



Optimizing ILD for the FCC-ee and main R&D for ILD

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A detector for the next CERN flagship project: ILD

Workshop CERN, 16/09/2026

Current R&D for ILD

Sub-detectors from heavier to lighter

= “easier” to “harder”

e.g. “outside” to “inside”

- Muons / HCAL / ECALs
- Luminometers
- PID
- Trackers
- Vertex

Quality of presentations
(12 on instrumentation & System
Lively discussions
Specificity of ILD by “external”

System

- Services (Blood and Nerves)
 - (T)DAQ and Cooling
- Coil
- Construction and Installation

How to optimise ?

Sub-detectors

Basic Assumption

- Triggerless / software-based event selection
- Z peak: 40 MHz bunch crossing, ~ 100 kHz interaction rate

Expected rate in the barrel $\ll 1$ kHz/cm²

Expected rate in the endcap < 10 kHz/cm²

Complementary System Role

Complements the tracker and calorimeters by providing robust muon identification, background suppression, sensitivity to long-lived particles (LLP), and calorimeter leakage recovery.

Primary Muon System Tasks

- High-efficiency **muon ID** at large radius with low fake rate
- Rejection of hadron **punch-through** from the calorimeter
- Calorimeter leakage recovery support (**tail catcher** role)
- Sensitivity to long-lived particle decays outside the central tracker
- **High-precision tracking capability** for long-lived particle signatures

Physics Case

- Beam Energy Spread (BES) measurement
- Rare decays (e.g. $B \rightarrow K^* \mu^+ \mu^-$, $B_s \rightarrow \mu^+ \mu^-$)
- Higgs recoil-mass measurement ($e^+ e^- \rightarrow ZH$, $Z \rightarrow \mu^+ \mu^-$)

Typical signatures

+ Long-Lived Particles

- Isolated prompt muons
- Clean dimuon final states

Event reconstruction

- **Tracking/PID system**
 - Precise muon momentum reconstruction
 - Reconstruction of the Z invariant mass and Higgs recoil mass
- **Muon system**
 - Muon identification confirmation
 - Rejection of hadron punch-through

Muon-system requirements

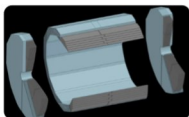
- High muon-identification efficiency
- Very low $\pi/K/p$ misidentification probability
- Low fake rate

Muons systems: review



Overview of the muon systems at FCC-ee

AGORA



Tech: plastic scintillator strips

Layout: 6 layers in iron yoke

Purpose: tagging muon system

ALFA

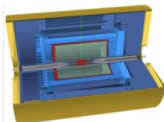


Tech: RPC or Scint. under discussion, possibly same HCAL

Layout: under discussion

Purpose: tagging muon system

ALLEGRO

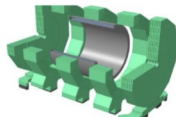


Tech: Squared drift tubes and Scintillator strips or Micromegas or Bigap RPCs

Layout: under discussion

Purpose: both tagging muon system and tracking muon system are considered

CLD

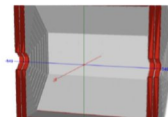


Tech: RPCs with 30x30 mm² cells.

Layout: 6 equidistant layers embedded in yoke slots. and 1 extra layer behind solenoid as tail-catcher.

Purpose: high granularity tagging and calorimetry support.

IDEA

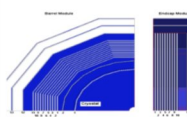


Tech: 50x50 cm² μ -RWELL chambers with 1.2 mm strip pitch

Layout: 4 stations interleaved with 30/50 cm iron yoke

Purpose: standalone tracking muon system for LLP

ILD



Tech: Scintillators (SiPM/WLS) or X-Y RPCs, possibly same HCAL

Layout: 14 active layers in barrel, 12 layers in endcap in iron yoke

Purpose: Robust tagging and 2D reconstruction

ILD

The Muon Detector Design

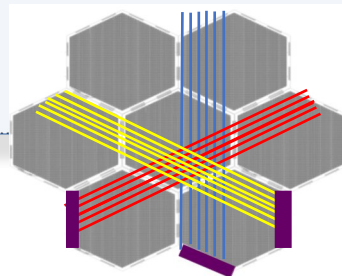
- **Simulation:** advanced and validated via detailed geometry software
- **Purpose:** tagging muon system with very low $\pi \rightarrow \mu$ fake rate

Performance: over 95% efficiency, under 1% $\pi \rightarrow \mu$ fake rate

Coverage: over 98% solid angle

Resolution: 1 ns time resolution and 1 cm spatial for tagging muon system or 200 μ m spatial for tracking muon system

Rate: 50 Hz/cm² in the barrel and 10 kHz/cm² in the endcap



No show stopper
Applications of solid or new ideas ?

ILD Muon

- $\times 2-3$ others
- Thick Yoke due to
 - $B = 4T$ max
 - $< 5mT$ Stray Field
- Loose 2-3 layers if $B \searrow 2-3 T$, $SF \times 2$

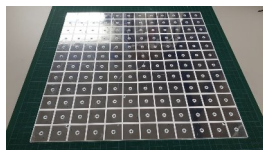
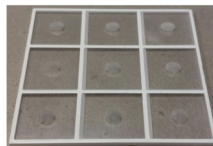
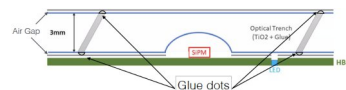
R&D:

- Update technologies...
- Improve timing ?
 - MRPC ?
- Reduce cost
 - Multiplexing ?
- Integrate in PFA (?)
 - HCAL + μ track fitting

Very mature: large technological prototypes... with old electronics

AHCAL

- Many Beam Tests
 - $\mathcal{O}(100\text{M})$ events
 - $<1\%$ dead channels
 - Low noise
- “Application” as HGCAL-HCAL
- Cost & Efficiency: MegaTiles
- SPIROC2E ASIC

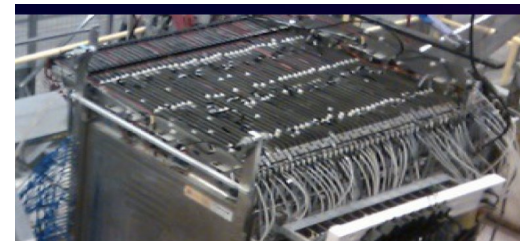


↓
Klausv7

- low power,
lpBGT compatible

SDHCAL

- Many Beam Test
 - Very high granularity
 - Low noise
- T-SDHCAL
 - MGRP for improved rates and timing, energy resolution and shower separation
- Eco-friendly gases
- Higher rates RPC
- New electronics: CALOROC2D?

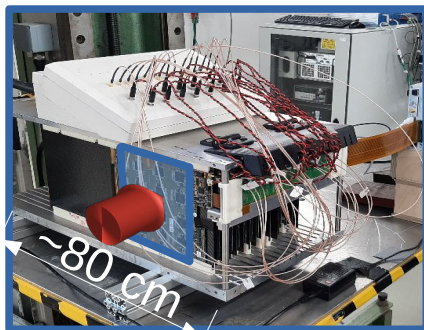


New electronics, new readout scheme, construction need time

Technological prototypes in Beam Tests (BT)

SiW-ECAL

- 15 layers prototype
 - $18 \times 18 \text{ cm}^2$; 1024 ch/layer
 - Ω mega SKIROC2
- BT @CERN in 2026
 - Smooth operations, analysis just started
- Applications in fixed-target exp't in the making
 - EBES, LUXE, SHiP, Lohengrin



R&D:

- New Electronics: CALOROC1C
 - New design for Very-Front-end started...
- Re-optimisation of layout for improved γ reconstruction
- Improve timing (Bulk and dedicated layers with LGAD ?)

ScW-ECAL

- 32 layers; $22 \times 22 \text{ cm}^2$ strips of $5 \times 45(90) \text{ mm}^2$
 - Ω mega SPIROC2E
- BT @CERN 2022–23, @KEK, 2025 (low E)
 - Large sample taken; analysis on-going
 - Some noise issues at KEK



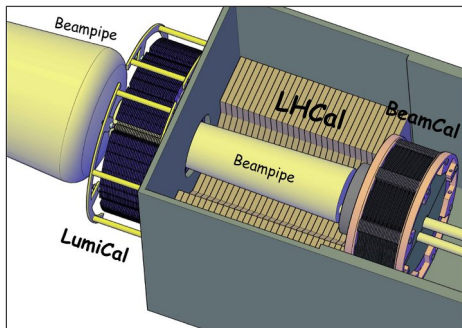
R&D:

- SiPM; strip geometry

New electronics, new readout scheme, construction need time

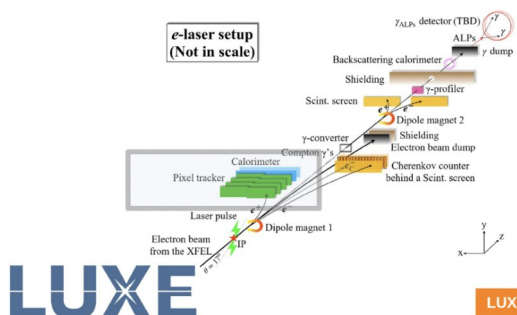
FCAL collaboration

- ‘Compact’ calorimeters for the forward regions:
 - “on-hold”, for years
- now revived by new design for FCC-ee



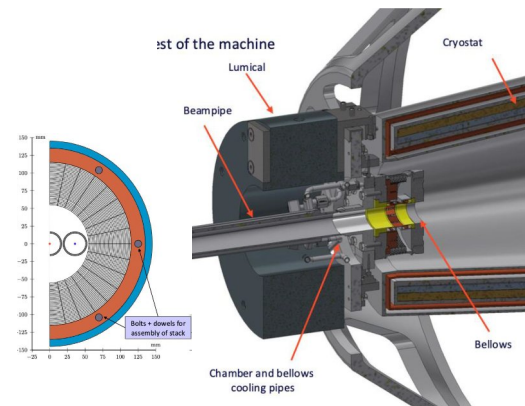
Application: LUXE ECALp

- Compact SiW for γ in non-linear QED
- SiW-ECAL sensors + Kapton
 - Many BT @ DESY
- ‘FCAL’ FLAME ASIC → operational experience



FCC-ee luminosity

- 14 mrad → 30 mrad crossing
- 1 μm mechanical precision needed
- $\Delta T_{\text{BX}} = 25 \text{ ns}$



Lumi Workshop (July 2026)

- Precision at 10^{-4} seems achievable
- Wide angle $ee \rightarrow \gamma\gamma$ to be investigated
- MAPS could be an alternative to Si layers
- Integration will be challenging
 - Sensitivity to machine background ?

Work started in FCC-ee framework

Tracker Enveloppe : ToF – Graham

Si Tracker timing – P. Martinez



Optical TOF layers ?

- Particles ID at low P
- Background rejection
- BX ID

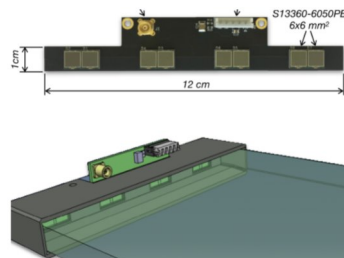


OPAL-like: Scint + WLS

- $\sigma(t) \sim 50$ ps per MIP? New WLS ?
(CDF achieved ~ 125 ps).

Cherenkov-Correlated-Timing (CCT) :

- 2 cm fused silica bar
- Internal reflexions
+ imaging the rings
→ $\theta_c + \text{time} + \text{position}$
- $\sigma(t) \sim 110$ ps at centre



is 50 ps enough?

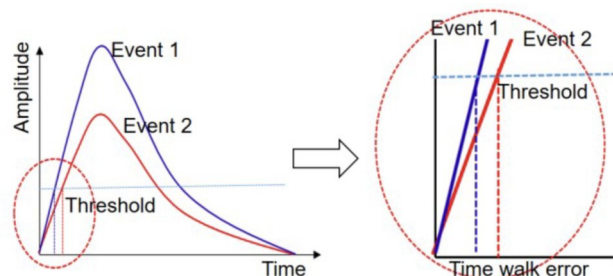
Implement a digitizer for Si-tracker timing

– Motivations:

- Training (Key4HEP) , implementation of timing in digitization of tracker hits
- Not a proposal

– Signal

- Shape: $V(t) = V_0 \exp(-t/\tau_1)(1 - \exp(-t/\tau_2))$
+ Gaussian Smearing
- Aims at 30 ps after time-walk correction



Useful for other detectors

TPC Workshop summary (7/9/26) – Peter Kluit

“Identity of ILD” (↔ CLD)

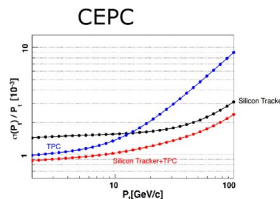


- ILD like detector concept with a TPC central tracker can be used for FCC
- Challenging tracking precision
 - driven by Higgs running
- For Z running the requirement on $\delta(1/p_t)$ can IMO be loosened by e.g. a factor 10 (LEP like)

Many advantages:

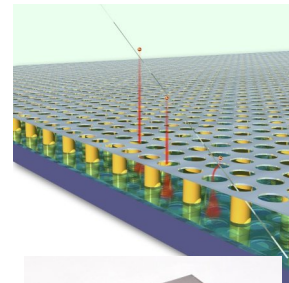
– Esp when combined with Si-tracker

- Low material budget that allows high precision tracking
- Continuous 3D tracking (x,y, t) and track following
 - Excellent v_0 reconstruction
 - Ideal for particle flow and combined calorimetry
- TPC is sliced between silicon detectors
 - provides required momentum resolution and constraints
- Very powerful particle identification based on dEdx
 - for electrons (suppress pions)
 - for kaons ($H \rightarrow ss$) and protons
- TPC excellent option for FCCee WW, ZH, tt etc running
- Running at the Z is challenging due to synchrotron backgrounds
- A pixel TPC combines a large drift volume with a silicon read out plane
 - tracking with high granularity and low systematic uncertainties due to “silicon” precision (1-10 μm) in the production process
 - the best (see slides) PID performance dEdx and cluster counting



Readout technologies

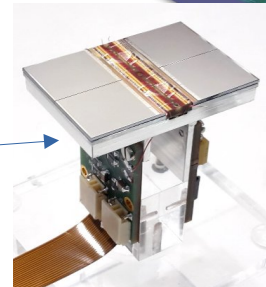
- GridPix + TimePix3:
 - Pixel chip with integrated Grid (Micromegas-like)
 - Detection of individual e⁻
 - 256×256 pixels; 55 μm pitch; $\gg$ timestamp
 - 2 W / (14.1 mm)²



Beam Test Results

- Residuals xy 13 μm , z 20 μm ;
- L = 1 m, B = 1 T

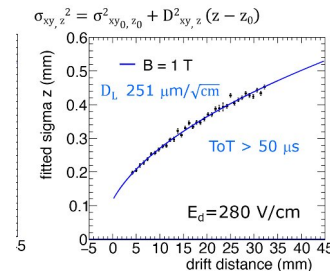
Cooling plate



Simulation & T2K:

- 10 000 hits/tracks (≥ 1 e⁻)
 - Previous: 200 pads (≥ 22 e⁻)
- 10 cm for precision $\sim 20\mu\text{m}$ @ 3.5T but 30 μm @ 2.0T

B=1 T p=5 and 6 GeV



dE/dx vs dN/dx

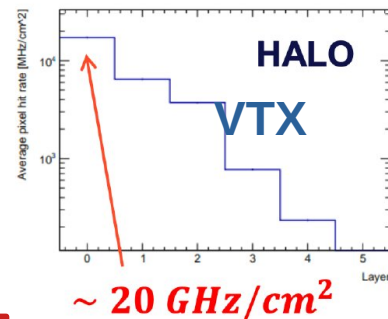
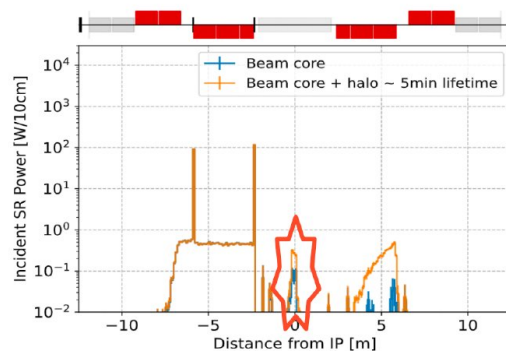
- e^- of 5,6 GeV, $L=1\text{m}$ with 60% coverage, 1T
- dE/dx filtering out large clusters $\sigma/\mu=3.6\%$
- $\langle dN/dx \rangle$ by fit of bulk of distribution, $\sigma/\mu=2.9\%$

Extrapolated to ILD

- $R_i=329\text{ mm}$; $R_o=1770\text{ mm}$
- $\sigma/\mu = 2.4\%$ (3%)
- separation of K/π for $P<45\text{ GeV}$ with more than 5.5σ (4.5σ) for $\cos\theta=0$.

But huge background from Synchr. Radiation

- Large hit rate
→ electronics heat
- Charge Buildup
→ distortions
- Ion Back Flow
→ distortion++
 - R&D DRD1
 - Use Ne gas (vs Ar) for Tera-Z ?



Technologically mature, services to be integrated in simulation ?
Very first concern: SR background

Machine Backgrounds – Victor Schwan



Study of D. Jeans

- presented at FCC Week 2026

<https://indico.cern.ch/event/1552126/contributions/7128849/>

Incoherent Pair Creation (IPC)

Synchrotron Radiation (SR) from particles in beam *core* and *halo*

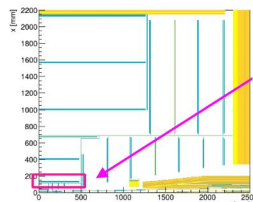
[assuming perfect orbit]

Beam Gas interactions – “worst case” before full vacuum conditioning

expect 100x less after conditioning

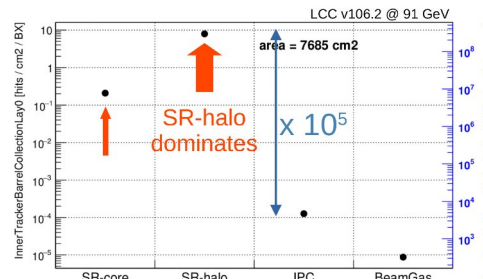
all for recent machine optics LCC v106.2 @ 91 GeV

fresh results → preliminary !



average hit density
energy > MIP/5
pixel multiplicity=1
no safety factor

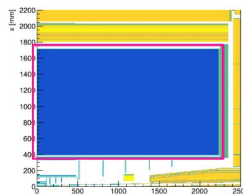
Silicon tracker (CLD_o2_v08)



for IPC background @ FCCee-91,
distortion typically several mm
can reach few cm
(with optimistic ion backflow assumption)
distortions seem stable @ μm

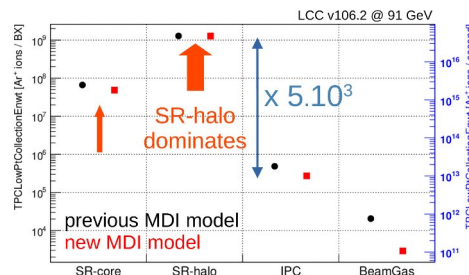
concern about much larger SR-induced bg.

TPC (ILD_FCCee_v01)



New MDI description
modest improvement for
some sources,
no change for dominant SR

Ion production



**Meter-size
deviations**

SR background – Guila Nigrelli on behalf of the SR Task Force



Very high rate in VTX:

- up to $\sim 20 \text{ GHz/cm}^2$ (HALO) and $\sim 1 \text{ GHz/cm}^2$ (CORE).
- Dipole and Quadrupoles + reflected on surfaces

Task Force formed

- Simulations beam core in BDSIM/FLUKA/SYNRAD
 - lattice LCC 106 at Z pole
 - Disagreements reduced (in good direction)
→ gain in confidence
 - $\triangle$ No Xray reflection

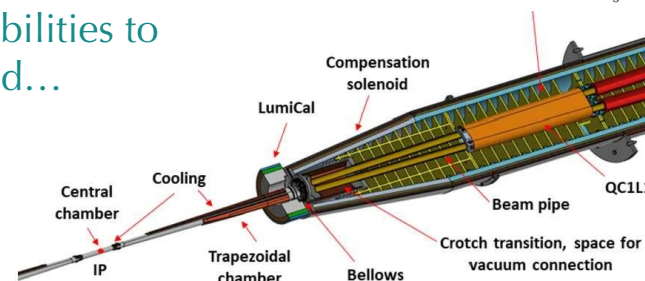
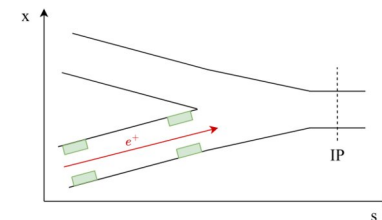
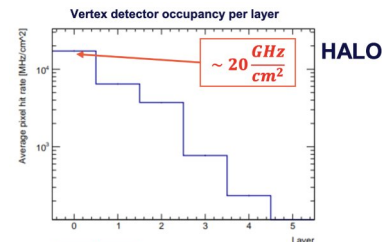
**Quick progresses but
SR still dominates by far...
Validation in real life ?
CAD and DD4HEP model ?**

Main source: beam halo

- $\times 100$ core (stopped by dump)
↔ $1/(\text{beam lifetime})$

Mitigation:

- Modified Final doublet : $\rightarrow / 10 !$
- Masking @1.3m from IP
 - Prelim results:
 - $R/100$ in vertex
- Other possibilities to be evaluated...



Vertex – Jeremy Andrea



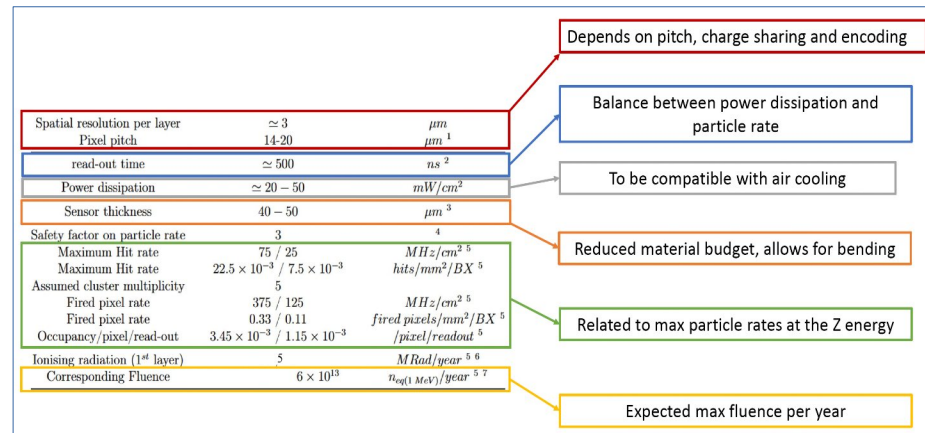
Resolutions

- Internal precision $\sigma_{rp} \sim 3\mu\text{m}$
- From scattering: r_0 as small as possible

System

- Thin device $\rightarrow$ MAPS !
- $3\mu\text{m}$ but low Power ($50\text{mW}/\text{cm}^2$)

“Every aspect is interconnected” (Spaghetti diagram)



$$\Delta d_0|_{res.} \approx \frac{3\sigma_{rp}}{\sqrt{N+5}} \sqrt{1 + \frac{8r_0}{L_0} + \frac{28r_0^2}{L_0^2} + \frac{40r_0^3}{L_0^3} + \frac{20r_0^4}{L_0^4}}$$

$$\Delta d_0|_{m.s.} \approx \frac{0.0136 \text{ GeV}/c}{\beta p_T} r_0 \sqrt{\frac{d}{X_0 \sin \theta}} \sqrt{1 + \left(\frac{r_0}{L_0}\right) + \left(\frac{r_0}{L_0}\right)^2}$$

FCCee

$$\sigma_{d_0} = a \oplus \frac{b}{p \sin^{3/2} \theta}$$

$a \approx 3\mu\text{m}$ (or better); $b \approx 15\mu\text{m}$

Technologies (Chips)

Technology	Geometry	Time to first hit	Time to first hit
CLD	CLD (ILD), [2]	Time to first hit	Time to first hit
IDEA	IDEA (ALLEGRO), [3]	Time to first hit	Time to first hit
Ultra-light inner VXD	Ultra-light inner VXD (IDEA/ALLEGRO), [7]	Time to first hit	Time to first hit
FCC-SEED	FCC-SEED (soon available to any det. concept)	Time to first hit	Time to first hit

Implementations (in DD4HEP)

CLD
(CLD/ILD), [2]

- Adapted from CLIC design
- $r_{min} = 13\text{mm}$
- Three double-layer barrel layers and disks, $0.6-0.7\% X_0$ per double layer
- No specific sensor chosen, assume $3\mu\text{m}$ resolution

IDEA stave-based
(IDEA/ALLEGRO), [3]

- $r_{min} = 13.7\text{mm}$
- 3 inner barrel ($0.25\% X_0$), 2 outer barrel layers and 3 disks ($\sim 0.5\% X_0$)
- Engineered design (Pisa) integrated with machine (LNF [4])
- IDEA: ARCADIA [5] (inner barrel) and ATLASPix3 [6] (rest)
- ALLEGRO: OCTOPUS

Ultra-light inner VXD
(IDEA/ALLEGRO), [7]

- Curved, 2D-stitched MAPS (ALICE ITS3-like [8])
- Four layers $0.075\% X_0$ per layer
- Sensitive sensor fraction of $\sim 0.05\%$

FCC-SEED
(soon available to any det. concept)

- Curved, 1D-stitched MAPS
- Five layers, $\approx 0.1\% X_0$ per layer
- Overlapping curved sensors to avoid gaps

$\sim 0.5-0.6\% X_0$ at $\theta = 90^\circ$

Powering and readout via long flex cables

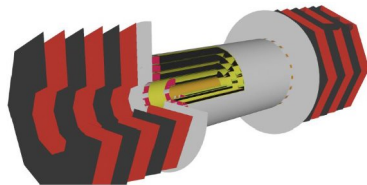
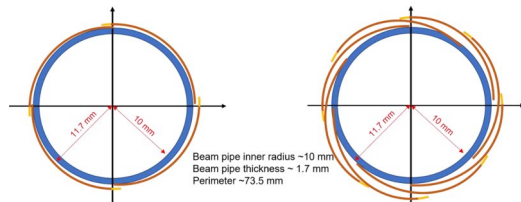
VXD (long barrel)
inner VXD (long barrel + 2 layers of ladders)

Material budget [% of X_0]

Legend: Carbon Fibre, Silicon, Kapton, Carbon Foam, Aluminium

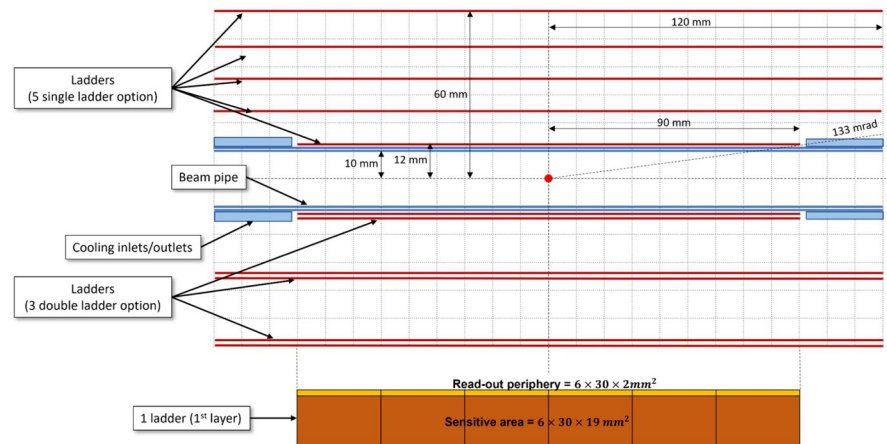
FCC-Seed :

- Octopus reading bended layers (ALICE-like)
- Single layer or Double layers (redundancy)
 - 0.5mm between overlaps
- $R_0 \sim 10\text{--}12\text{ mm}$
- $\sim 0.6\text{--}1.2\% X_0$
- Curved sensors
- $R_{r0} = 1\text{ cm}$



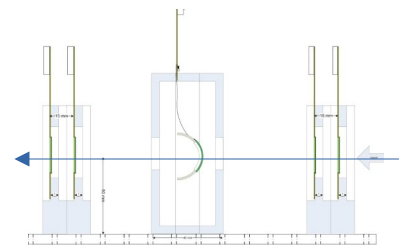
Simulation

- Exists (Disk = CLD)
- Air cooling tubes and fixation to be added
- CAD Mechanics, etc



Prototyping

- MIMOSIS chips close to what is needed
 - Bending tests done
- Beam test of MIMOSIS (50 μm thickness) in preparation
- Funded by French ANR



**Recent rejoining of ILD
Very active...
Who for the disk ?**

System

Conclusions concerning the “low-level” reconstruction (close to the dirty HW)

- Si & Calo digi: should become more realistic, application of new developments to ILD
- TPC digi: major work to make more realistic and apply FCC conditions, overlap with AGORA
- In-depth discussions (focus: Vtx, FT, PFlow) at the FCC Reco WS in Oct!

→ Effort is needed

- Some started.
- TPC a key player; lack of man power → 1/2 day to remove the technical hurdles ?

Z-pole most challenging experimentally:

- 100 kHz physics rate, ~200 kHz including backgrounds
- 25 ns bunch spacing (40 MHz BX rate) → only about 1 in 200 is a physics event
- No pileup / no underlying event (pile-up parameter $\sim 2.5 \times 10^{-3}$)

But background dominated...

Precision EW:

- $\delta R/R \sim 2e-5$
 - → Same DT for all events.
 - → trigger bias $< 1e-6$

FCC-ee parameters		Z	W ⁺ W ⁻	ZH	ttbar
$\sqrt{s}$	GeV	91.2	160	240	350-365
Luminosity / IP	$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$	140	20	7.5	1.5
Bunch spacing	ns	25	160	680	5000
"Physics" cross section	pb	35,000	10	0.2	0.5
Total cross section	pb	70,000	30	10	8
Event rate	Hz	100,000	6	0.5	0.1
"Pile up" parameter [μ]	10^{-6}	2,500	1	1	1

TDAQ or DAQ (streaming) ?

- Streaming feasible ? YES, Should we ?
 - 0.2Mb events @ 200 kHz (→) 10 Tb/s
→ 100 GB/s on storage?
 - But more material & power
→ Optimal to be found

Trigger and DAQ: backgrounds

TDAQ Workshop FCC Week 2026

Sources:

- IPC irreducible, soft,
Shielded by 2Tbut
- Dominated VTX ~ 30 hits in 1st layers / BX
→ 70 MHz/cm²
- SR can saturate innermost is not tamed
- Top-up injection:
 - $\leq \sim 1\%$ full beam intensity 1/10s
 - 12% of injected beam lost around ring
 - Sim. improves...

BW ~ OK, but lobal effort on light and low power readout needed ($\supset$ connectors) $\leftrightarrow$ DRD7 + (VBY) Monitoring close to the HW

[FCC Week 2026 - Jona Dilg](#)

Realistic digitisation: the tools to actually decide

Occupancy, data-rate and readout numbers are only as good as the digitisation behind them.

A coordinated FCC effort now provides two complementary digitisers (to be merged into one Gaudi algorithm):

- Projection-based: simple, technology-agnostic, minimal parameters; general use; merged & tested in CLD
- LUT-based: maximum precision; sensor-design & BIB hit-rate studies; merge in progress

Together they span everyday physics studies → expert sensor/layout optimisation, also feeding realistic data rates

[FCC Week 2026 - Thorsten Wengler](#)

Plans & Priorities

Too early to fix a TDAQ design, but the groundwork is being laid now:

- Occupancy & bandwidth database: collect TDAQ-relevant numbers consistently across all concepts, as optics & layouts evolve building on the [Google Sheets](#)
- Refined background simulation: newest optics (LCC), updated IPC & SR samples, realistic digitisation feeding the numbers
- Hardware, via [DRD7](#) light-weight/high-throughput readout links (silicon photonics, wireless), timing distribution, on-detector/on-FPGA ML

Common TDAQ(base) functions needed regardless of trigger choice:

zero-suppression at source, timing distribution, bunch-crossing ID, unstable-bunch veto

Commonality is the priority! We solve the same problems across concepts

Cooling

Continuous running

- Power Pulsing → Power×100 (same electronics)
- Embedded Electronic

Cooling Systems:

- Vertex: Air flow
(Mechanical stability from old AIDA program)
- TPC: CO₂ ?
 - Room temperature = high pressure = thick tubes
 - Uniformity required ?
- Calorimeters
 - (ongoing) Estimation of power with CaloFlux

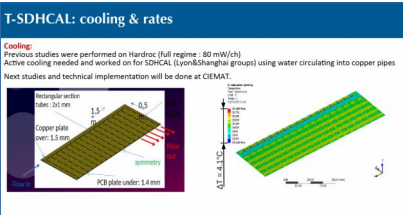
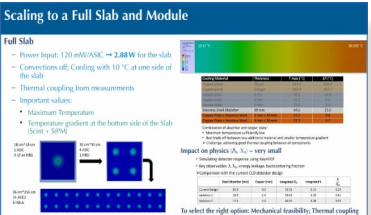
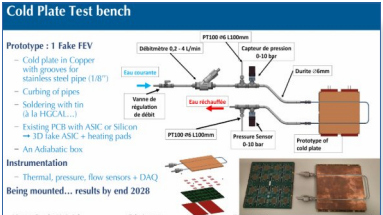
Estimation of Power and Rates (no SR!!!)			
SK2 in SiW-EndCaps		Klaus6 in AHCAL	
Metric	Layers 3-8	Layers 9-15	Layers 16-21
Average hit rate	1.13 × 10 ¹⁰ hits/s	200 × 10 ¹⁰ hits/s	400 × 10 ¹⁰ hits/s
Hit rate per hit	1.13 × 10 ¹⁰ hits/s	200 × 10 ¹⁰ hits/s	400 × 10 ¹⁰ hits/s
Maximum hit rate per event	1.040	7.800	1000
Rate rate	14.01 GB/s	5.18 GB/s	3.30 GB/s
Number of events	3,700,000	3,700,000	3,700,000
Occupancy per bunch crossing	1.3 × 10 ⁻⁴	2.7 × 10 ⁻⁴	2.8 × 10 ⁻⁴
Base power	10.4 kW	16.8 kW	16.8 kW
Conversion power	1.071 kW	105.8 W	107.1 W
Total power	11.471 kW	17.4 kW	17.2 kW
Conversion rate	10.27%	2.76%	2.46%

Calculations parameters: bunch crossing frequency: 5.00 × 10¹⁰ Hz

Calculation and Prototypes

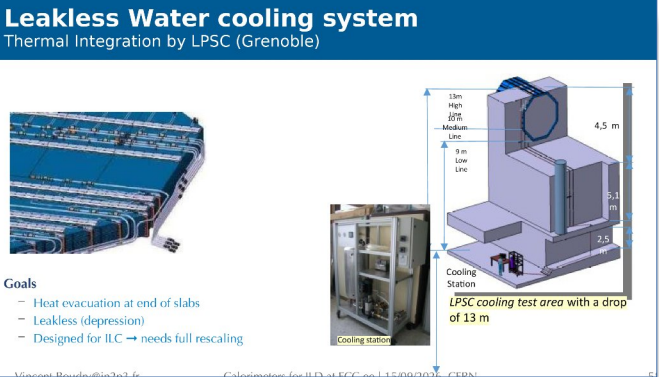
SiW-ECAL

AHCAL

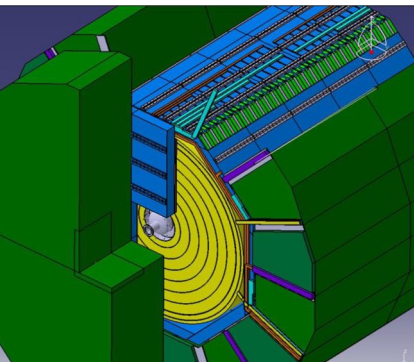


System & Piping to be revisited

Engineering ...



Physics (DD4HEP)



Coil and Installation – Karsten Buesser



ILD CAD models ready

- Adaptation “easy”

Stray Field:

- 5 mT (50G) at ILC
- If 10 mT → Yoke -60 cm (500t)
(no work nearby, idem CMS)

Construction timeline

- 10 years $\supset$ construction site
→ Start before stop of LHC...
- $\neq$ assembly scheme wrt transportation by road
(20 t or 200 t)
 - FCC : What is the largest piece ? → $\emptyset$ shaft (Δ €€€)

ILD in the FCC-ee envelope documents

- Not with reduced Yoke.
ILD = largest detector...

FCC-ee Detector Envelopes and Masses

Table 4 FCC-ee detectors radial envelope estimations of services and support structures

Detector	Service code	1st radial envelope (cm)	2nd radial envelope (cm)	3rd radial envelope (cm)
ILC	001	100	100	100
ILC	002	100	100	100
ILC	003	100	100	100
ILC	004	100	100	100
ILC	005	100	100	100
ILC	006	100	100	100
ILC	007	100	100	100
ILC	008	100	100	100
ILC	009	100	100	100
ILC	010	100	100	100
ILC	011	100	100	100
ILC	012	100	100	100
ILC	013	100	100	100
ILC	014	100	100	100
ILC	015	100	100	100
ILC	016	100	100	100
ILC	017	100	100	100
ILC	018	100	100	100
ILC	019	100	100	100
ILC	020	100	100	100
ILC	021	100	100	100
ILC	022	100	100	100
ILC	023	100	100	100
ILC	024	100	100	100
ILC	025	100	100	100
ILC	026	100	100	100
ILC	027	100	100	100
ILC	028	100	100	100
ILC	029	100	100	100
ILC	030	100	100	100
ILC	031	100	100	100
ILC	032	100	100	100
ILC	033	100	100	100
ILC	034	100	100	100
ILC	035	100	100	100
ILC	036	100	100	100
ILC	037	100	100	100
ILC	038	100	100	100
ILC	039	100	100	100
ILC	040	100	100	100
ILC	041	100	100	100
ILC	042	100	100	100
ILC	043	100	100	100
ILC	044	100	100	100
ILC	045	100	100	100
ILC	046	100	100	100
ILC	047	100	100	100
ILC	048	100	100	100
ILC	049	100	100	100
ILC	050	100	100	100
ILC	051	100	100	100
ILC	052	100	100	100
ILC	053	100	100	100
ILC	054	100	100	100
ILC	055	100	100	100
ILC	056	100	100	100
ILC	057	100	100	100
ILC	058	100	100	100
ILC	059	100	100	100
ILC	060	100	100	100
ILC	061	100	100	100
ILC	062	100	100	100
ILC	063	100	100	100
ILC	064	100	100	100
ILC	065	100	100	100
ILC	066	100	100	100
ILC	067	100	100	100
ILC	068	100	100	100
ILC	069	100	100	100
ILC	070	100	100	100
ILC	071	100	100	100
ILC	072	100	100	100
ILC	073	100	100	100
ILC	074	100	100	100
ILC	075	100	100	100
ILC	076	100	100	100
ILC	077	100	100	100
ILC	078	100	100	100
ILC	079	100	100	100
ILC	080	100	100	100
ILC	081	100	100	100
ILC	082	100	100	100
ILC	083	100	100	100
ILC	084	100	100	100
ILC	085	100	100	100
ILC	086	100	100	100
ILC	087	100	100	100
ILC	088	100	100	100
ILC	089	100	100	100
ILC	090	100	100	100
ILC	091	100	100	100
ILC	092	100	100	100
ILC	093	100	100	100
ILC	094	100	100	100
ILC	095	100	100	100
ILC	096	100	100	100
ILC	097	100	100	100
ILC	098	100	100	100
ILC	099	100	100	100
ILC	100	100	100	100

Table 5 FCC-ee detectors longitudinal envelope estimations of services and support structures

Detector	Service code	1st longitudinal envelope (cm)	2nd longitudinal envelope (cm)	3rd longitudinal envelope (cm)
ILC	001	100	100	100
ILC	002	100	100	100
ILC	003	100	100	100
ILC	004	100	100	100
ILC	005	100	100	100
ILC	006	100	100	100
ILC	007	100	100	100
ILC	008	100	100	100
ILC	009	100	100	100
ILC	010	100	100	100
ILC	011	100	100	100
ILC	012	100	100	100
ILC	013	100	100	100
ILC	014	100	100	100
ILC	015	100	100	100
ILC	016	100	100	100
ILC	017	100	100	100
ILC	018	100	100	100
ILC	019	100	100	100
ILC	020	100	100	100
ILC	021	100	100	100
ILC	022	100	100	100
ILC	023	100	100	100
ILC	024	100	100	100
ILC	025	100	100	100
ILC	026	100	100	100
ILC	027	100	100	100
ILC	028	100	100	100
ILC	029	100	100	100
ILC	030	100	100	100
ILC	031	100	100	100
ILC	032	100	100	100
ILC	033	100	100	100
ILC	034	100	100	100
ILC	035	100	100	100
ILC	036	100	100	100
ILC	037	100	100	100
ILC	038	100	100	100
ILC	039	100	100	100
ILC	040	100	100	100
ILC	041	100	100	100
ILC	042	100	100	100
ILC	043	100	100	100
ILC	044	100	100	100
ILC	045	100	100	100
ILC	046	100	100	100
ILC	047	100	100	100
ILC	048	100	100	100
ILC	049	100	100	100
ILC	050	100	100	100
ILC	051	100	100	100
ILC	052	100	100	100
ILC	053	100	100	100
ILC	054	100	100	100
ILC	055	100	100	100
ILC	056	100	100	100
ILC	057	100	100	100
ILC	058	100	100	100
ILC	059	100	100	100
ILC	060	100	100	100
ILC	061	100	100	100
ILC	062	100	100	100
ILC	063	100	100	100
ILC	064	100	100	100
ILC	065	100	100	100
ILC	066	100	100	100
ILC	067	100	100	100
ILC	068	100	100	100
ILC	069	100	100	100
ILC	070	100	100	100
ILC	071	100	100	100
ILC	072	100	100	100
ILC	073	100	100	100
ILC	074	100	100	100
ILC	075	100	100	100
ILC	076	100	100	100
ILC	077	100	100	100
ILC	078	100	100	100
ILC	079	100	100	100
ILC	080	100	100	100
ILC	081	100	100	100
ILC	082	100	100	100
ILC	083	100	100	100
ILC	084	100	100	100
ILC	085	100	100	100
ILC	086	100	100	100
ILC	087	100	100	100
ILC	088	100	100	100
ILC	089	100	100	100
ILC	090	100	100	100
ILC	091	100	100	100
ILC	092	100	100	100
ILC	093	100	100	100
ILC	094	100	100	100
ILC	095	100	100	100
ILC	096	100	100	100
ILC	097	100	100	100
ILC	098	100	100	100
ILC	099	100	100	100
ILC	100	100	100	100

Table 6 FCC-ee detectors largest component for CMS upgrade, estimated dimensions

Detector	Service code	Longitudinal envelope (cm)	Radial envelope (cm)	Angular envelope (cm)
ILC	001	100	100	100
ILC	002	100	100	100
ILC	003	100	100	100
ILC	004	100	100	100
ILC	005	100	100	100
ILC	006	100	100	100
ILC	007	100	100	100
ILC	008	100	100	100
ILC	009	100	100	100
ILC	010	100	100	100
ILC	011	100	100	100
ILC	012	100	100	100
ILC	013	100	100	100
ILC	014	100	100	100
ILC	015	100	100	100
ILC	016	100	100	100
ILC	017	100	100	100
ILC	018	100	100	100
ILC	019	100	100	100
ILC	020	100	100	100
ILC	021	100	100	100
ILC	022	100	100	100
ILC	023	100	100	100
ILC	024	100	100	100
ILC	025	100	100	100
ILC	026	100	100	100
ILC	027	100	100	100
ILC	028	100	100	100
ILC	029	100	100	100
ILC	030	100	100	100
ILC	031	100	100	100
ILC	032	100	100	100
ILC	033	100	100	100
ILC	034	100	100	100
ILC	035	100	100	100
ILC	036	100	100	100
ILC	037	100	100	100
ILC	038	100	100	100
ILC	039	100	100	100
ILC	040	100	100	100
ILC	041	100	100	100
ILC	042	100	100	100
ILC	043	100	100	100
ILC	044	100	100	100
ILC	045	100	100	100
ILC	046	100	100	100
ILC	047	100	100	100
ILC	048	100	100	100
ILC	049	100	100	100
ILC	050	100	100	100
ILC	051	100	100	100
ILC	052	100	100	100
ILC	053	100	100	100
ILC	054	100	100	100
ILC	055	100	100	100
ILC	056	100	100	100
ILC	057	100	100	100
ILC	058	100	100	100
ILC	059	100	100	100
ILC	060	100	100	100
ILC	061	100	100	100
ILC	062	100	100	100
ILC	063	100	100	100
ILC	064	100	100	100
ILC	065	100	100	100
ILC	066	100	100	100
ILC	067	100	100	100
ILC	068	100	100	100
ILC	069	100	100	100
ILC	070	100	100	100
ILC	071	100	100	100
ILC	072	100	100	100
ILC	073	100	100	100
ILC	074	100	100	100
ILC	075	100	100	100
ILC	076	100	100	100
ILC	077	100	100	100
ILC	078	100	100	100
ILC	079	100	100	100
ILC	080	100	100	100
ILC	081	100	100	100
ILC	082	100	100	100
ILC	083	100		

Selected Open Questions

No personpower!

Physics requirements

- ILD magnet and yoke were designed for 4 T maximum field
- FCC-ee has lower energy range than Linear Colliders, so is 4 T still required?
- Smaller magnetic field would probably change magnet and yoke geometries

Detector Assembly Strategy

- On-surface assembly (CMS-style) was chosen at ILC because of integrated timeline studies together with the machine experts
- ATLAS-type assembly is also possible for ILD, would come with relaxed constraints for the shaft size
 - Biggest element probably the magnet, not the yoke
- Surface and underground facility layouts depend on assembly strategy and detector infrastructure requirements

Cryogenics

- The detector magnet will be assembled on-site and it has to be tested
- Lowering can be done before or after testing
- Testing before requires cryogenic on surface to be ready in time
- Testing after requires cryogenic infrastructure in the hall to be ready in time

Stray field requirements

- Yoke size and mass depends on this, any guidelines available?
- Relaxing requirement from 5 mT to 10 mT reduces yoke radius by 60 cm and mass by ~500 t

Radiation shielding

- ILD@ILC is designed to be fully self-shielding, access to the hall is possible during machine operations
- How is this at FCC-ee? Might also have an impact on yoke thickness...

What and how to optimize ?

PED Letter of Mission (July 20th, P. Janot)

(my exerpt for information)

Reference Design Phase (RDP; 2026–2028)

- 39 preliminary EoI RnD for Feasibility Study
- WG structure
- 6 concepts
 - common sub-systems
 - ILD, CLD, Allegro, IDEA, ALFA, ...

Next goals

- EoI det concepts end of RDP (**end 2028**)
 - Framework for ideas, techs, eng/phys., needed R&D
 - → "Clear direction for DRDs",
 - "expected to align with needs of FCC-ee"

More meetings, and sharing

- Det-Concept ≠ exp. collab
 - Fondation for future collabs.
 - LHC: Evian 1992
 - 4 future det.

Lol **beg of 2030**

- **Strong signal for the Funding agencies**

Optimizing ILD for the FCC-ee... in a few prompts.

Dear “Claude”, you will act as the Technical and Software and Physics Coordinators of ILD...

- 1) For every detector technology used in ILD, extrapolate from the detector and technical groups results, the expected performances in 10 years from now. **
- 2) Write some digitiser code reflecting those performances, allowing for flexibility in speed, amplitude and granularities... *
- 3) Create a parametric model of ILD in Key4HEP with those technologies, taking into account the services, construction and security constraints at the FCC-ee (pit, magnetic field) **
- 4) Simulate the main physics channel and machine backgrounds at the FCC-ee at 91, 180, 240 and 365 GeV using the ILD Model and Digitisers *
- 5) Write a Particle Flow Method giving the best jet energy resolution, and τ reconstruction purity and tagging for Flavour physics and Higgs, Z, W and top measurements,... don't forget the sensibility to any new possible physics **
- 6) Optimise the ILD model in 3) for performance and cost **
- 7) Write a Letter of Intention *
- 8) You have three years...

*** hum? ** Not “quite” there... will still have to be made “brainly”**

Some experiment attempts at LLM...

full presentations attached on indico ; error spotted not reviewed, avoid “I want to believe” effect
ChatPGT (4m50s) Claude (~9 m, 90% of daily free plan)

Higgs hadronic branching ratios: $H \rightarrow bb / cc / gg / ss$

Analysis-specific detector leverage: what improvement could actually buy.

ANALYSIS

Current status

ACTIVE

The September 2026 study explicitly targets the measurement precision for b , c , g and s couplings and quantifies gains from upgraded flavor tagging. The old LCFIPlus chain is being superseded by a transformer-based approach.

Where detector enters

Flavor tagging sits on top of track/particle reconstruction; new ParT + CPID uses dE/dx and ToF, with Kaon identification helping strange-jet discrimination.

Potential gain

Better vertex point resolution / material budget $\rightarrow$ stronger b/c separation. Better PID (especially K ID) $\rightarrow$ stronger s-tagging. Better ECAL/HCAL imaging and timing $\rightarrow$ cleaner particle-flow inputs and lower jet confusion.

Bottom line

Detector improvements matter only if they move the analysis away from its present bottleneck: classification, jet assignment, missing-energy resolution, acceptance or systematics.

Where detector improvement buys the most physics

A practical ranking based on the 2026 analyses and detector reports.

1	Vertex material + hermeticity	b/c/τ tagging, LLPs, rare Higgs	
2	PFA / calorimeter confusion	ZH, H hadronic, H→inv, high-energy jets	
3	Tracking + forward acceptance	Z-pole, recoil, charge ID, H→inv	
4	PID / ToF	H→ss, τ physics, flavor / exotic signatures	
5	Luminosity systematics	All rate-based Z and FCC-ee precision results	
6	Calorimeter timing	Background rejection + 5D PFA / possible PID	
7	Muon outer system	LLP / robustness more than core Higgs	

Key point: “better detector” means fewer analysis bottlenecks, not uniformly smaller hit resolution everywhere.

Prompt asked to Mistral, ChatGPT (5.6), Claude (Sonnet)

Based on the presentation on the indico page <https://agenda.linearcollider.org/event/11033/timetable/?view=standard>, provide me with a status of the recent and future R&D for each of the sub-detectors of ILD.

You will format the output as a presentation of about 30 slides.

Order subdetectors from the outside to the inside: muon, SDHCAL, AHCAL, SCW-ECAL, SIW-ECAL, Luminometer, ToF and PID, TPC, silicon tracker and vertex. Then discuss the global aspects: coil and yoke, TDAQ, cooling.

Then for each of the analysis presented, specify what could be gained by an improvement of the detector (if any).

PHYSICS ANALYSES

Higgs hadronic branching ratios ($H \rightarrow bb/cc/gg/ss/bs$)

- Goal: separate $H \rightarrow bb/cc/gg/ss$ (and the flavour-changing $H \rightarrow bs$) to probe light-quark Yukawa couplings and BSM patterns of coupling deviation
- New tools: Particle Transformer (ParT) jet-flavour tagger combined with dE/dx- and ToF-based hadron PID (“Comprehensive PID”) sharpen b/g-jet separation; template-fit analysis improves $H \rightarrow bb$ (0.5%) and $H \rightarrow gg$ (5.1%) precision at 250 GeV over earlier LCFIPlus-based studies
- $H \rightarrow cc$ remains stubbornly limited (<10% precision) despite the new tagger; $H \rightarrow ss$ and $H \rightarrow bs$ are only just starting, currently background- and statistics-dominated

WHAT A BETTER DETECTOR BUYS

Charged-hadron PID quality is the single biggest lever here: the ComprehensivePID score (built from TPC dE/dx and, if realised, a ToF layer) directly feeds ParT’s strange/kaon identification. Sharper kaon ID from an improved ToF/PID system would most directly move the needle on $H \rightarrow ss$ and $H \rightarrow bs$ sensitivity; a lower-material vertex detector improves the c/b separation that currently bottlenecks $H \rightarrow cc$.

OUTLOOK

Summary & outlook

It’s an adaptation problem, not a redesign

- ILD’s outside-in system is technically mature at the linear-collider energy/timing point
- FCC-ee adaptation is dominated by continuous operation (power, cooling, DAQ) and background (SR, IPC) — not by new physics-driven redesign

Recurring detector-improvement threads

- Charged-hadron PID (ToF layer + TPC dE/dx) recurs across $H \rightarrow ss/bs$, ttH-CPV and flavour-tagging analyses
- Forward acceptance & jet/flavour tagging recur across ZHH, $H \rightarrow$ invisible and exotic-scalar searches
- Vertex-detector material budget recurs across essentially every flavour-sensitive measurement

What’s next

- Cooling engineering and services integration, not physics performance, are the near-term pacing items for calorimeters and tracking
- FCC reference-design material is due by end of 2027
- ILD is formally transitioning to new management to carry this programme forward

Source: “A detector for the next CERN flagship project: ILD” — CERN, 14–16 September 2026 — agenda.linearcollider.org/event/11033

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Adaptation to FCC-ee – Key elements

Identical Physics* : e^+e^- at 91, 165, 240, 360 GeV but

- Collisions rates $\times 20,000$
- $\neq$ Machine-Detector Interface
- (Much) Higher Machine Backgrounds

MDI / forward region

- Mitigation of machine backgrounds — especially at high-lumi

Different bunch structure of beam

- Impact on operation of Time Projection Chamber
- Thermal load management in subdetectors
 - Opportunity: add timing !

Miscellaneous

- Lower energies $\rightarrow$ less granular calorimeters ?
- No close-by detector (push-pull operation) $\rightarrow$ no need for self-shielding $\rightarrow$ thinner yoke ?
- If lower magnetic field (2T) $\rightarrow$ Do we need a larger tracker ?

	ILC	FCC-ee
Crossing angles	14 mrad	30 mrad
L^* (distance from IP to last accel. Focusing magnet)	4.1 m	2.0 m
Solenoid field	3.5 T	2.0 (3 ?) T
Additional B-fields	anti-DID	– Compensating – Screening
Bunch separation	~ 350 ns @ 5–10 Hz	2–5000 ns cont.

*Identical Physics : but Tera-Z calls

- **PPM Systematics**
- Less explored aspects (by ILD):
 - Extended Flavour physics program
 - QCD, ...

TPC inner radius

Discussed at <https://agenda.linearcollider.org/event/11107/>, missing in report...

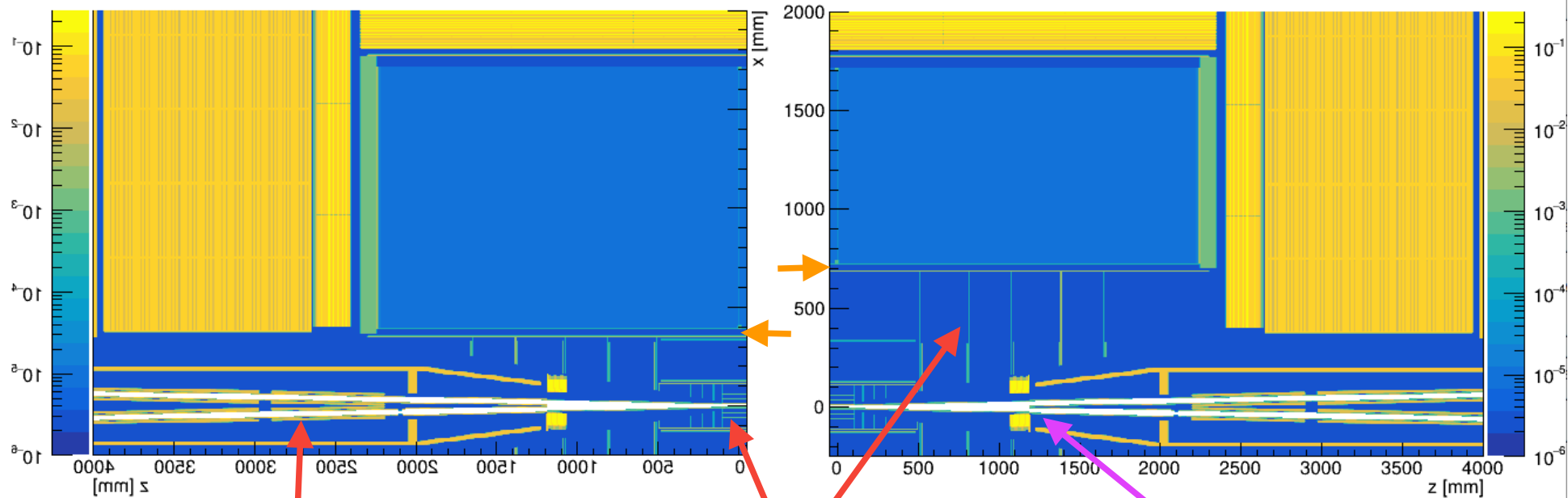
A bit in Victor's

“o1”: ILD-Like TPC

materialScan at $Y=0.01 \text{ mm} : 1/X_0$

“o2”: Shrunk TPC, more Si

materialScan at $Y=0.01 \text{ mm} : 1/X_0$



*Common FCCee MDI
Beampipe, LumiCal,
quads, solenoids*

*CLD-like silicon tracker
vertex, inner silicon*

*Beampipe
forking*

Tentative To Do List...

Instrumentation

- Continue R&D on detectors ↔ DRD's
- Foster transverse collaboration on missing parts (e.g. Silicon trackers)
- Involve new partners: e.g maps for calorimeters (Lumi, SiW), Cherenkov / ToF
- Build scenarios for TPC (if;then;else)
- Revise Magnet + Yoke + Muons ← Q? From Karsten: Who ? Major cost issue (material, pit size)

Models

- Update detector descriptions in 2(3?) steps:
 - 1st version simulations with upgraded sub-detectors (⊃ digitisers, timing, cooling for VTX, TPC, Calos) → prelim. Physics performance, rates, granularity, etc (→ Eol ?)
 - 2nd version Sim/CAD for full physics performance / large Production
 - Prelim Cost estimates → Lol ? (beg. 2030)

Work Ahead

◆ Vertex Detector & MDI Region:

- ❑ Sensor technology exists (MAPS, DRD3); lightweight support structures, low-material power and cooling infrastructure to be developed
- ❑ Continue and strengthen engineering effort on MDI region, support of vertex detectors + LumiCal; develop MDI for all detector concepts

◆ Tracking:

- ❑ Different proposals: Scintillating Fibre, Si tracker (DRD3), gaseous tracker (DRD1): drift chamber, straw tracker, TPC
- ❑ Establish whether (long) drift times are compatible with high-rate Z-pole operation and related backgrounds (synchrotron radiation, beamstrahlung, radiative Bhabha scattering)
- ❑ Minimize material, start engineering of support structures, services, power, cooling, ...

◆ Particle ID:

- ❑ Consolidation of cluster-counting method for DCH and straw
- ❑ Potentially complement Si tracker with ARC Cherenkov detector; need for low GWP gasses
- ❑ ToF detectors (e.g. LGADs)

◆ Calorimetry

- ❑ Continue building prototypes of all proposed calorimeters, testbeams (DRD6)
- ❑ Define needed granularity, performance optimisation
- ❑ Engineering

◆ Muon system:

- ❑ Large area scintillator and gas detector technologies exist; need for low GWP gasses
- ❑ Need to define what is needed for optimal physics reach

◆ Luminometry

- ❑ LumiCals satisfying extreme precision requirements to be developed
- ❑ Consolidation of luminosity measurement via large angle di-photons

◆ Magnet coils

- ❑ Effort to re-establish availability of reinforced aluminum-stabilized Nb-Ti conductors needed;
- ❑ Investigate novel HTS-based conductors technology

◆ Cryostats

- ❑ Development of low-material carbon-composite cryostats as well as carbon fibre and aluminum honeycomb
- ❑ Construction and test of prototypes

◆ Trigger and DAQ:

- ❑ Is a trigger needed or can all (zero-suppressed) data be streamed out
- ❑ Closely linked to studies of occupancies caused by backgrounds

◆ Software:

- ❑ Full simulation of detector concepts gradually becoming available; important for performance and detector optimisation studies.
- ❑ Detailed digitizers important for quantification of background rates
- ❑ Reconstruction including particle flow appearing