Developments for the ALICE 3 Inner Tracker and prospects for future colliders

International Conference on
Instrumentation for Colliding Beam Physics

中国科学技术大学, 合肥，中国

2026年10月12日

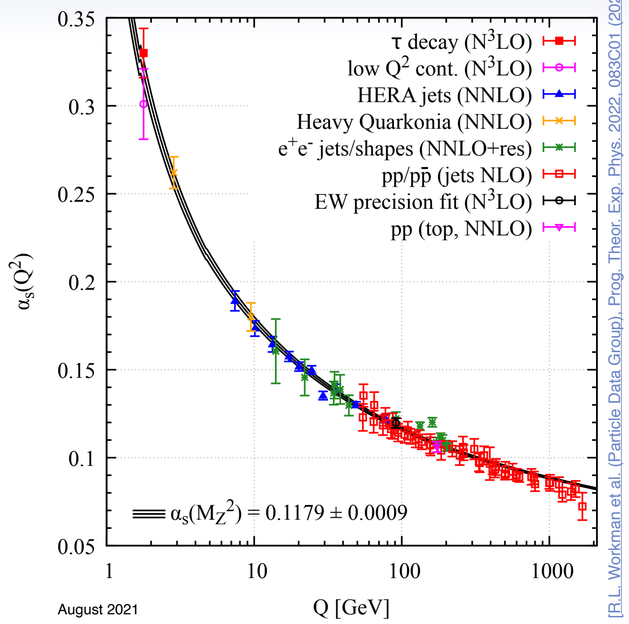
Jochen Klein (CERN)

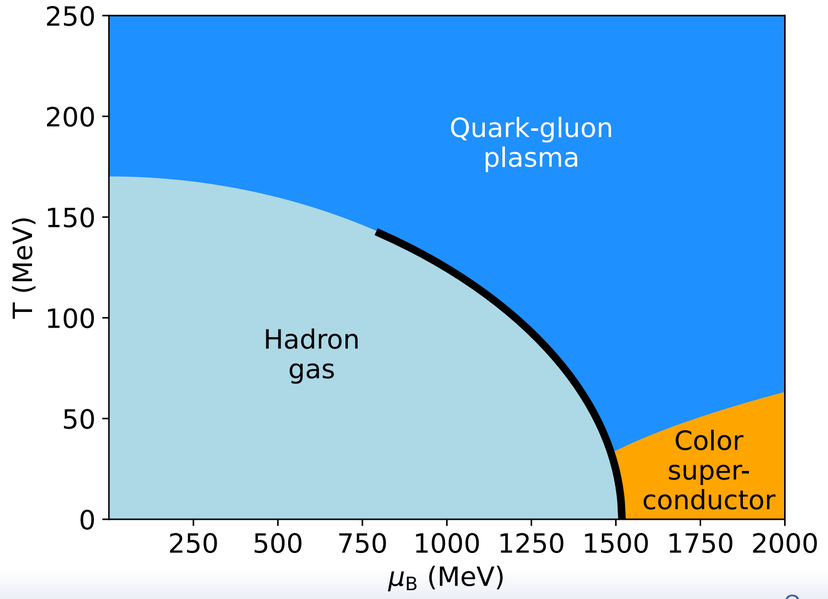
Strong Interaction

- **Interactions with high Q^2 well described by perturbative calculations**

- **Many non-trivial features of Quantum Chromodynamics emerge from low-Q^2 regime**
  - confinement → no free quarks
  - chiral symmetry breaking → nucleon mass
  - fragmentation → formation of hadrons
  - QCD matter → thermodynamic properties

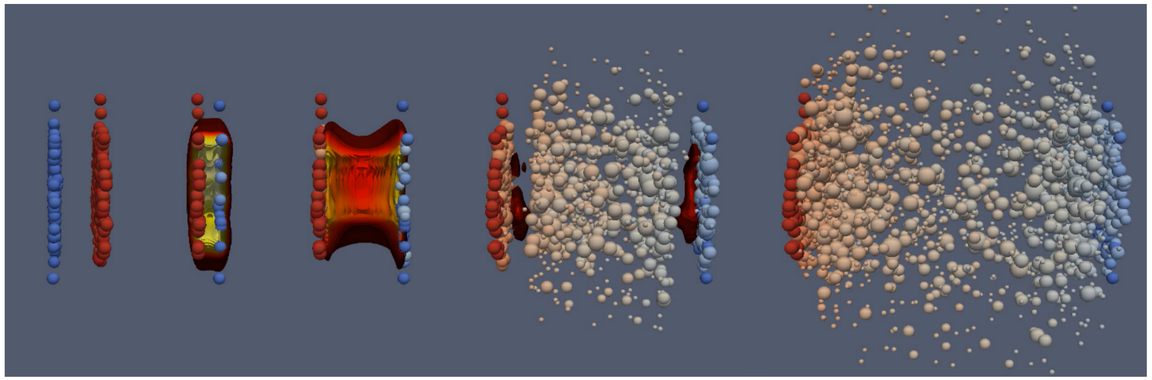
➠ **experimentally challenge current understanding**
➠ **look where no one else could look before**





Nuclear collisions at the LHC

- **Various collision systems at highest energies:**
  $\sqrt{s_{\mathrm{NN}}} = 5.36\,\mathrm{TeV}$ for Pb-Pb
  ➟ **QCD matter with**
  - highest energy density > 12 GeV/fm^3
  - highest initial temperature ≳ 300 MeV
  - longest lifetime ≳ 10 fm/c
  - largest heavy-flavour yields
    ~200 $\mathrm{c\bar{c}}$ pairs in central Pb-Pb collision
  - vanishing net-baryon density $\mu_{\mathrm{B}} \approx 0$
    (at mid-rapidity)



Electromagnetic radiation probing temperature

Hadron momentum distributions, azimuthal anisotropy

Hadron abundances 'hadrochemistry'

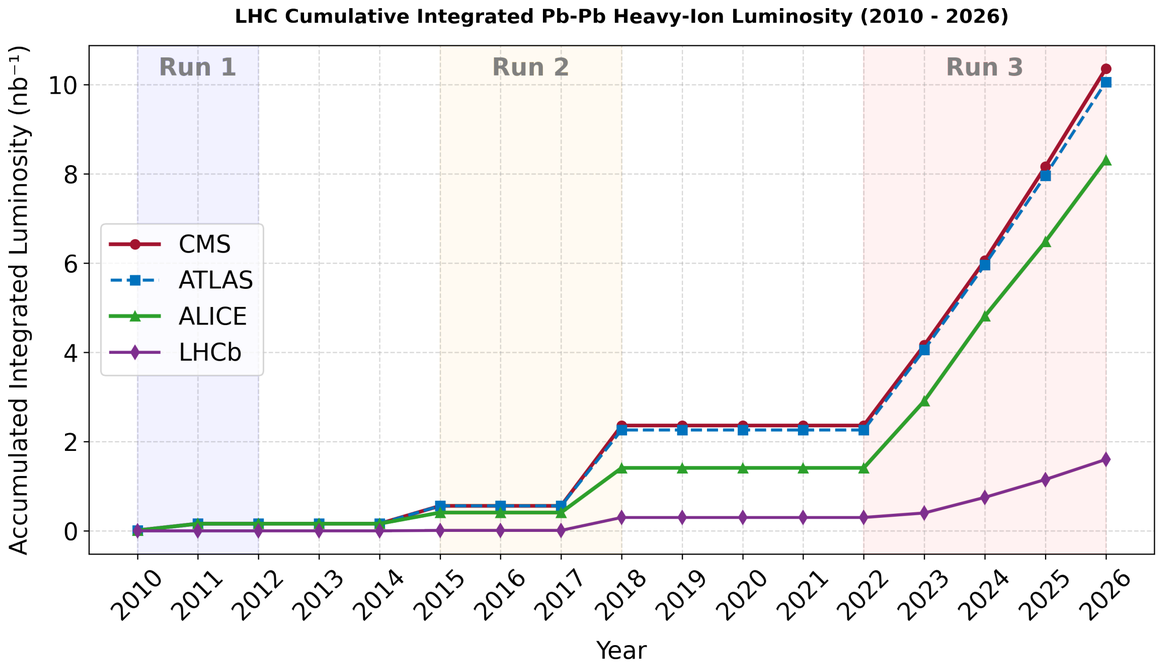
Hadron correlations, fluctuations

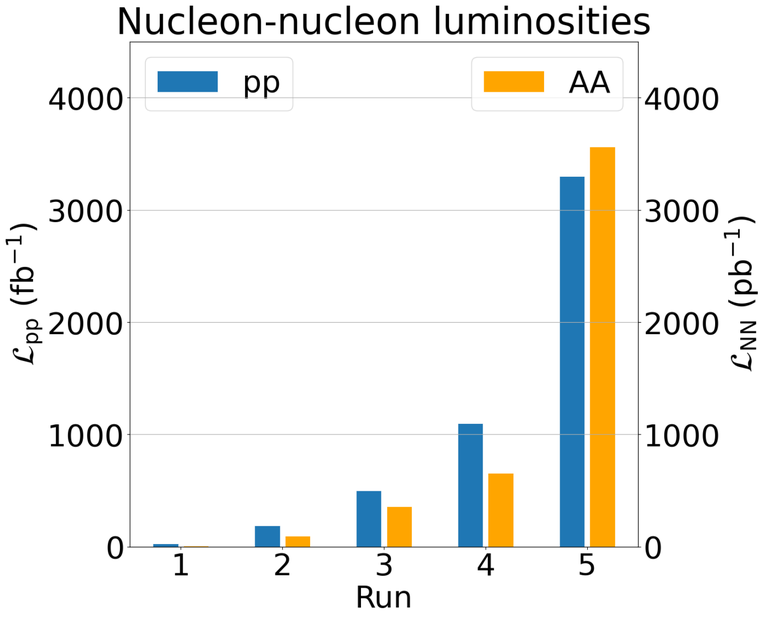
LHC provides **ideal and unique environment**
to study hot QCD matter with heavy ions

NB: Other facilities required to cover complementary areas of phase diagram!

Evolution of the LHC

Collision systems	pp, pPb, Pb-Pb	pp, pPb, Xe-Xe, Pb-Pb	pp, pO, pPb, OO, Ne-Ne, Pb-Pb	pp, pPb, Pb-Pb, AA w/ A=?	pp, pA, AA
LHC schedule	Run 1 2009 - 2013	Run 2 2015 - 2018	Run 3 2022 - 2026	Run 4 2030 - 2033	Run 5 2036 - 2041



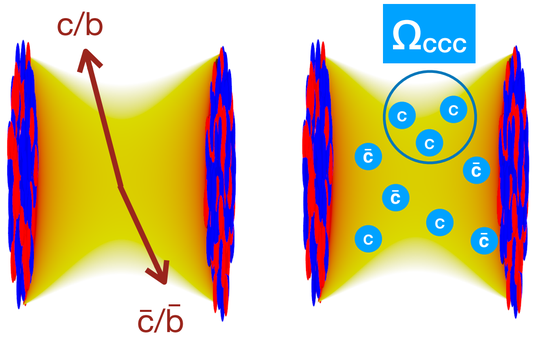


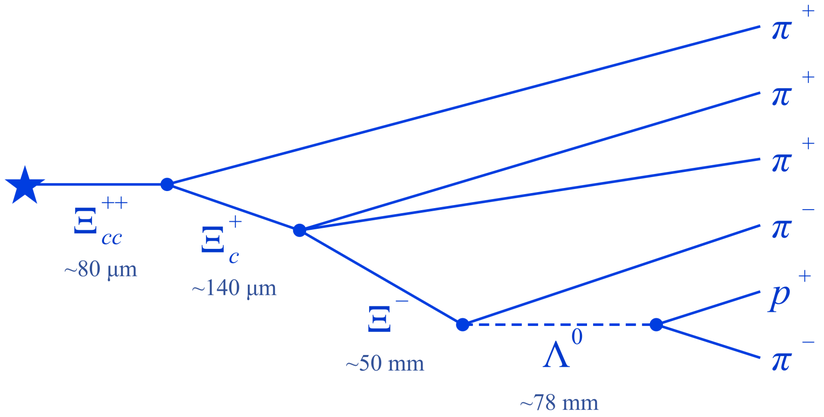
Spectacular performance of the LHC!
Excellent prospects for Run 4 and 5!

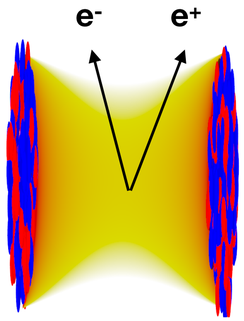
Open physics questions at LHC

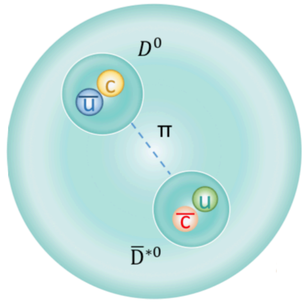
(not exhaustive)

- **Systematic measurements of (multi-)heavy-flavoured hadrons**
  - ➟ transport properties in the quark-gluon plasma
  - ➟ mechanisms of hadronisation from the quark-gluon plasma
- **Precision measurements of dileptons**
  - ➟ evolution of the quark gluon plasma before hadronisation
  - ➟ mechanisms of chiral symmetry restoration in the quark-gluon plasma
- **Hadron correlations**
  - ➟ interaction potentials
  - ➟ fluctuations









Background from heavy-flavour decays
$c\bar{c} \rightarrow D\bar{D} \rightarrow e^+ e^- \ldots$

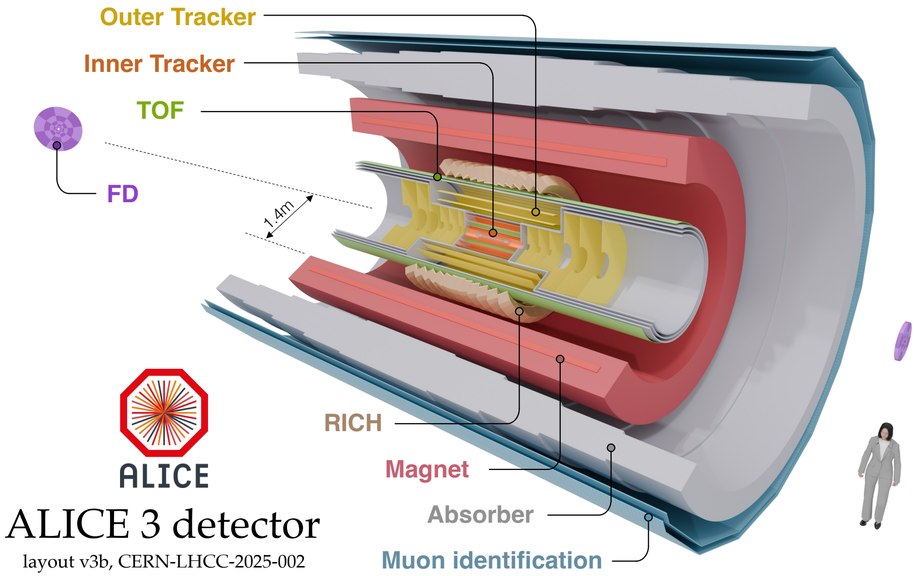
Programme out of reach with existing or other planned experiments!

ALICE 3

100 kHz Pb-Pb (dN/dη ~400)
24 MHz pp (dN/dη ~7)

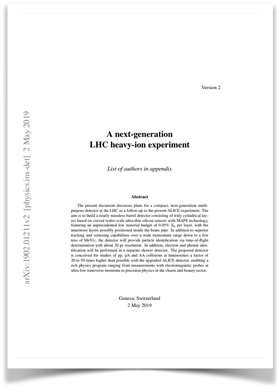
Novel detector concept for Run 5

- superconducting magnet system → p_T resolution
- compact, lightweight tracker → efficient down to $p_T \approx 0$
- retractable vertex detector → pointing resolution
- complementary techniques → excellent particle ID
- high rate and large acceptance → large data samples



ALICE 3 detector
layout v3b, CERN-LHCC-2025-002

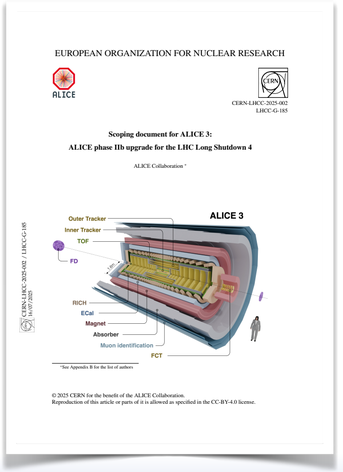
2019:
Expression of Interest



2022:
Letter of Intent



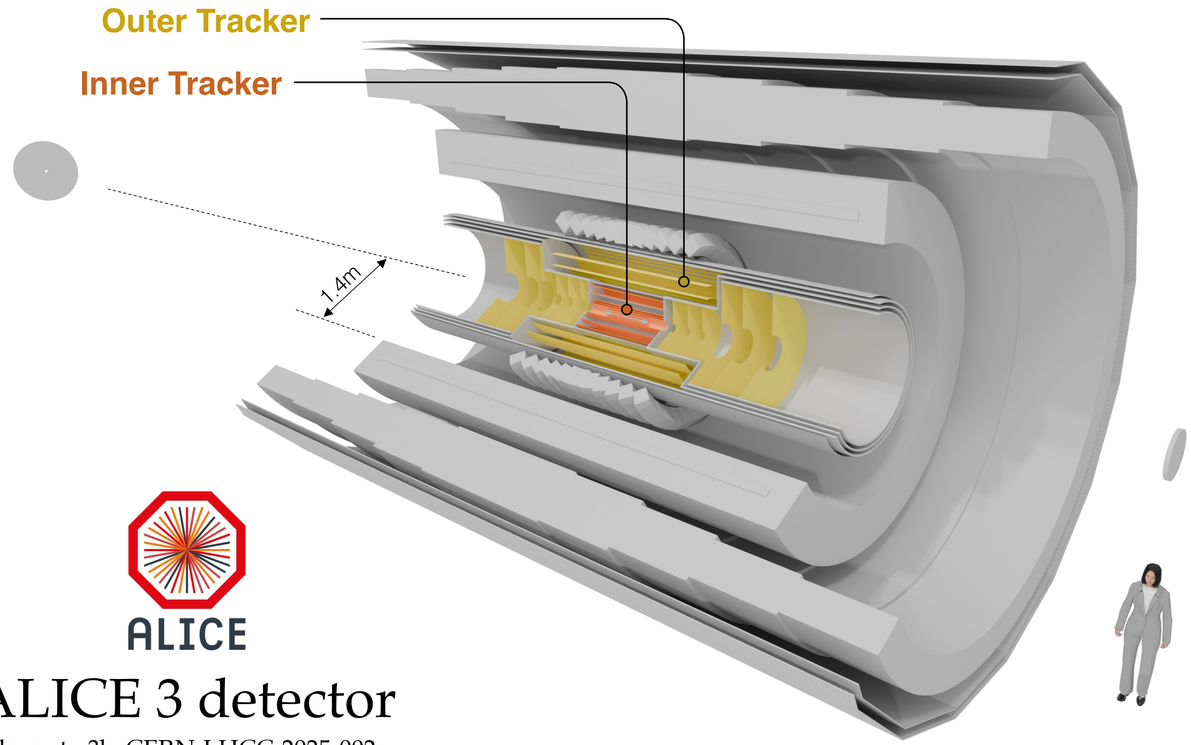
2025:
Scoping Document



2026:
Approval to proceed to Technical Design Reports

ALICE 3 trackers

- **Significant step in instrumented surface**
  (Inner Tracker ~6 m², Outer Tracker ~40 m²)
  - sensor design & production (yield, cost, synergies)
  - modularisation (yield, industrialisation)
  - fault tolerance (redundancy)
- **Challenging for integration and maintainability**
  - mechanical concept with minimal material
  - maintainable integration
- **New concepts for power distribution**
  - current reduction, e.g. through serial powering
  - granularity
  - failure handling



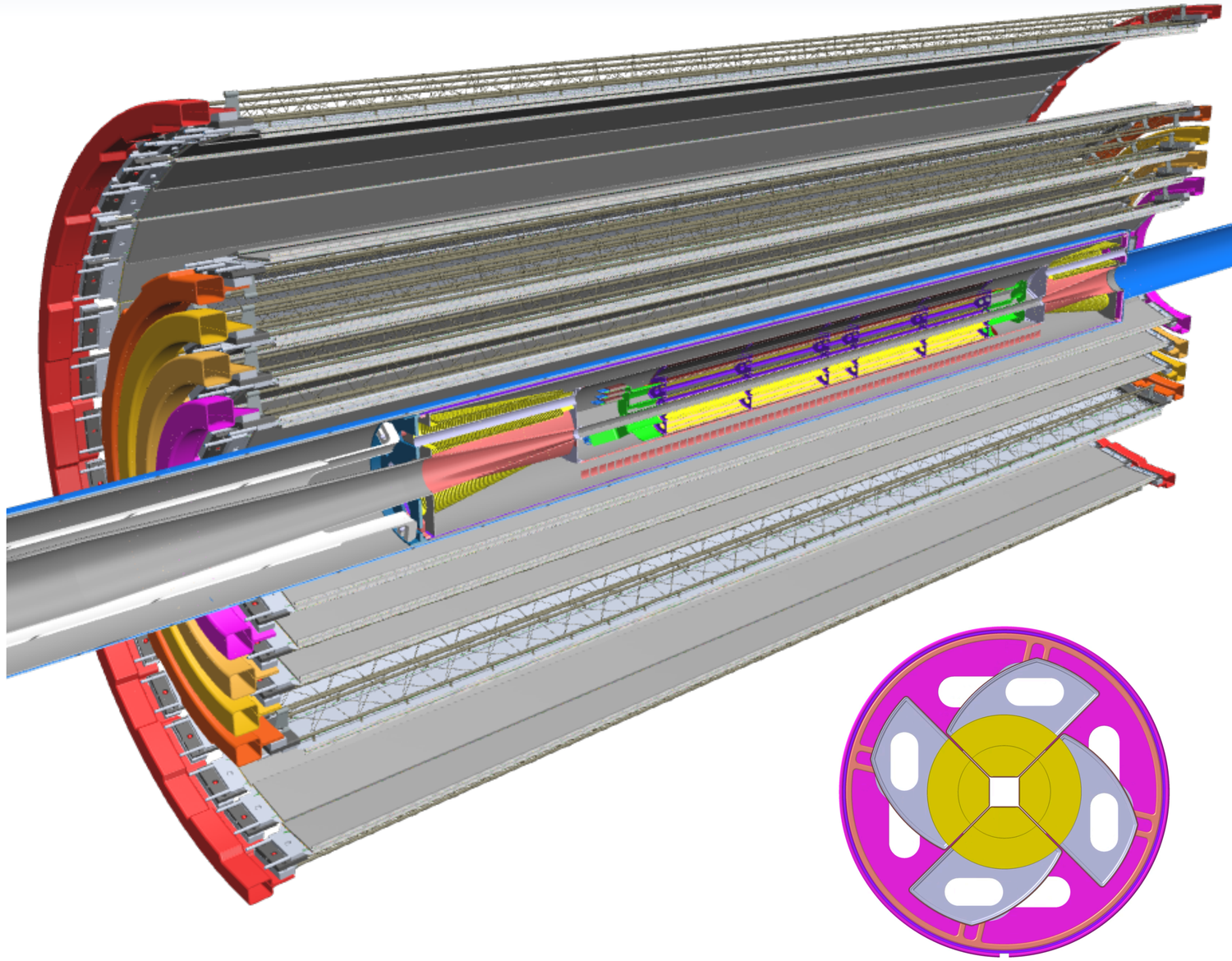
ALICE 3 detector
layout v3b, CERN-LHCC-2025-002

Vertex Detector + Middle Layer → Inner Tracker
Outer Layers + Forward Disks → Outer Tracker

ALICE 3 Inner Tracker

- **5 Middle Layers in barrel configuration**
  - radii between 9 and 30 cm
  - ~1% X_0 per layer
  - σ_{pos} ~10 µm
  - lightweight staves
- **3 cylindrical layers (Vertex Detector) inside beam pipe**
  - radii between 5 and 25 mm
  - 0.1 % X_0 per layer
  - σ_{pos} ~2.5 µm
  - petals for secondary vacuum

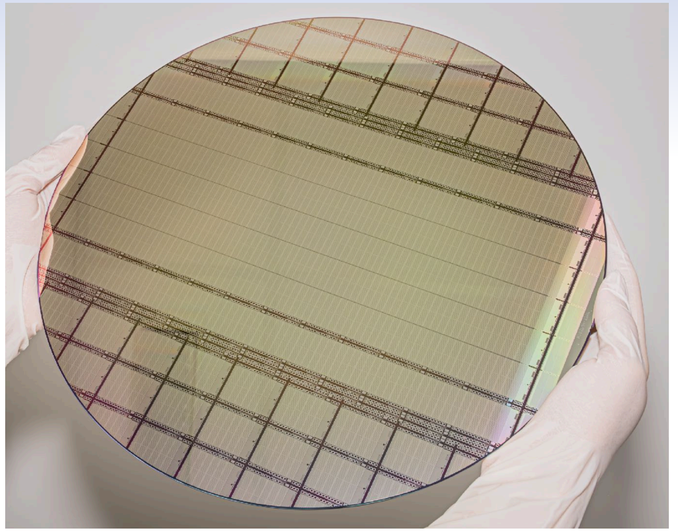
➟ **Silicon pixel sensors**



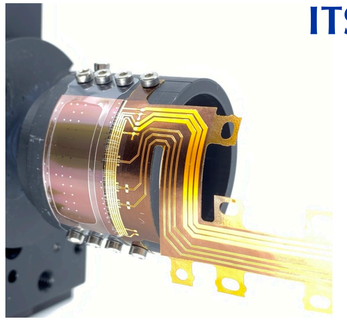
Pixel chips

- **Monolithic pixel sensors** optimised in different processes
  - low noise, low power, low material budget
- **Stitching of reticle-sized sensor unit** demonstrated
  - wafer-scale sensors
- **Bending of silicon sensors** demonstrated
  - ALPIDE performance shows no degradation
  - models with wafer-scale silicon

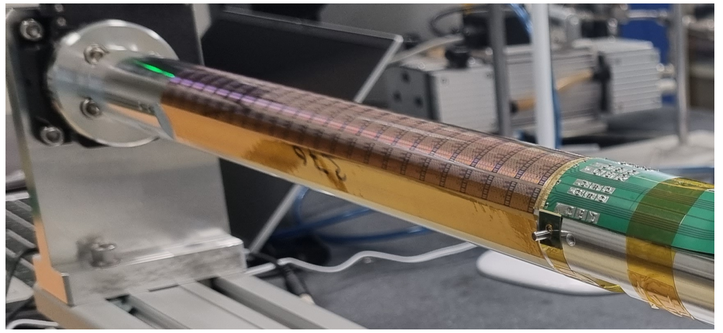
ALICE 3 developments can leverage ample experience but need to go beyond



ITS3 ER2 wafer → MOSAIX



Bent ALPIDE



Processed wafer on mandrill

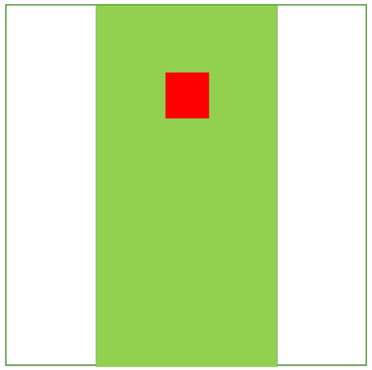
ALICE 3 tracker chip

- **Common R&D line for VD, ML, OL**
  → **ALMIRA as joint technology project**

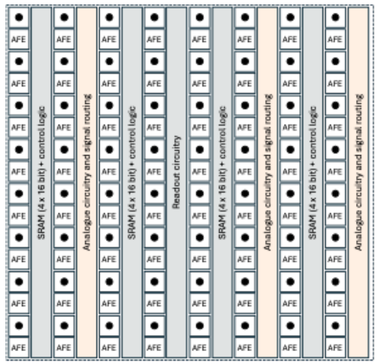
- **Pixel with different pitches** down to **10x10 µm²**
  - collection electrode
  - analogue front-end

- **Pixel macro**
  → modular architecture with two variants
  - discrimination and fast-OR
  - memory for multi-event buffering (controlled by periphery)
  - analogue circuitry
  - control logic

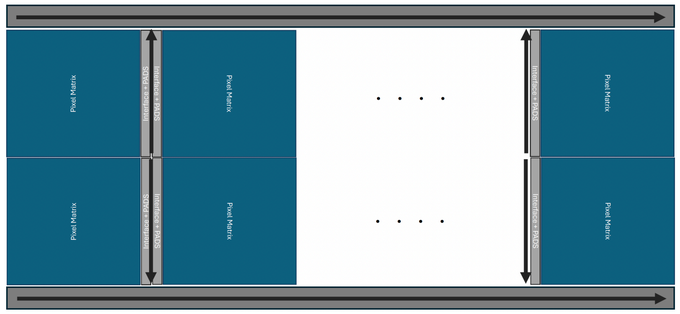
Single pixel (10x10 µm²)



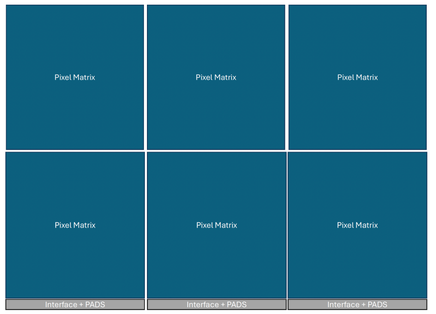
Pixel macro



Ex. of stitched sensor



Ex. of reticle-size chip



Extensive characterisation required

Pixel chip characterisation

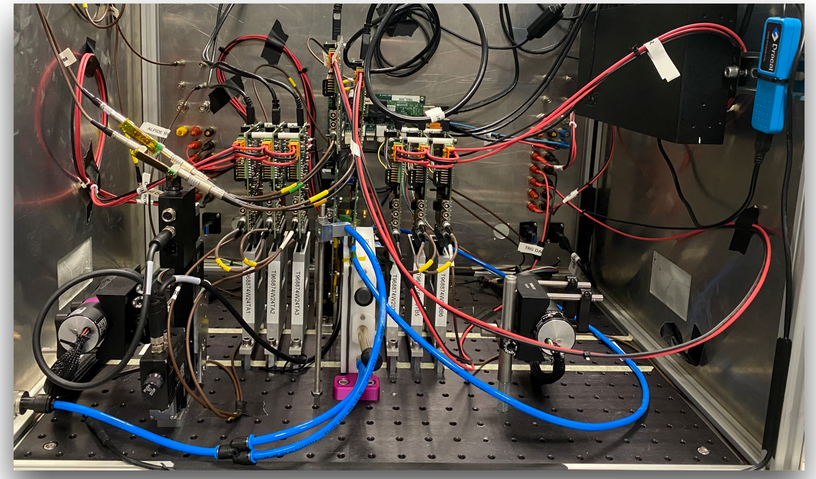
→ N. Bouchhar

- **Analogue Pixel Test Structures (APTS)**
  from ITS3 ER-2 extensively tested
  - characterisation of new process splits
  - validation of pixel layout
    with more space for circuitry (P5)
  - optimisation of pixel pitch
    (for tracking layers)

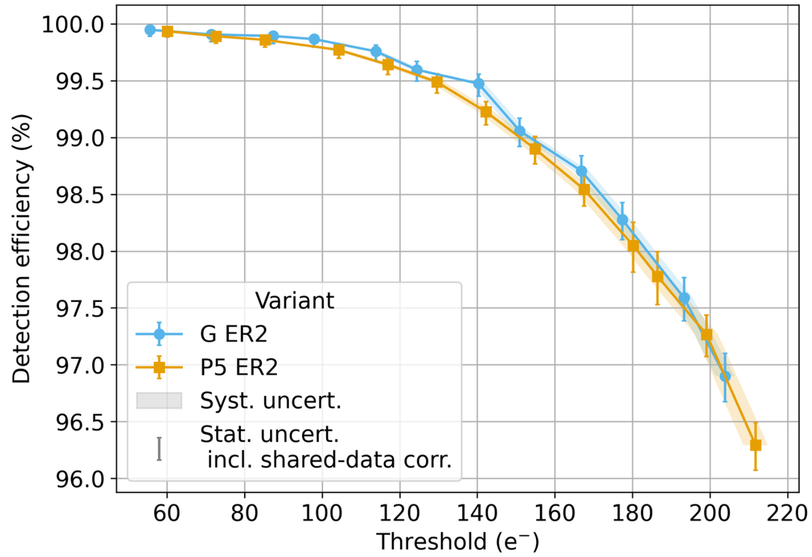
- **ALMIRA submission in preparation**
  - pixel with (new) analogue front-end
  - pixel macro with buffering and fast-OR
  - periphery with control and readout

Design needs to consider sensor assembly

Telescope with cold box



APTS



Non-irradiated
Split 7
19.0 °C
Pitch 10x10 µm^2

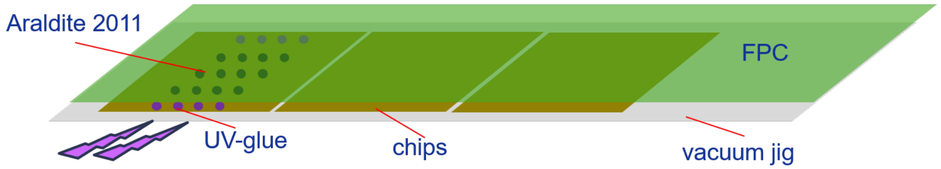
V_{reset}: 500 mV
V_{psub}: -4.8 V
I_{reset}: 100 pA
I_{biasp}: 0.5 µA
I_{biasn}: 5 µA
I_{bias3}: 200 µA
I_{bias4}: 150 µA

Pixel chip assemblies

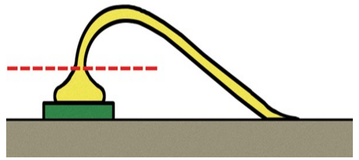
- **Requirements**
  - **Small-scale but complex VD layer assembly**
    → bending, in-vacuum, bake-out procedure, …
  - **Large-scale production of ML modules**
    → scaling, yield, material budget

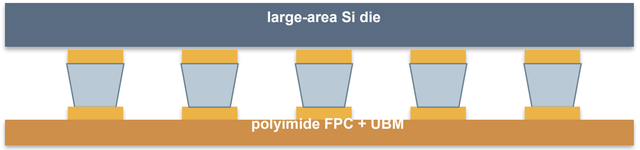
- **R&D to identify ideal interconnect**
  - **Wire bonding** (established)
  - **Au-stud bonding** (R&D ongoing)
    → high temperatures, mechanical stress
  - **Indium bump bonding** (R&D starting)
    → low temperature, flexible, oxide formation
  - **TAB bonding** (R&D ongoing)
  - **Laser-assisted bonding** (R&D starting)
    → properties of process to be understood

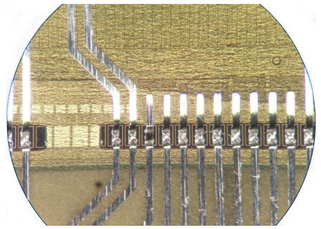
UV curing

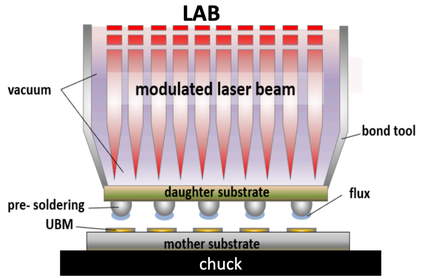


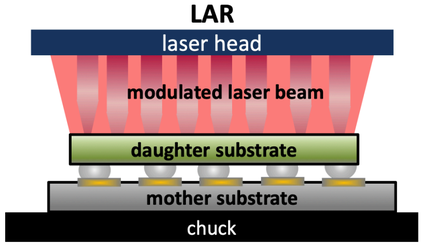
Creation of Au stud





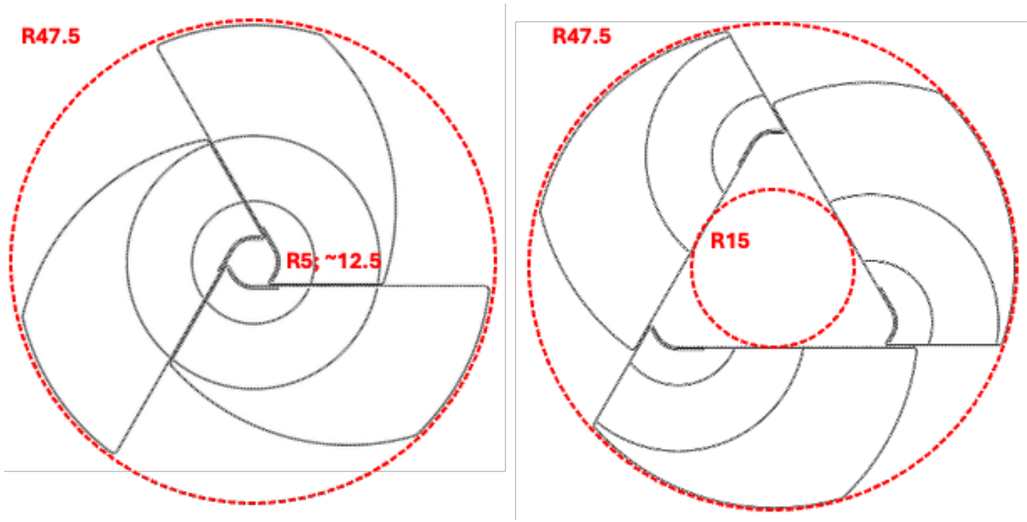


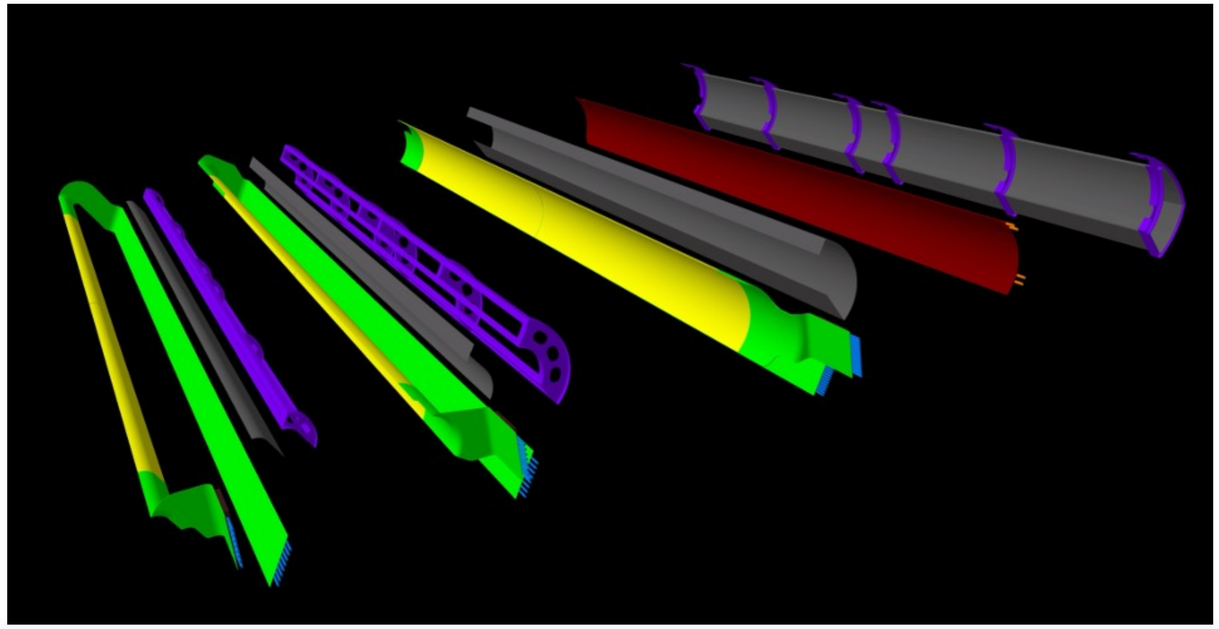


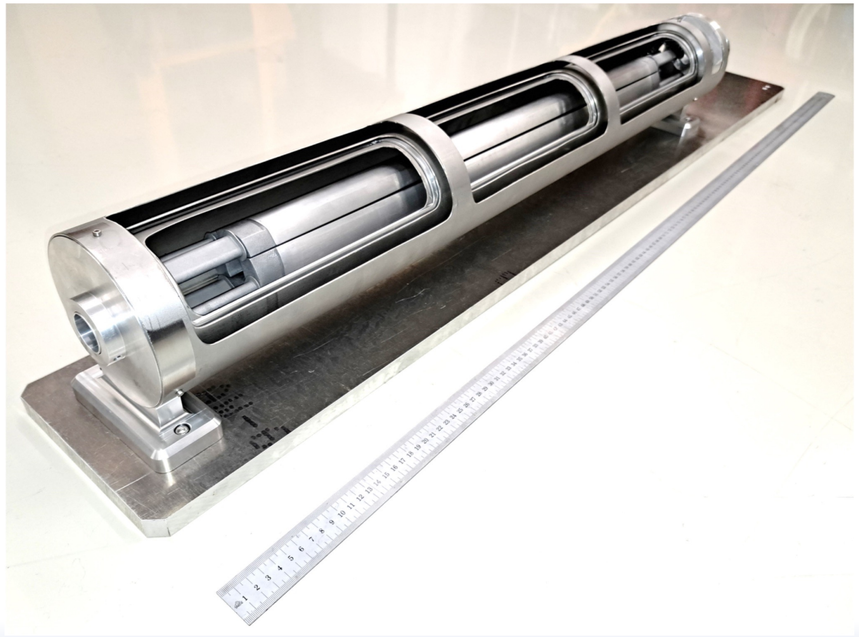


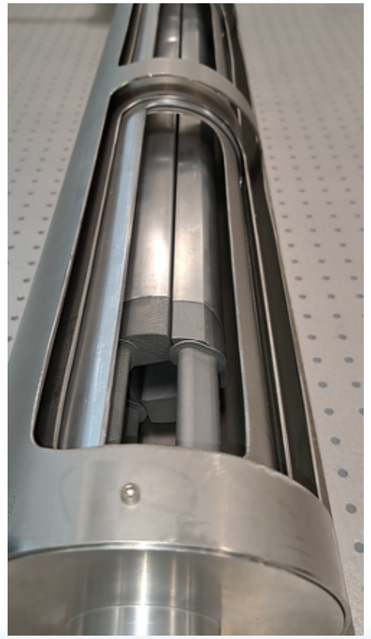
Vertex Detector integration

- **Extruded petals** to host sensor assemblies
  - two-phase CO_2 cooling with walls as heat spreaders
- **Rotary mechanism** for retraction
  - friction-less operation in vacuum
- **Feed-throughs** for power, readout, cooling
  - Vacuum compatibility of services and placement outside of acceptance



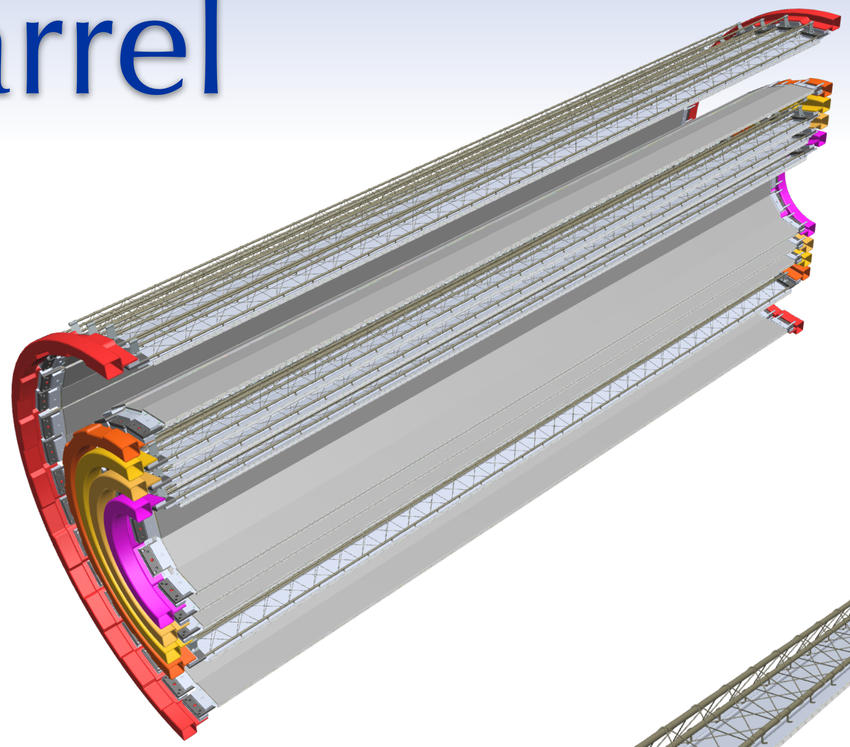


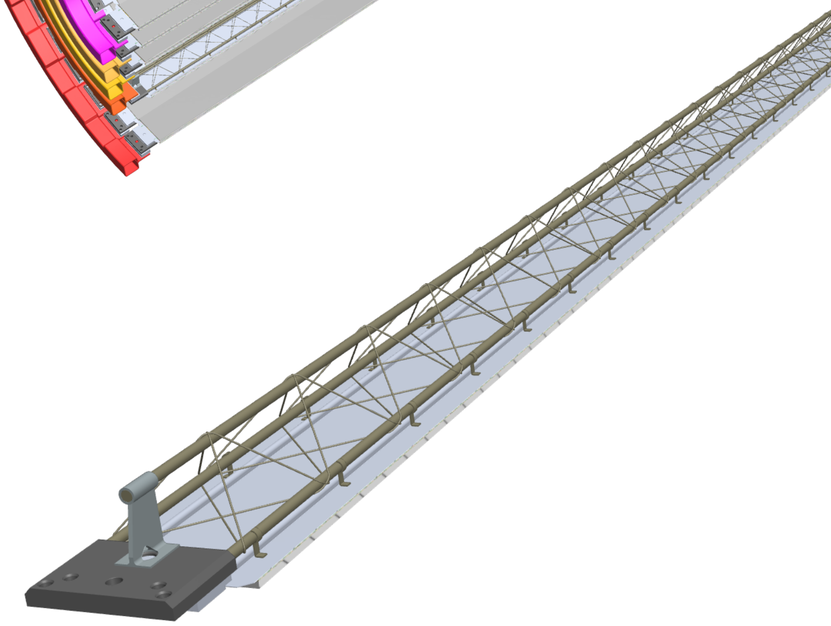




Middle Layer barrel

- **Modules** to host 2x4 reticle-size chips
  - FPC for power distribution and readout
- **Staves** to host modules
  - spaceframe based on pultruded longerons and continuous winding
  - coldplate with embedded tubes for water cooling
- **End wheels** to host staves
- **Service barrels**
  - joint structure for installation



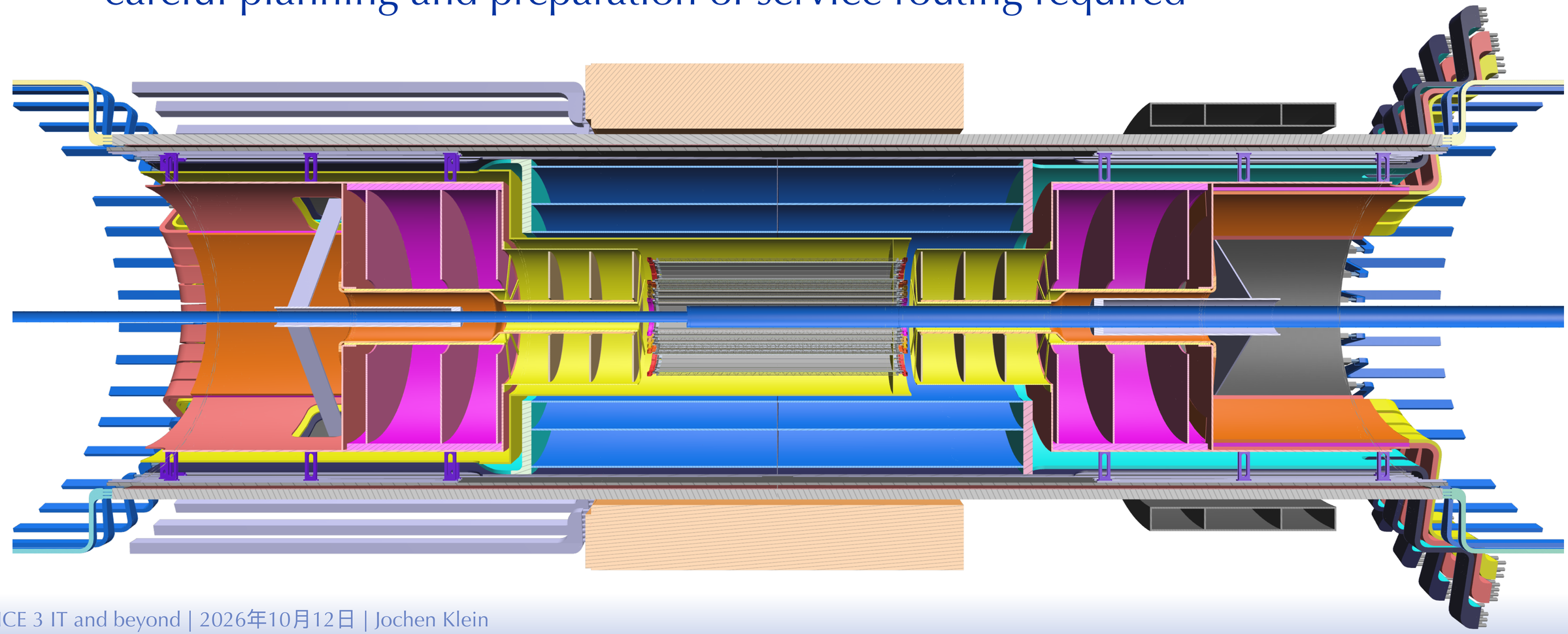


A3IT stave

Need to consider reworkability and effective installation

Integration

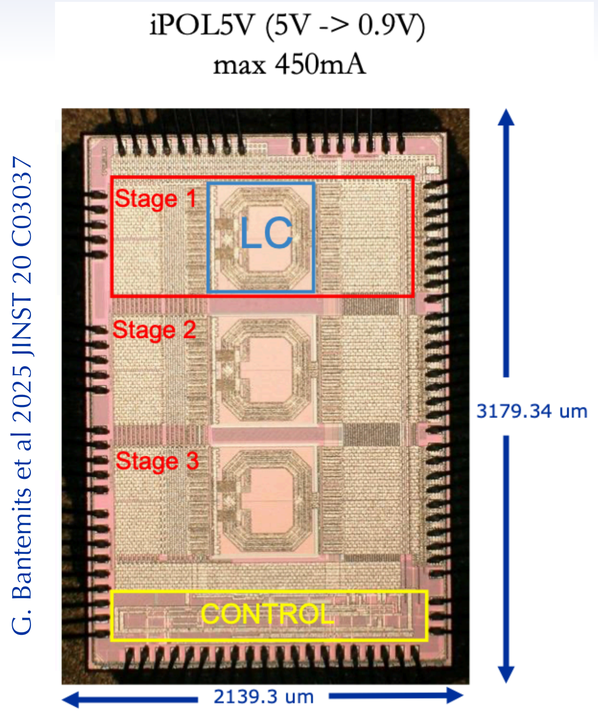
- **Peacock structure** for sequential installation of fully prepared detectors
  → installation in short period of Long Shutdown 4
  - careful planning and preparation of service routing required

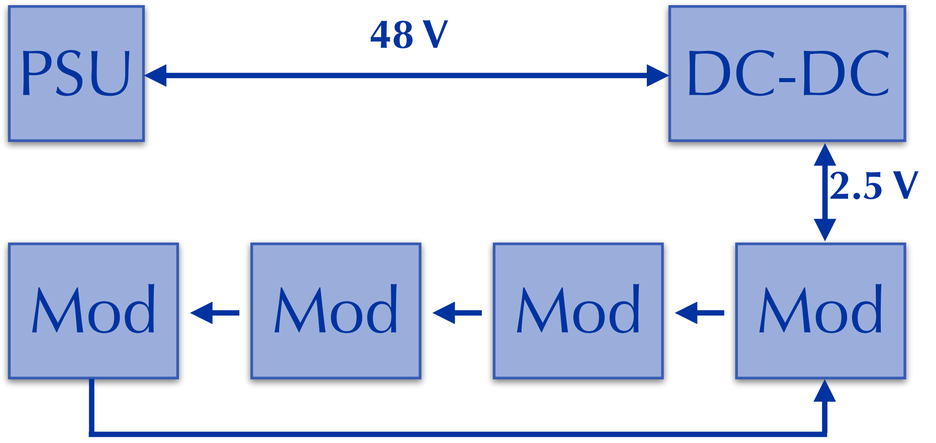


Powering

- **Parallel powering** → parallel voltage supplies for each module
  - conceptually simple and easy to control
  - prohibitive in terms of material
- **DC-DC conversion** → higher voltage → reduce current
  - rad. hard buck converters available (bPOL…)
  - ongoing R&D for higher currents (50 A), including new processes
  - iPol developments could be well suited
- **Serial powering** → reuse and reduce current
  - requires (integrated) shunt regulators
  - complex system architecture
- **Consider all aspects:**
  integration, stability, availability (also in China!)
  → study concrete concepts
  → plan relevant tests

Fully integrated DC-DC converter (28 nm)

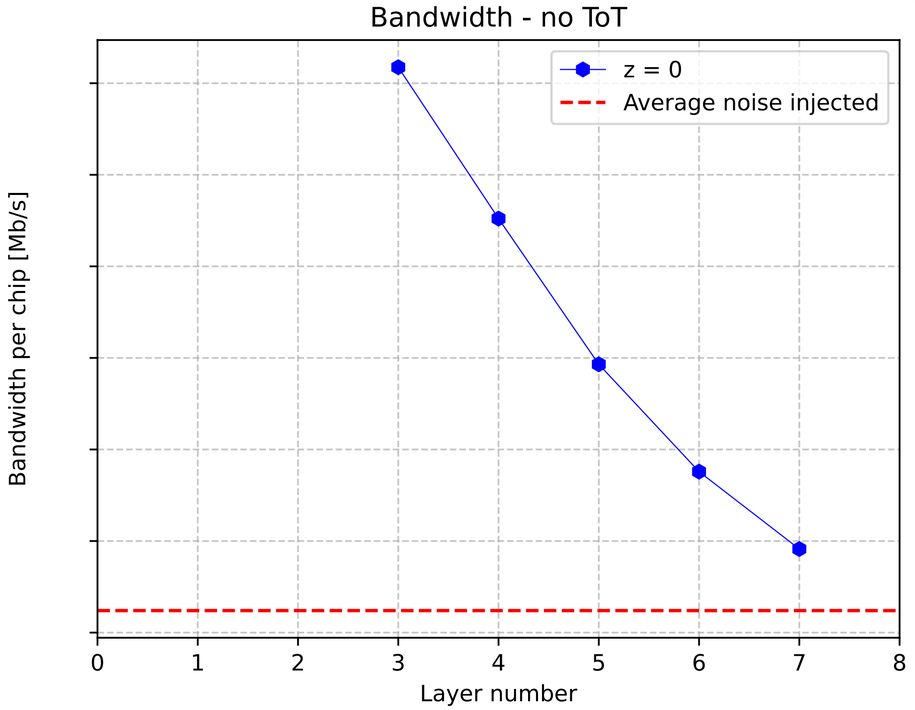


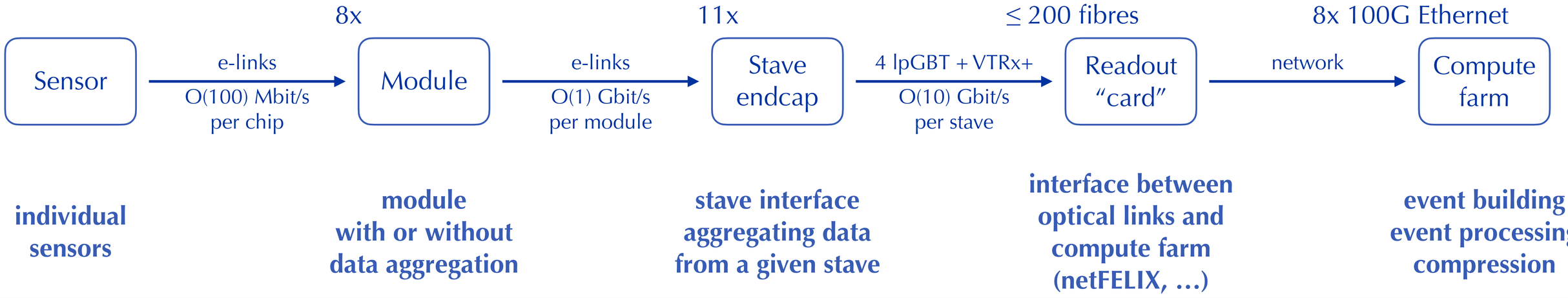


Simplified powering scheme

Readout and processing

- **Continuous, trigger-less read-out**
  - highly parallel processing exploiting GPUs
- **Data aggregation and buffering**
  with large spread of required readout bandwidth
  - consider total bandwidths to judge feasibility
  - consider different schemes for data aggregation and buffering in different regions
  - Versatile Link (lpGBT and VTRX+) used as example, alternatives to be evaluated





Prospects at future colliders

NB: Selected developments, impossible to be exhaustive.

Prospects for FCC-ee

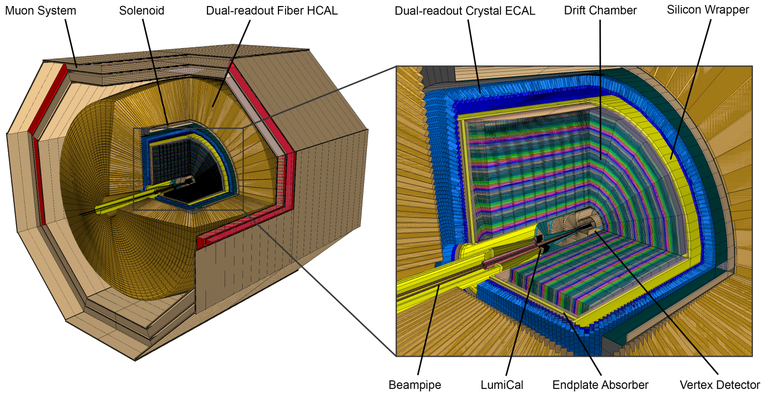
- **Detector concepts for 4 IPs**
  - AGORA
  - Advanced Lightweight and Fine-grained Apparatus (ALFA)
  - A Lepton Lepton collider Experiment with Granular Read-Out (ALLEGRO)
  - CLIC-like Detector (CLD)
  - Innovative Detector for Electron-Positron Accelerator (IDEA)
  - International Large Detector (ILD)

- **Precision flavour tagging**
  → excellent impact-parameter resolution → minimal material
  - **IDEA**: ultra-light vertex detector using ITS3-like curved, wafer-scale MAPS
  - **ALFA**: all-MAPS tracker from vertexing to large-area tracking

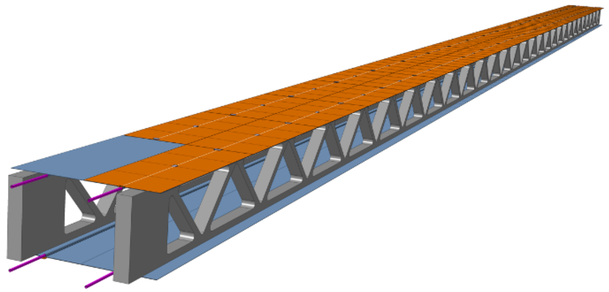
- **Pixel chip developments**
  - **MOSAIX:** wafer-scale bendable sensors
  - **ALMIRA:** thin, bendable sensors up to wafer scale
  - Manta, Octopus

Mode	Energy (GeV)	L/IP (10^{34} cm^{-2}s^{-1})
Z pole	91.2	140
W mode	160	20
Higgs	240	7.5
$t\bar{t}$	365	1.4

IDEA concept



ALFA stave



Prospects for CEPC

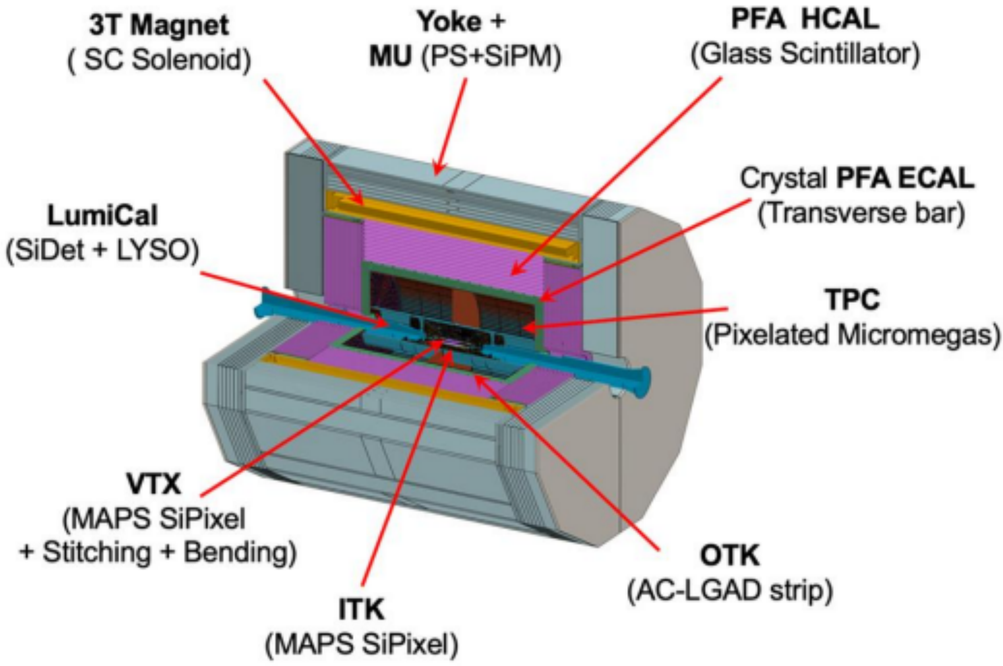
- **Detector concepts for 2 IPs**
  - CEPC reference detector (TDR published)
    → Advanced Glass Optimized Research Apparatus (AGORA)
  - ILD (cf. FCC-ee)
  - IDEA (cf. FCC-ee)

- **Precision flavour tagging → Inner Tracker** (ITk)
  - ~3 µm single-point resolution and <0.15% X_0 per layer
  - wafer-scale stitching
  - ultra-low-mass integration

- **Pixel chip developments**
  - **TaichuPix-3:**
    180 nm CMOS, 25 µm pixel pitch,
    ALPIDE-derived analogue front-end with faster response
  - **JadePix:**
    20x30 µm² pitch, ~1 µs timing,
    ALPIDE-derived analogue front-end with hit-driven readout

Mode	Energy (GeV)	L/IP for 30/50 MW (10^{34} cm^{-2}s^{-1})
Z pole	91.2	116 / 192
W mode	~160	16 / 27
Higgs	240	5 / 8
ttbar	360	0.5 / 0.8

[https://arxiv.org/abs/2312.14363]



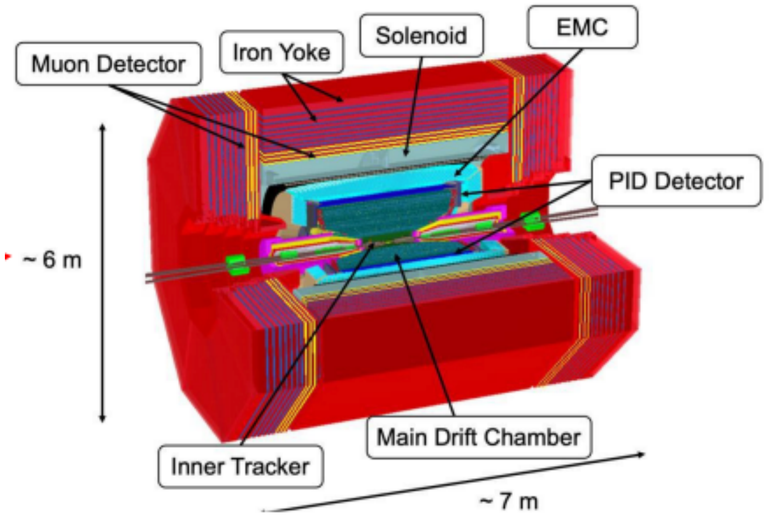
[CEPC Study Group, Reference Detector TDR, arXiv:2510.05260 (2025)]

Prospects for STCF

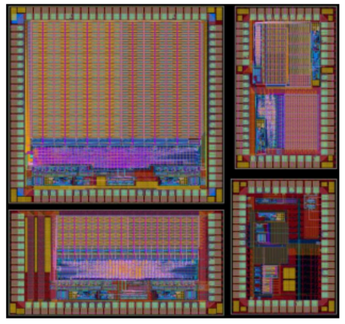
- **Low-material inner tracker** with ~0.3% X_0 per layer for low-momentum tracking

- **Development of CharTPix**
  - prototypes with ALPIDE-derived front-end
  - optimised column-drain readout
  - elongated 31 × 170 μm² pixels to reduce power
    → projection ~56 mW/cm²

Mode	Energy (GeV)	L/IP (10^{34} cm^{-2}s^{-1})
	2-7	5 @ 4 GeV

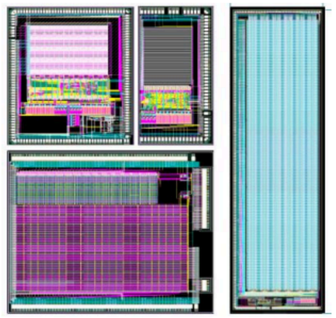


CharTPix_180



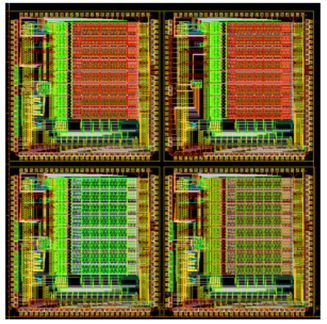
Chips returned in Dec. 2024

CharTPix_130



Chips returned in Mar. 2025

CharTPix_180_modified

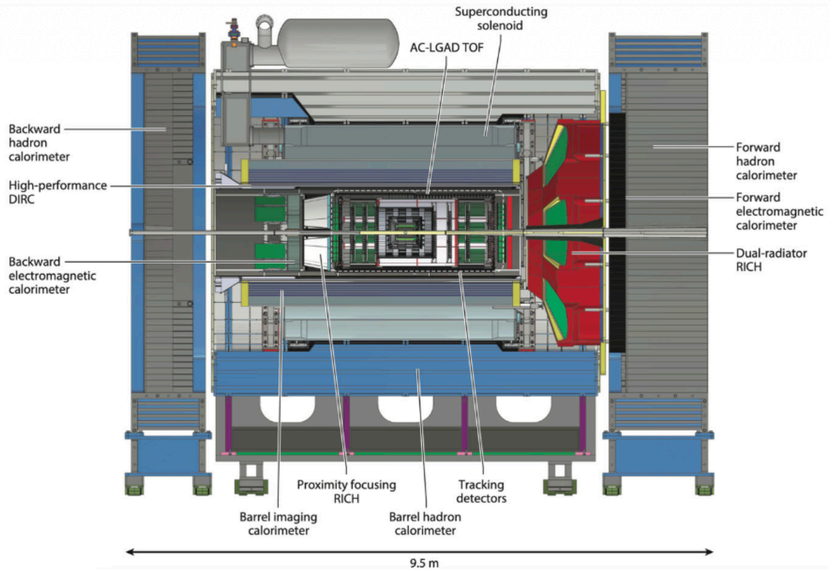


Chips returned in Oct. 2025

Prospects for EIC

Energy (GeV)	L/IP (10^{34} cm^{-2}s^{-1})
10 - 100	5 @ 4 GeV

- **Detector concepts** for 2 interaction point
  - electron Proton- and Ion Collider experiment (ePIC) (emerged out of ECCE, ATHENA, CORE)
  - second detector to be added later
- **Precision vertexing and tracking**
  - ITS3-based vertex detector and tracking layers



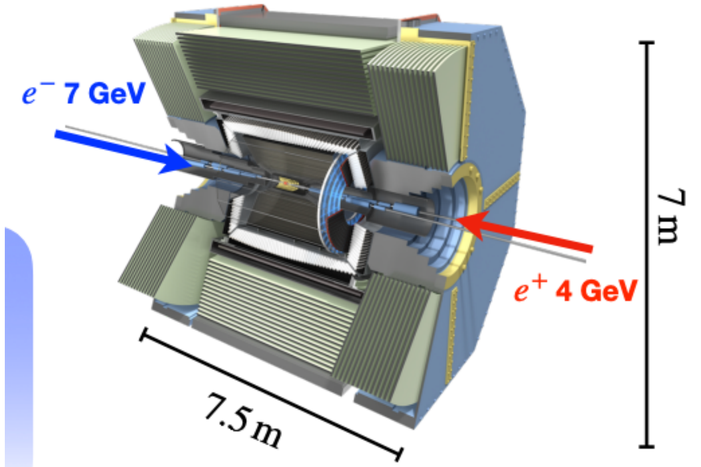
ePIC

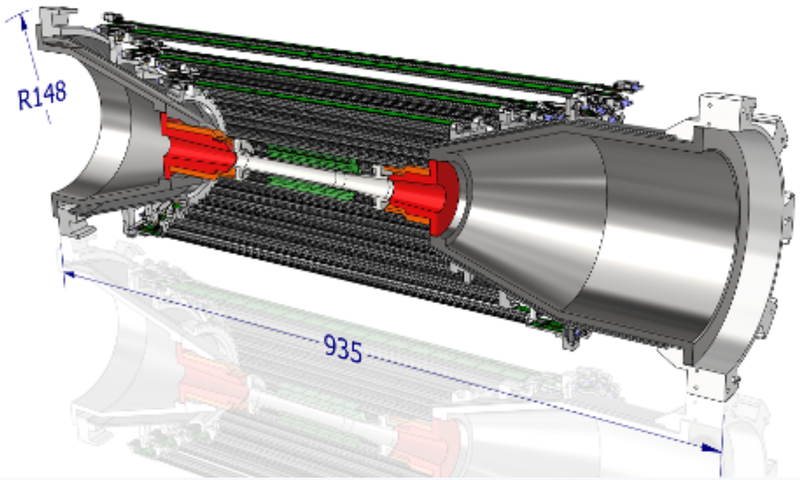
Belle II upgrade

- Fully pixelated **DMAPS VTX** to replace DEPFET pixel and silicon-strip vertex detectors

- **OBELIX** (derived from TJ-Monopix2)
  - 33 μm pitch
  - 50–100 ns timestamp bins
  - dedicated trigger buffering
  - 120 MHz/cm² average hit rate, 30 kHz triggers with 10 μs latency
  - ~ 0.3% X_0 per layer for inner layers
  - 200 mW/cm² power density

Mode	Energy (GeV)	L/IP (10^{34} cm^{-2}s^{-1})
Y (4S)	10.58	60





Conclusions

- **Silicon pixel chips technology of choice for many experiments**
  → different optimisations and realisations

- **Exciting R&D on many fronts for future collider experiments**
  → identify and exploit beneficial synergies

- **Intense programme on a tight schedule for installation of ALICE 3 in LS4**
  → many activities and opportunities for collaboration

