Next-Generation MAPS Sensors for ALICE 3 Outer Tracker

R. Guernane (LPSC Grenoble CNRS/IN2P3–UGA)
on behalf of the [ALICE 3] Project

FJKPPN Workshop

May 14–16, 2025

Nantes, France

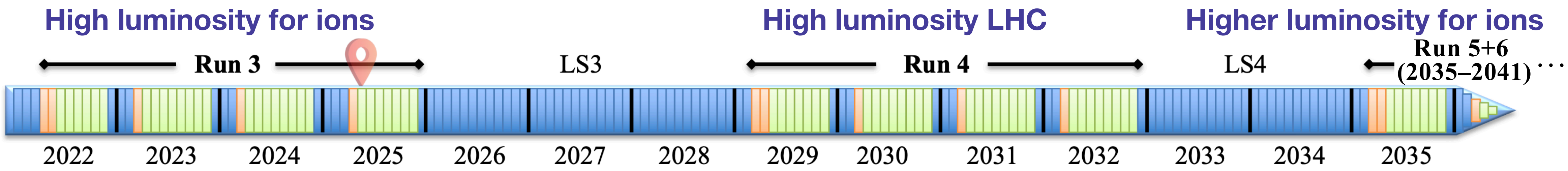
Toshiko Yuasa Laboratory

France-Japan Particle Physics

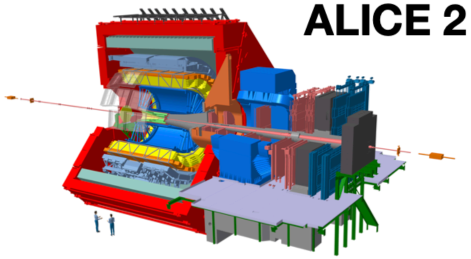
FKPPN

ALICE Upgrade Roadmap

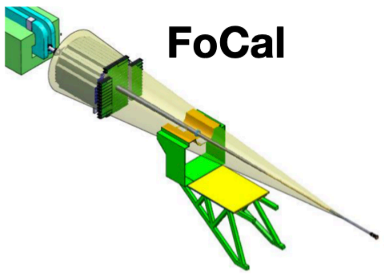
- ALICE designed to study the microscopic dynamics of the **strongly-interacting matter** produced in heavy-ion collisions at the LHC
  - Variety of detector systems for measuring **hadrons**, **leptons** and **photons**
- To exploit the full potential of the LHC luminosity increase
  - Major upgrade during LHC LS2 → **ALICE 2**
  - Intermediate upgrades during LS3 → **ALICE 2.1**
  - Phase IIb upgrade during LS4 → **ALICE 3**
    - Next-generation experiment



ALICE 2



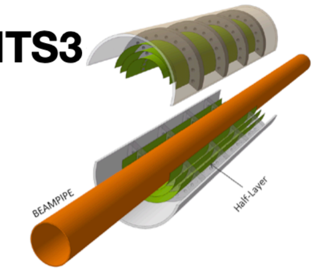
FoCal



CERN-LHCC-2020-009

CERN-LHCC-2024-004

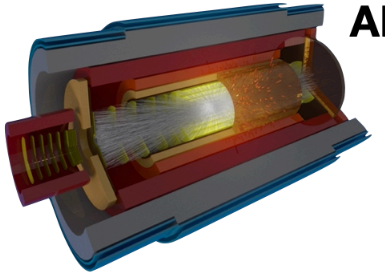
ITS3



CERN-LHCC-2019-018

CERN-LHCC-2024-003

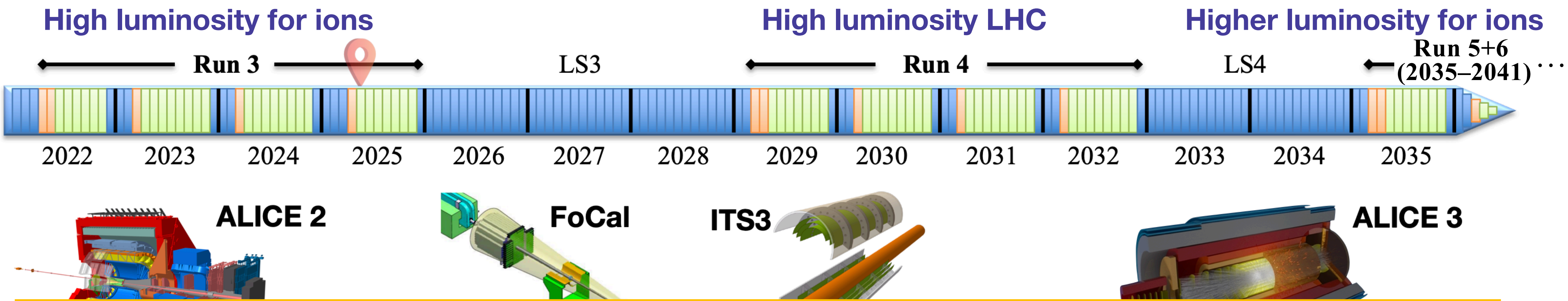
ALICE 3



CERN-LHCC-2022-009

ALICE Upgrade Roadmap

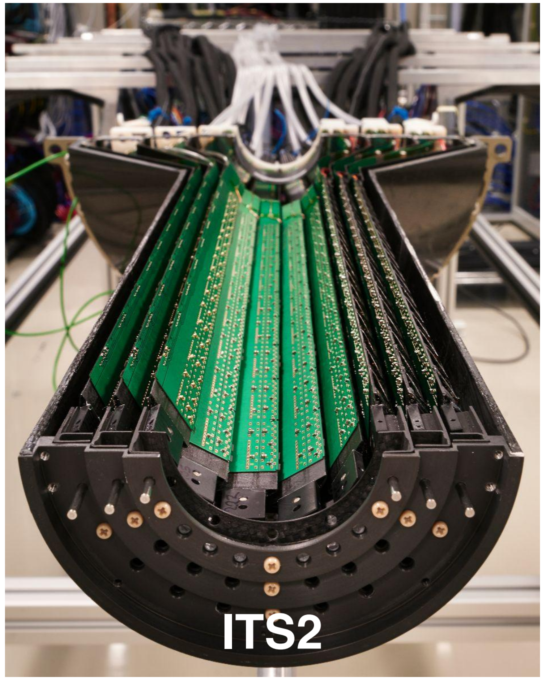
- ALICE designed to study the microscopic dynamics of the **strongly-interacting matter** produced in heavy-ion collisions at the LHC
  - Variety of detector systems for measuring **hadrons**, **leptons** and **photons**
- To exploit the full potential of the LHC luminosity increase
  - Major upgrade during LHC LS2 → **ALICE 2**
  - Intermediate upgrades during LS3 → **ALICE 2.1**
  - Phase IIb upgrade during LS4 → **ALICE 3**
    - Next-generation experiment

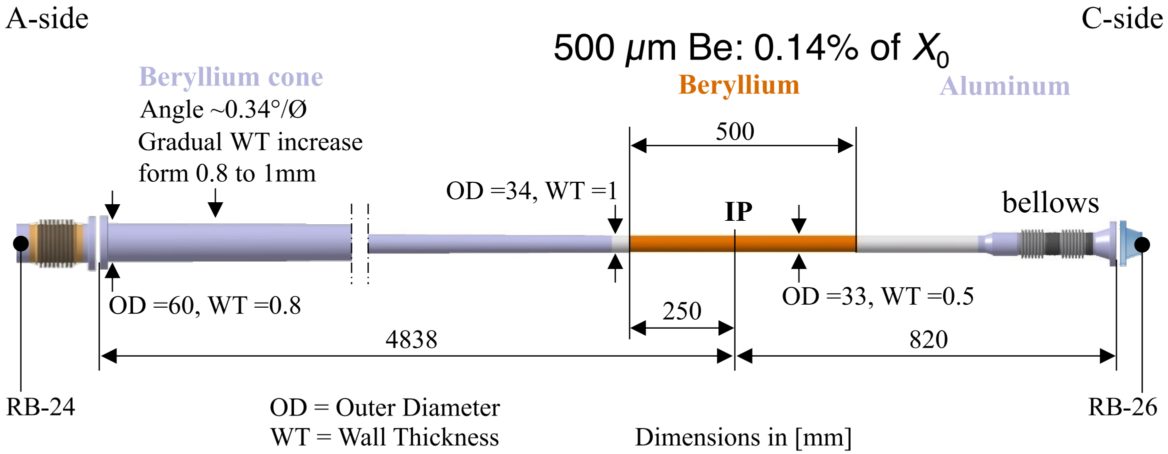


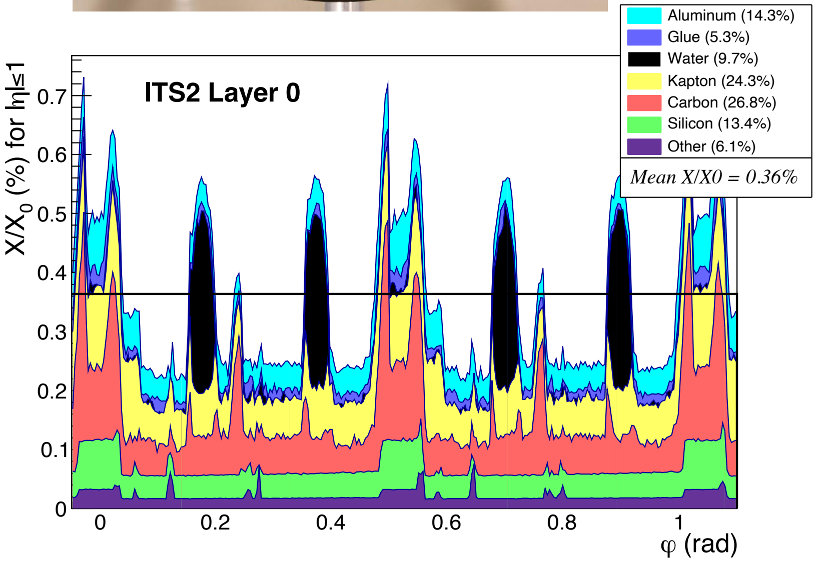
The ALICE experiment is at the forefront of the R&D of MAPS detectors with the ITS2, ITS3 & ALICE 3 projects

ITS3 Concept

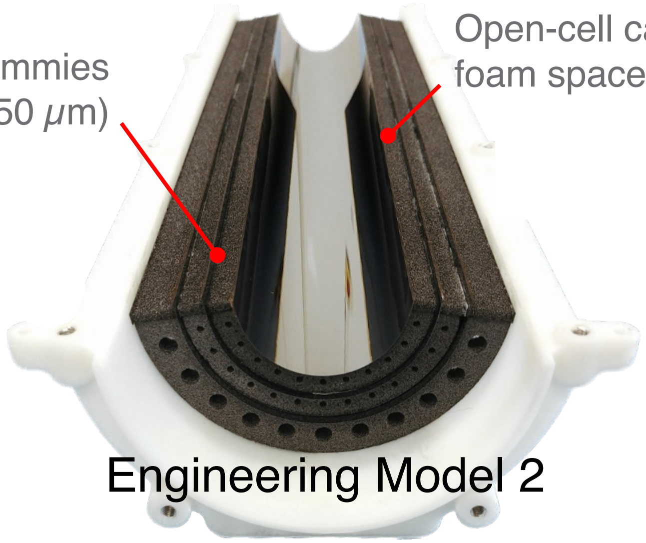
- Reduce the **material thickness** of the ITS2 inner layers
  - The silicon sensor contributes to **only 1/7th** of the total material budget!
    - Remove the **electrical substrate**, **mechanical support**, and active **cooling** circuit in the detector acceptance
- Bring the first detection layer **closer to the interaction point**
  - **New beam pipe** with a central section of smaller inner radius (18.2 mm → 16 mm) but still well within the LHC aperture requirements



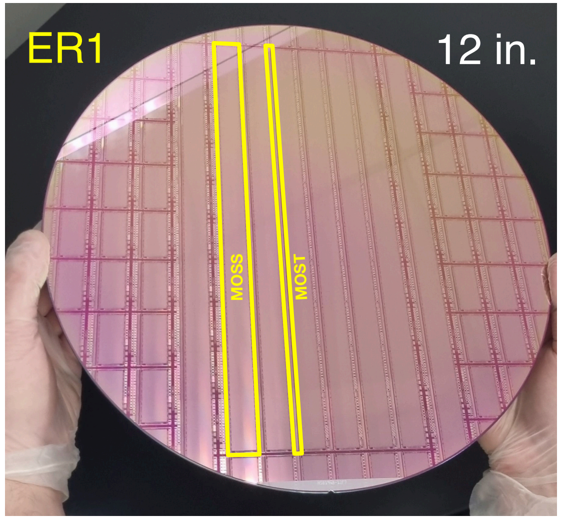




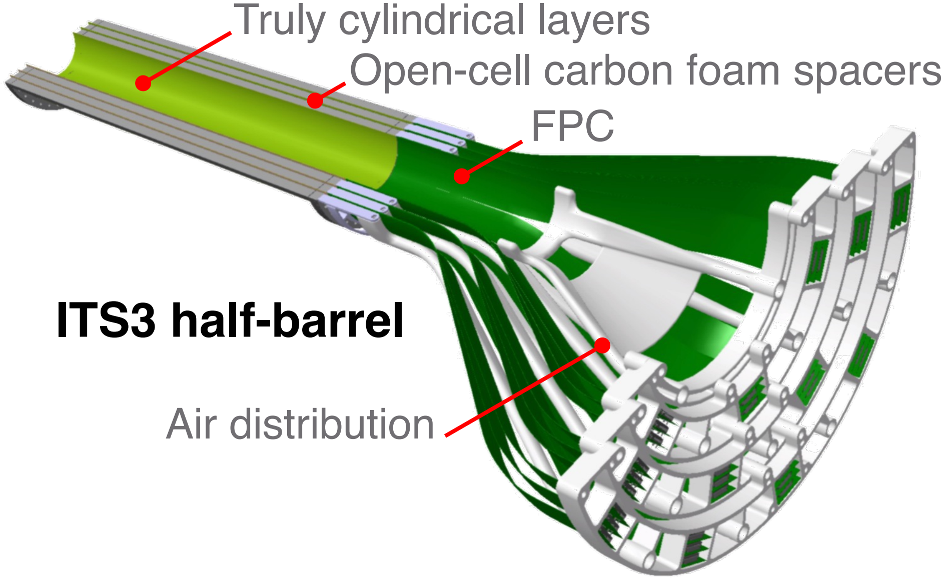
ITS3 Detector



From 432 to 6 bent sensors
(1 per half-layer)

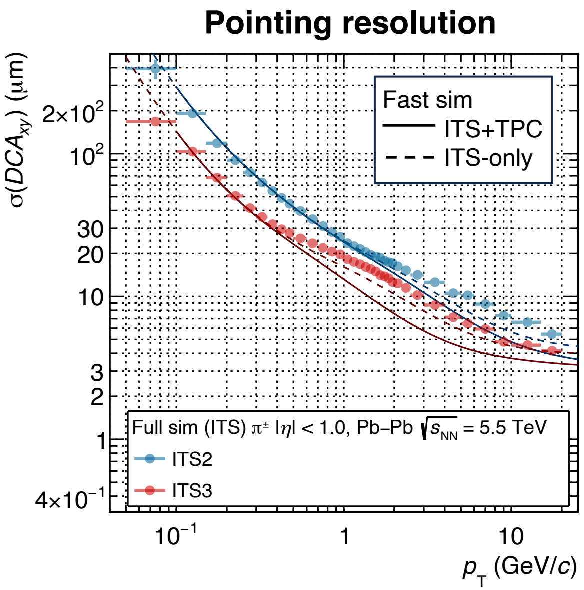


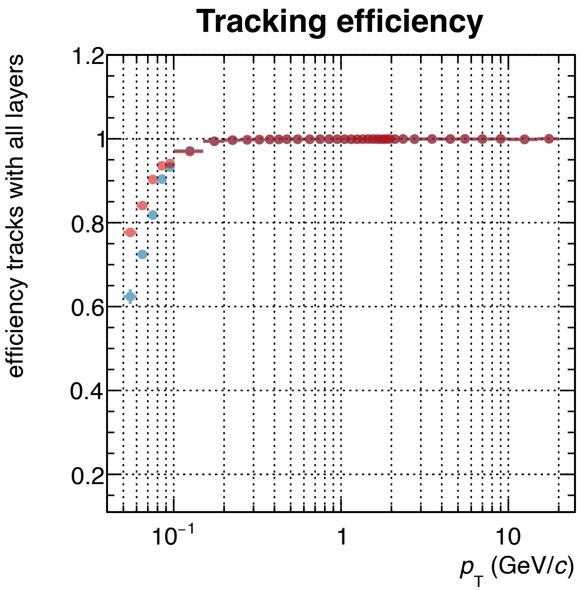
First stitchted MAPS

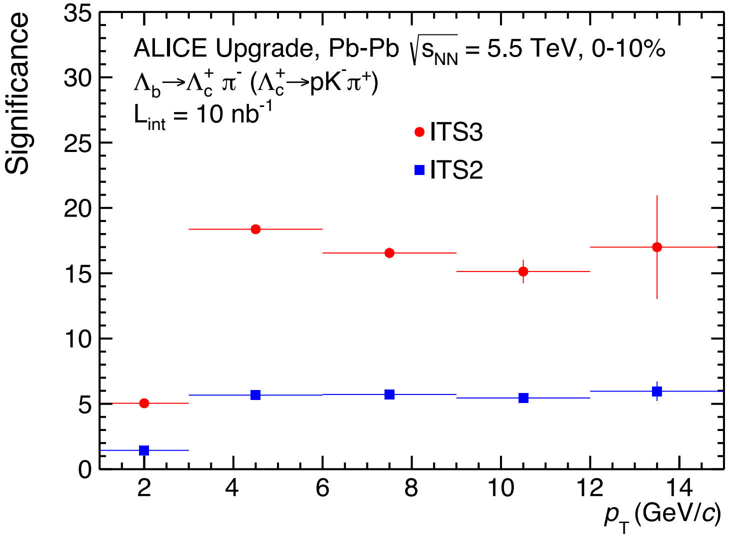


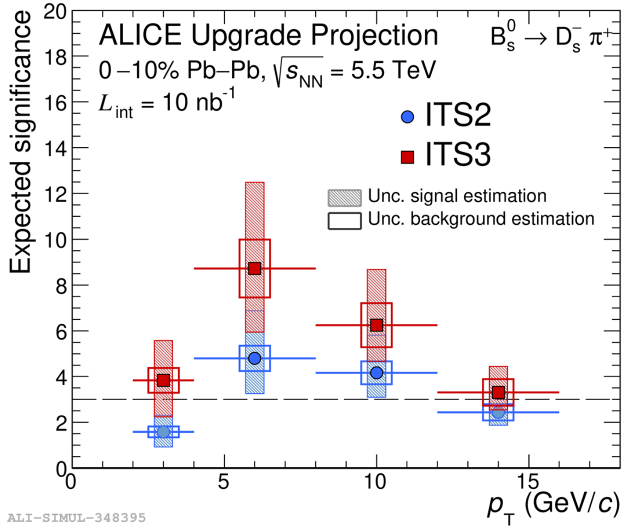
- Replace the 3 innermost layers of ITS2 with new **ultra-light**, **truly cylindrical** layers made of **wafer-scale 65 nm MAPS**
  - **Low material budget** (0.05 % of X_0)
  - **Bent** to the target radii (Layer 0 from 23 mm to 19 mm)
  - 300 mm wafer-scale MAPS sensors, fabricated using **stitching**
  - Mechanically held in place by **carbon foam** ribs
  - **Air cooling** between the layers
- **Broad interest** on ALICE ITS3 developments from other experiments!
  - ITS3 R&D will pave the way for an **ultimate vertex detector concept** → ALICE 3

ITS3 Performance









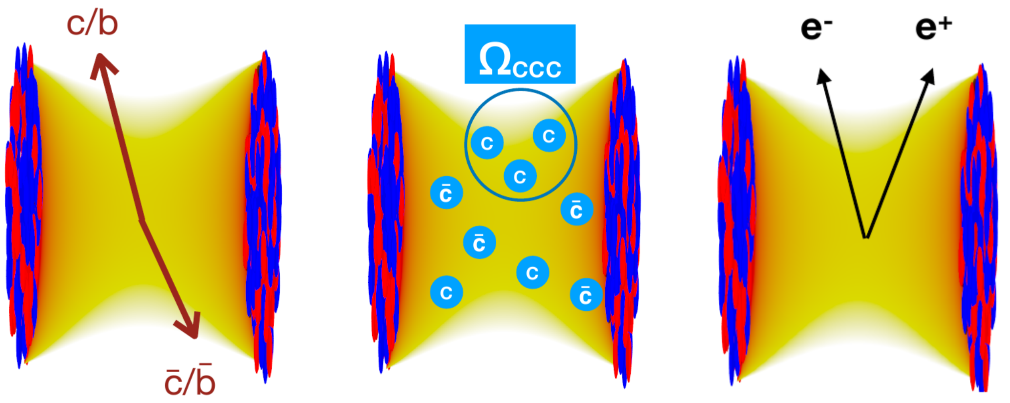
- Improvement by a **factor 2** on DCA resolution at all p_T's
  - Clear **separation** of the secondary from primary interaction vertex
- Significant improvement of **tracking efficiency** for $p_T < 200$ MeV/c
- New **fundamental observables** into reach
  - Charmed and beauty baryons
  - Low-mass di-electrons
  - Multi-flavour particles via decays to strange baryons
  - Full topological reconstruction of B_s
  - c-deuterons…

ALICE 3: a Next-generation Heavy-ion Experiment at the LHC

- Address **fundamental questions** which will remain open at the end of LHC Run 4 because of limitations in detector performance or available luminosity
  - Underlying dynamics of **chiral symmetry restoration**
  - Partonic **equation of state** and its **temperature** dependence
  - QGP properties driving its constituents to **equilibration**
  - **Hadronization** mechanisms of the QGP

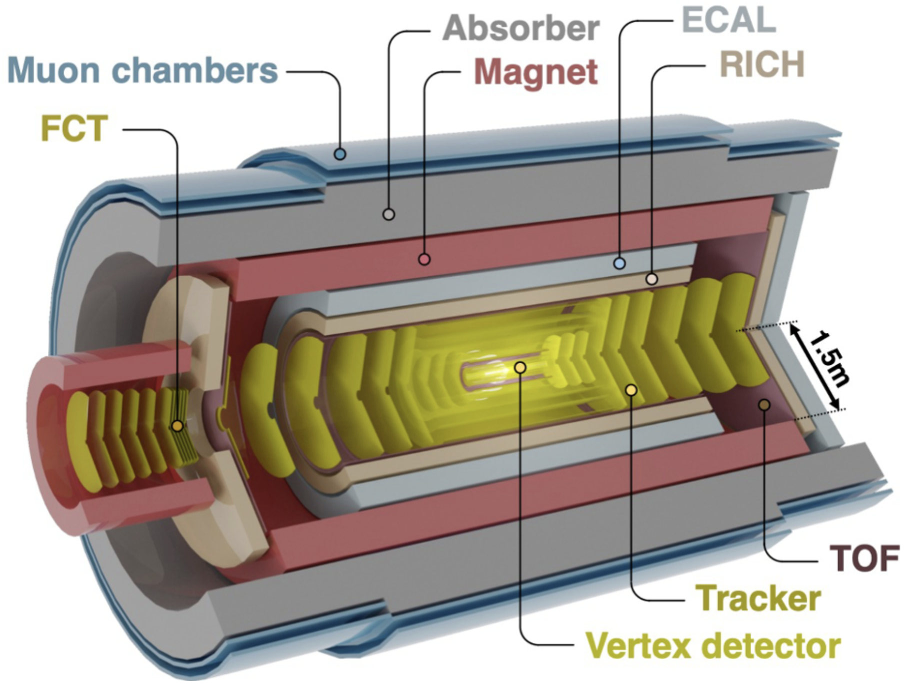
Precision measurements of (multi-)heavy flavour hadrons and di-electrons
→ Requires **high statistics** and **excellent vertexing!**

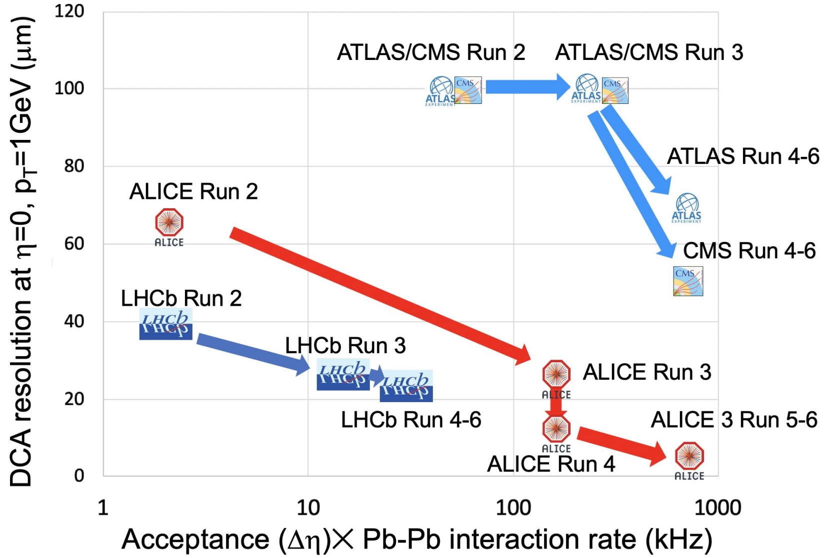
- ALICE 3 planning
  - **2023-25:** Selection of technologies, small-scale proof of concept prototypes
    - Scoping document in preparation
  - **2026-27:** Large-scale engineered prototypes
    - Technical Design Reports
  - **2028-31**: Construction and testing
  - **2032:** Contingency
  - **2033-34:** Preparation of cavern and installation



ALICE 3: Detector Concept

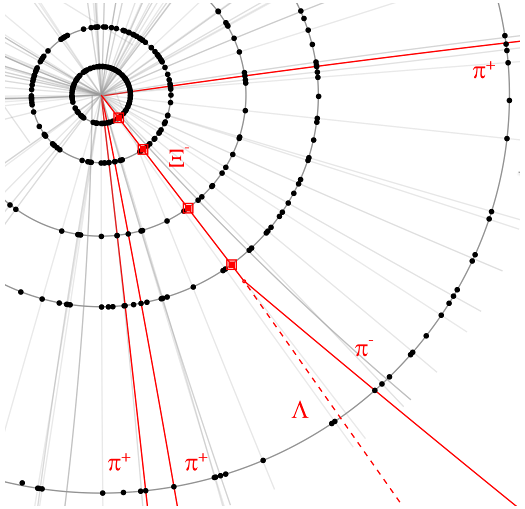
- Novel detector concept based on innovative technologies relevant for future HEP experiments
  - Large acceptance $|\eta| < 4$
  - **Compact** and **ultra-low-mass all-silicon tracker** with excellent **pointing resolution**
    - **Retractable** vertex detector
  - Extensive **particle identification**
    - Silicon-based TOF (target resolution < 20 ps), aerogel ring-imaging Čerenkov, ECal, and muon ID detectors
  - Housed in a magnetic field provided by a **superconducting magnet** system up with $B = 2$ T
  - Forward conversion tracker to reconstruct photons at very low momentum from their conversions to electron–positron pairs
  - **Continuous readout** and **online processing**
- R&D started on many fronts!
  - MAPS sensors → this project

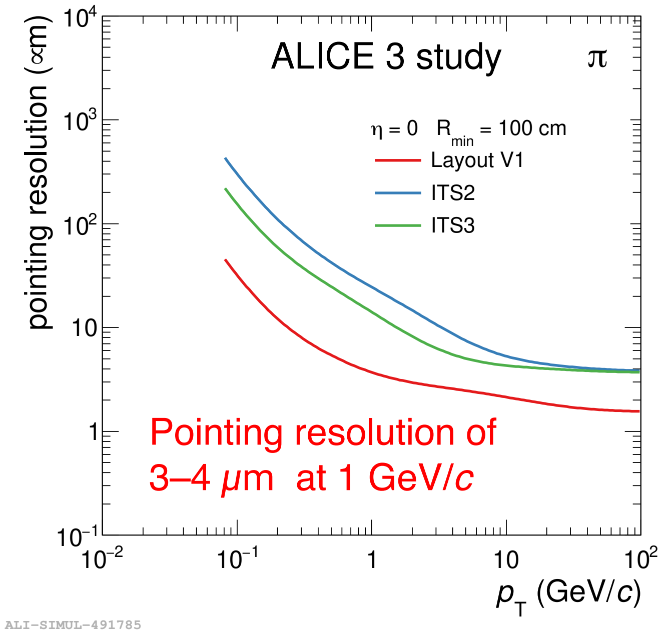




ALICE 3: Tracking Performance

- To achieve the ultimate **pointing resolution** $\propto r_0 \cdot \sqrt{x/X_0}$
  - The first hits must be detected as close as possible to the interaction point (5 mm)
    - Essential to enable the so-called *strangeness tracking* – the direct detection of strange baryons before they decay – to improve the **pointing resolution** and **suppress combinatorial background**
      - Measurement of multi-charm baryon decays
  - The amount of material in front of it must be kept to a minimum
- A dedicated/futuristic vertex detector that will have to be **retractable** to provide the required aperture for the LHC at injection energy
- Many challenges
  - Power consumption, radiation hardness, timing, integration, mass production, etc

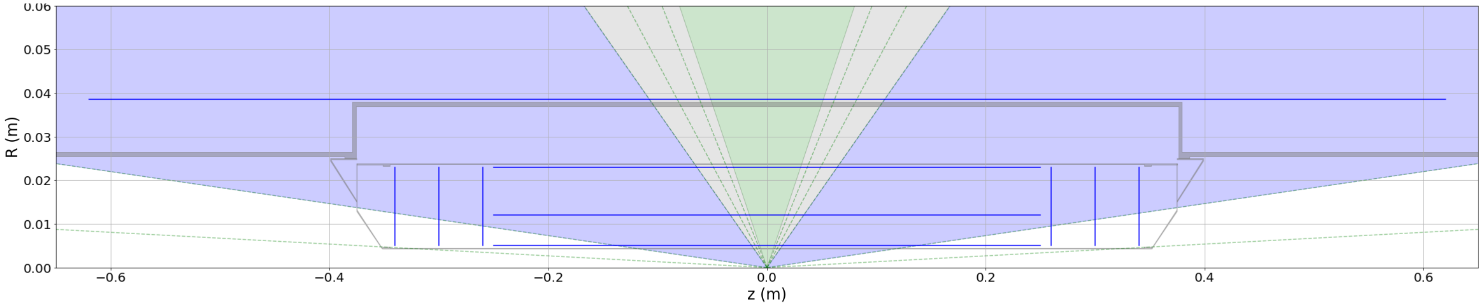




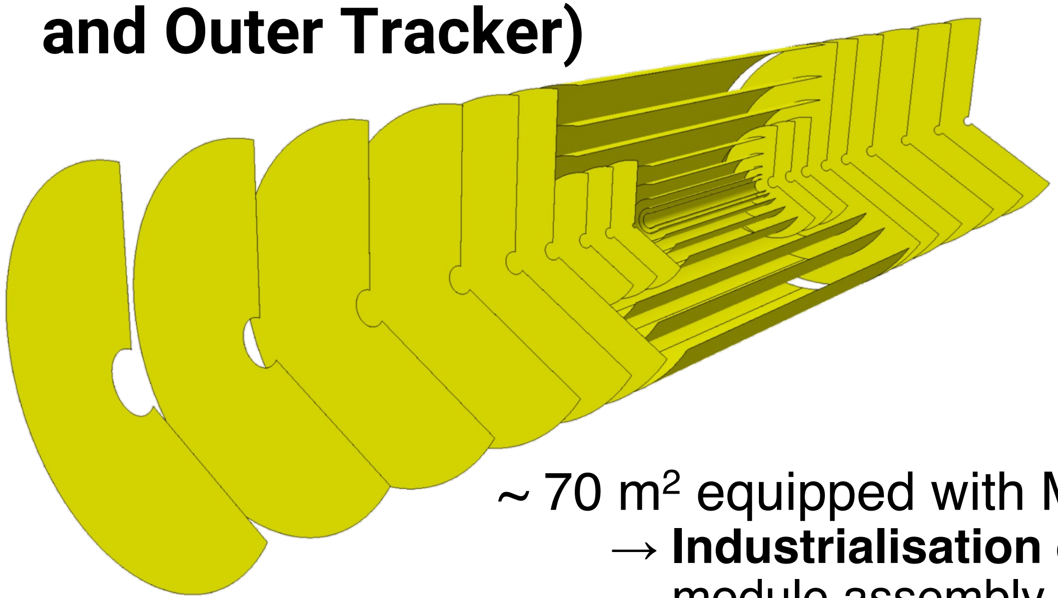
5x better than ALICE 2.1 (ITS3 + TPC) → e.g. S/B ~10x for D^0

ALICE 3: Tracking System

Vertexer (w/i the beam pipe)

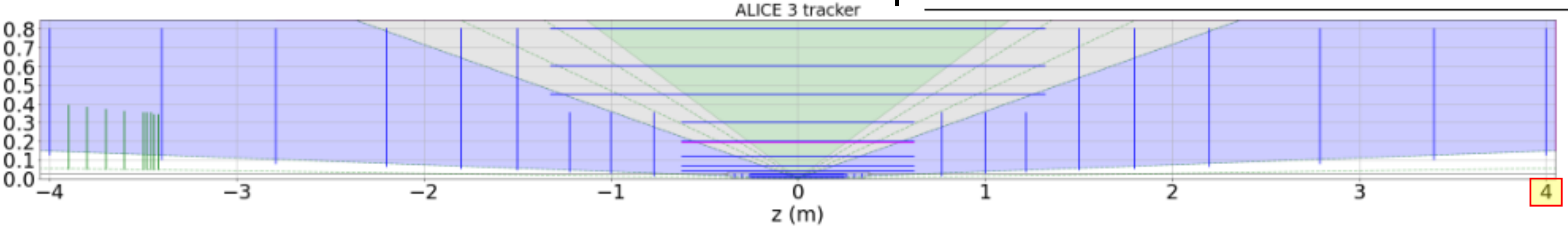


Tracker (Middle layers and Outer Tracker)



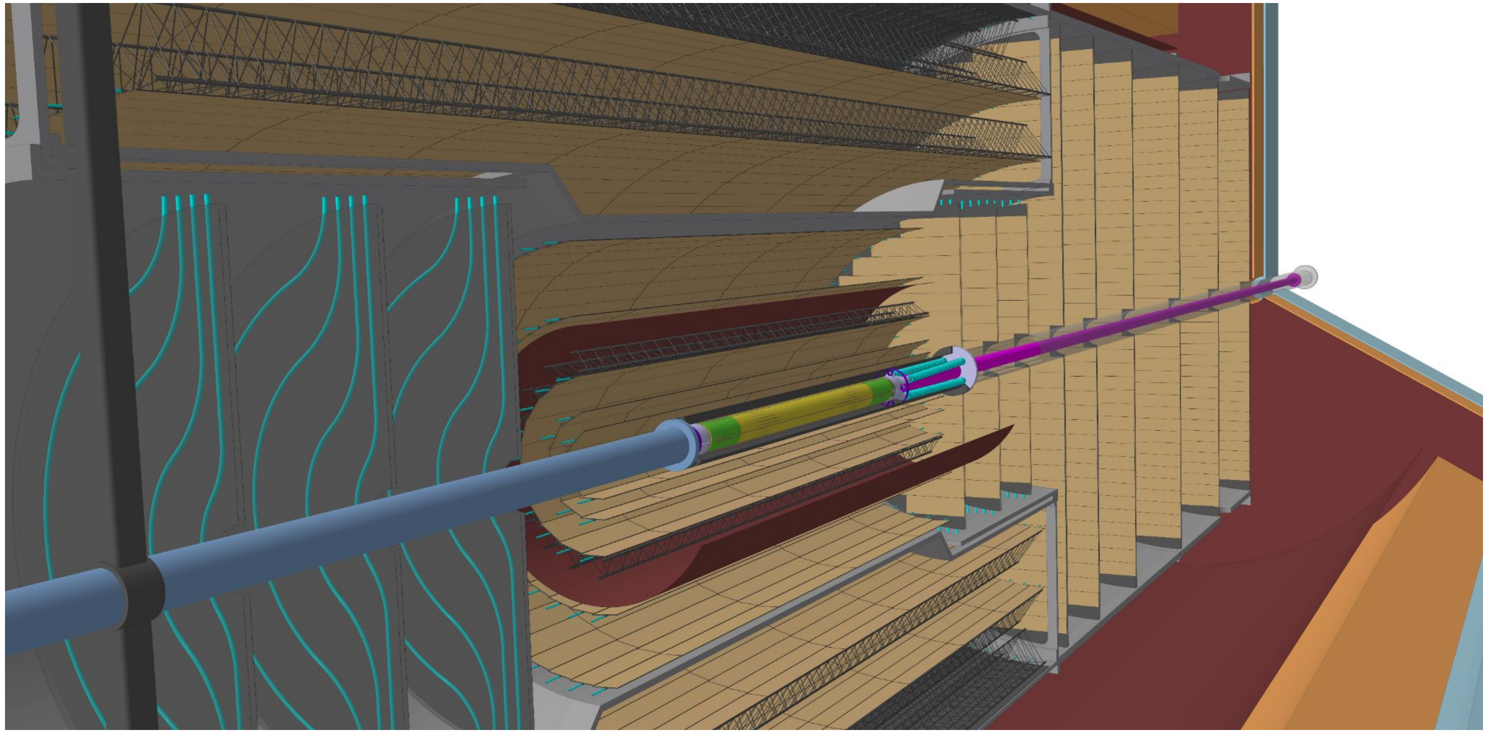
~ 70 m² equipped with MAPS!
→ **Industrialisation** of the module assembly

	Layer	Material thickness ($\%X_0$)	Intrinsic resolution (µm)	Barrel layers Length ($\pm z$) (cm)	Barrel layers Radius (r) (cm)	Forward discs Position ($\lvert z \rvert$) (cm)	Forward discs R_{in} (cm)	Forward discs R_{out} (cm)
Vertexer	0	0.1	2.5	50	0.50	26	0.005	3
Vertexer	1	0.1	2.5	50	1.20	30	0.005	3
Vertexer	2	0.1	2.5	50	2.50	34	0.005	3
Middle Layers	3	1	10	124	3.75	77	0.05	35
Middle Layers	4	1	10	124	7	100	0.05	35
Middle Layers	5	1	10	124	12	122	0.05	35
Middle Layers	6	1	10	124	20	150	0.05	80
Middle Layers	7	1	10	124	30	180	0.05	80
Outer Tracker	8	1	10	264	45	220	0.05	80
Outer Tracker	9	1	10	264	60	279	0.05	80
Outer Tracker	10	1	10	264	80	340	0.05	80
Outer Tracker	11	1				400	0.05	80



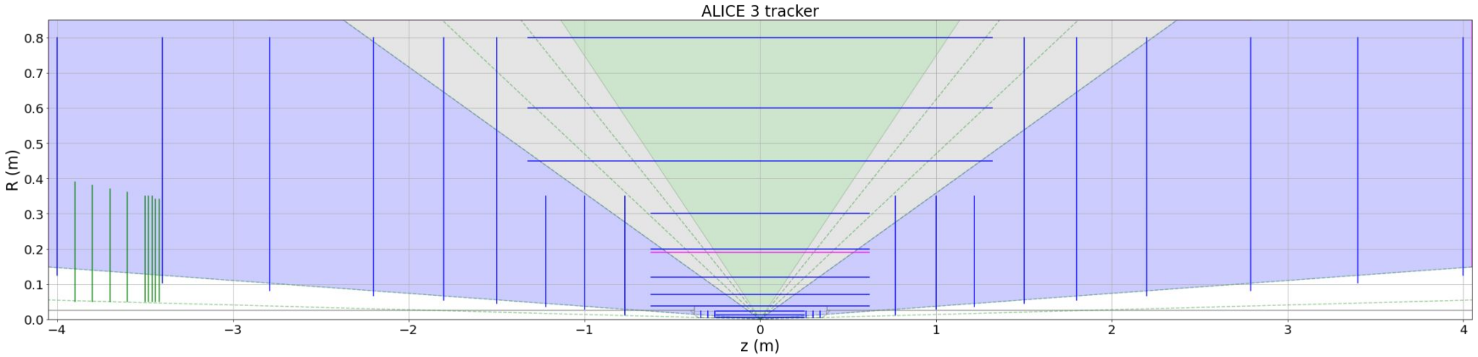
ALICE 3 Outer Tracker

- 8 barrel layers (3.5 cm < R < 80 cm) and 2 × 9 end-cap disks
- Material budget: 1 % X/X_0 per layer (< 10 % X/X_0 for entire tracker)
- Space resolution: 10 μm (50 μm pixel pitch)
- Low power consumption: 20 mW/cm^2
- 100 ns time resolution to mitigate pileup



Main R&D challenges

- Modules integration for mass **industrialization**
- **Power consumption** while preserving timing performance



Specs of the CMOS sensor for OT

	VD	ML	OT	FCT
Area (m^2)	0.15	5.6	50.4	0.35
Spatial resolution (μm)	2.5	10	10	10
Hit rate (MHz/cm^2)	96	0.6	0.6	0.6
Material budget per layer ($\%X_0$)	0.1	1	1	1
Power density (mW/cm^2)	70	20	20	20
Time resolution (ns)	100	100	100	100
Radiation tolerance NIEL (1 MeV n_{eq}/cm^2)	$1.0 \cdot 10^{16}$	$2 \cdot 10^{14}$	$6 \cdot 10^{12}$	$5 \cdot 10^{13}$
Radiation tolerance TID (rad)	$3 \cdot 10^8$	$5 \cdot 10^6$	$2 \cdot 10^5$	$2 \cdot 10^6$

	ITS3	ALICE 3 VTX	ALICE 3 TRK	ePIC	FCC-ee
Single-point res. (μm)	5	2.5	10	5	3
Time res. (ns RMS)	2000	100	100	2000	20
In-pixel hit rate (Hz)	54	96	42		few 100
Fake-hit rate (/pixel/event)	10^{-7}	10^{-7}	10^{-7}		
Power cons. (mW / cm^2)	35	70	20	<40	50
Hit density (MHz/cm^2)	8.5	96	0.6		200
NIEL (1 MeV n_{eq}/cm^2)	$4 \cdot 10^{12}$	$1 \cdot 10^{16}$	$2 \cdot 10^{14}$	few 10^{12}	10^{14} (/year)
TID (Mrad)	0.3	300	5	few 0.1	10 (/year)
Material budget (X_0/layer)	0.09%	0.1%	1%	0.05%	~0.3%
Pixel size (μm)	20	10	50	20	15-20

Specs of the CMOS sensor for OT

	VD	ML	OT	FCT
Area (m^2)	0.15	5.6	50.4	0.35
Spatial resolution (μm)	2.5	10	10	10
Hit rate (MHz/cm^2)	96	0.6	0.6	0.6
Material budget per layer ($\%X_0$)	0.1	1	1	1
Power density (mW/cm^2)	70	20	20	20
Time resolution (ns)	100	100	100	100
Radiation tolerance NIEL (1 MeV n_{eq}/cm^2)	$1.0 \cdot 10^{16}$	$2 \cdot 10^{14}$	$6 \cdot 10^{12}$	$5 \cdot 10^{13}$
Radiation tolerance TID (rad)	$3 \cdot 10^8$	$5 \cdot 10^6$	$2 \cdot 10^5$	$2 \cdot 10^6$

	ITS3	ALICE 3 VTX	ALICE 3 TRK	ePIC	FCC-ee
Single-point res. (μm)	5	2.5	10	5	3
Time res. (ns RMS)	2000	100	100	2000	20
In-pixel hit rate (Hz)	54	96	42		few 100
Fake-hit rate (/pixel/event)	10^{-7}	10^{-7}	10^{-7}		
Power cons. (mW / cm^2)	35	70	20	<40	50
Hit density (MHz/cm^2)	8.5	96	0.6		200
NIEL (1 MeV n_{eq}/cm^2)	$4 \cdot 10^{12}$	$1 \cdot 10^{16}$	$2 \cdot 10^{14}$	few 10^{12}	10^{14} (/year)
TID (Mrad)	0.3	300	5	few 0.1	10 (/year)
Material budget (X_0/layer)	0.09%	0.1%	1%	0.05%	˜0.3%
Pixel size (μm)	20	10	50	20	15-20

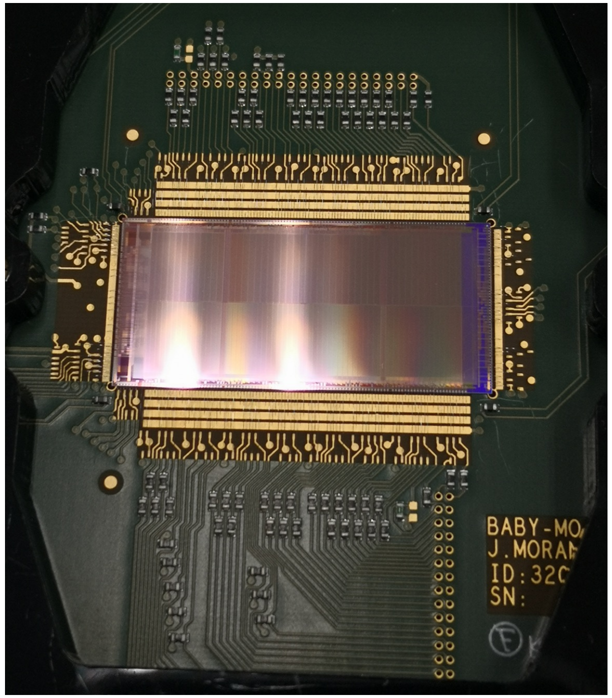
Specs of the CMOS sensor for OT

	VD	ML	OT	FCT
Area (m^2)	0.15	5.6	50.4	0.35
Spatial resolution (μm)	2.5	10	10	10
Hit rate (MHz/cm^2)	96	0.6	0.6	0.6
Material budget per layer ($\%X_0$)	0.1	1	1	1
Power density (mW/cm^2)	70	20	20	20
Time resolution (ns)	100	100	100	100
Radiation tolerance NIEL (1 MeV n_{eq}/cm^2)	$1.0 \cdot 10^{16}$	$2 \cdot 10^{14}$	$6 \cdot 10^{12}$	$5 \cdot 10^{13}$
Radiation tolerance TID (rad)	$3 \cdot 10^8$	$5 \cdot 10^6$	$2 \cdot 10^5$	$2 \cdot 10^6$

	ITS3	ALICE 3 VTX	ALICE 3 TRK	ePIC	FCC-ee
Single-point res. (μm)	5	2.5	10	5	3
Time res. (ns RMS)	2000	100	100	2000	20
In-pixel hit rate (Hz)	54	96	42		few 100
Fake-hit rate (/pixel/event)	10^{-7}	10^{-7}	10^{-7}		
Power cons. (mW / cm^2)	35	70	20	<40	50
Hit density (MHz/cm^2)	8.5	96	0.6		200
NIEL (1 MeV n_{eq}/cm^2)	$4 \cdot 10^{12}$	$1 \cdot 10^{16}$	$2 \cdot 10^{14}$	few 10^{12}	10^{14} (/year)
TID (Mrad)	0.3	300	5	few 0.1	10 (/year)
Material budget (X_0/layer)	0.09%	0.1%	1%	0.05%	˜0.3%
Pixel size (μm)	20	10	50	20	15-20

Aims of the ALICE 3 FJPPN project 1/2

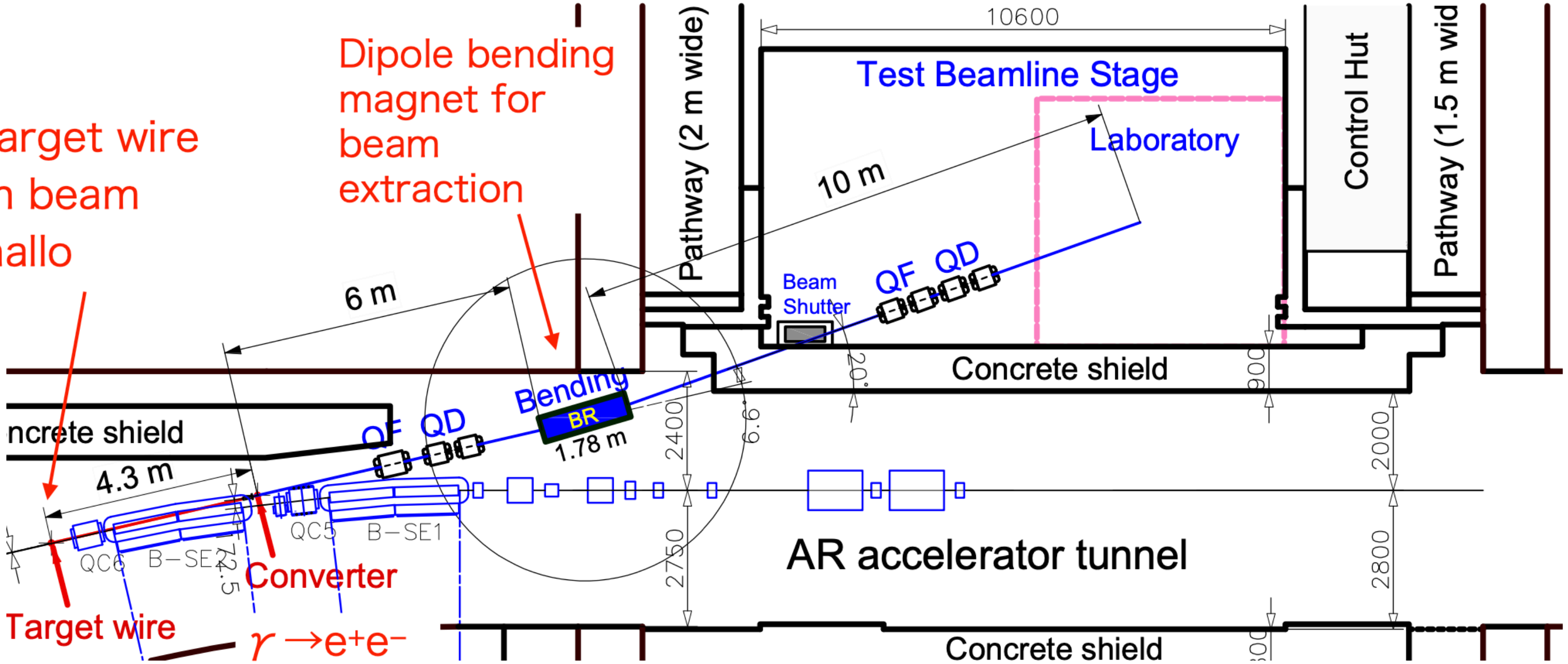
- The R&D for the ALICE 3's pixel chip will be a continuation of the work ongoing for the ALICE ITS3
  - 65-nm CMOS imaging process which is also the choice for the ongoing ITS3 development → TPSco Panasonic Japan
  - Focus on highly demanding requirements on radiation tolerance, small pixel size and data rates
- Synergies
  - FJPPN D_RD_24 (see J. Baudot's presentation), D_RD_29, FKPPN ALICE-HF
  - ECFA silicon detector R&D (DRD3/DRD7)
    - Versatile MAPS project
    - Strongest priorities for ALICE 3 are position precision, low material budget (x/X_0), low power and large-area sensors for tracker
- Beam tests conducted at KEK PF-AR beam line to characterize ITS3 chiplets babyMOSS (ER1), babyMOSAIX & SPARC (ER2) sensors
  - Dictate sensor design for ALICE 3 Outer Tracker
- Simulation TCAD Allpix2



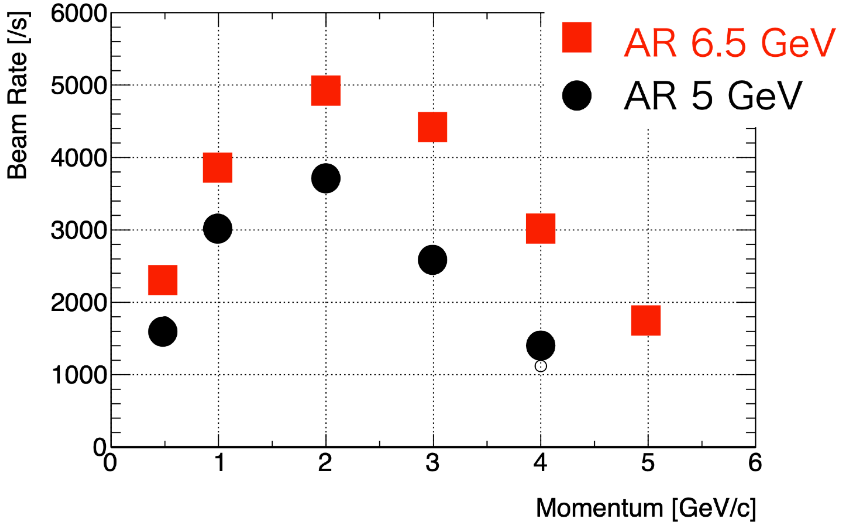
Aims of the ALICE 3 FJPPN project 2/2

- **Training** people getting familiar with the various sensors is an important part of the project (many project members are new to silicon detector technologies)
  - Pool of experts available from IPHC C4Pi facility, ALICE-Ko, KEK ITDC
  - Hands-on approach program to disseminate information on eg:
    - Usage & setup of sensors
    - DAQ with EUDAQ
    - Software & containers
    - Data analysis with Corryvreckan
    - …
- Full **characterisation** w/ feedback given to CMOS sensor designers
  - Close collaboration with the IPHC C4Pi team (+ versatile tracker project: Germany, Italy)

KEK PF-AR Test Beam Line



https://itdc.kek.jp/en/testBeamLine/index.html

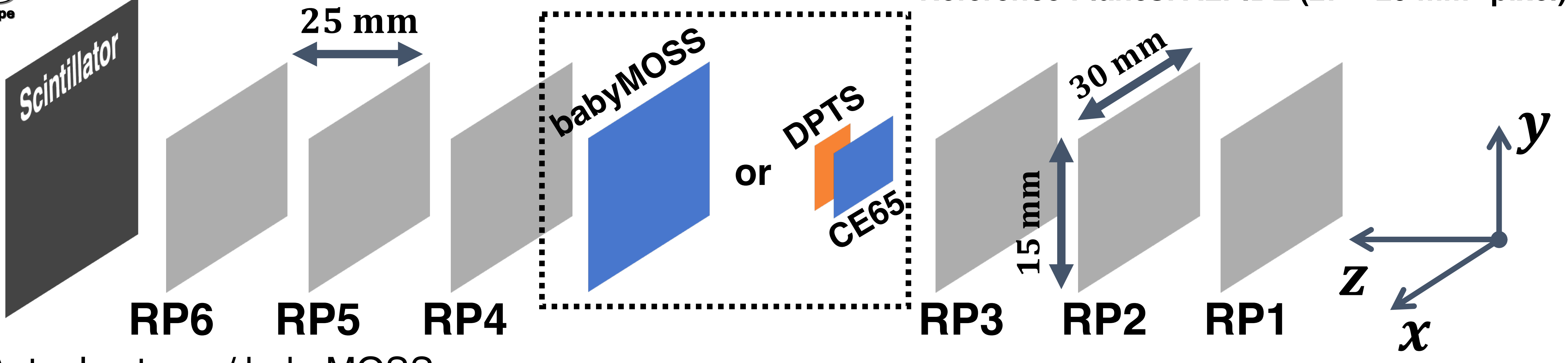


- Electrons produced from the copper converter ($\gamma \rightarrow e^+e^-$)
- Dipole bending magnet extracts electrons with momentum ranging from 0.5 to 5 GeV/*c*
  - Thanks to the KEK ITDC group for their constant support! (including trainings)

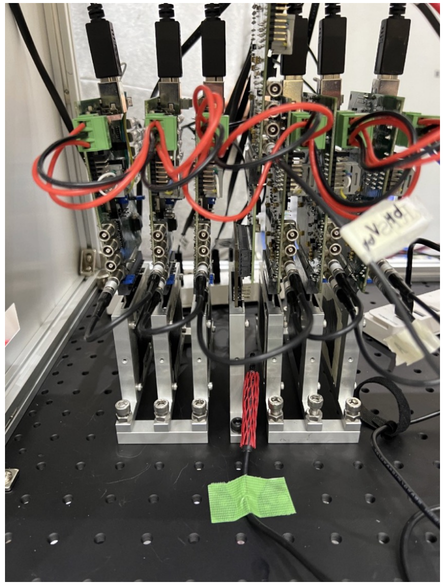
BT Setup & Performance

KATS
Korean ALICE TeleScope

Telescope setup



Actual setup w/ babyMOSS



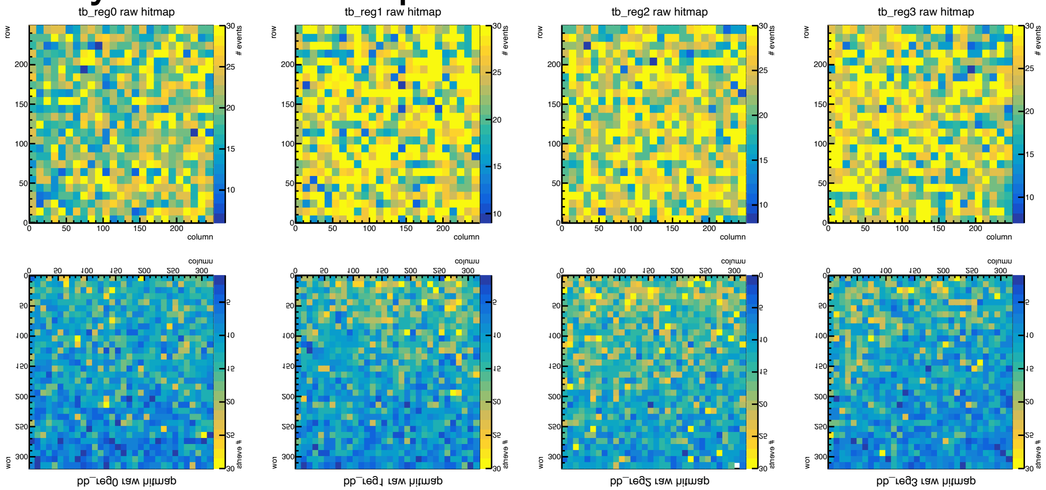
- **6 ALPIDE + 1 babyMOSS (with raiser board) + 1 Scintillator trigger module** (4 cm × 8 cm)
- TRG propagation: Scintillator → NIM Modules → Trigger board → RPs(ALPIDE0, 1, 2, 3, 4, 5) → DUT
- BUSY propagation: DUT → RPs(ALPIDE6, 5, 4, 3, 2, 1) → Trigger board

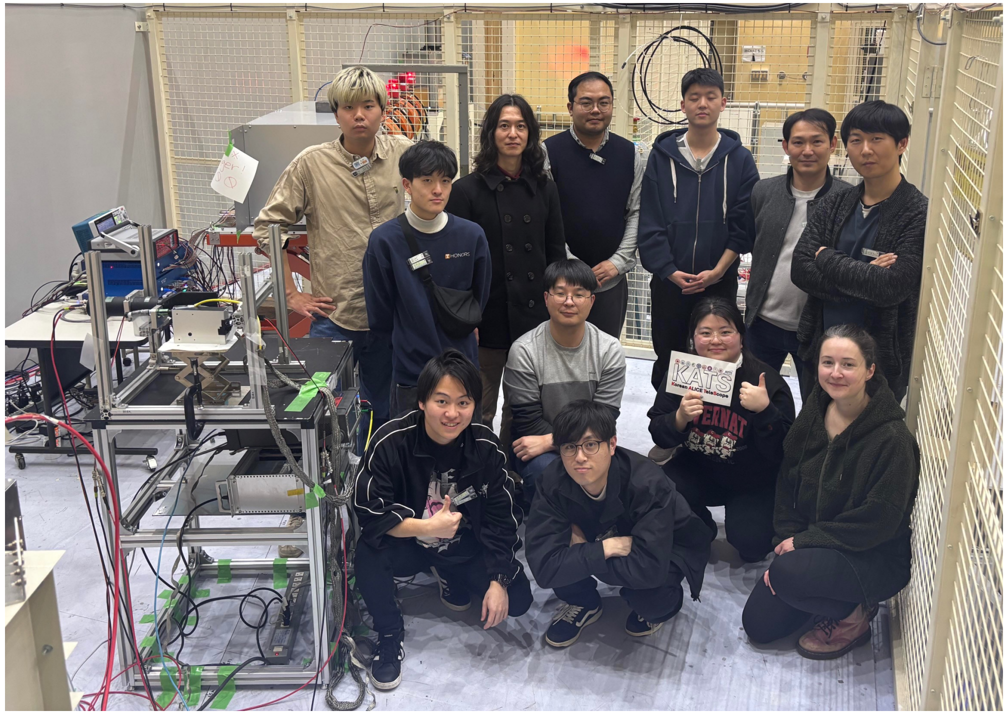
Beam test campaigns in FY2024

Two campaigns in 2024 involving a France–Japan–Korea collaboration

1. `2024ARTBL014`: 2024.12.11–16
   - CE65 characterization with different inner structures → FJPPN D_RD_29 project (see [Okazaki-san presentation on Wed](#))
   - BabyMOSS region scan (see next slide)
2. `2024ARTBL019`: 2025.03.06–11
   - Configuration parameter scans of babyMOSS

babyMOSS hit map for track-associated clusters



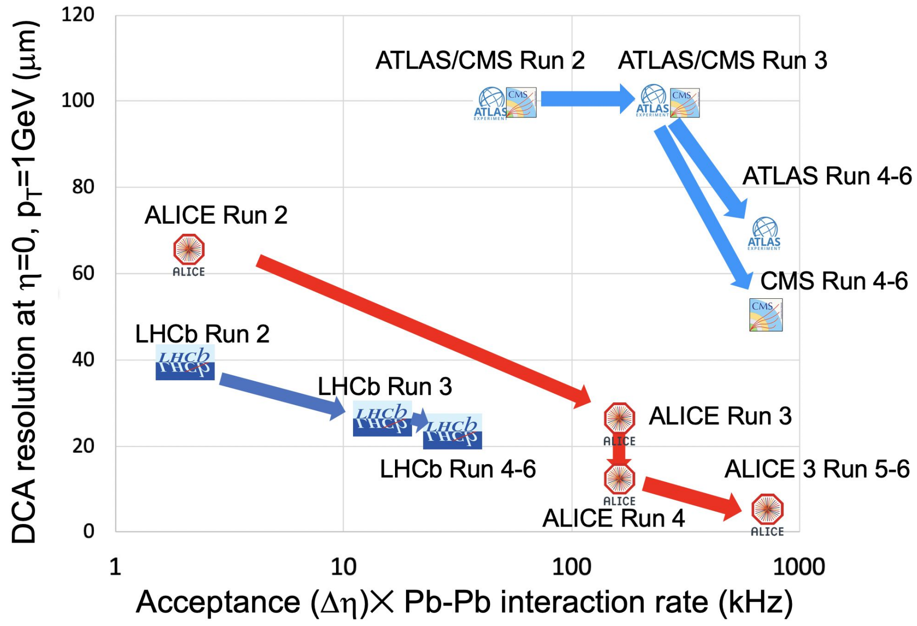


ALICE 3 project plan for 2025–2026

- New BT to be scheduled at KEK PF-AR in 2025–2026
  - Region, parameter scans
  - Detection efficiency and spatial resolution
  - Fake-Hit Rate & Threshold Scan
  - ToT studies with the BabyMOSS/SPARC to investigate the ability of amplitude measurement which would have an immense impact on the performance of MAPS trackers of the future
    - Motivation: dE/dx measurement with the outer tracker layers would…
      - Support the PID capabilities of ALICE3
      - Potentially improve the timing resolution of the tracker
- Bi-weekly beam test data analysis meetings
- Student exchange in 2025
  - Master student from Univ. Grenoble Alpes to Tsukuba Univ.
  - Master student from Hiroshima Univ. to IPHC

Summary

- ALICE has an **ambitious upgrade program**
  - **LS3 (2026–2028):** new upgrades for LHC Run 4
    - ITS3: truly cylindrical silicon layers made of ultra-thin wafer-size MAPS
      - Low-mass di-electrons (→ QGP temperature)
      - Improve heavy flavour particle performance and search for exotic charm nuclei
  - **Beyond Run 4:** continue the heavy-ion programme during the HL-LHC era
    - Proposal of a new experiment ALICE 3 with “nearly-massless” tracker installed during LS4
      - Multi-charm and beauty particles
      - Low-mass di-electrons and soft photons
  - FJPPN support for exchange of personnel and students



END

ALICE 3: Tracking System Key Features

Component	Observables	$\lvert\eta\rvert < 1.75$ (barrel)	$1.75 < \lvert\eta\rvert < 4$ (forward)	Detectors
Vertexing	Multi-charm baryons, dielectrons	**Best possible DCA resolution, $\sigma_{DCA} \approx 10$ µm at 200 MeV/*c***	**Best possible DCA resolution, $\sigma_{DCA} \approx 30$ µm at 200 MeV/*c***	Retractable silicon pixel tracker: $\sigma_{pos} \approx 2.5$ µm, $R_{in} \approx 5$ mm, $X/X_0 \approx 0.1$ % for first layer
Tracking	Multi-charm baryons, dielectrons	**σ_{p_T} / p_T ~1-2 %**		Silicon pixel tracker: $\sigma_{pos} \approx 10$ µm, $R_{out} \approx 80$ cm, $X/X_0 \approx 1$ % / layer

	Vertex Detector	Middle Layers	Outer Tracker	ITS3	ITS2
Pixel size (µm²)	÷ 9 *O*(10 x 10)	• 2.8 *O*(50 x 50)	• 2.8 *O*(50 x 50)	*O*(20 x 20)	*O*(30 x 30)
Position resolution (µm)	÷ 2 2.5	• 2 10	• 2 10	5	5
Time resolution (ns RMS)	÷ 10 100	÷ 10 100	÷ 10 100	100* / O(1000)	O(1000)
Shaping time (ns RMS)	÷ 25 200	÷ 25 200	÷ 25 200	200* / O(5000)	O(5000)
Fake-hit rate (/ pixel / event)	≈ $< 10^{-8}$	≈ $< 10^{-8}$	≈ $< 10^{-8}$	$<10^{-7}$	$<< 10^{-6}$
Power consumption (mW / cm²)	+ 75% 70	20	20	20**	47 / 35***
Particle hit density (MHz / cm²)	• 20 94	1.7	67% 0.06	8.5	5
Non-Ionising Energy Loss (1 MeV n_{eq} / cm²)	• 3000 1×10^{16}	• 100 2×10^{14}	≈ 5.6×10^{12}	3×10^{12}	3×10^{12}
Total Ionising Dose (Mrad)	• 1000 300	• 10 5	≈ 0.2	0.3	0.3
Surface (m²)	• 2.5 0.15	÷ 2 5	• 6 57	0.06	10
Material budget (% X_0)	0.1	1	1	0.05	0.36 / 1.1 ***

* goal, not crucial, like not possible due to power budget

** Pixel matrix

*** Innermost layers / outer layers