correctly its thickness
- ❑ Proposal: Study internal stresses by using new sensors : optical fiber Bragg grating sensors embedded directly within ribs (strain gauge behaviour)

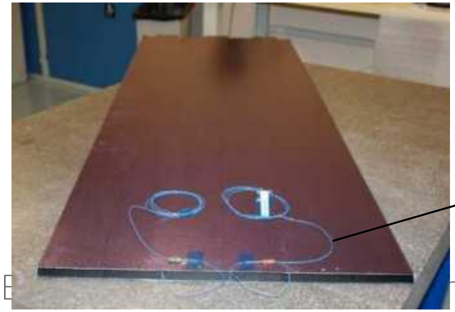




Global deformation of ECAL module (static case)



Global déformation (Response spectrum in lateral only)

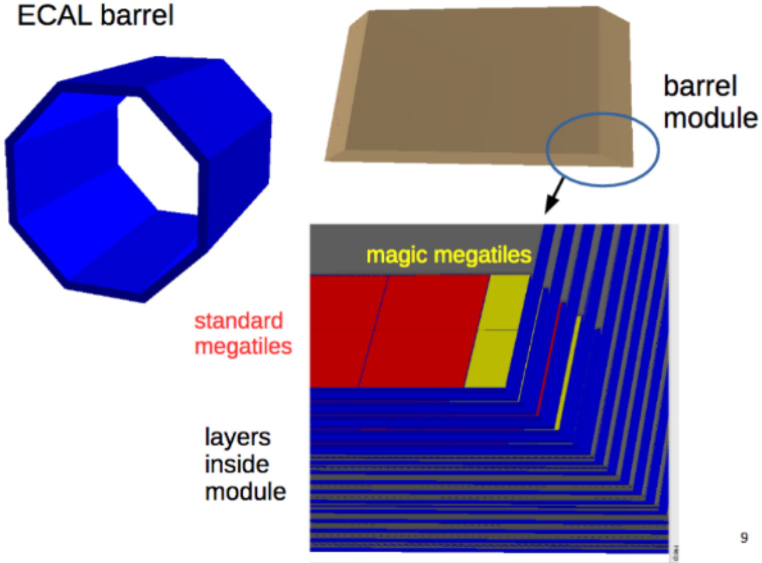


Optical fiber equipped with BG sensors

Simulation

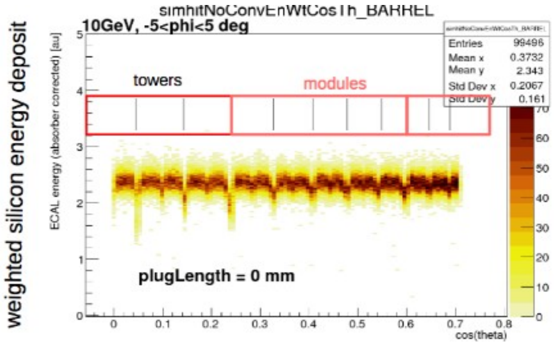
ECAL driver used in ILD models has been largely re-written (Mokka → DD4HEP)

- more modular code:
- less duplication Barrel & Endcap
- more configurable…

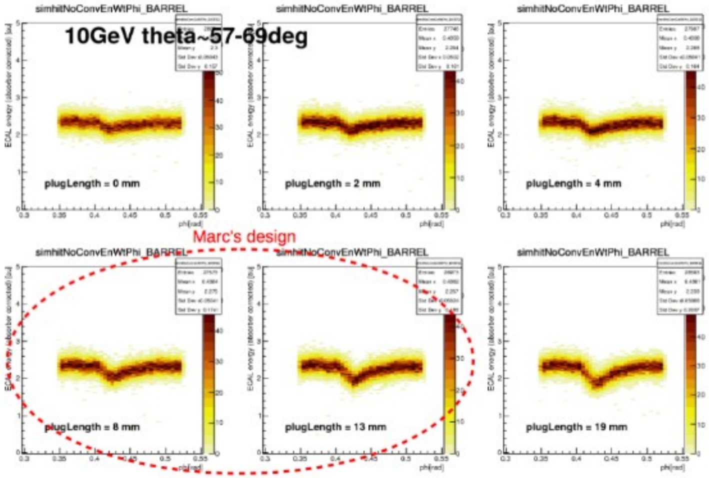


Effect of cracks [RAW= no correction at all!!]

- Drop ~ 15%



Effect of plug (missing in previous simulations)



ECAL Services & Cables (Baseline)

Realistic detector proposal

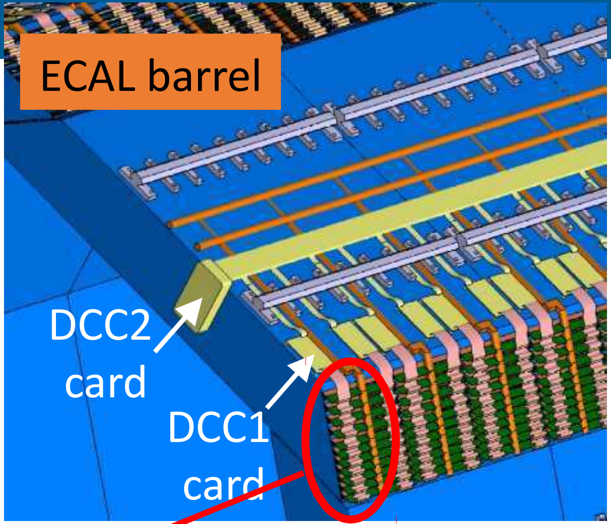
Power, cables and cooling would run between HCAL and ECAL on the back of ECAL (the way it is shown in the picture which exhibits the principle rather than any real design)

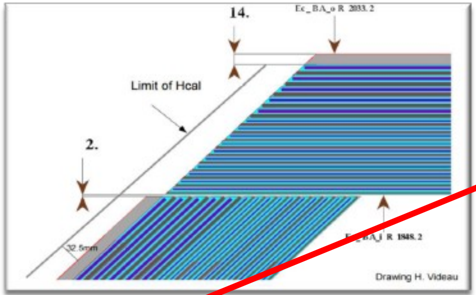
The paths of cables and cooling interfere strongly (cross).
As a working assumption the cables would run to one end of the staves and the cooling to the other end.

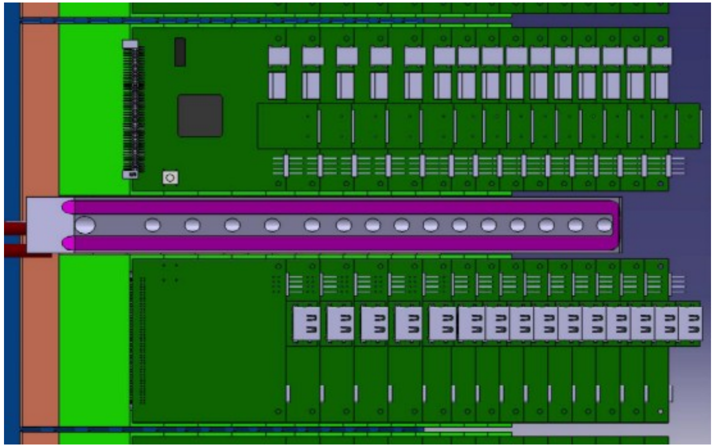
- DCC1 figures a concentration/distribution at the alveoli level
- DCC2 (or Hub2) a concentration/distribution at the stave level.

From then cables or fibres run along each sub-detectors to the outside

Same principle will apply for End cap cooling and cables



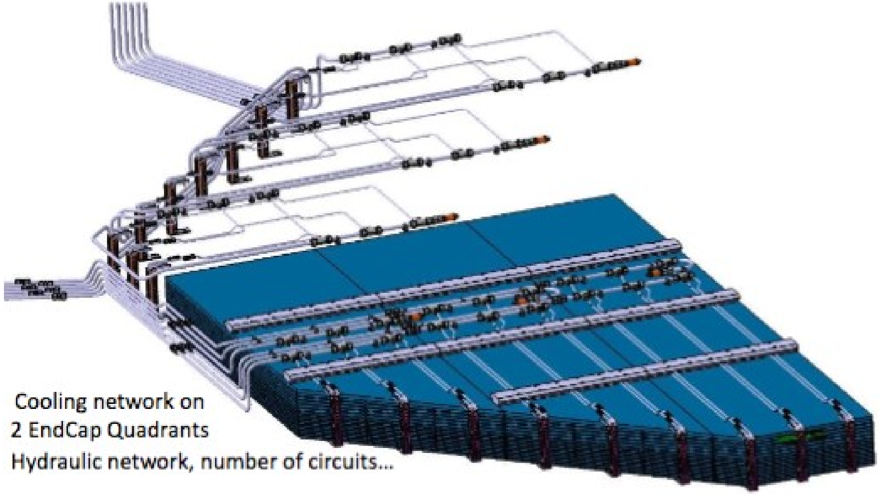




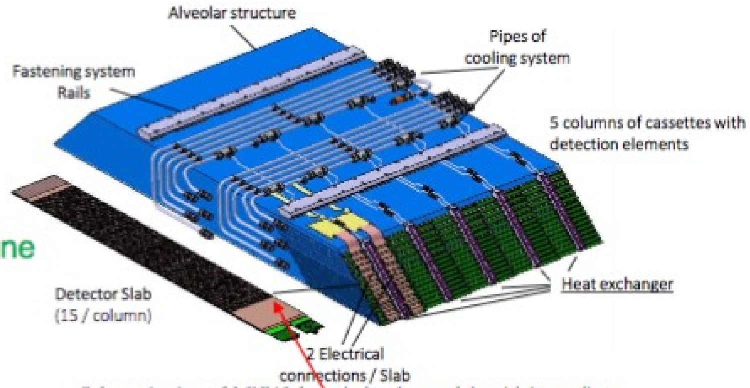
Cooling

ECAL: (CFRP+W structures + Silicon detectors)
The cooling technology is active, using fluid circulation

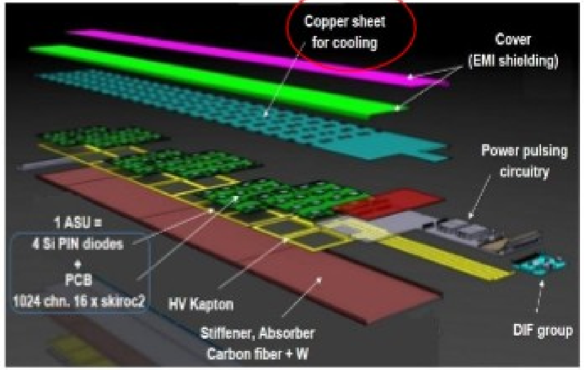
- **Tests and simulation on detector** (EUDET module)
  - Demonstration and performance of Thermal model ⟹ done
- **Integration**
  - Detailed design of cooling pipes scalable to ECAL detector ⟹ done
- **Thermal model**
  - Full Leakless System Design and Analysis: update in for estimation of global pressure drops ⟹ done



Cooling network on
2 EndCap Quadrants
Hydraulic network, number of circuits…

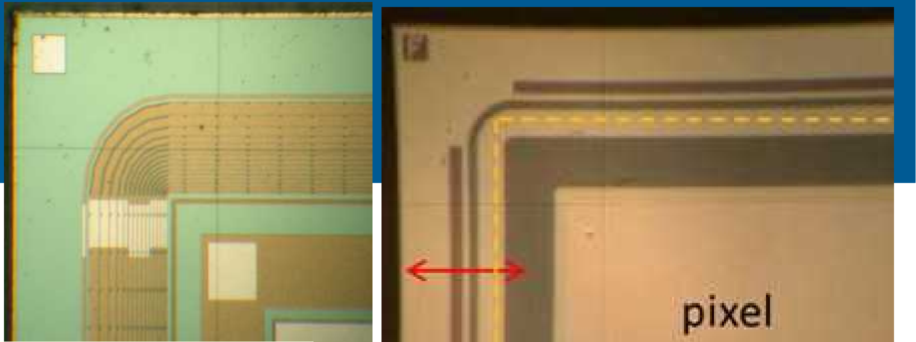


Schematic view of 1 ECAL barrel alveolar module with its cooling system - 10 to 15 layers of double sided integrated detector elements (SLABs) in a Tunsgten-Carbon Fiber (W-CF) support



Exploded view of half a long slab with 6 ASU – (An assembly line for long slabs with 8 connected ASU is AIDA-2020 deliverable D14.3) final goal with power pulsing 1/100 s: ECAL 4.6 Kw

Silicon Sensors

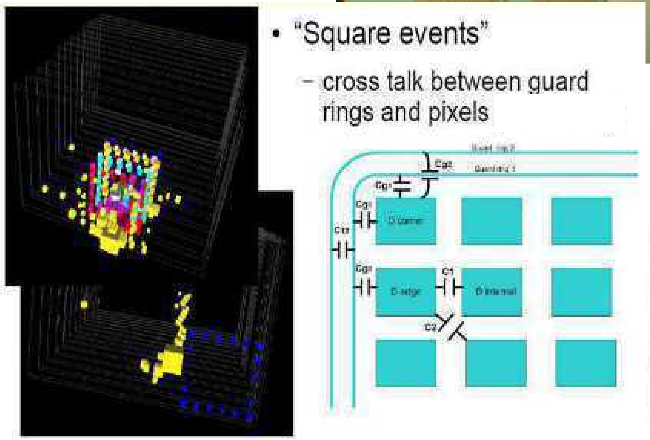


Cost driven

- ~30% of the total cost of the SiW-ECAL
    - ⇒ Units Cost reduction(CALIIMAX program)
- Decoupling of Guard Ring (Square Events).
- new design of ILD detector

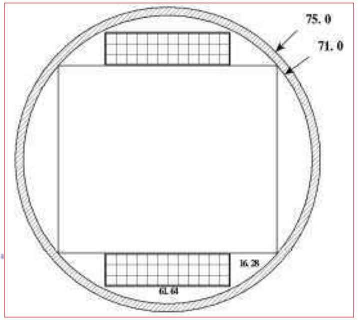
Command Sensors (@ Hamamatsu)

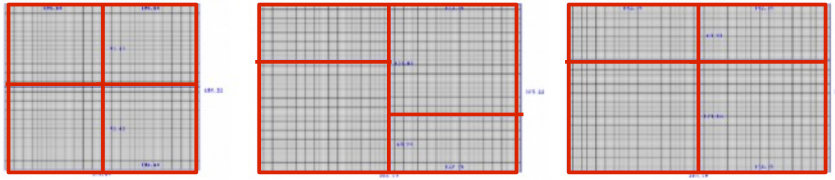
- ⚠ Minimal cost of Command ≥ 20k€
- direct contact with HPK engineers
- Possibility of design for 8'' in 186mm alveola



- "Square events"
    - cross talk between guard rings and pixels

'quantum unit' of ILD dimensions (here 6'' wafer)





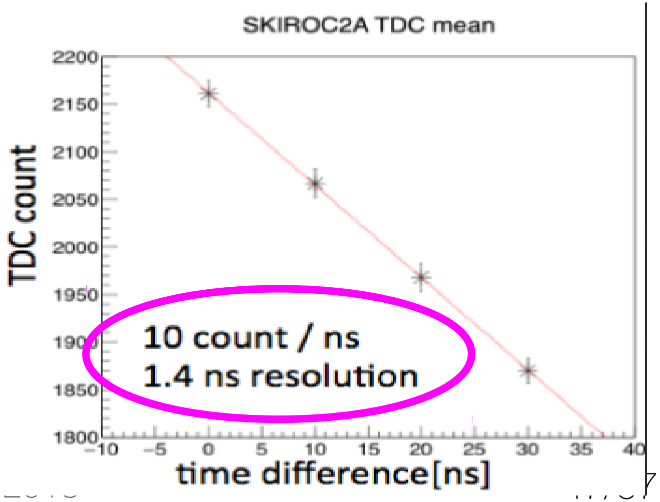
Test of SK2A → Timing ?

Adding 5th dimension:

- Can:
  - Improve Particle Flow SW ***with ~ns mip precision***
    - Tracking of particles
    - Removal of late neutrons
    - Identification of back scattered
  - Allow Particle identification by ToF ***with sub-ns precision***
- *Clean Clock distribution*
  - *Shower timing ~ 1/√E*
- *@ LHC See presentation on HGCAL*

Checked SK2A on Test Board

- Thorough checks on 1–2 mip injected signal
  - All seems OK
  - No difference in Analog part
- Trigger:
  - large channel-by-channel adjustment ✔
  - TDC: OK



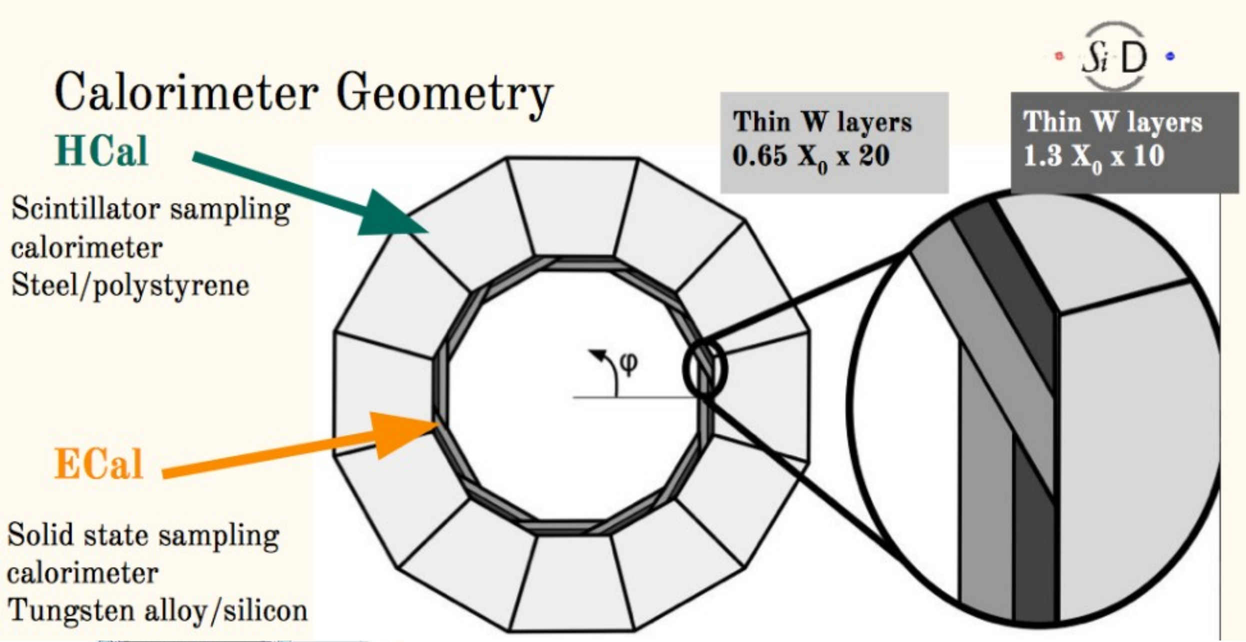
SiD SiW-ECAL

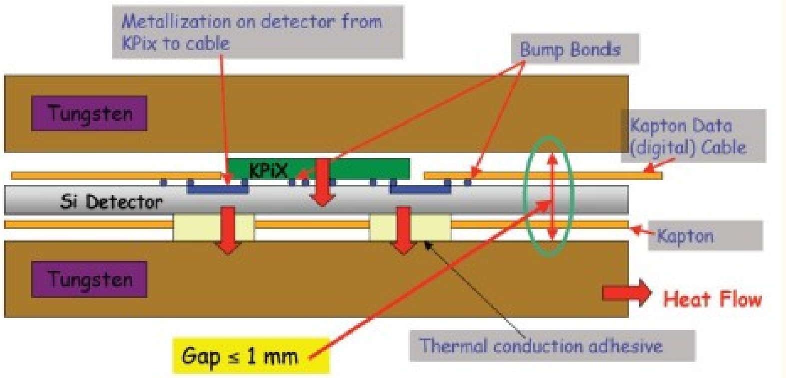
20 + 10 layers

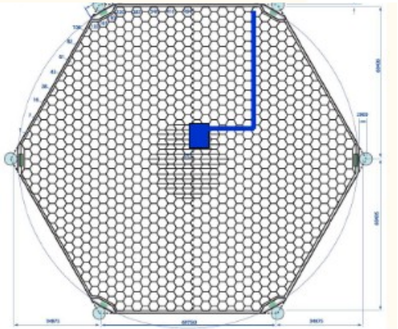
1.25 mm gap between W layers

- Minimize R_M (~ 13 mm effective)
- Keep calorimeter compact

Tungsten plates ⇒ thermal bridge to cooling



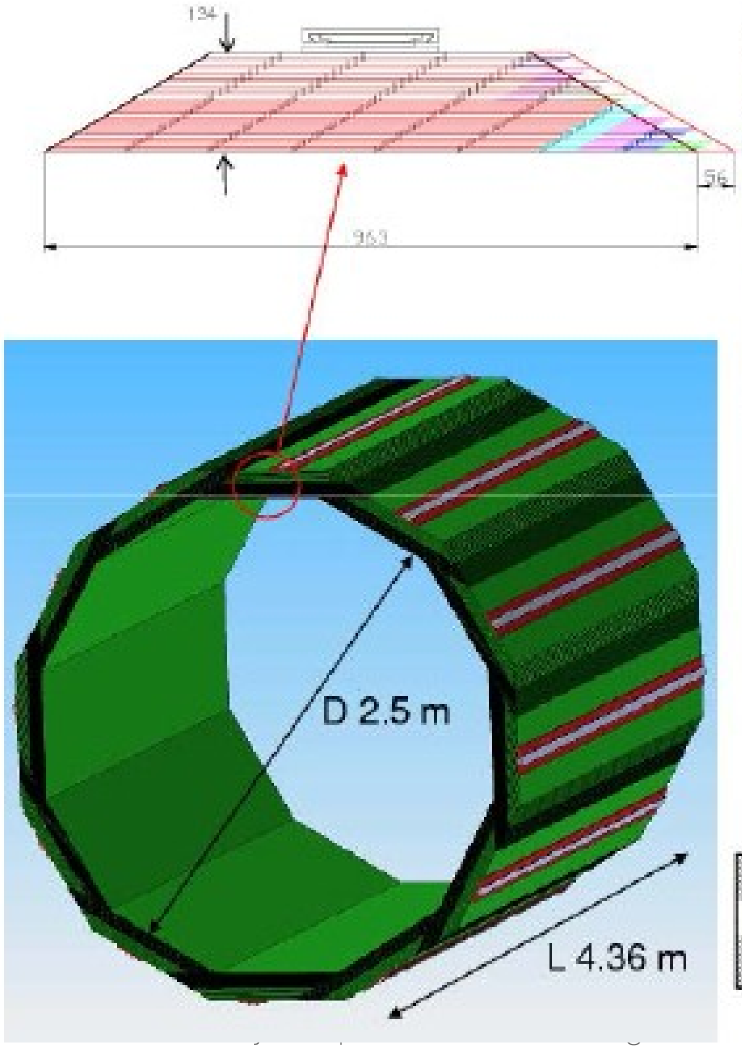


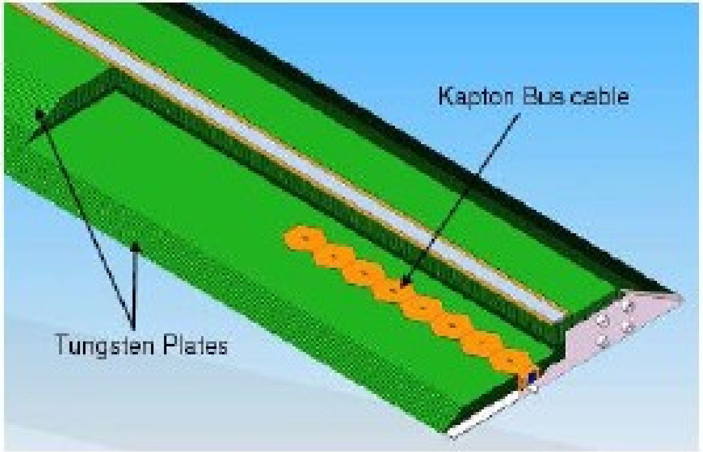


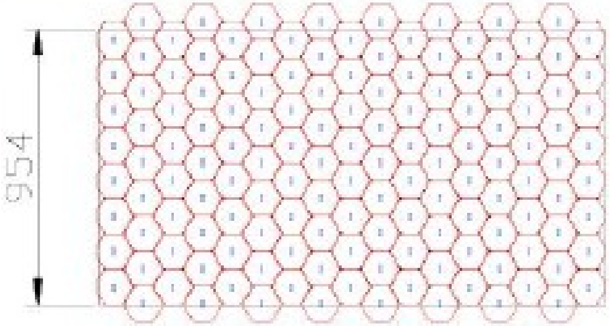
Hexagonal Wafers (optim material)

1 Kpix Chips (1024 ch) per Wafer

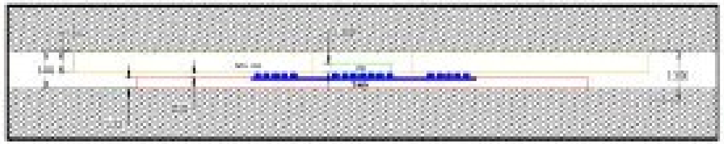
- Bump Bounder on Sensor.







Hexagon sensors arrangement



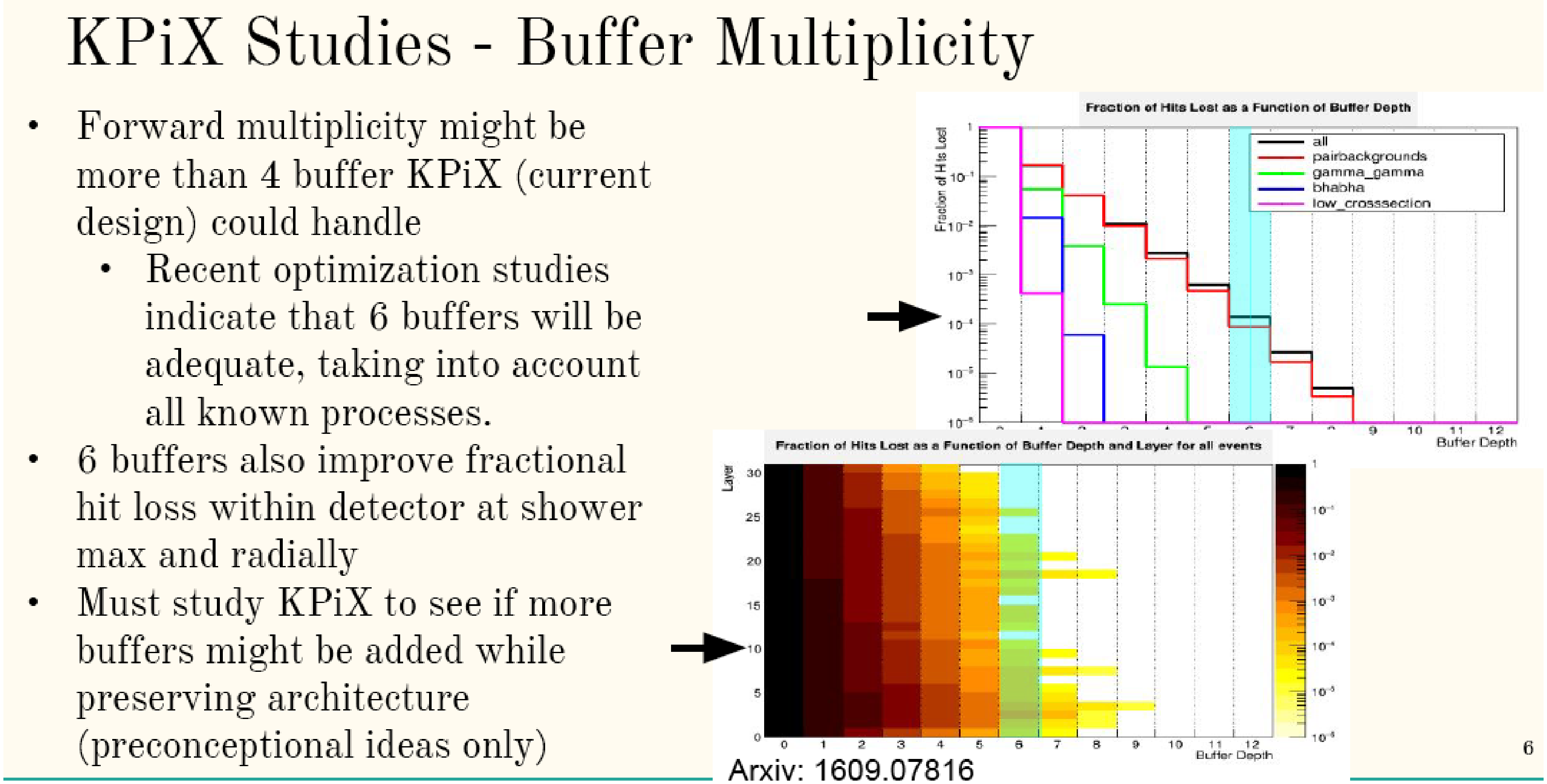
detector module between tungsten plates

<u>Baseline configuration:</u>

- transverse: 12 mm^2 pixels
- longitudinal: (20 x 5/7 X_0) + (10 x 10/7 X_0) ⇒ 17%/sqrt(E)
- 1 mm readout gaps ⇒ 13 mm effective Moliere radius

Occupancy

A. Steinhebel @ ALCW2017



KPiX Studies - Buffer Multiplicity

- Forward multiplicity might be more than 4 buffer KPiX (current design) could handle
    - Recent optimization studies indicate that 6 buffers will be adequate, taking into account all known processes.
- 6 buffers also improve fractional hit loss within detector at shower max and radially
- Must study KPiX to see if more buffers might be added while preserving architecture (preconceptional ideas only)

Arxiv: 1609.07816

6

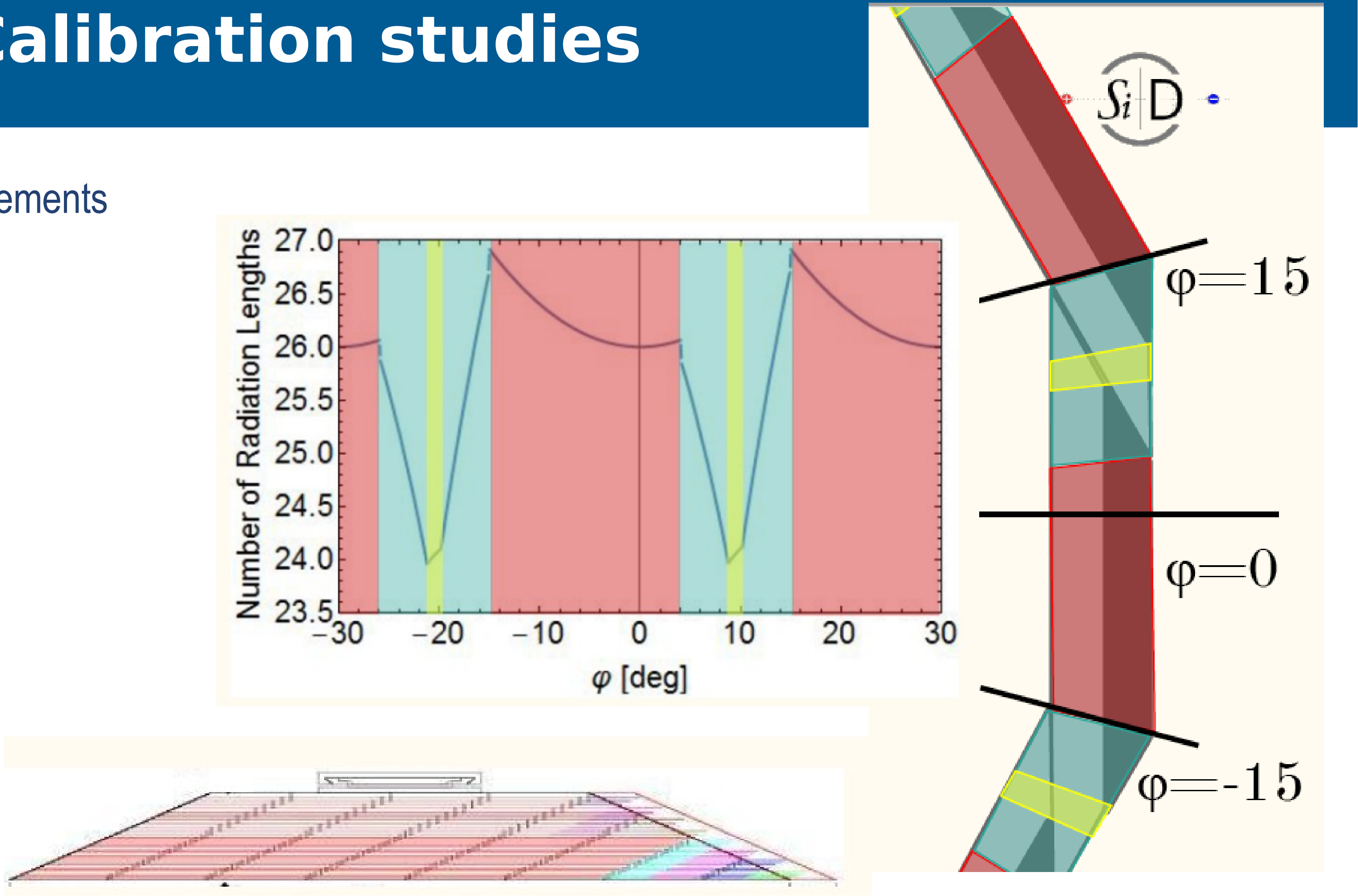
Geometry & Calibration studies

Periodic structure - φ = 30o increments

- Entire module,
- overlap region,
- thin overlap region

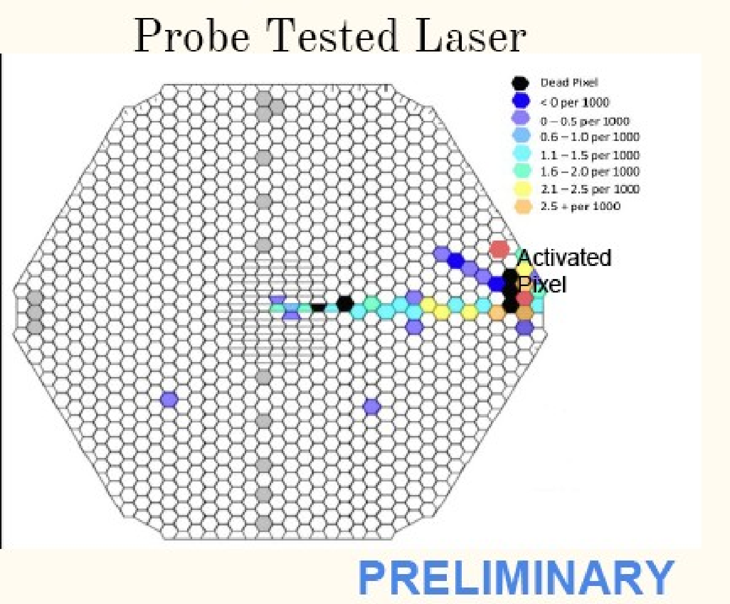
30% of detector coverage has overlapped modules

+ leakage corrections

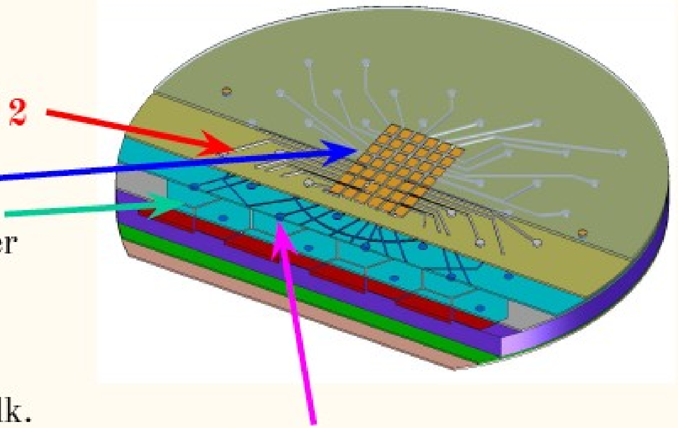


Prototype testing

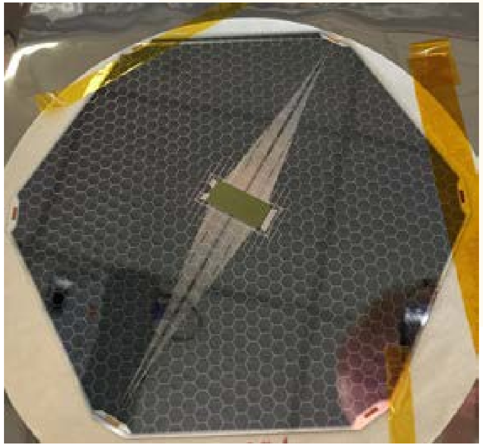
Laser injection in single pad



In present design, metal 2 traces from pixels to pad array run over other pixels: parasitic capacitances cause crosstalk.

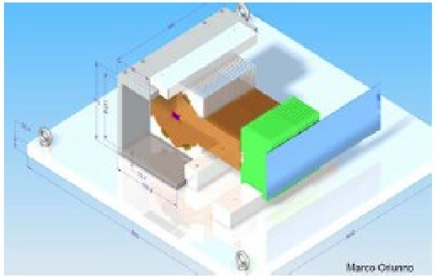


New scheme has "same" metal 2 traces, but a fixed potential metal 1 trace shields the signal traces from the pixels.



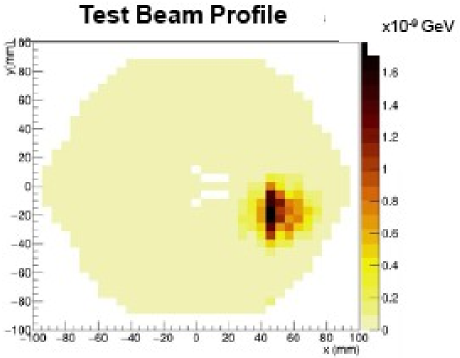
Beam test of 9 layers @ DESY

U of Oregon, SLAC, UC Davis

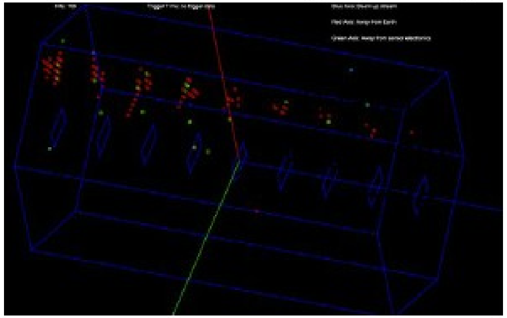


9 layer Si/W
Calorimeter
~ 6 X_0
13 mm^2 pixels

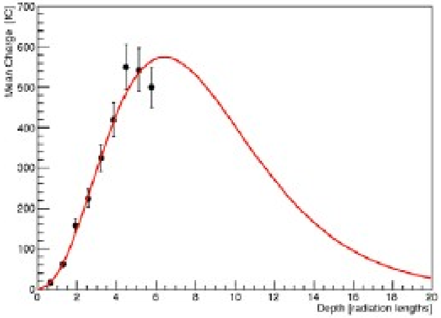
12.1 GeV electrons



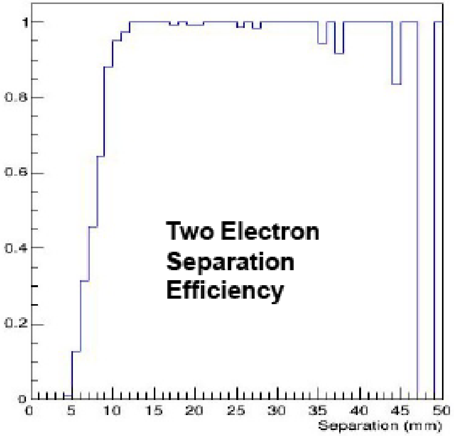
Single electron in 9-layer prototype



Longitudinal charge deposition



- Parasitic crosstalk – new design has additional shield layer
- Issue with KPiX resets causing “monster events” – understood/small change
- Move from aluminum bond pads to gold for next sensors



Prospective for SiW-ECAL's

Very attractive solution

- despite price…

  … "almost ready" for real implementation

all Particle Flow Detector Concept for e+e- colliders:

- ILC, CEPC, CLIC
- ≠ running conditions,energies "minor" adaptations:
  - Cooling (Active, Passive)
  - Thickness

Recent addition: timing

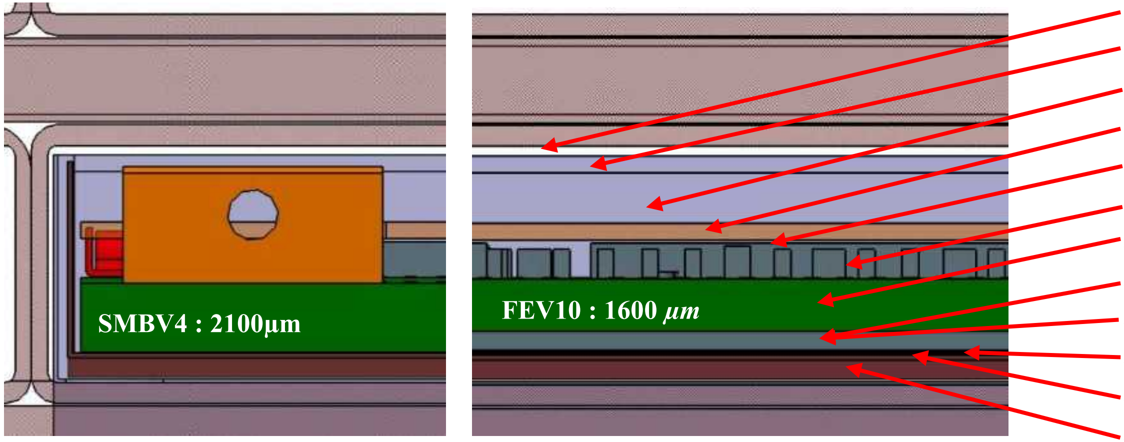
CMS-HGCAL as first "½ scale" detector

Extras

3-Sectional view of the BGA slab

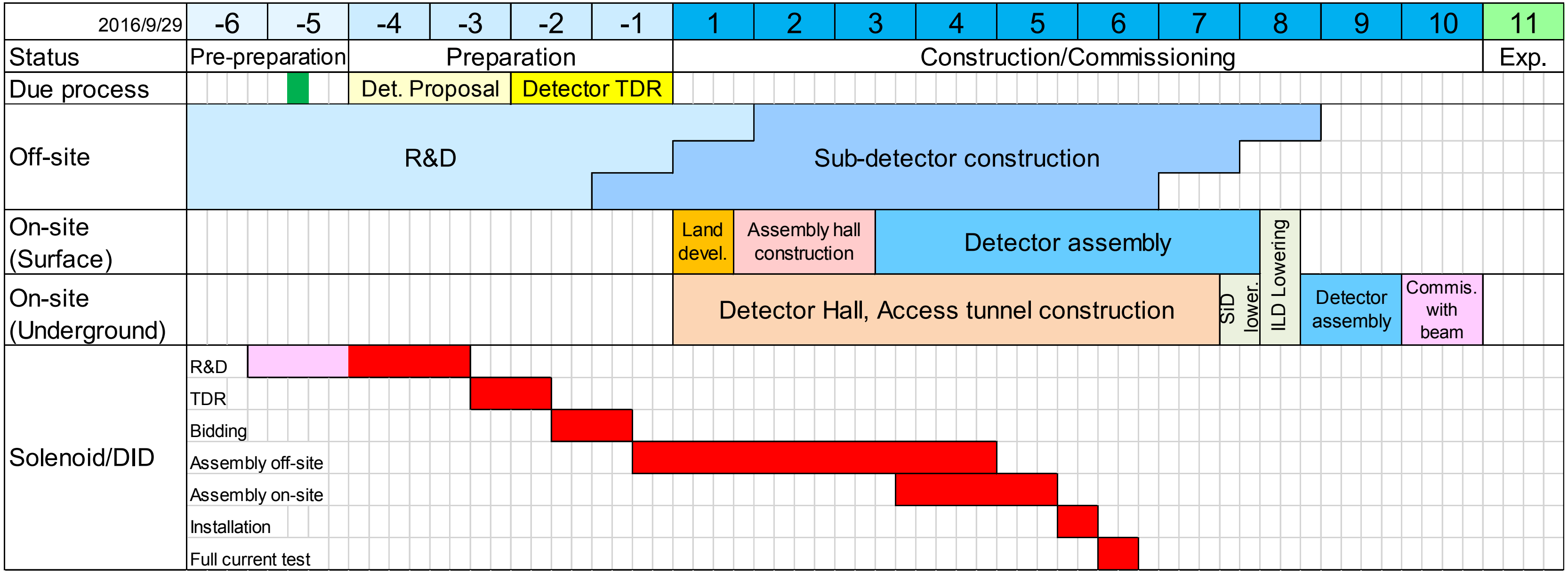
3.0 – SLAB THICKNESS

⇨ **Conservative design: Short U Slab CIP BGA, height of cell 7,3 mm**



- ⇨ *Gaps (slab integration) : 410 µm*
- ⇨ *Shield Cover : 100 µm*
- ⇨ *Gaps : 1859 µm*
- ⇨ *Heat shield : 500 µm (LLR)*
- ⇨ *Pad thermique : 100 µm (LLR)*
- ⇨ *Chips : 1100 µm*
- ⇨ *PCB FEV 10 : 1600 µm (flatness ok)*
- ⇨ *Thickness of glue : 250 µm (LPNHE)*
- ⇨ *Thickness of wafer : 325 µm (LLR)*
- ⇨ *Thickness of glue : 150 µm (LAL)*
- ⇨ *Kapton® film HV : 100 µm (LAL)*
- ⇨ *Thickness of Carbon : 800 µm (LLR)*

ILC Detector Construction Schedule



2016/9/29		-6	-5	-4	-3	-2	-1	1	2	3	4	5	6	7	8	9	10	11
Status		Pre-preparation		Preparation				Construction/Commissioning										Exp.
Due process			🟩	Det. Proposal		Detector TDR												
Off-site		R&D					Sub-detector construction											
On-site (Surface)								Land devel. Assembly hall construction		Detector assembly					ILD Lowering			
On-site (Underground)								Detector Hall, Access tunnel construction						SiD lower.	ILD Lowering	Detector assembly	Commis. with beam	
Solenoid/DID	R&D	🟪		🟥														
	TDR				🟥													
	Bidding					🟥												
	Assembly off-site						🟥	🟥	🟥	🟥	🟥							
	Assembly on-site									🟥	🟥	🟥						
	Installation											🟥						
	Full current test												🟥					