Highly granular sandwich calorimeters for Experiments

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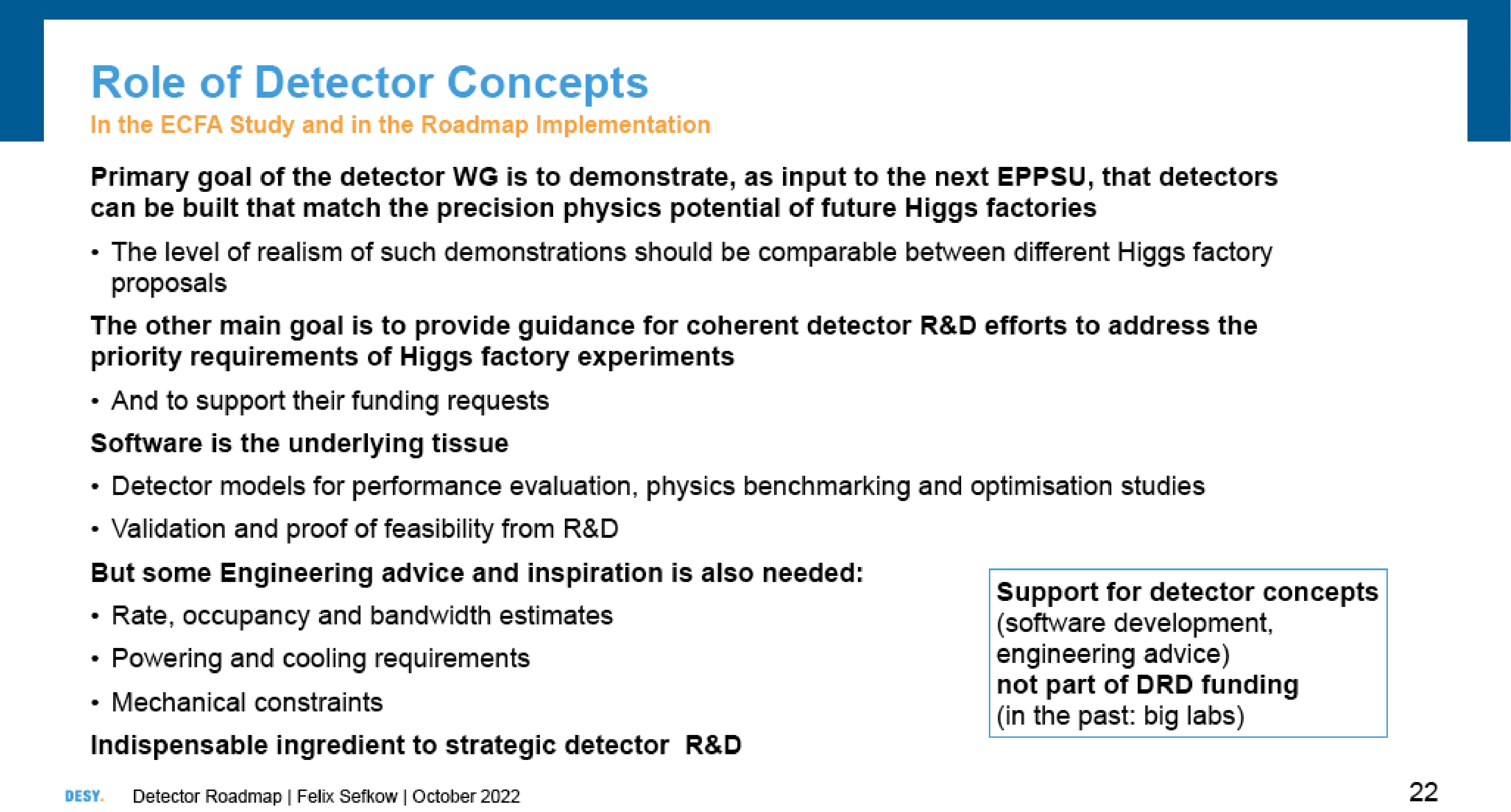
ECFA WG3 WS
03/05/2023, CERN

Introduction

Purpose of this presentation:

- Give an overview of the existing Detector Concepts based on Particle Flow and their Highly Granular Calorimeter Systems (“sandwiched”)
- Remind the needed tools to assess their performances
- Give a status of the existing technologies & achievements
- and of the achievemnt and required developpments for the Concepts



Role of Detector Concepts

In the ECFA Study and in the Roadmap Implementation

Primary goal of the detector WG is to demonstrate, as input to the next EPPSU, that detectors can be built that match the precision physics potential of future Higgs factories

- The level of realism of such demonstrations should be comparable between different Higgs factory proposals

The other main goal is to provide guidance for coherent detector R&D efforts to address the priority requirements of Higgs factory experiments

- And to support their funding requests

Software is the underlying tissue

- Detector models for performance evaluation, physics benchmarking and optimisation studies
- Validation and proof of feasibility from R&D

But some Engineering advice and inspiration is also needed:

- Rate, occupancy and bandwidth estimates
- Powering and cooling requirements
- Mechanical constraints

Indispensable ingredient to strategic detector R&D

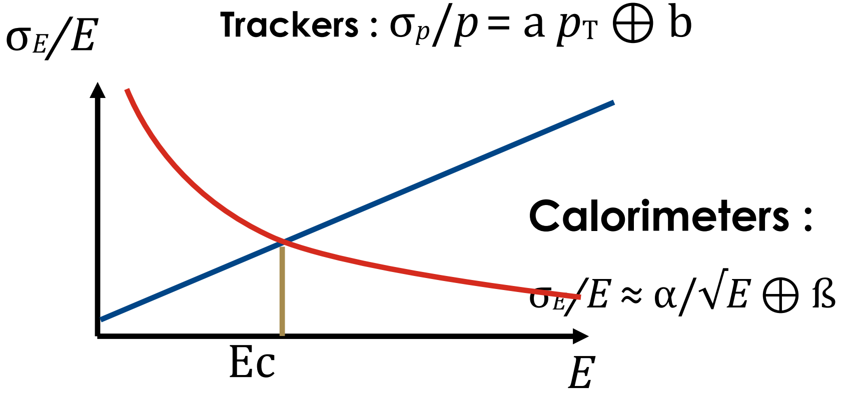
Support for detector concepts
(software development, engineering advice)
not part of DRD funding
(in the past: big labs)

DESY. Detector Roadmap | Felix Sefkow | October 2022 22

Particle Flow Approch

Paradigm of Particle Flow:

- Charged particles are almost always best measured by trackers;
- Calorimeters are only needed for neutrals
  - h°, γ
- Track-Calorimeter clusters
  purely spatial (maybe time ?) linking
  avoids back propagation of calorimeters uncertainties.

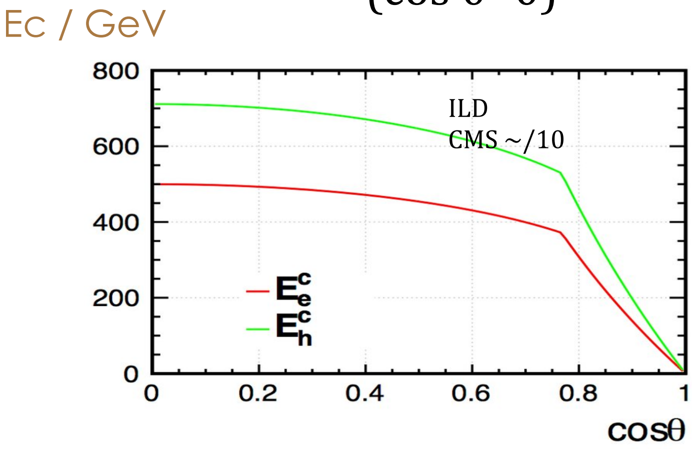


Trackers : $\sigma_p/p = a\ p_T \oplus b$

Calorimeters :

$\sigma_E/E \approx \alpha/\sqrt{E} \oplus ß$

(cos θ=0)



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Highly-Granular Calorimeters at Higgs Factories for Particle Flow Approach based detectors

→ **Large Tracker**

- Precision and low X_0 budget
- Pattern recognition

→ **High precision on Si trackers**

- Tagging of beauty and charm

Large acceptance

→ **Highly Granular Imaging Calorimetry**

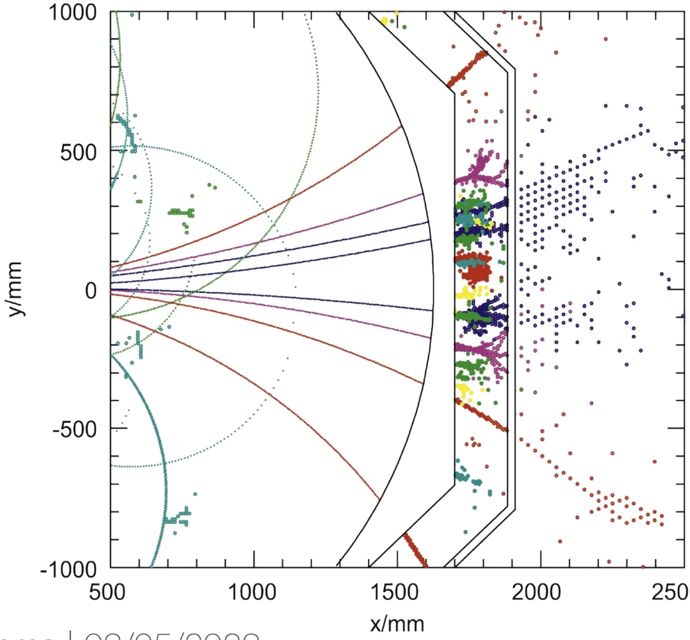
typical size : 0.5 – 3 cm

Particle Flow Algorithms :

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

τ tagging + timing

H. Videau and J. C. Brient, “Calorimetry optimised for jets,” (CALOR 2002)



Reconstruction & Optimisation

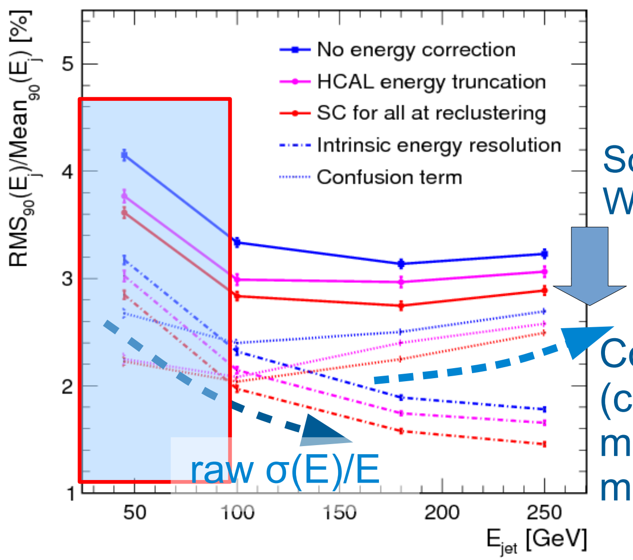
Performances: (for a given configuration of detectors)

- Will depend on the Reconstruction SW (ex. PandoraPFA, ARBOR, APRIL, SW compensation, ML, ..)
- *and* it's proper tuning (~ generic ? not universal)
  - JER, τ reconstruction, b physics, …

Optimisation (best configuration):

- on **simulation,** needs:
  - proper HW description
  - proper Electronics description (Digitization)
- needs the tuning o the Reconstruction SW for each

Pandora PFA: EPJ C77 (2017) 10, 698



Software Weigthing

Confusion (cluster misattrib, merging)

raw σ(E)/E

Low E jets ⇒ where PFA brings most

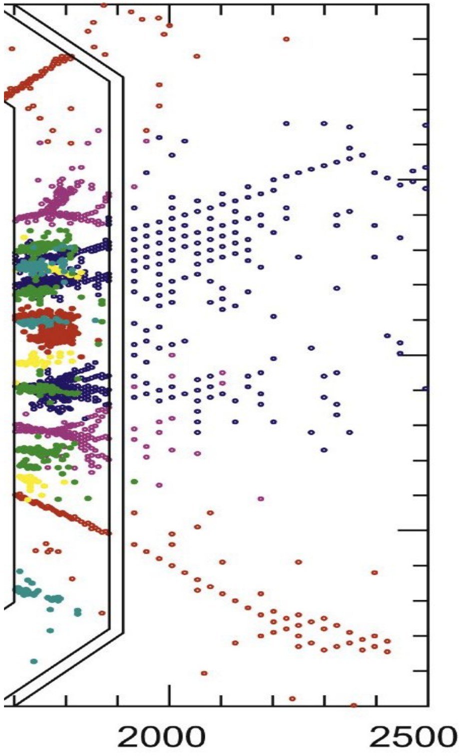
Geometrical on Calorimetric System

Ideally:

- 1 calorimeter fits all, uniform, covering ~ 4π, containing all but ν, μ
  - Costs, Mechanics, Performances for EM vs Had.

In practice:

- ECAL ~ 25 X_0 (= containement of photons), ≤ 1 λ_{had} : absorber = W, Pb, Cu
  - PFA : laterally : shower separations : mip ($h^\pm$, μ) ; γ, e± ; γ, h^0 ; mip, γ-γ (τ physics)
    longs: shower profile, had. shower start., timing
- HCAL ~ 5–6 λ_{had} (= containement of h^0's)
  - PFA: shower separation (h± – h^0), Shower shape (compensation, leakage), …
- Geometry:
  - PFA: As close as possible (tracking), Compatible Granularities, No Dead Spaces



Performances

Estimations of RAW performances:

- Single particle response :
  - GEANT4 simulation ⊗ Digitization [Sensors ⊕ Electronics]: cell's *E*,*t* ⬌ Prototypes in Beam {See presentation from D. Newbold, A. Irles, K. Kruger}
- Two-particle response:
  - Particle separation from beam test data

Physics response :

- Cases: JER, τ, b, …
  - On realistics **Full Simulation** ⊗ Digitization ⊗ Reconstruction(PFA)
  - **FastSim** tuned on Full Sim ⊗ Reconstruction
- Different level of realism, certainty

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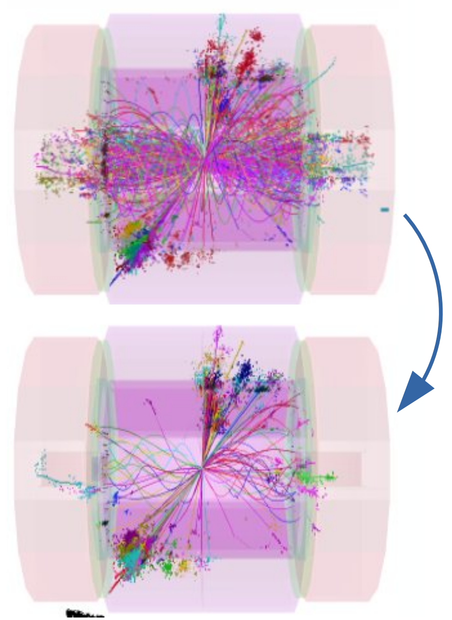
Timing in Calorimeters: 0.1–1 ns range

1 cm/c = 30 ps

Cleaning of Events

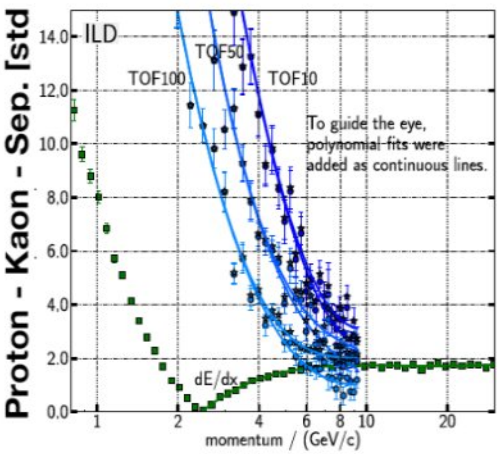


time cut

[CLIC CDR: 1202.5940]
adapted from L. Emberger

Particle ID by Time-of-Flight

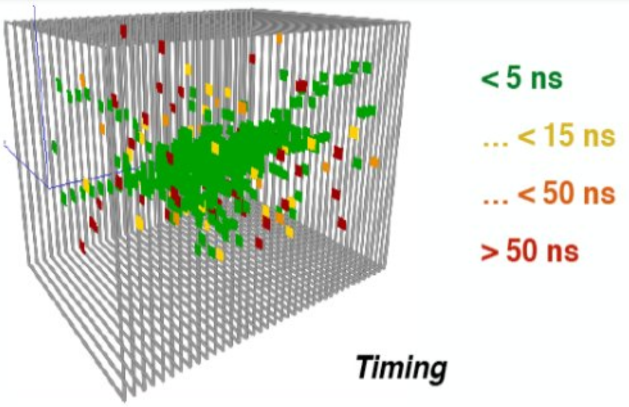
- Complementary to dE/dx
  - here with 100 ps on 10 ECAL hits



S. Dharani, U. Einhaus, J. List

Ease Particle Flow:

- Identify primers in showers
- Help against confusion
  better separation of showers
- Cleaning of late neutrons & back scattering.
- Requires 4D clustering

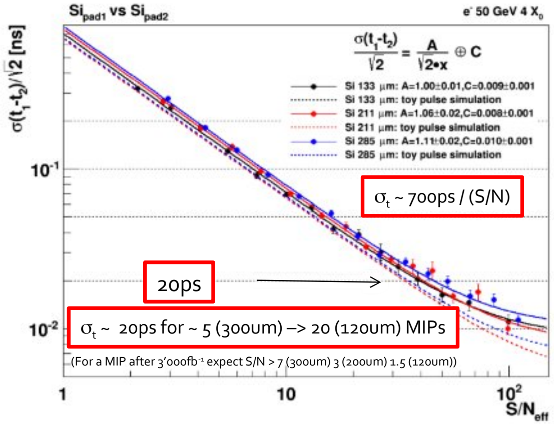


Ch. Graf

Timing Studies

2015 CMS HGCAL CERN timing test beam

– Time resolution vs S/N ratio

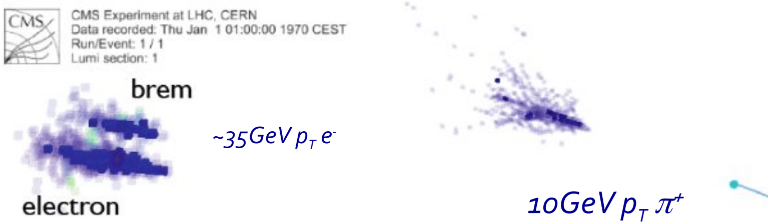


σ_t ~ 700ps / (S/N)

20ps

σ_t ~ 20ps for ~ 5 (300um) –> 20 (120um) MIPs

(For a MIP after 3'000fb^{-1} expect S/N > 7 (300um) 3 (200um) 1.5 (120um))



brem

~35GeV p_T e^-

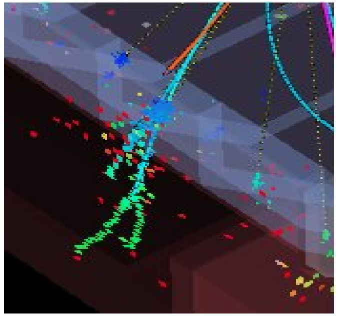
electron

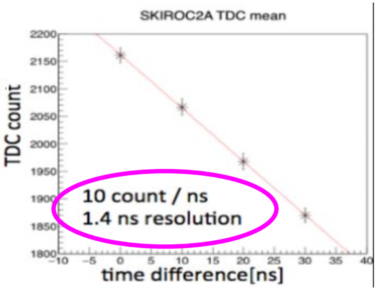
10GeV p_T π^+

Transparent cells => no timing

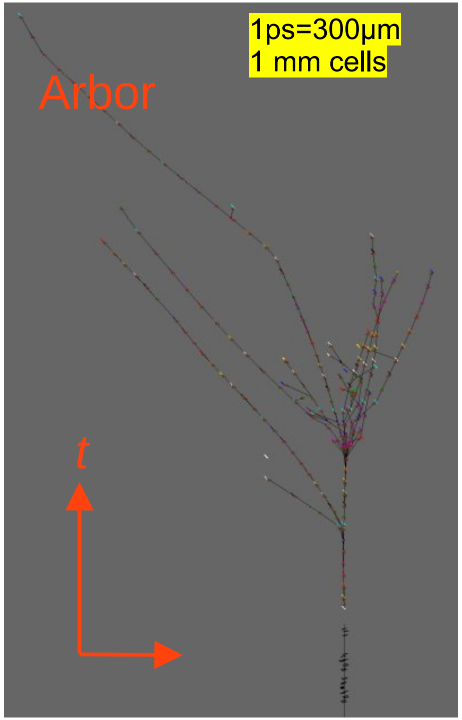
Solid cells = > timing information ~50ps

Option 1) Bulk Timing





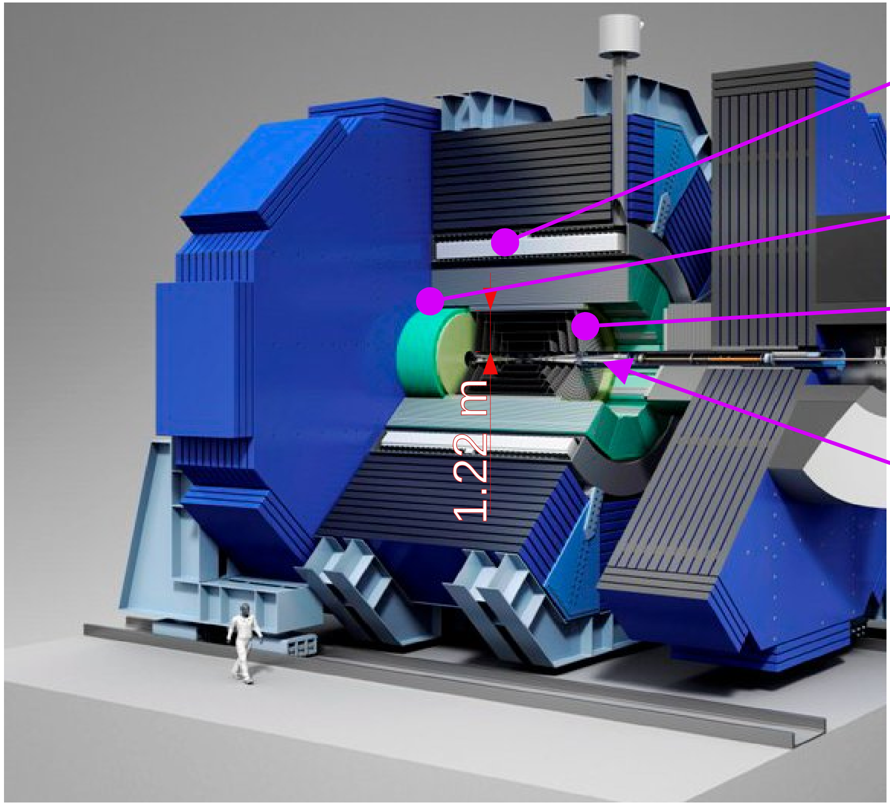
10 count / ns
1.4 ns resolution



1ps=300µm
1 mm cells

Option 2) Dedicated layers with fast sensors (LGADs, MAPs, …)

ILC: ILD & SiD



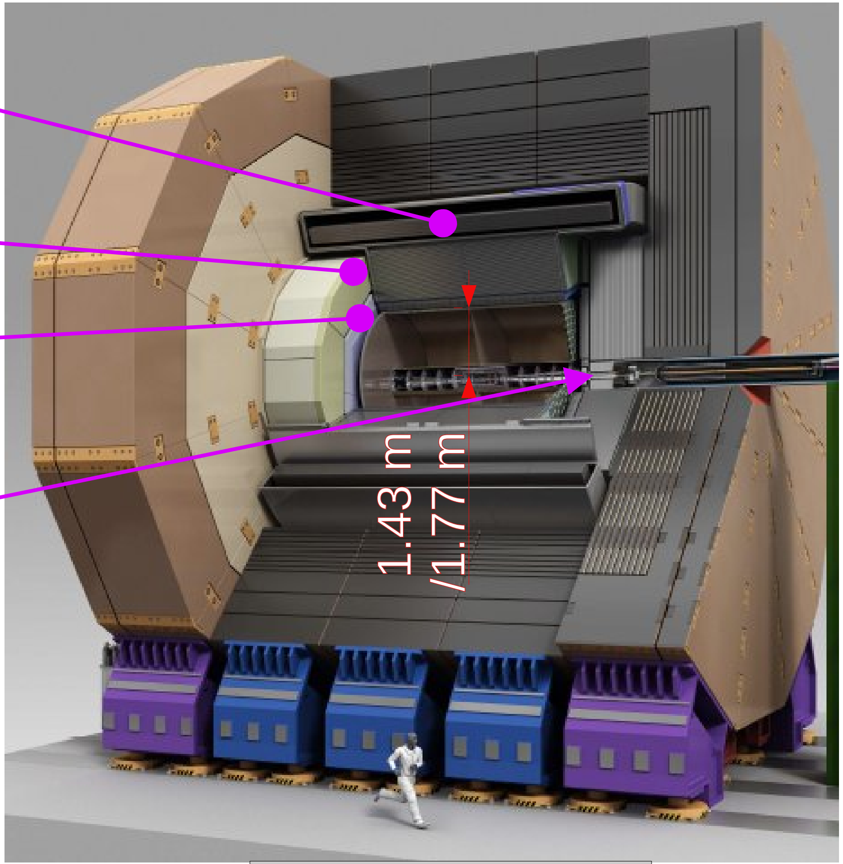
DBD (2013), dd4sim model

Coil
5T vs 3.5T

HCAL
4.5λ_I vs 6 λ_I

ECAL
SiW vs SiW
Scint-W
1.22m vs 1.77/
1.43 m

FCAL



DBD (2013), dd4sim model

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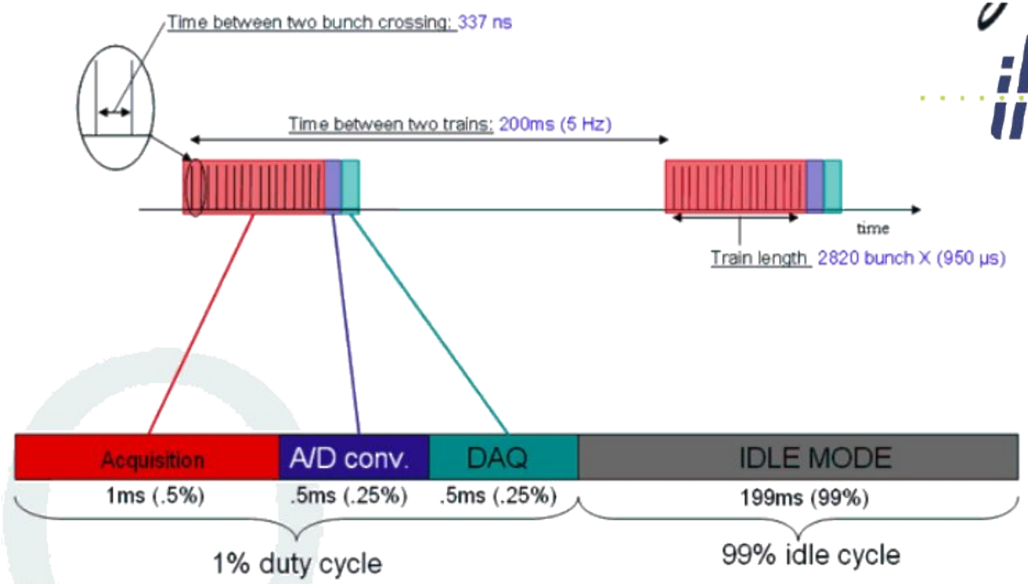
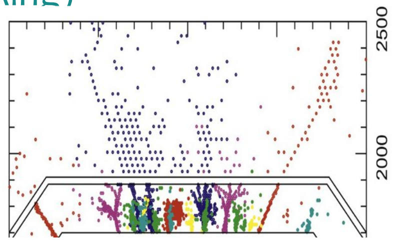
ILC Calorimetric conditions



N.B. Final numbers may vary

e+e- physics

- Energy ranges: 250 – 500 GeV
  - 90 and 1000 GeV envisaged
- Low occupancy in central region
  - but at low angles (FCAL / Ring)
- Self-triggering, local buffering and conversion

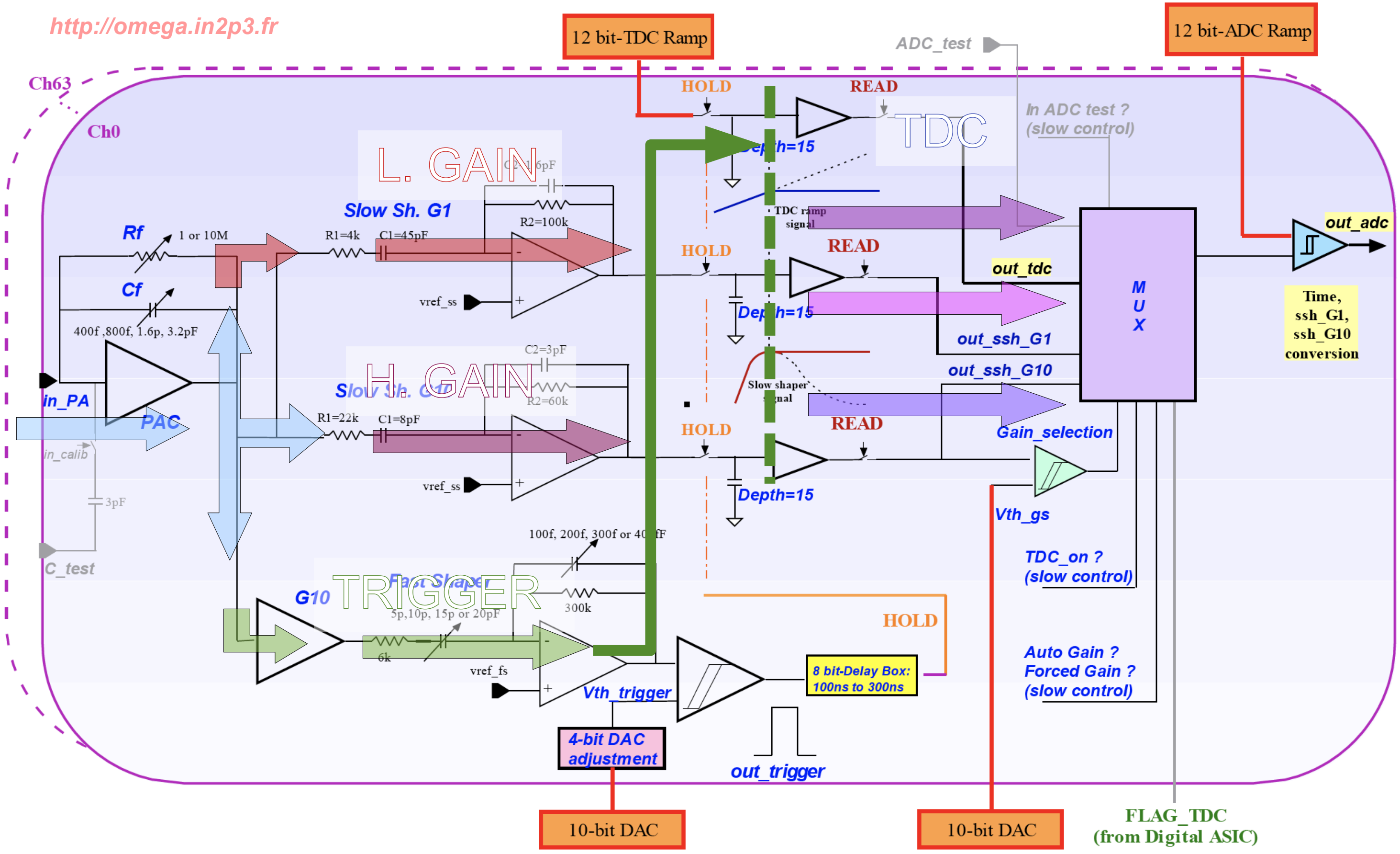


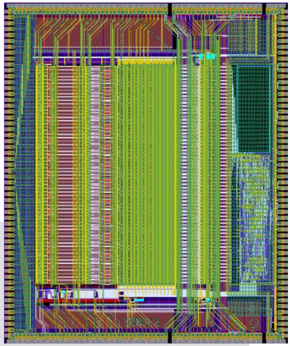
Pulsed operation:

- Very limited (1%) acquisition time
- bunch train ~ 1 ms
  - largely spaced bunches (2-400 ns)
- Ample time for delayed conversion and readout

ΩMEGA Microelectronics

http://omega.in2p3.fr





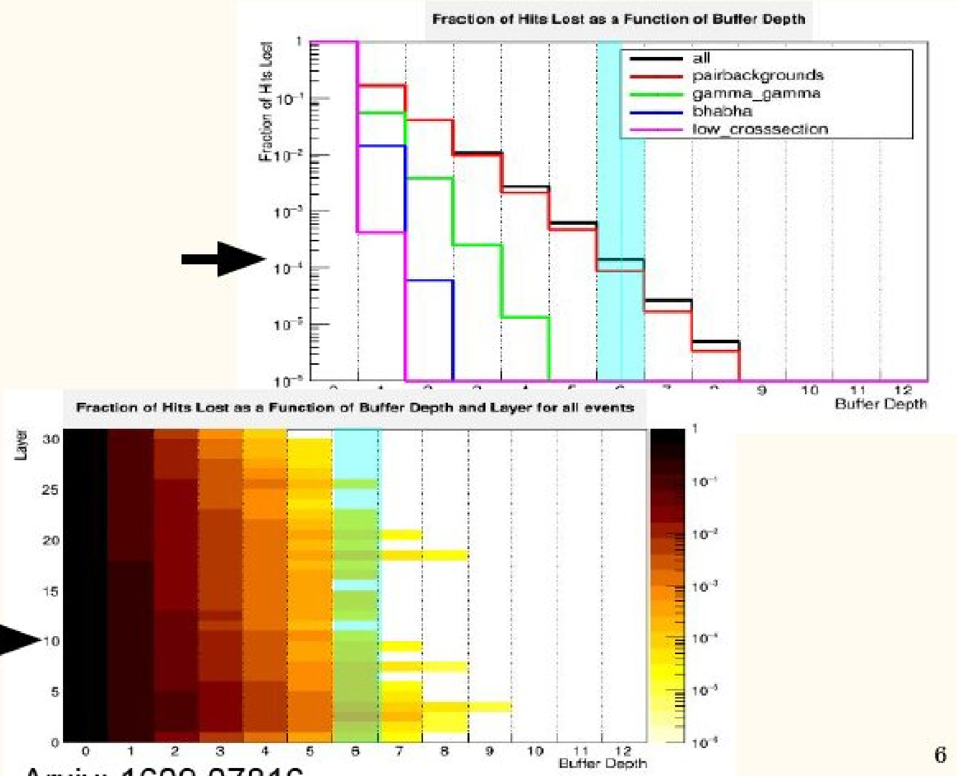
- **64 channels**
- **Auto-triggered**
  - per cell adj.
  - 1 cell triggers all
- Preamp
  + 2 Gains + Auto-select
  + TDC (~1.4ns)
- 15 (×2) analogue memories
- Dyn range 0.1 ~ 2500 mips
  - mip in 320 μm (4 fC)
  - 12 bits ADC’s
- *616 config bits*
- Low consumption
  - 25 μW/ch with 0.5% ILC-like duty cycle
- Power-Pulsed

Occupancy

A. Steinhebel @ ALCW2017

KPiX Studies - Buffer Multiplicity

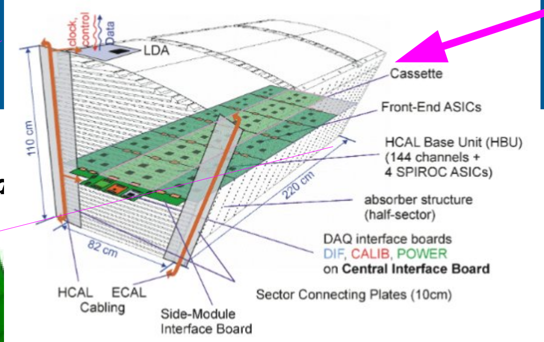
- Forward multiplicity might be more than 4 buffer KPiX (current design) could handle
  - Recent optimization studies indicate that 6 buffers will be adequate, taking into account all known processes.
- 6 buffers also improve fractional hit loss within detector at shower max and radially
- Must study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



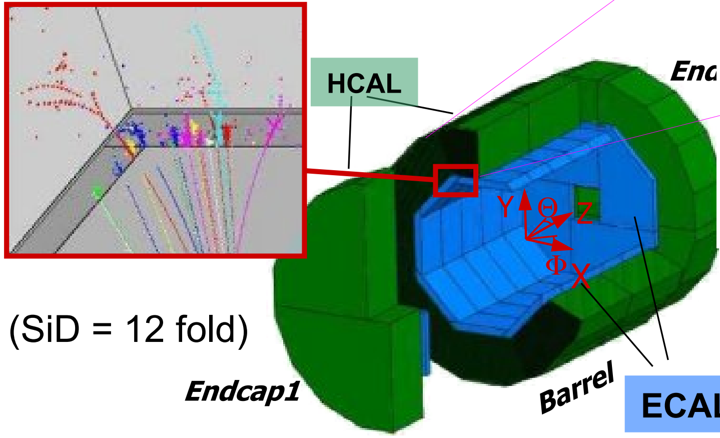
Arxiv: 1609.07816

Geometries & Services

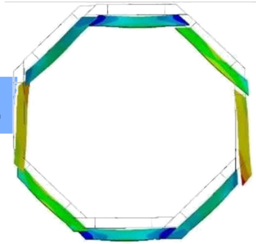
HCAL elec ‘accessibilty’

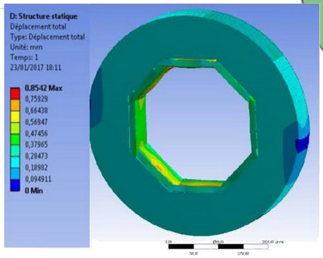


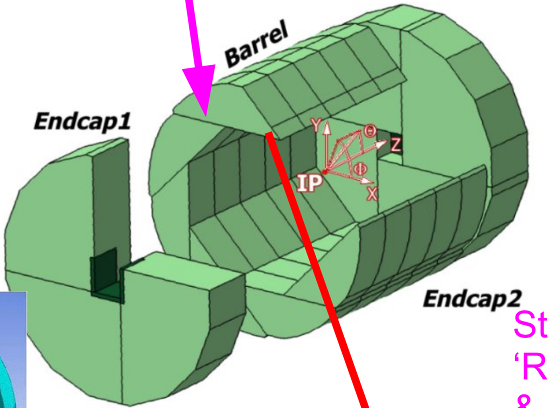
Prism vs diapragm



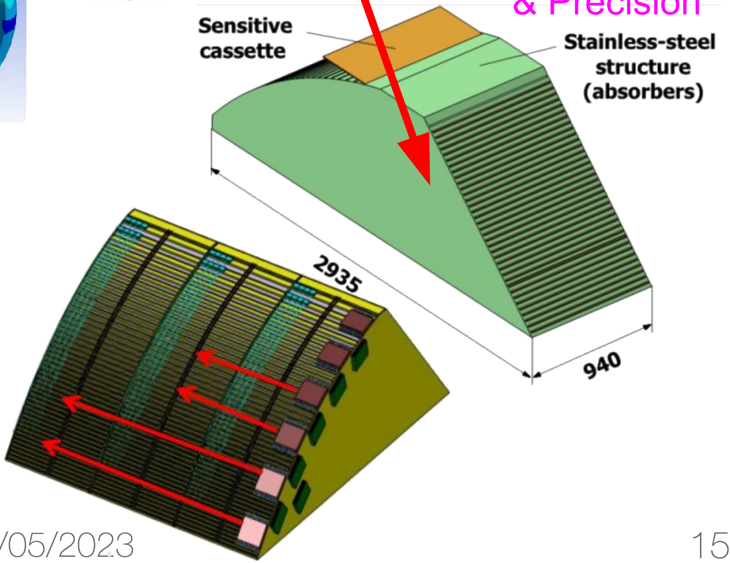
(SiD = 12 fold)

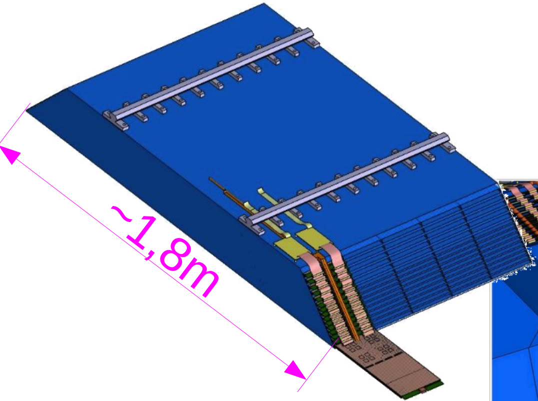


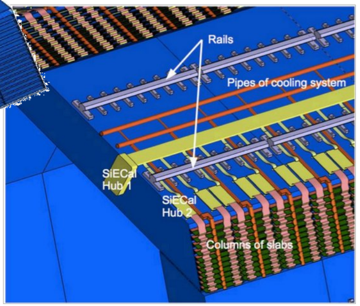




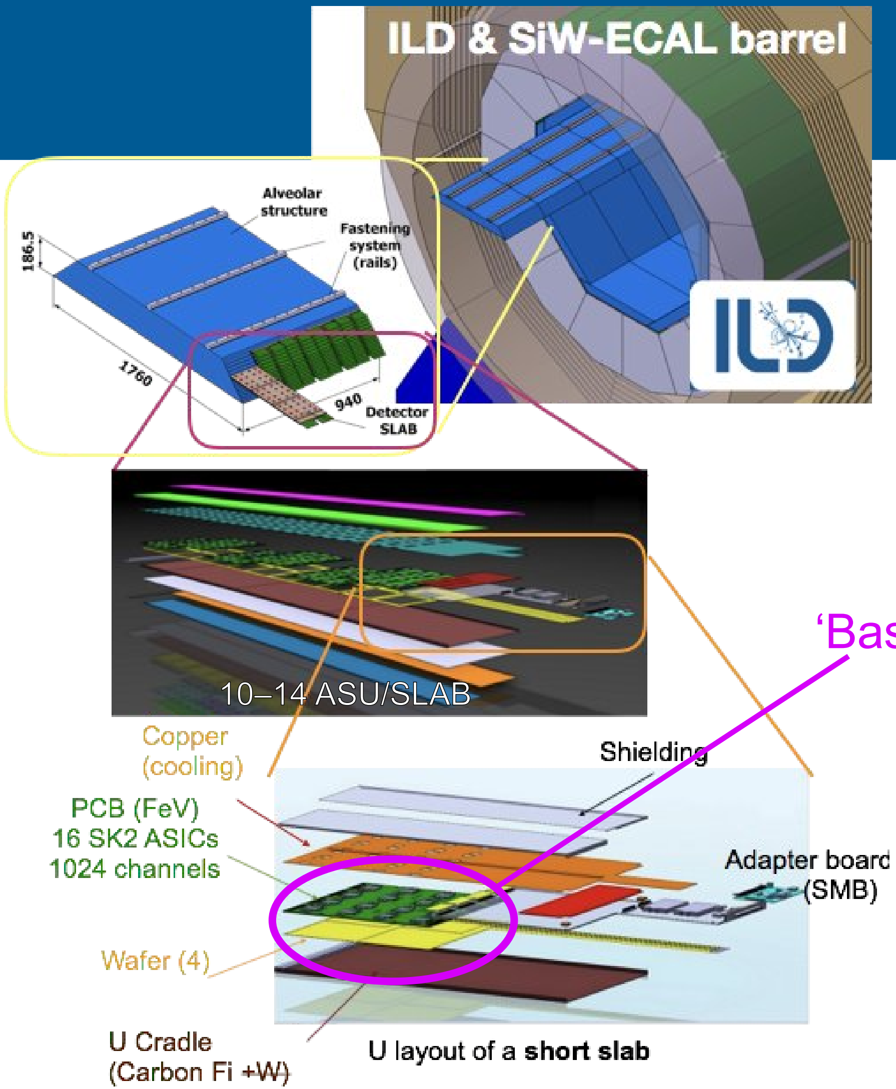
Structural ‘Robusteness & Precision’



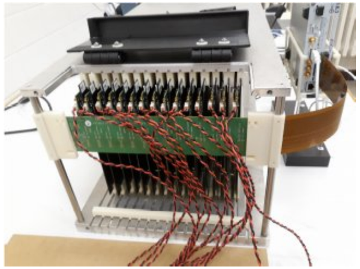




Large Scale Building : CALICE ECALs



ILD 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.

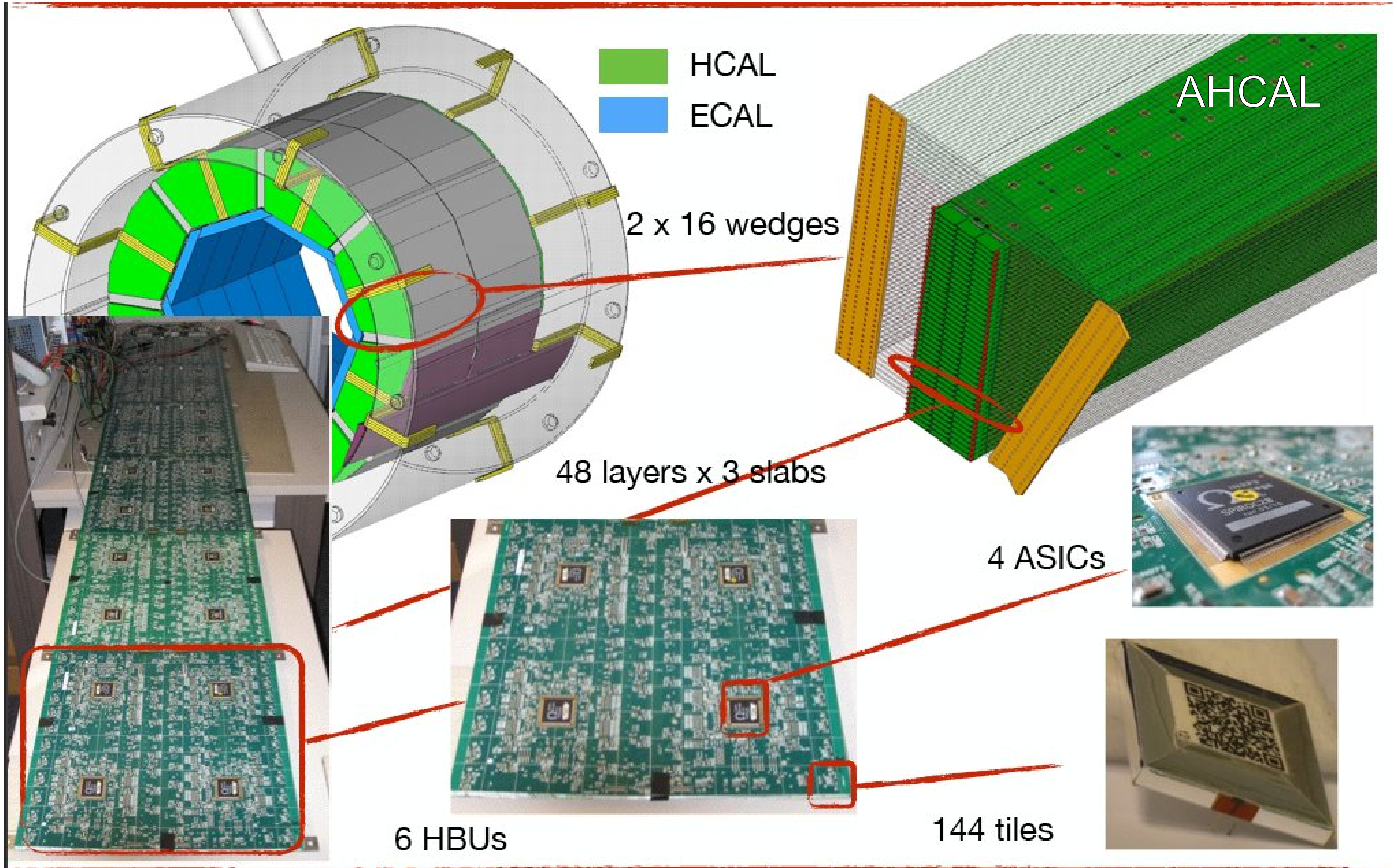


SiW-ECAL
0,5×0,5 cm²
×15 couches +W

ScW-ECAL
0,5×4,5 cm²
×30 layers + SS

See Adrian's presentation

Large Scale Building : CALICE HCALs



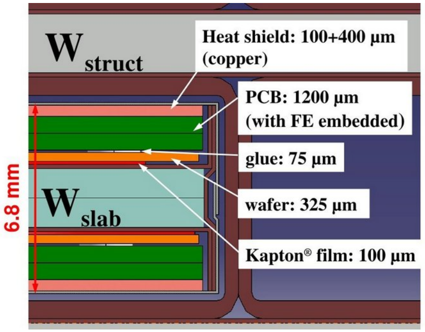
- 48 layers
- 1x 1 cm² granularity
  r 3-threshold, 500000 channels
- Power-Pulsed
- Triggerless DAQ system
- Self-supporting mechanical structure

JINST 10 (2015) P10039

See Katja’s presentation

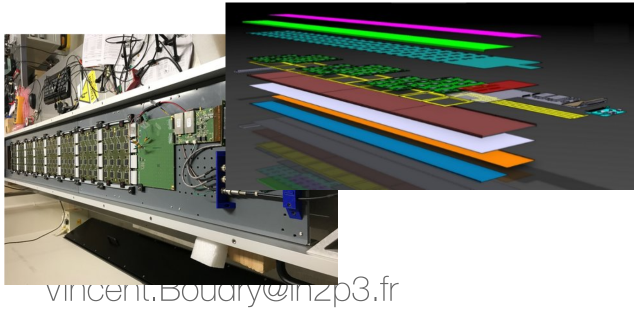
CALICE Thin, long cassettes → all prototyped

Silicon / Scint W-ECAL

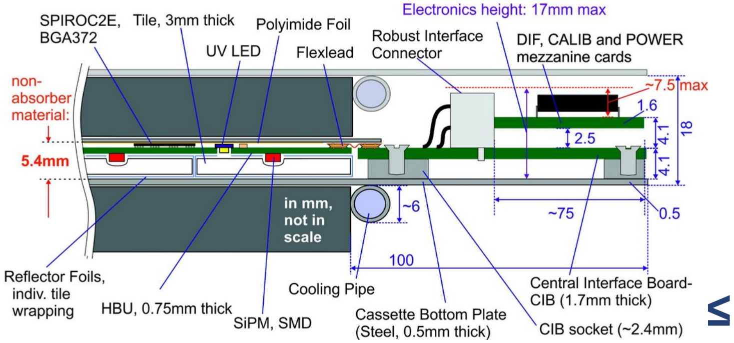


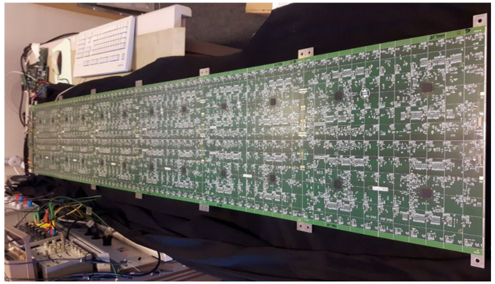
≤1.8m long

- Passive cooling

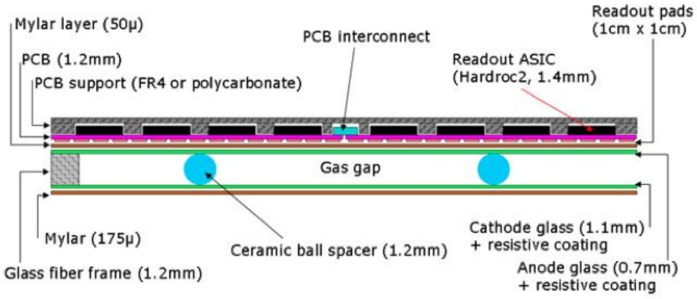


Scint Analog HCAL (also used for HGCAL)



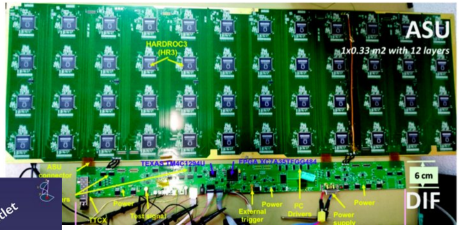


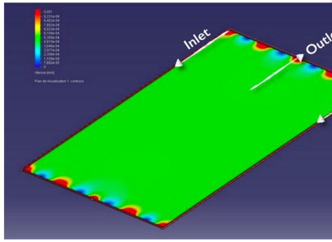
(Semi)Digital Gaseous HCAL

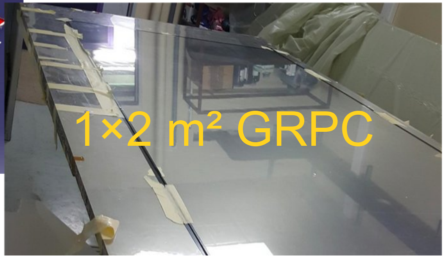


≤ 3m long

No cooling or gas flow

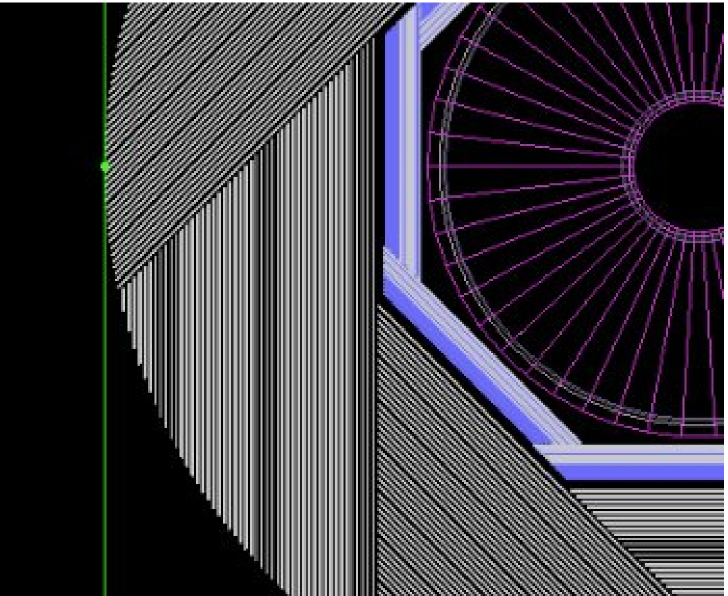


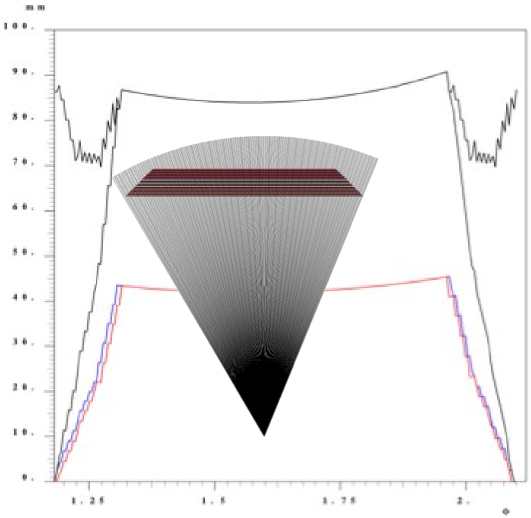


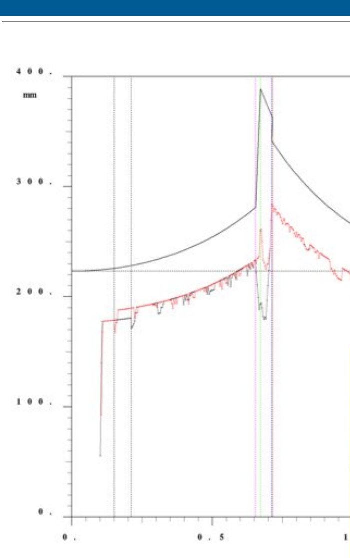


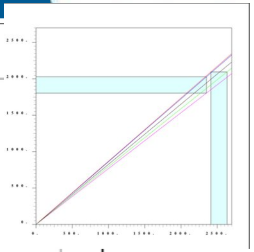
1×2 m² GRPC

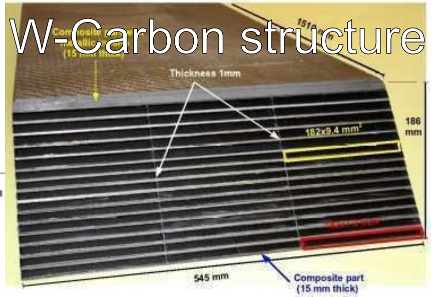
A crack-less ECAL geometry



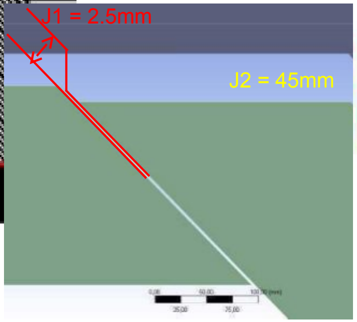


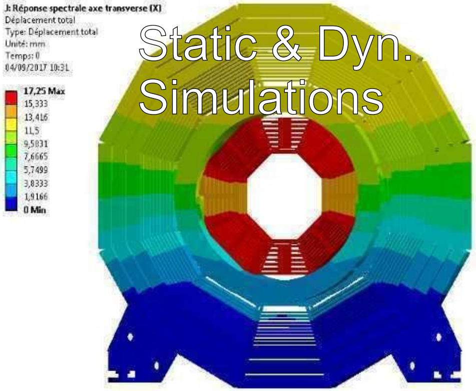


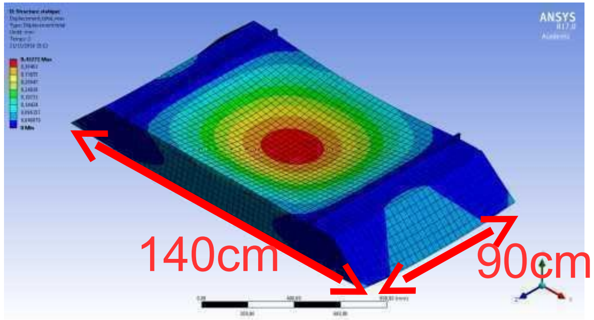



W-Carbon structure


3×1m²
Stainless Steel
Electron Beam
welded structure



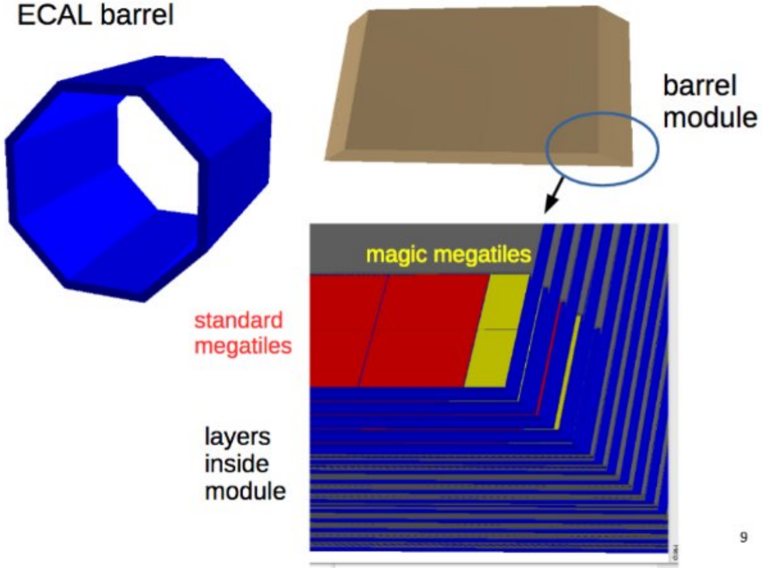

Static & Dyn.
Simulations



Simulation

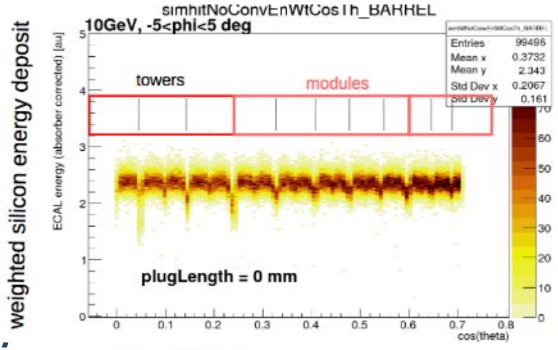
ECAL driver used in ILD models has been largely re-written (Mokka → DD4HEP)

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

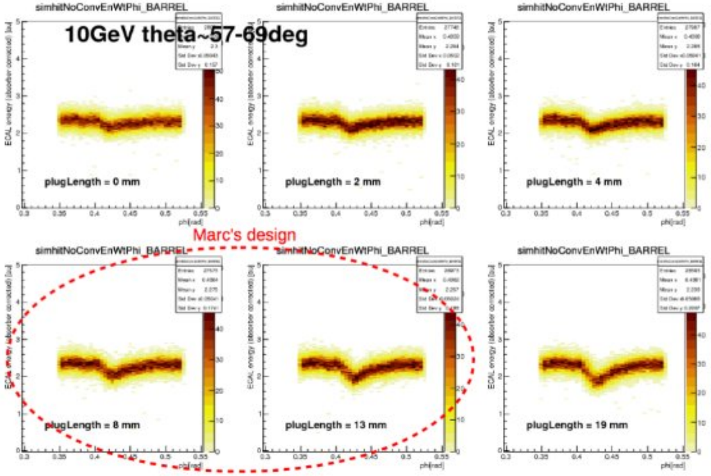


Effect of cracks [RAW= no correction at all!!]

- Drop ~ 15%



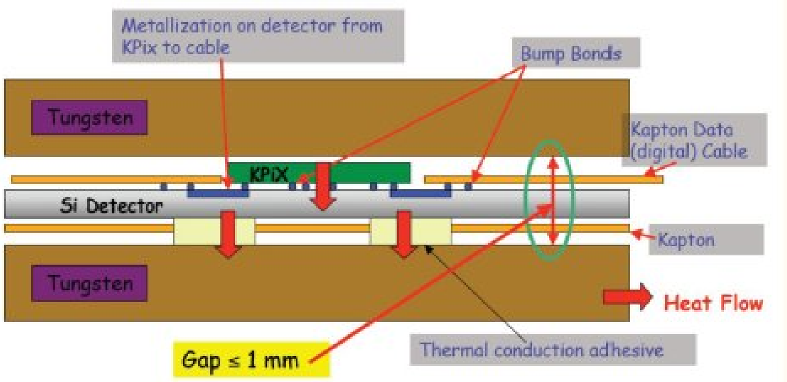
Effect of plug (missing in previous simulations)

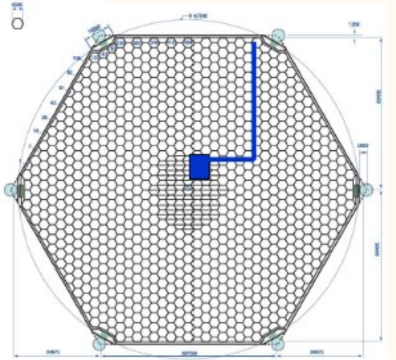


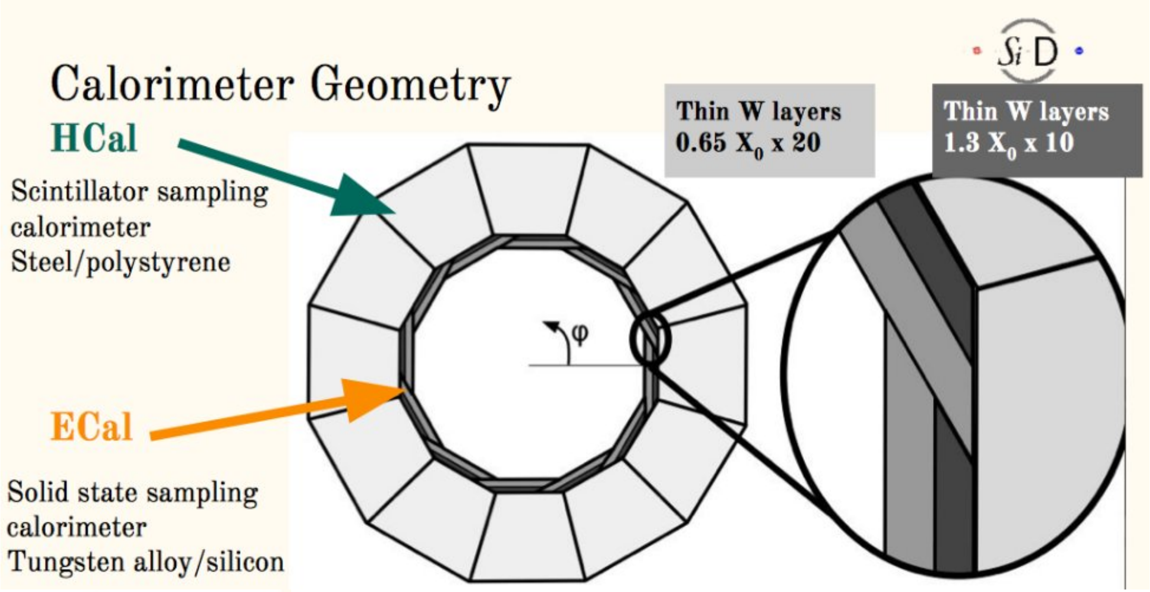
SiD SiW-ECAL

HCALS ~similar to ILD's: DHCAL, AHCAL

- 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.

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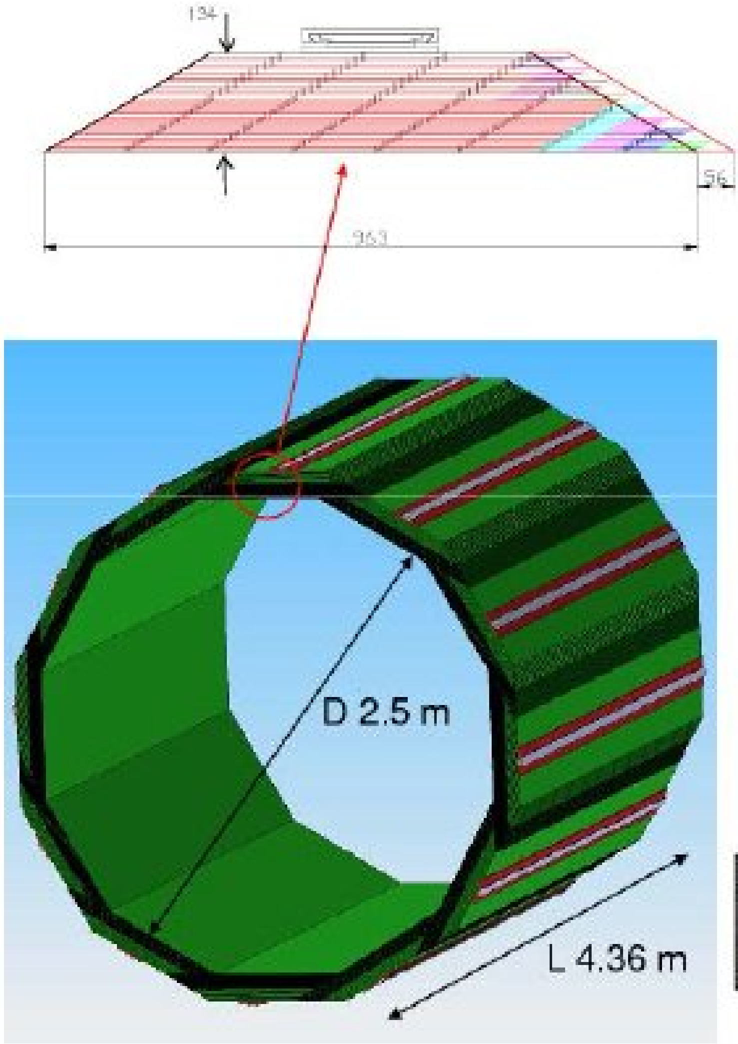
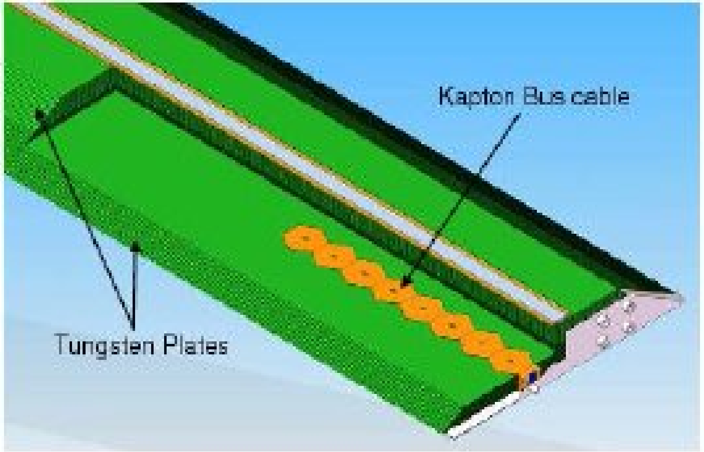
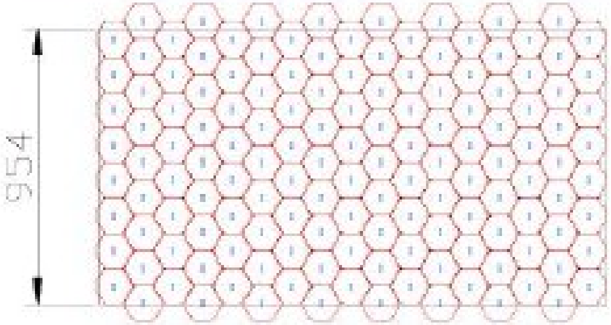
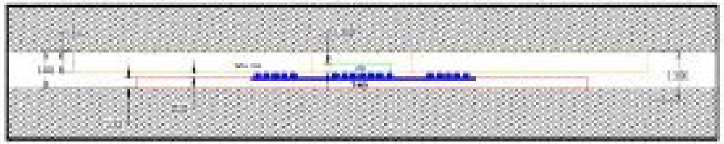






Hexagon sensors arrangement



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

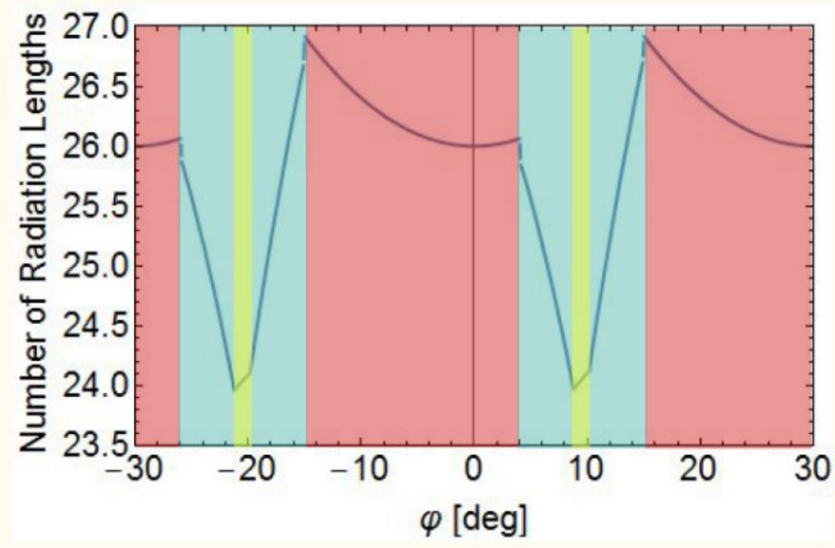
Geometry & Calibration studies

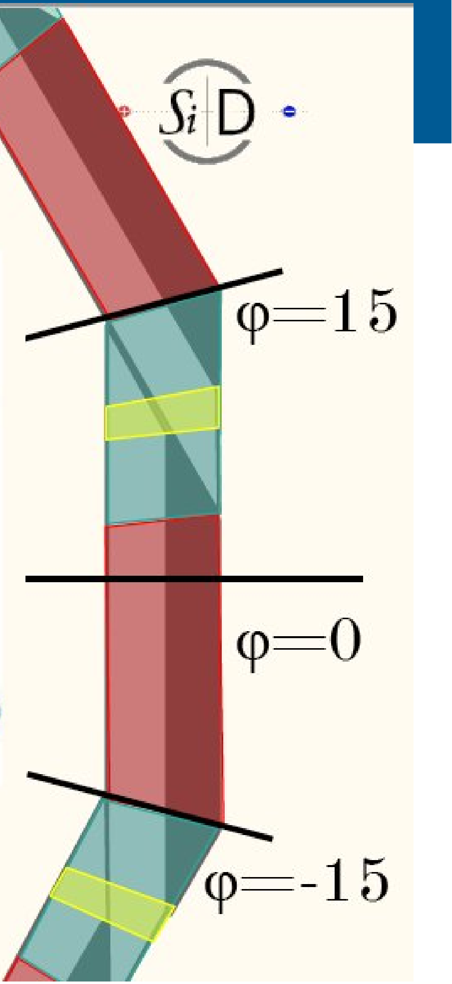
Periodic structure - φ = 30o increments

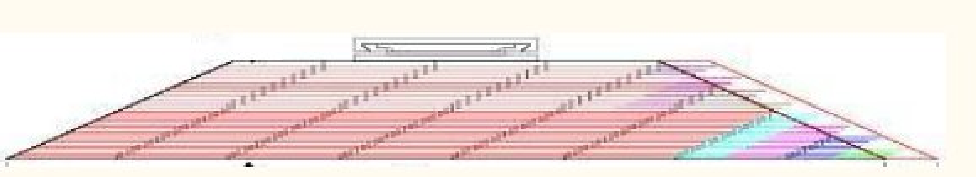
- Entire module,
- overlap region,
- thin overlap region

30% of detector coverage has overlapped modules

+ leakage corrections

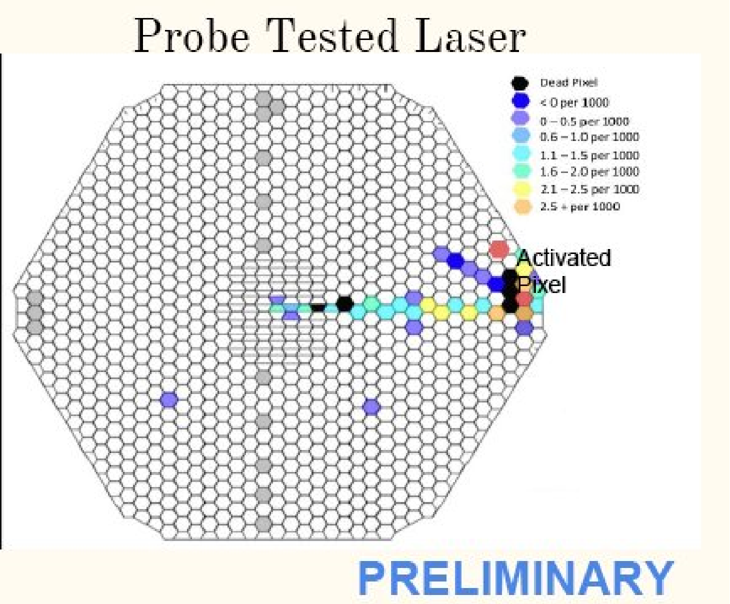




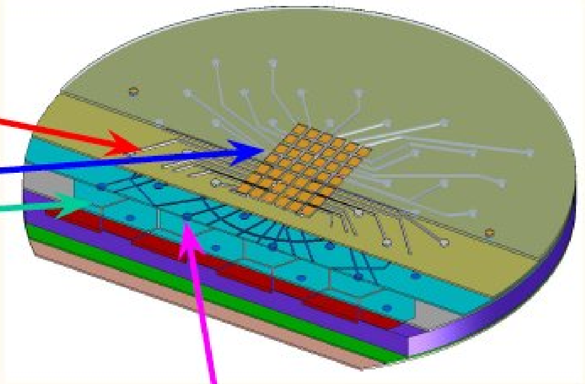


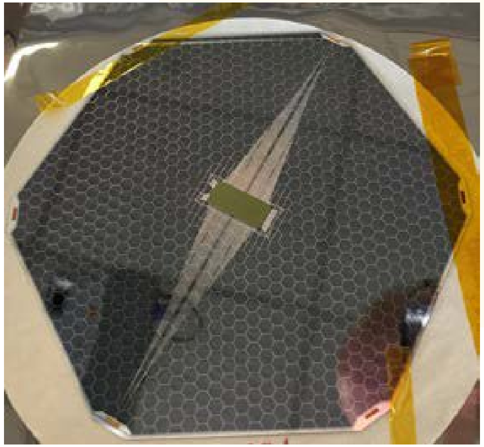
Prototype testing

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.

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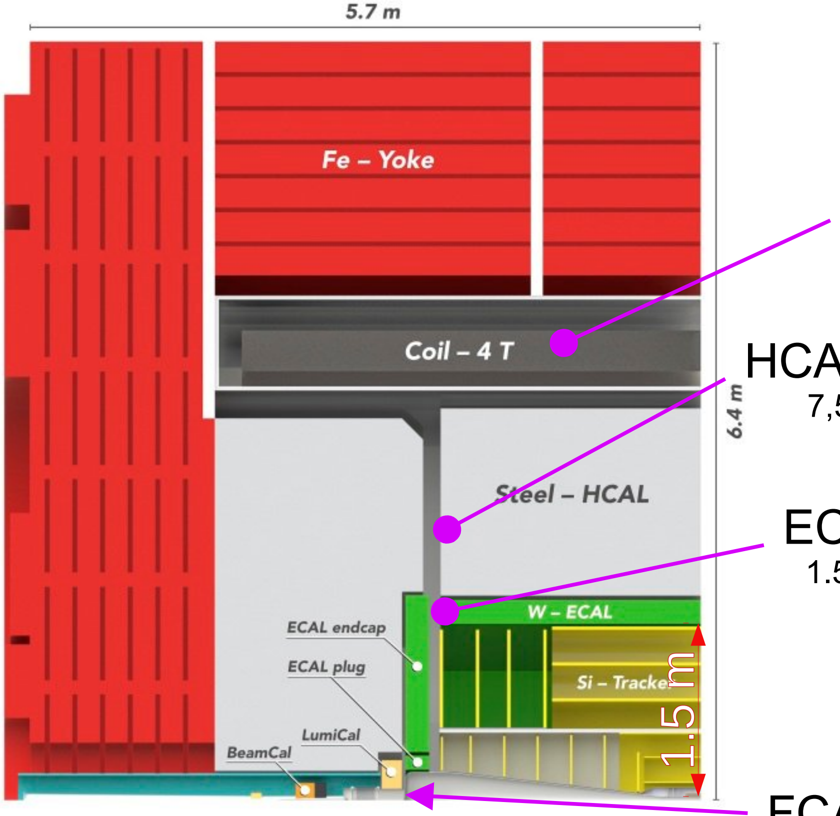
CLICdet



Coil
4T

HCAL Fe-Scint
7,5 λ_I (60 lay)

ECAL Si-W
1.5 m (40 lay)

FCAL's

CLICdp-Note-2018-005

ILD and SiD-based

CLIC:

- Energy range : 380 GeV – 3 TeV
- Beam timing :
  - at CLIC: $\Delta t_{bunches}$ = 0.5 ns; frep = 50 Hz
  - at ILC: $\Delta t_{bunches}$ = 554 ns; frep = 5 Hz
- Power Pulsing ✔

ILD-based

- SiTracker
- ECAL : 30 ➞ 40 Layers
- HCAL: 40 ➞ 60 Layers
  - (W envisaged & dropped)

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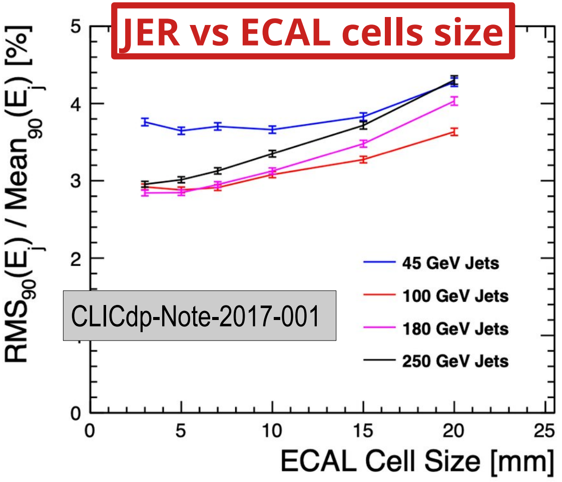
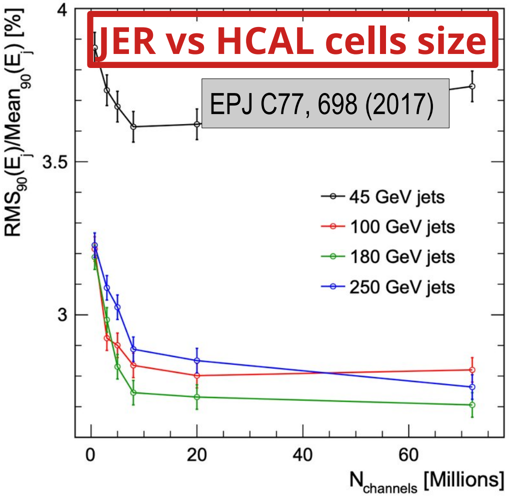
Some CLICdp optimisation studies



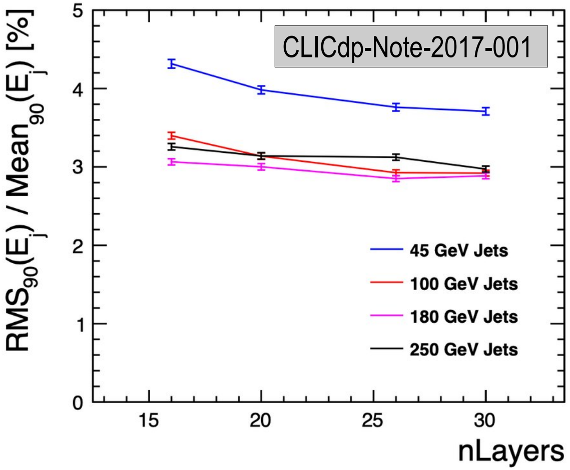
JER vs ECAL cells size

CLICdp-Note-2017-001



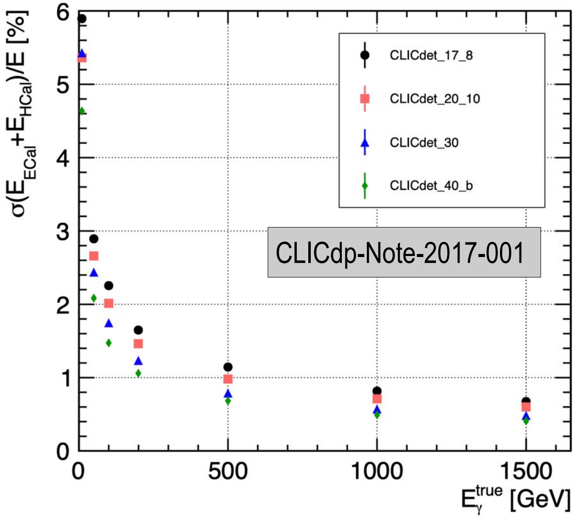
JER vs HCAL cells size

EPJ C77, 698 (2017)



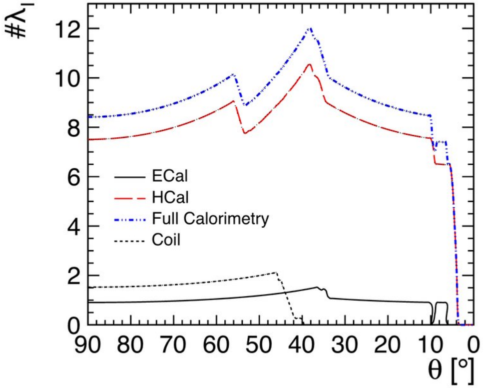
JER vs ECAL sampling

CLICdp-Note-2017-001



Photon ER vs ECAL sampling

CLICdp-Note-2017-001



Implication of HL schemes

Higher $\mathscr{L}$ ⇒

- Occupation / bunch train ↗
  - More memory for events
    - But large margins

Higher repetition rates × longer bunch

- Power = $f_{\text{rep}} \times \sum P_{\text{ASIC\_part}} \times \tau_{\text{spill\_part}}$
  - $\tau_{\text{spill}} = \tau_{\text{Ramp-up}} + \tau_{\text{Train}} + \tau_{\text{Conv}}$
    $= \mathcal{O}(\mu s) + \{ \dots \} + \mathcal{O}(100\text{'s } \mu s)$
    - $\tau_{\text{Train}} = \Delta T_{\text{bunches}} \times N_{\text{bunches}}$
    - $\tau_{\text{Conv}} \propto (\text{occupancy} + \underbrace{\text{Noise} \geq \text{thr.}})$

Critical also for Power budget

⇒ Full ZERO suppr. needed

HL-ILC:

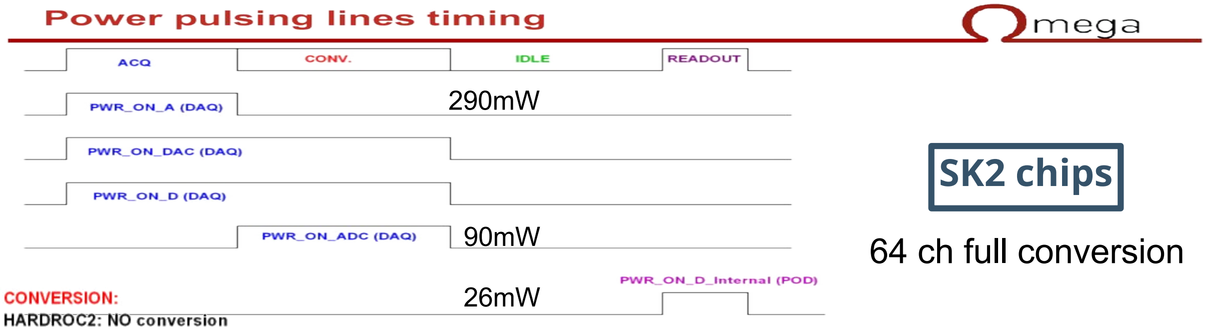
- $\mathscr{L} \times 4\ (6)$
- $N_{\text{bunches}} \times 2 :\ \tau_{\text{Train}:}\ 1 \to 2\text{ ms}$
- $f_{\text{rep}} \times 2\ (3){:}\ 5 \to 15\text{ Hz}$

Dominated by ACQ time:
P(~25µW/ch) × 6

HL-CLIC:

- $\mathscr{L} \times 2$
- $N_{\text{bunches}} \to\ :\ \tau_{\text{Train}:}\ 176\text{ ns}$
- $f_{\text{rep}} \times 2 : 50 \to 100\text{ Hz}$

Dominated by Set-up & Conversion time: P (~82µW/ch) ×2



SK2 chips

64 ch full conversion

CONVERSION:
HARDROC2: NO conversion
SPIROC2: max time (Full chip)= 16 SCAx 2 (HG or LG/Time) x103 µs=3.2ms
SKIROC2: max time (Full chip)= 15 SCA x2 (HG or LG/Time) x103 µs= 3 ms

READOUT:
HARDROC2: 127 (memory depth)x [64 channelsx 2 trigger bits + 24 BCID bits + 8 Header bits]=20 320 bits => 200 nsx20k=4 ms/ Full Chip (WORST case)
SPIROC2: 16 SCAx2 (HG or LG/Time) x 36 ch x 16 ADC bits + 16 SCAx16 BCID bits + 16 Header bits= 18 704 bits => 3.8 ms/Full Chip (Worst case)
SKIROC2: 15 SCAx2 (HG or LG/Time) x 64 ch x 16 ADC bits + 15 SCAx16 BCID bits + 16 Header bits= 30 976 bits => 6 ms/Full Fhip (Worst case)

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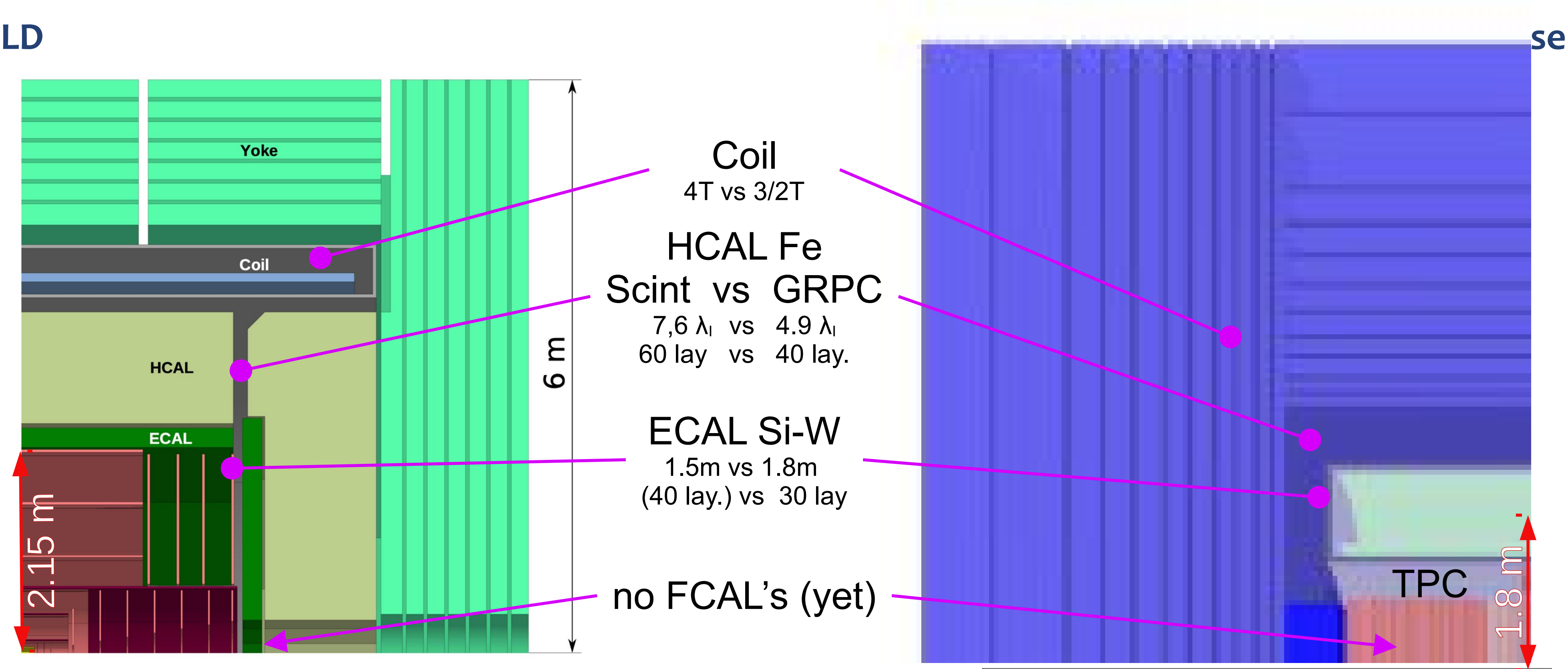
FCC-ee CLD & CEPC ‘baseline’

CLD

seline



Coil
4T vs 3/2T

HCAL Fe
Scint vs GRPC
7,6 λ_I vs 4.9 λ_I
60 lay vs 40 lay.

ECAL Si-W
1.5m vs 1.8m
(40 lay.) vs 30 lay

no FCAL’s (yet)

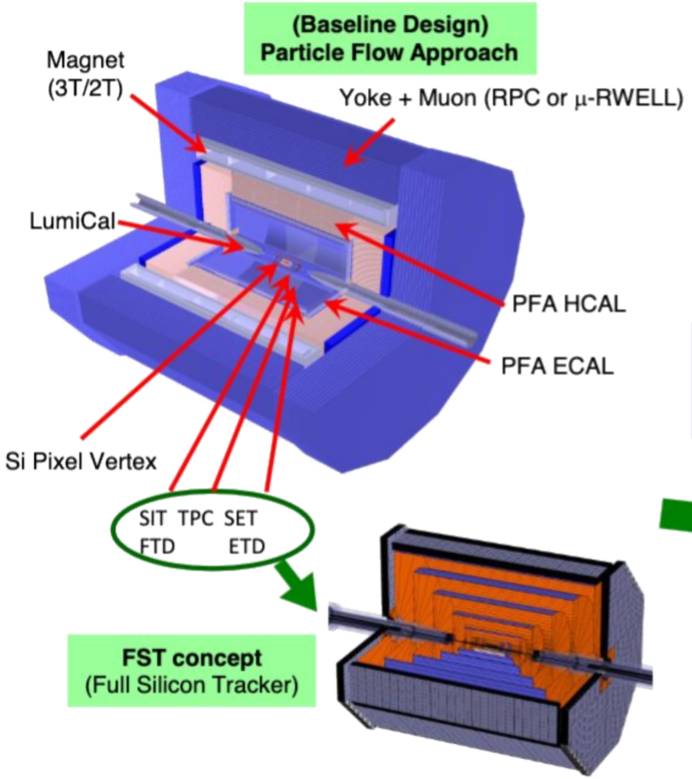
LCD-Note-2019-001

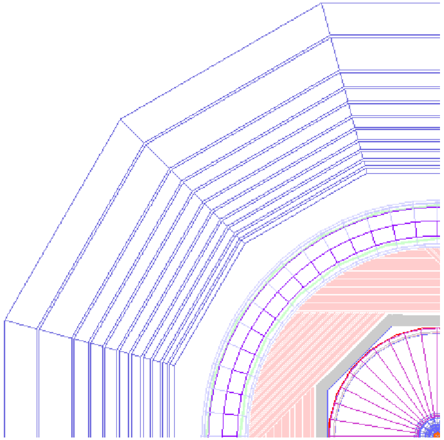
CLICdet based

ILD-based

CEPC CDR (2018)
G. Li @ ECFA HF : 1st topical meeting on simulations, Feb. 2022

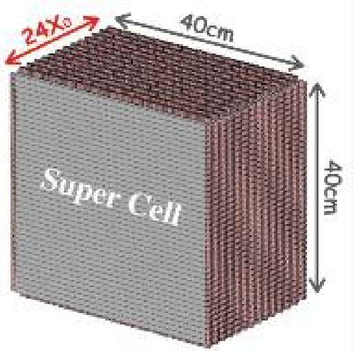
CEPC Baseline Options





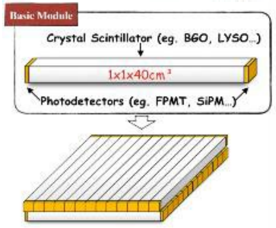
ECAL:

- **SiW-ECAL :**
- Strip scintillators
- Crystals



HCAL:

- **SDHCAL**
- Scintillators (AHCAL)



Linear vs Circular Collider’s Conditions

Linear (ILC, HL-ILC…)

- 250 GeV (ZH), 365 GeV (tt), 500 GeV (ZHH) + [1000 GeV], $\mathscr{L} \sim$ cst.
- Power pulsing : 5 [10–15]Hz × 1 [2] ms

HL-ILC:

- $\mathscr{L} \times 4\ (6)$
- $N_{\text{bunches}} \times 2:\ \tau_{\text{Train}}: 1 \rightarrow 2$ ms
- $f_{\text{rep}} \times 2\ (3): 5 \rightarrow 15$ Hz

Dominated by ACQ time:
P(~25µW/ch) × 6

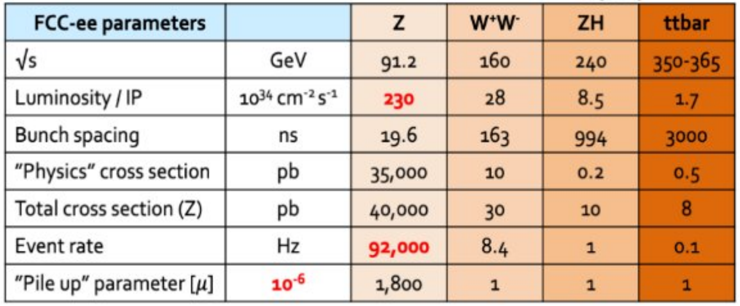
HL-CLIC:

- $\mathscr{L} \times 2$
- $N_{\text{bunches}} \rightarrow:\ \tau_{\text{Train}}: 176$ ns
- $f_{\text{rep}} \times 2: 50 \rightarrow 100$ Hz

Dominated by Set-up &
Conversion time: P (~82µW/ch) ×2

Moere diverse et stringer conditions:

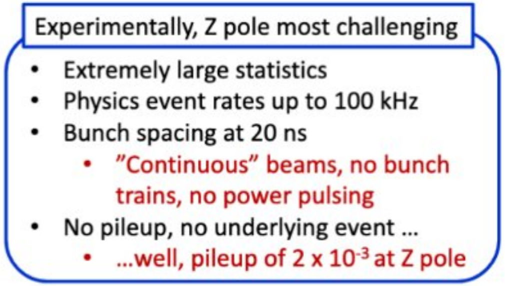
- 90GeV × 10^7 fb × $5{\cdot}10^{36}$ cm^{-2} s^{-1} (qq × 20,000 ILC @ 250)
- 150 GeV (WW) + 250 GeV (ZH)+ 365 GeV (tt)
  ~10^4 fb × $5{\cdot}10^{35}$ cm^{-2} s^{-1} (qq × 5–10 ILC @ 250)



FCC-ee parameters		Z	W⁺W⁻	ZH	ttbar
√s	GeV	91.2	160	240	350-365
Luminosity / IP	10^{34} cm^{-2}s^{-1}	230	28	8.5	1.7
Bunch spacing	ns	19.6	163	994	3000
"Physics" cross section	pb	35,000	10	0.2	0.5
Total cross section (Z)	pb	40,000	30	10	8
Event rate	Hz	92,000	8.4	1	0.1
"Pile up" parameter [μ]	10^{-6}	1,800	1	1	1

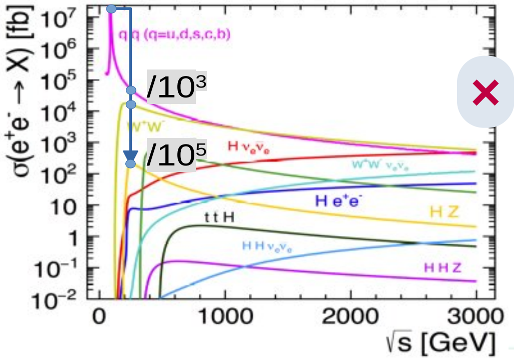
From Pulsed to Contious operation

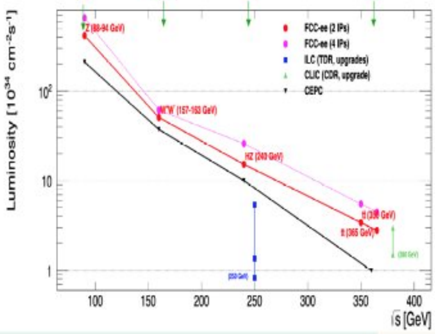
- ASIC, Power/Cooling, DAQ, *Granularity*, *Precisions (E, t)*, New ideas…



Experimentally, Z pole most challenging

- Extremely large statistics
- Physics event rates up to 100 kHz
- Bunch spacing at 20 ns
  - "Continuous" beams, no bunch trains, no power pulsing
- No pileup, no underlying event …
  - …well, pileup of 2 x 10^{-3} at Z pole





https://indico.cern.ch/event/1064327/contributions/4893208/
Mogens Dam @ FCC Week, 10/06/2022

Detector Parameters: scaling rules

- Cell lateral size
  - Shower separation (EM~2×cell size)
  - Cell time resolution (1 cm/c ~ 30 ps)
    - Time performance for showers
      - ParticleID, easier reconstruction
- Longitudinal segmentation
  - sampling fraction
    - E resolution (ECAL ~15%/√E)
  - shower separation/start
- ECAL inner radius; Barrel Z_{Start}
- ECAL–HCAL distance
- Barrel–Endcap distance
- Dead-zones sizes (from Mechanics, Cooling)

Number of cells ↗ ⇒ Cost ↗ (1/size^2)
Cell density ↗ ⇒ Power consumption ↗
Time resolution ↘ ⇒ Power ↗

threshold, passive vs active
cooling
dead-zones ↗

NEED TO BE FULLY RE-EVALUATED
for EW region
→ Cooling change ?
→ New electronics !

Inner Radius ↗ ⇒ Tracking performance ↗
Cost ↗^{2} (⊃ Magnet, Iron)
Gaps ↗ ⇒ PFlow performances ↘

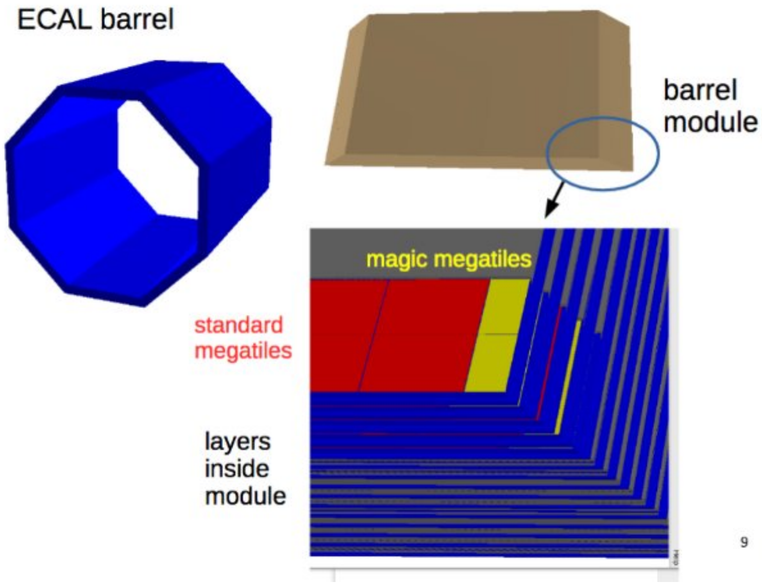
Review of physical implication (from TeV): see Linear collider detector requirements and CLD, F. Simon @ FCC-Now (nov 2020)
Physics Requirement studies @ 250 GeV: see Higgs measurements and others, M. Ruan @ CEPC WS, (nov 2018)

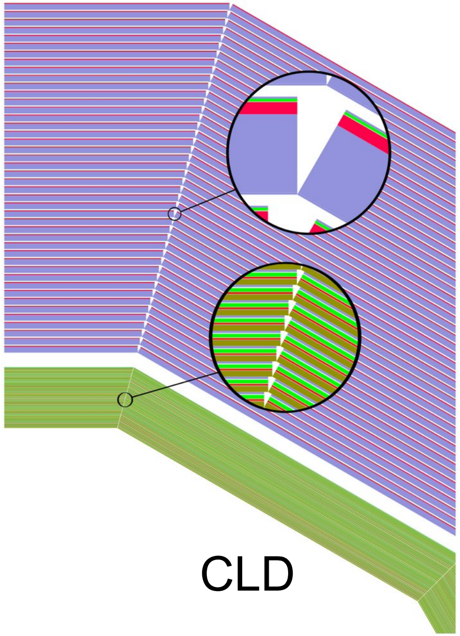
Software

Full Simulations:

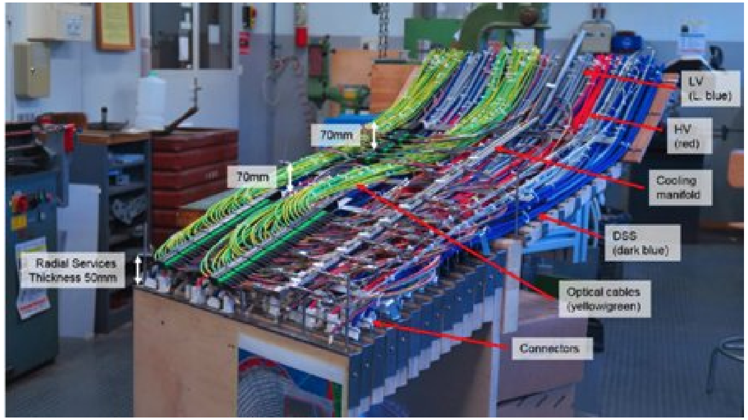
- All models in DD4SIM (⊃ beam tests)
  - Sharing of models easier
- ILD Model: dual technology
  - No PCB's
    - Scint layer AND Silicon layer
    - GRPC and Scintillators
- Simpler models in CLICdet, CLD, CEPC baseline

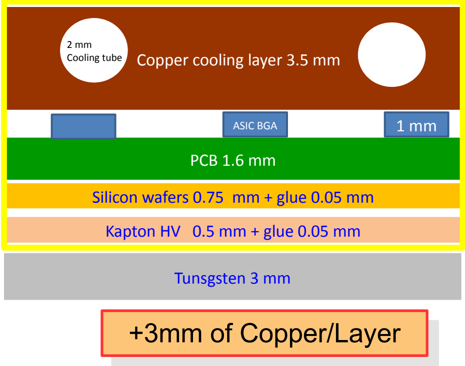
ILD



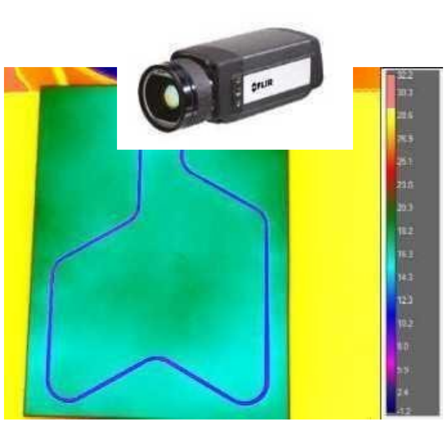


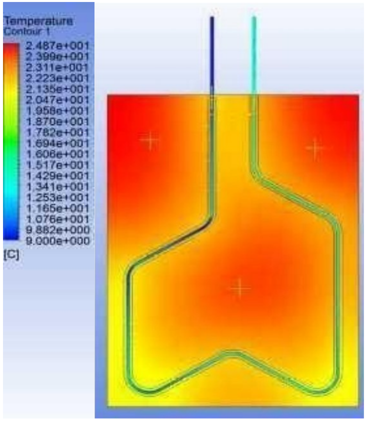
Services: integration & cooling





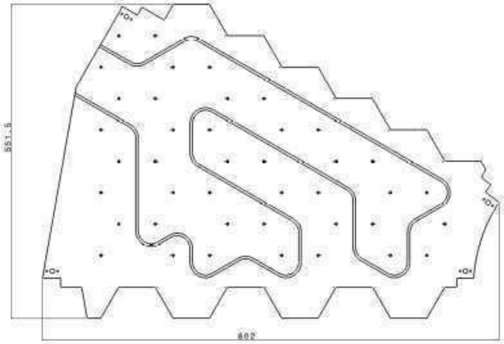
+3mm of Copper/Layer

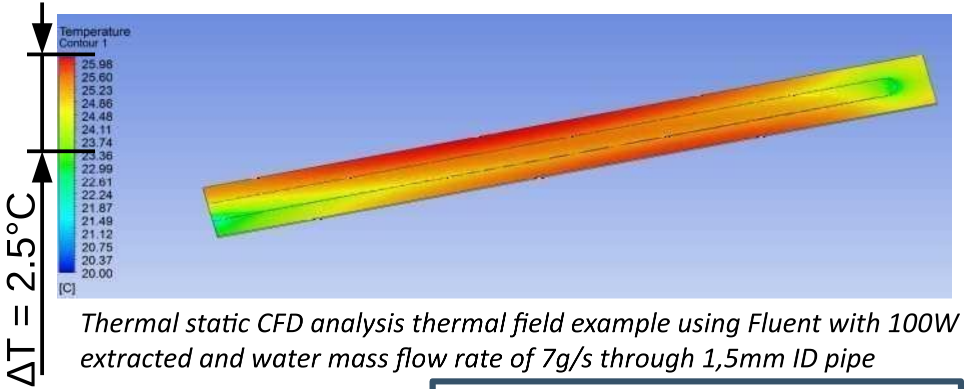




Pipe insertion on a cooling prototype

- Pipe insertion process introduces some efficiency loss due to the thermal contact resistance.
- The benefit remains significant with regard to a passive cooling

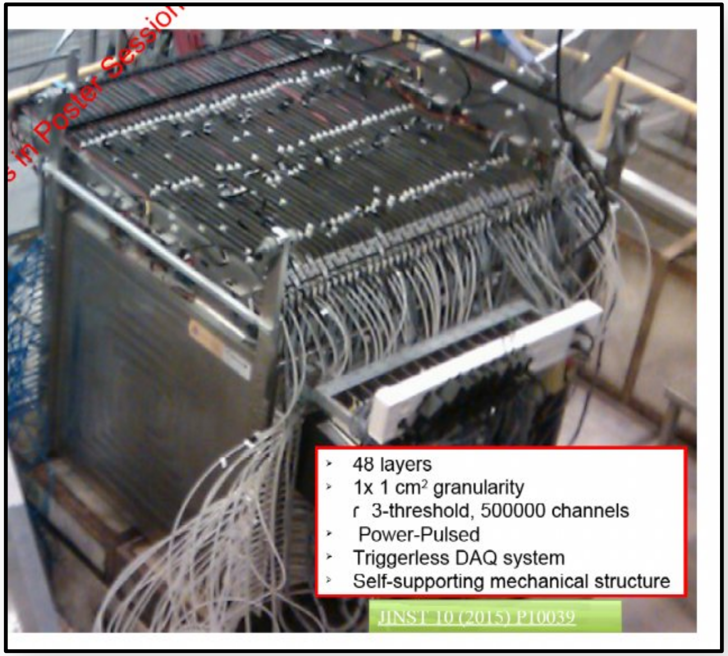




Thermal static CFD analysis thermal field example using Fluent with 100W extracted and water mass flow rate of 7g/s through 1,5mm ID pipe

= 2× cont. operation of a SLAB

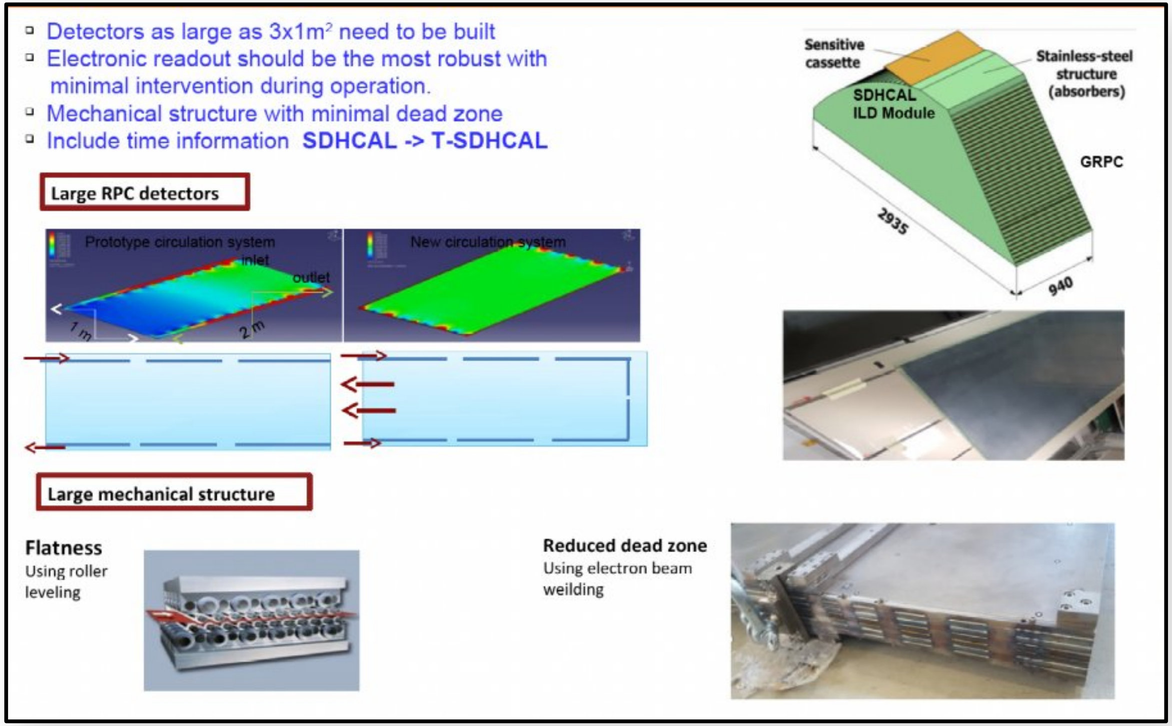
CALICE SDHCAL



s in Poster Session

- 48 layers
- 1x 1 cm² granularity
- 3-threshold, 500000 channels
- Power-Pulsed
- Triggerless DAQ system
- Self-supporting mechanical structure

JINST 10 (2015) P10039



- Detectors as large as 3x1m² need to be built
- Electronic readout should be the most robust with minimal intervention during operation.
- Mechanical structure with minimal dead zone
- Include time information **SDHCAL -> T-SDHCAL**

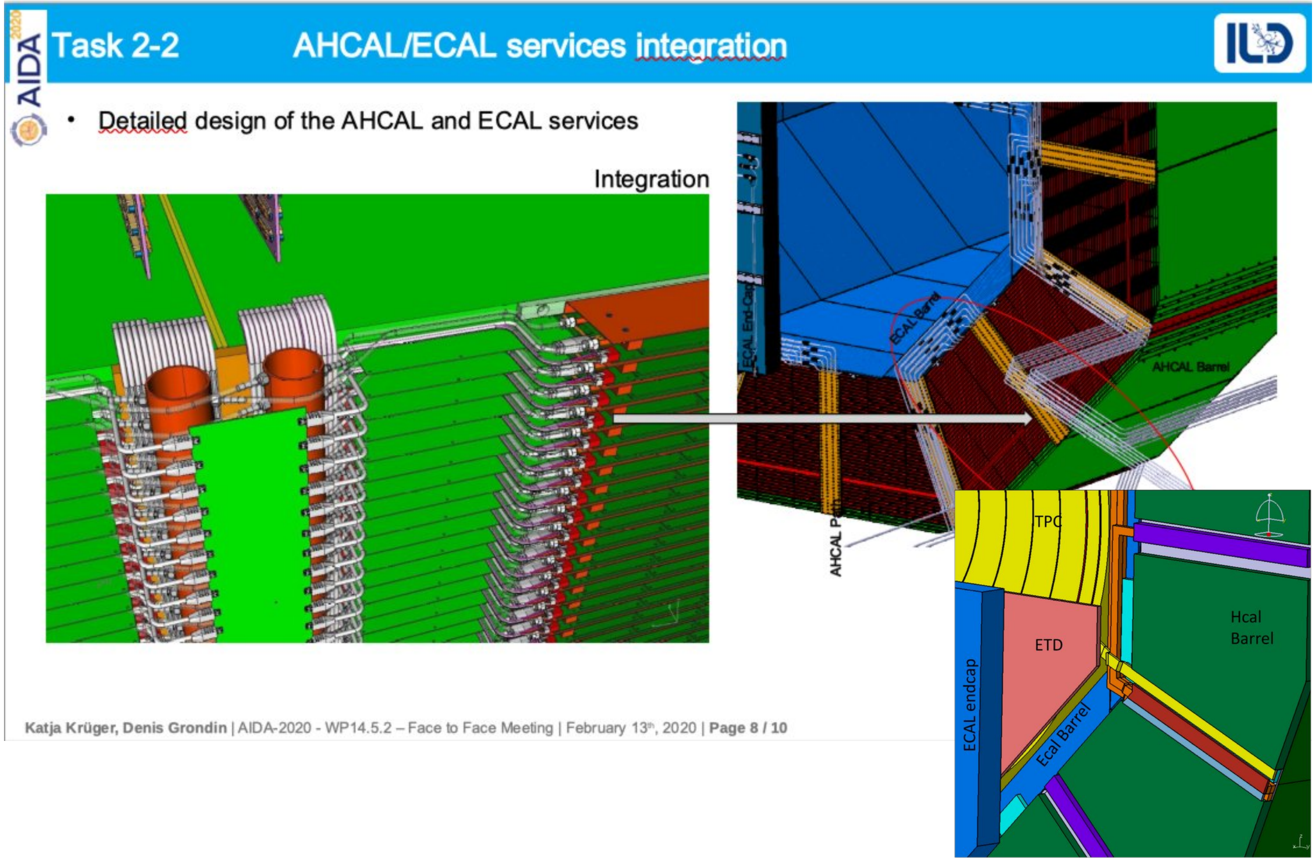
Large RPC detectors

Large mechanical structure

Flatness
Using roller leveling

Reduced dead zone
Using electron beam weilding

Services: integration & cooling

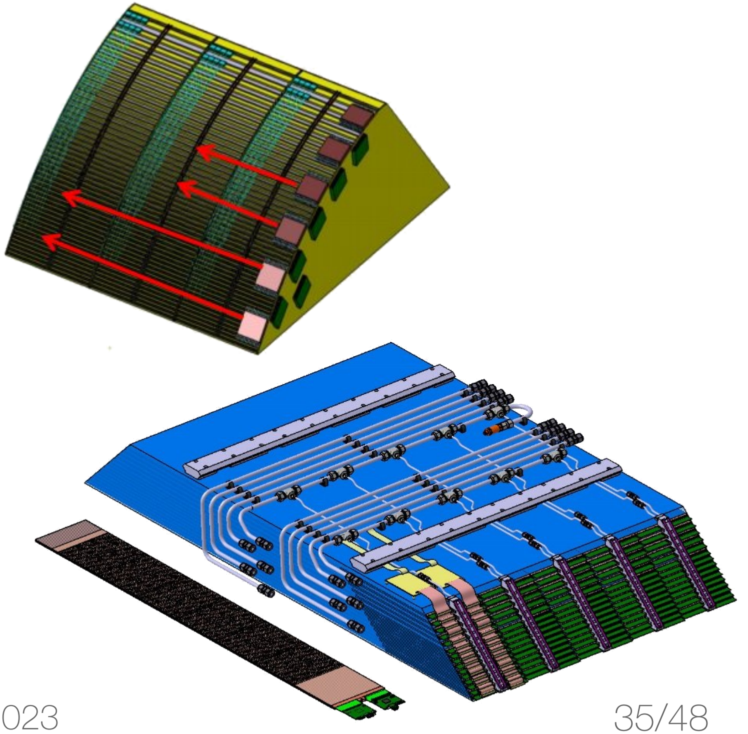


Task 2-2 AHCAL/ECAL services integration

- Detailed design of the AHCAL and ECAL services

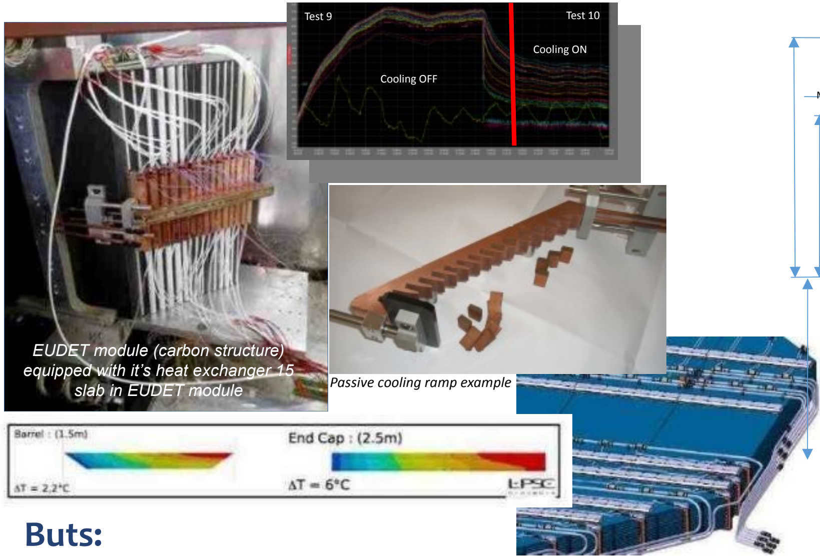
Integration

Katja Krüger, Denis Grondin | AIDA-2020 - WP14.5.2 – Face to Face Meeting | February 13th, 2020 | Page 8 / 10



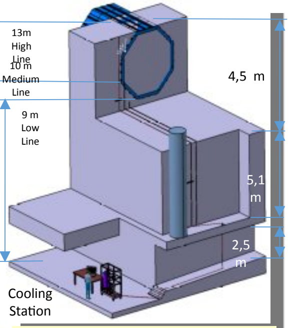
Leakless Water cooling system

Thermique/Intégration



EUDET module (carbon structure) equipped with it's heat exchanger 15 slab in EUDET module

Passive cooling ramp example



LPSC cooling test area with a drop of 13 m

Cooling station

Buts:

- Heat evacuation at end of slabs
- Caloduc compatible with ECAL–HCAL spacing (3 cm)
- Leakless (depression)

Modèle : sur module pilote

Maquette 1: 1:1

- simple circuit

Maquette 2: 3:4

- heat model in C-W structure

To Do:

- **Test sur on a full ECAL module**

For FCC-ee:

- 1) Dimensioning for continous working, if possible, without active cooling
- 2) if not, include a active cooling CO_2 (in Cu or W)

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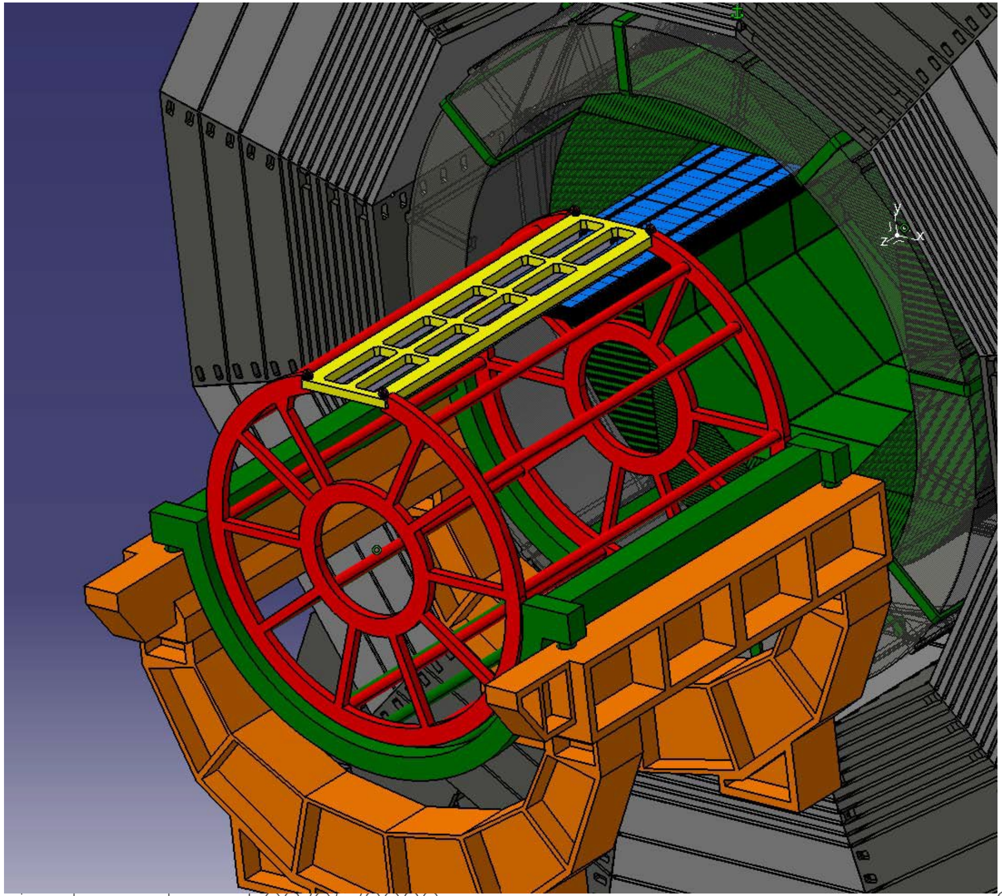
Building tools and procedure

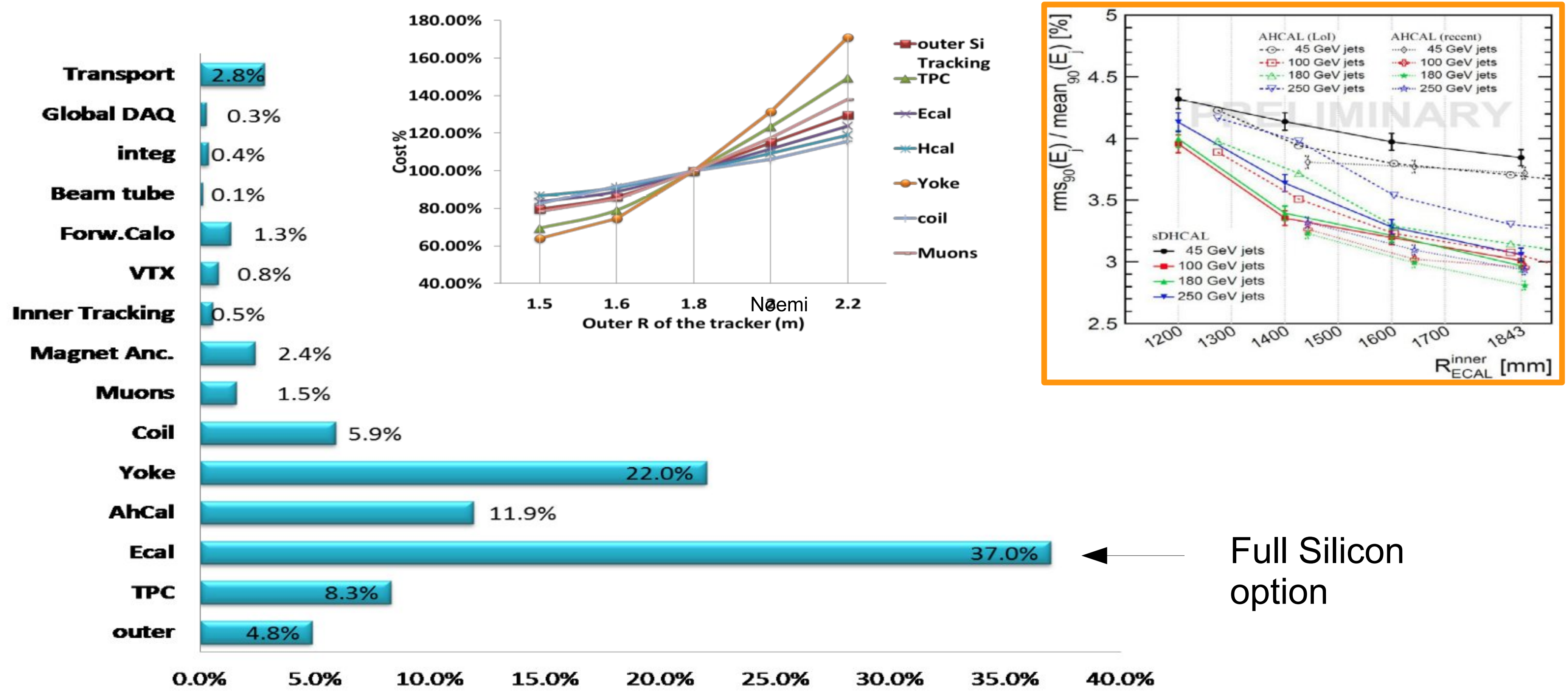
Documented for ILD

- incuding space and manpower estimations

Handling and positioning tool for integration & tests



Cost Structure of ILD



Full Silicon option

FCAL Collaboration: LumiCal & BeamCAL

Needs to be adapted for FCC (Mechanical precision)

LumiCal :

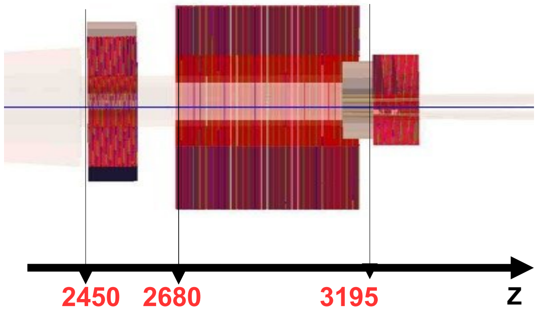
- Precise integrated luminosity measurements (Bhabha events)
- Extend calorimetric coverage to small polar angles. Important for physics analysis

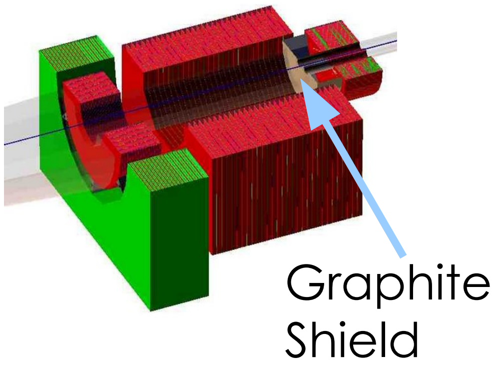
LHCal :

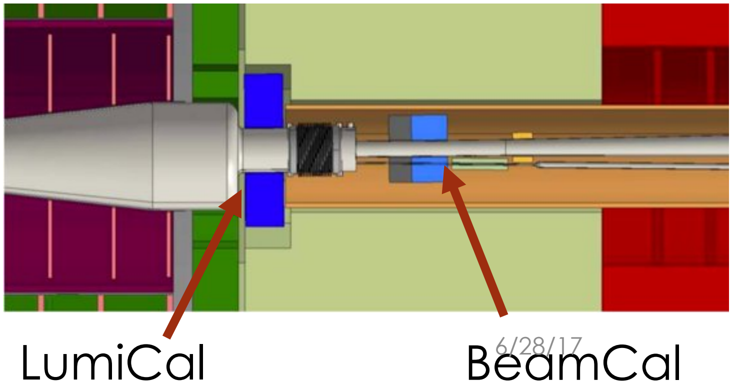
- Extend the hadronic calorimeter coverage
- 29 layers of 16mm thickness. Absorber : tungsten or iron

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)





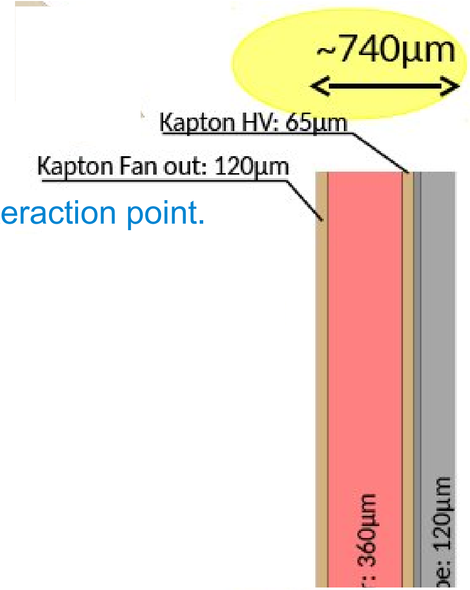


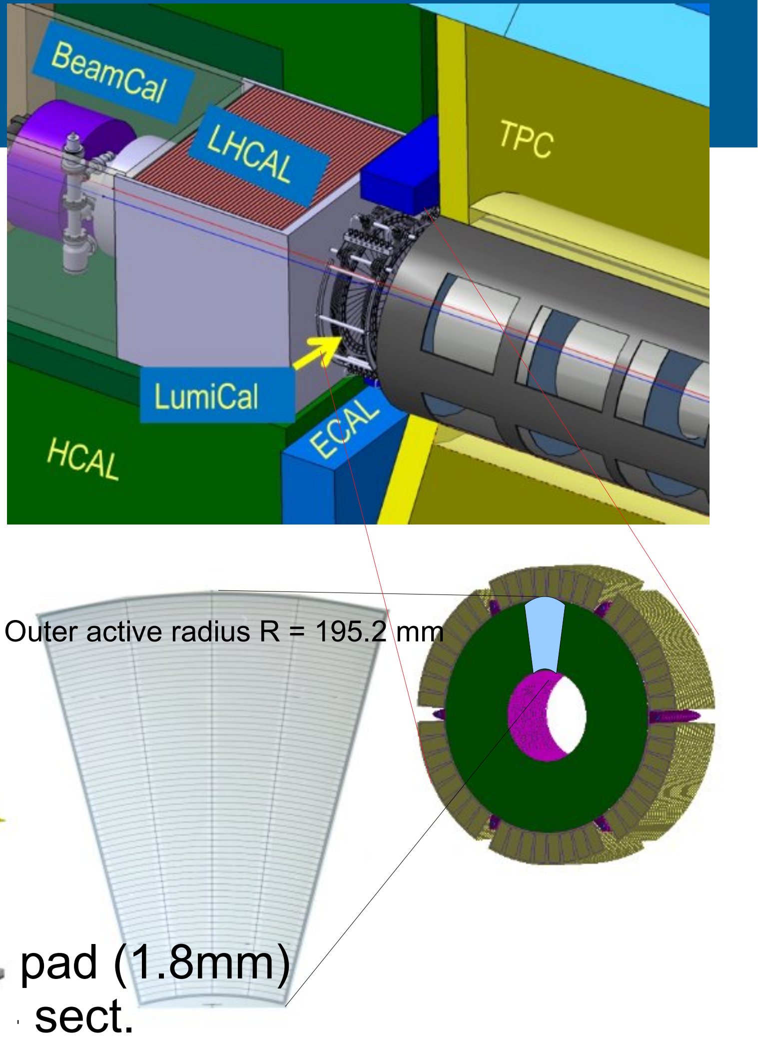
FCAL collaboration: LumiCal

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

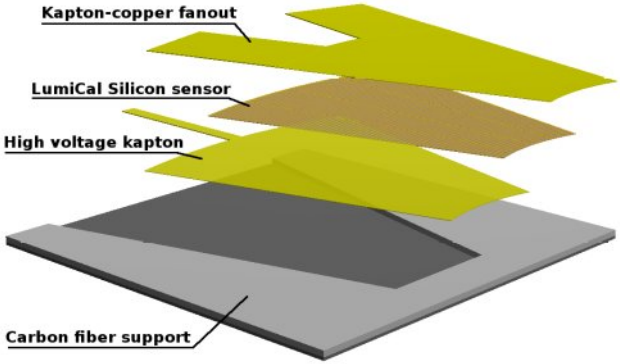




Outer active radius R = 195.2 mm

pad (1.8mm)

sect.

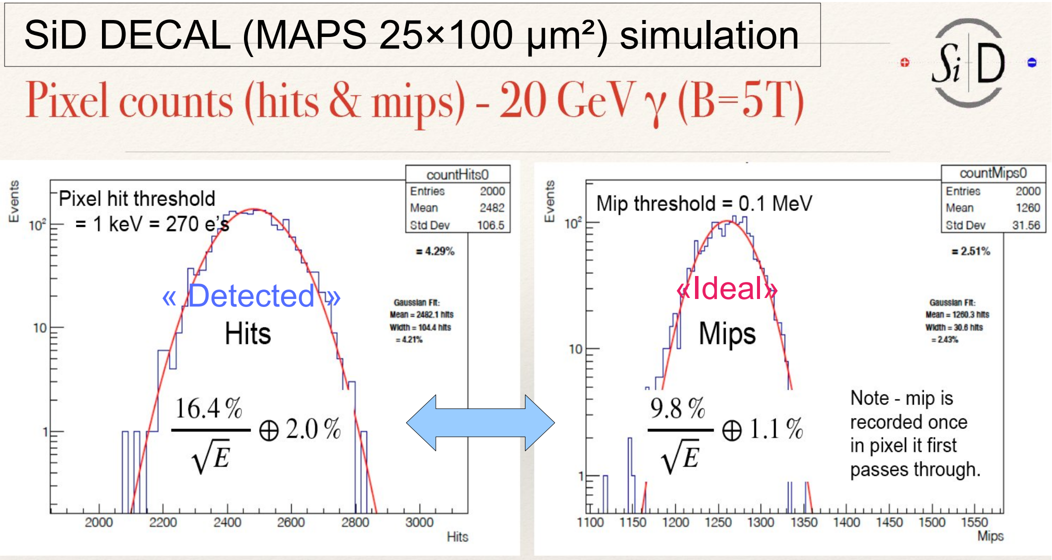


[NEW] Optimisation of a Digital Readout

Digital readout:

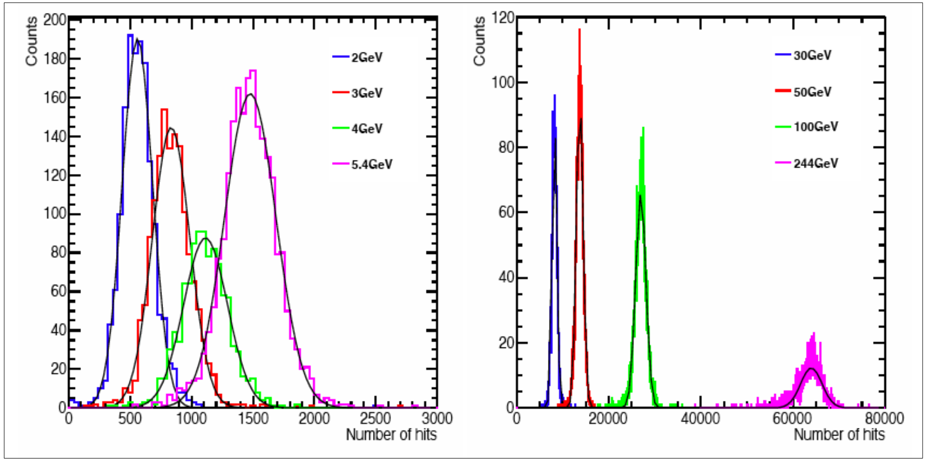
- Count “hits” = number of readout cells above a threshold
  - Best Threshold ? ½ ~ ¼ of a MIP = Minimum Ionising Particle, perp. to the sensor ≡ ~ minimum signal for a particle
- Known : Very good behaviour with 100–25 mm² cells at low E (few GeV)
- ~New: excellent behaviour with very small cells (using MAPS):

SiD DECAL (MAPS 25×100 µm²) simulation

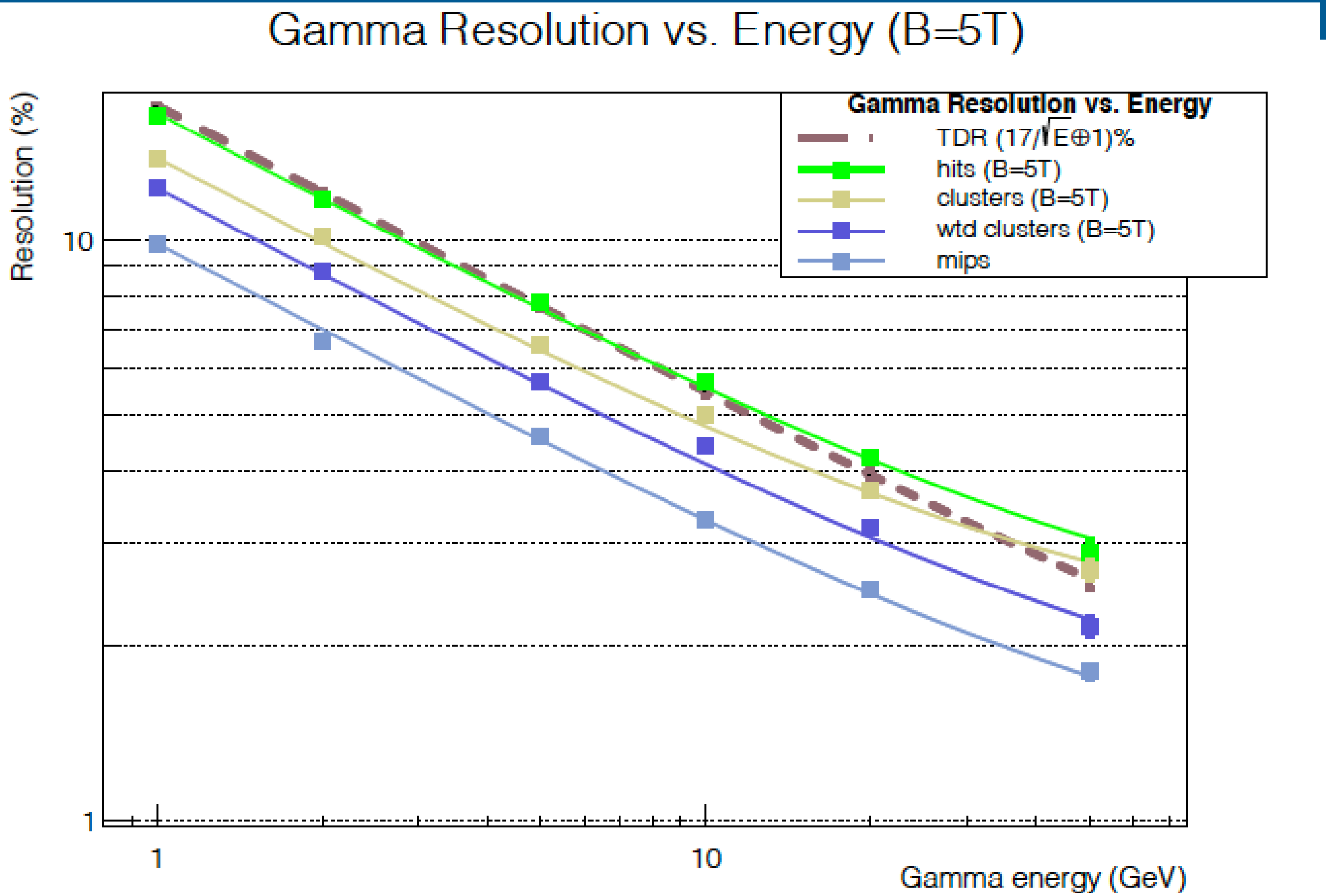


Note - mip is recorded once in pixel it first passes through.

Real prototype :
FOCAL prototype (↔ ALICE) [see APICAL2 as well]
MIMOSA23 MAPS, 640×640 arrays of (30 µm)² pixels

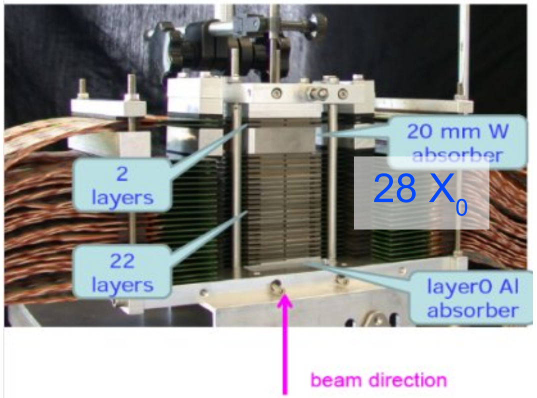


SiD Simulations



MAPS & DECAL

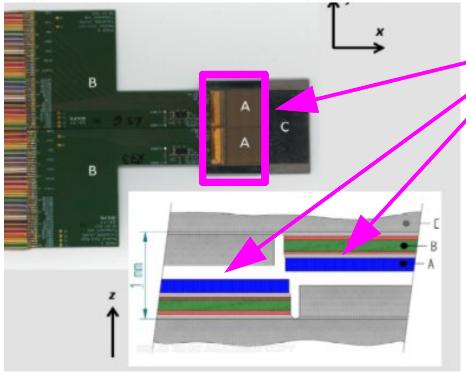
FOCAL DECAL prototype



FOCAL = 2 layers of MAPS

but How to build a full detector ?

- Services: Power + Cooling ?
  - Gains by going fully digital ?
- For what physical gain ?
  - Improved separation ✔
  - Improved resolution ?

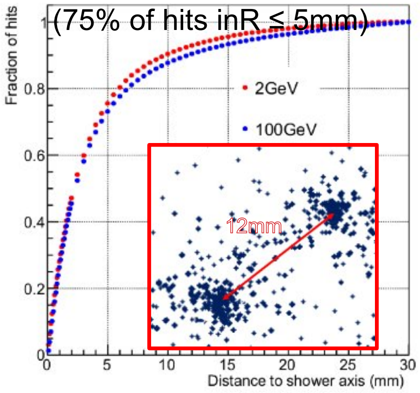


4 MIMOSA-26 / Layer
CMOS sensors (IPHC)

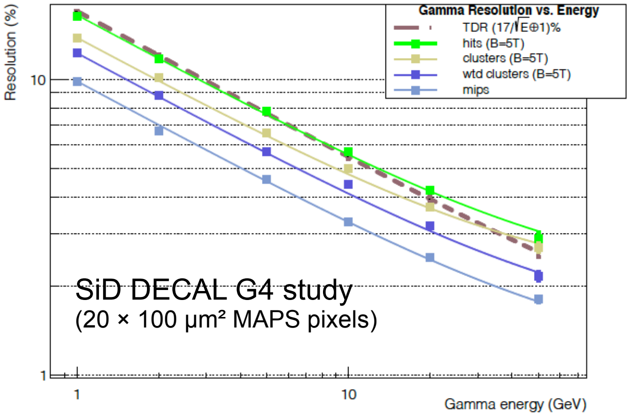
- 6×6 cm²
- 30×30 µm² pixels
- 39 M pixels
  = full readout

R_M = 10.5mm

(75% of hits in R ≤ 5mm)



Gamma Resolution vs. Energy (B=5T)



SiD DECAL G4 study
(20 × 100 µm² MAPS pixels)

Detector concepts for PF

Calorimeters ILD, SiD, CLIC-Dp, CEPC-Baseline

- Many similarities
  - Magnet outside
  - Compact design, min dead space,
  - small gap ECAL–HCAL
- Small differences:
  - Inner diameter
  - Granularity: cell-size, number of layers
  - Sensor's technology (next slides)

Differences in level of details in implementations

- Simulation, costs
- Integration of services:
  - power, cooling, readout

Geometry:

- ECAL hangs to
  HCAL hangs to
  Coils
- for ILD: 2 geometry explored for the HCAL
  - TESLA : barrel made of staves (sectors)
    - electronics between barrel and endcaps
  - «a la Videau» / H1: barrel made of rigid wheels
    - services outside (cooling , power, readout interface)

Base elements of HG PFlow calorimeters:

- "Standard" stitchable elements with embedded FE (ASIC's) driven at a single end.
  - gases, power, readout, cooling

High Granularity Calorimetry Ins & Outs

Pluses

- Small constant term
- Particle Tracking (with mip sensitivity)
  - “online” Calibration
- new Particle ID tools
  - Shower shapes, Fractal Dim, Tracks in calo, ...
- SW compensations
  - Global (density) ↔ EM fraction
  - Start of shower → leakage corr.
  - in-calo tracking
    - "Not yet fully exploited"
    - new estim.
    - loss leakage,

Minuses

- Complex Calibration (100M+ channels)
- System: Power & Cooling, Integration

Scaling laws

- cell size = d, N_{layers}
- Sensor & Electronics cost, power ~ $1/d^2 \times N_{layers}$
- Raw timing precision ~ d/2 / (2/3c) (25 ps for 1 cm)
- FE elect. power ~ ...

Conclusions

Linear Colliders

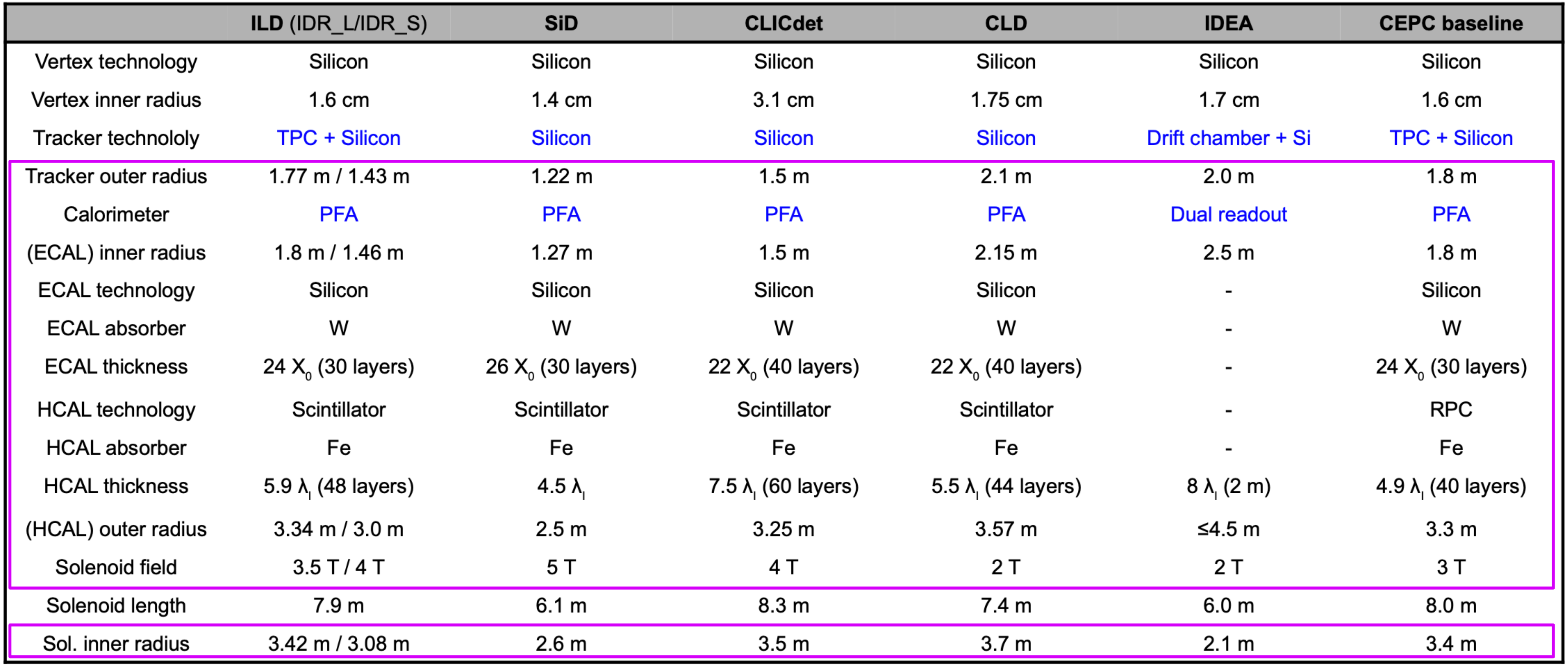
- Mature technologies & designs
- Marginal (?) gains from optimisation ?
  - Gain from timing ➞ PID, PFA, Event Cleaning

Circular Colliders Calorimeters

- Large effort still needed
  - (e.g. CEPC baseline ≠ FCC-ee)
    - ILD collaboration joined the effort (late 2022)
- Many technological options explored
  - Will require in-depth performance comparisons

Common tools:

- Simulation (dd4sim, key4hep)
- Reconstruction SW (key4hep)
  - ⬌ beam test data
- ASICs ? DRD6 new chips
- Services & Scaling
  - TDAQ
  - Cooling
  - Global power/thermal simulations
  - Mechanical simulations (⊃ coil)



	ILD (IDR_L/IDR_S)	**SiD**	**CLICdet**	**CLD**	**IDEA**	**CEPC baseline**
Vertex technology	Silicon	Silicon	Silicon	Silicon	Silicon	Silicon
Vertex inner radius	1.6 cm	1.4 cm	3.1 cm	1.75 cm	1.7 cm	1.6 cm
Tracker technololy	TPC + Silicon	Silicon	Silicon	Silicon	Drift chamber + Si	TPC + Silicon
Tracker outer radius	1.77 m / 1.43 m	1.22 m	1.5 m	2.1 m	2.0 m	1.8 m
Calorimeter	PFA	PFA	PFA	PFA	Dual readout	PFA
(ECAL) inner radius	1.8 m / 1.46 m	1.27 m	1.5 m	2.15 m	2.5 m	1.8 m
ECAL technology	Silicon	Silicon	Silicon	Silicon	-	Silicon
ECAL absorber	W	W	W	W	-	W
ECAL thickness	24 X_0 (30 layers)	26 X_0 (30 layers)	22 X_0 (40 layers)	22 X_0 (40 layers)	-	24 X_0 (30 layers)
HCAL technology	Scintillator	Scintillator	Scintillator	Scintillator	-	RPC
HCAL absorber	Fe	Fe	Fe	Fe	-	Fe
HCAL thickness	5.9 λ_I (48 layers)	4.5 λ_I	7.5 λ_I (60 layers)	5.5 λ_I (44 layers)	8 λ_I (2 m)	4.9 λ_I (40 layers)
(HCAL) outer radius	3.34 m / 3.0 m	2.5 m	3.25 m	3.57 m	≤4.5 m	3.3 m
Solenoid field	3.5 T / 4 T	5 T	4 T	2 T	2 T	3 T
Solenoid length	7.9 m	6.1 m	8.3 m	7.4 m	6.0 m	8.0 m
Sol. inner radius	3.42 m / 3.08 m	2.6 m	3.5 m	3.7 m	2.1 m	3.4 m

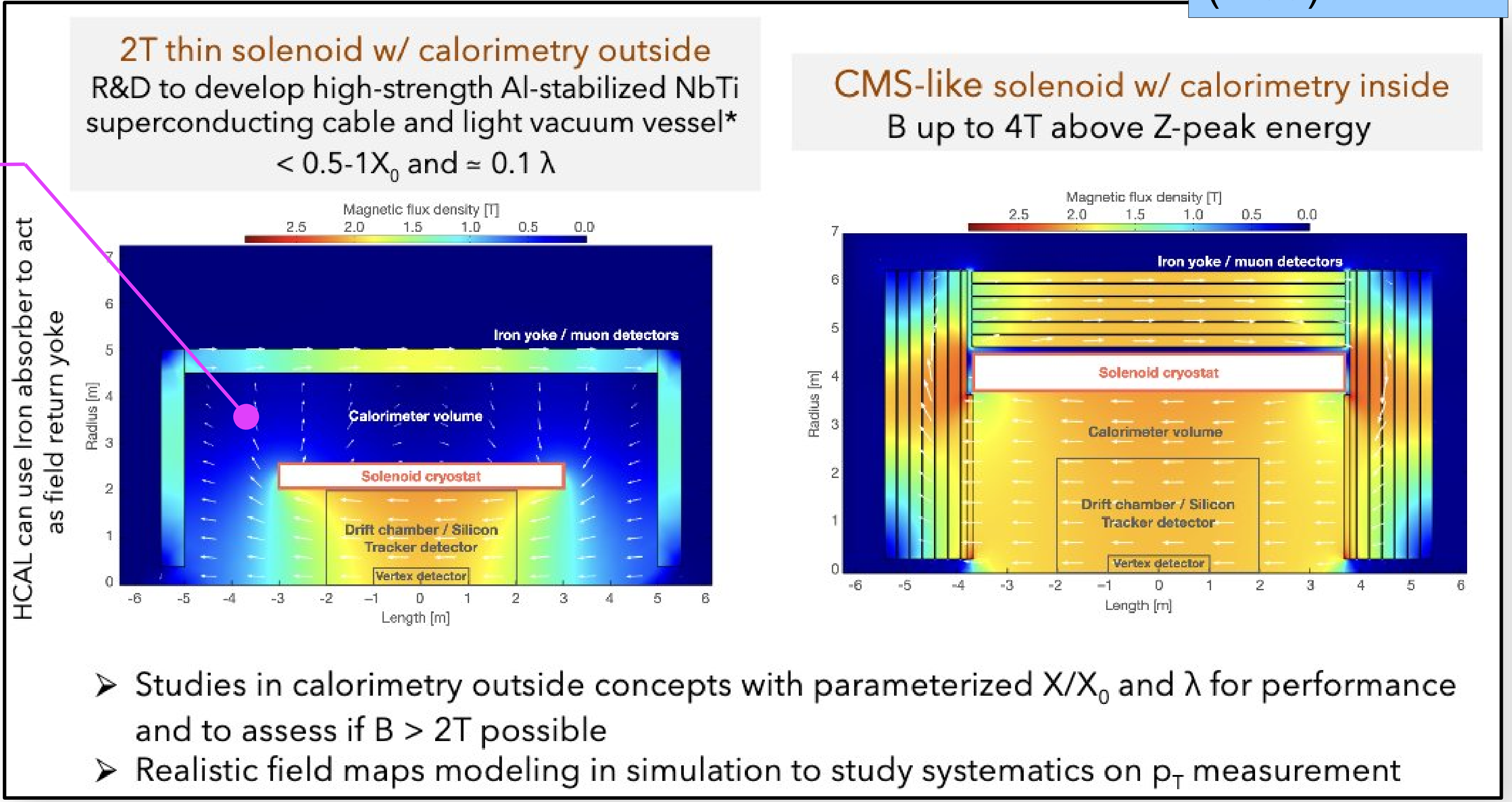
F. Simon @ FCC Week, Nov. 2022

Vincent.Boudry@in2p3.fr

D. Contardo
(Mod)

Discussed :
Here Brass

Uniform with
S. Steel



2T thin solenoid w/ calorimetry outside

R&D to develop high-strength Al-stabilized NbTi superconducting cable and light vacuum vessel*
< 0.5-1X_0 and ≃ 0.1 λ

CMS-like solenoid w/ calorimetry inside

B up to 4T above Z-peak energy

HCAL can use Iron absorber to act as field return yoke

- Studies in calorimetry outside concepts with parameterized X/X_0 and λ for performance and to assess if B > 2T possible
- Realistic field maps modeling in simulation to study systematics on p_T measurement