Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

Detectors: Highlights

Mogens Dam, Marc-André Pleier, Felix Sefkow

The small print: personal selection only, all mißtäks owned by the speaker

8th FCC Physics workshop, CERN, January 16, 2025

@BrookhavenLab

Overview of Sessions this week

Tuesday:

1. Joint MDI and detectors: Vertex detector, LumiCal, and Integration
2. Joint MDI and Software and Detectors: Beam backgrounds
3. Detectors: Tracking and vertexing

Wednesday:

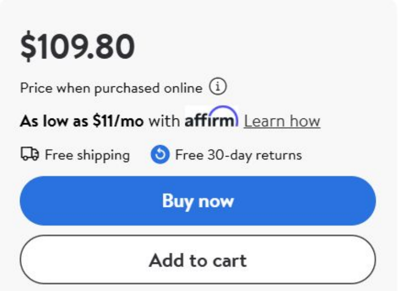
4. Detectors: Detector concepts, large-scale structures and cryostats
5. Joint session Detectors and Software
6. Detectors: PID, Calorimetry

Thursday:

7. Joint Software, Physics Performance & Detectors: reconstruction I
8. Joint Software, Physics Performance & Detectors: reconstruction II

Friday:

9. Satellite meeting: preparing detector EoIs



$109.80

Price when purchased online ⓘ

As low as $11/mo with affirm Learn how

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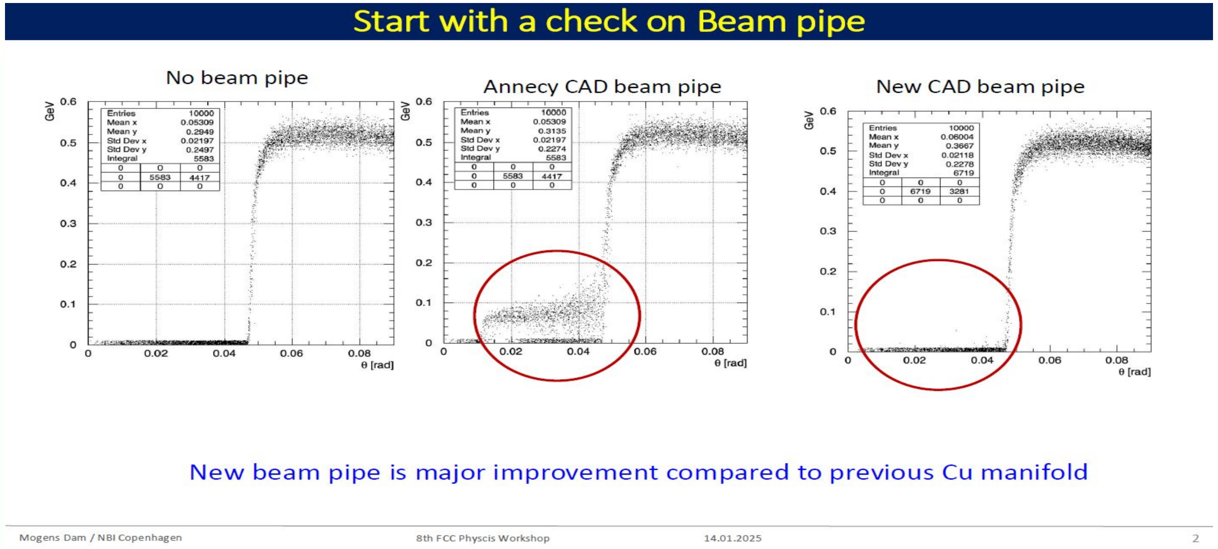
Lumi Cal

Lumical - residual B field effects

Mogens Dam



Start with a check on Beam pipe

New beam pipe is major improvement compared to previous Cu manifold

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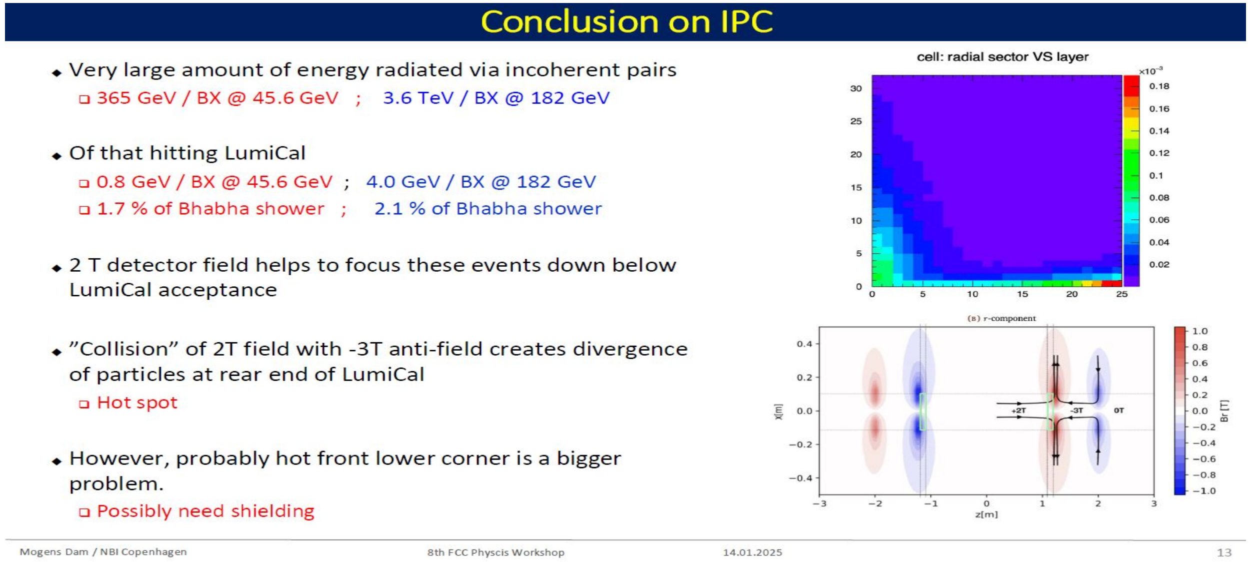

Conclusion on IPC

- Very large amount of energy radiated via incoherent pairs
  - 365 GeV / BX @ 45.6 GeV ; 3.6 TeV / BX @ 182 GeV
- Of that hitting LumiCal
  - 0.8 GeV / BX @ 45.6 GeV ; 4.0 GeV / BX @ 182 GeV
  - 1.7 % of Bhabha shower ; 2.1 % of Bhabha shower
- 2 T detector field helps to focus these events down below LumiCal acceptance
- ”Collision” of 2T field with -3T anti-field creates divergence of particles at rear end of LumiCal
  - Hot spot
- However, probably hot front lower corner is a bigger problem.
  - Possibly need shielding

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AlBeMet as cooling manifold material lowers energy deposited in LumiCal

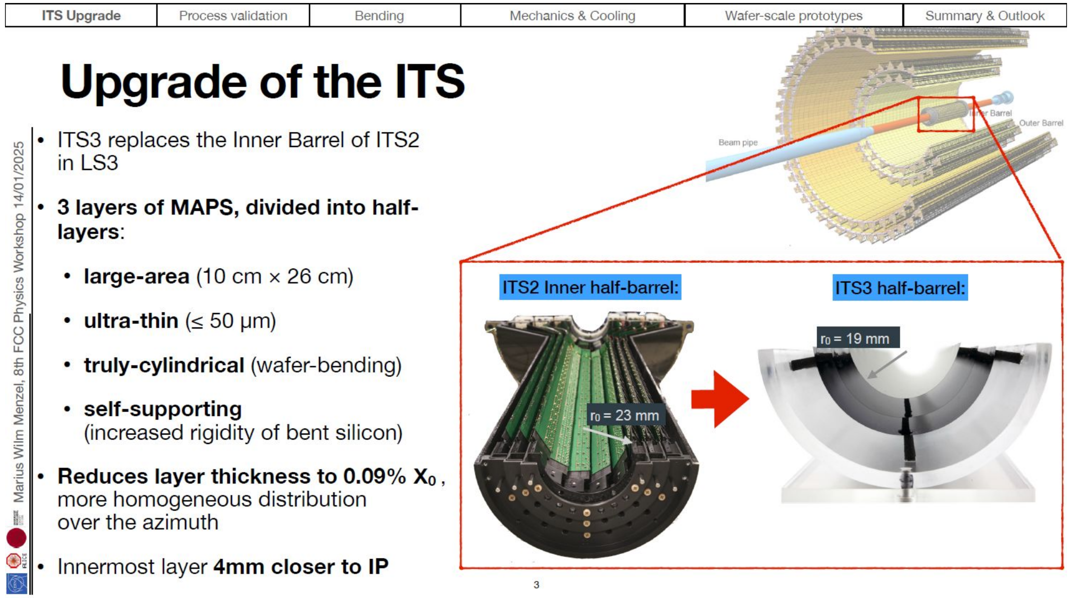
Energy radiated via incoherent pairs might warrant shielding (below the LumiCal acceptance) - to be studied in more detail

Big progress overall on beam backgrounds, but need more integrated framework for accelerator/detector simulations

Vertex Detector

Status of the ALICE ITS3 development

Marius Wilm Menzel



ITS Upgrade | Process validation | Bending | Mechanics & Cooling | Wafer-scale prototypes | Summary & Outlook

Upgrade of the ITS

- ITS3 replaces the Inner Barrel of ITS2 in LS3
- **3 layers of MAPS, divided into half-layers**:
  - **large-area** (10 cm × 26 cm)
  - **ultra-thin** (≤ 50 μm)
  - **truly-cylindrical** (wafer-bending)
  - **self-supporting** (increased rigidity of bent silicon)
- **Reduces layer thickness to 0.09% X_0**, more homogeneous distribution over the azimuth
- Innermost layer **4mm closer to IP**

Marius Wilm Menzel, 8th FCC Physics Workshop 14/01/2025

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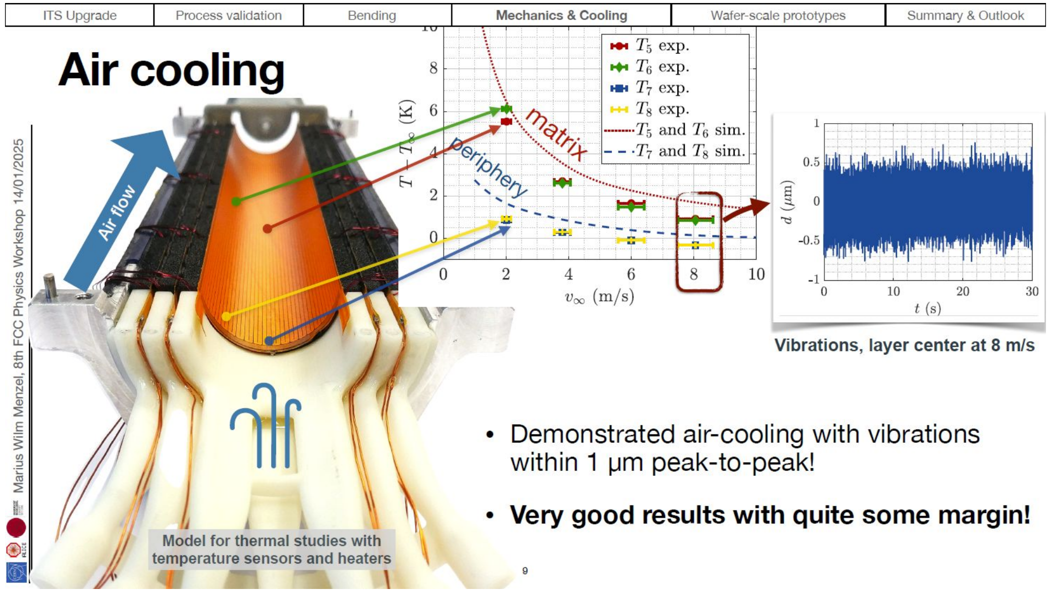

ITS Upgrade | Process validation | Bending | Mechanics & Cooling | Wafer-scale prototypes | Summary & Outlook

Air cooling

Vibrations, layer center at 8 m/s

Model for thermal studies with temperature sensors and heaters

- Demonstrated air-cooling with vibrations within 1 μm peak-to-peak!
- **Very good results with quite some margin!**

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ITS3 is the current gold standard in MAPS development

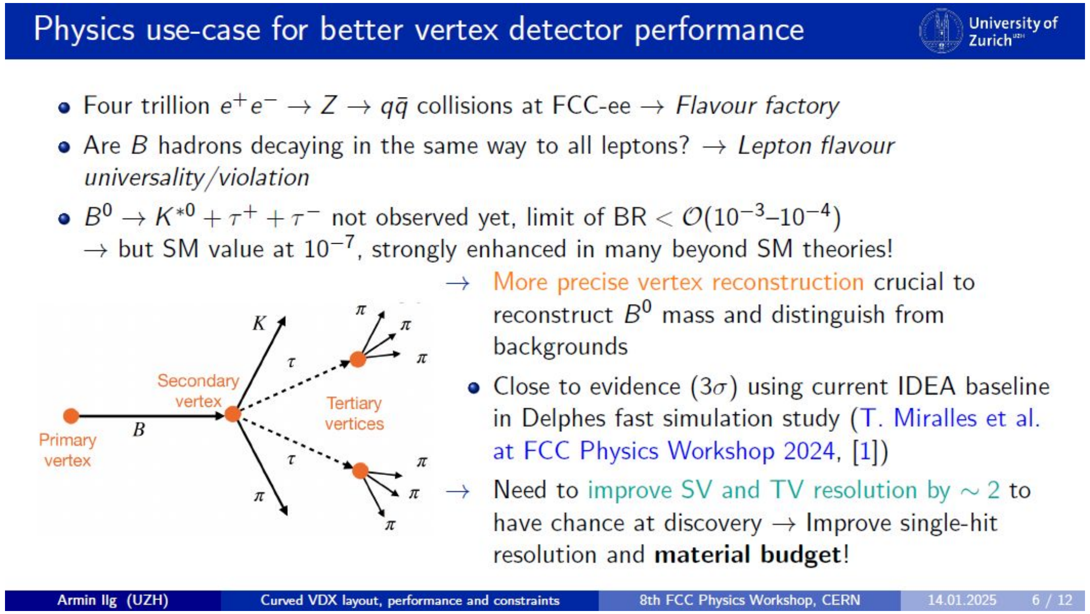
Shorts observed in monolithic stitched sensors (MOSS) understood & expected to be mitigated

Bent sensors show no performance degradation from flat chips, promising in-beam performance

First fully functional, full-sized prototype sensor (MOSAIX) will be submitted early 2025!

Curved VDX layout, performance and constraints

Armin Ilg



Physics use-case for better vertex detector performance

University of Zurich

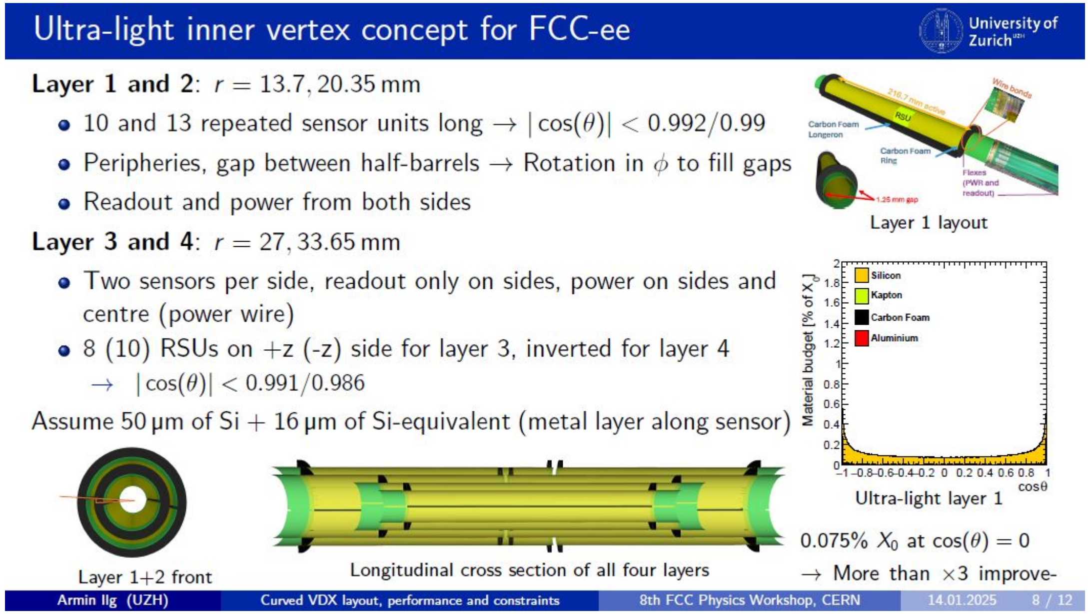
- Four trillion $e^+e^- \to Z \to q\bar{q}$ collisions at FCC-ee → *Flavour factory*
- Are B hadrons decaying in the same way to all leptons? → *Lepton flavour universality/violation*
- $B^0 \to K^{*0} + \tau^+ + \tau^-$ not observed yet, limit of BR $< \mathcal{O}(10^{-3}\text{–}10^{-4})$
  → but SM value at 10^{-7}, strongly enhanced in many beyond SM theories!

→ More precise vertex reconstruction crucial to reconstruct B^0 mass and distinguish from backgrounds

- Close to evidence (3σ) using current IDEA baseline in Delphes fast simulation study (T. Miralles et al. at FCC Physics Workshop 2024, [1])

→ Need to improve SV and TV resolution by ~ 2 to have chance at discovery → Improve single-hit resolution and **material budget**!

Armin Ilg (UZH) | Curved VDX layout, performance and constraints | 8th FCC Physics Workshop, CERN | 14.01.2025 | 6 / 12



Ultra-light inner vertex concept for FCC-ee

University of Zurich

Layer 1 and 2: $r = 13.7, 20.35\,\text{mm}$

- 10 and 13 repeated sensor units long → $|\cos(\theta)| < 0.992/0.99$
- Peripheries, gap between half-barrels → Rotation in ϕ to fill gaps
- Readout and power from both sides

Layer 3 and 4: $r = 27, 33.65\,\text{mm}$

- Two sensors per side, readout only on sides, power on sides and centre (power wire)
- 8 (10) RSUs on +z (-z) side for layer 3, inverted for layer 4
  → $|\cos(\theta)| < 0.991/0.986$

Assume 50 µm of Si + 16 µm of Si-equivalent (metal layer along sensor)

Layer 1 layout

Ultra-light layer 1

Layer 1+2 front

Longitudinal cross section of all four layers

$0.075\%\ X_0$ at $\cos(\theta) = 0$

→ More than ×3 improve-

Armin Ilg (UZH) | Curved VDX layout, performance and constraints | 8th FCC Physics Workshop, CERN | 14.01.2025 | 8 / 12

Use (B) physics benchmark to evaluate impact of detector change

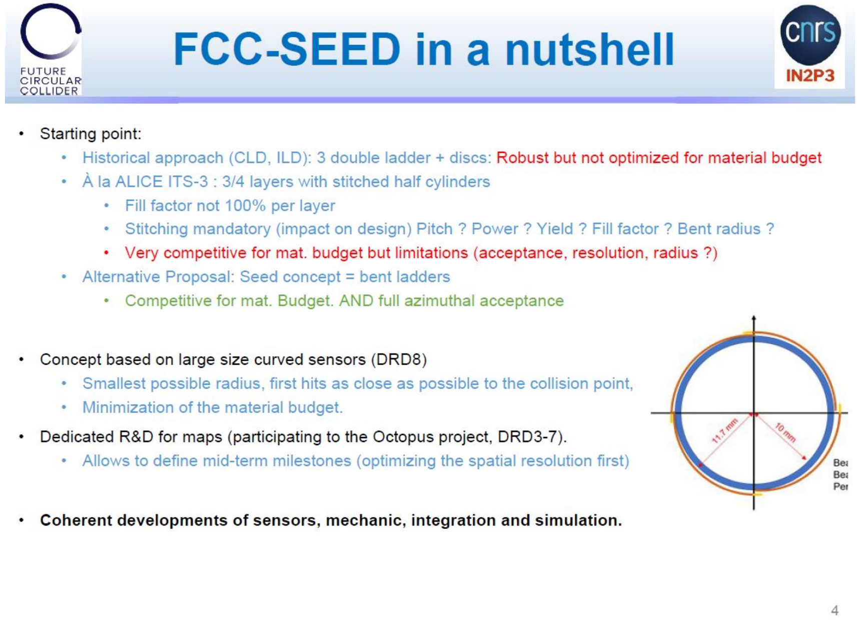
Four cylindrical layers ensure ≥ 3 hits, minimise sensor periphery impact

Factor 3 improvement in X_0 at cos(θ) = 0, but need forward design, services,...

No MAPS exists **yet** that can fulfil all FCC-ee vertex requirements simultaneously

FCC-Seed : a Snail-shape vErtEx Detector for FCCee

Auguste Besson



FCC-SEED in a nutshell

- Starting point:
  - Historical approach (CLD, ILD): 3 double ladder + discs: Robust but not optimized for material budget
  - À la ALICE ITS-3 : 3/4 layers with stitched half cylinders
    - Fill factor not 100% per layer
    - Stitching mandatory (impact on design) Pitch ? Power ? Yield ? Fill factor ? Bent radius ?
    - Very competitive for mat. budget but limitations (acceptance, resolution, radius ?)
  - Alternative Proposal: Seed concept = bent ladders
    - Competitive for mat. Budget. AND full azimuthal acceptance
- Concept based on large size curved sensors (DRD8)
  - Smallest possible radius, first hits as close as possible to the collision point,
  - Minimization of the material budget.
- Dedicated R&D for maps (participating to the Octopus project, DRD3-7).
  - Allows to define mid-term milestones (optimizing the spatial resolution first)
- **Coherent developments of sensors, mechanic, integration and simulation.**

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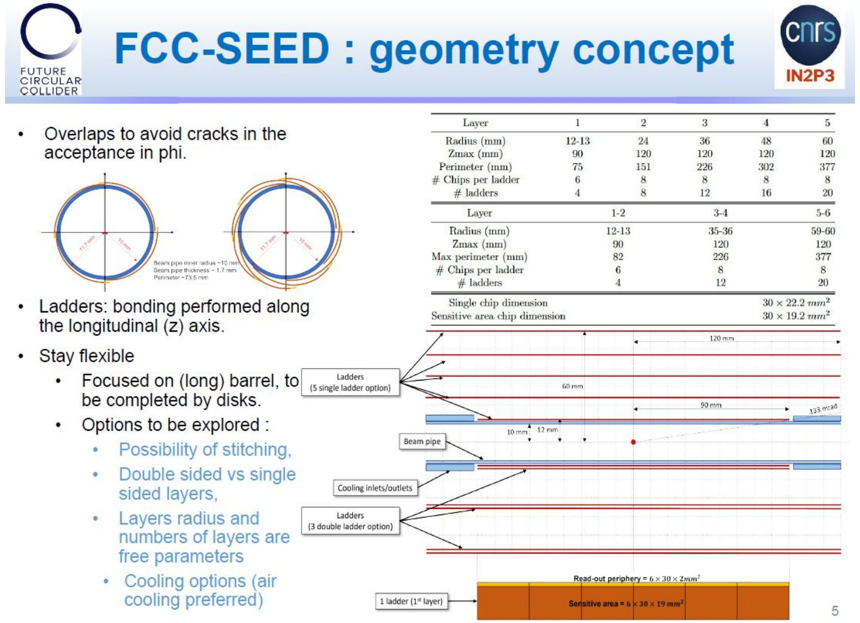

FCC-SEED : geometry concept

- Overlaps to avoid cracks in the acceptance in phi.
- Ladders: bonding performed along the longitudinal (z) axis.
- Stay flexible
  - Focused on (long) barrel, to be completed by disks.
  - Options to be explored :
    - Possibility of stitching,
    - Double sided vs single sided layers,
    - Layers radius and numbers of layers are free parameters
    - Cooling options (air cooling preferred)

Layer	1	2	3	4	5
Radius (mm)	12-13	24	36	48	60
Zmax (mm)	90	120	120	120	120
Perimeter (mm)	75	151	226	302	377
# Chips per ladder	6	8	8	8	8
# ladders	4	8	12	16	20

Layer	1-2	3-4	5-6
Radius (mm)	12-13	35-36	59-60
Zmax (mm)	90	120	120
Max perimeter (mm)	82	226	377
# Chips per ladder	6	8	8
# ladders	4	12	20

Single chip dimension	$30 \times 22.2\ mm^2$
Sensitive area chip dimension	$30 \times 19.2\ mm^2$

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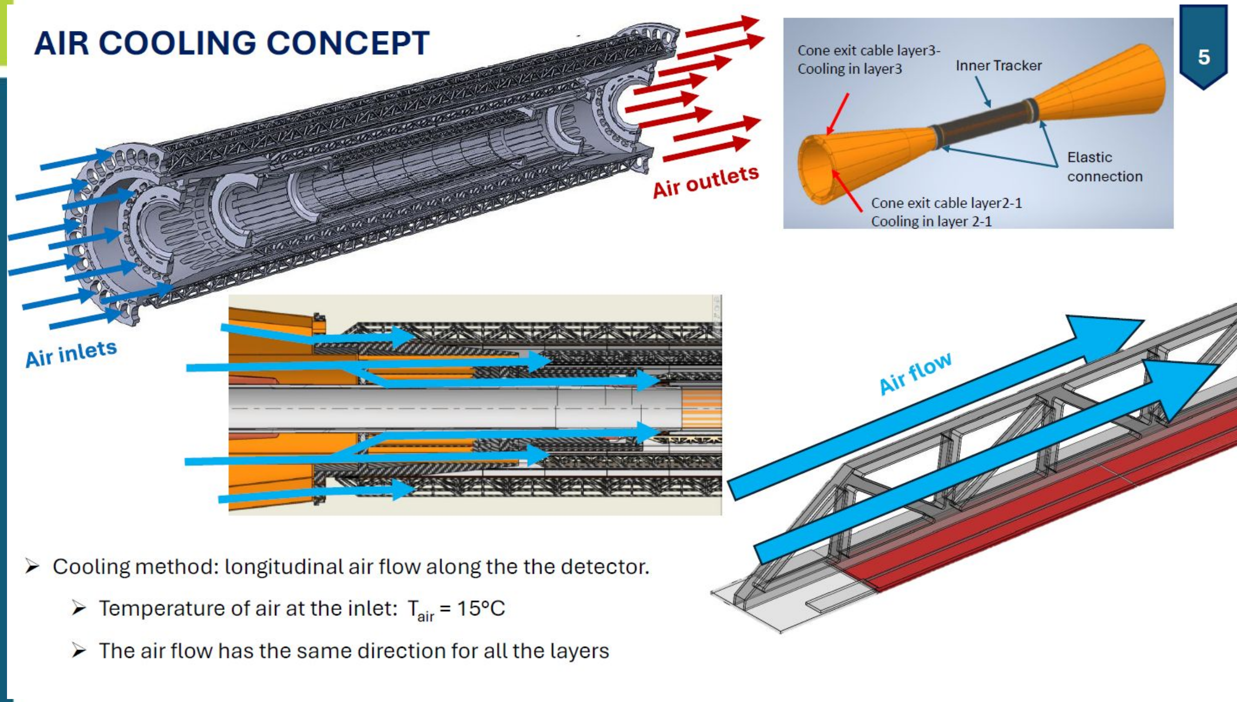
Use bent MAPS ladders, competitive for material budget and full azimuthal acceptance

Dedicated R&D for MAPS, participation in Octopus project, DRD3&7

Coherent development of sensors, mechanics, integration and simulation

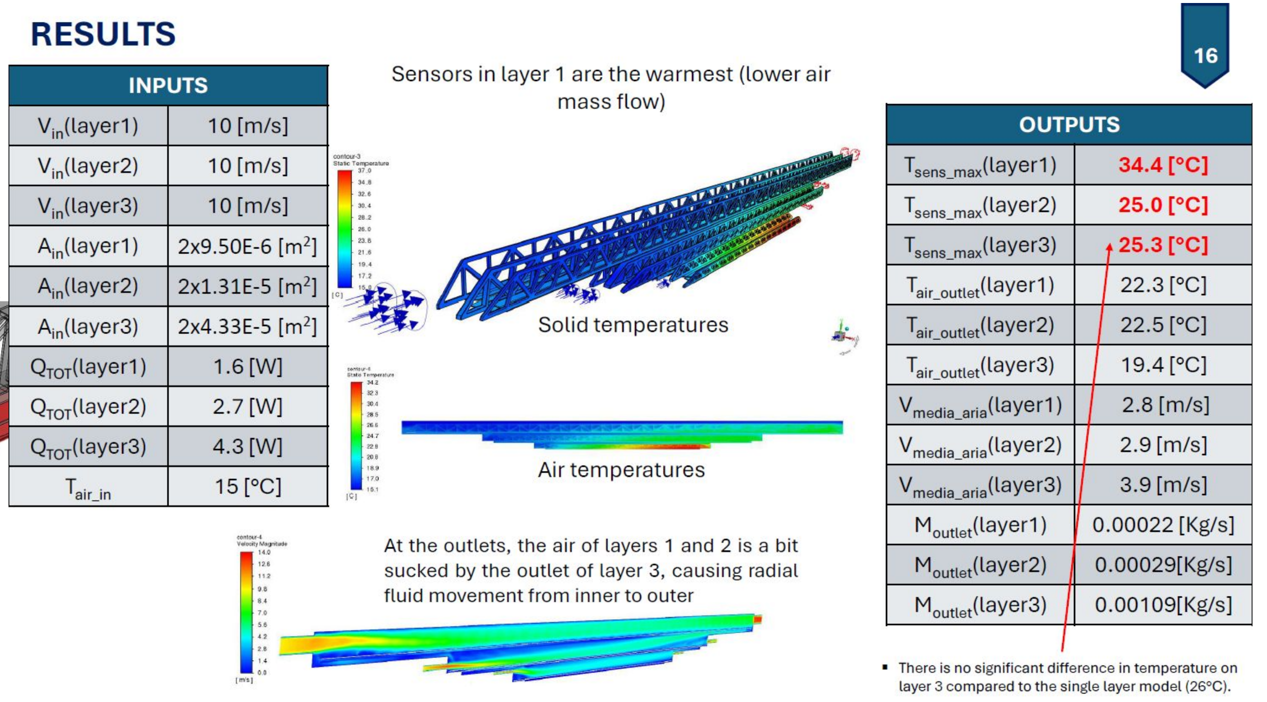
Vertex Detector Cooling simulations

Giorgio Baldinelli



AIR COOLING CONCEPT

- Cooling method: longitudinal air flow along the the detector.
  - Temperature of air at the inlet: T_{air} = 15°C
  - The air flow has the same direction for all the layers



RESULTS

INPUTS	
V_{in}(layer1)	10 [m/s]
V_{in}(layer2)	10 [m/s]
V_{in}(layer3)	10 [m/s]
A_{in}(layer1)	2x9.50E-6 [m^2]
A_{in}(layer2)	2x1.31E-5 [m^2]
A_{in}(layer3)	2x4.33E-5 [m^2]
Q_{TOT}(layer1)	1.6 [W]
Q_{TOT}(layer2)	2.7 [W]
Q_{TOT}(layer3)	4.3 [W]
T_{air_in}	15 [°C]

Sensors in layer 1 are the warmest (lower air mass flow)

Solid temperatures

Air temperatures

At the outlets, the air of layers 1 and 2 is a bit sucked by the outlet of layer 3, causing radial fluid movement from inner to outer

OUTPUTS	
T_{sens_max}(layer1)	**34.4 [°C]**
T_{sens_max}(layer2)	**25.0 [°C]**
T_{sens_max}(layer3)	**25.3 [°C]**
T_{air_outlet}(layer1)	22.3 [°C]
T_{air_outlet}(layer2)	22.5 [°C]
T_{air_outlet}(layer3)	19.4 [°C]
V_{media_aria}(layer1)	2.8 [m/s]
V_{media_aria}(layer2)	2.9 [m/s]
V_{media_aria}(layer3)	3.9 [m/s]
M_{outlet}(layer1)	0.00022 [Kg/s]
M_{outlet}(layer2)	0.00029[Kg/s]
M_{outlet}(layer3)	0.00109[Kg/s]

- There is no significant difference in temperature on layer 3 compared to the single layer model (26°C).

Have model simultaneously simulating all 3 layers of baseline Si vtx det

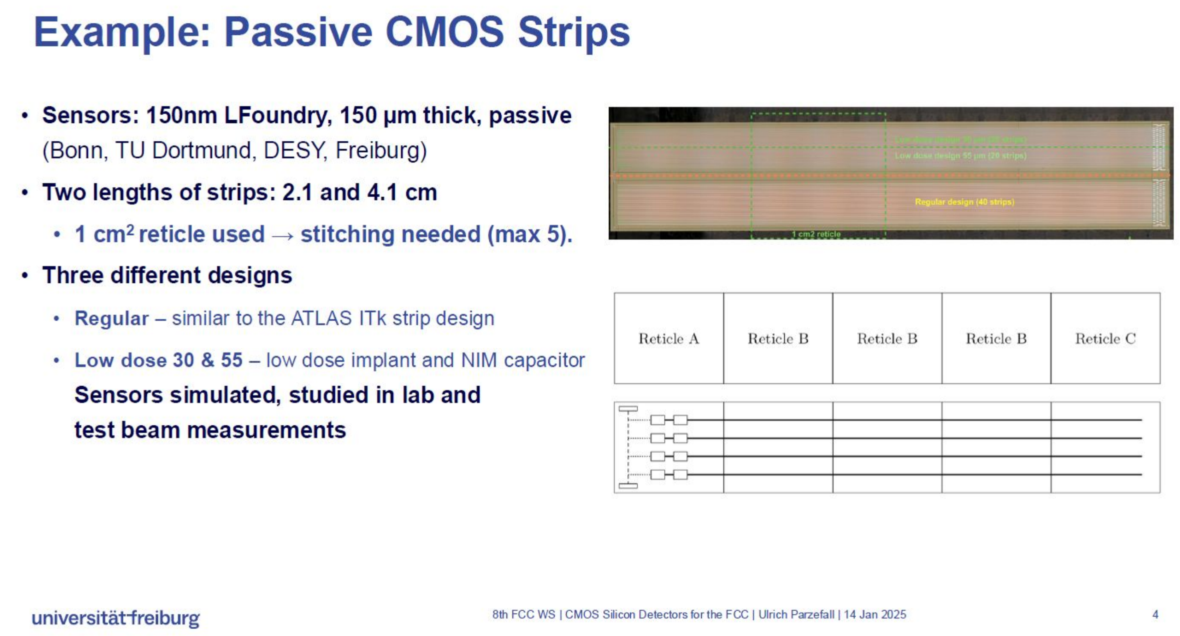
Max. ΔT (air @ 10 m/s, sensors): 10° C for layers 3 & 2; 20° C for layer 1

Air has the potential to cool the vtx det, need to optimize layer 1&2 inlets

Main Tracking

Large area silicon detectors for FCC

Ulrich Parzefall



Example: Passive CMOS Strips

- **Sensors: 150nm LFoundry, 150 µm thick, passive** (Bonn, TU Dortmund, DESY, Freiburg)
- **Two lengths of strips: 2.1 and 4.1 cm**
  - **1 cm^2 reticle used → stitching needed (max 5).**
- **Three different designs**
  - **Regular** – similar to the ATLAS ITk strip design
  - **Low dose 30 & 55** – low dose implant and NIM capacitor

  Sensors simulated, studied in lab and test beam measurements

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8th FCC WS | CMOS Silicon Detectors for the FCC | Ulrich Parzefall | 14 Jan 2025

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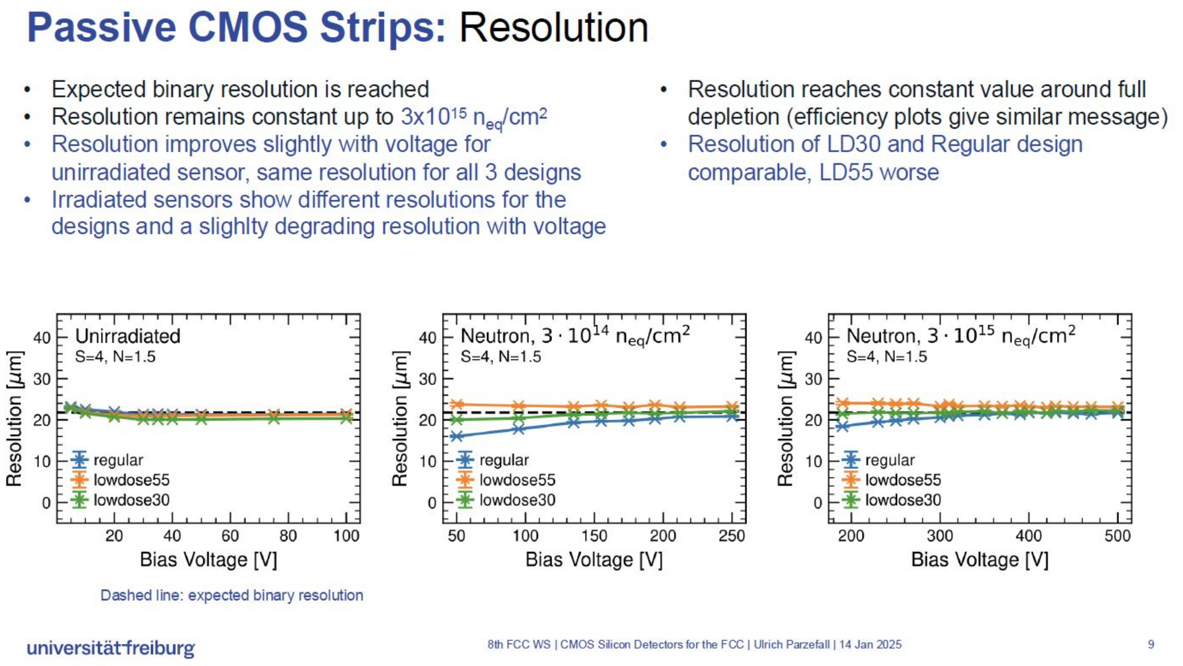

Passive CMOS Strips: Resolution

- Expected binary resolution is reached
- Resolution remains constant up to 3x10^{15} n_{eq}/cm^2
- Resolution improves slightly with voltage for unirradiated sensor, same resolution for all 3 designs
- Irradiated sensors show different resolutions for the designs and a slighlty degrading resolution with voltage
- Resolution reaches constant value around full depletion (efficiency plots give similar message)
- Resolution of LD30 and Regular design comparable, LD55 worse

Dashed line: expected binary resolution

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8th FCC WS | CMOS Silicon Detectors for the FCC | Ulrich Parzefall | 14 Jan 2025

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Many international projects on (CMOS) Silicon sensors for FCC tracker underway: DRD3 WP1

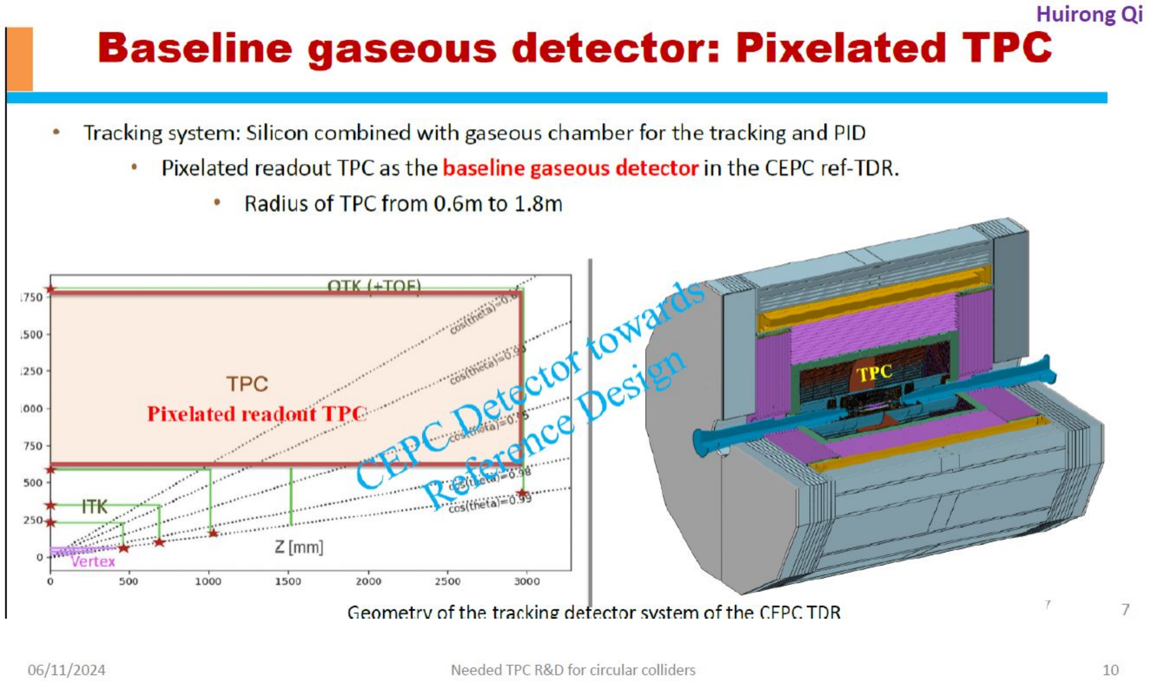
Various technologies under study, from 180nm down to 55nm (mostly 65nm)

Radiation hardness up to 3x10^{15} n_{eq}/cm^2 demonstrated already

FCC-hh fluences are a challenge, but can be met on the time scale given

Time Projection Chamber

Paul Colas
Victor Schwan



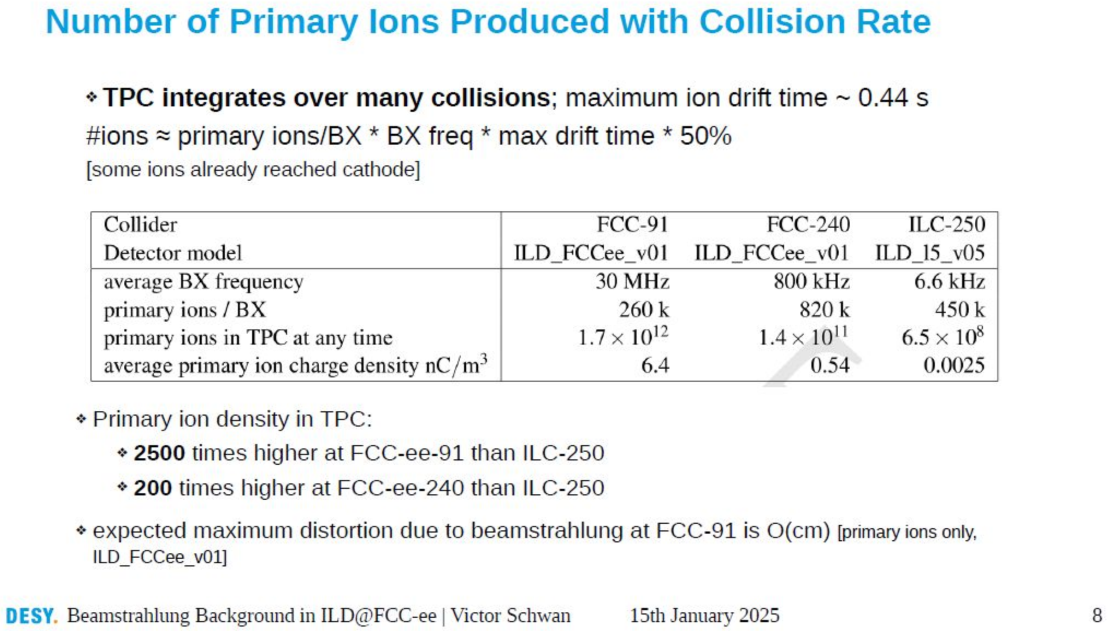
Huirong Qi

Baseline gaseous detector: Pixelated TPC

- Tracking system: Silicon combined with gaseous chamber for the tracking and PID
  - Pixelated readout TPC as the **baseline gaseous detector** in the CEPC ref-TDR.
    - Radius of TPC from 0.6m to 1.8m

Geometry of the tracking detector system of the CEPC TDR

06/11/2024 Needed TPC R&D for circular colliders 10



Number of Primary Ions Produced with Collision Rate

- **TPC integrates over many collisions**; maximum ion drift time ~ 0.44 s

#ions ≈ primary ions/BX * BX freq * max drift time * 50%
[some ions already reached cathode]

Collider Detector model	FCC-91 ILD_FCCee_v01	FCC-240 ILD_FCCee_v01	ILC-250 ILD_l5_v05
average BX frequency	30 MHz	800 kHz	6.6 kHz
primary ions / BX	260 k	820 k	450 k
primary ions in TPC at any time	1.7×10^{12}	1.4×10^{11}	6.5×10^{8}
average primary ion charge density $\mathrm{nC/m^3}$	6.4	0.54	0.0025

- Primary ion density in TPC:
  - **2500** times higher at FCC-ee-91 than ILC-250
  - **200** times higher at FCC-ee-240 than ILC-250
- expected maximum distortion due to beamstrahlung at FCC-91 is O(cm) [primary ions only, ILD_FCCee_v01]

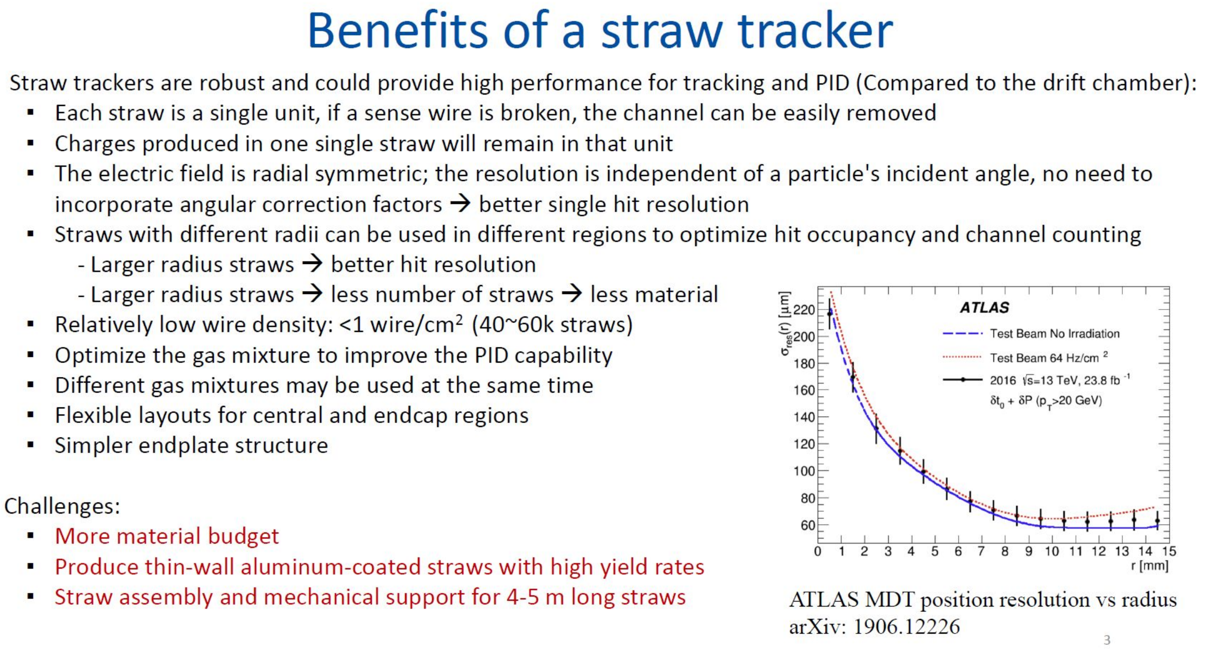
DESY. Beamstrahlung Background in ILD@FCC-ee | Victor Schwan 15th January 2025 8

CEPC Reference Detector usesTPC for high energy running (10 years of HZ + 6 years of top)

Large (cm!) distortions from ion space charge when running at Z pole -
operability at FCC-ee luminosities is being actively investigated (MDI mods, corrections)

Straw tube tracker for FCC-ee

Chihao Li



Benefits of a straw tracker

Straw trackers are robust and could provide high performance for tracking and PID (Compared to the drift chamber):

- Each straw is a single unit, if a sense wire is broken, the channel can be easily removed
- Charges produced in one single straw will remain in that unit
- The electric field is radial symmetric; the resolution is independent of a particle's incident angle, no need to incorporate angular correction factors → better single hit resolution
- Straws with different radii can be used in different regions to optimize hit occupancy and channel counting
  - Larger radius straws → better hit resolution
  - Larger radius straws → less number of straws → less material
- Relatively low wire density: <1 wire/cm² (40~60k straws)
- Optimize the gas mixture to improve the PID capability
- Different gas mixtures may be used at the same time
- Flexible layouts for central and endcap regions
- Simpler endplate structure

Challenges:

- More material budget
- Produce thin-wall aluminum-coated straws with high yield rates
- Straw assembly and mechanical support for 4-5 m long straws

ATLAS MDT position resolution vs radius
arXiv: 1906.12226

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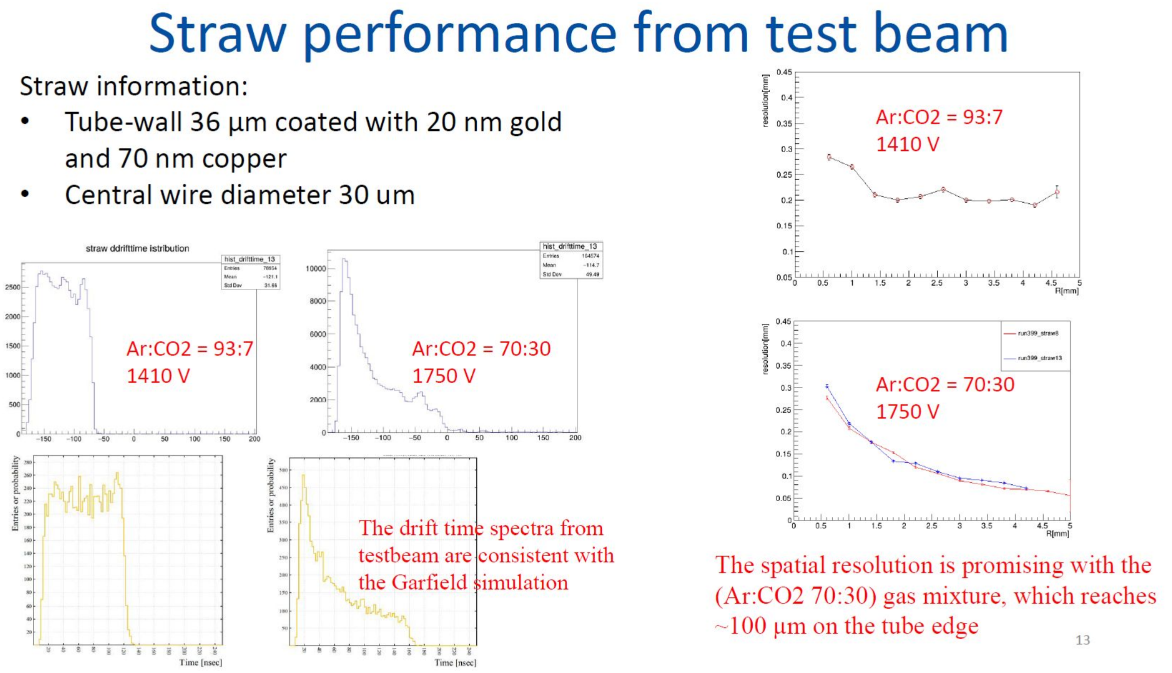

Straw performance from test beam

Straw information:

- Tube-wall 36 μm coated with 20 nm gold and 70 nm copper
- Central wire diameter 30 um

The drift time spectra from testbeam are consistent with the Garfield simulation

The spatial resolution is promising with the (Ar:CO2 70:30) gas mixture, which reaches ~100 μm on the tube edge

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A new FCC-ee gaseous tracker option proposed, effort embedded in DRD1 WP3

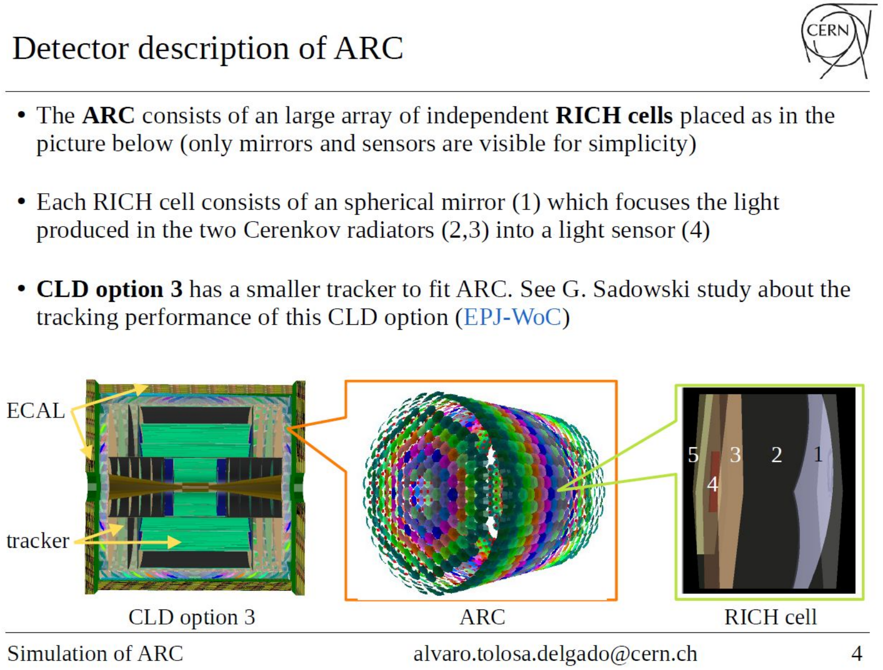
Strong synergies with drift chamber studies (gas, front-end electronics, dE/dx(dN/dx))

First test beam results, ongoing effort on detector layout and optimization

PID & Calorimetry

ARC concept for a compact RICH detector

Alvaro Tolosa-Delgado

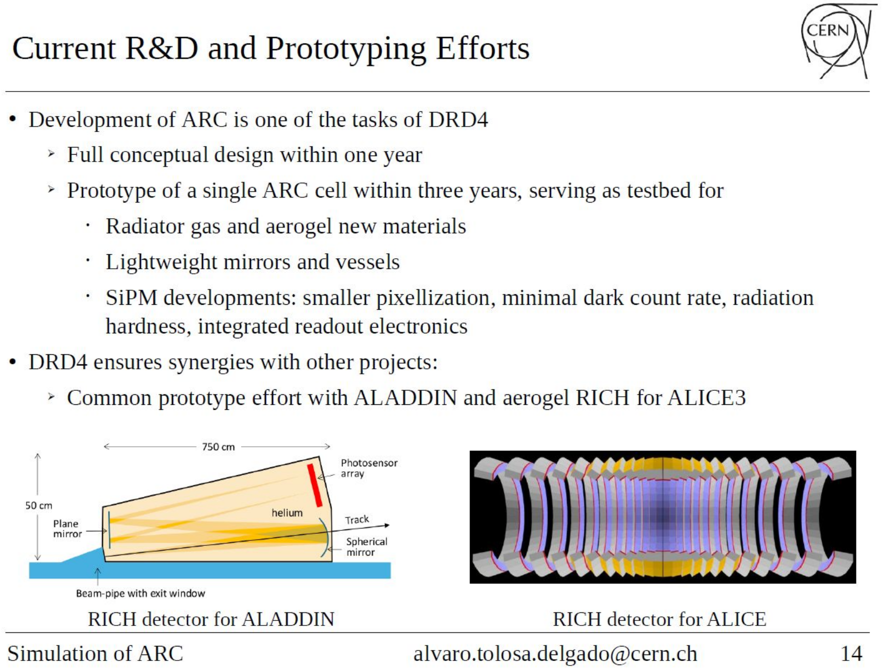


Detector description of ARC

- The **ARC** consists of an large array of independent **RICH cells** placed as in the picture below (only mirrors and sensors are visible for simplicity)
- Each RICH cell consists of an spherical mirror (1) which focuses the light produced in the two Cerenkov radiators (2,3) into a light sensor (4)
- **CLD option 3** has a smaller tracker to fit ARC. See G. Sadowski study about the tracking performance of this CLD option (EPJ-WoC)

CLD option 3 ARC RICH cell

Simulation of ARC alvaro.tolosa.delgado@cern.ch 4



Current R&D and Prototyping Efforts

- Development of ARC is one of the tasks of DRD4
  - Full conceptual design within one year
  - Prototype of a single ARC cell within three years, serving as testbed for
    - Radiator gas and aerogel new materials
    - Lightweight mirrors and vessels
    - SiPM developments: smaller pixellization, minimal dark count rate, radiation hardness, integrated readout electronics
- DRD4 ensures synergies with other projects:
  - Common prototype effort with ALADDIN and aerogel RICH for ALICE3

RICH detector for ALADDIN RICH detector for ALICE

Simulation of ARC alvaro.tolosa.delgado@cern.ch 14

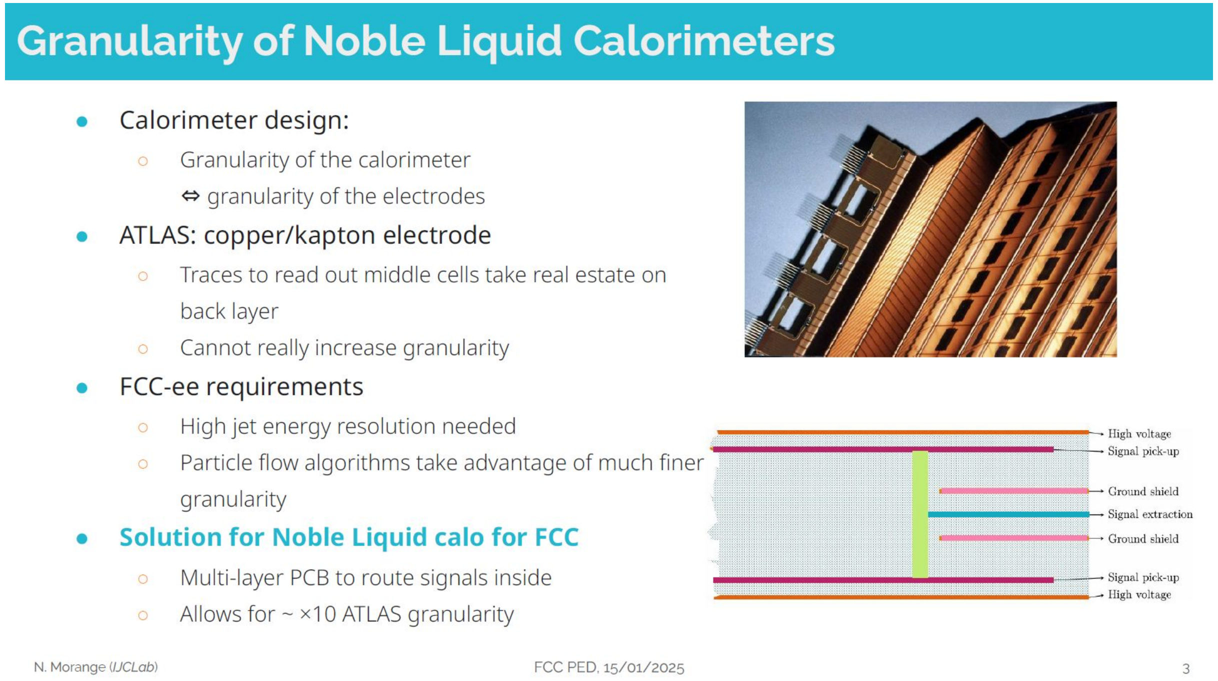
ARC provides accurate particle identification for FCC-ee detector concepts, integration into CLD full sim chain is ongoing

Pressurized Xenon can be an alternative to C_4F_{10}

First ARC prototype to be delivered in 3 years in framework of DRD4

Noble liquid calorimetry

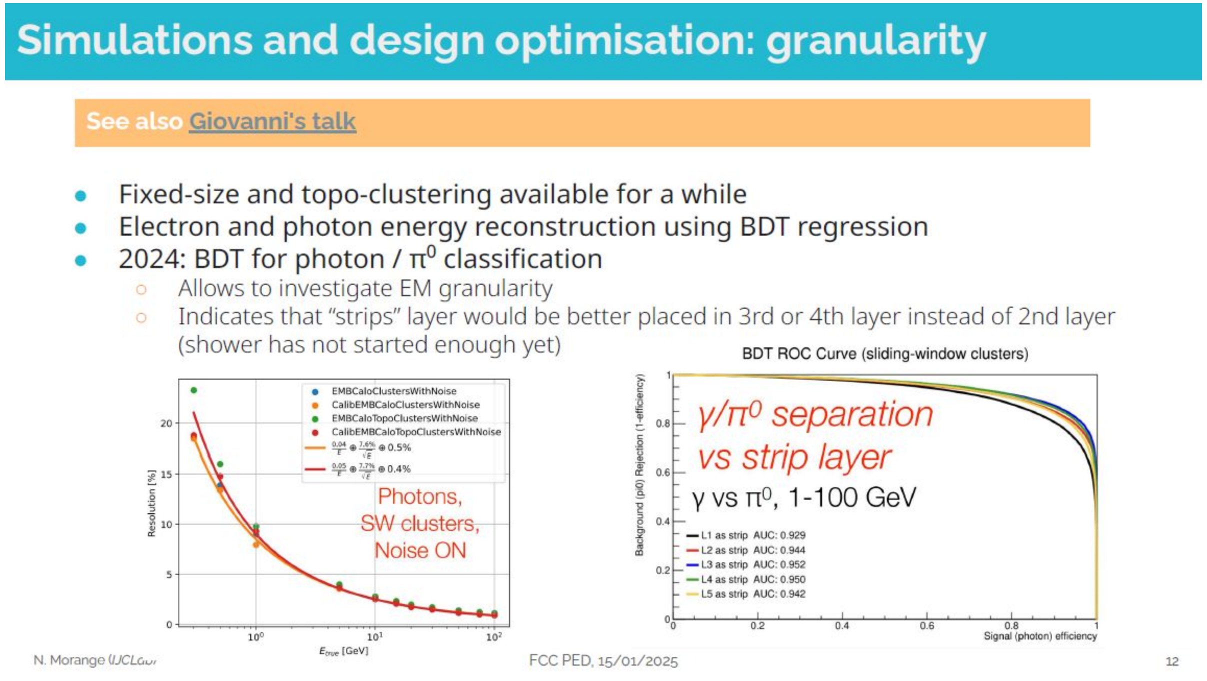
Nicolas Morange



Granularity of Noble Liquid Calorimeters

- Calorimeter design:
  - Granularity of the calorimeter ⇔ granularity of the electrodes
- ATLAS: copper/kapton electrode
  - Traces to read out middle cells take real estate on back layer
  - Cannot really increase granularity
- FCC-ee requirements
  - High jet energy resolution needed
  - Particle flow algorithms take advantage of much finer granularity
- **Solution for Noble Liquid calo for FCC**
  - Multi-layer PCB to route signals inside
  - Allows for ~ ×10 ATLAS granularity

N. Morange (IJCLab) FCC PED, 15/01/2025 3



Simulations and design optimisation: granularity

See also Giovanni's talk

- Fixed-size and topo-clustering available for a while
- Electron and photon energy reconstruction using BDT regression
- 2024: BDT for photon / π^0 classification
  - Allows to investigate EM granularity
  - Indicates that "strips" layer would be better placed in 3rd or 4th layer instead of 2nd layer (shower has not started enough yet)

N. Morange (IJCLab) FCC PED, 15/01/2025 12

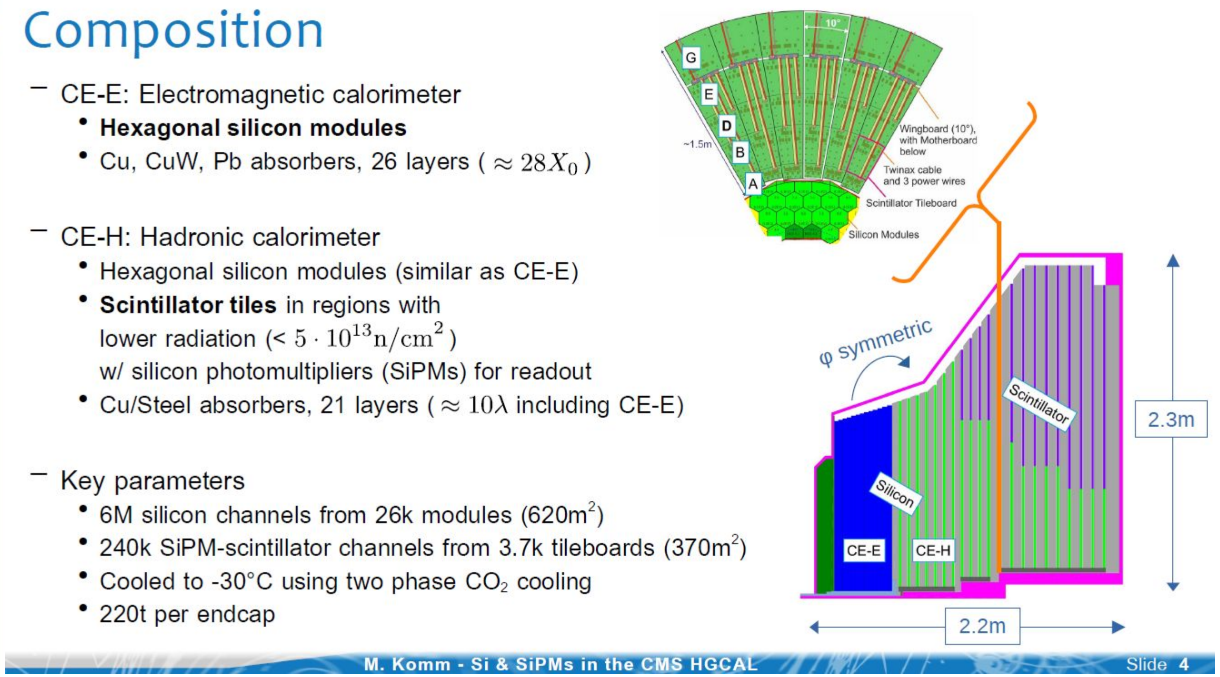
New large-scale electrode prototype in fabrication at CERN PCB Lab (Jan 2025)

Advanced full simulation enables electrode design optimization

Good progress in mechanics, end-caps concept, starting cold readout electronics efforts

Si and SiPM-on-Tile: scalability

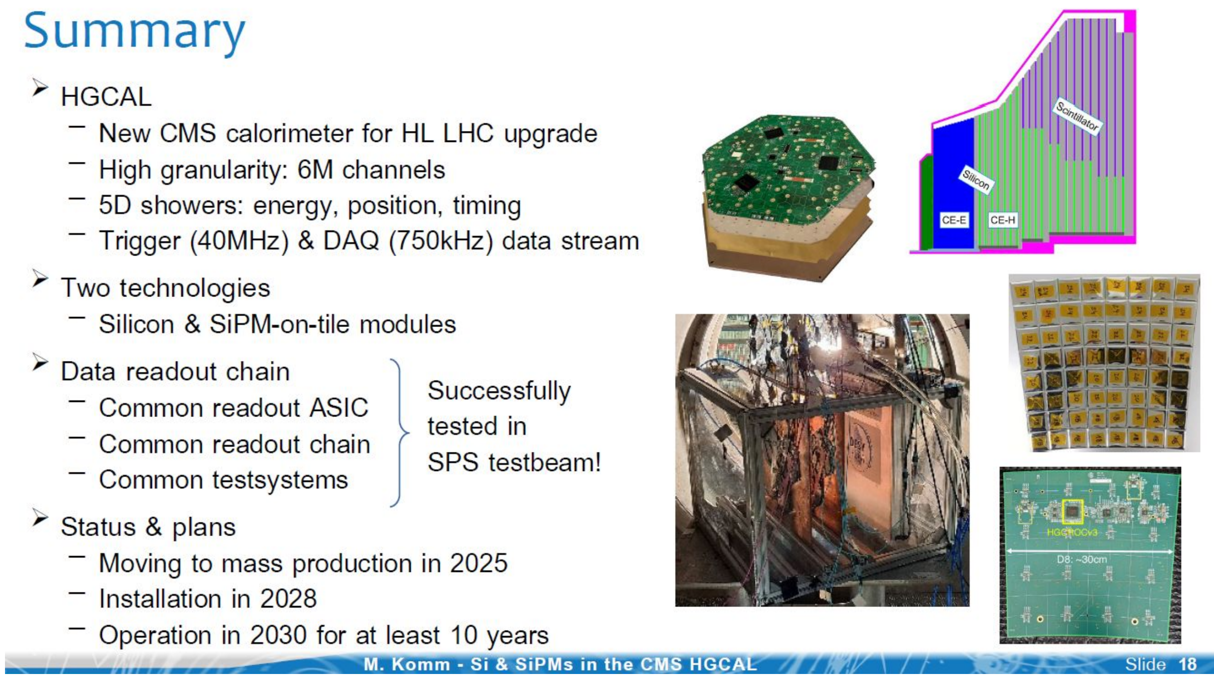
Matthias Komm



Composition

- CE-E: Electromagnetic calorimeter
  - **Hexagonal silicon modules**
  - Cu, CuW, Pb absorbers, 26 layers ($\approx 28X_0$)
- CE-H: Hadronic calorimeter
  - Hexagonal silicon modules (similar as CE-E)
  - **Scintillator tiles** in regions with lower radiation (< $5 \cdot 10^{13}\mathrm{n/cm^2}$) w/ silicon photomultipliers (SiPMs) for readout
  - Cu/Steel absorbers, 21 layers ($\approx 10\lambda$ including CE-E)
- Key parameters
  - 6M silicon channels from 26k modules ($620\mathrm{m}^2$)
  - 240k SiPM-scintillator channels from 3.7k tileboards ($370\mathrm{m}^2$)
  - Cooled to -30°C using two phase CO_2 cooling
  - 220t per endcap

M. Komm - Si & SiPMs in the CMS HGCAL Slide 4



Summary

- HGCAL
  - New CMS calorimeter for HL LHC upgrade
  - High granularity: 6M channels
  - 5D showers: energy, position, timing
  - Trigger (40MHz) & DAQ (750kHz) data stream
- Two technologies
  - Silicon & SiPM-on-tile modules
- Data readout chain
  - Common readout ASIC
  - Common readout chain
  - Common testsystems

Successfully tested in SPS testbeam!

- Status & plans
  - Moving to mass production in 2025
  - Installation in 2028
  - Operation in 2030 for at least 10 years

M. Komm - Si & SiPMs in the CMS HGCAL Slide 18

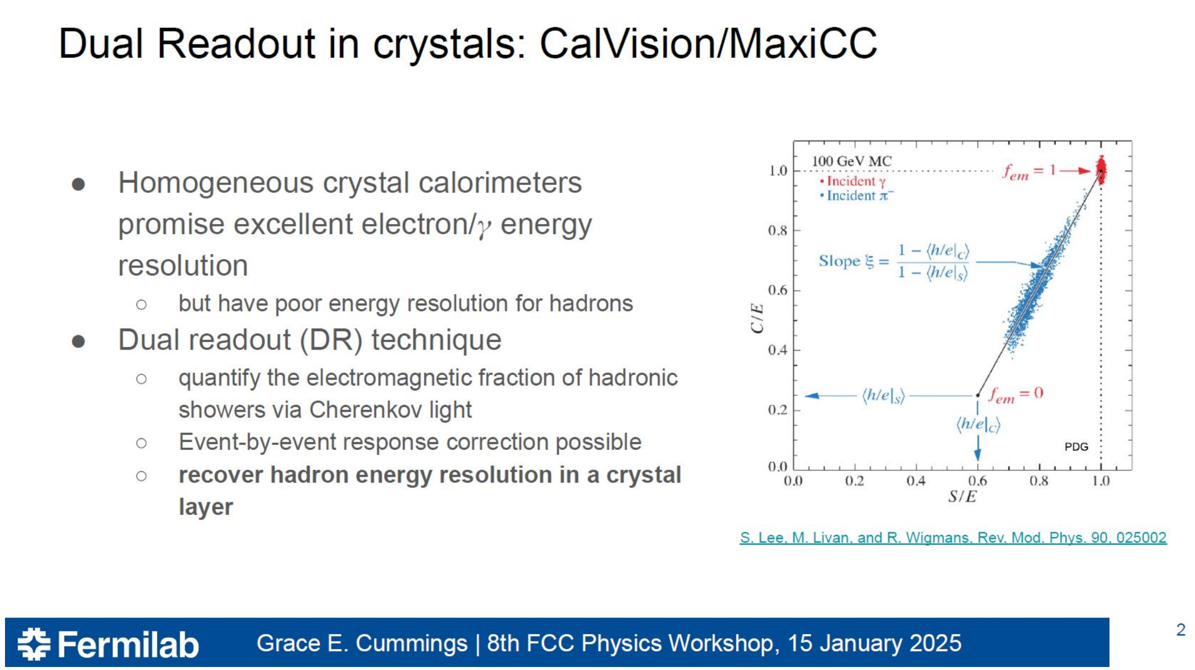
CMS High-GranularCalorimeter (HGCAL) as current construction example - 6M channels with energy, position, timing!

Hexagonal silicon modules & scintillator tiles w/ silicon photomultipliers for readout

Production starting in 2025 - we should listen very closely to lessons learned!

Crystals - CalVision/MaxiCC

Grace Cummings



Dual Readout in crystals: CalVision/MaxiCC

- Homogeneous crystal calorimeters promise excellent electron/γ energy resolution
  - but have poor energy resolution for hadrons
- Dual readout (DR) technique
  - quantify the electromagnetic fraction of hadronic showers via Cherenkov light
  - Event-by-event response correction possible
  - **recover hadron energy resolution in a crystal layer**

S. Lee, M. Livan, and R. Wigmans, Rev. Mod. Phys. 90, 025002

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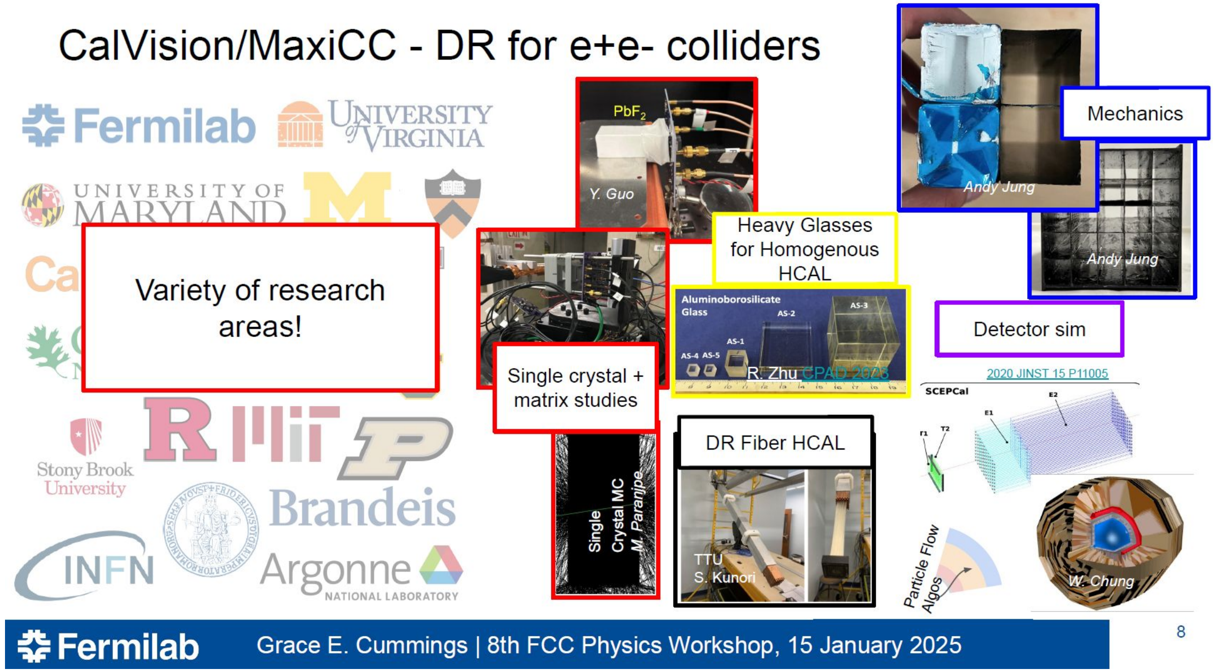

CalVision/MaxiCC - DR for e+e- colliders

Variety of research areas!

Mechanics

Heavy Glasses for Homogenous HCAL

Detector sim

Single crystal + matrix studies

DR Fiber HCAL

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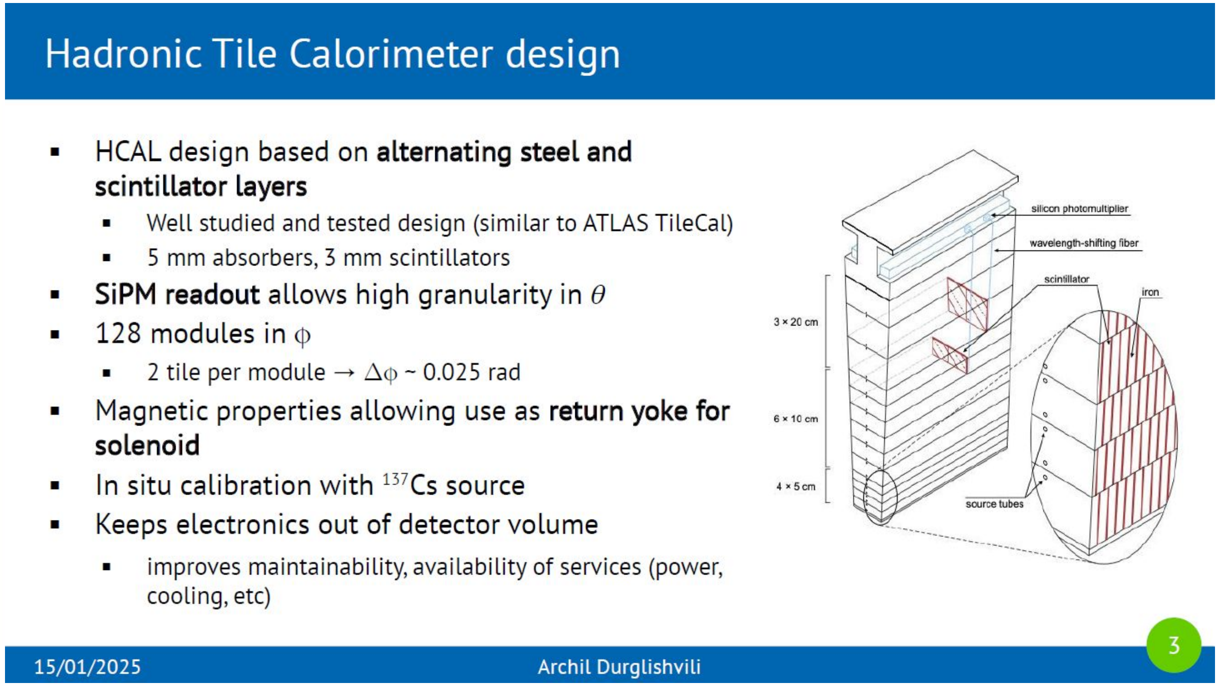
Separating Cherenkov and Scintillation light using Wavelength Filters and Time structure (waveform analysis) depending on scintillating material

First time, heavy glasses have been used in a beam test! Targets a homogenous HCAL

DESY test beam comfortably surpasses goal of > 50 Cherenkov photoelectrons / GeV

TileCal

Archil Durglishvili



Hadronic Tile Calorimeter design

- HCAL design based on **alternating steel and scintillator layers**
  - Well studied and tested design (similar to ATLAS TileCal)
  - 5 mm absorbers, 3 mm scintillators
- **SiPM readout** allows high granularity in θ
- 128 modules in ϕ
  - 2 tile per module → $\Delta\phi$ ~ 0.025 rad
- Magnetic properties allowing use as **return yoke for solenoid**
- In situ calibration with ^{137}Cs source
- Keeps electronics out of detector volume
  - improves maintainability, availability of services (power, cooling, etc)

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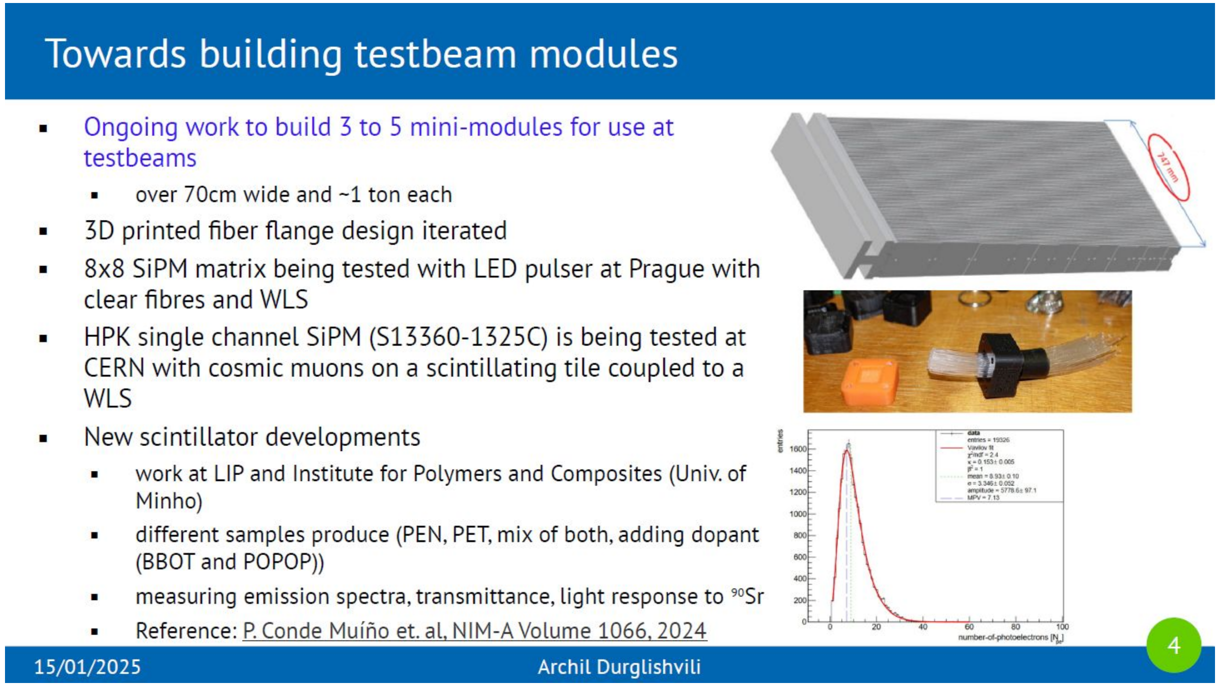


Towards building testbeam modules

- Ongoing work to build 3 to 5 mini-modules for use at testbeams
  - over 70cm wide and ~1 ton each
- 3D printed fiber flange design iterated
- 8x8 SiPM matrix being tested with LED pulser at Prague with clear fibres and WLS
- HPK single channel SiPM (S13360-1325C) is being tested at CERN with cosmic muons on a scintillating tile coupled to a WLS
- New scintillator developments
  - work at LIP and Institute for Polymers and Composites (Univ. of Minho)
  - different samples produce (PEN, PET, mix of both, adding dopant (BBOT and POPOP))
  - measuring emission spectra, transmittance, light response to ^{90}Sr
  - Reference: P. Conde Muíño et. al, NIM-A Volume 1066, 2024

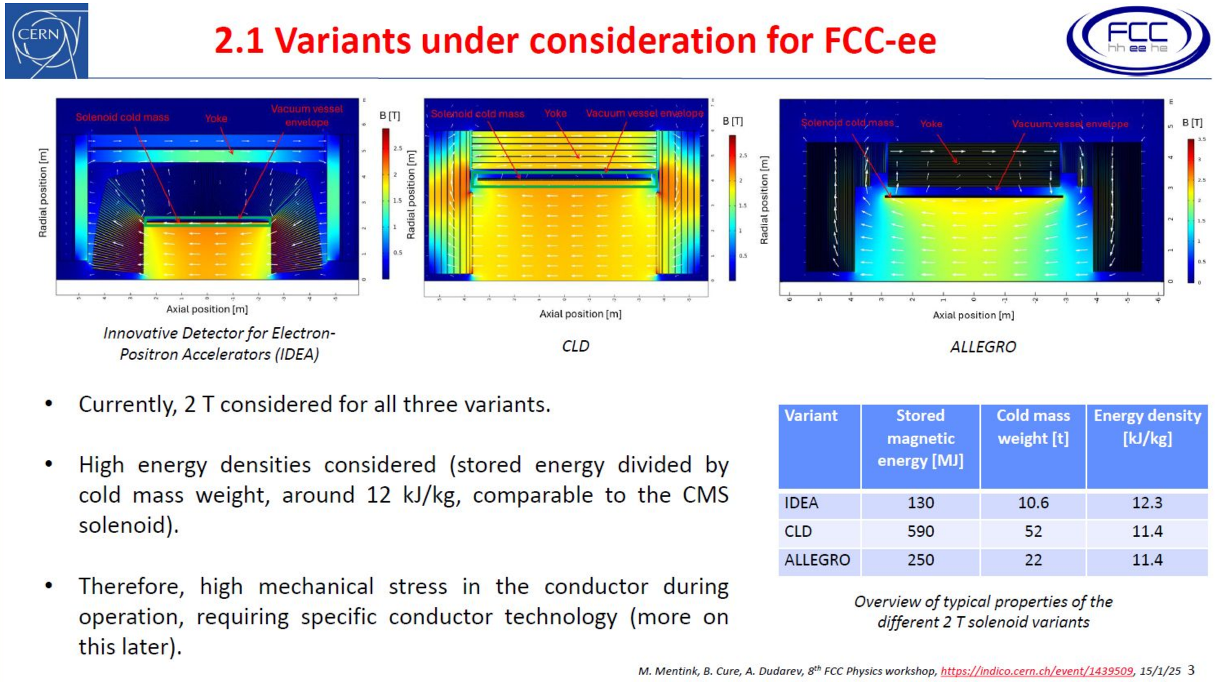
15/01/2025 Archil Durglishvili 4

- Design based on alternating steel and scintillator layers (similar to ATLAS TileCal) with SiPM readout
- Ongoing work to build testbeam modules
- First version of the TileCal barrel and endcap is implemented in the simulation within key4hep framework
- Ongoing work to implement PandoraPFA in ALLEGRO simulation

Solenoid / Cryostat

Solenoid detector magnets for FCC-ee

Matthias Mentink



2.1 Variants under consideration for FCC-ee

Innovative Detector for Electron-Positron Accelerators (IDEA)

CLD

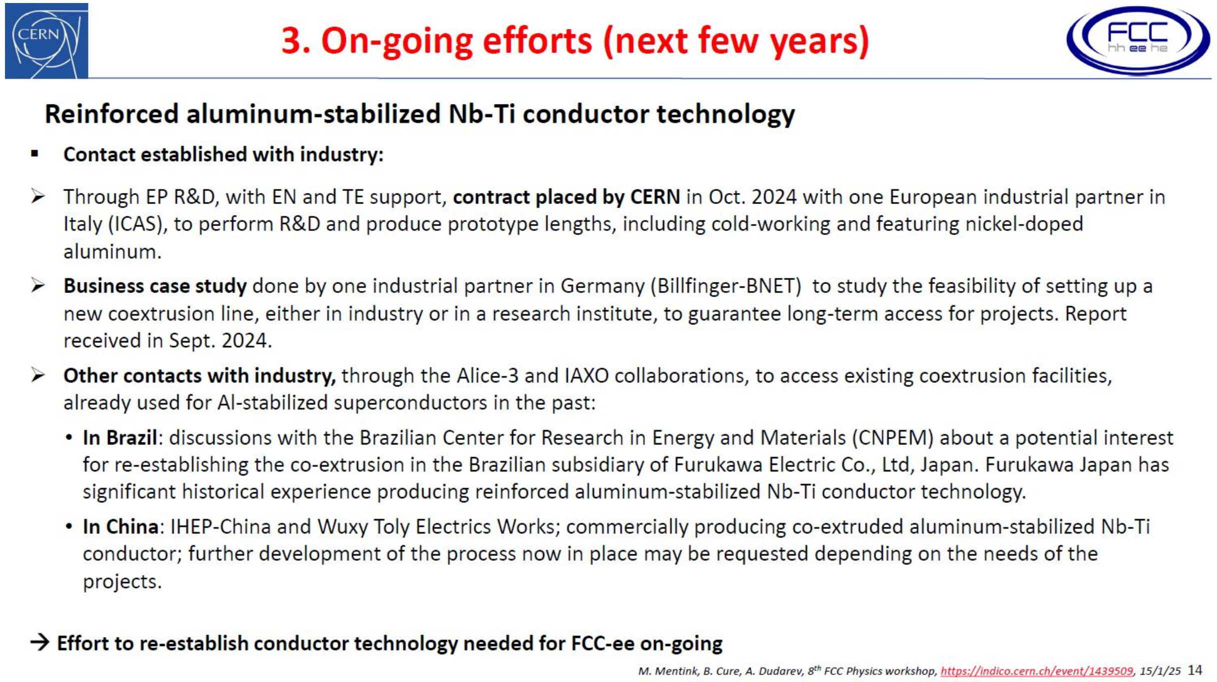
ALLEGRO

- Currently, 2 T considered for all three variants.
- High energy densities considered (stored energy divided by cold mass weight, around 12 kJ/kg, comparable to the CMS solenoid).
- Therefore, high mechanical stress in the conductor during operation, requiring specific conductor technology (more on this later).

Variant	Stored magnetic energy [MJ]	Cold mass weight [t]	Energy density [kJ/kg]
IDEA	130	10.6	12.3
CLD	590	52	11.4
ALLEGRO	250	22	11.4

Overview of typical properties of the different 2 T solenoid variants

M. Mentink, B. Cure, A. Dudarev, 8th FCC Physics workshop, https://indico.cern.ch/event/1439509, 15/1/25 3



3. On-going efforts (next few years)

Reinforced aluminum-stabilized Nb-Ti conductor technology

- **Contact established with industry:**

- Through EP R&D, with EN and TE support, **contract placed by CERN** in Oct. 2024 with one European industrial partner in Italy (ICAS), to perform R&D and produce prototype lengths, including cold-working and featuring nickel-doped aluminum.
- **Business case study** done by one industrial partner in Germany (Billfinger-BNET) to study the feasibility of setting up a new coextrusion line, either in industry or in a research institute, to guarantee long-term access for projects. Report received in Sept. 2024.
- **Other contacts with industry,** through the Alice-3 and IAXO collaborations, to access existing coextrusion facilities, already used for Al-stabilized superconductors in the past:
  - **In Brazil**: discussions with the Brazilian Center for Research in Energy and Materials (CNPEM) about a potential interest for re-establishing the co-extrusion in the Brazilian subsidiary of Furukawa Electric Co., Ltd, Japan. Furukawa Japan has significant historical experience producing reinforced aluminum-stabilized Nb-Ti conductor technology.
  - **In China**: IHEP-China and Wuxy Toly Electrics Works; commercially producing co-extruded aluminum-stabilized Nb-Ti conductor; further development of the process now in place may be requested depending on the needs of the projects.

→ **Effort to re-establish conductor technology needed for FCC-ee on-going**

M. Mentink, B. Cure, A. Dudarev, 8th FCC Physics workshop, https://indico.cern.ch/event/1439509, 15/1/25 14

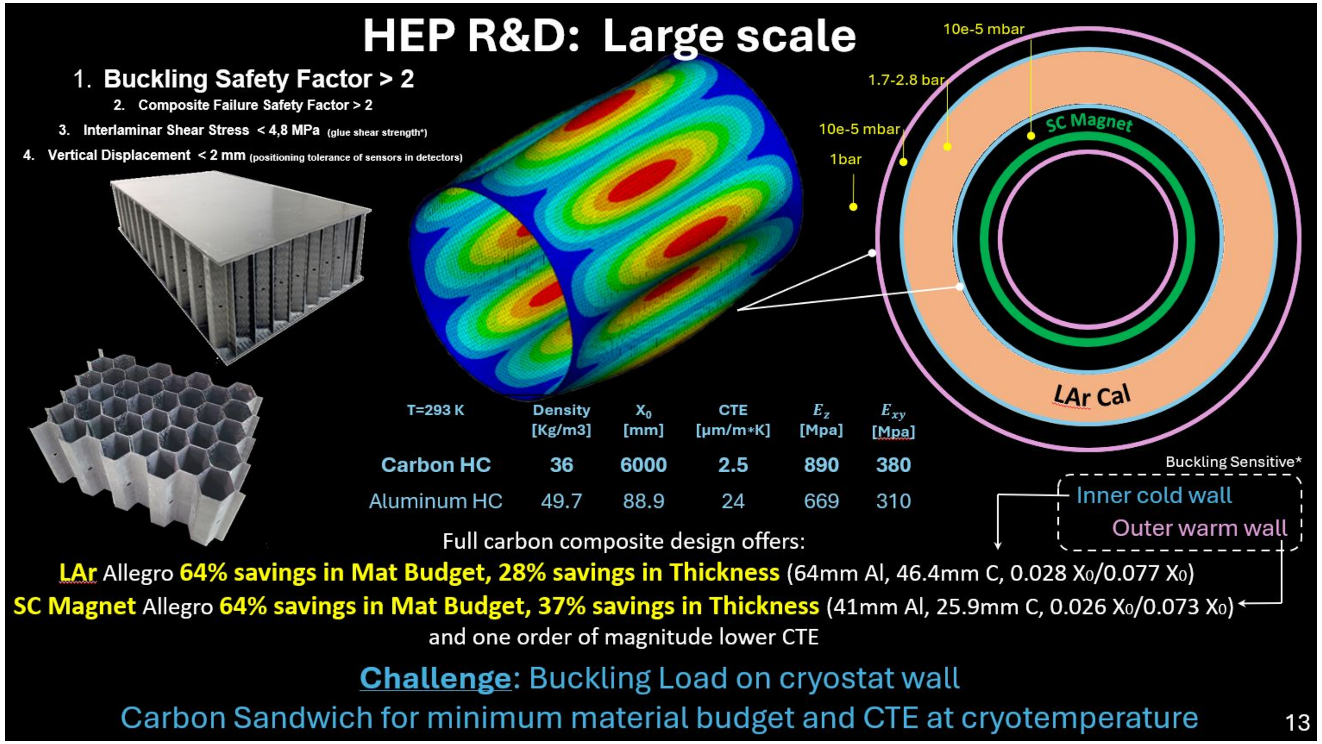
2 T => high energy densities comparable to the CMS solenoid => high mechanical stress in conductor

Production of aluminum stabilized Nb Ti conductor technology used so far stopped => mitigation efforts at CERN to re-establish production; High Temperature Superconductor tech. might be an alternative, but needs more studies

History of ATLAS + CMS magnet projects: **15 years** from start of engineering design to completion of commissioning

Light composite material cryostats

Corrado Gargiulo



HEP R&D: Large scale

1. **Buckling Safety Factor > 2**
2. **Composite Failure Safety Factor > 2**
3. **Interlaminar Shear Stress < 4,8 MPa** (glue shear strength*)
4. **Vertical Displacement < 2 mm** (positioning tolerance of sensors in detectors)

T=293 K	Density [Kg/m3]	X_0 [mm]	CTE [µm/m∗K]	E_z [Mpa]	E_{xy} [Mpa]
Carbon HC	**36**	**6000**	**2.5**	**890**	**380**
Aluminum HC	49.7	88.9	24	669	310

Full carbon composite design offers:

LAr Allegro **64% savings in Mat Budget, 28% savings in Thickness** (64mm Al, 46.4mm C, 0.028 X_0/0.077 X_0)

SC Magnet Allegro **64% savings in Mat Budget, 37% savings in Thickness** (41mm Al, 25.9mm C, 0.026 X_0/0.073 X_0)

and one order of magnitude lower CTE

Challenge: Buckling Load on cryostat wall

Carbon Sandwich for minimum material budget and CTE at cryotemperature

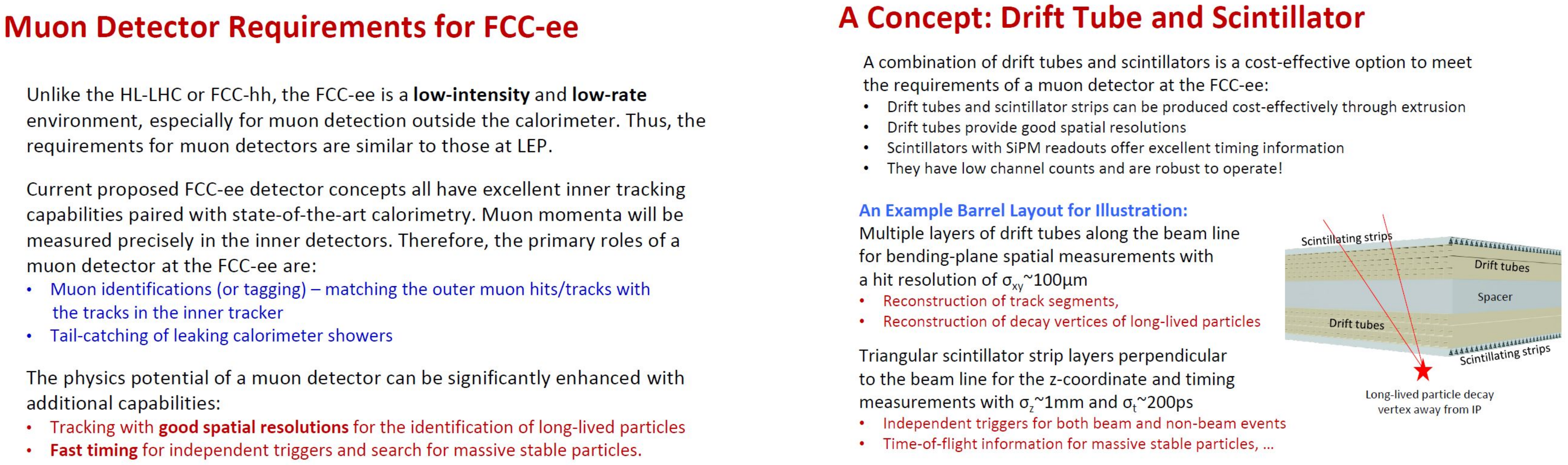
Carbon Cryostat R&D for future detectors within CERN EP R&D, collaborating to develop a larger-scale cryostat demonstrator (1m^3) with the Superconducting Magnet Group and the LAr Calorimeter Groups

Liner-less carbon sandwich wall offers a significant advantage in terms of material budget and thickness when compared to more conventional aluminum solutions.

Muon System

Muon Detector Technologies for FCC-ee

Jianming Qian



Muon Detector Requirements for FCC-ee

Unlike the HL-LHC or FCC-hh, the FCC-ee is a **low-intensity** and **low-rate** environment, especially for muon detection outside the calorimeter. Thus, the requirements for muon detectors are similar to those at LEP.

Current proposed FCC-ee detector concepts all have excellent inner tracking capabilities paired with state-of-the-art calorimetry. Muon momenta will be measured precisely in the inner detectors. Therefore, the primary roles of a muon detector at the FCC-ee are:

- Muon identifications (or tagging) – matching the outer muon hits/tracks with the tracks in the inner tracker
- Tail-catching of leaking calorimeter showers

The physics potential of a muon detector can be significantly enhanced with additional capabilities:

- Tracking with **good spatial resolutions** for the identification of long-lived particles
- **Fast timing** for independent triggers and search for massive stable particles.

A Concept: Drift Tube and Scintillator

A combination of drift tubes and scintillators is a cost-effective option to meet the requirements of a muon detector at the FCC-ee:

- Drift tubes and scintillator strips can be produced cost-effectively through extrusion
- Drift tubes provide good spatial resolutions
- Scintillators with SiPM readouts offer excellent timing information
- They have low channel counts and are robust to operate!

An Example Barrel Layout for Illustration:

Multiple layers of drift tubes along the beam line for bending-plane spatial measurements with a hit resolution of σ_{xy}~100µm

- Reconstruction of track segments,
- Reconstruction of decay vertices of long-lived particles

Triangular scintillator strip layers perpendicular to the beam line for the z-coordinate and timing measurements with σ_z~1mm and σ_t~200ps

- Independent triggers for both beam and non-beam events
- Time-of-flight information for massive stable particles, …

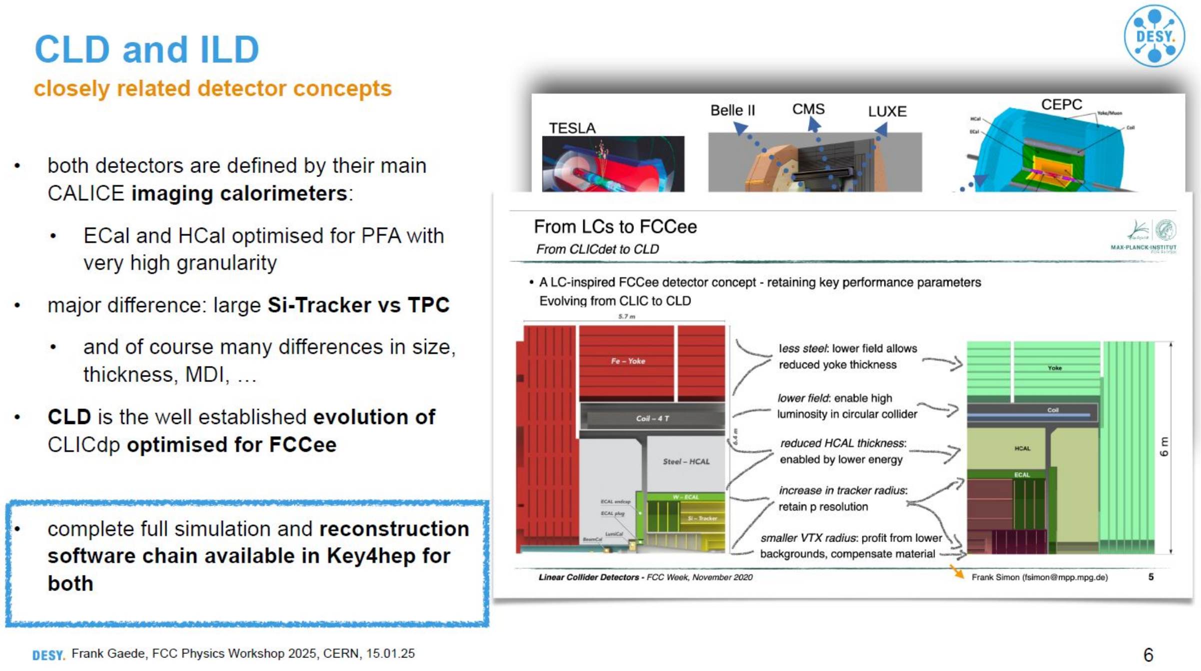
Aim for precision position measurements from drift tubes, fast timing information from scintillators, using cost-effective (inexpensive to construct, <100k channels) mature technologies, reliable and robust to operate

Considering repurposing of ATLAS (s)MDT chambers (tubes glued together)

Detector Concepts

CLD / ILD rationale and full-sim based studies

Frank-Dieter Gaede



CLD and ILD

closely related detector concepts

- both detectors are defined by their main CALICE **imaging calorimeters**:
  - ECal and HCal optimised for PFA with very high granularity
- major difference: large **Si-Tracker vs TPC**
  - and of course many differences in size, thickness, MDI, …
- **CLD** is the well established **evolution of** CLICdp **optimised for FCCee**
- complete full simulation and **reconstruction software chain available in Key4hep for both**

From LCs to FCCee

From CLICdet to CLD

- A LC-inspired FCCee detector concept - retaining key performance parameters
  Evolving from CLIC to CLD

less steel: lower field allows reduced yoke thickness

lower field: enable high luminosity in circular collider

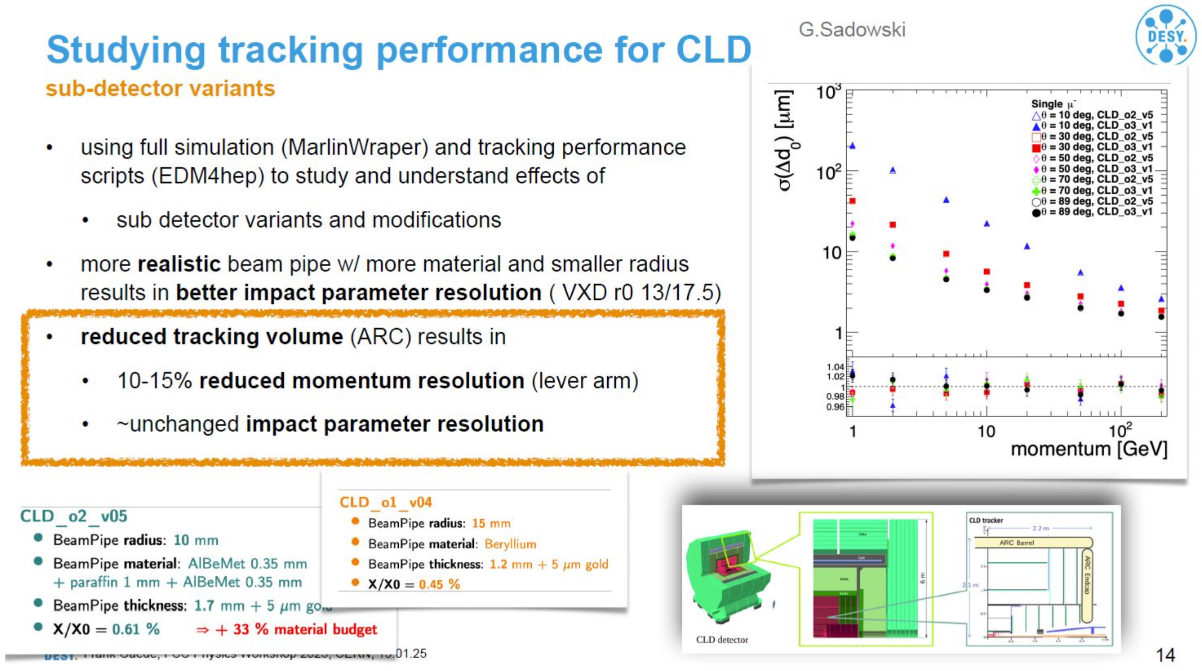
reduced HCAL thickness: enabled by lower energy

increase in tracker radius: retain p resolution

smaller VTX radius: profit from lower backgrounds, compensate material

Linear Collider Detectors *- FCC Week, November 2020* Frank Simon (fsimon@mpp.mpg.de) 5

DESY. Frank Gaede, FCC Physics Workshop 2025, CERN, 15.01.25 6



Studying tracking performance for CLD

sub-detector variants

G.Sadowski

- using full simulation (MarlinWraper) and tracking performance scripts (EDM4hep) to study and understand effects of
  - sub detector variants and modifications
- more **realistic** beam pipe w/ more material and smaller radius results in **better impact parameter resolution** (VXD r0 13/17.5)
- **reduced tracking volume** (ARC) results in
  - 10-15% **reduced momentum resolution** (lever arm)
  - ~unchanged **impact parameter resolution**

CLD_o2_v05

- BeamPipe **radius**: 10 mm
- BeamPipe **material**: AlBeMet 0.35 mm + paraffin 1 mm + AlBeMet 0.35 mm
- BeamPipe **thickness**: 1.7 mm + 5 μm gold
- X/X0 = 0.61 % ⇒ + 33 % material budget

CLD_o1_v04

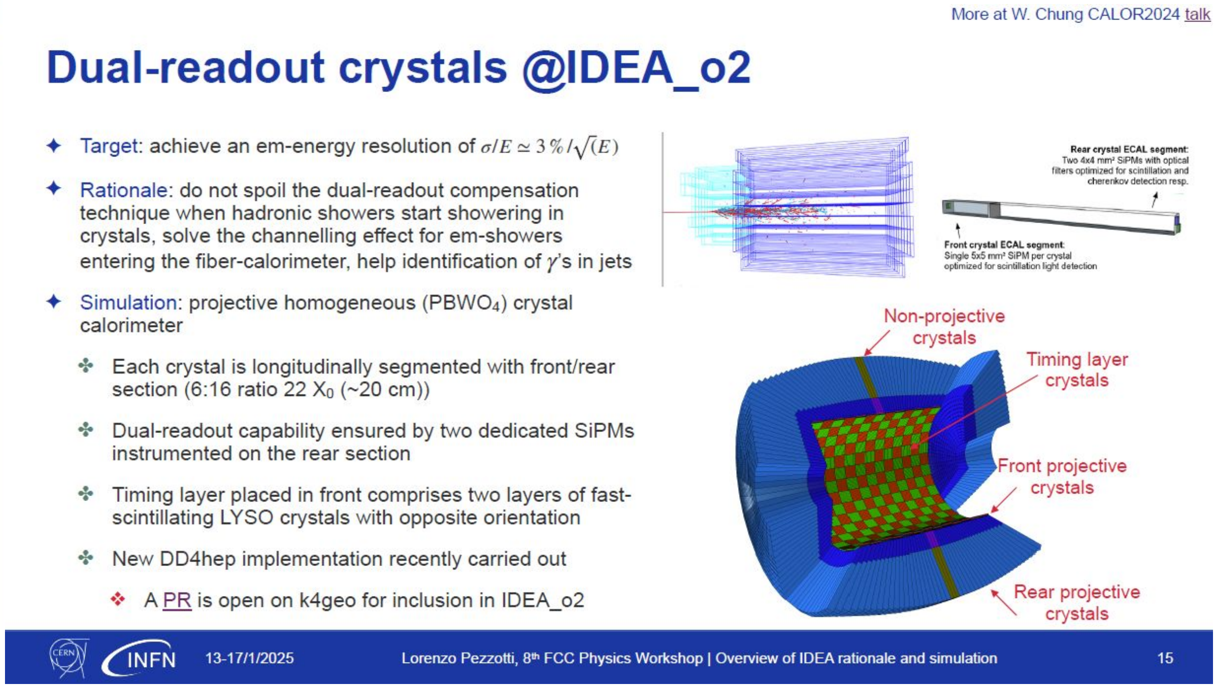
- BeamPipe **radius**: 15 mm
- BeamPipe **material**: Beryllium
- BeamPipe **thickness**: 1.2 mm + 5 μm gold
- X/X0 = 0.45 %

.01.25 14

- ILD and CLD are closely related detector concepts, with CALICE imaging calorimeters
- Complete reconstruction code for both is available in Key4hep - easy plug&play, adding new sub-detectors
- Full-simulation is needed for full performance studies (esp. using AI/ML algorithms)

IDEA: rationale, full simrec focus

Lorenzo Pezzotti

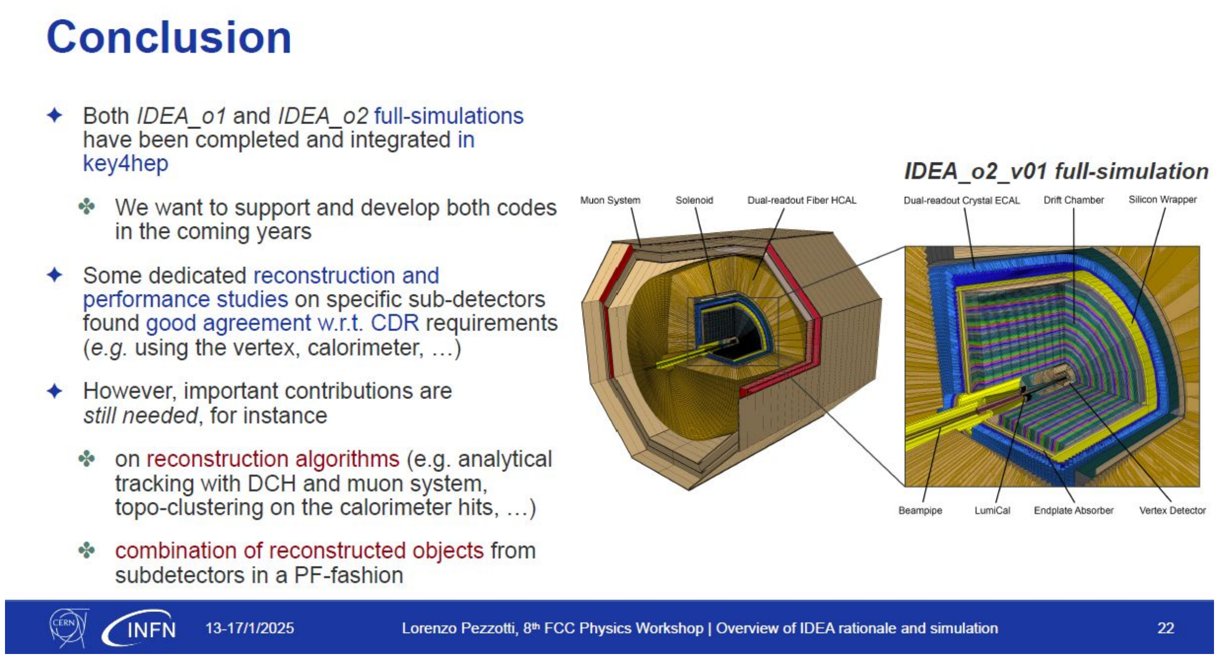


More at W. Chung CALOR2024 talk

Dual-readout crystals @IDEA_o2

- Target: achieve an em-energy resolution of $\sigma/E \simeq 3\,\%/\sqrt{(E)}$
- Rationale: do not spoil the dual-readout compensation technique when hadronic showers start showering in crystals, solve the channelling effect for em-showers entering the fiber-calorimeter, help identification of γ's in jets
- Simulation: projective homogeneous (PBWO$_4$) crystal calorimeter
  - Each crystal is longitudinally segmented with front/rear section (6:16 ratio 22 X_0 (~20 cm))
  - Dual-readout capability ensured by two dedicated SiPMs instrumented on the rear section
  - Timing layer placed in front comprises two layers of fast-scintillating LYSO crystals with opposite orientation
  - New DD4hep implementation recently carried out
    - A PR is open on k4geo for inclusion in IDEA_o2

INFN 13-17/1/2025 Lorenzo Pezzotti, 8th FCC Physics Workshop | Overview of IDEA rationale and simulation 15



Conclusion

- Both *IDEA_o1* and *IDEA_o2* full-simulations have been completed and integrated in key4hep
  - We want to support and develop both codes in the coming years
- Some dedicated reconstruction and performance studies on specific sub-detectors found good agreement w.r.t. CDR requirements (*e.g.* using the vertex, calorimeter, …)
- However, important contributions are *still needed*, for instance
  - on reconstruction algorithms (e.g. analytical tracking with DCH and muon system, topo-clustering on the calorimeter hits, …)
  - combination of reconstructed objects from subdetectors in a PF-fashion

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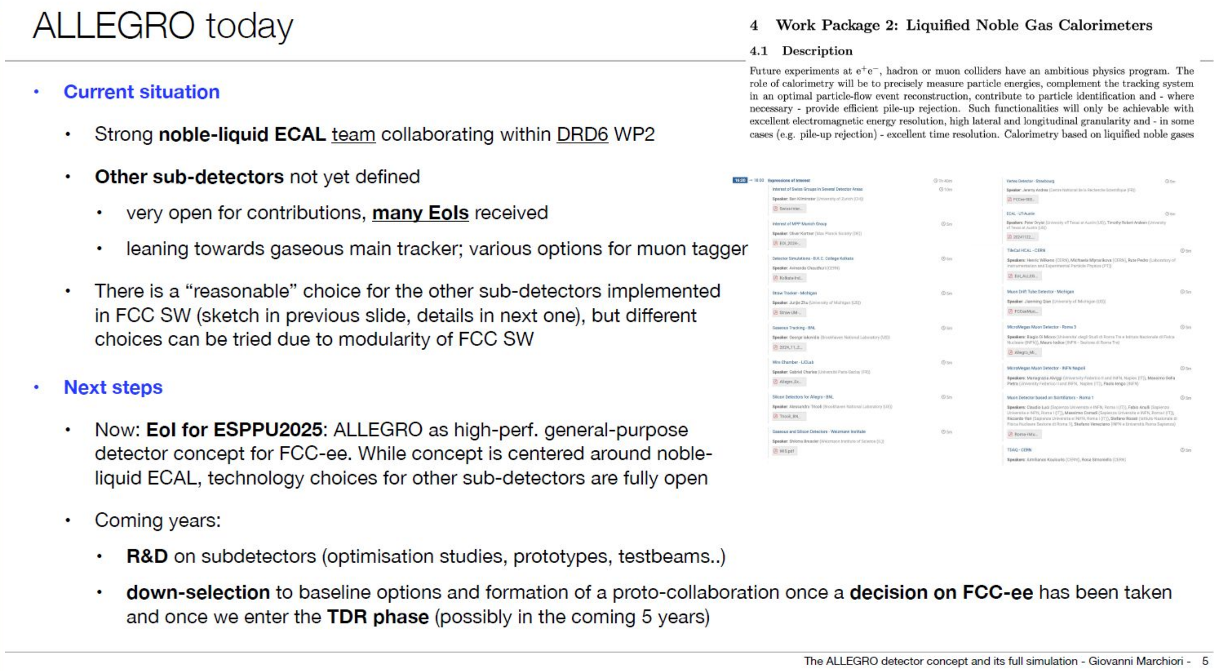
IDEA concept is evolving - new “crystal EM calorimeter before solenoid” baseline

Full geometries/sensitive detectors available for both old and new calorimetry options

Ongoing effort on digitization and reconstruction algorithms

ALLEGRO: rationale, full simrec focus

Giovanni Marchiori



ALLEGRO today

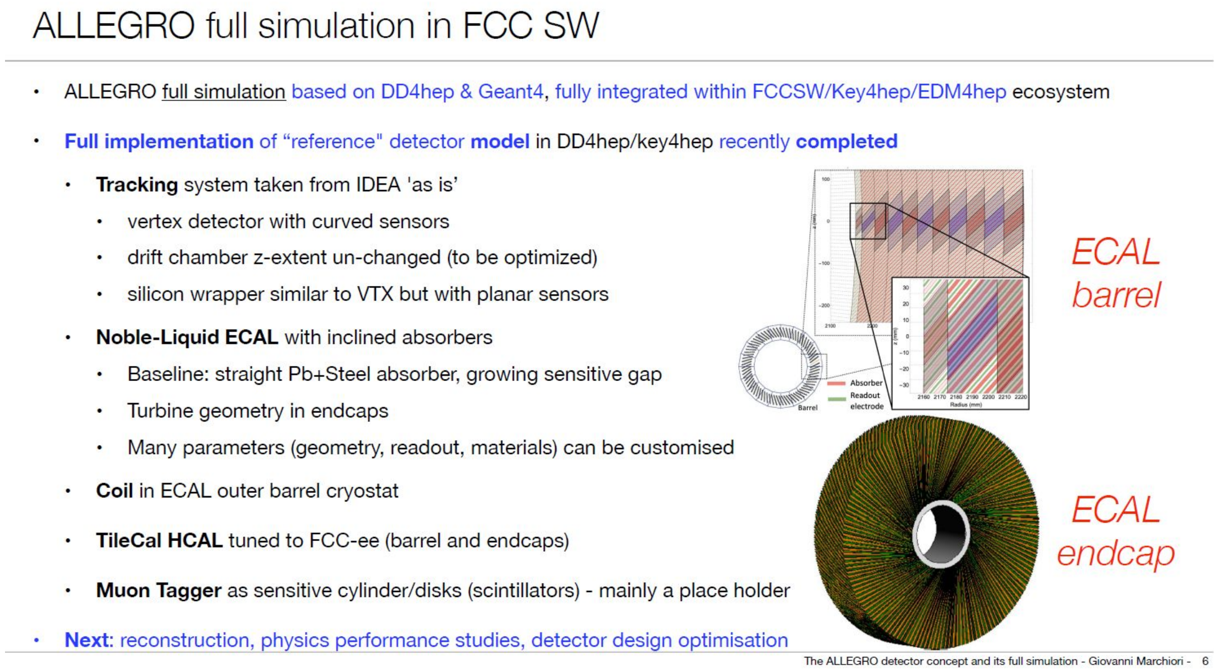
- **Current situation**
  - Strong **noble-liquid ECAL** team collaborating within DRD6 WP2
  - **Other sub-detectors** not yet defined
    - very open for contributions, **many EoIs** received
    - leaning towards gaseous main tracker; various options for muon tagger
  - There is a “reasonable” choice for the other sub-detectors implemented in FCC SW (sketch in previous slide, details in next one), but different choices can be tried due to modularity of FCC SW
- **Next steps**
  - Now: **EoI for ESPPU2025**: ALLEGRO as high-perf. general-purpose detector concept for FCC-ee. While concept is centered around noble-liquid ECAL, technology choices for other sub-detectors are fully open
  - Coming years:
    - **R&D** on subdetectors (optimisation studies, prototypes, testbeams..)
    - **down-selection** to baseline options and formation of a proto-collaboration once a **decision on FCC-ee** has been taken and once we enter the **TDR phase** (possibly in the coming 5 years)

4 Work Package 2: Liquified Noble Gas Calorimeters

4.1 Description

Future experiments at e^+e^-, hadron or muon colliders have an ambitious physics program. The role of calorimetry will be to precisely measure particle energies, complement the tracking system in an optimal particle-flow event reconstruction, contribute to particle identification and - where necessary - provide efficient pile-up rejection. Such functionalities will only be achievable with excellent electromagnetic energy resolution, high lateral and longitudinal granularity and - in some cases (e.g. pile-up rejection) - excellent time resolution. Calorimetry based on liquified noble gases

The ALLEGRO detector concept and its full simulation - Giovanni Marchiori - 5



ALLEGRO full simulation in FCC SW

- ALLEGRO full simulation based on DD4hep & Geant4, fully integrated within FCCSW/Key4hep/EDM4hep ecosystem
- **Full implementation** of “reference" detector **model** in DD4hep/key4hep recently **completed**
  - **Tracking** system taken from IDEA 'as is'
    - vertex detector with curved sensors
    - drift chamber z-extent un-changed (to be optimized)
    - silicon wrapper similar to VTX but with planar sensors
  - **Noble-Liquid ECAL** with inclined absorbers
    - Baseline: straight Pb+Steel absorber, growing sensitive gap
    - Turbine geometry in endcaps
    - Many parameters (geometry, readout, materials) can be customised
  - **Coil** in ECAL outer barrel cryostat
  - **TileCal HCAL** tuned to FCC-ee (barrel and endcaps)
  - **Muon Tagger** as sensitive cylinder/disks (scintillators) - mainly a place holder
- **Next**: reconstruction, physics performance studies, detector design optimisation

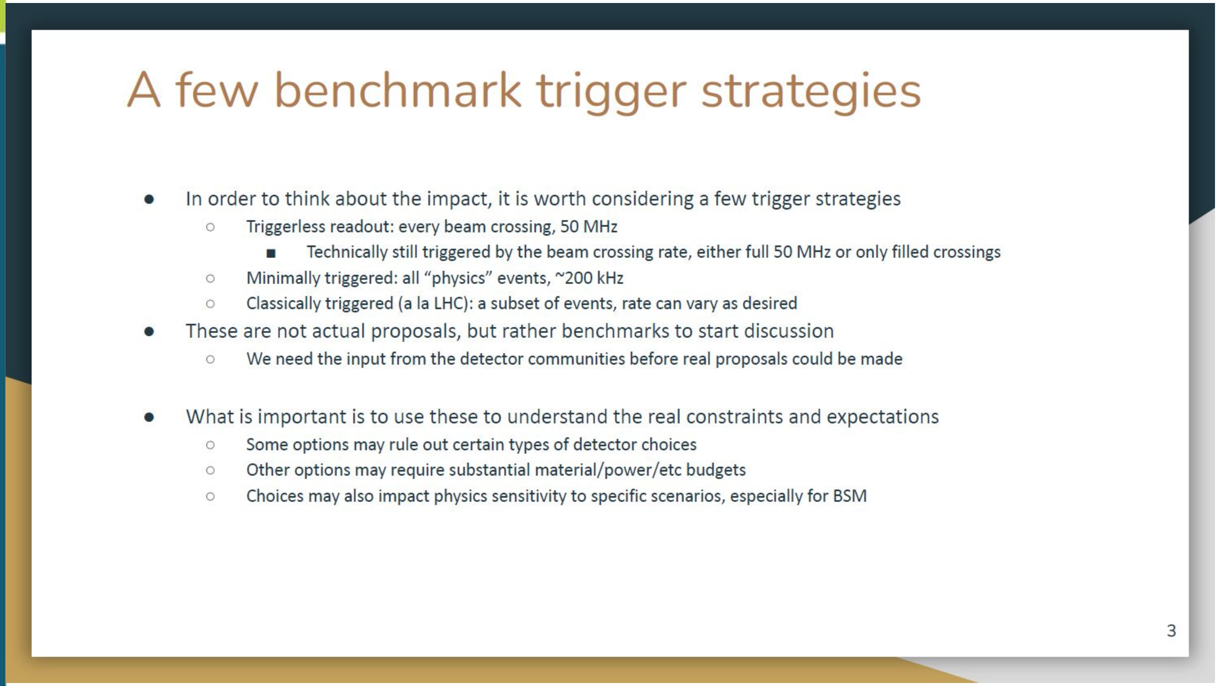
The ALLEGRO detector concept and its full simulation - Giovanni Marchiori - 6

Actively soliciting suggestions for sub-detectors complementing noble liquid calorimetry
Full implementation of “reference" detector model in DD4hep/key4hep recently completed (using IDEA tracking)

Further work on reconstruction, physics performance studies, detector design optimisation

Ideas on getting started with FCCee TDAQ activities

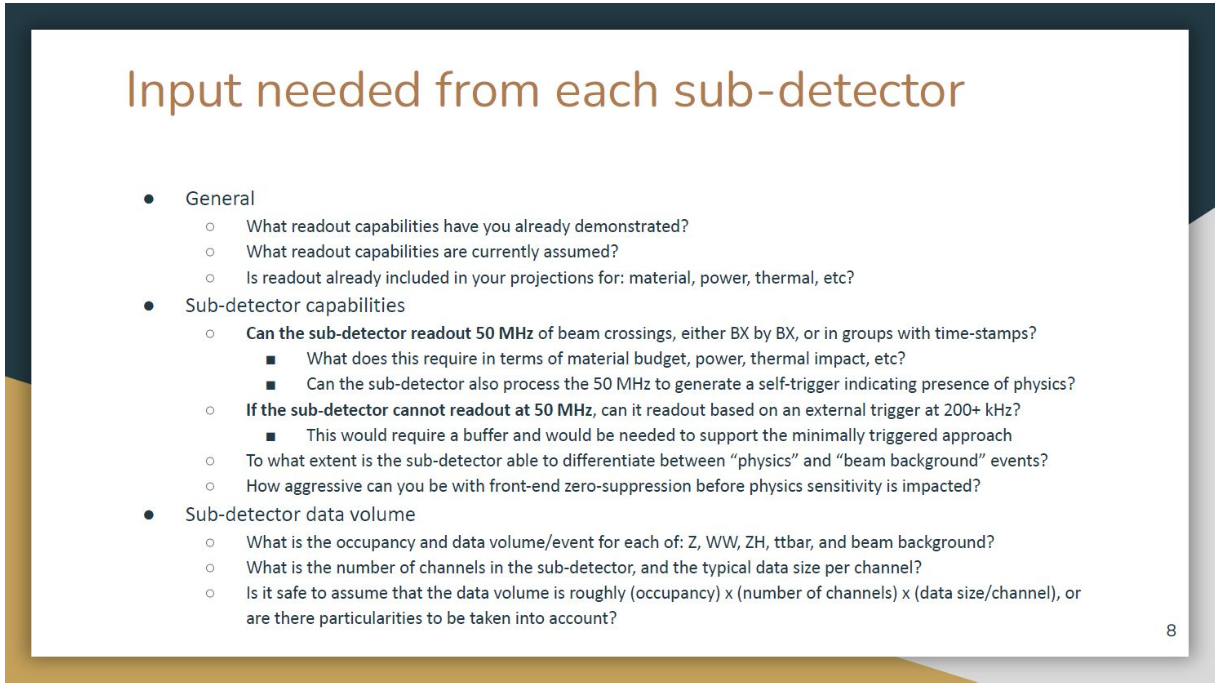
Steven Schramm



A few benchmark trigger strategies

- In order to think about the impact, it is worth considering a few trigger strategies
  - Triggerless readout: every beam crossing, 50 MHz
    - Technically still triggered by the beam crossing rate, either full 50 MHz or only filled crossings
  - Minimally triggered: all "physics" events, ~200 kHz
  - Classically triggered (a la LHC): a subset of events, rate can vary as desired
- These are not actual proposals, but rather benchmarks to start discussion
  - We need the input from the detector communities before real proposals could be made
- What is important is to use these to understand the real constraints and expectations
  - Some options may rule out certain types of detector choices
  - Other options may require substantial material/power/etc budgets
  - Choices may also impact physics sensitivity to specific scenarios, especially for BSM

3



Input needed from each sub-detector

- General
  - What readout capabilities have you already demonstrated?
  - What readout capabilities are currently assumed?
  - Is readout already included in your projections for: material, power, thermal, etc?
- Sub-detector capabilities
  - **Can the sub-detector readout 50 MHz** of beam crossings, either BX by BX, or in groups with time-stamps?
    - What does this require in terms of material budget, power, thermal impact, etc?
    - Can the sub-detector also process the 50 MHz to generate a self-trigger indicating presence of physics?
  - **If the sub-detector cannot readout at 50 MHz**, can it readout based on an external trigger at 200+ kHz?
    - This would require a buffer and would be needed to support the minimally triggered approach
  - To what extent is the sub-detector able to differentiate between "physics" and "beam background" events?
  - How aggressive can you be with front-end zero-suppression before physics sensitivity is impacted?
- Sub-detector data volume
  - What is the occupancy and data volume/event for each of: Z, WW, ZH, ttbar, and beam background?
  - What is the number of channels in the sub-detector, and the typical data size per channel?
  - Is it safe to assume that the data volume is roughly (occupancy) x (number of channels) x (data size/channel), or are there particularities to be taken into account?

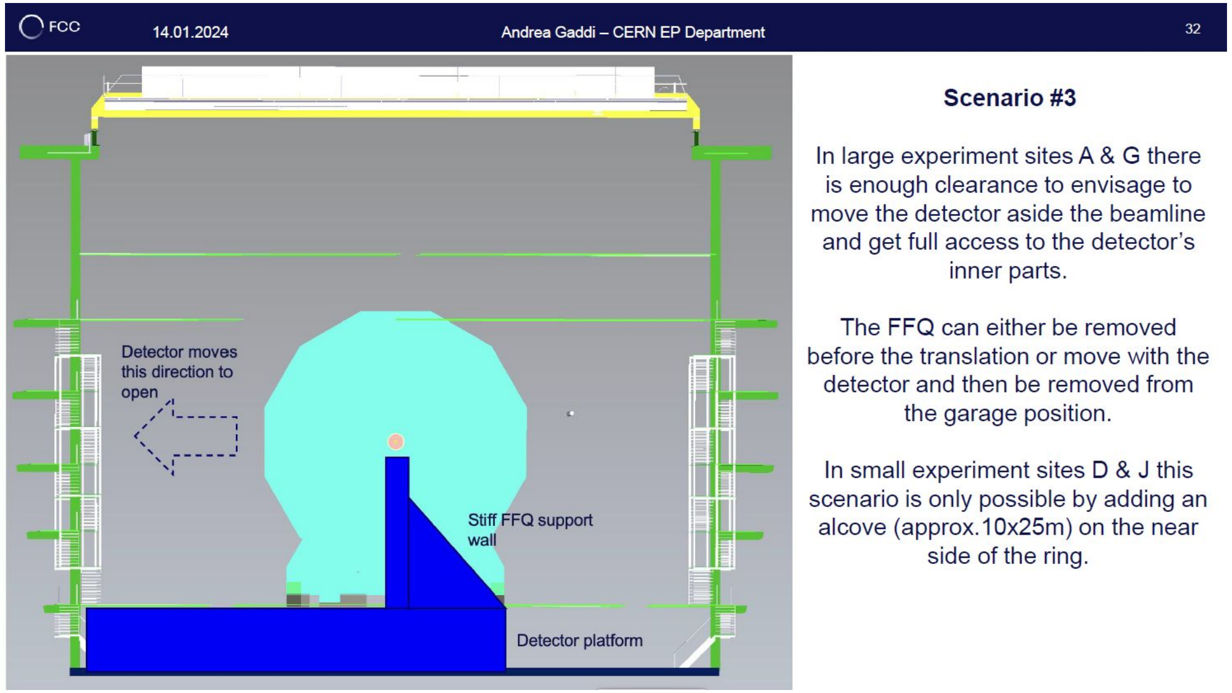
8

Triggerless system is not a foregone conclusion
Different scenarios outlined to solicit input from sub-detectors

Need a systematic evaluation enabling an **early** decision on a system

Detector integration and maintenance

Andrea Gaddi



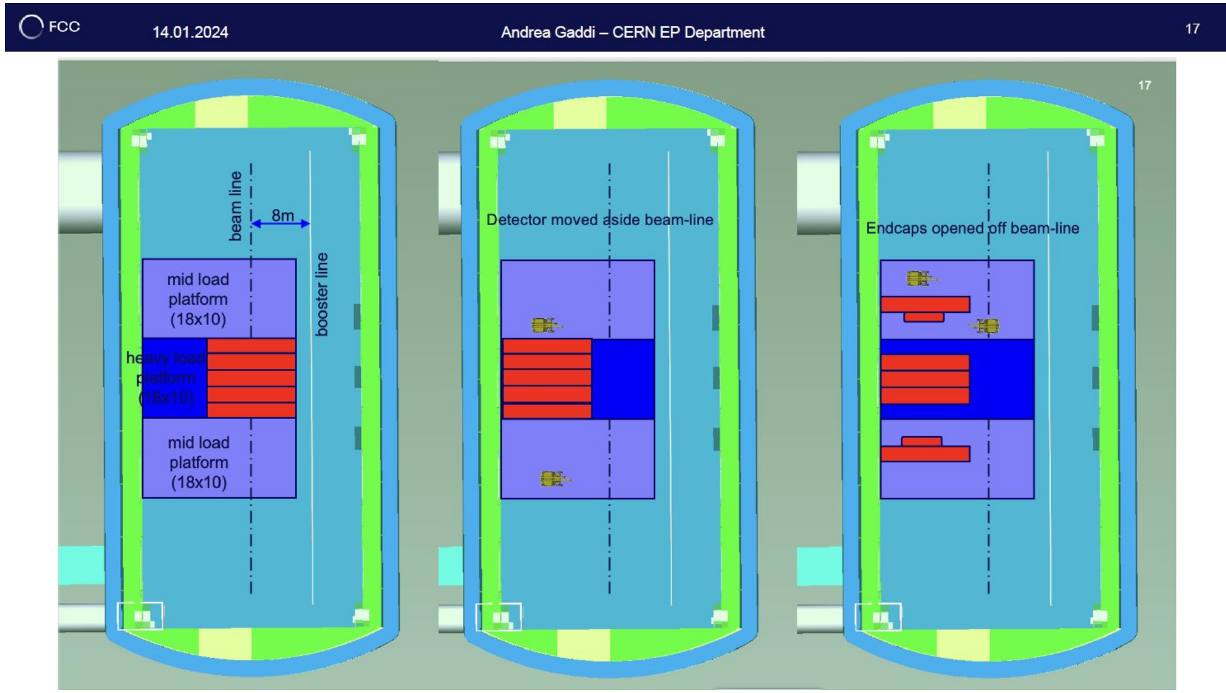
FCC 14.01.2024 Andrea Gaddi – CERN EP Department 32

Scenario #3

In large experiment sites A & G there is enough clearance to envisage to move the detector aside the beamline and get full access to the detector's inner parts.

The FFQ can either be removed before the translation or move with the detector and then be removed from the garage position.

In small experiment sites D & J this scenario is only possible by adding an alcove (approx.10x25m) on the near side of the ring.



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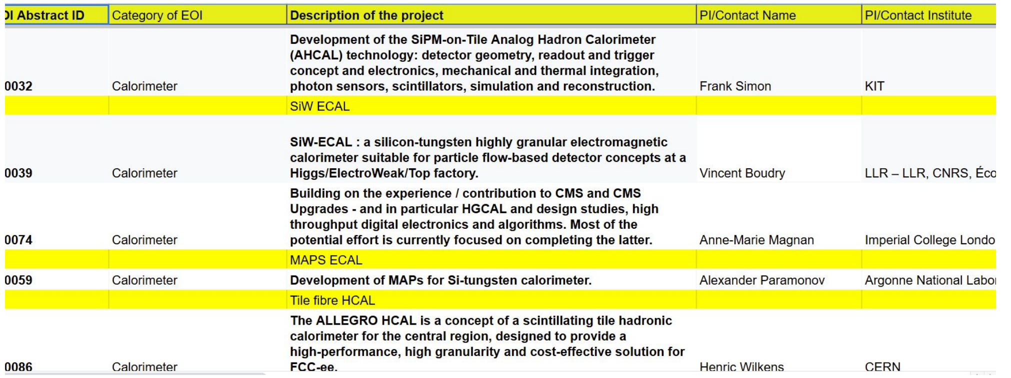
Currently preferred detector opening scenario: transversal shift of full detector, longitudinal opening of the detector **solid** endcaps => maximise detector access time!

To enable four FCC-ee detectors of same size, would need alcove in small caverns and/or enable off-center ee beamline (or make all caverns the same width).

Summary

- Increasing level of activity on both the sub-detector and detector concept level in the past year - let’s keep that trajectory!
- New ideas for (sub-)detectors being pursued - more are welcome!
- Need to move towards full simulation and reconstruction to evaluate detector (concept) performance - and validate with prototypes, think about engineering and integration:
  Plenty of work for the pre-TDR phase!
- Community starting to come together for EoIs, see [satellite meeting]() tomorrow.



I Abstract ID	Category of EOI	**Description of the project**	PI/Contact Name	PI/Contact Institute
0032	Calorimeter	**Development of the SiPM-on-Tile Analog Hadron Calorimeter (AHCAL) technology: detector geometry, readout and trigger concept and electronics, mechanical and thermal integration, photon sensors, scintillators, simulation and reconstruction.**	Frank Simon	KIT
		SiW ECAL		
0039	Calorimeter	**SiW-ECAL : a silicon-tungsten highly granular electromagnetic calorimeter suitable for particle flow-based detector concepts at a Higgs/ElectroWeak/Top factory.**	Vincent Boudry	LLR – LLR, CNRS, Éco
0074	Calorimeter	**Building on the experience / contribution to CMS and CMS Upgrades - and in particular HGCAL and design studies, high throughput digital electronics and algorithms. Most of the potential effort is currently focused on completing the latter.**	Anne-Marie Magnan	Imperial College Londo
		MAPS ECAL		
0059	Calorimeter	**Development of MAPs for Si-tungsten calorimeter.**	Alexander Paramonov	Argonne National Labo
		Tile fibre HCAL		
0086	Calorimeter	**The ALLEGRO HCAL is a concept of a scintillating tile hadronic calorimeter for the central region, designed to provide a high-performance, high granularity and cost-effective solution for FCC-ee.**	Henric Wilkens	CERN