The CEPC Reference Detector TDR

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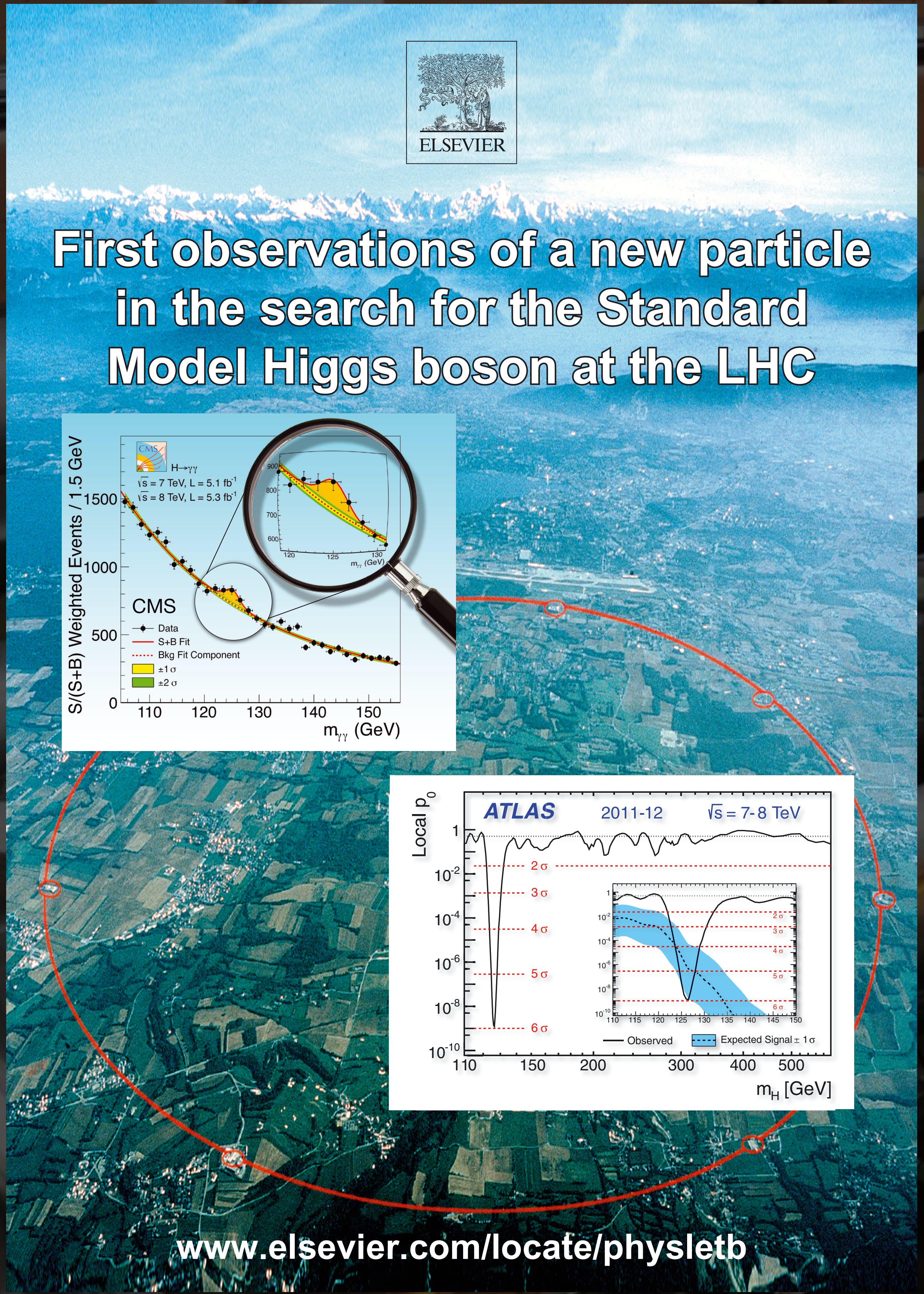
Guangzhou, November 6, 2025

The Higgs Boson Discovery at LHC

Predicted in 1964, discovered in 2012! 48 year hunting!

An effort by tens of thousands scientists and engineers from all over the world

ATLAS & CMS Observation



2013 Nobel Prize

François Englert and Peter Higgs

Huge impact to humanity

Technology
Cultural
International Collaboration

The next step for HEP was clear!

A Higgs factory

Steps Towards Reference Detector TDR

2015

IHEP-CEPC-DR-2015-01
IHEP-EP-2015-01
IHEP-TH-2015-01

CEPC-SPPC

Preliminary Conceptual Design Report

Volume I - Physics & Detector

Preliminary CDR

The CEPC-SPPC Study Group

March 2015

2018

IHEP-CEPC-DR-2018-02
IHEP-EP-2018-01
IHEP-TH-2018-01

CEPC

Conceptual Design Report

Volume II - Physics & Detector

CDR

The CEPC Study Group

October 2018

October 2025

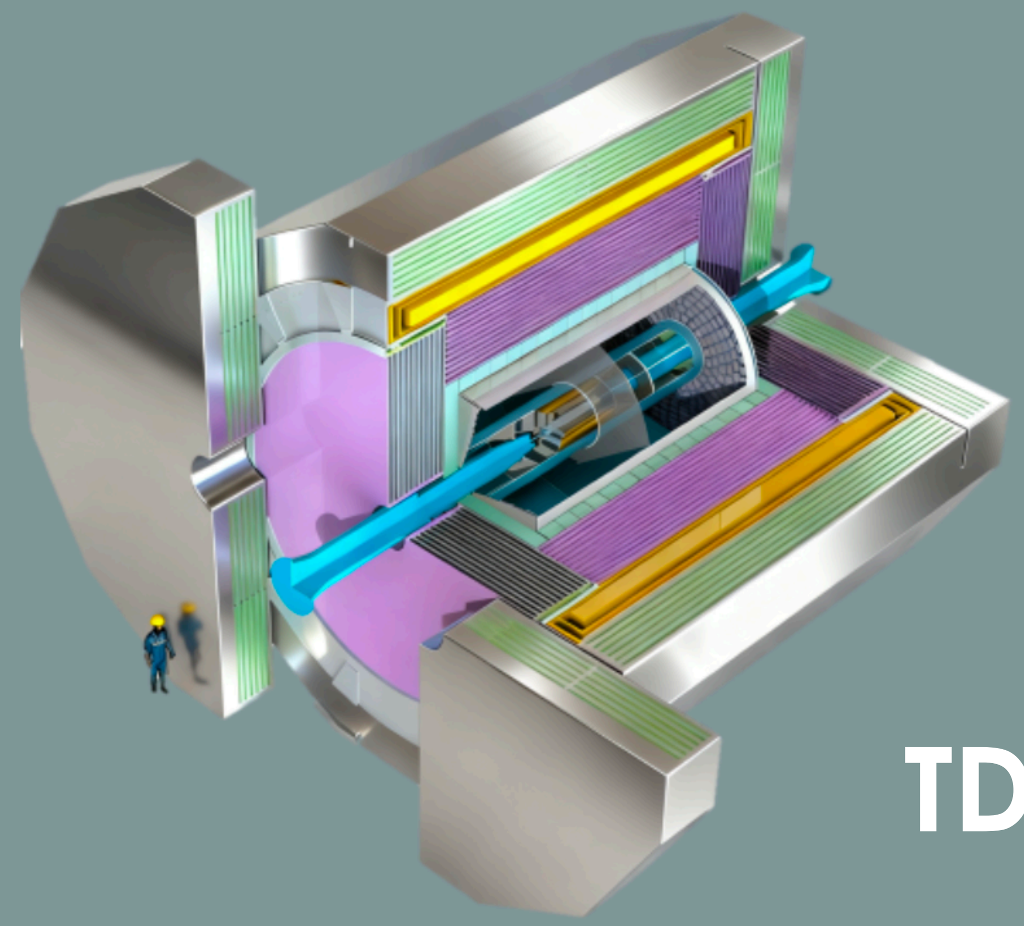
IHEP-CEPC-DR-2025-01
IHEP-EP-2025-01

CEPC Reference Detector

Technical Design Report

Version: v1.0.1 build: 2025-11-02 11:13:11+08:00

https://arxiv.org/abs/2510.05260



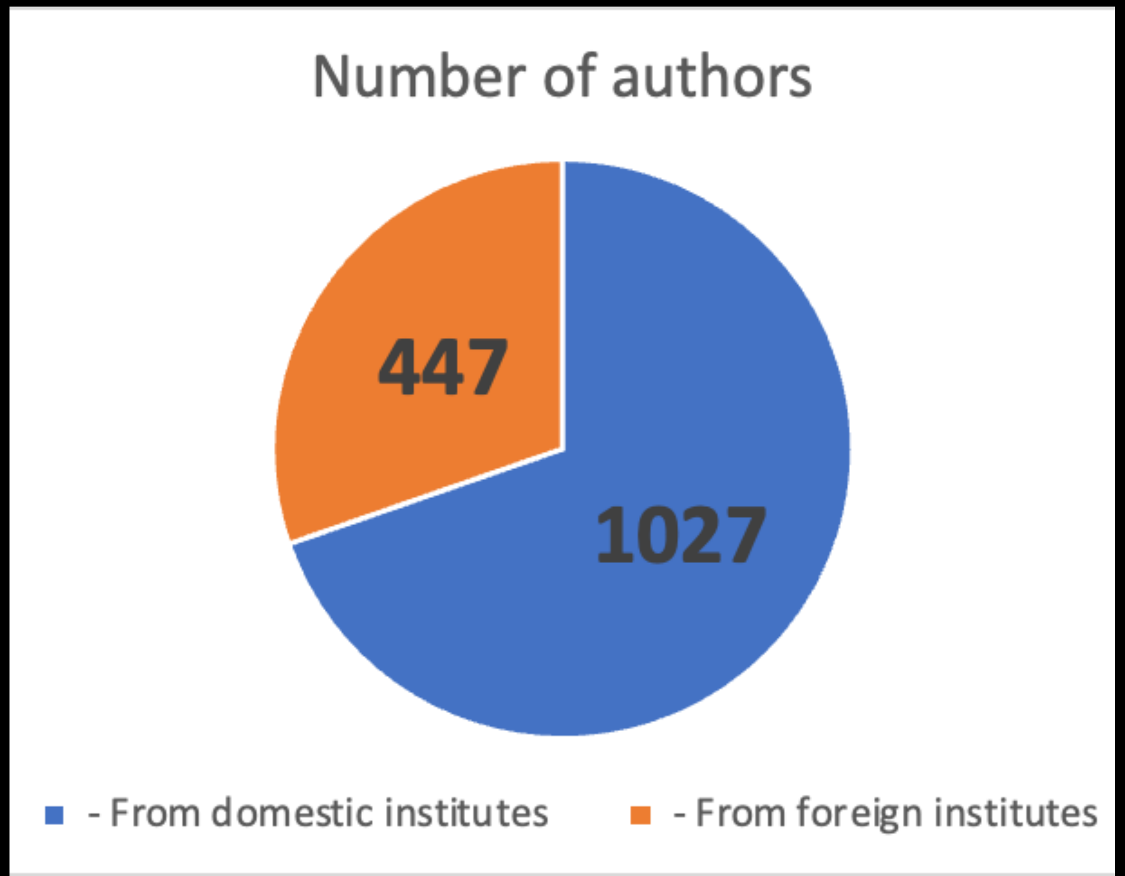
TDR

The CEPC Study Group
October, 2025

http://cepc.ihep.ac.cn

Reference Detector TDR Authorship

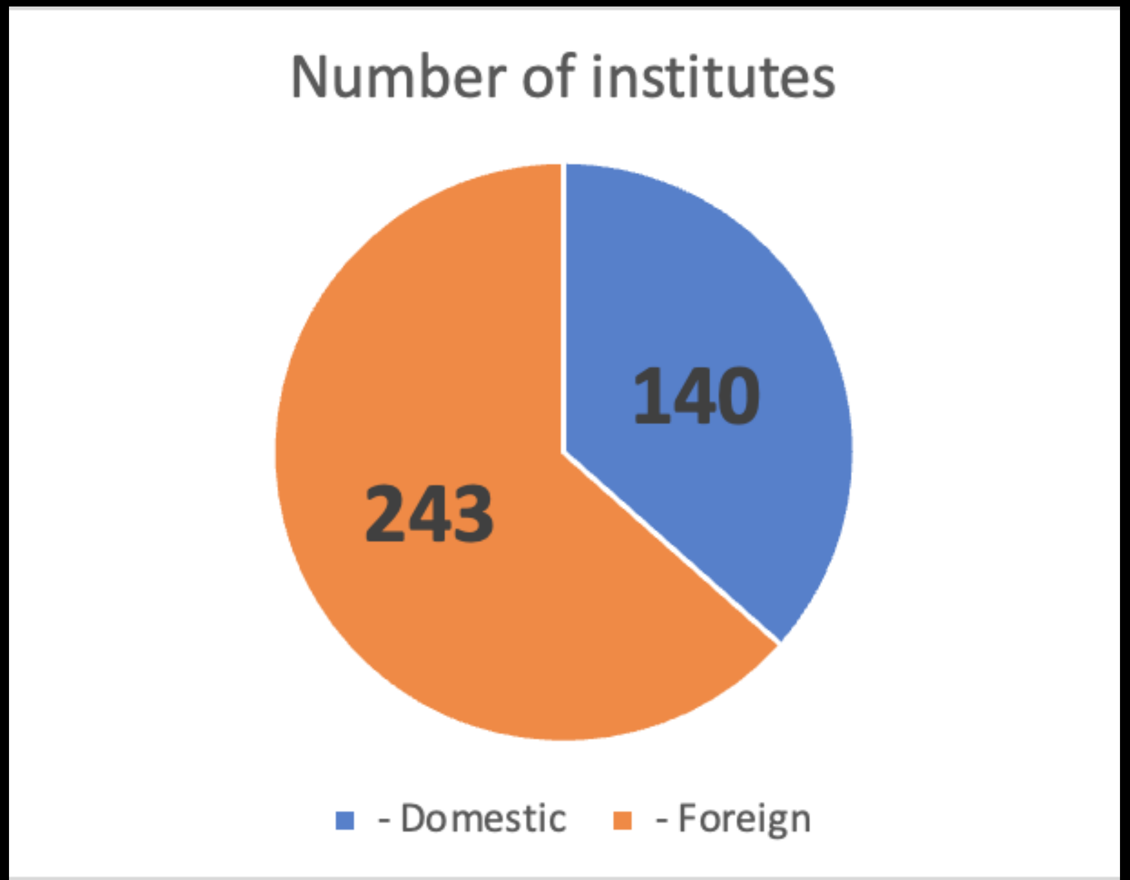
30% authors from foreign institutes

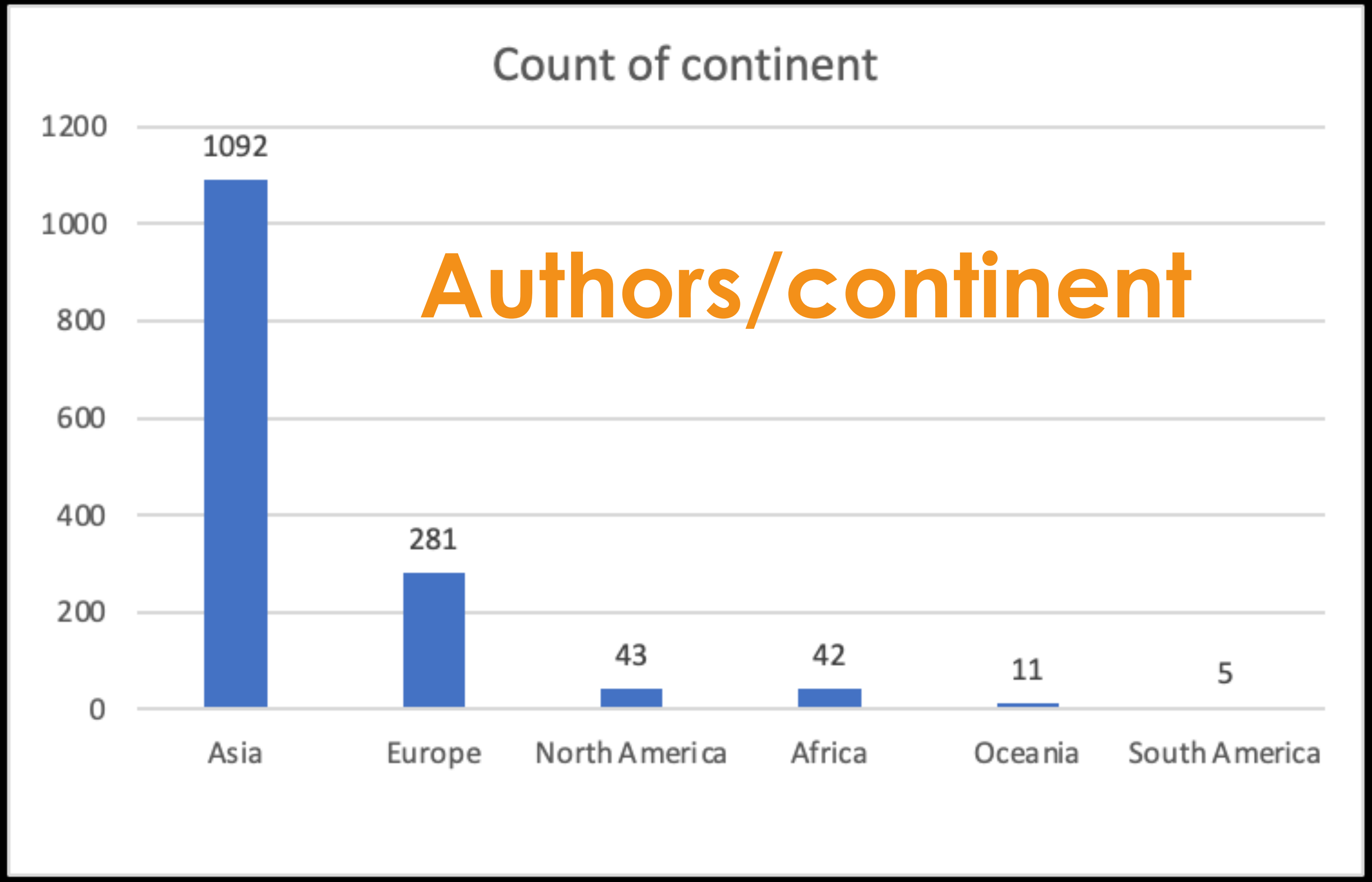


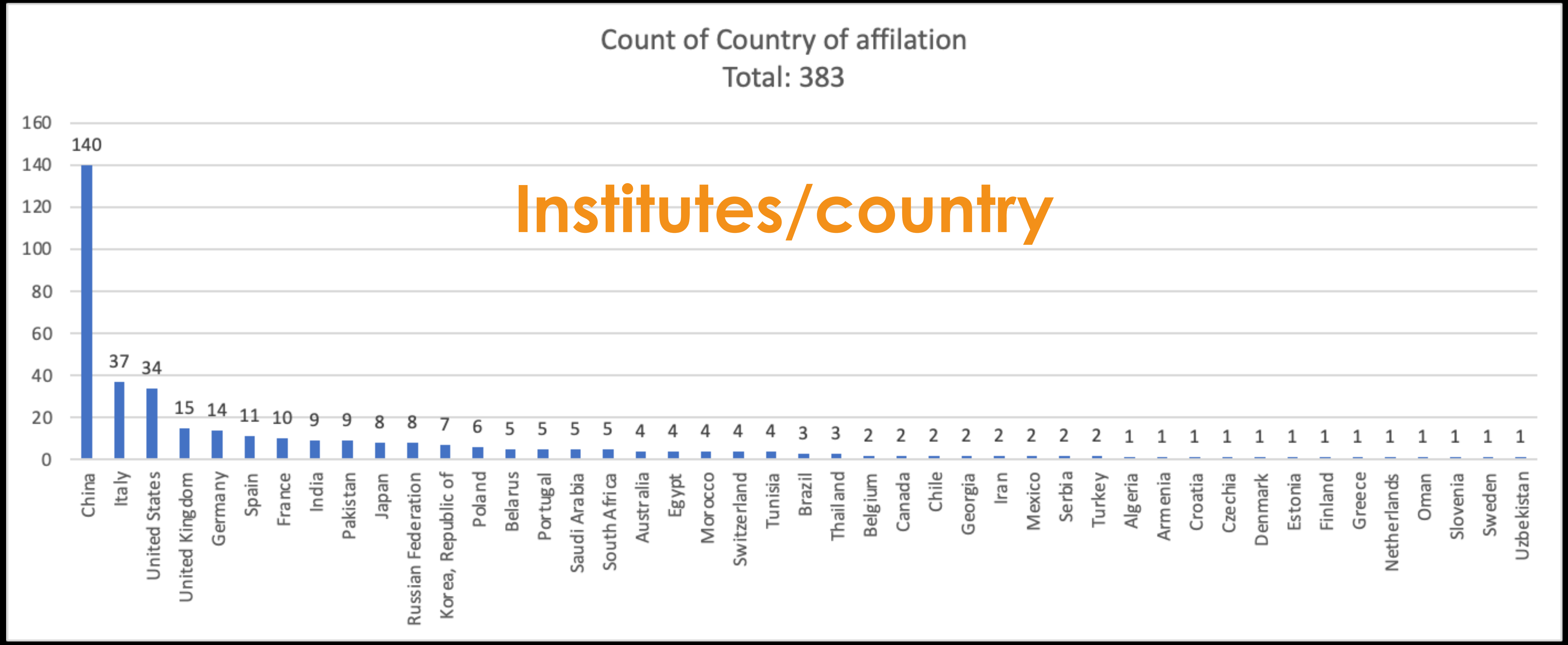
1474 authors { 383 institutions / 43 countries }

~30% increase relative to accelerator TDR and CDR

63% foreign institutes





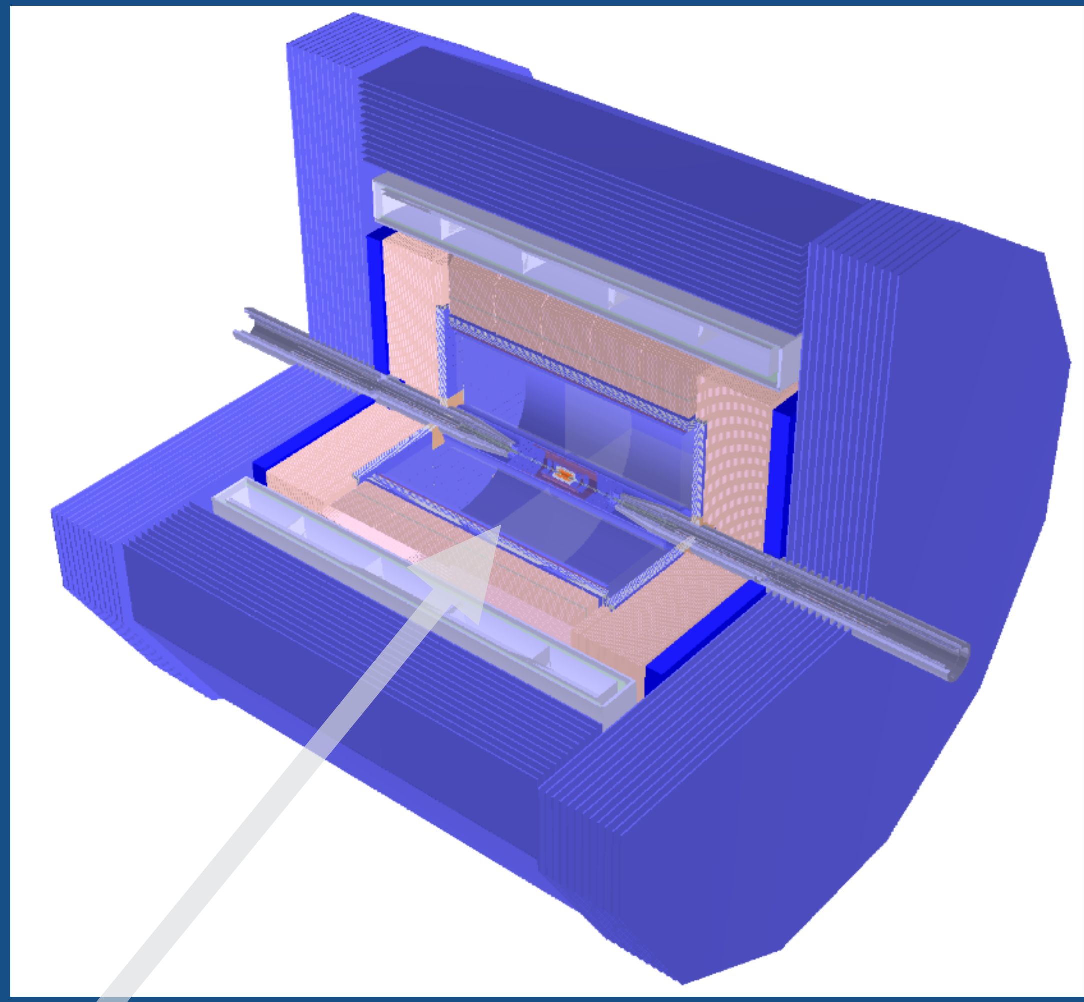


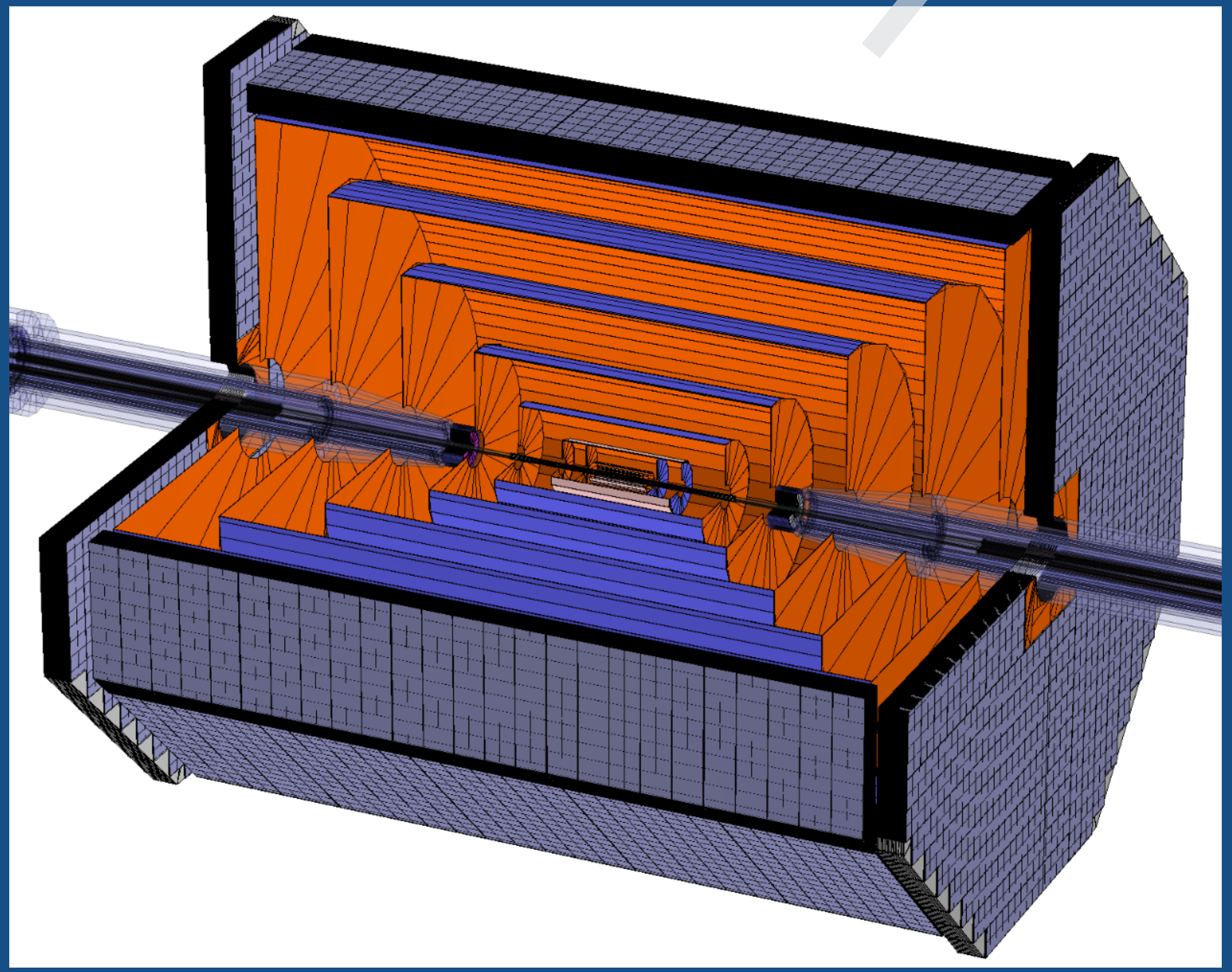
The Conceptual Detector Proposals at CDR

Particle Flow Approach

High magnetic field concept (3 Tesla)

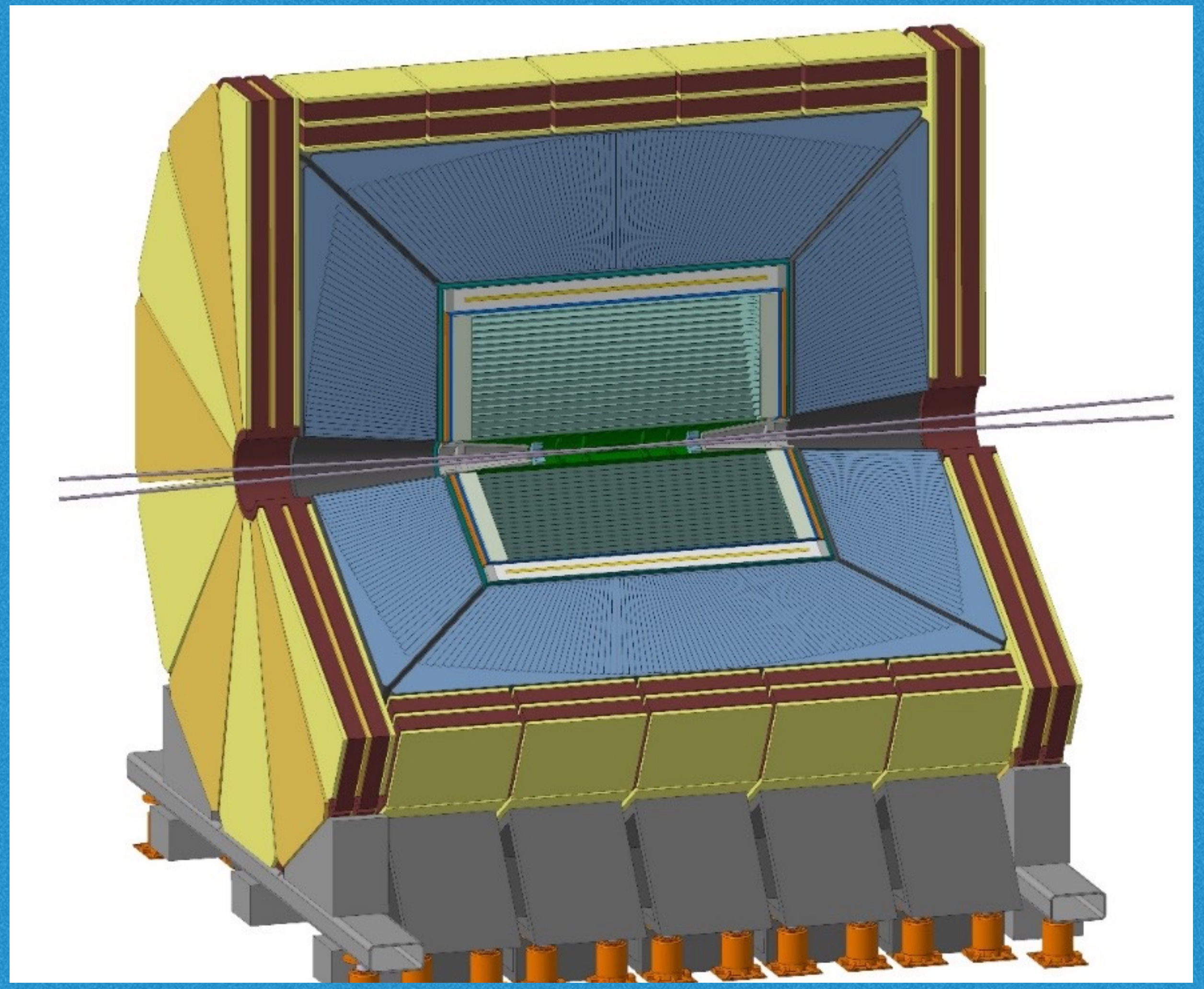
ILD-like





Full silicon tracker concept

Low magnetic field concept (2 Tesla)



IDEA Concept

also proposed for FCC-ee

Promised at the time:

Final two detectors WILL be a mix and match of different options

CEPC Ultimate Accelerator EDR Design Parameters

Main Parameters: High luminosity - (upgrade version - 50 MW)

	Higgs	W	Z	ttbar
Number of IPs	2			
Circumference [km]	100.0			
SR power per beam [MW]	**50**			
Energy [GeV]	**120**	**80**	**45.5**	**180**
Bunch number	415	2161	19918	59
Emittance (εx/εy) [nm/pm]	0.64/1.3	0.87/1.7	0.27/1.4	1.4/4.7
Beam size at IP (σx/σy) [um/nm]	15/36	13/42	6/35	39/113
Bunch length (SR/total) [mm]	2.3/3.9	2.5/4.9	2.5/8.7	2.2/2.9
Beam-beam parameters (ξx/ξy)	0.015/0.11	0.012/0.113	0.004/0.127	0.071/0.1
RF frequency [MHz]	650			
Luminosity per IP[10^{34}/cm^2/s]	**8.3**	**27**	**192**	**0.83**

Increase relative to CDR: x 2.8 x 2.7 x 6

Reference Detector TDR: Context and Framework

CEPC Upgraded Scenario → **Ultimate Goal**: When resources from international sources are identified

Operation mode	$\sqrt{s}$ (GeV)	SR power (MW)	$\mathcal{L}$ (10^{34} cm^{-2}s^{-1})	$\int \mathcal{L}$/year (ab^{-1}, 2 IPs)	Years	Total $\int \mathcal{L}$ (ab^{-1}, 2 IPs)	Event yields
H	240	50	8.3	2.2	10	21.6	4.3×10^6
Z	91	50	192(*)	50	2	100	4.1×10^{12}
W^+W^-	155-170	50	26.7	6.9	1	6.9	5.5×10^7
$t\bar{t}$	360	50	0.8	0.2	5	1.0	0.6×10^6

Synchrotron radiation power at 50 MW

The Physics Goals — Shopping List

Precision tests of Standard Model (Higgs, W and Z) → **Potential to find new physics**

Higgs boson and electroweak symmetry breaking

Directly exploring new physics

- Exotic Higgs boson decays
- Exotics Z boson decays
- Dark matter and hidden sectors
- Extended Higgs sector

QCD precision measurements

- Precision α_S determination
- Jet rates at CEPC
- QCD dynamics, soft QCD effects
- QCD event shapes and light-quark Yukawa couplings

Flavor physics at the *Z* pole

- Rare B decays
- Tau lepton decays
- Flavor violating *Z* decays

Reference Detector TDR: Context and Framework

CEPC

CEPC Baseline Operation Scenario

Operation mode	$\sqrt{s}$ (GeV)	SR power (MW)	$\mathcal{L}$ (10^{34} cm^{-2}s^{-1})	$\int \mathcal{L}$/year (ab^{-1})	Years	Total $\int \mathcal{L}$ (ab^{-1})	Event yields
H	240	30	5	0.65	15	10	2.0×10^6
Z	91	12.1	26(*)	3.2	4	13	5.6×10^{11}
W^+W^-	155-170	30	16	1.2	1	1.2	1.0×10^7(†)

Main goal of CEPC Reference Detector TDR

Demonstrate readiness for construction of detector for baseline scenario

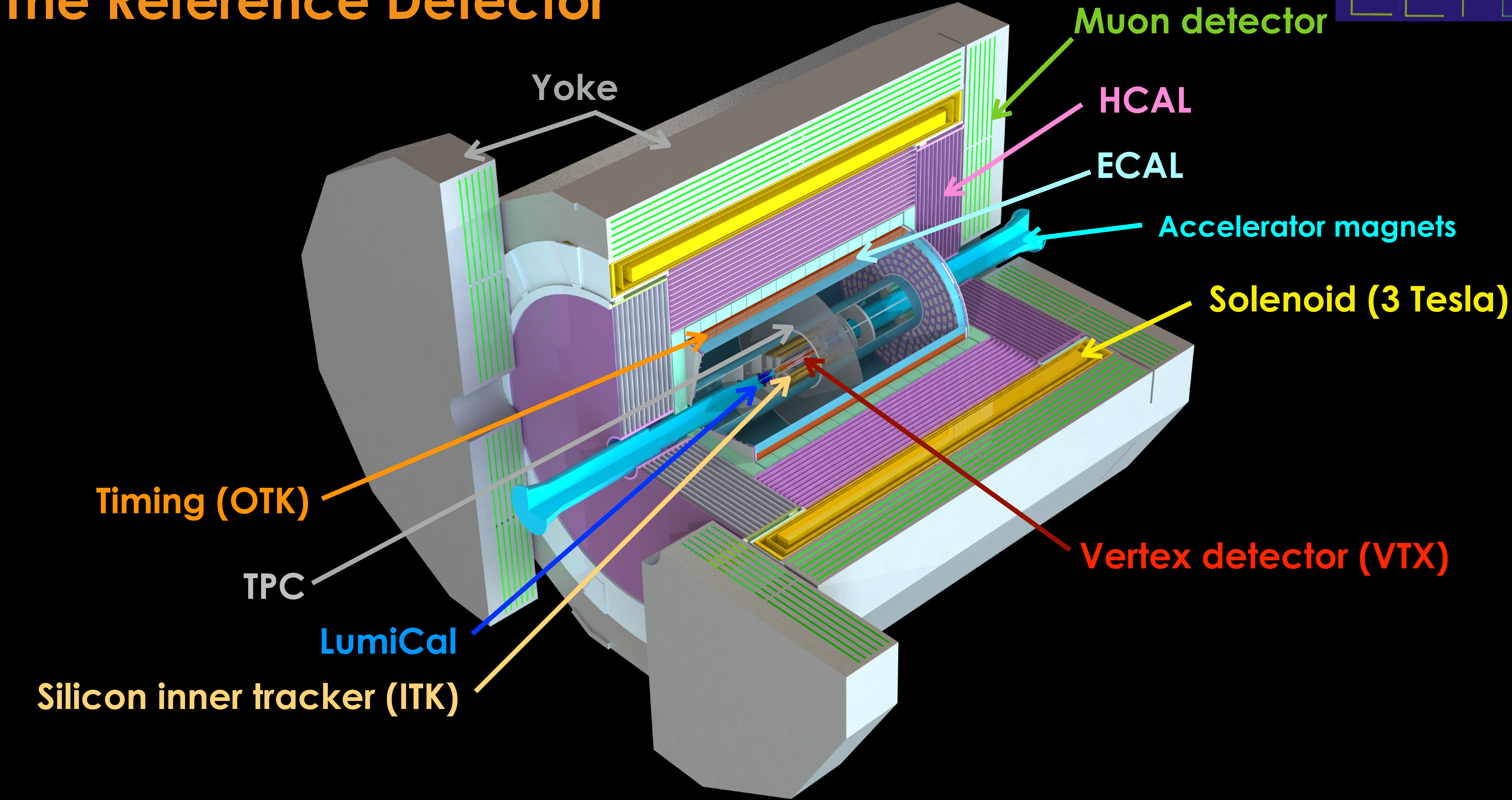
A detector that could be constructed and commissioned within a decade

After CEPC project approval:

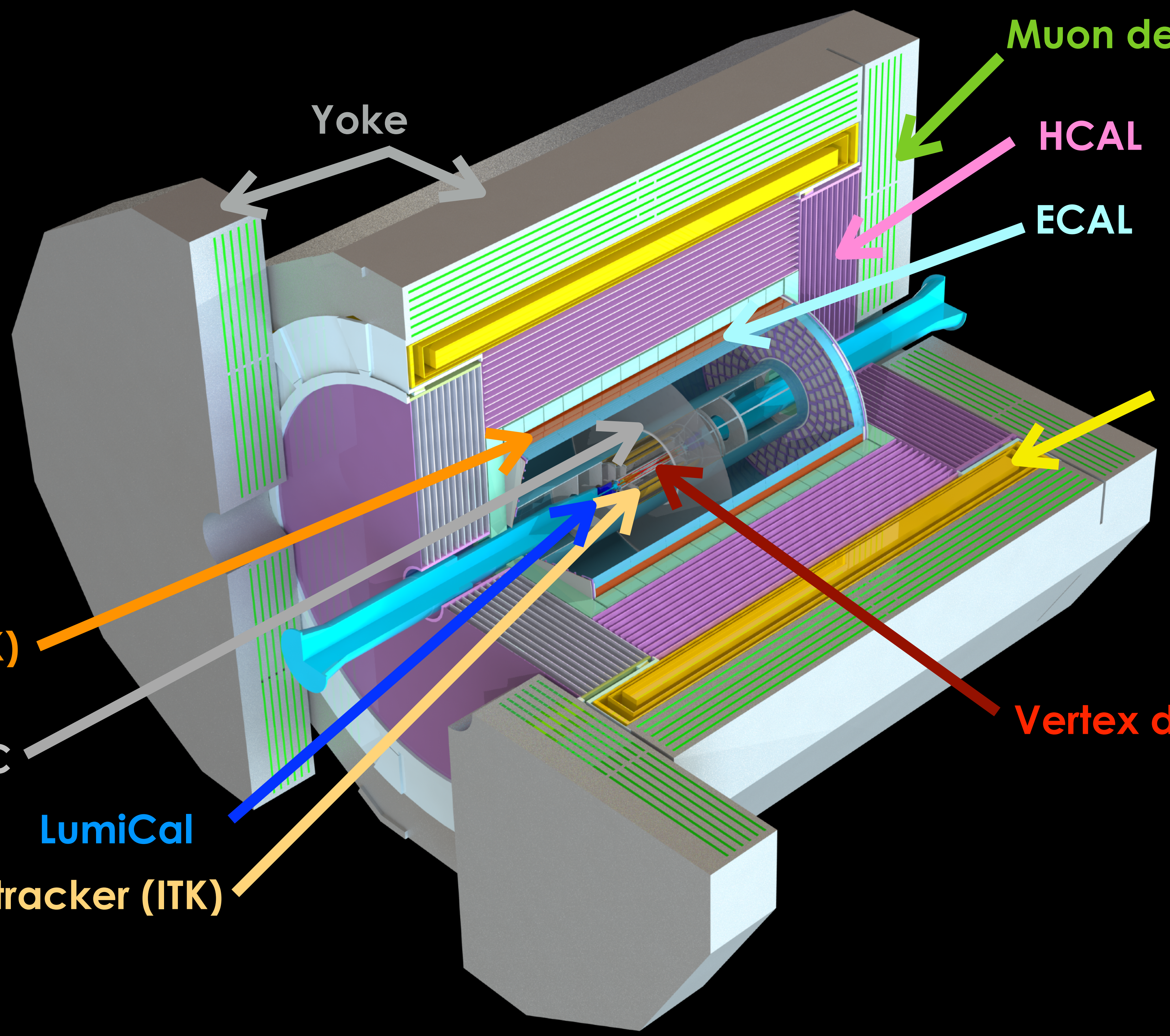
1) Two CEPC detectors will be selected among international proposals

2) International Collaborations will lead those detector designs and produce corresponding TDRs adapted to the final operational scenarios

The Reference Detector



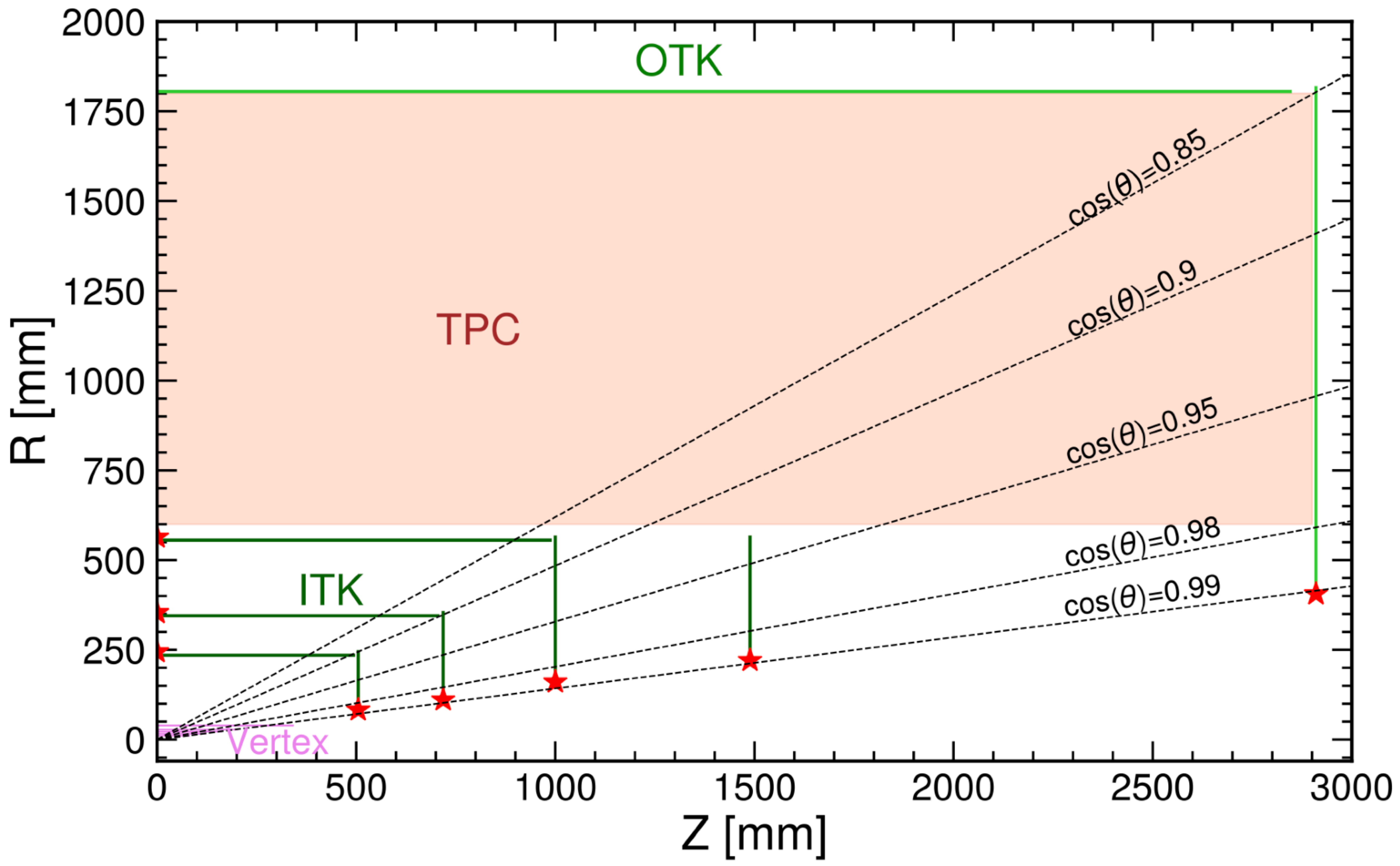
The Reference Detector

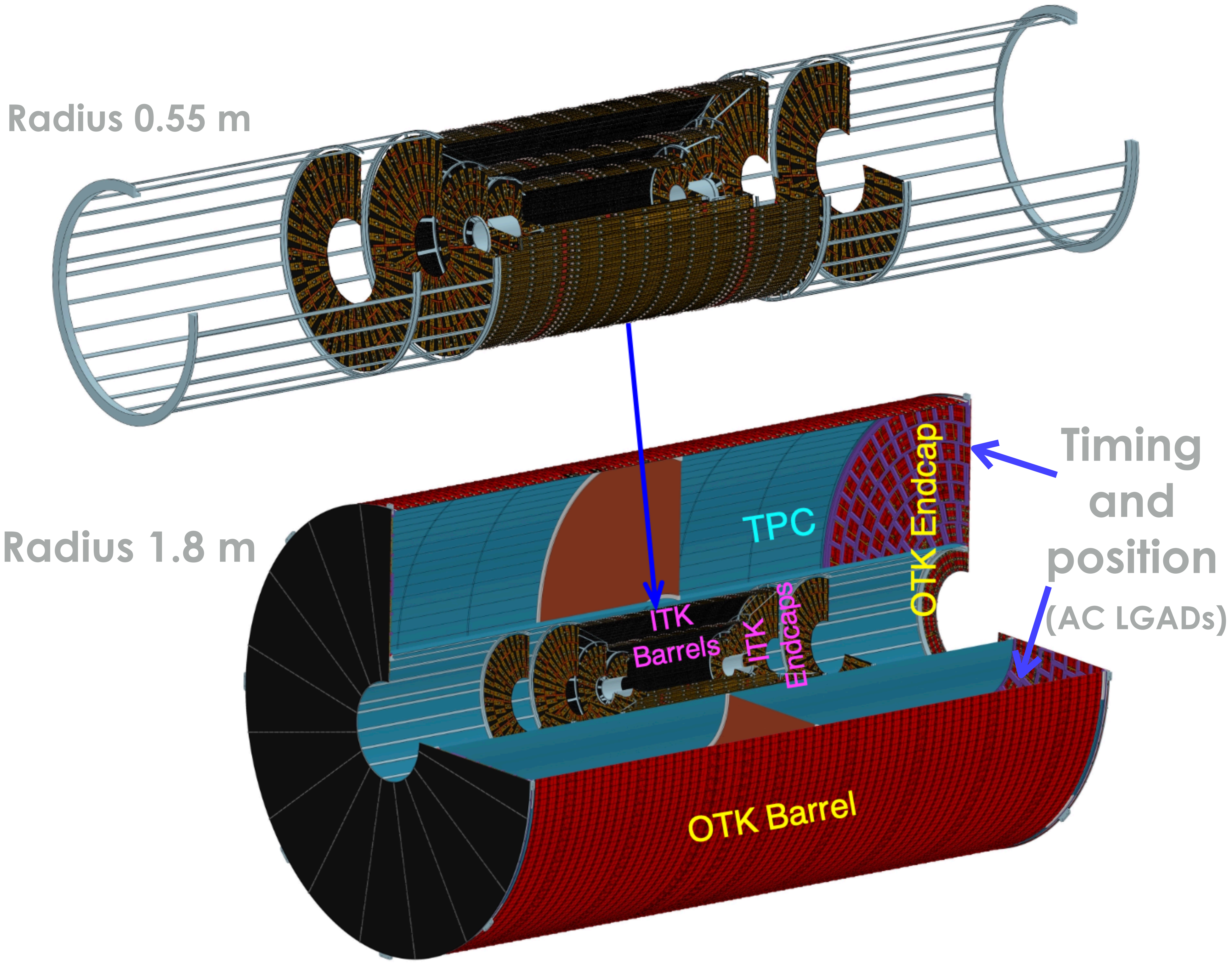


Sub-system	Technologies
Beam pipe	Beryllium, ϕ 20 mm
LumiCal	Silicon tracker + LYSO crystals
Vertex	Si Pixels: CMOS MAPS+stitching
Inner tracker (ITK)	Si Pixels: CMOS MAPS 55-nm
Gas detector	TPC with high granularity
Outer tracker (OTK)	AC-LGAD → TOF
ECAL	4D transverse crystal bars
HCal	Glass scintillator, SiPM + Fe
Magnet	LTS Solenoid
Muon	Plastic scintillator bars, SiPM
TDAQ	Conventional
Back-end electronics	Common

The Tracking System

Silicon tracker inside a Time Projection Chamber (TPC) with a timing layer outside



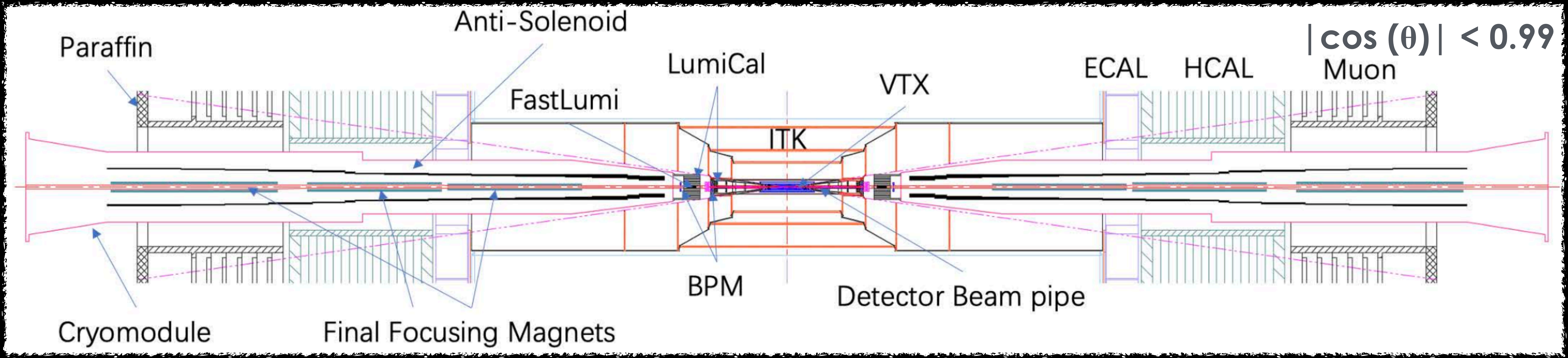


Measurands	**Performance requirement**
Coverage	$\lvert\cos\theta\rvert \leq 0.99$
Recon. efficiency	$\geq 99\%$ ($p_T > 1$ GeV/c)
Resolution in barrel	$\sigma_{p_T}/p_T < 0.3\%$ ($\lvert\cos\theta\rvert \leq 0.85$)
Resolution in endcap	$\sigma_{p_T}/p_T < 3\%$ ($\lvert\cos\theta\rvert > 0.85$)

Interaction Region: Machine Detector Interface

Likely the most challenging component of the project

Critical to deliver the maximum luminosity without affecting detector performance



Accelerator magnets
well inside the detector volume

Beryllium beam pipe ϕ_{out} = 20 mm
Two walls: 0.15 - 0.2 mm thick
Water coolant

Vertex detector mounted around the beam pipe

The Vertex Detector

Physics Requirements

Parameter	Requirement
Single-point resolution per layer	≤ 5 µm
Detector material budget	$\leq 0.9\%\ X_0$
Angular coverage	$\lvert\cos\theta\rvert < 0.99$
Beam pipe material budget	$< 0.5\%\ X_0$
Detector occupancy	$< 1\%$

Design Parameters

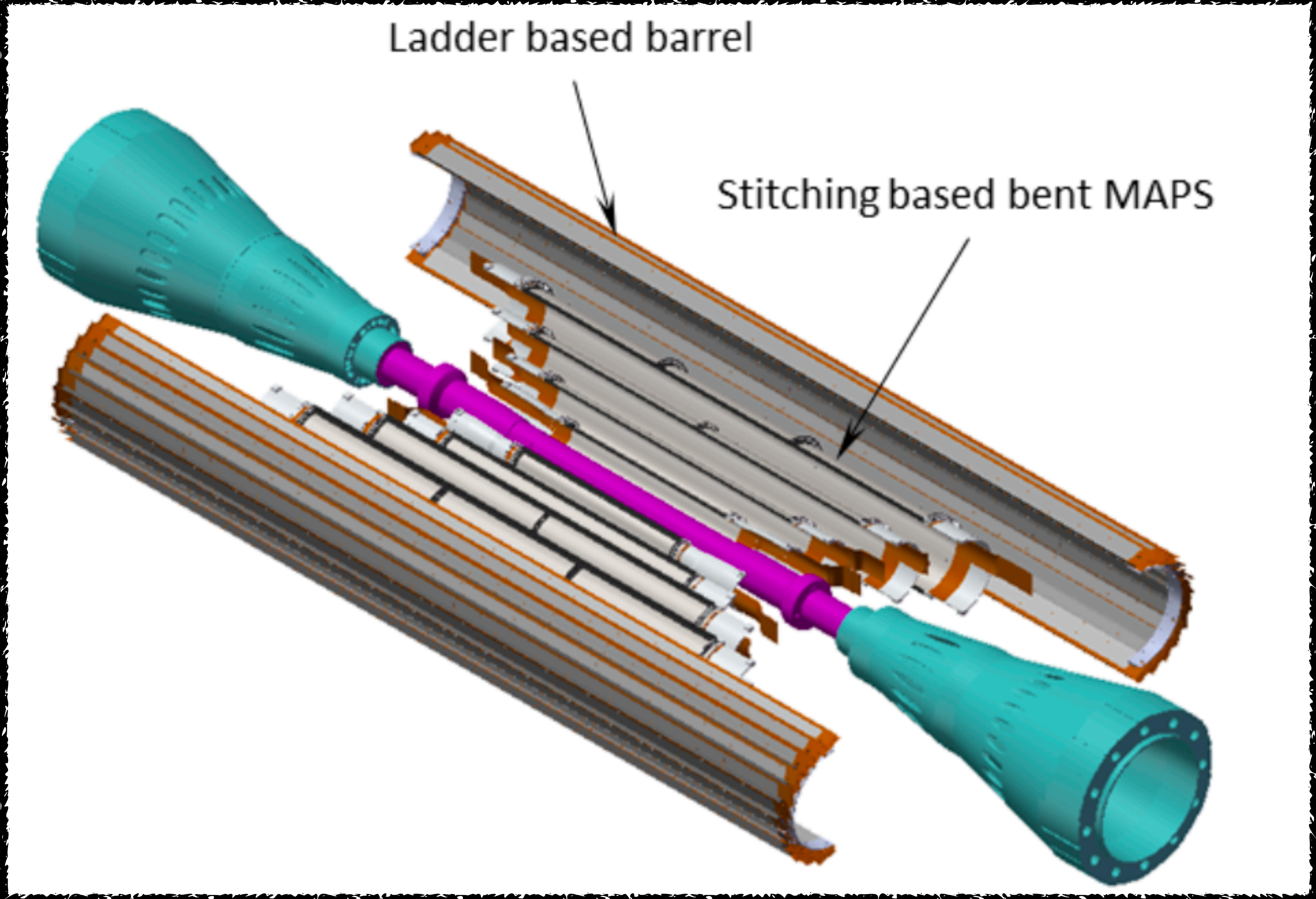
Parameter	Design
Spatial Resolution	~ 5 µm
Detector material budget	$\sim 0.8\%\ X_0$
First layer radius	11.1 mm
Power Consumption	< 40 mW/cm^2 (air cooling requirement)
Time stamp precision	100 ns
Fluence	$\sim 2 \times 10^{14}$ Neq/cm^2
Operation temperature	~ 5 °C to 30 °C
Readout electronics	Fast, low-noise, low-power
Mechanical Support	Ultralight structures
Angular Coverage	$\lvert\cos\theta\rvert < 0.99$

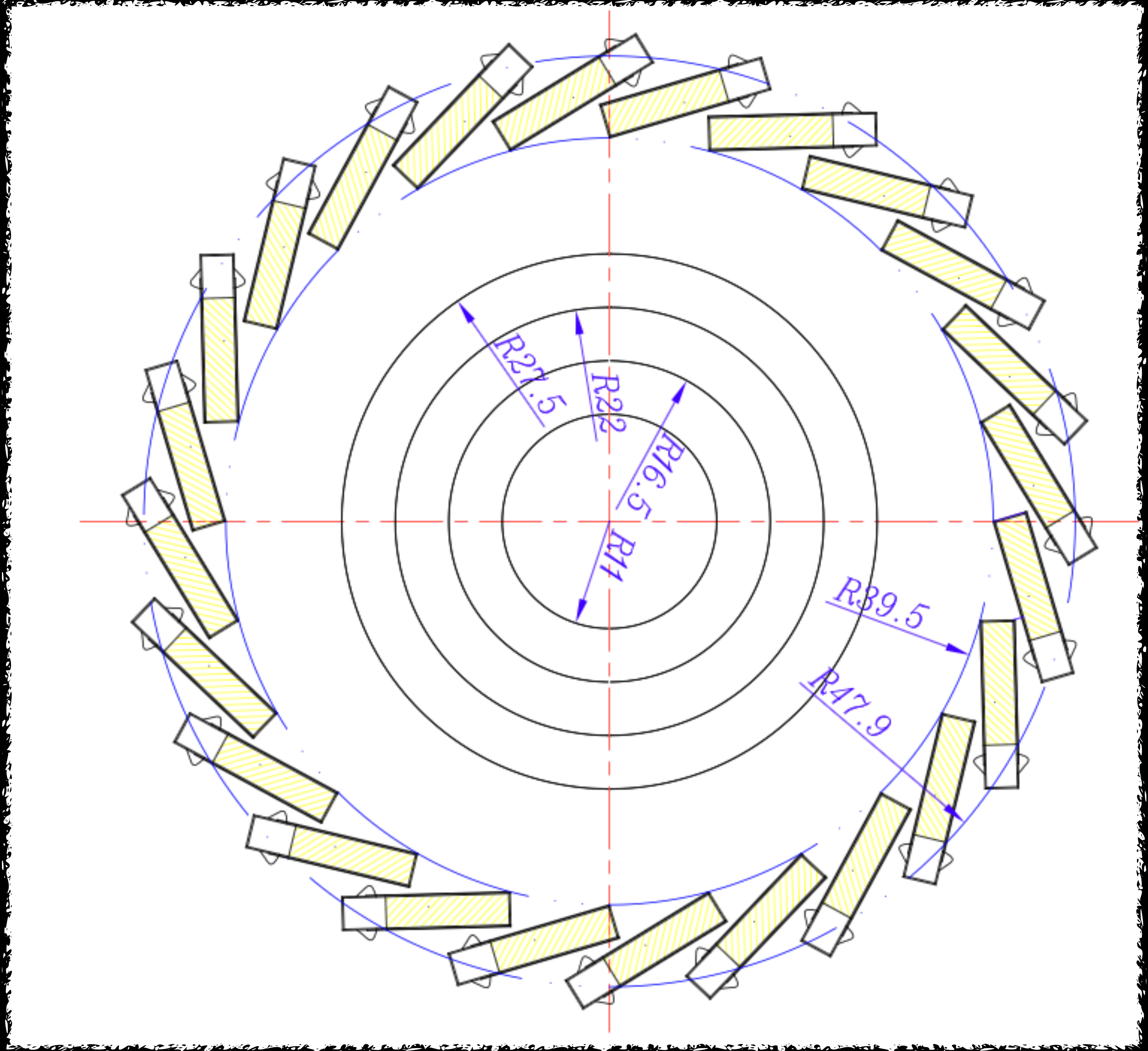
The Vertex Detector

Four single layers of bent MAPS stitched sensors

+

Two double-sided conventional ladders

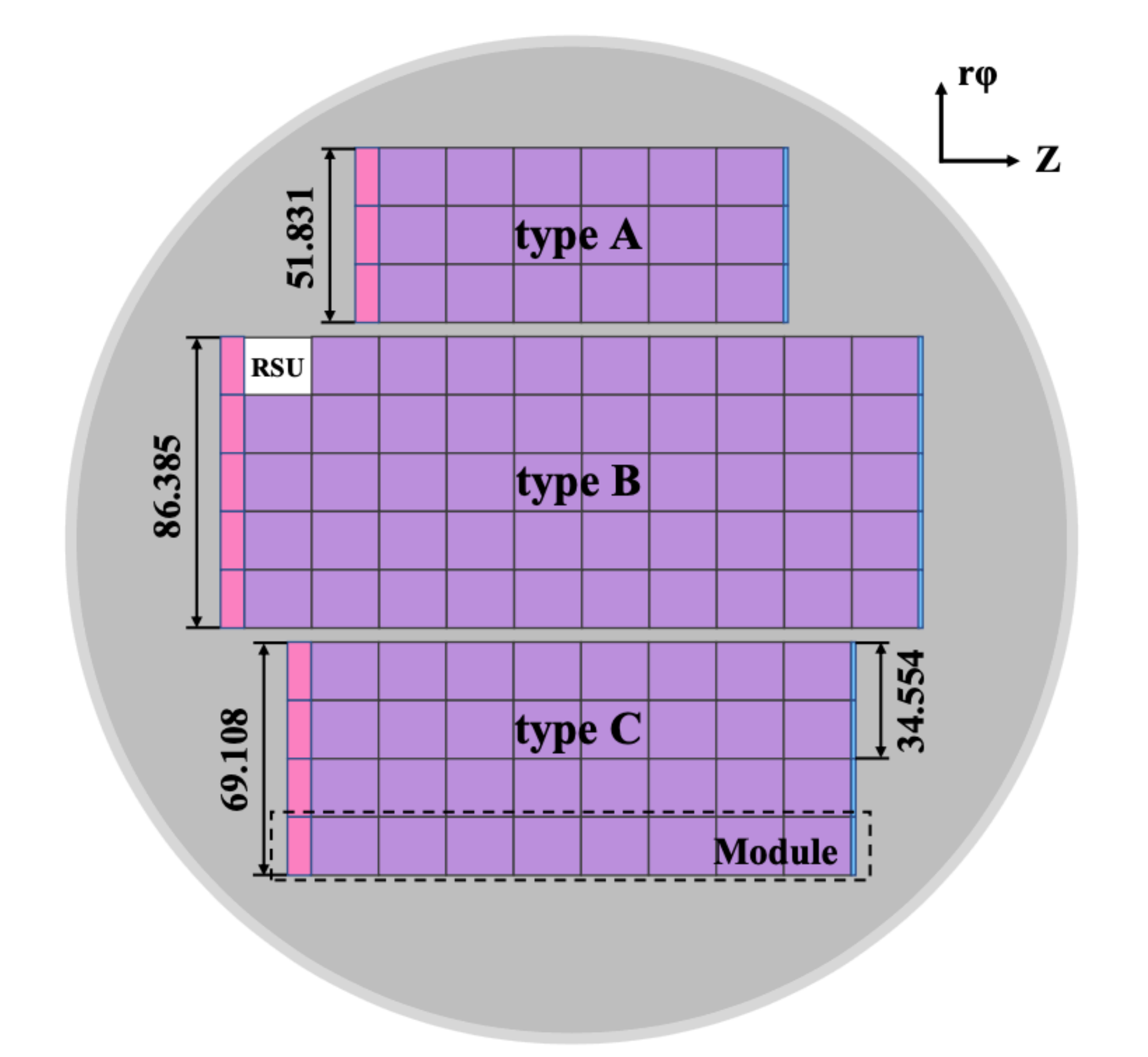


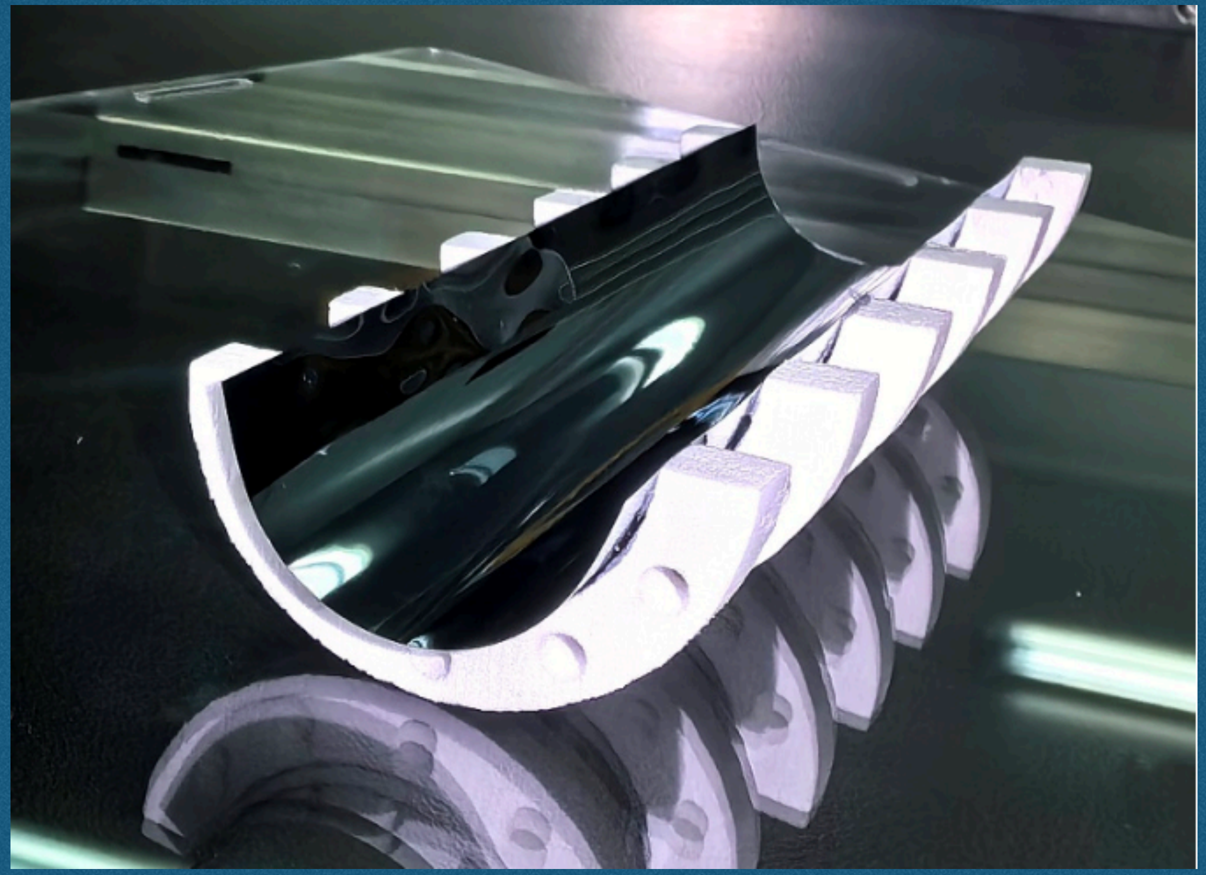


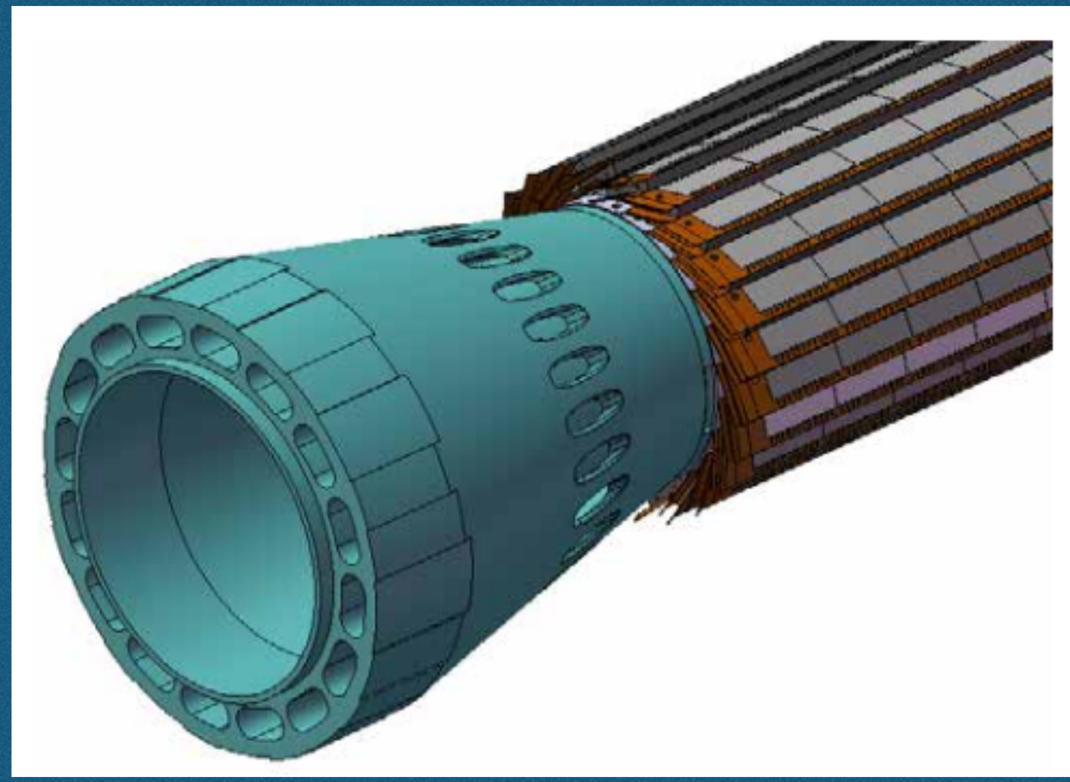
Sitting on top of beam pipe: inner layer radius 11.1 mm

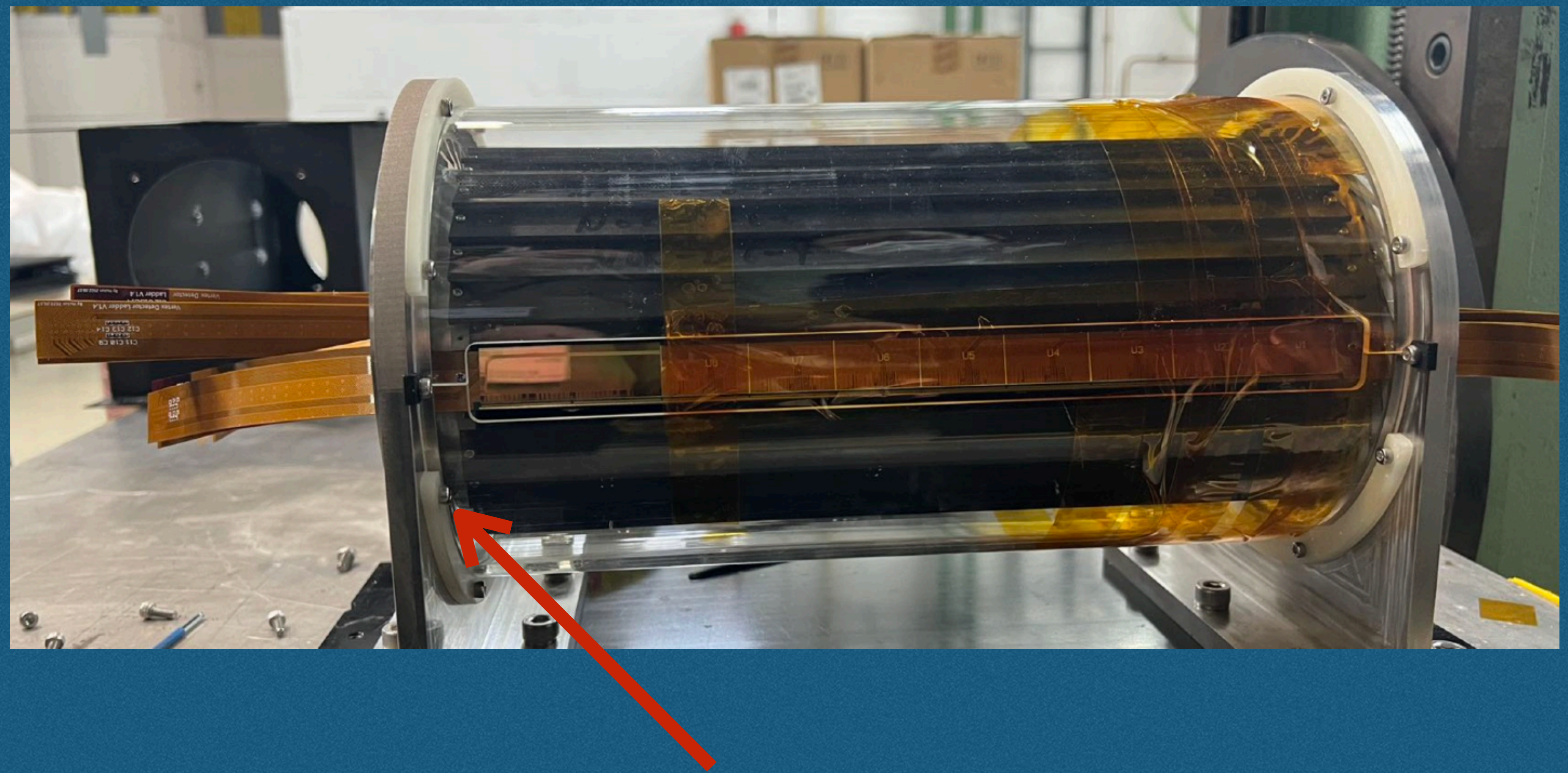
The Vertex Detector

Unit	Beam pipe	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6
$\bar{X}_0$ (X_0)	0.454%	0.067%	0.059%	0.058%	0.061%	0.280%	0.280%







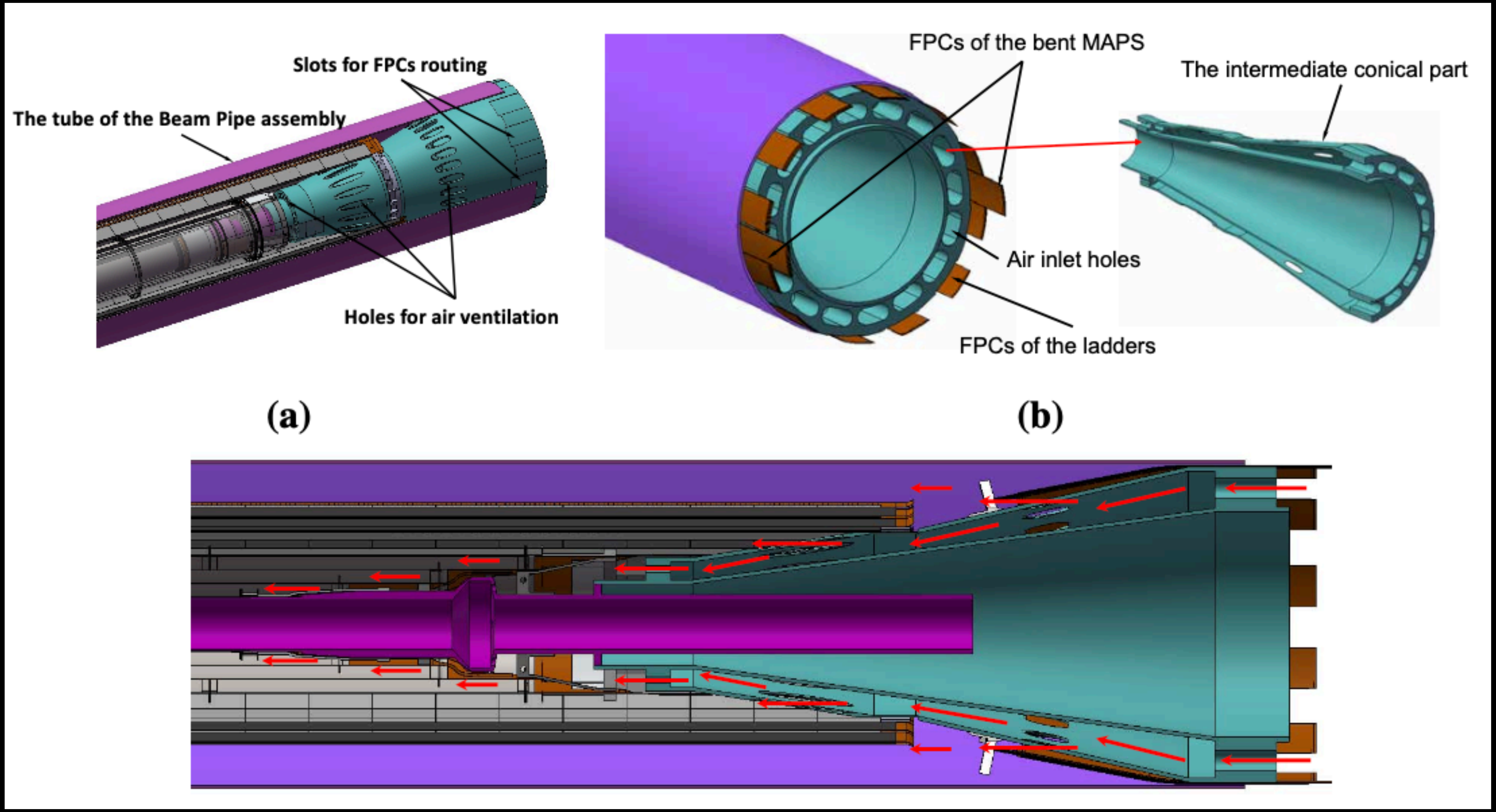


Prototype of standard vertex (no bent layers)

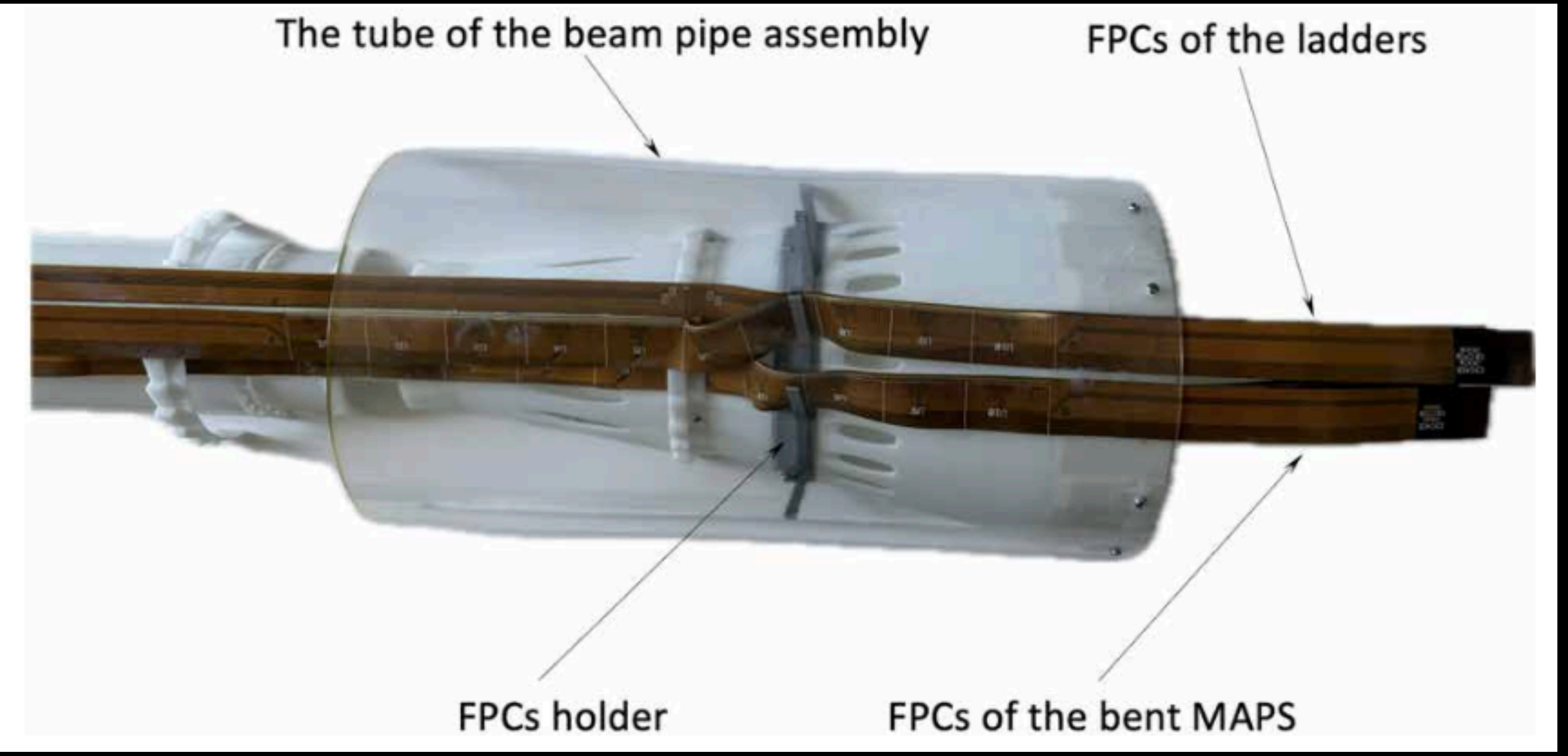
Technology: Tower Partners Semiconductor Co. (TPSCo) 65 nm MAPS

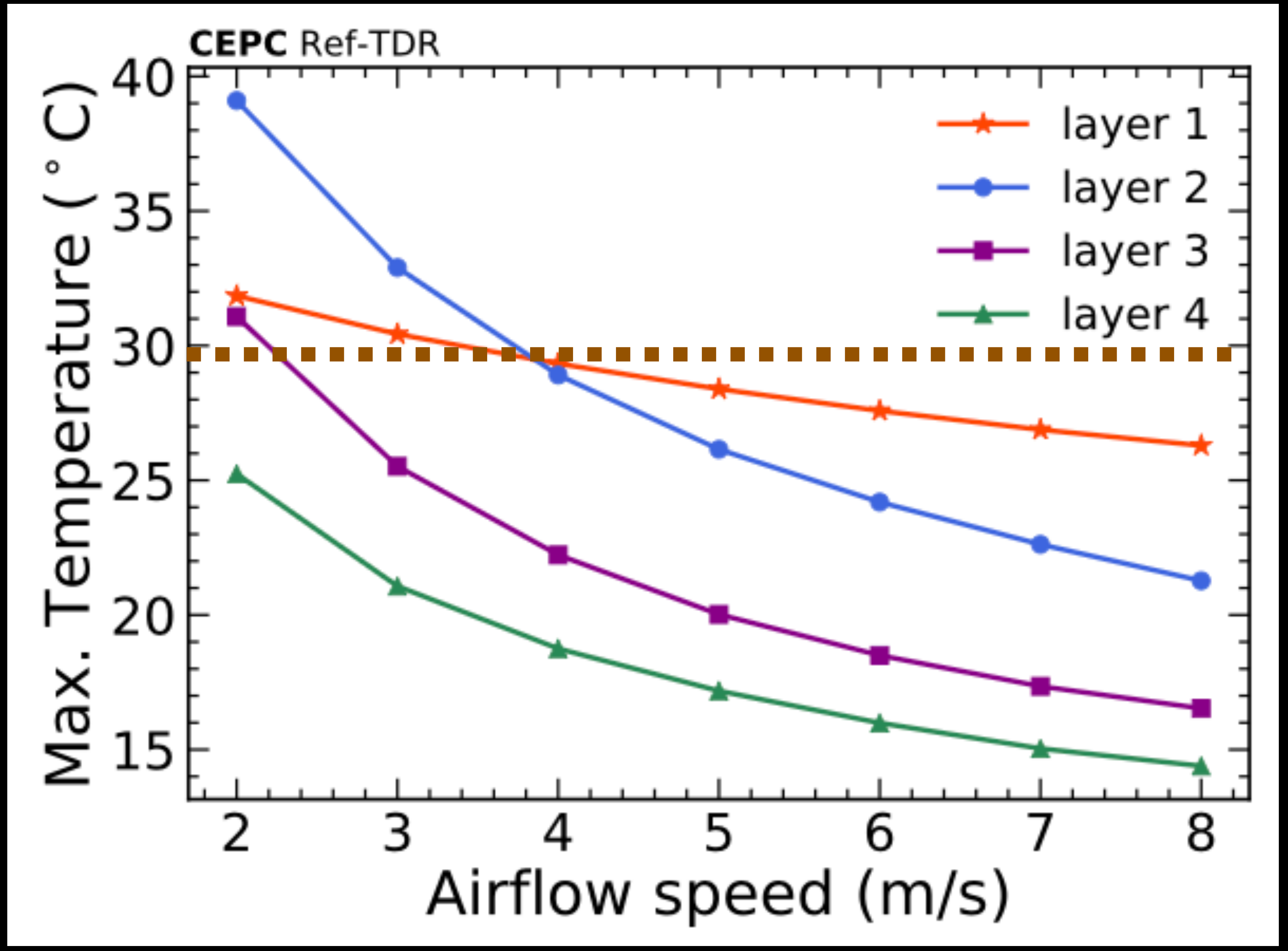
Alternative: Huali Microelectronics Corporation (HLMC) 55 nm MAPS

The Vertex Detector: Mechanics and Cooling



Dummy mock-up





- Airflow speed of 7 m/s, equivalent to a total flow rate of 3500 L/min
- Required to keep temperature safely below 30 °C

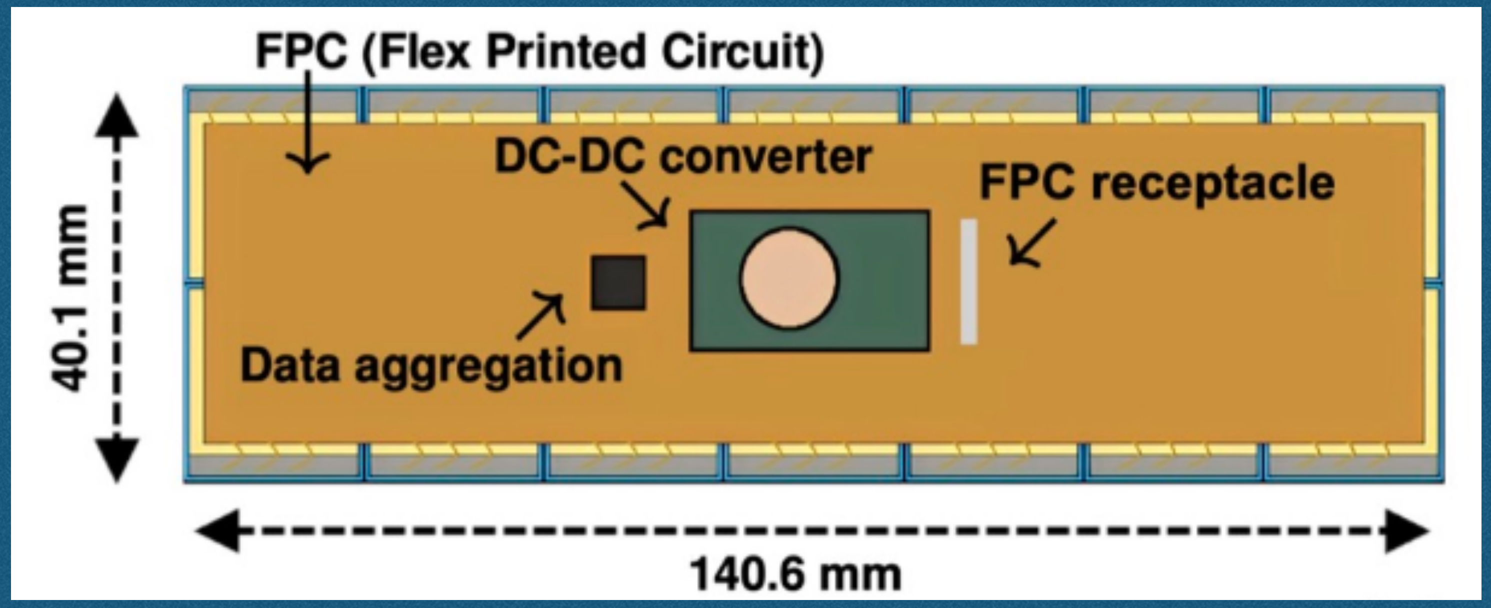
The Inner Silicon Tracker (ITK)

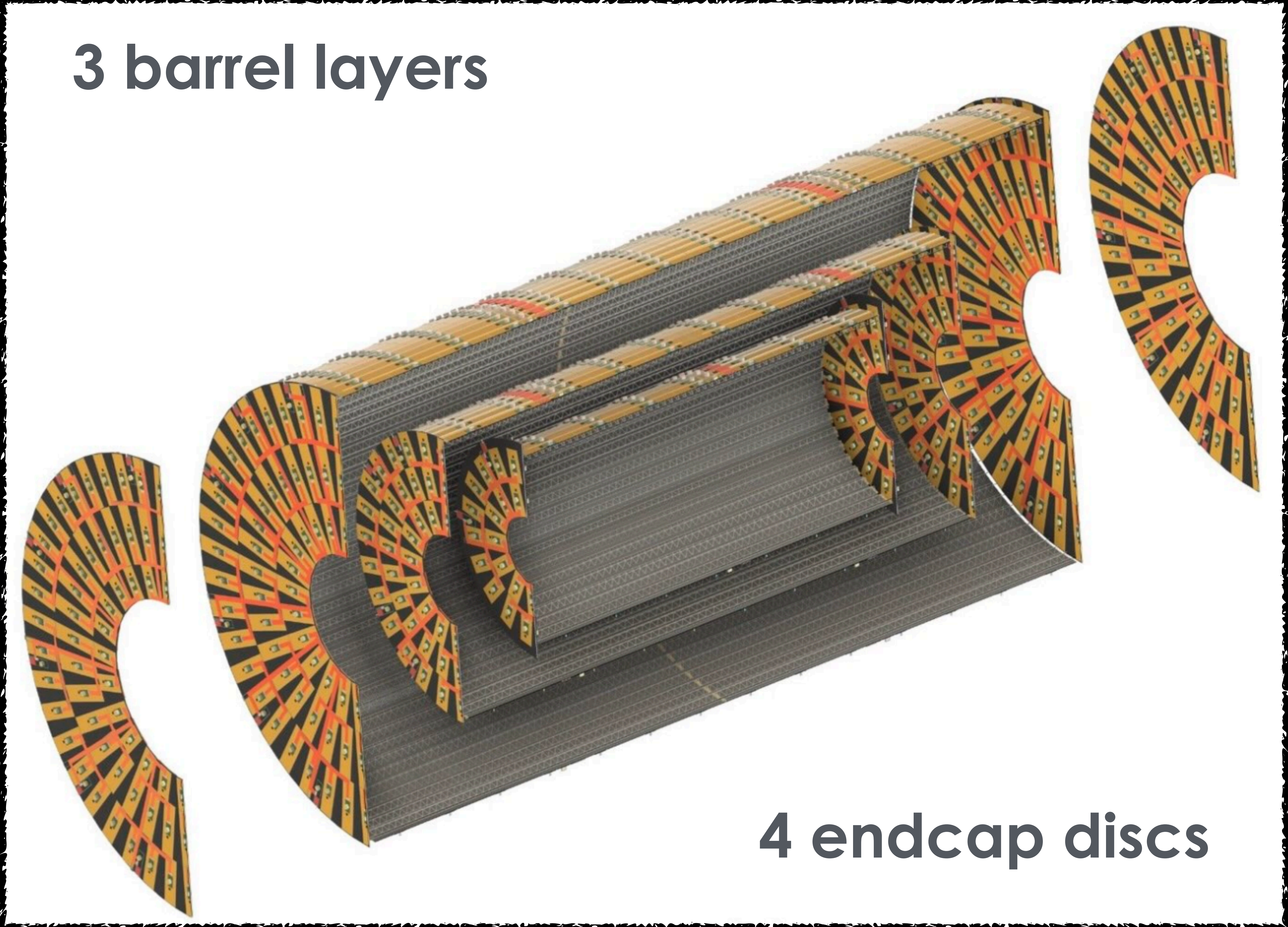
Monolithic HV-CMOS pixel sensors fabricated using a 55 nm CMOS process

Sensor key parameters

Parameter	Value
Sensor size	2 cm × 2 cm (active area: 1.74 cm × 1.92 cm)
Sensor thickness	150 µm
Array size	512 × 128
Pixel size	34 µm × 150 µm
Spatial resolution	8 µm × 40 µm
Time resolution	3–5 ns
Power consumption	200 mW/cm^2
Technology node	55 nm

Module with 14 sensors

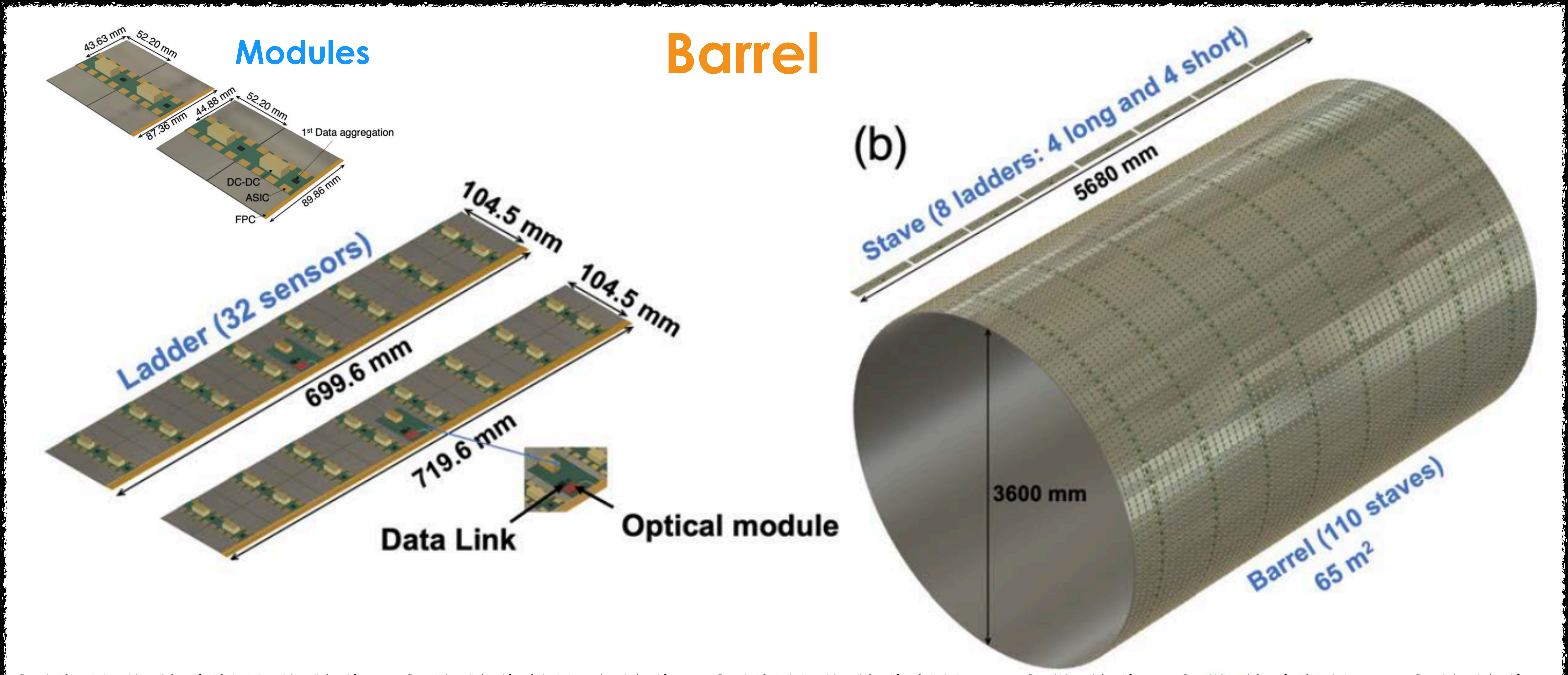




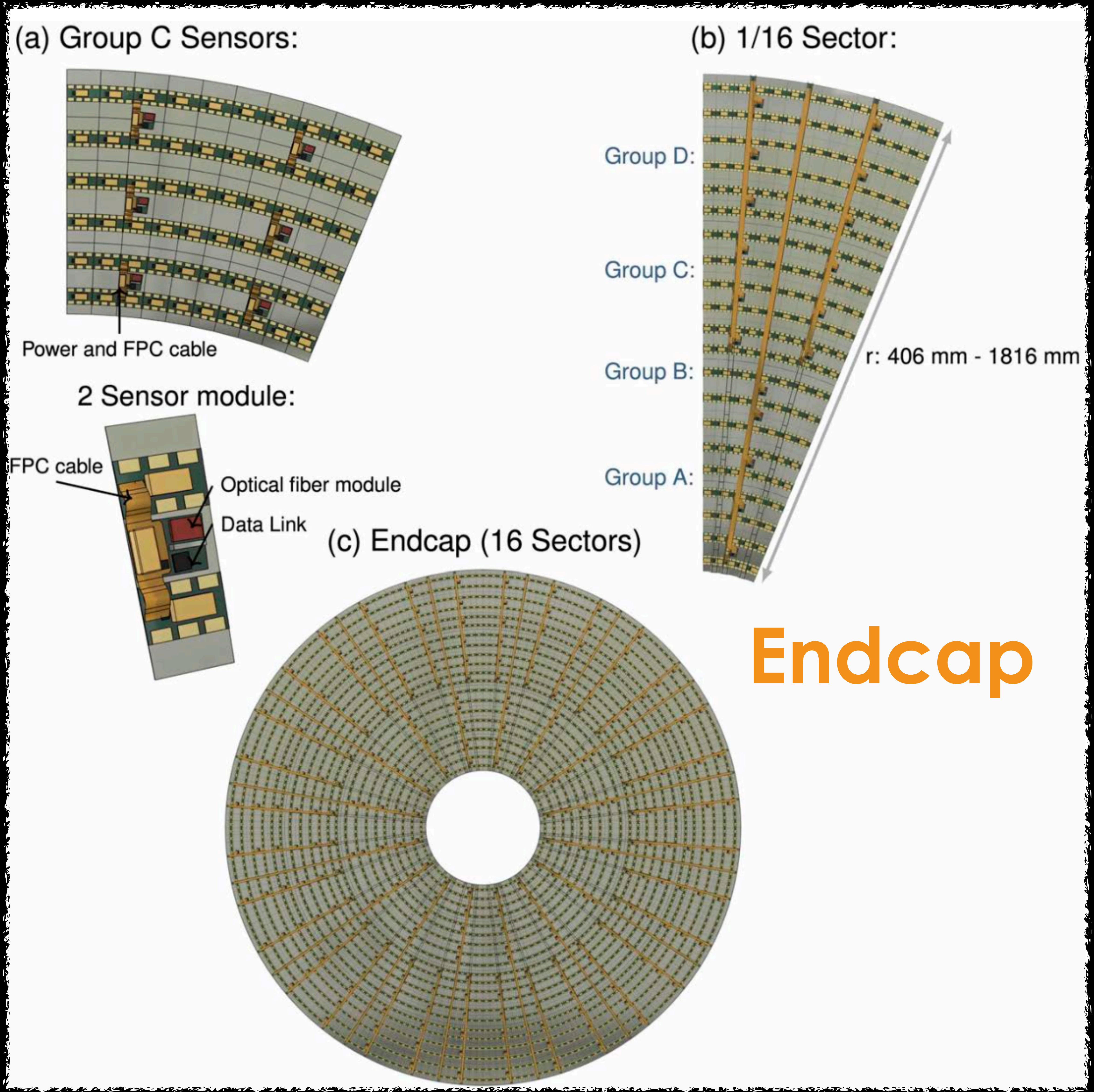
The Outer Tracker (OTK)

Designed to provide a spatial resolution of ~10 μm and a time resolution of ~50 ps

Using microstrip AC-LGAD technology to cover ~85 m^2

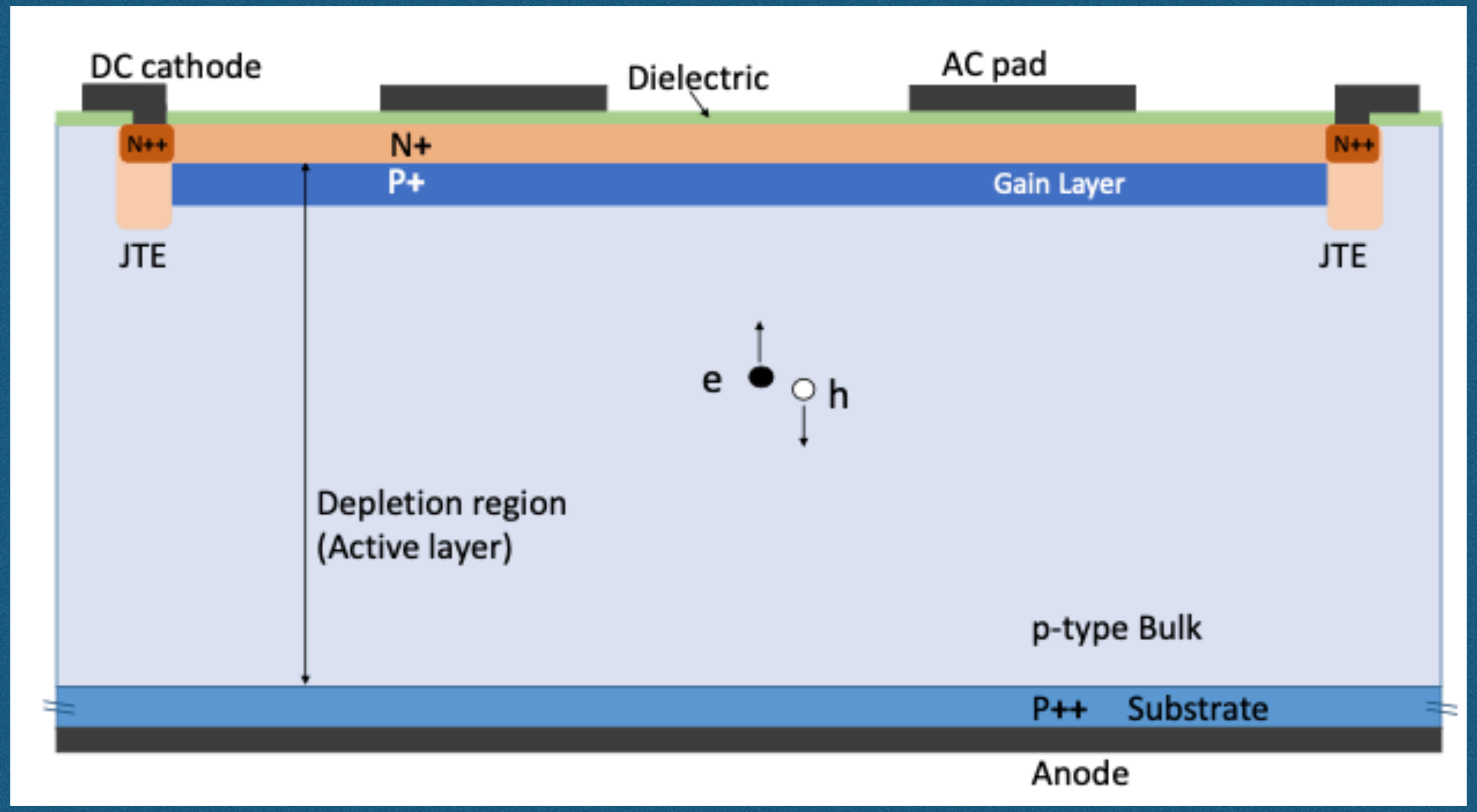


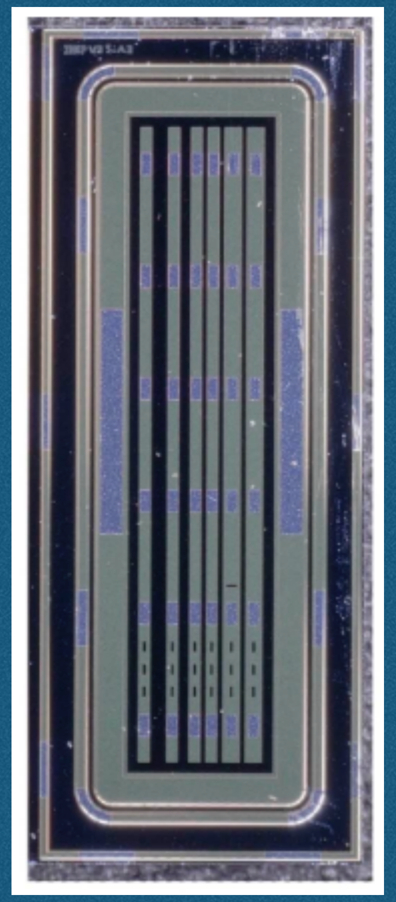
The Outer Tracker (OTK)



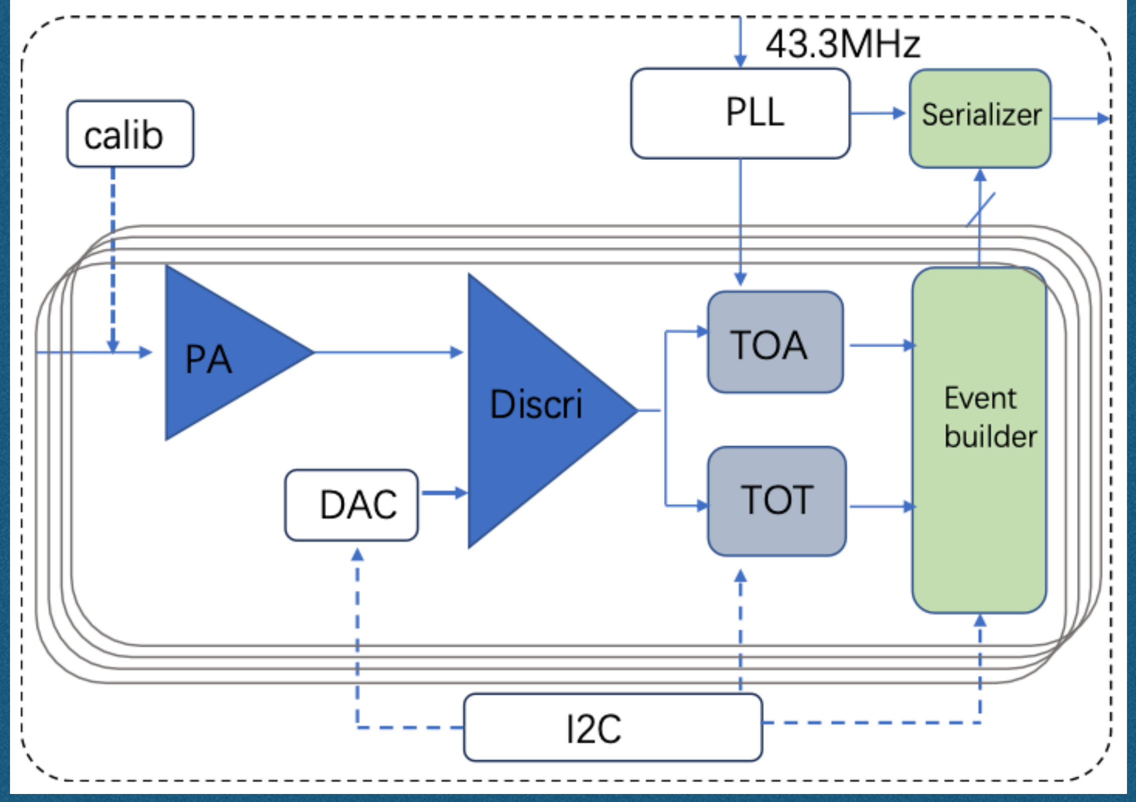
Endcap

AC-LGAD development:



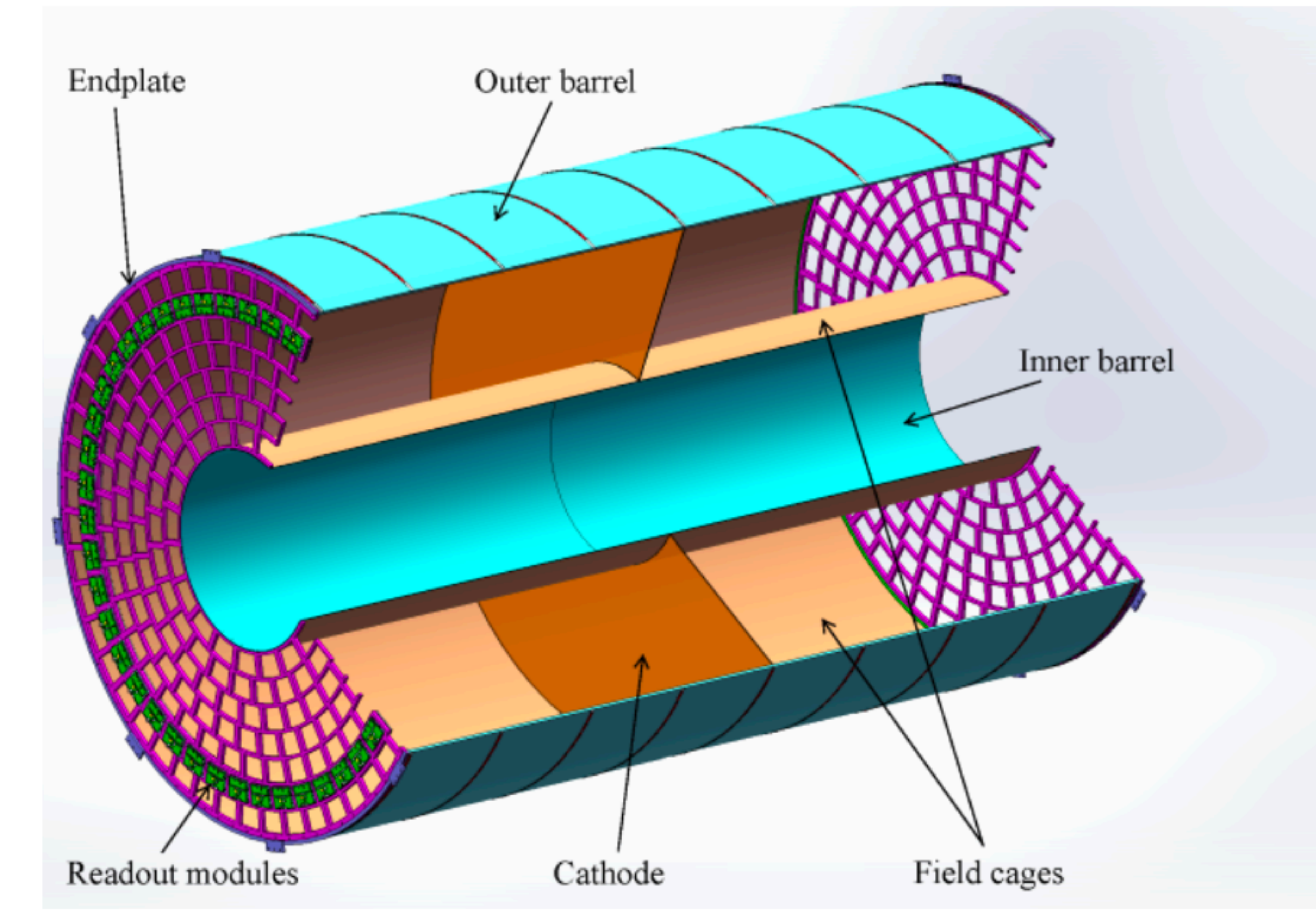


LATRIC: LGAD Readout Chip
(LGAD Timing and Readout Integrated Chip)



The Time Projection Chamber (TPC)

Detailed mechanical design:



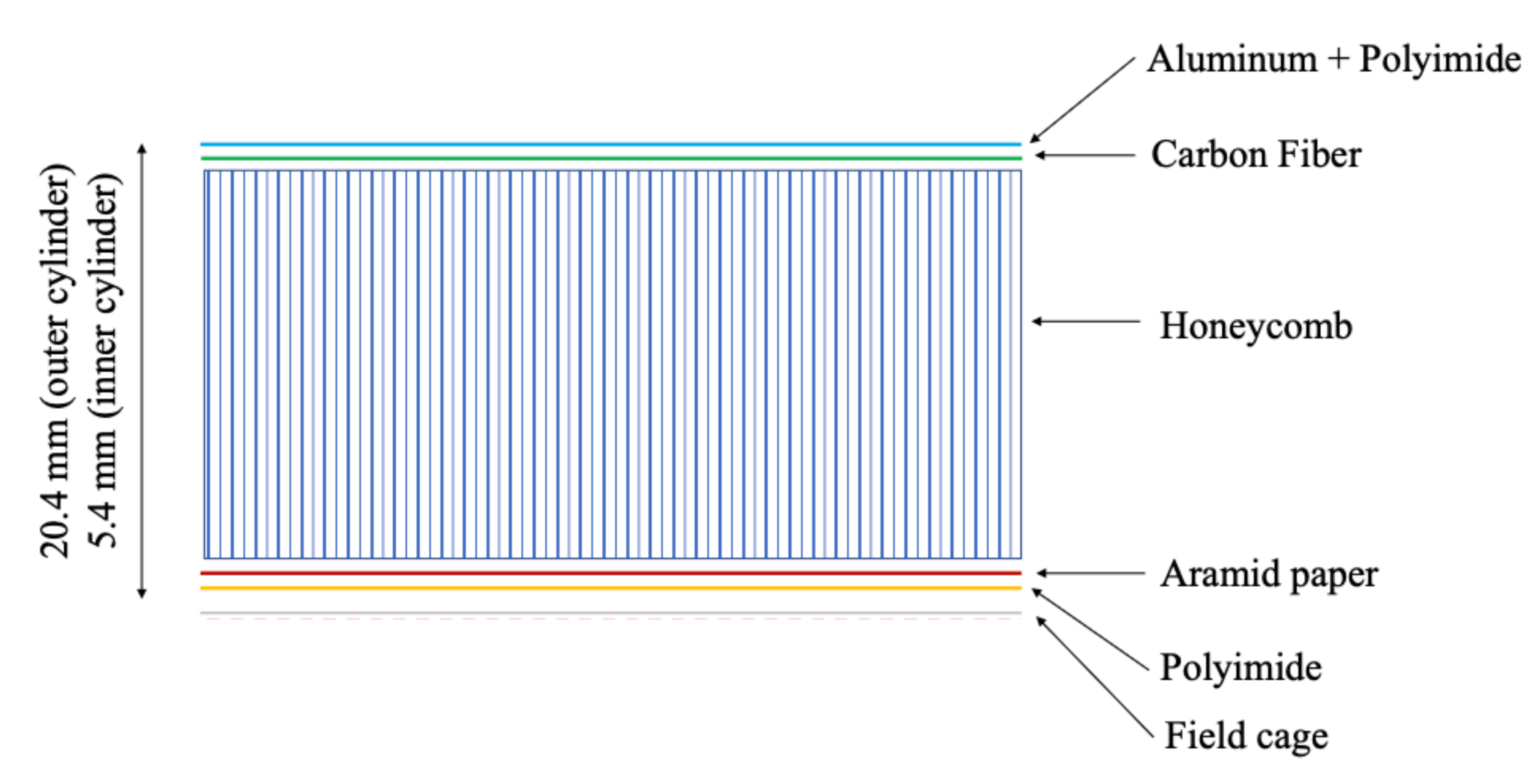


Table 6.1: Critical parameters of the TPC.

Parameters	Values
Length (outer dimensions)	5800 mm
Radial extension (outer dimensions)	600–1800 mm
Cathode potential	-63,000 V
Gas mixture	T2K: $Ar/CF_4/iC_4H_{10} = 95/3/2$
Drift velocity	~ 8 cm/μs
Maximum electron drift time	~ 34 μs
Readout detector	Double-mesh Micromegas
Pad size	500 μm × 500 μm
Gas gain	~ 2000
Readout modules per endplate	244
Cooling	Water cooling circulation system

Material budget estimation of the TPC barrel

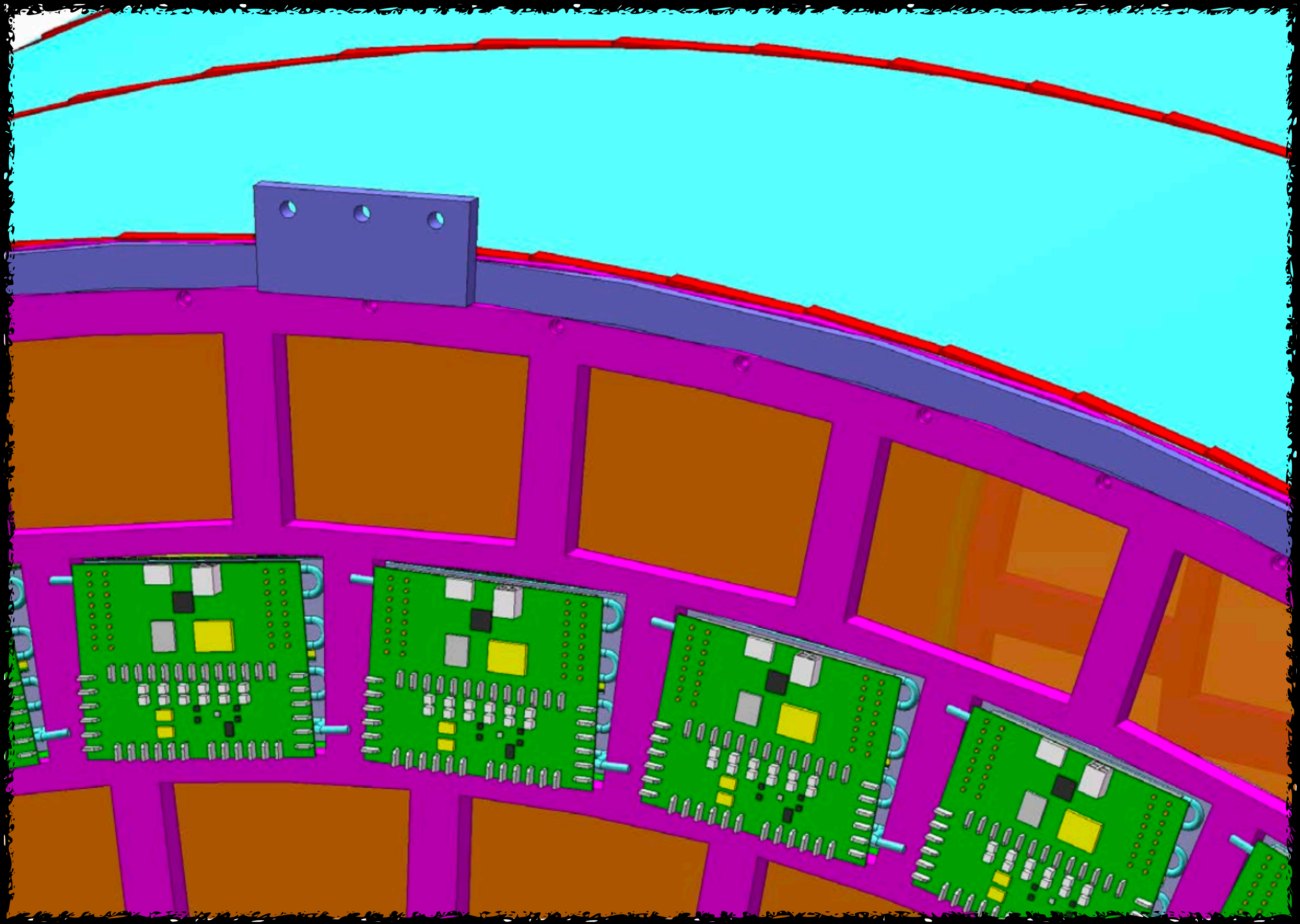
TPC outer wall: 0.69%

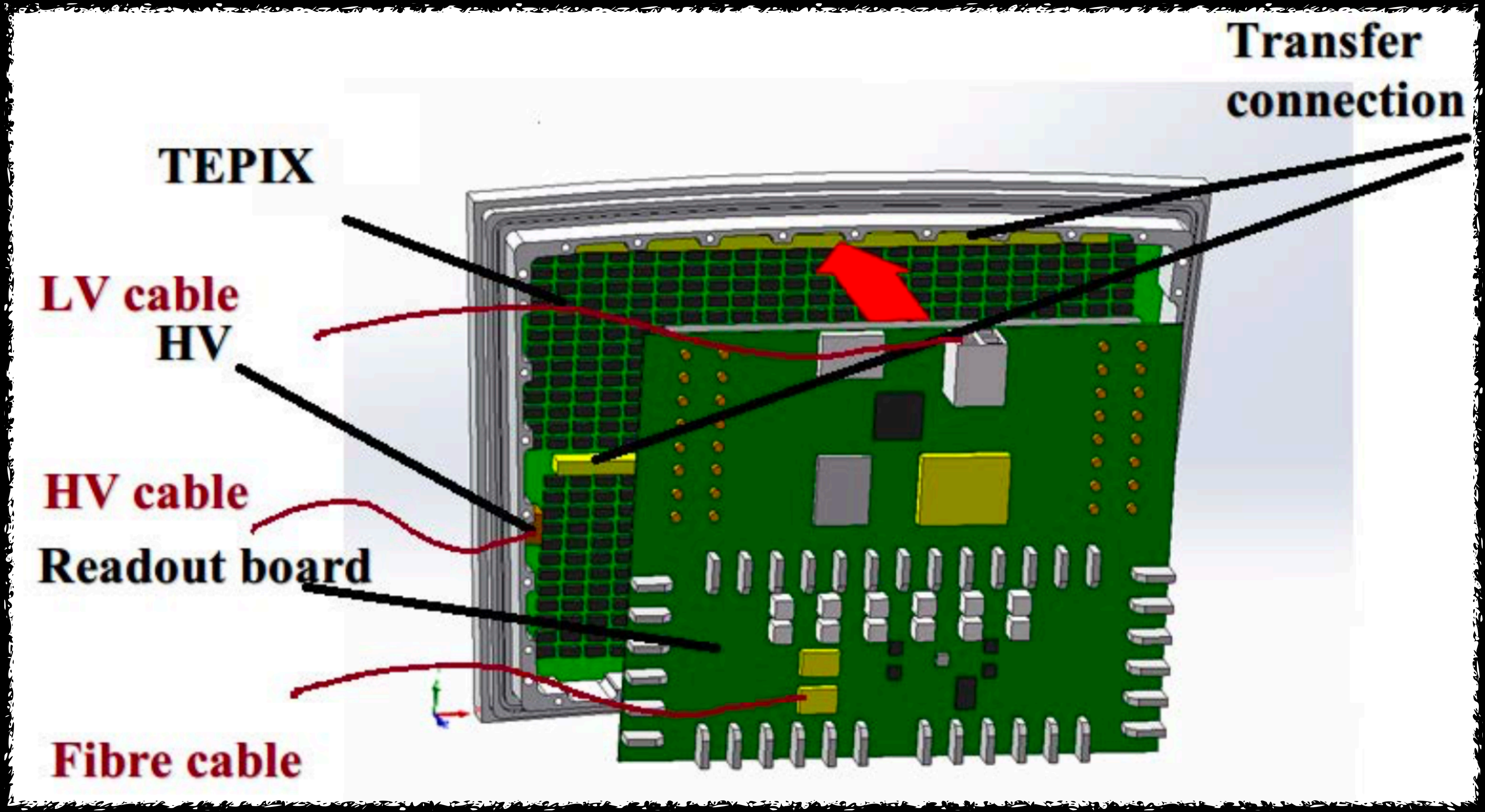
TPC inner wall: 0.45%

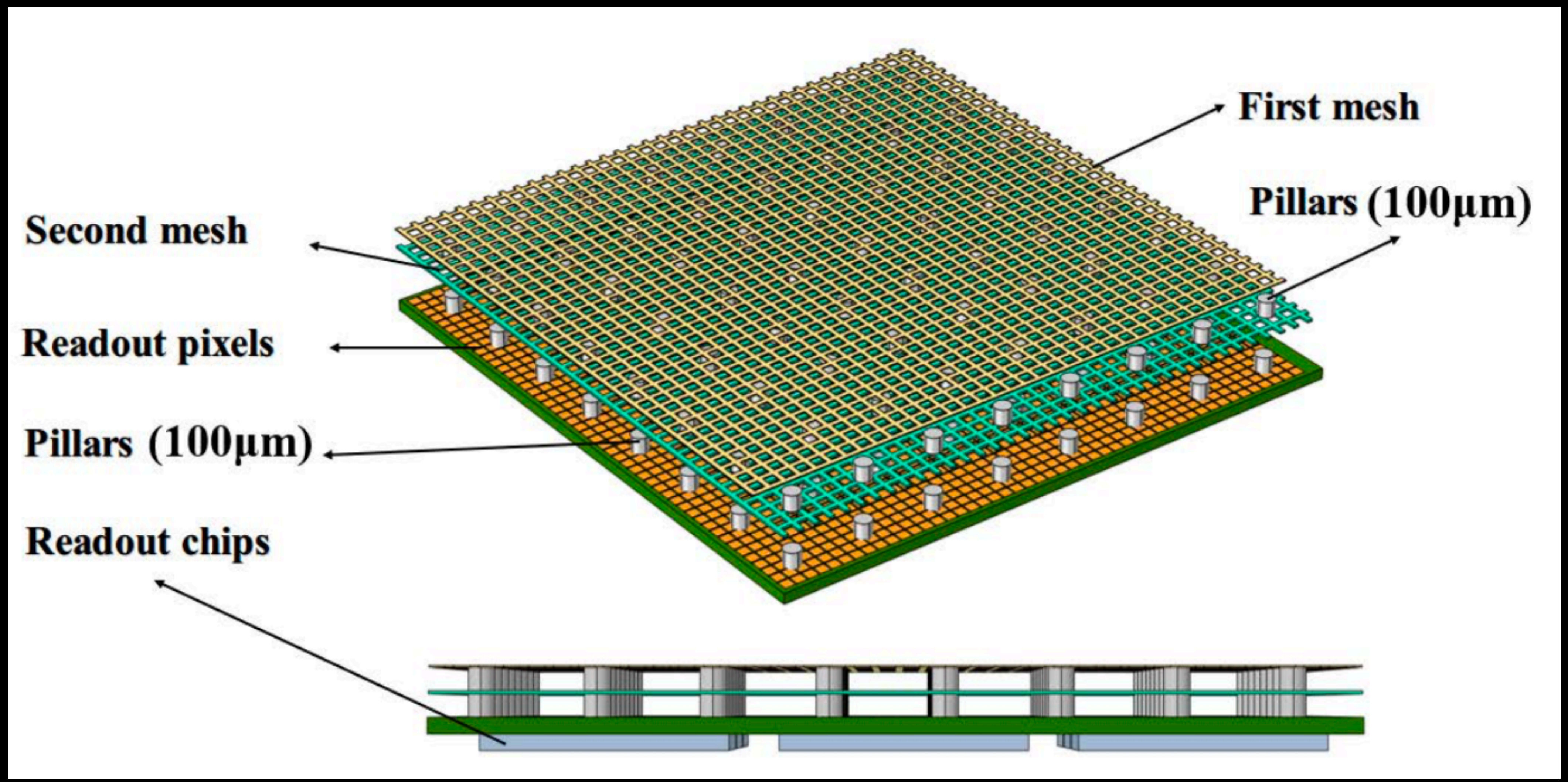
High granularity readout:

Pad size: 500 μm × 500 μm

The Time Projection Chamber (TPC) - Readout







244 detector modules per endplate

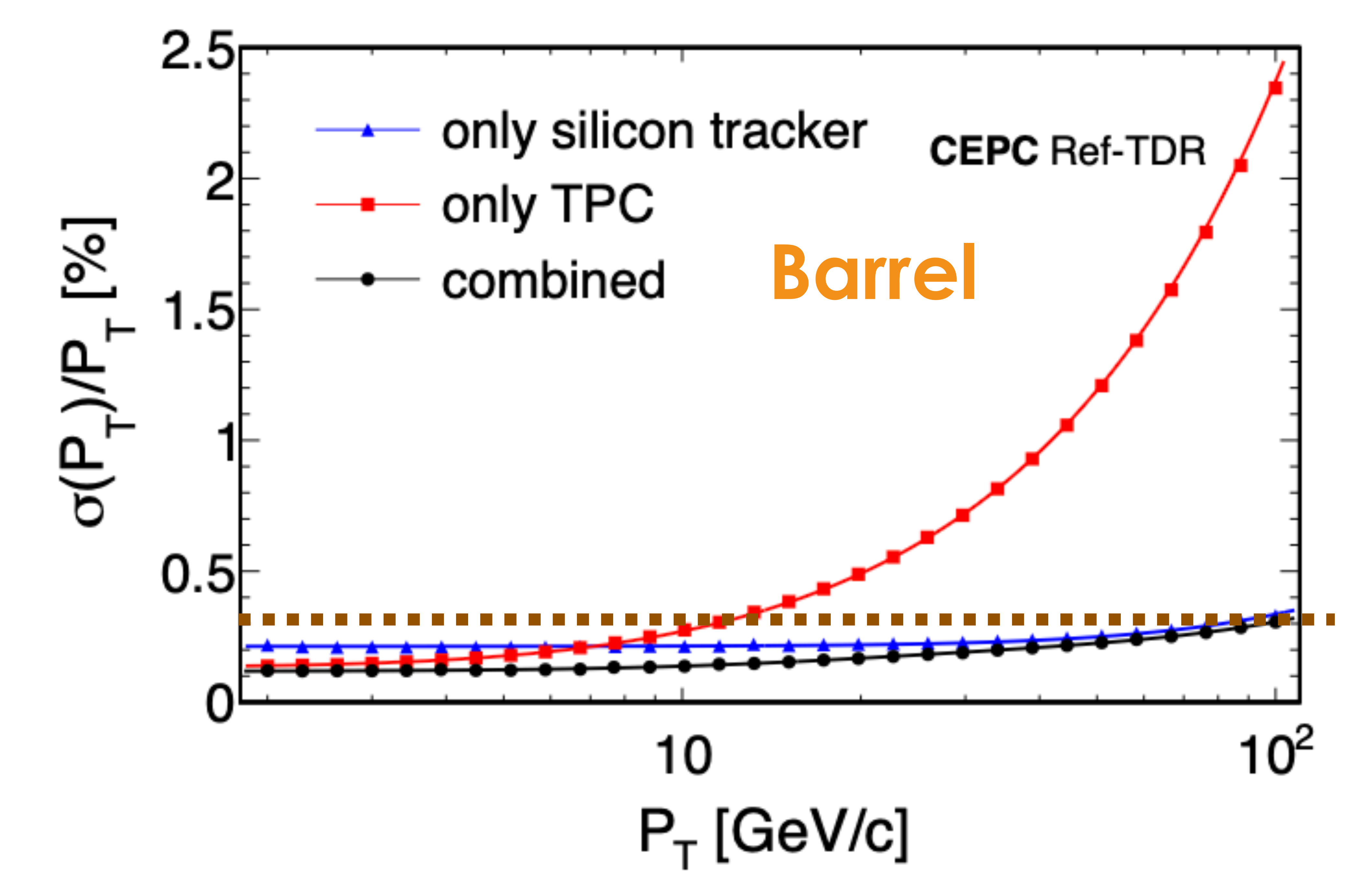
TEPIX: Low-power readout ASIC (<100 mW/cm²)
One ASIC for 256 small pads

Double mesh micromegas readout board

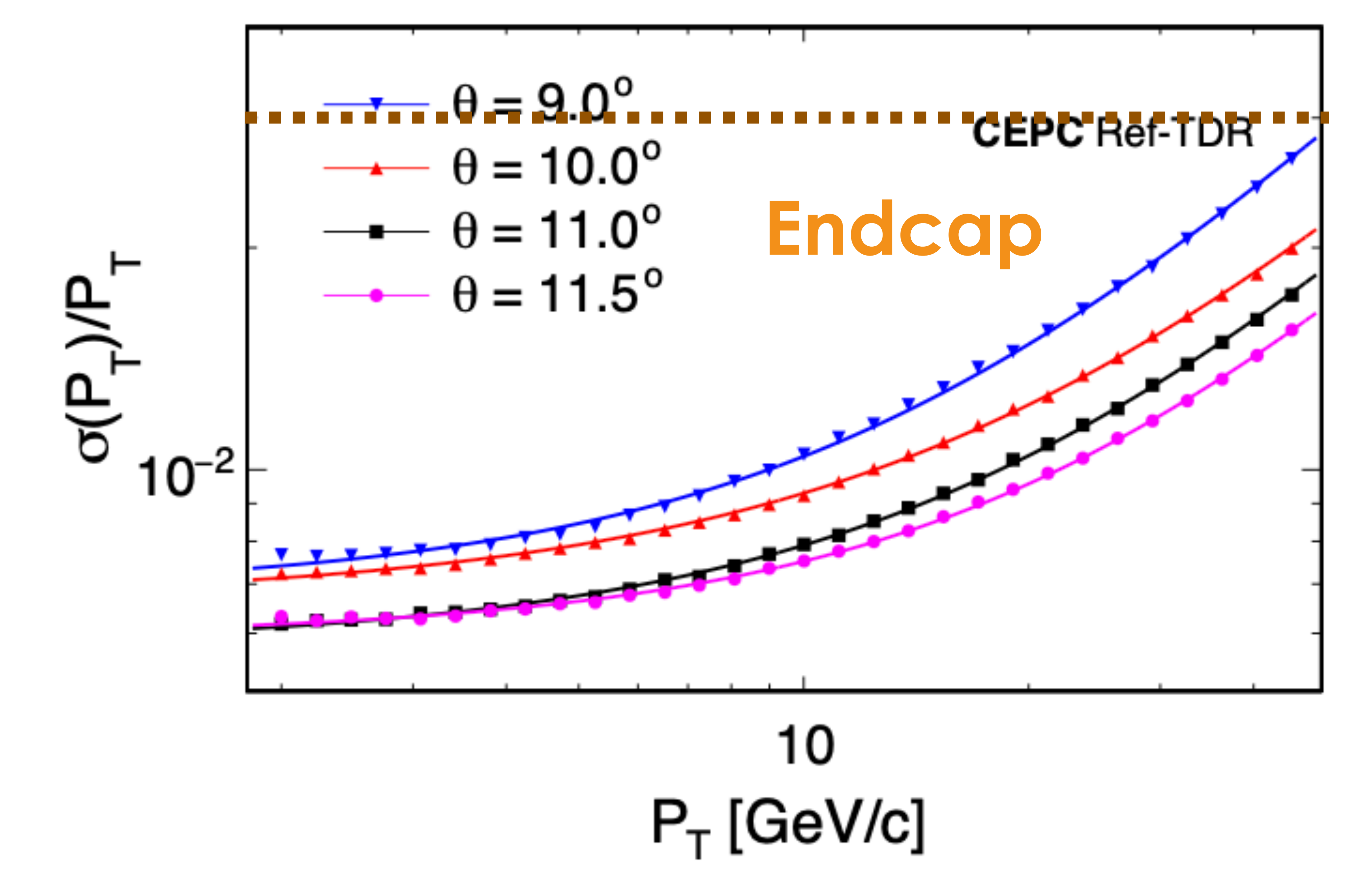
Tracking Performance

Transverse momentum resolution

Physics objects	Measurands	Detector subsystem	Performance requirement
Tracking	Coverage Recon. efficiency Resolution in barrel Resolution in endcap	Tracker	$\lvert\cos\theta\rvert \leq 0.99$ $\geq 99\%$ ($p_T > 1$ GeV/c) $\sigma_{p_T}/p_T < 0.3\%$ ($\lvert\cos\theta\rvert \leq 0.85$) $\sigma_{p_T}/p_T < 3\%$ ($\lvert\cos\theta\rvert > 0.85$)



Resolution of different detectors at 85°

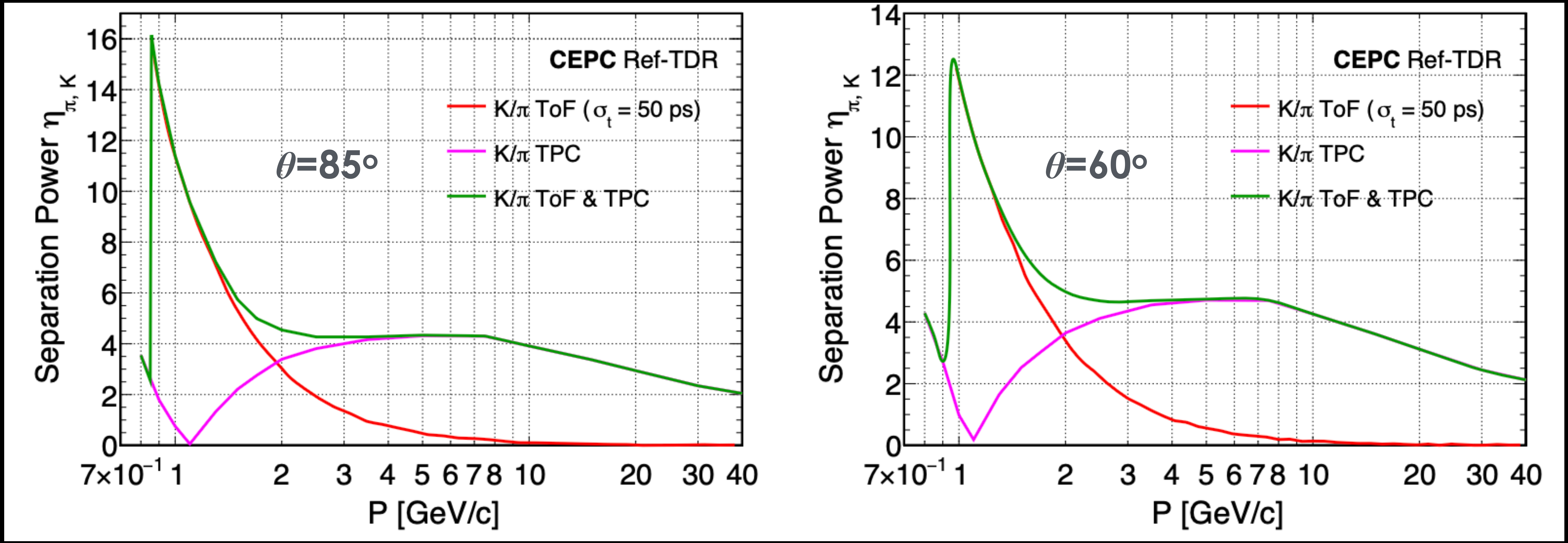


Resolution of the combined tracker at different polar angles

Tracking Performance

Particle Identification

K, pion separation using TPC-only, OTK-only and TPC+OTK measurements



Particle Flow (PFA) Calorimetry

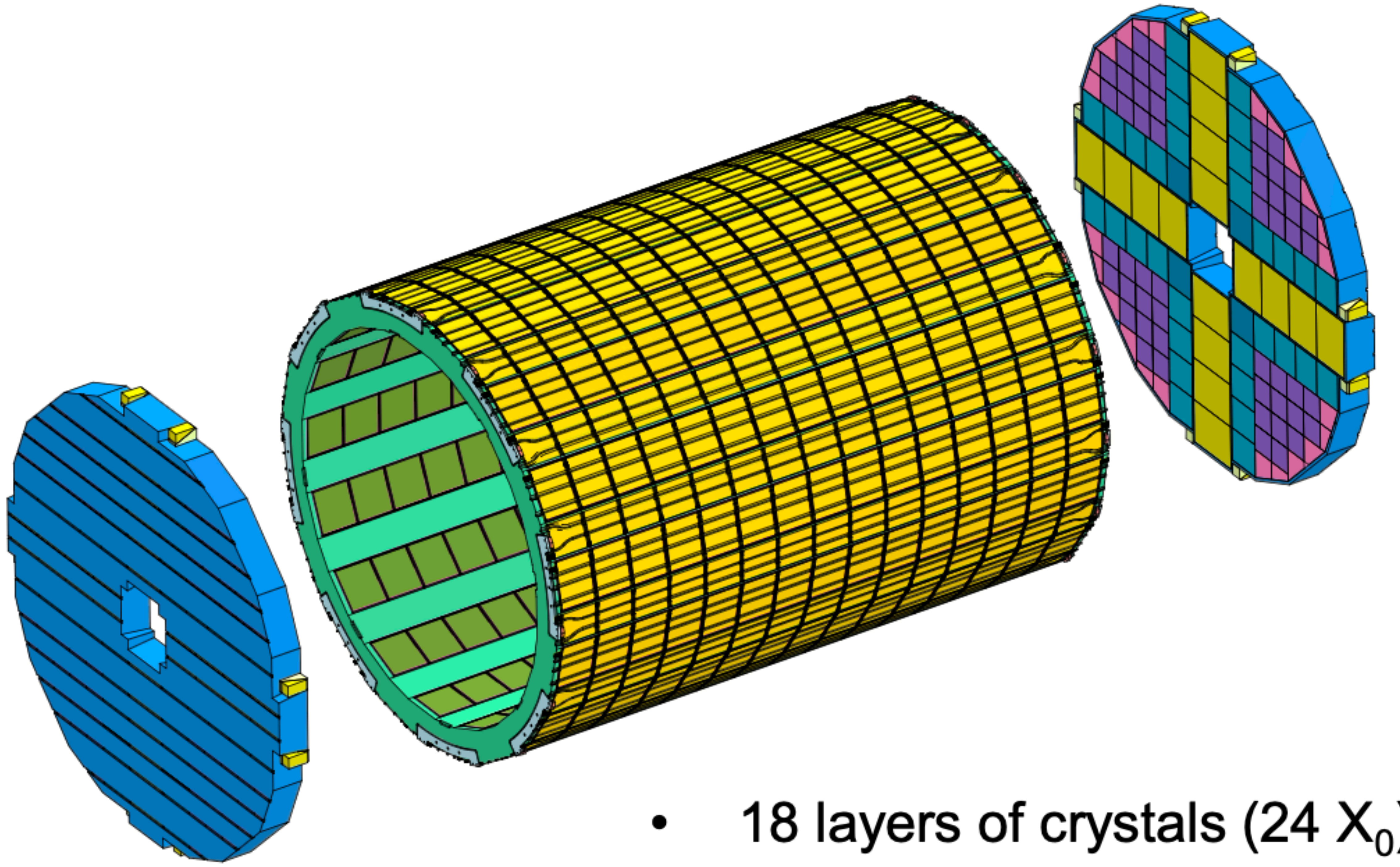
CEPC

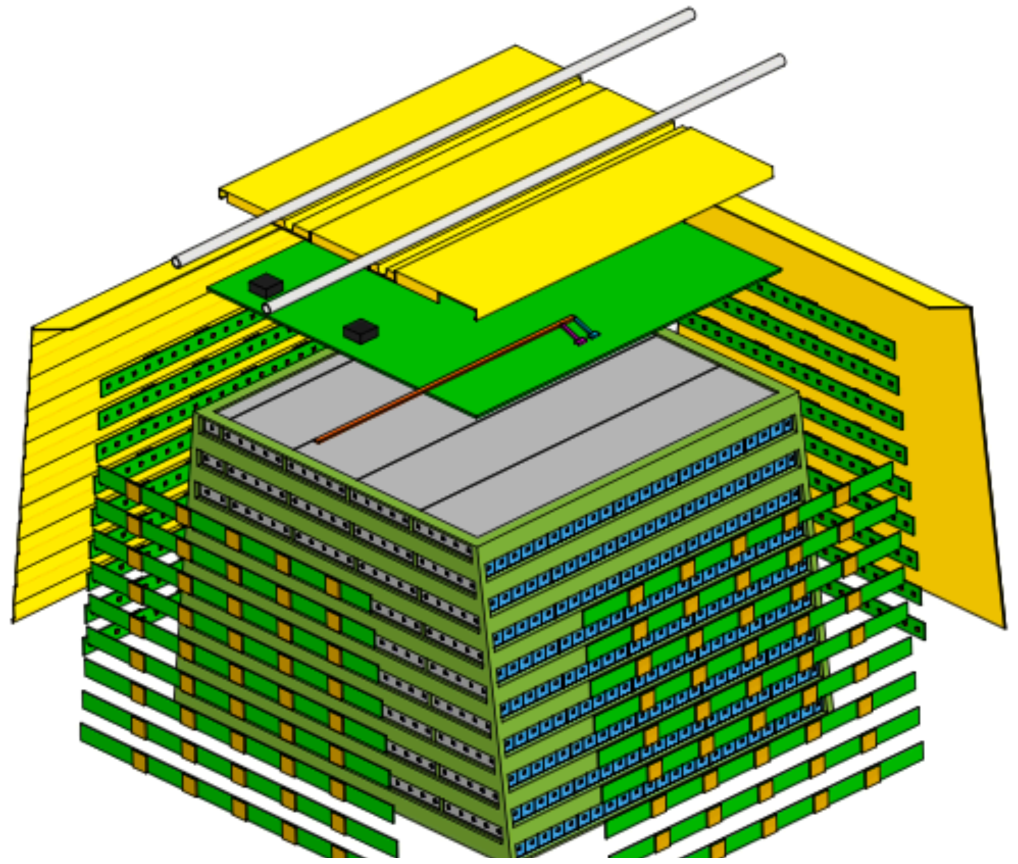
The CEPC Reference Detector embraces PFA Calorimetry, using the full detector for ultimate performance

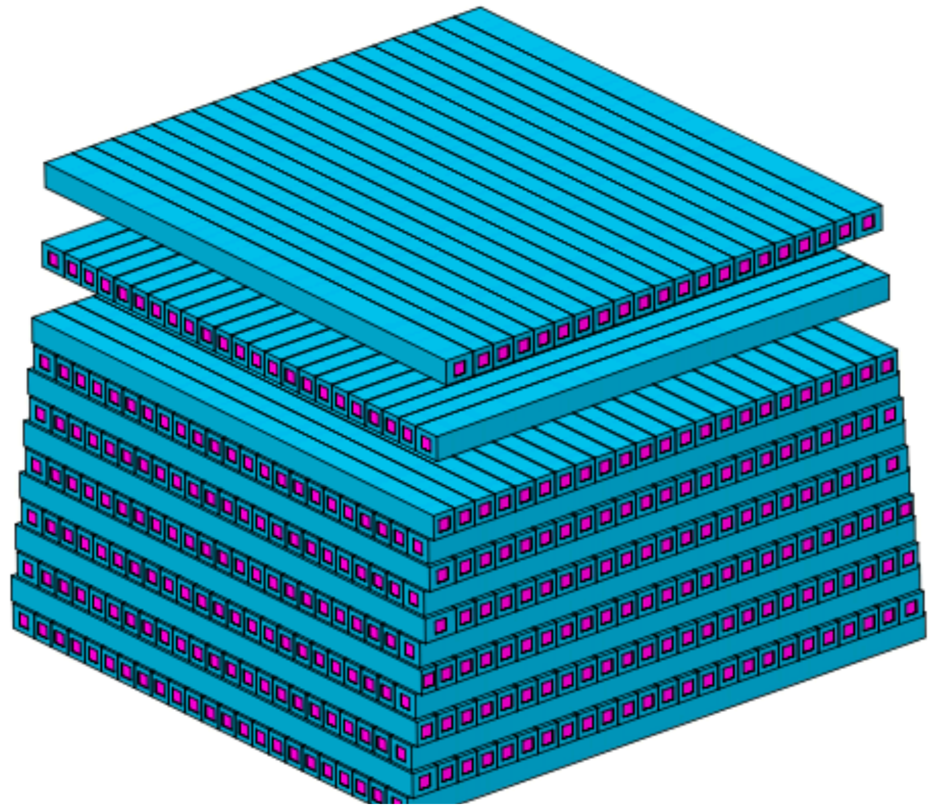
Physics objects	Measurands	Detector subsystem	Performance requirement
Leptons (e, μ)	PID efficiency Mis-ID rate	Tracker, ECAL HCAL, Muon	$\geq 99\%$ ($p > 5$ GeV$/c$, isolated) $\leq 2\%$ ($p > 5$ GeV$/c$, isolated)
Photons	PID efficiency Mis-ID rate Energy resolution	ECAL, HCAL	$\geq 95\%$ ($E > 3$ GeV, isolated) $\leq 5\%$ ($E > 3$ GeV, isolated) $\sigma_E/E \leq 3\%/\sqrt{E(\mathrm{GeV})} \oplus 1\%$
Hadronic jets	Energy resolution Mass resolution	Tracker ECAL, HCAL	$\sigma_E/E \sim 30\%/\sqrt{E(\mathrm{GeV})} \oplus 4\%$ BMR $\leq 4\%$
Jet flavor tagging	b-tagging efficiency c-tagging efficiency	Full detector	$\sim 80\%$, mis-ID of uds $< 0.3\%$ $\sim 50\%$, mis-ID of uds $< 1\%$

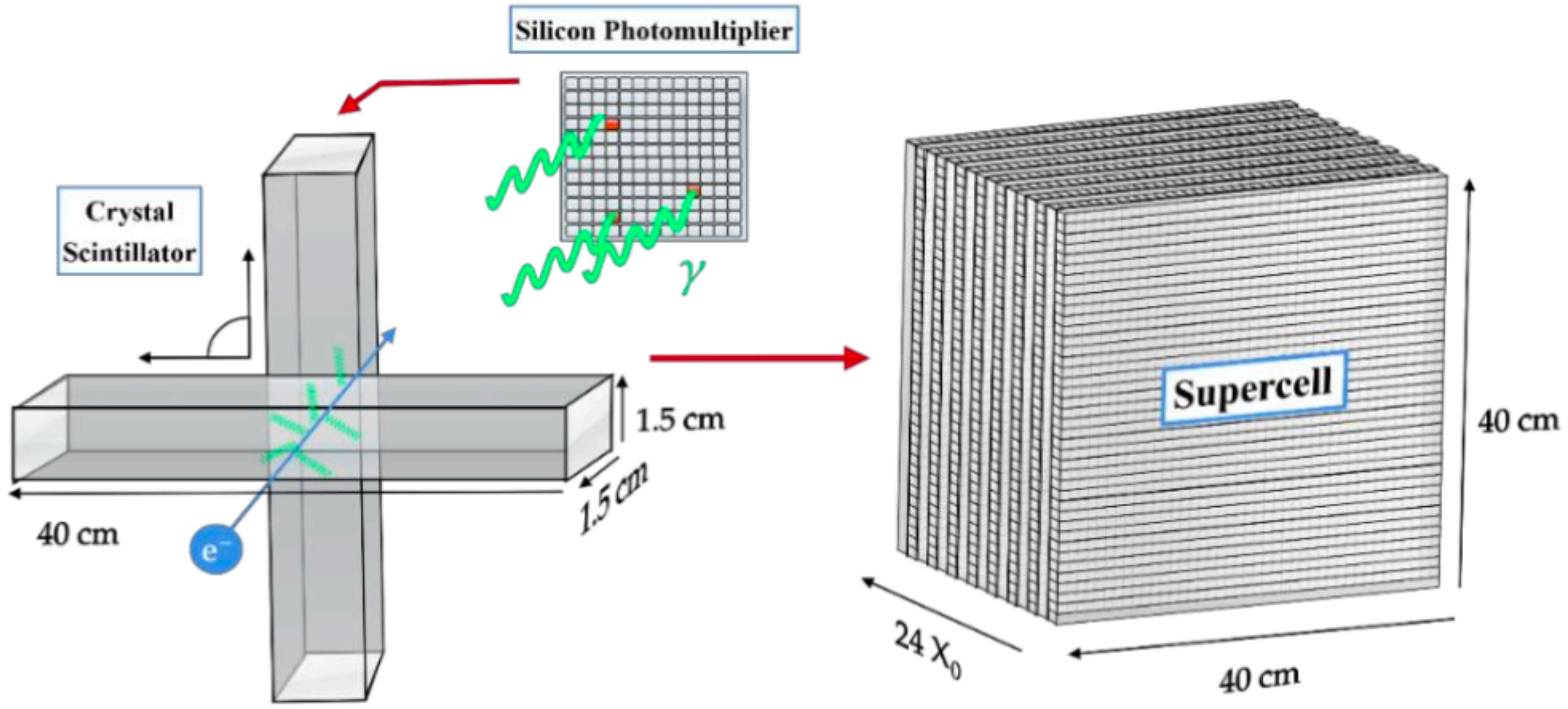
Benchmark physics requirements

A crystal electromagnetic calorimeter

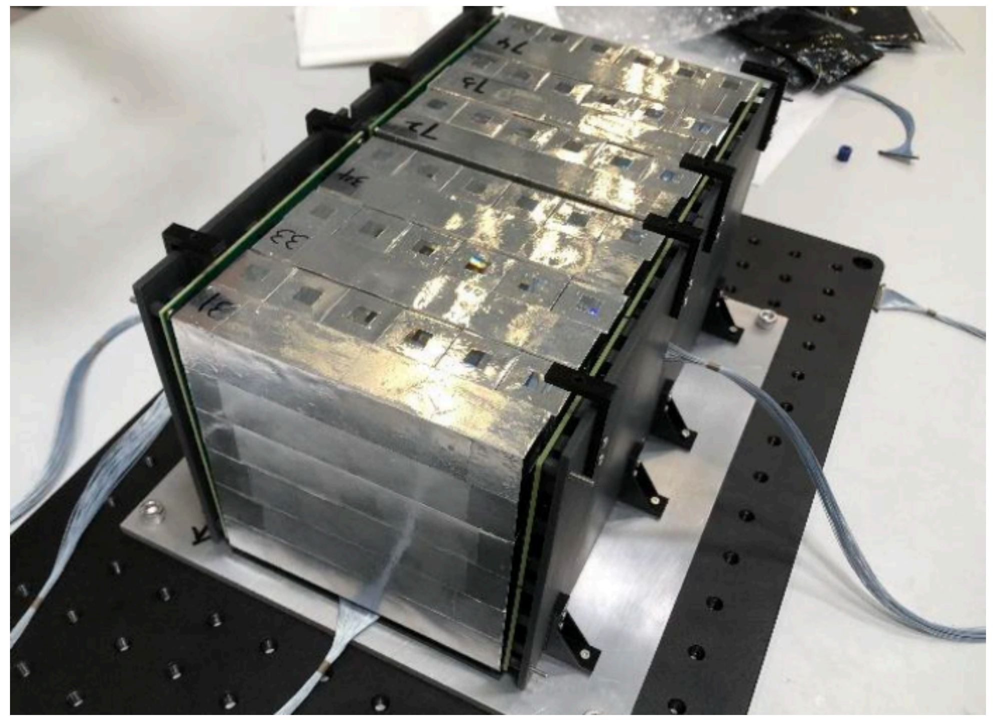








- 18 layers of crystals (24 X_0)
- Barrel: 32 towers per ring, 15 rings
- Endcap: 224 modules
- Total: 24m^3 BGO, 571k channels



Superb energy resolution but not cheap

$$\sigma_E/E \leq 3\%/\sqrt{E(\text{ GeV})} \oplus 1\%$$

A crystal electromagnetic calorimeter

Significant R&D on Silicon Photomultipliers (SiPM) and Readout Electronics

An issue common to ECAL, HCAL and Muon Detectors

The SiPM is required to have:
- high dynamic range
- moderate Photon Detection Efficiency (PDE)
- acceptable Dark Count Rate (DCR)

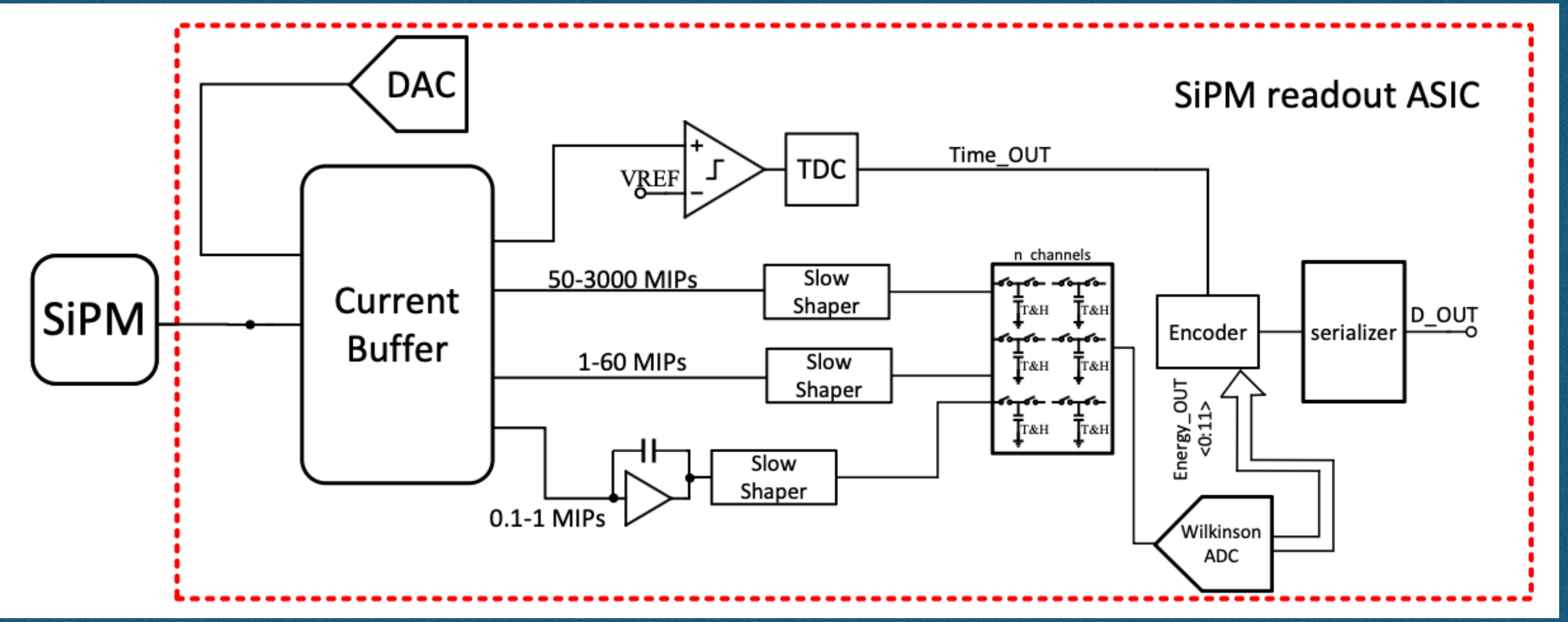
SiPM Type	NDL EQR06	NDL EQR10	HPK S14160-3010PS
Pixel Pitch μm	6	10	10
Pixel Quantity in 3×3 mm^2	244,719	90,000	89,984
Pixel Gain	8×10^4	1.7×10^5	1.8×10^5
Typical peak PDE	30 % (at 420 nm)	36 % (at 420 nm)	18 % (at 460 nm)
Typical DCR (20 °C)	2.5 MHz	3.6 MHz	700 kHz
Inter-pixel Crosstalk	12 %	N/A	< 1 %
Terminal Capacitance (pF)	45.9 pF	31.5 pF	530 pF

selected candidates

New ASIC

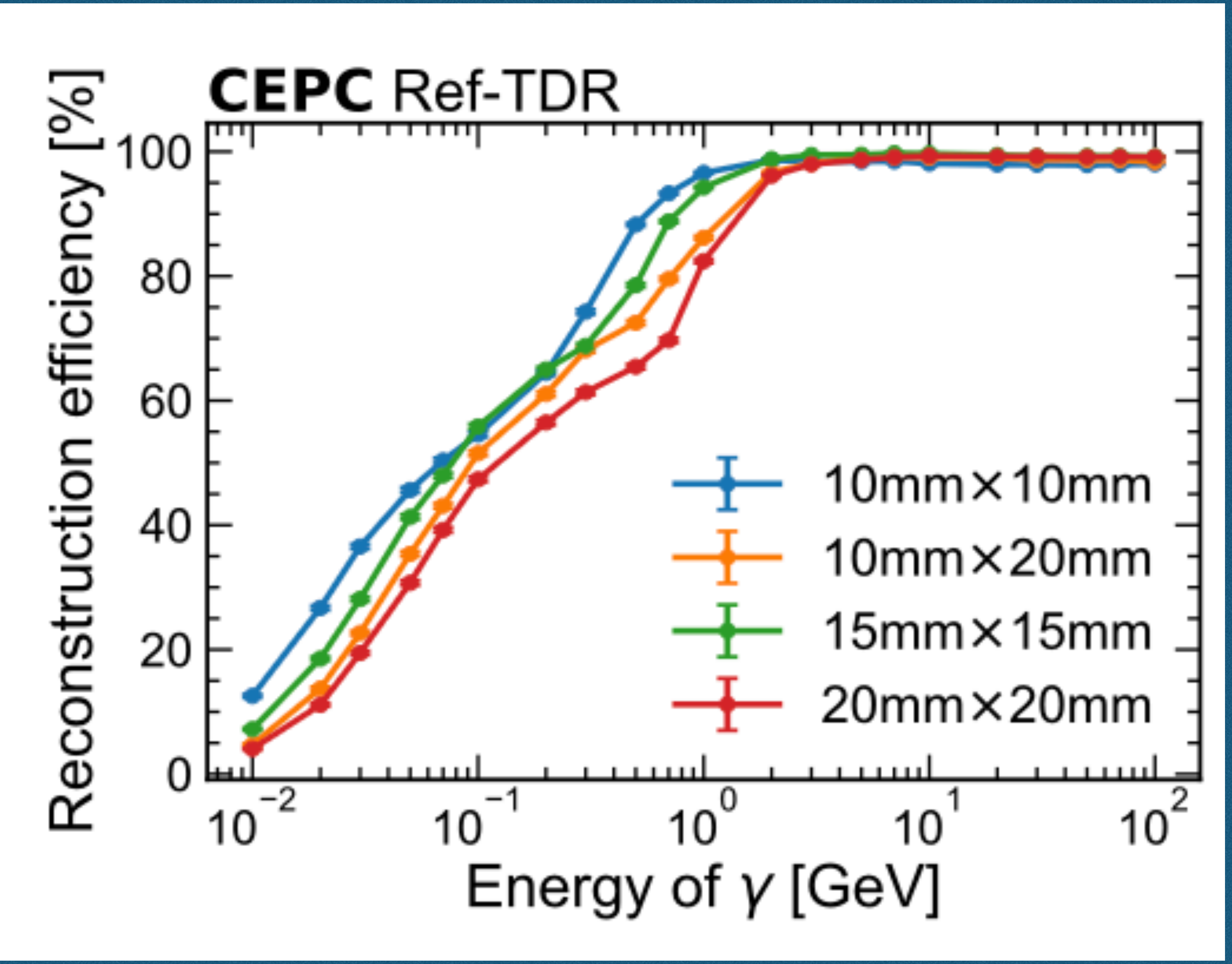
SIPAC: SiPM ASIC for Calorimeter

(to be commonly used)

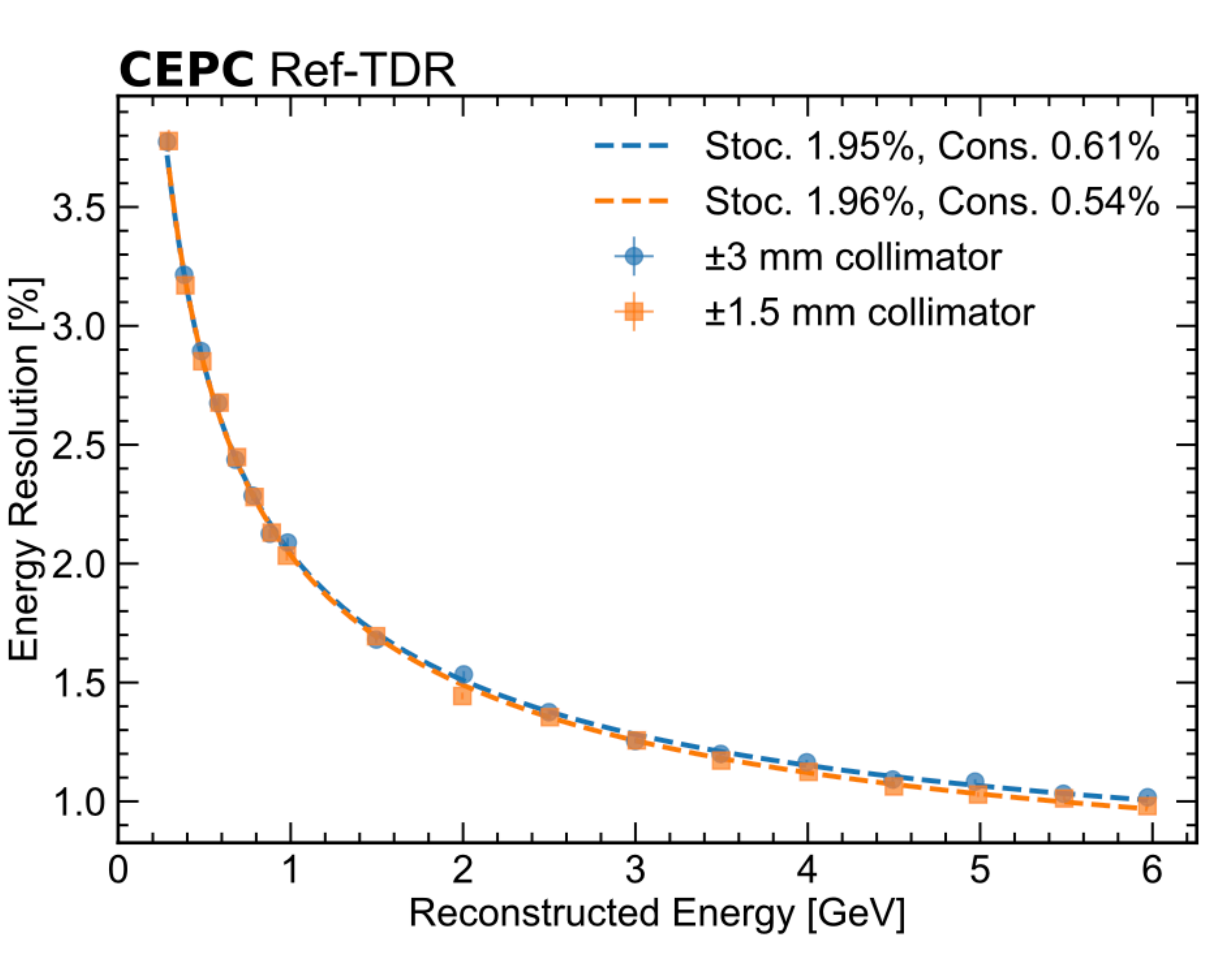


A crystal electromagnetic calorimeter

Crystal bar granularity was optimized for a balance between physics performance, crystal production, cost and design constraints.



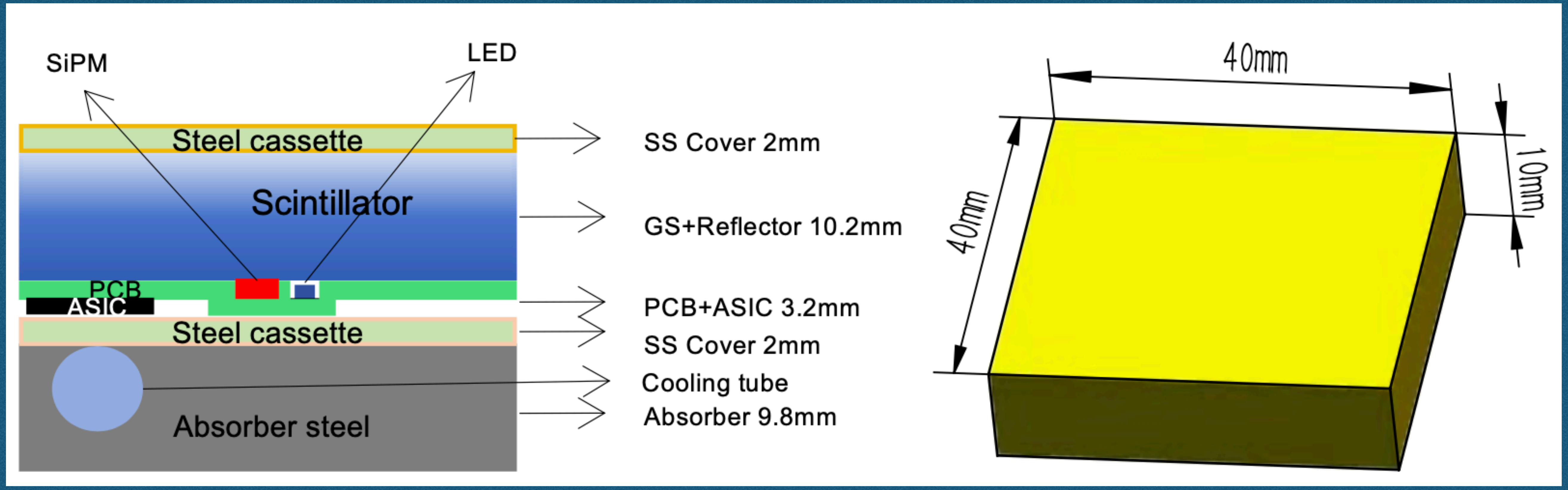
ECAL prototype in test beam:
EM energy resolution better than $2\%/\sqrt{E(\mathrm{GeV})} \oplus 1\%$

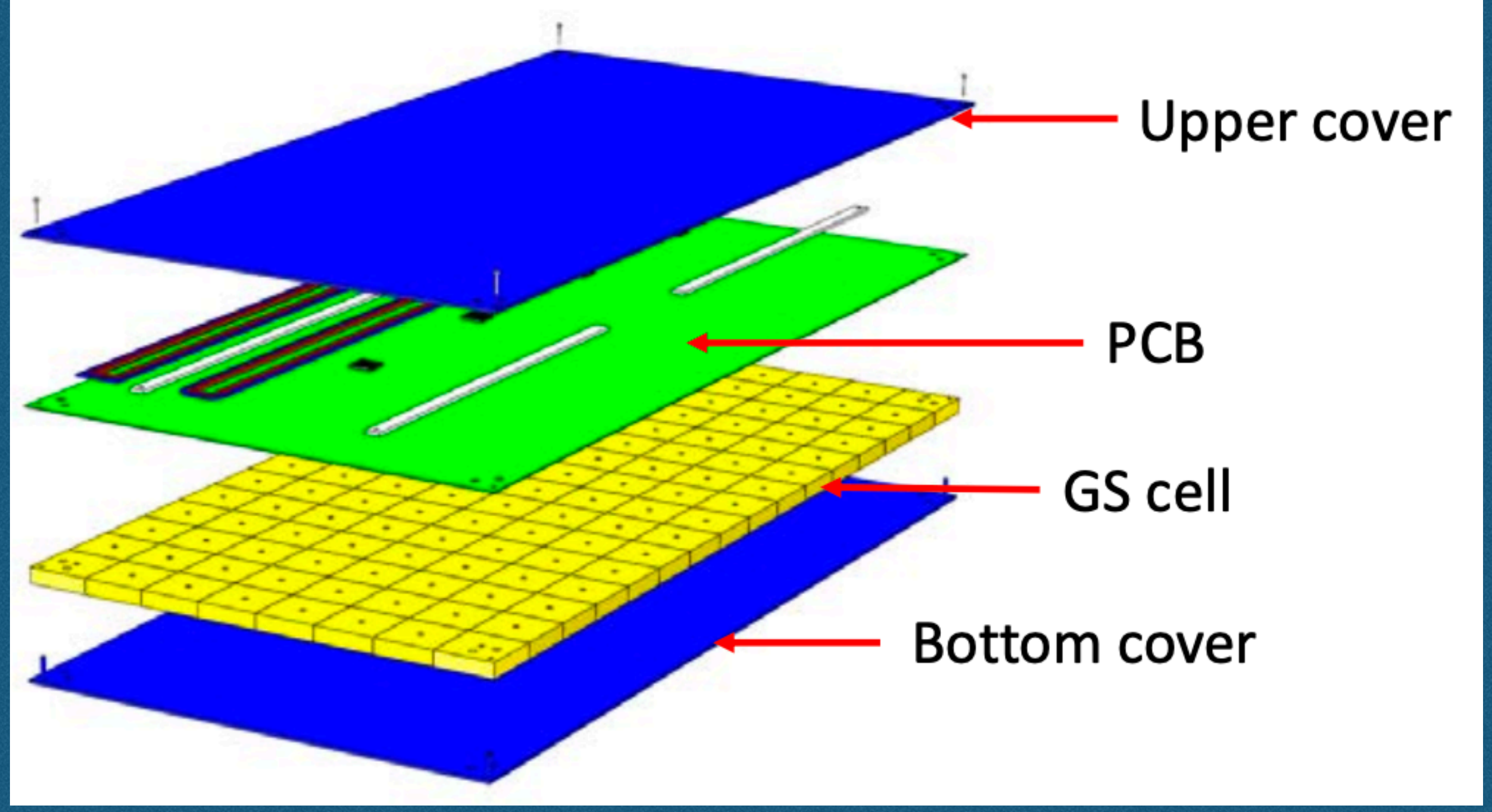


The Hadronic Calorimeter

GS-HCAL: a glass scintillator calorimeter

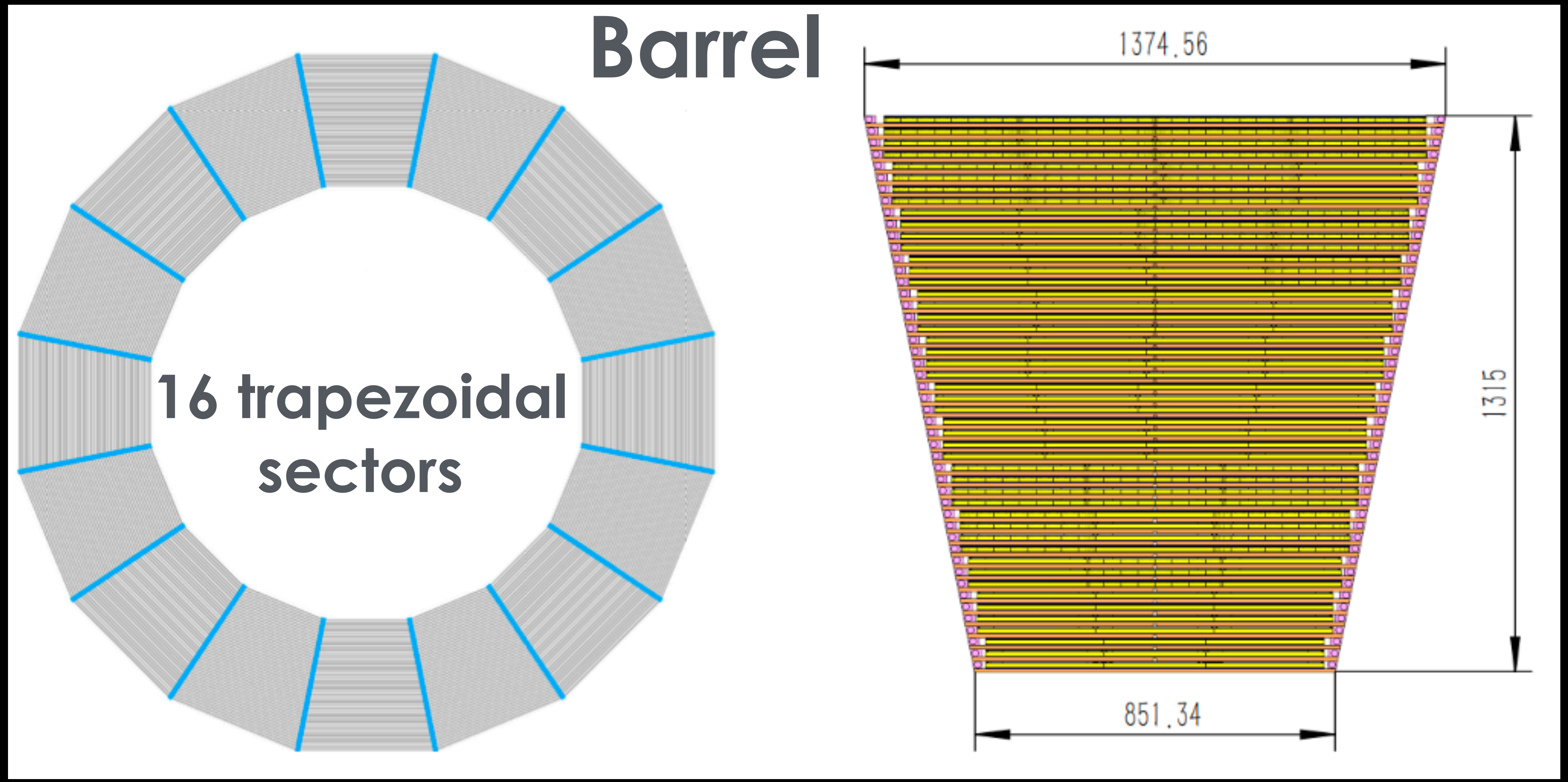
Single layer structure

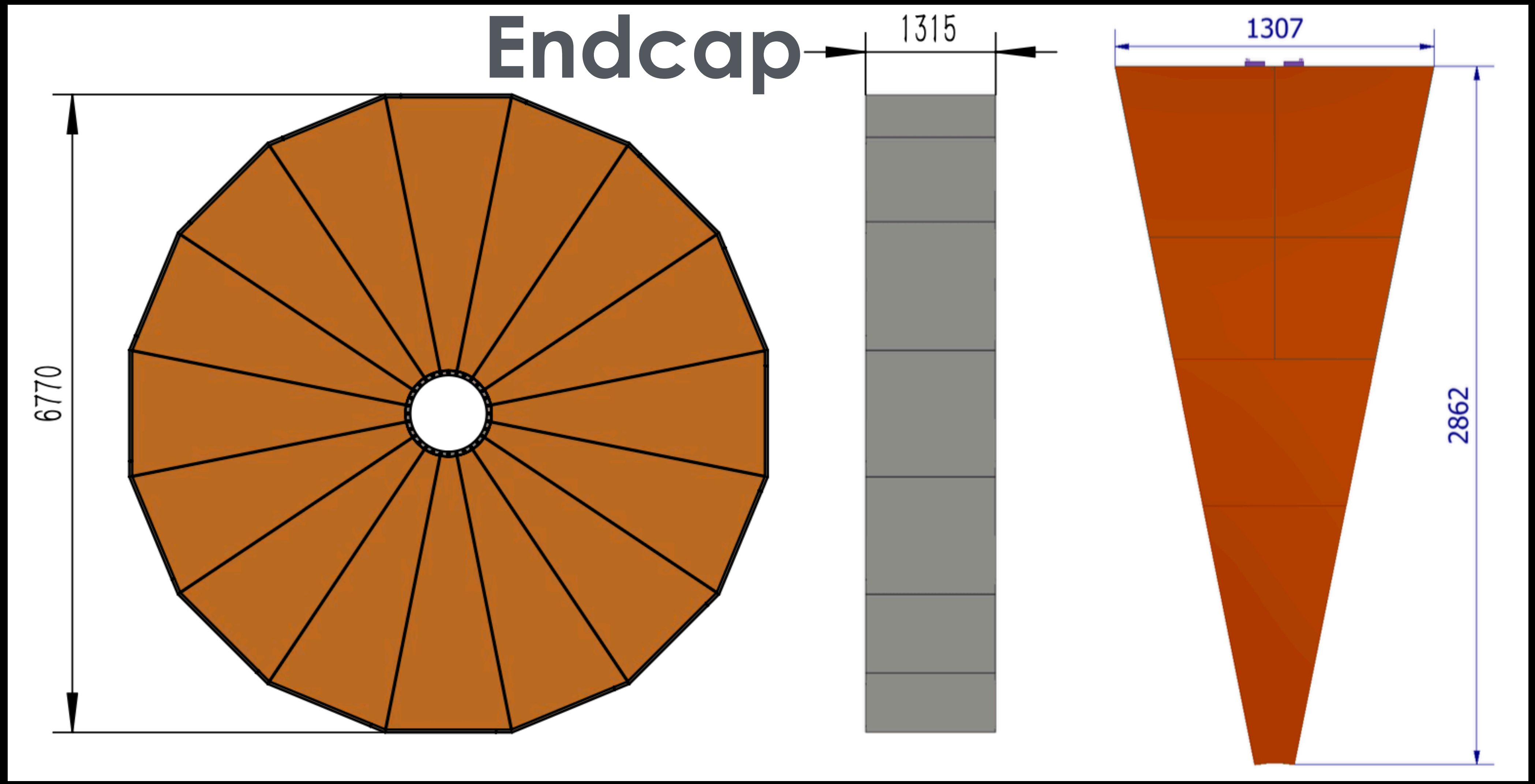




48 layers stacked per module

955 tons



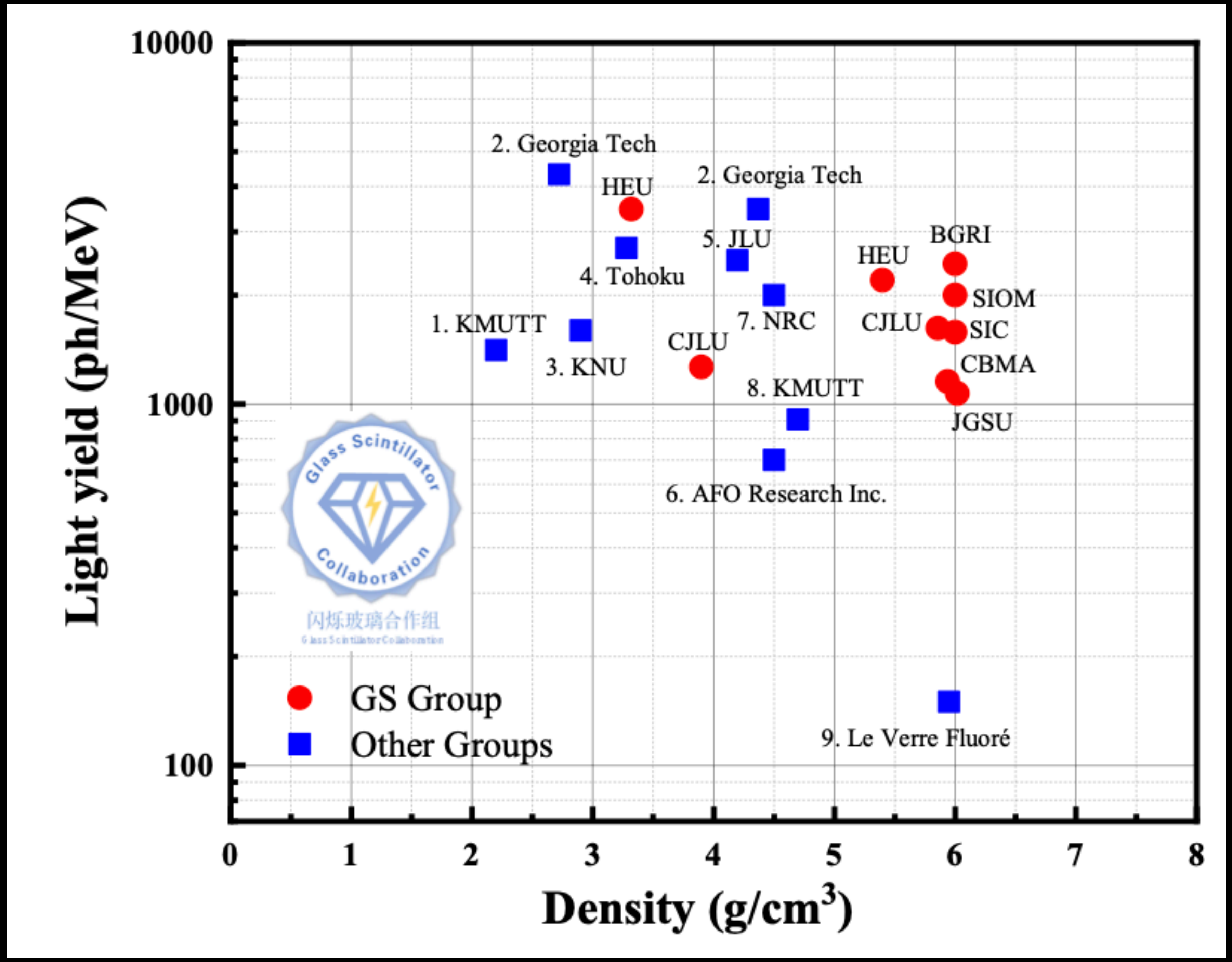


362 tons/endcap

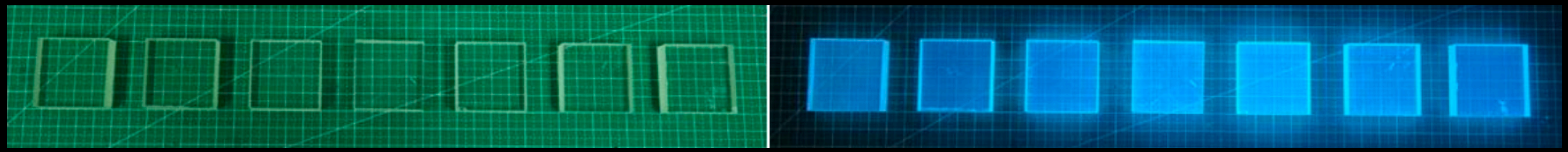
The Hadronic Calorimeter: Glass Scintillation

Using Gadolinium Fluoro-Oxide (GFO) glass

Key parameters	GFO glass	BGO	DSB Glass
Density (g/cm^3)	6.0	7.13	4.2
Melting point (℃)	1250	1050	1550
Radiation length (cm)	1.59	1.12	2.62
Molière radius (cm)	2.49	2.23	3.33
Nuclear interaction length (cm)	24.2	22.7	31.8
Z_{eff}	56.6	71.5	49.7
dE/dx (MeV/cm)	8.0	8.99	5.9
Emission peak (nm)	400	480	430
Refractive index	1.74	2.15	
Light yield (ph/MeV)	~ 1500	7500	2500
Energy resolution (% at 662 keV)	~ 23	9.5	
Scintillation decay time (ns)	~ 60, 500	60, 300	90, 400



Sample size of 5 × 5 × 5 mm³



Goal is **high light yield**, **large density** and lower attenuation length

The Hadronic Calorimeter: Glass Scintillation

Using Gadolinium Fluoro-Oxide (GFO) glass

Key parameters	GFO glass	BGO	DSB Glass
Density (g/cm^3)	6.0	7.13	4.2
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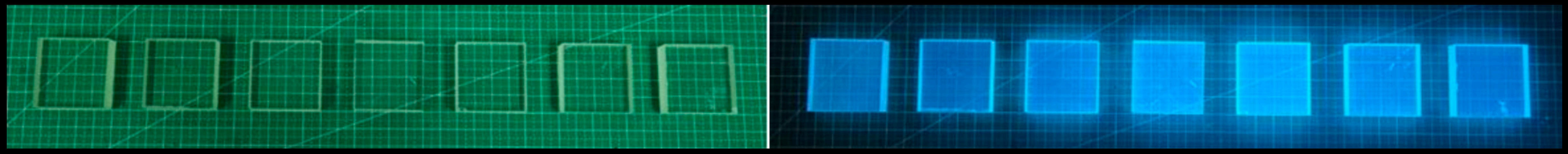
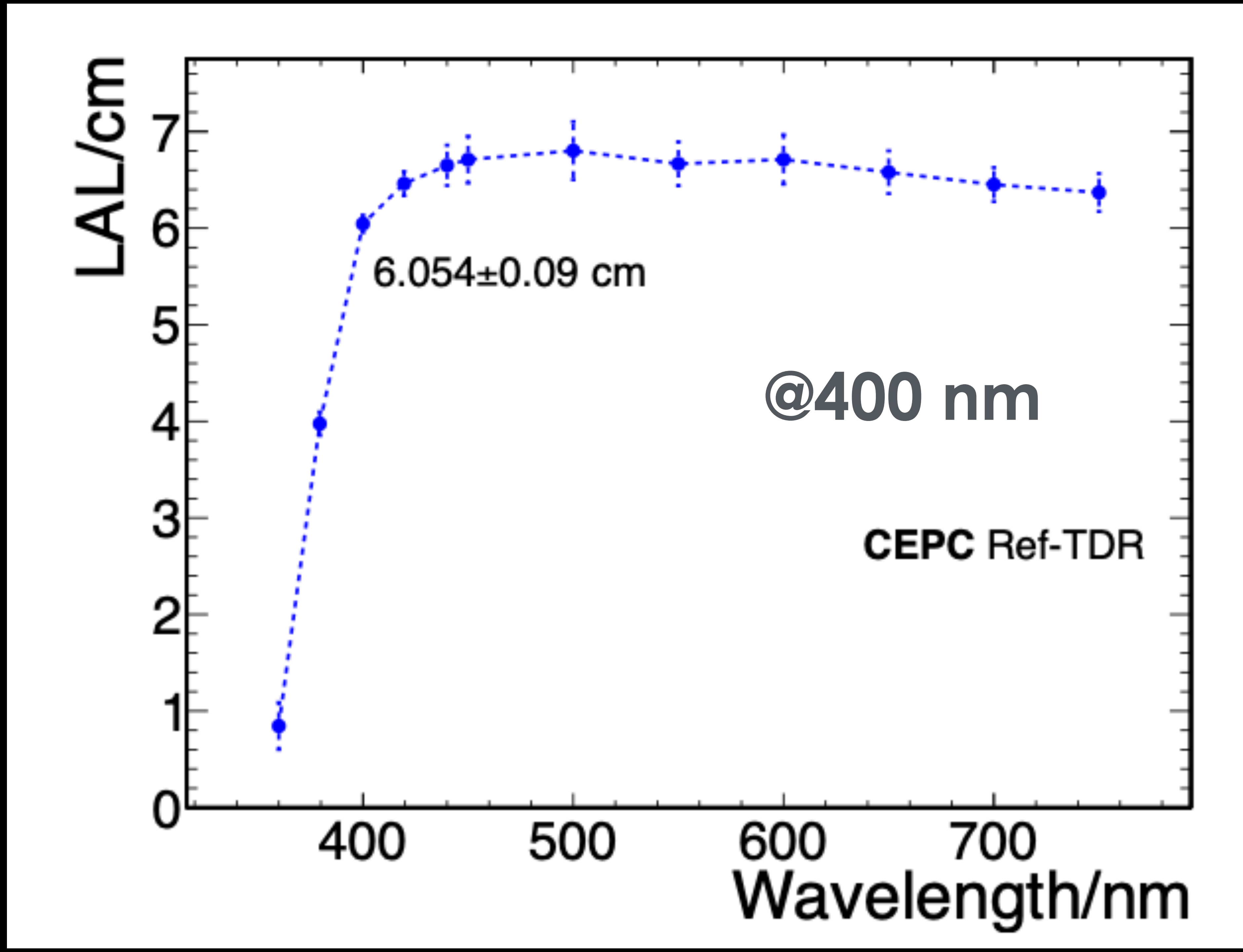
Sample size of 5 × 5 × 5 mm^3



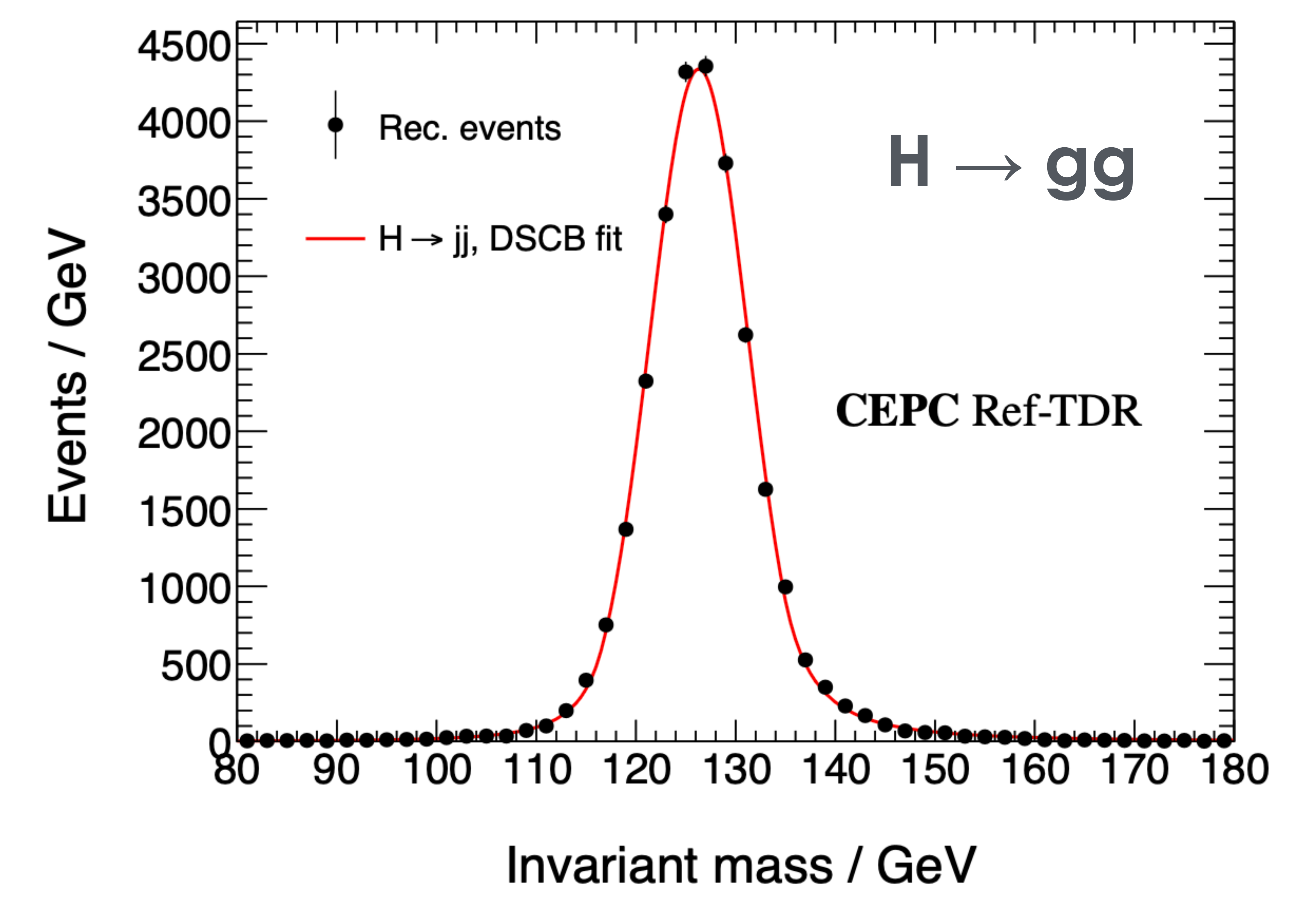
Best GFO GS sample



Goal is high light yield, large density and lower attenuation length

The Calorimeter Performance on Hadronic Jets

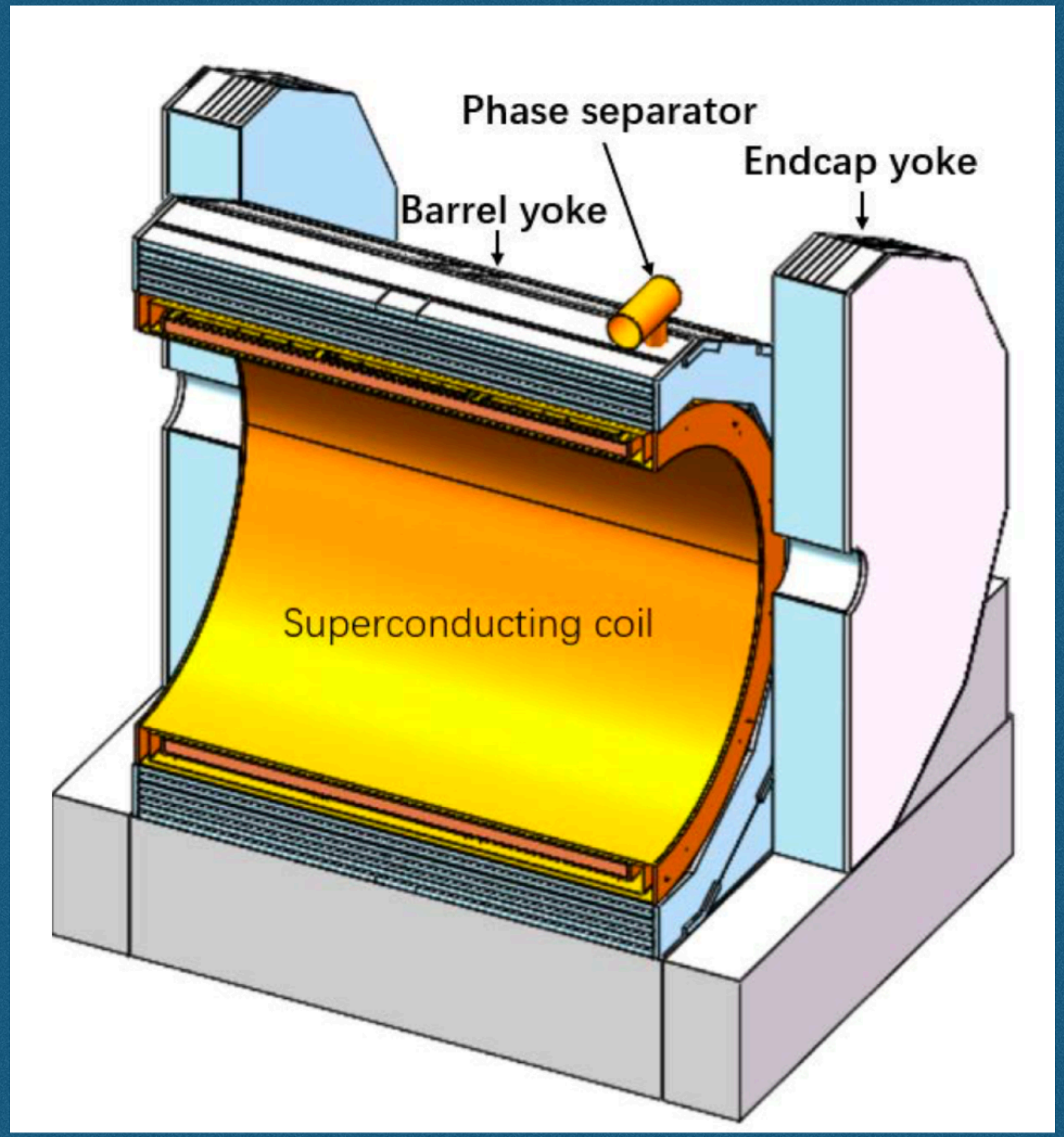
PFA detector performance on simulation events (includes tracker, ECAL, HCAL)



Higgs boson invariant mass resolution (BMR) = 3.88%

The Magnet System: Superconducting Solenoid

LTS: Low-temperature SC



Coil ϕ_{inner} = 7.3 m

Coil ϕ_{outer} = 7.92 m

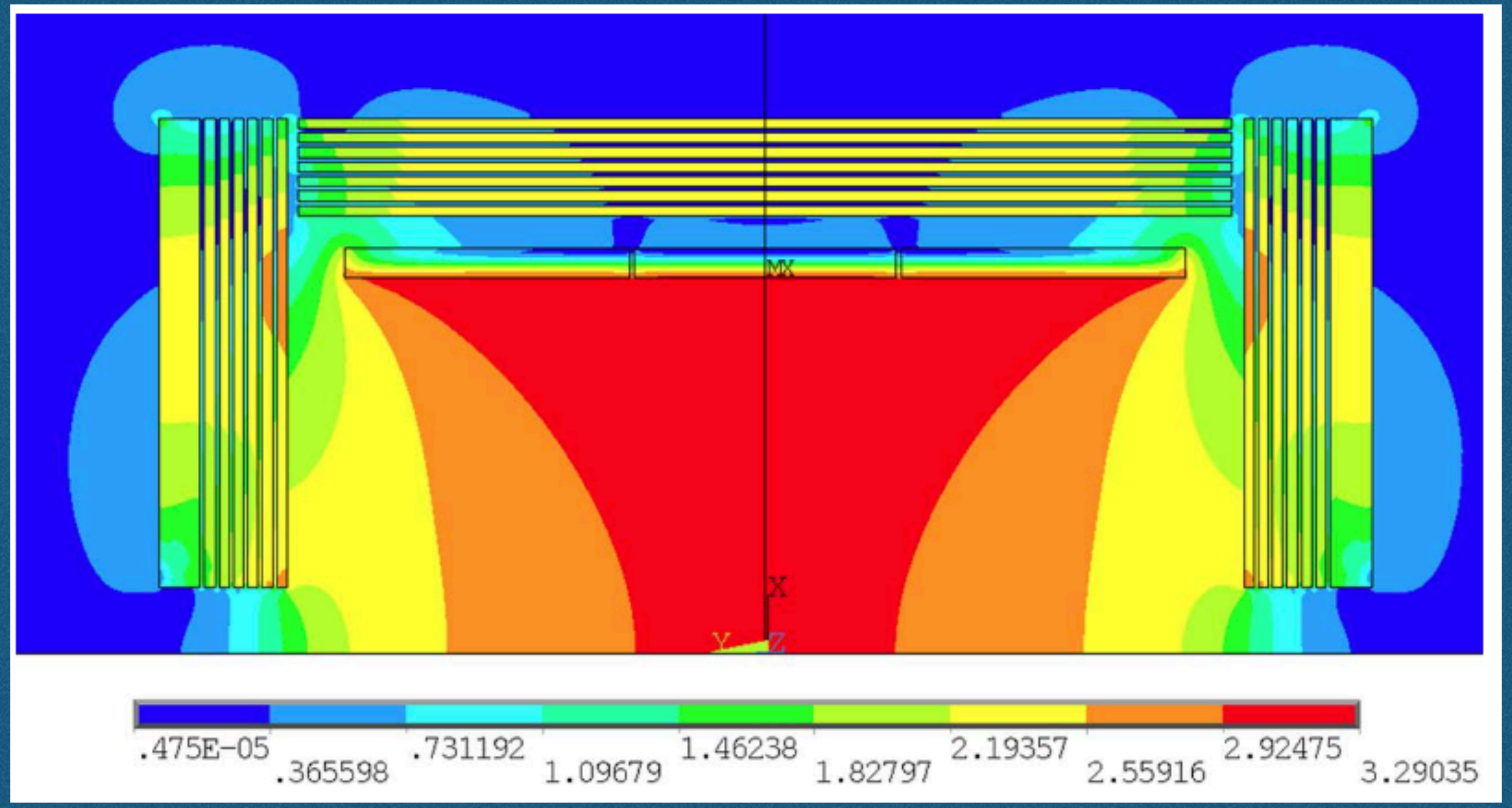
Coil length = 8.15 m

Operational conditions:

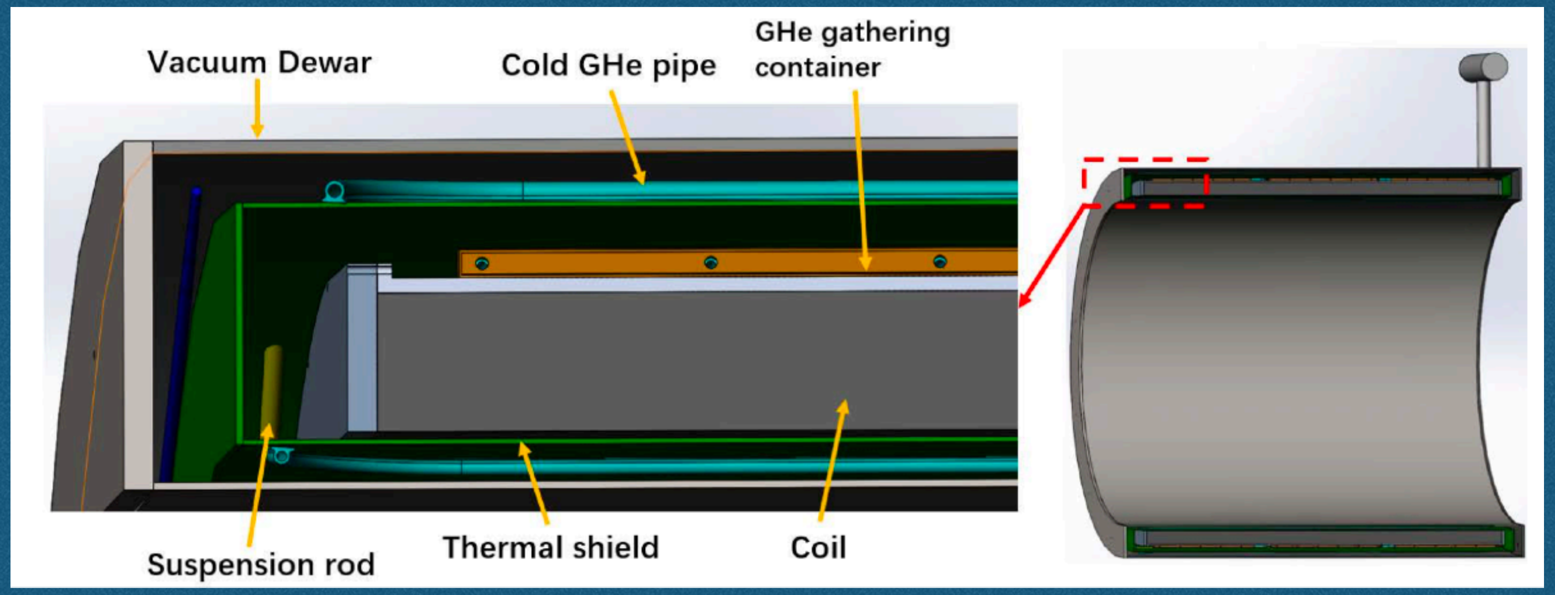
Central magnetic field: 3 T
Temperature: 4.5 K
Current: 17 kA

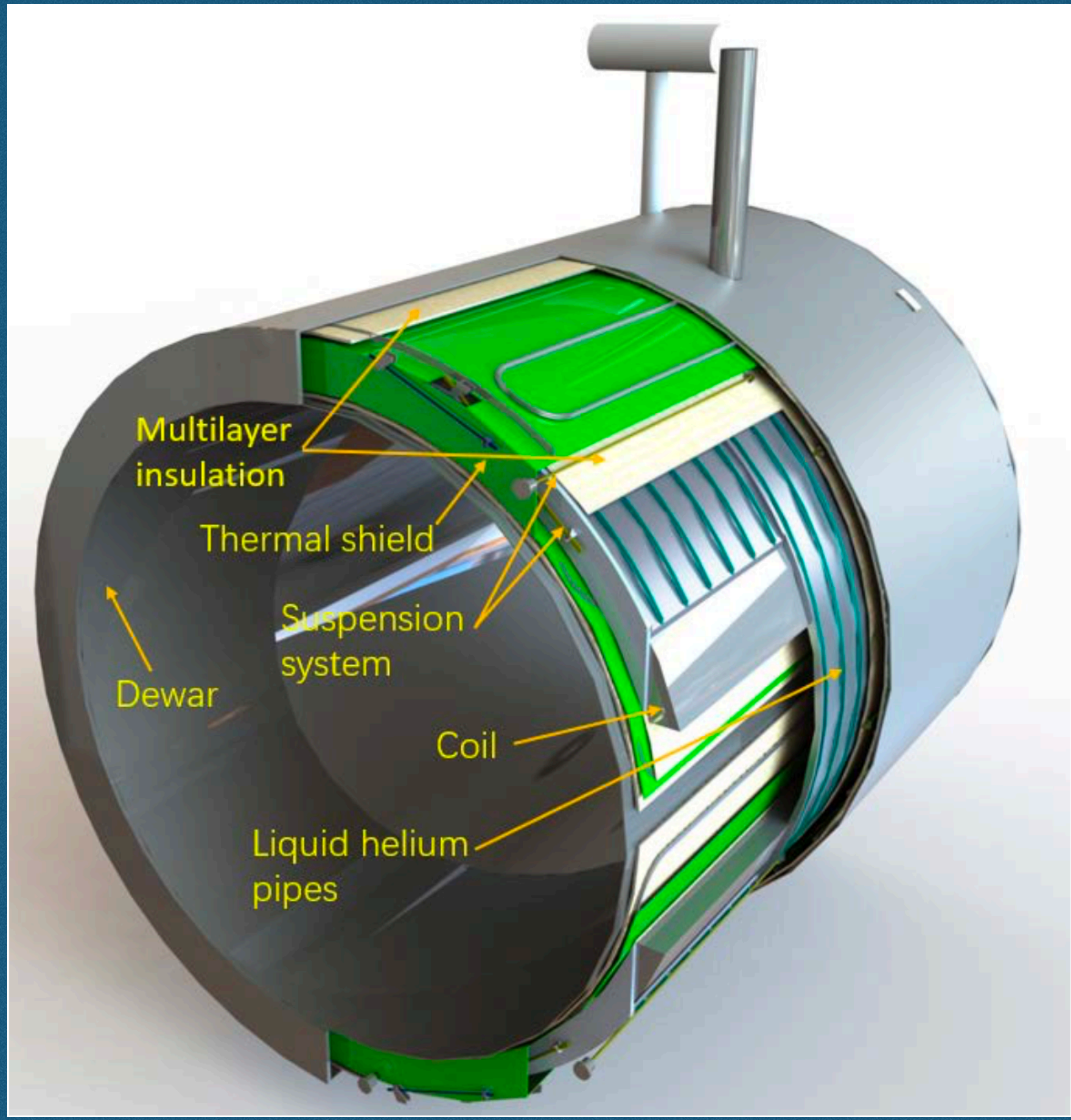
Magnetic field uniformity

~7% as required by TPC



Detailed mechanical design

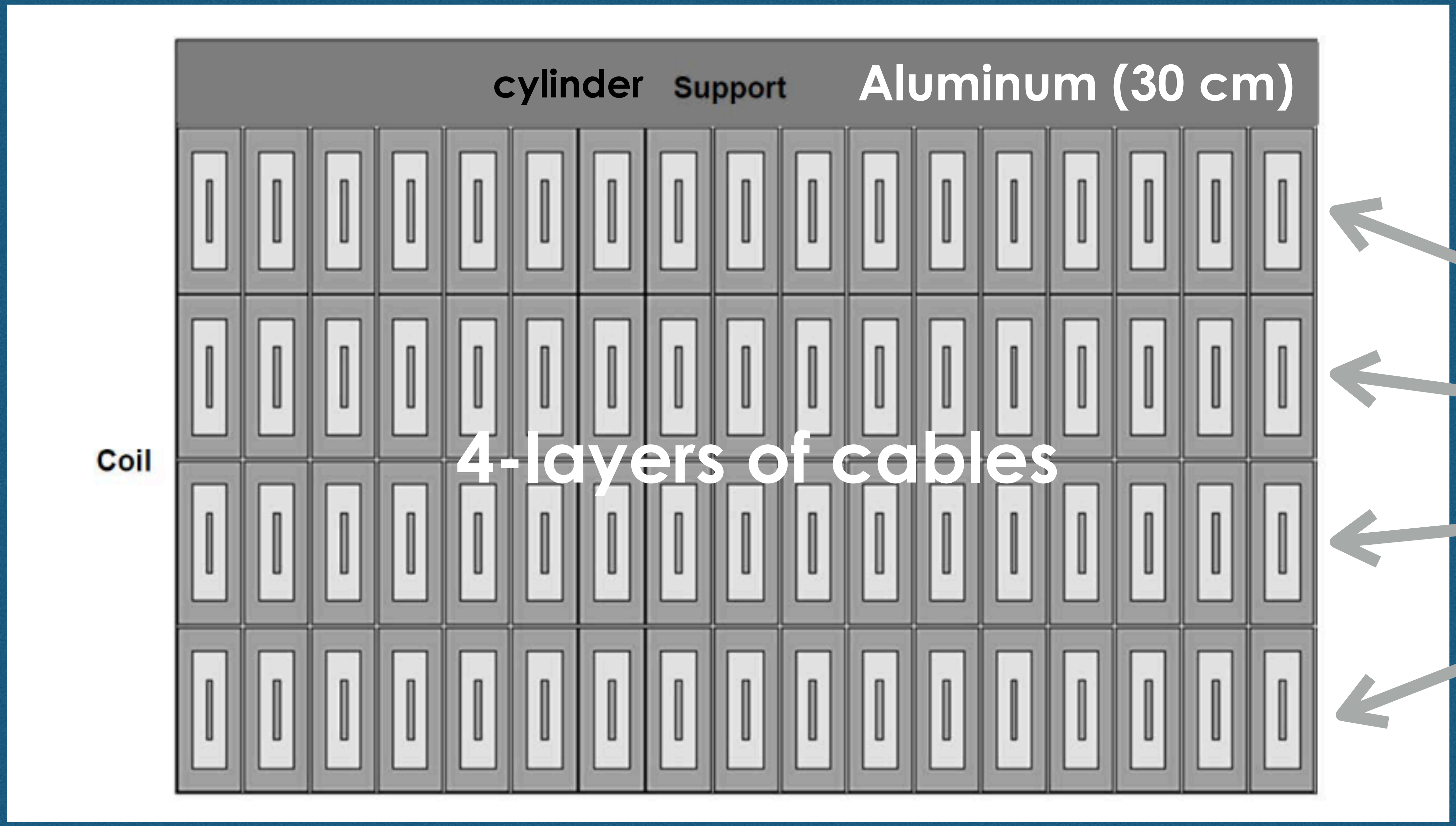


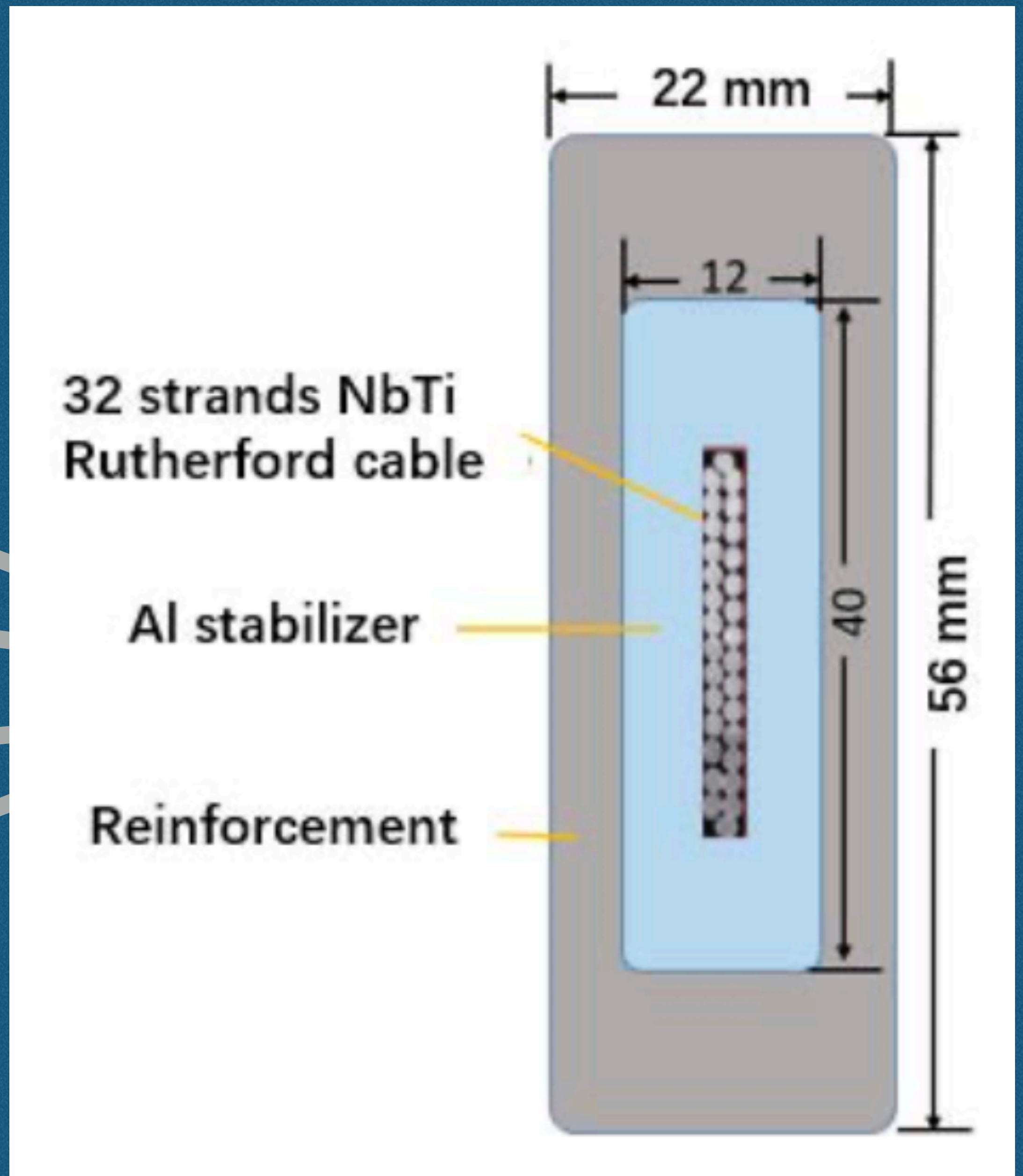


The Magnet System: Superconducting Solenoid

Aluminum Stabilized Superconducting Cable

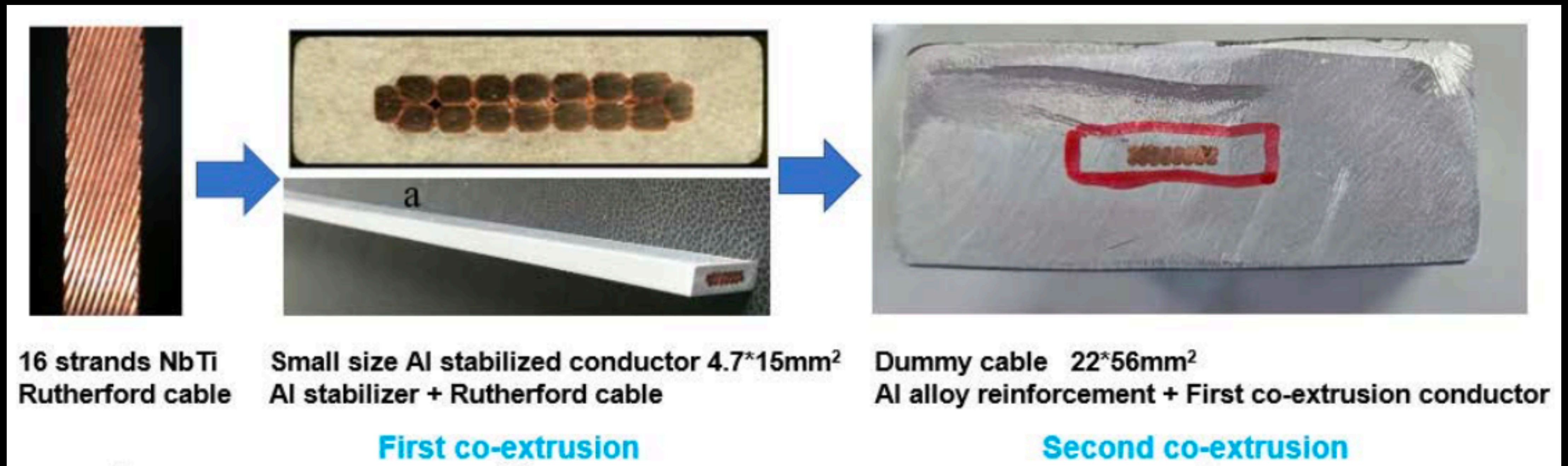
Aim to produce a thin solenoid puts pressure on the design of superconducting cable

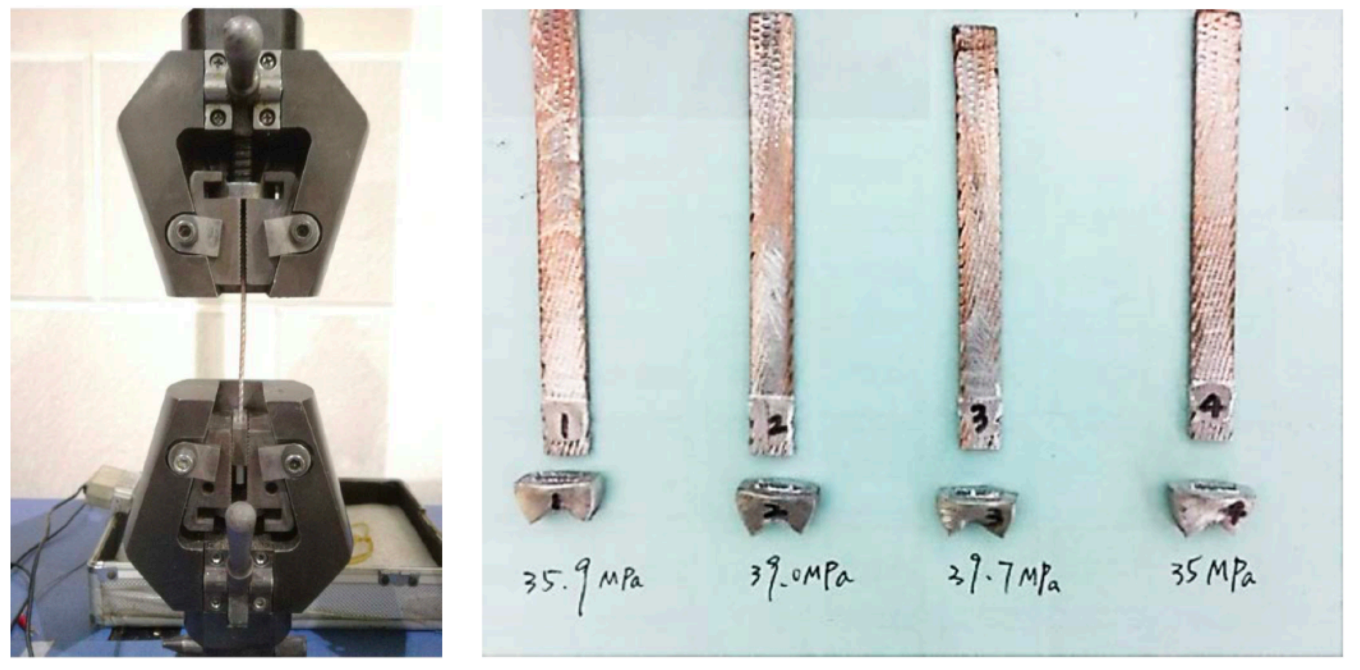




Requires
double extrusion cables
for sufficient strength to
survive stress energized
under cold

Complex cable
under development

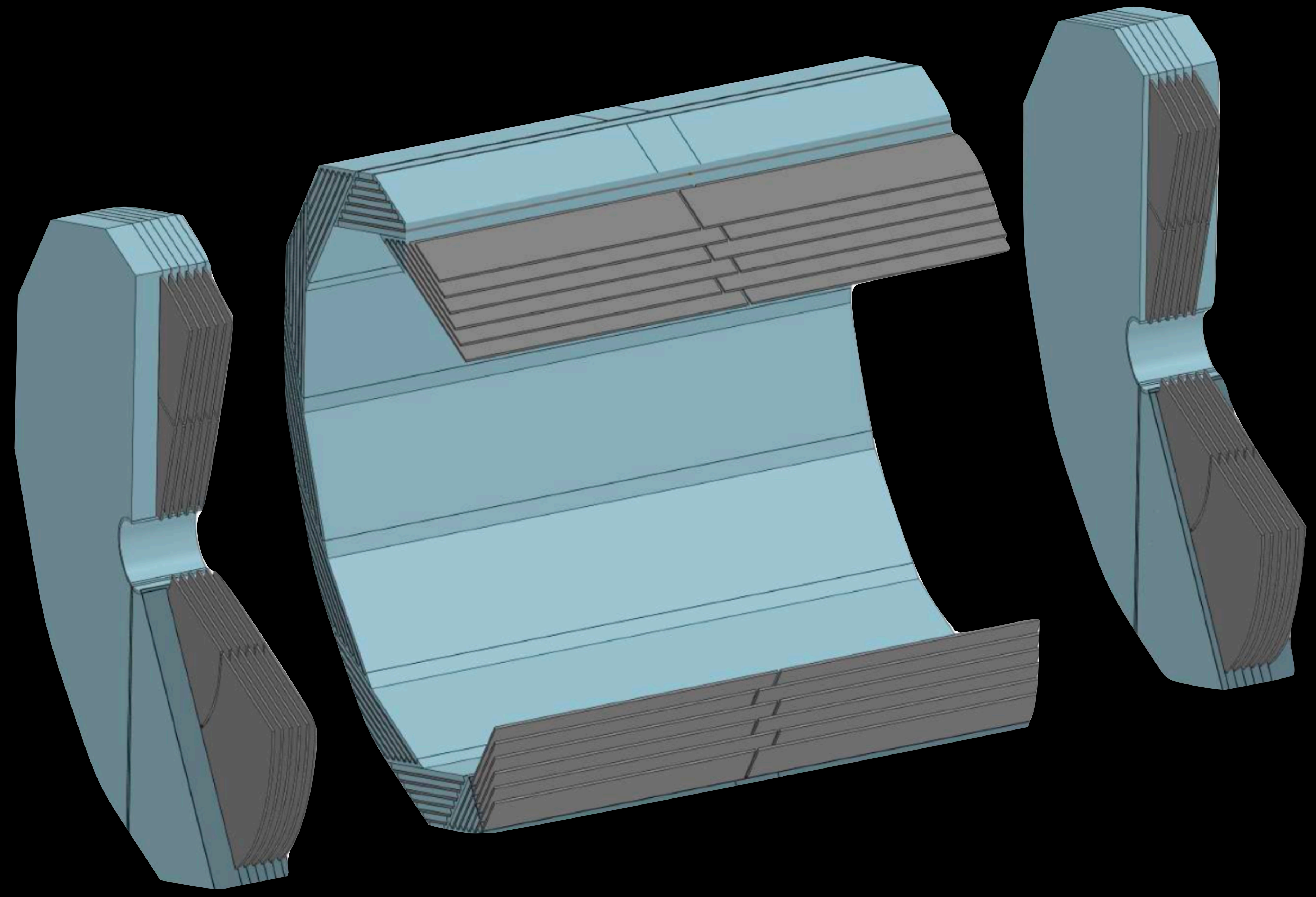




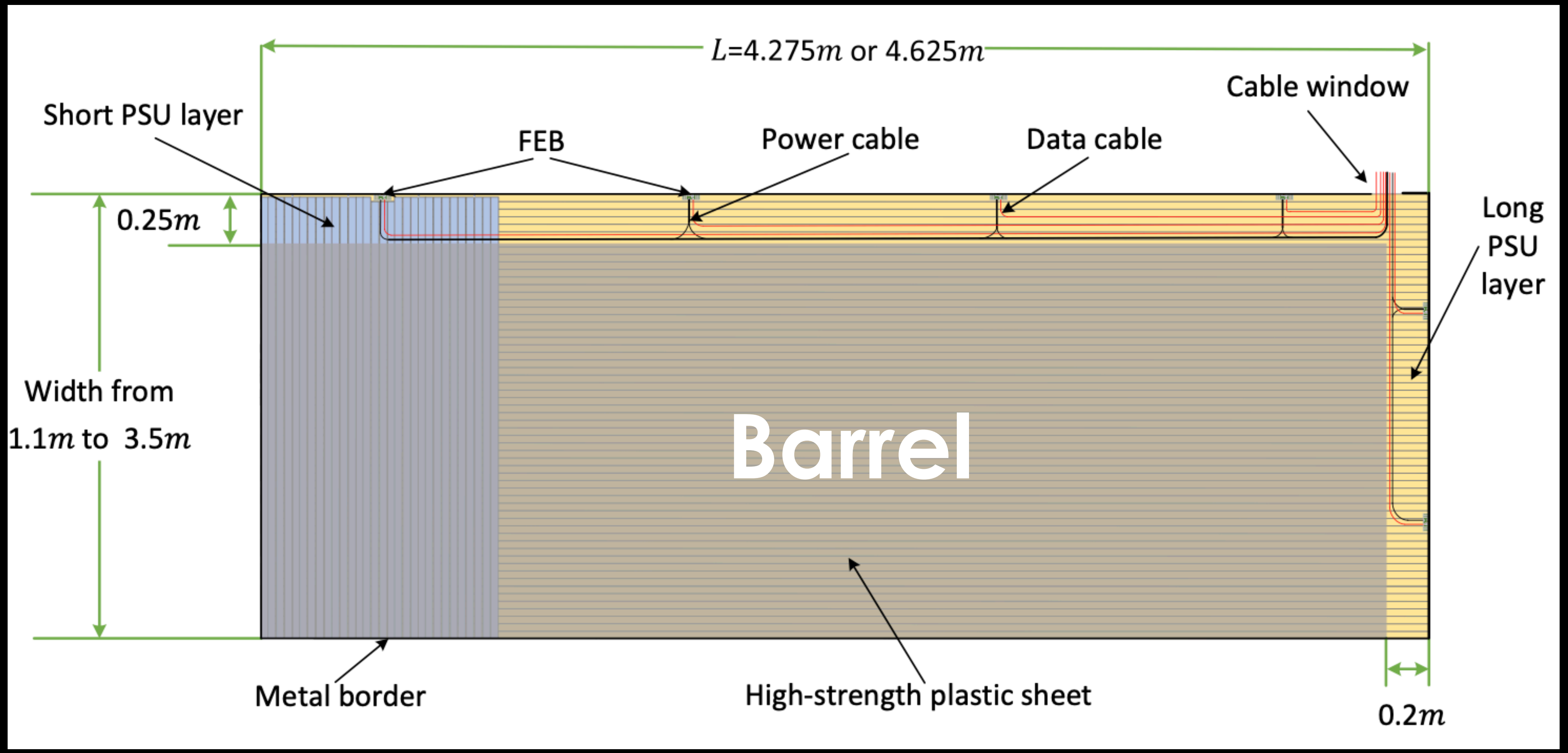
250-m dummy cable
produced and tested

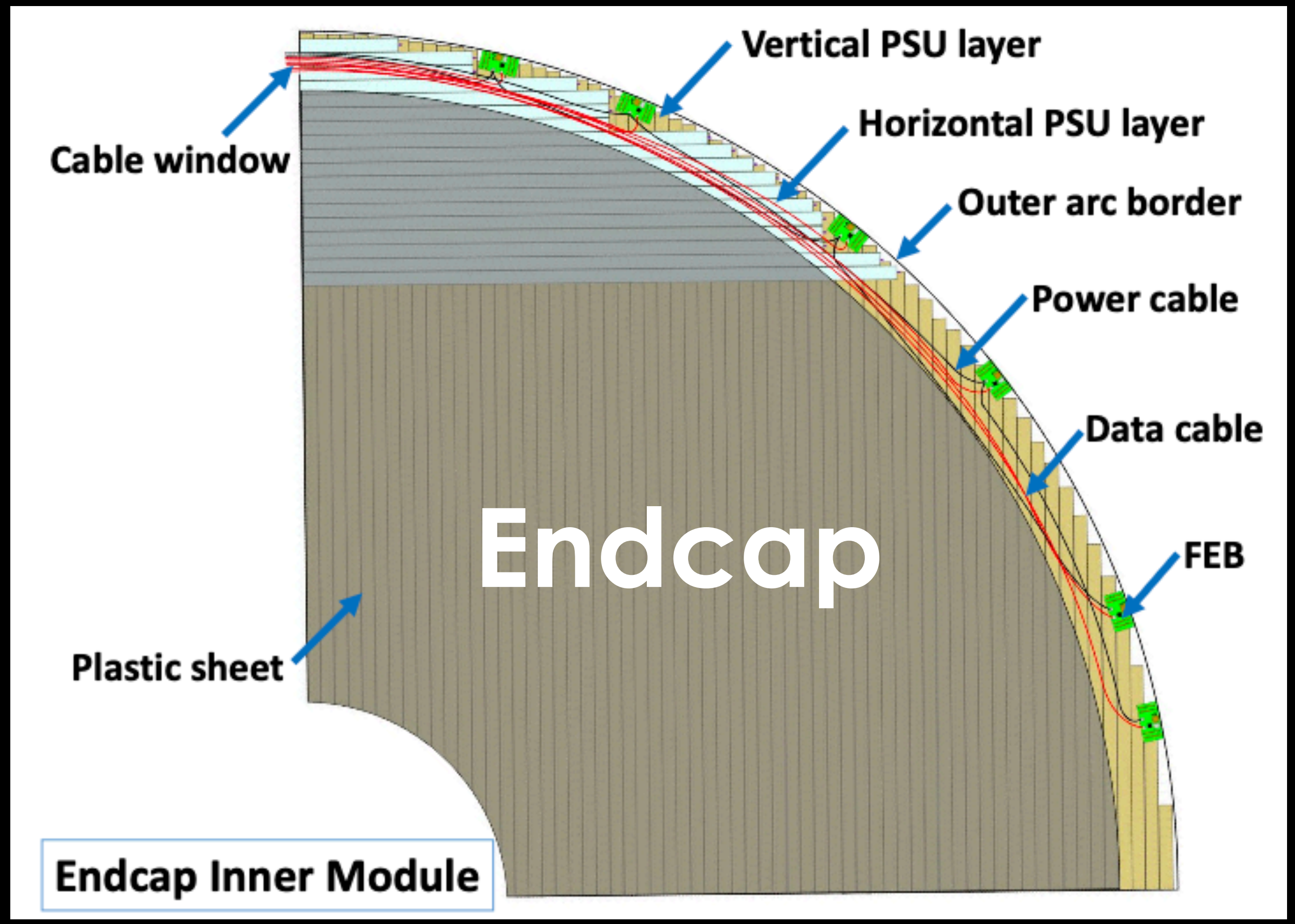
The Muon Detector

6 layers of plastic scintillator strips embedded in the iron Yoke



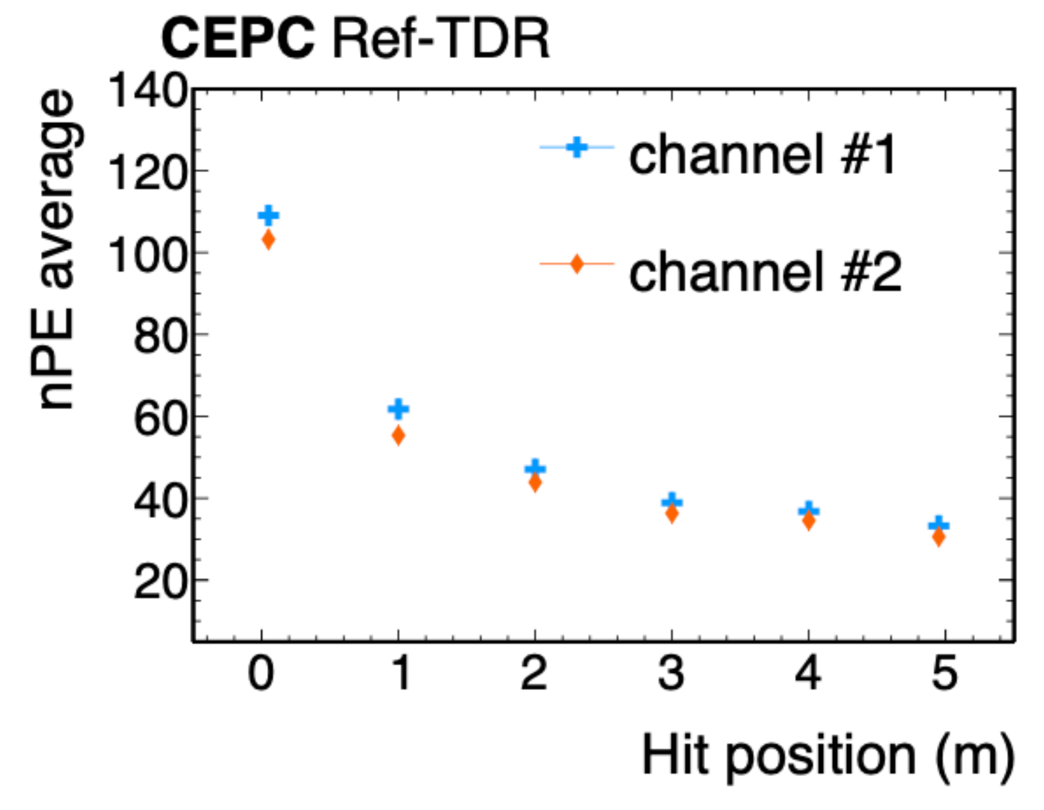
- Solid angle coverage: > 98% × 4π
- μ identification efficiency: > 95%
- $\pi \rightarrow \mu$ fake rate: <1%
- Spatial resolution: ~1 cm
- Time resolution: ~1 ns
- Rate capability: 50 Hz/cm^2

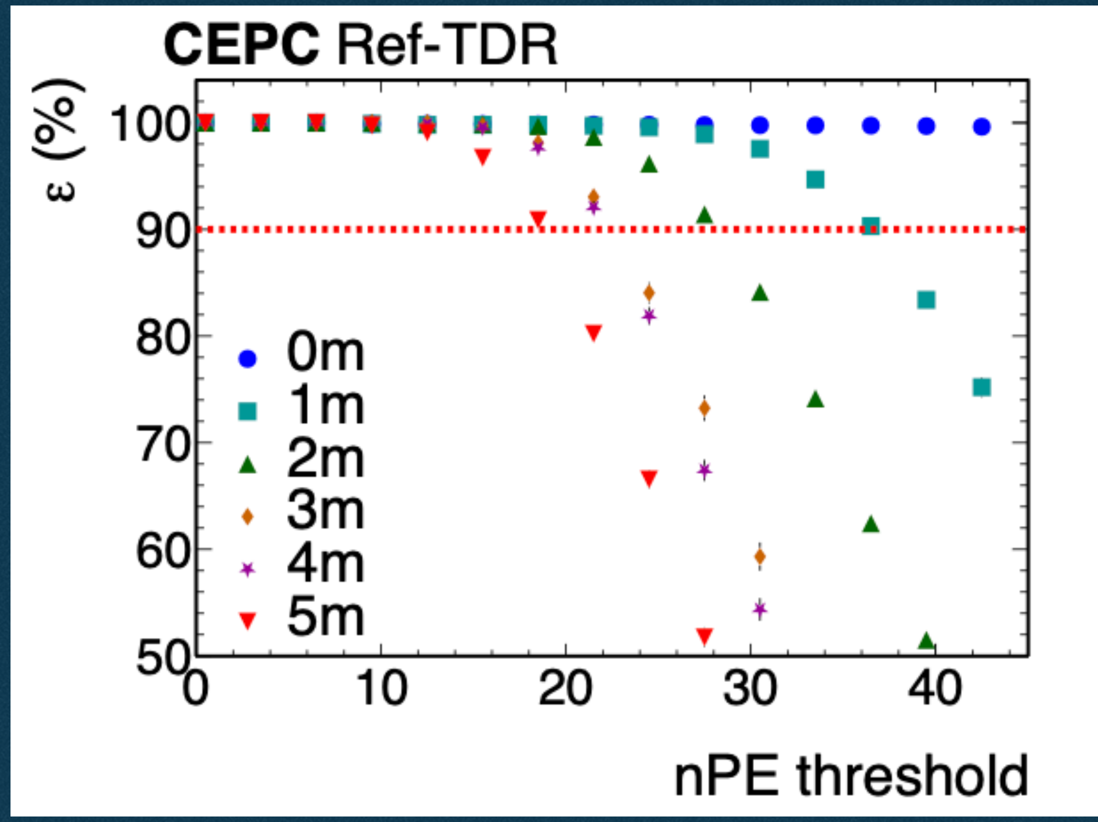


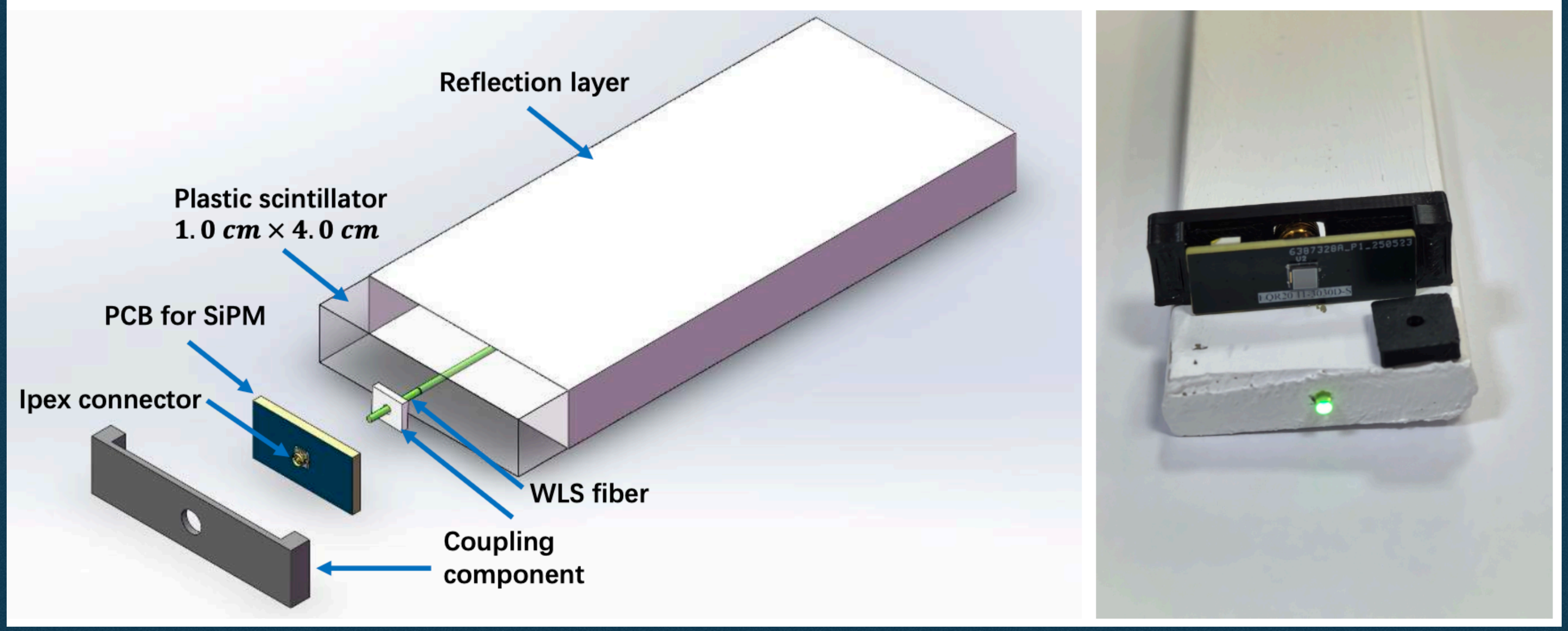


The Muon Detector

Extensive R&D on SiPM and long plastic scintillator strips with WLS fibers

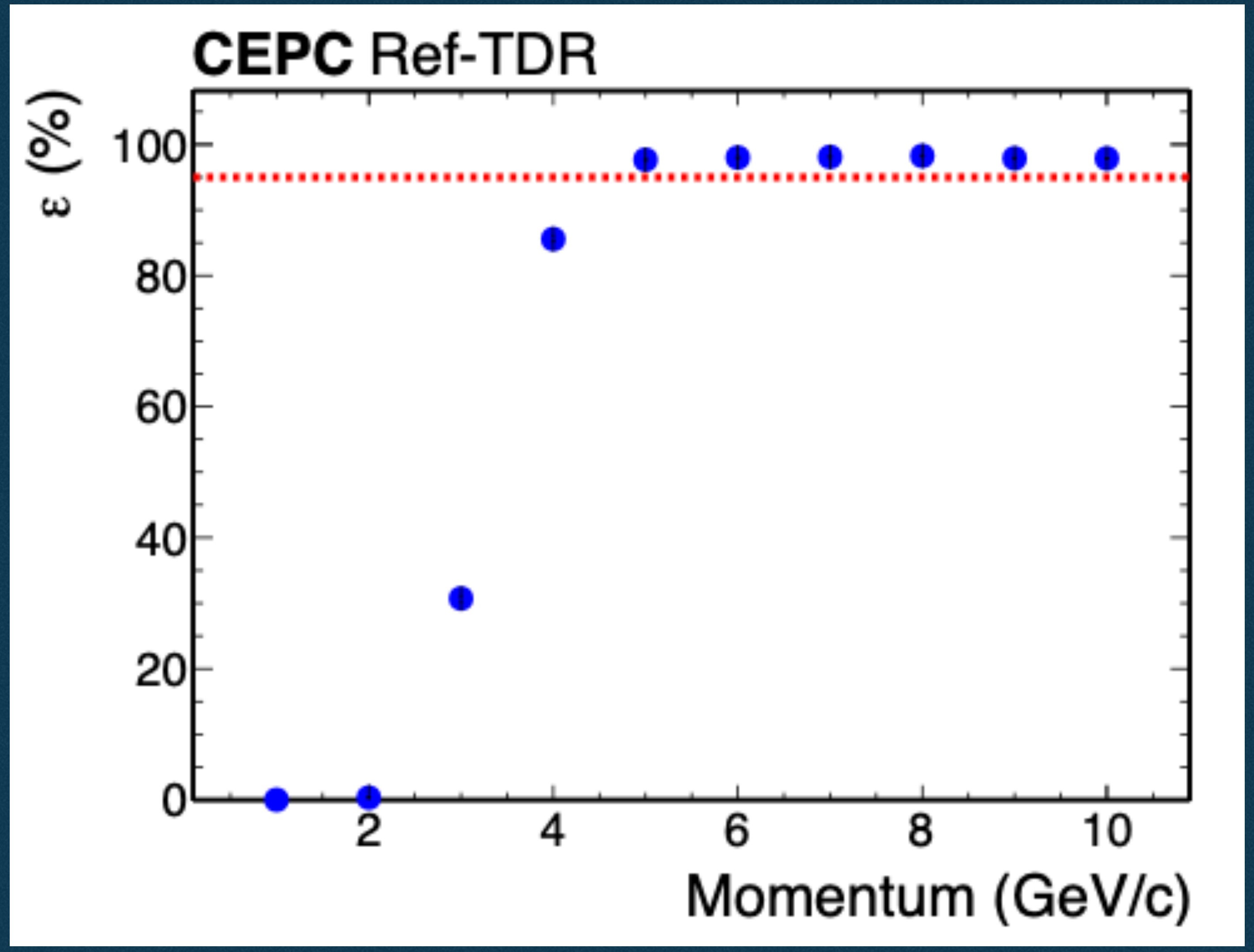


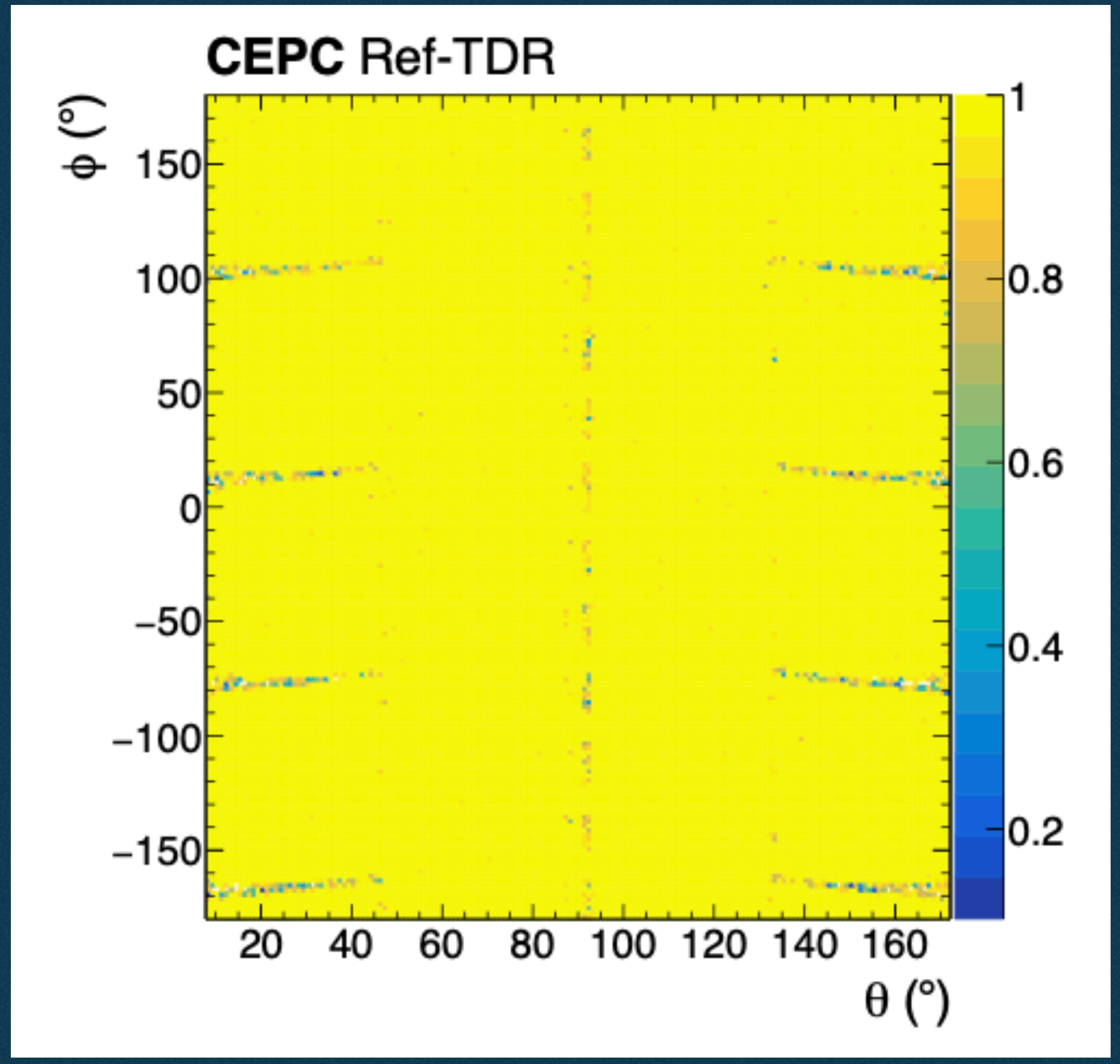




5 meter strips with >90% efficiency

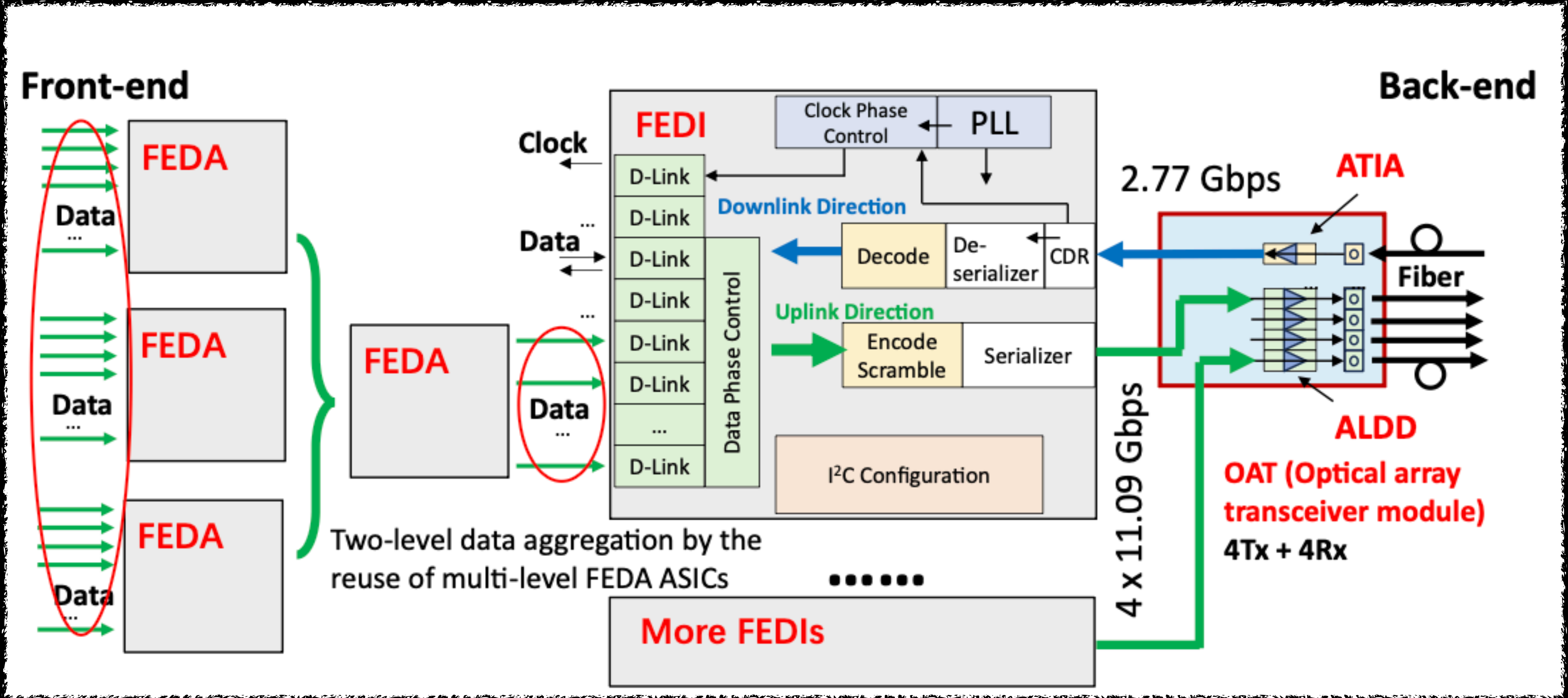
Standalone muon detector efficiency ~98% for muons above 4.5 GeV/c





Common Electronics

Significant effort put into defining common infrastructure, such as, the architecture of the data interface

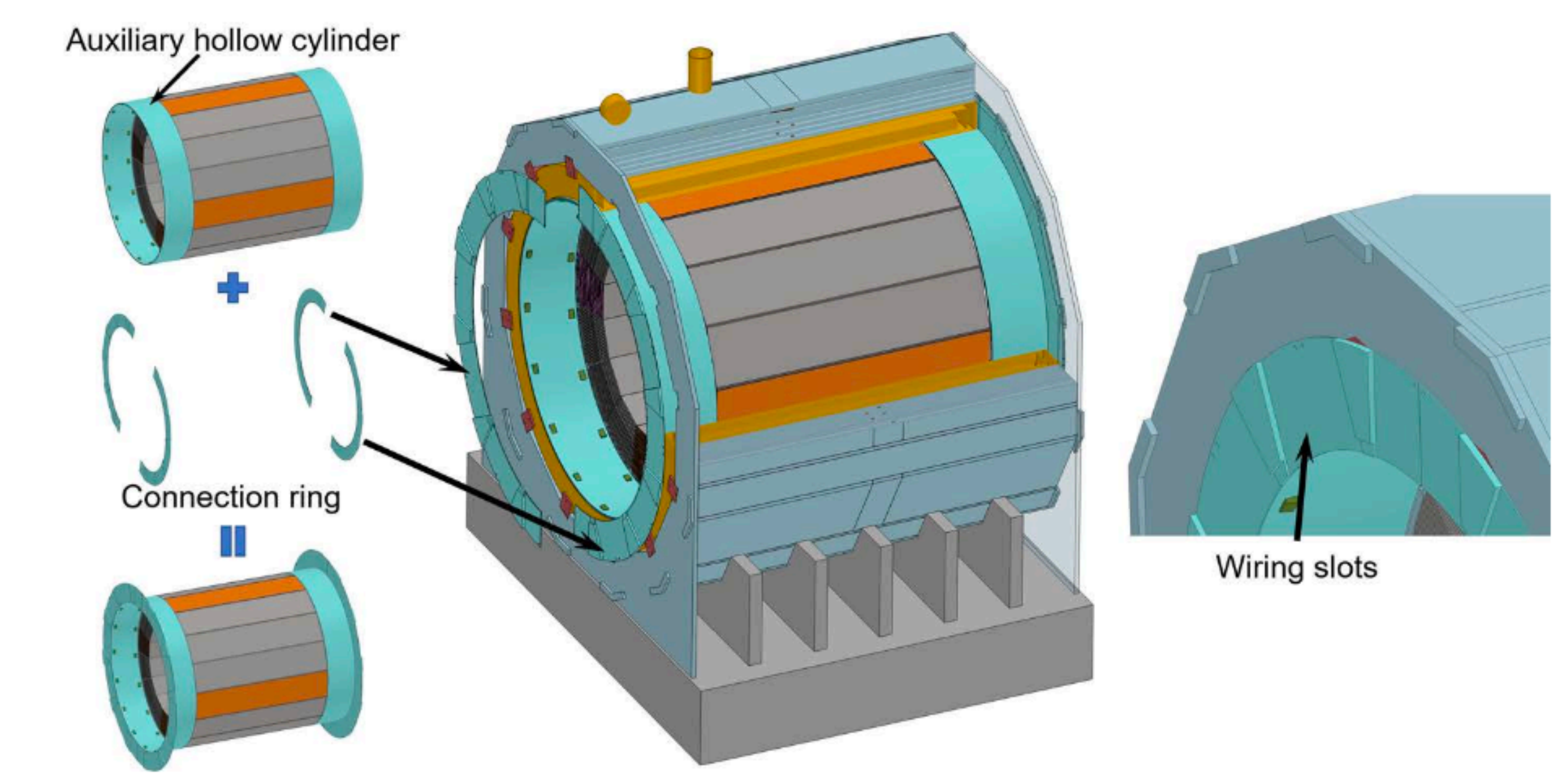


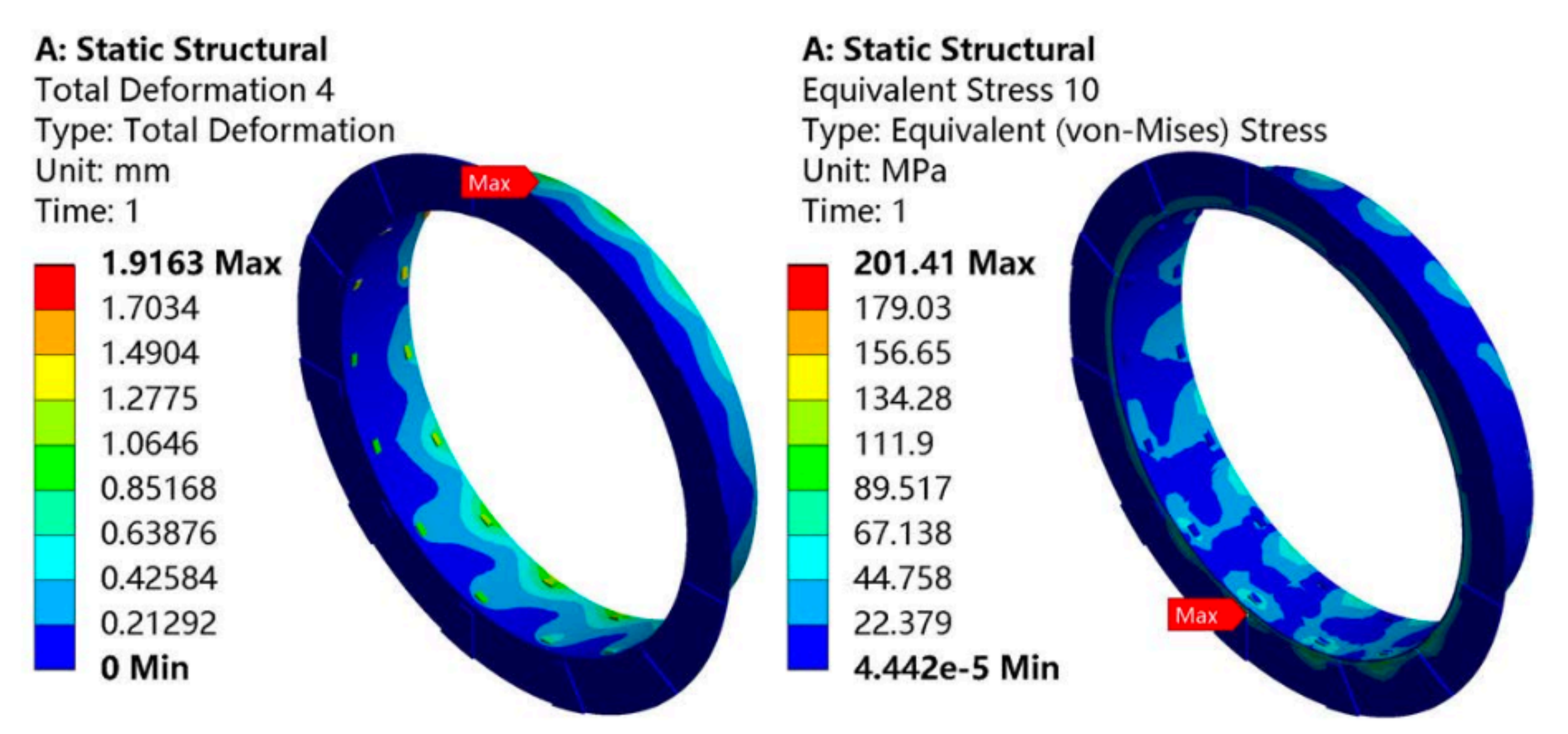
The data interface has a custom Optical Array Transceiver (OAT), and ASICs including: the Front-End Data Aggregator (FEDA), Front-End Data Interface(FEDI), Array Laser Diode Driver (ALDD), and Array Transimpedance Amplifier (ATIA)

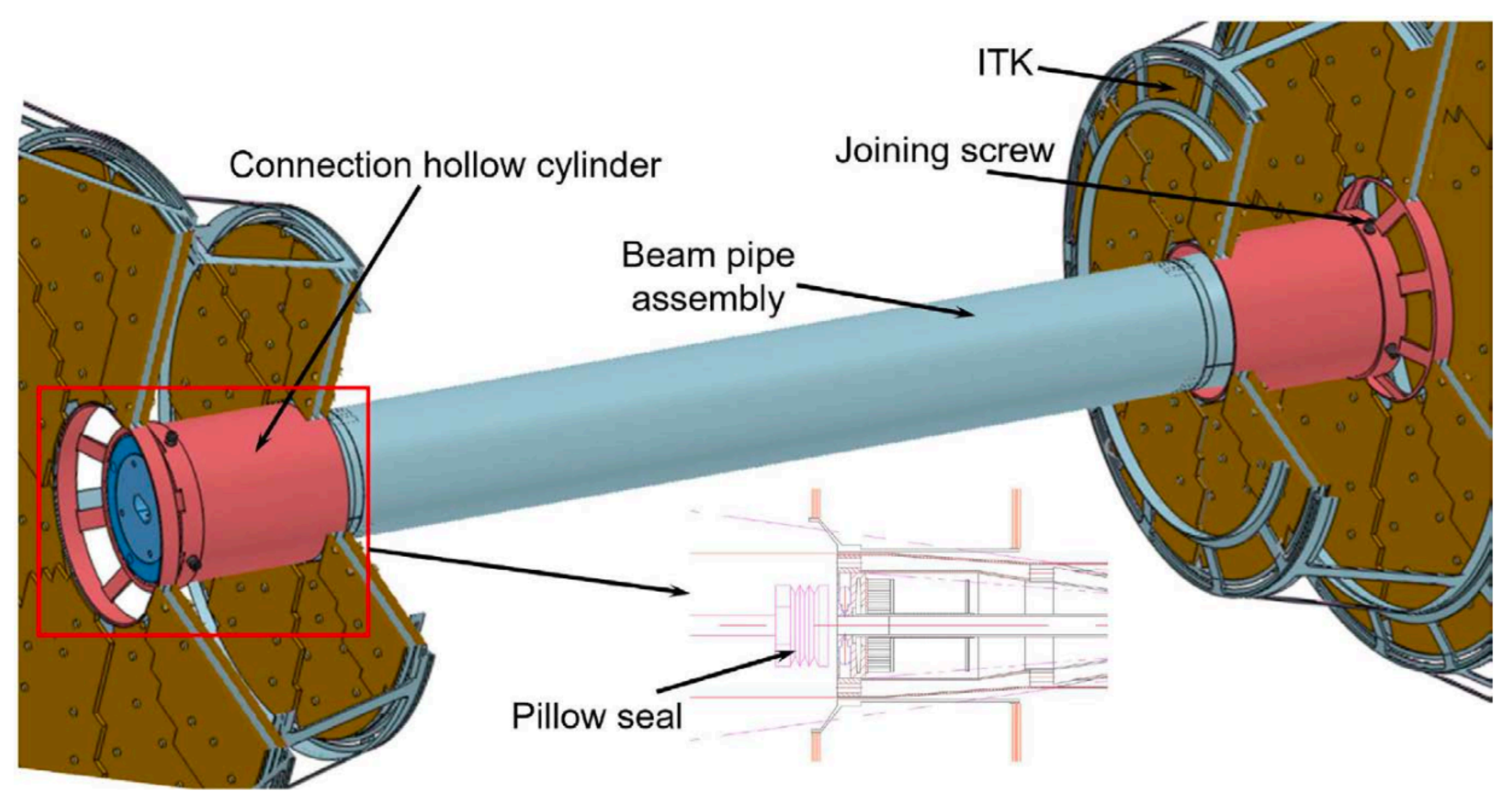
Mechanics and Integration

Sub-detector interconnections and installation was studied in detail (chapter 14)

Example: Connection structure of the barrel HCAL.





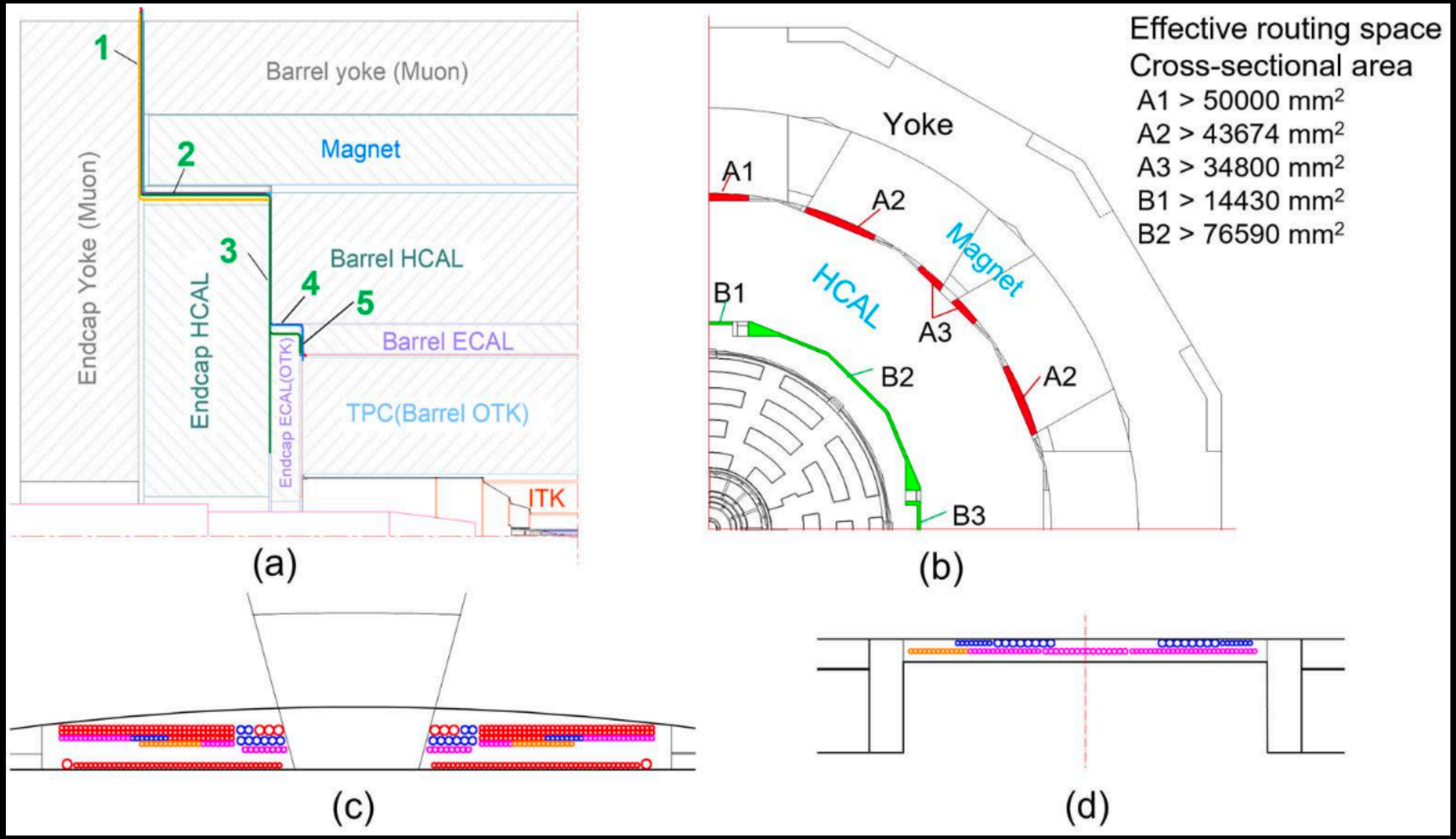


Example: Connection of ITK to beam pipe assembly and connection to the accelerator vacuum pipe

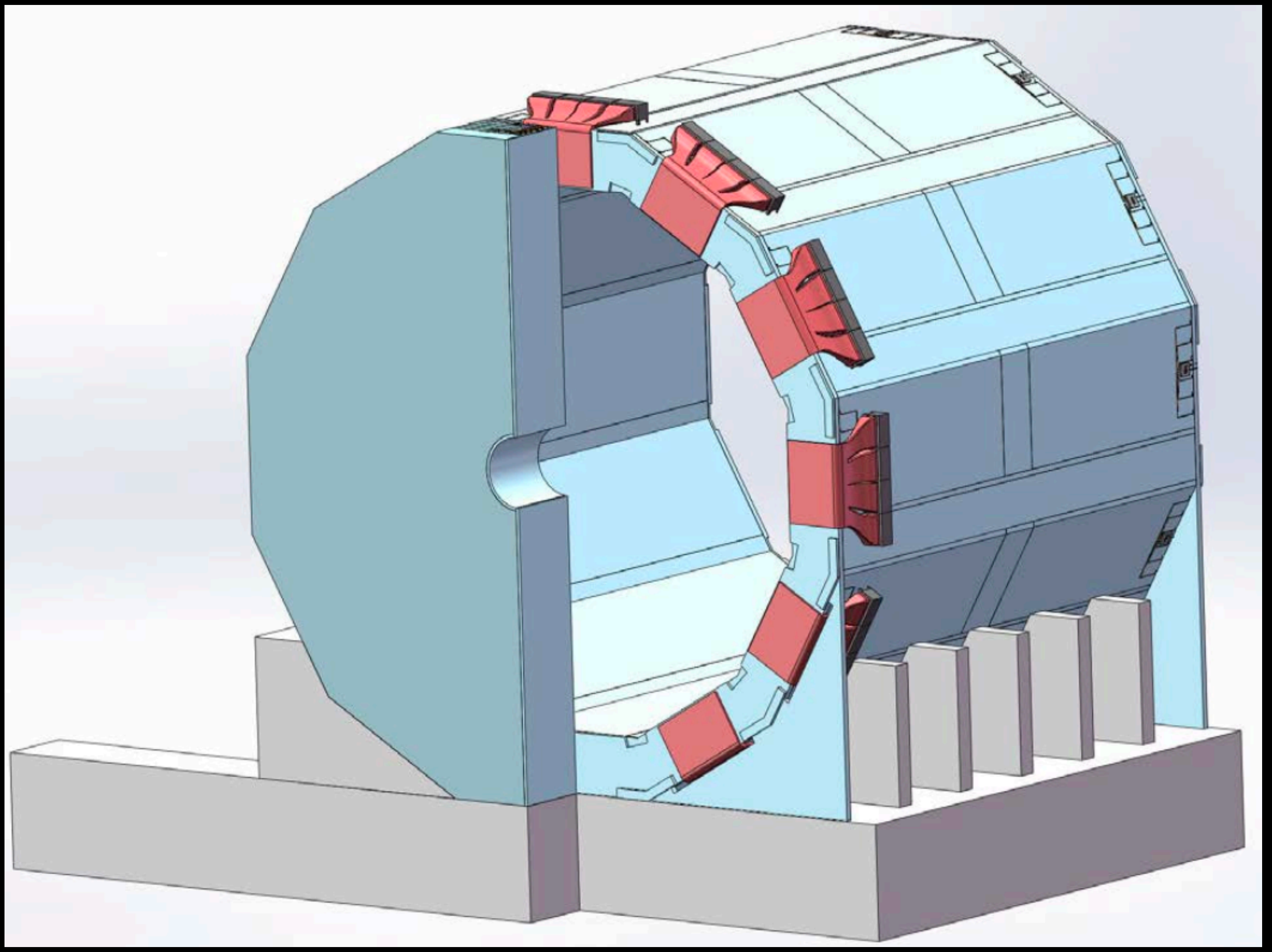
Mechanics and Integration

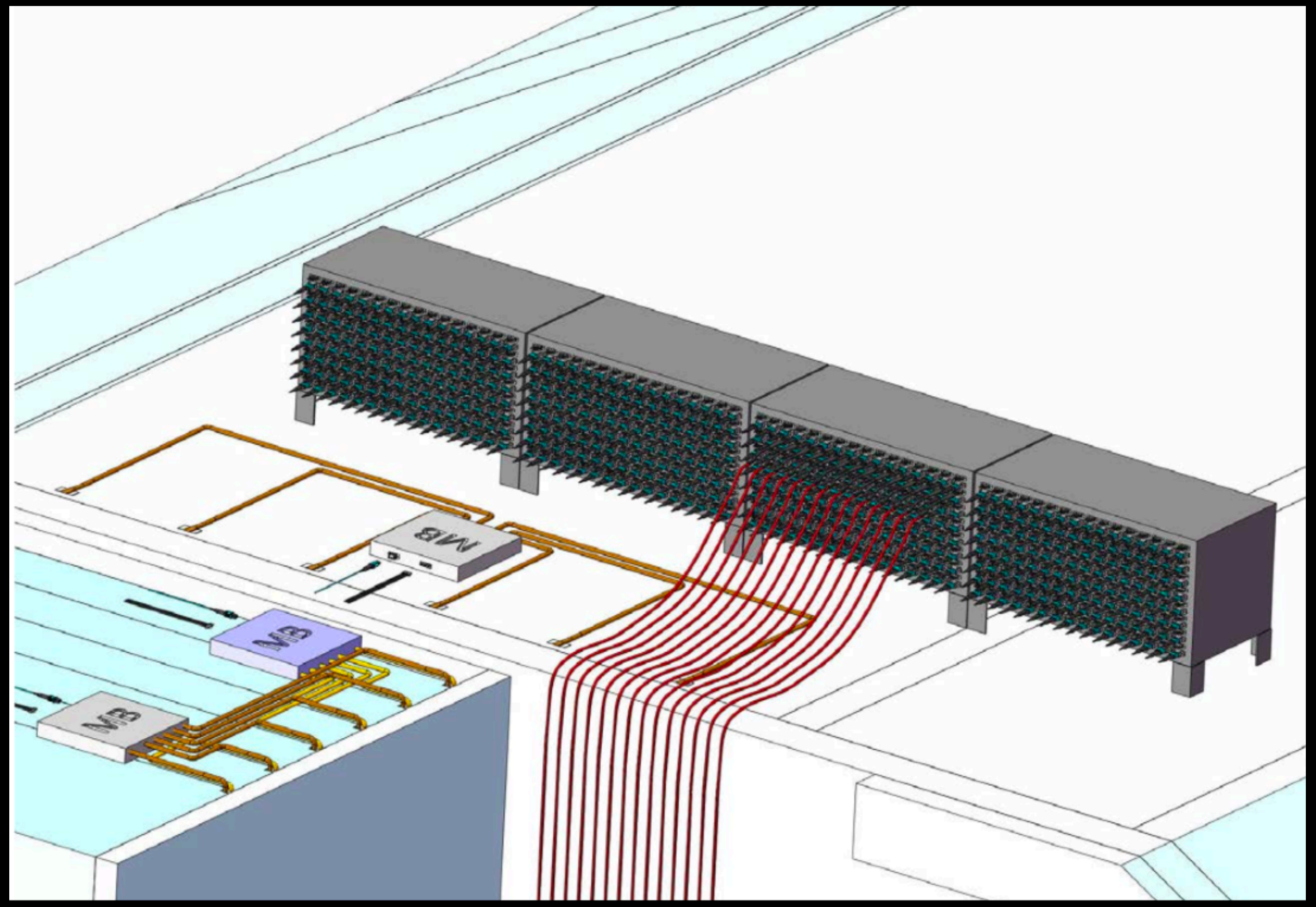
Cable routing and services connections

Inside Yoke



Outside Yoke





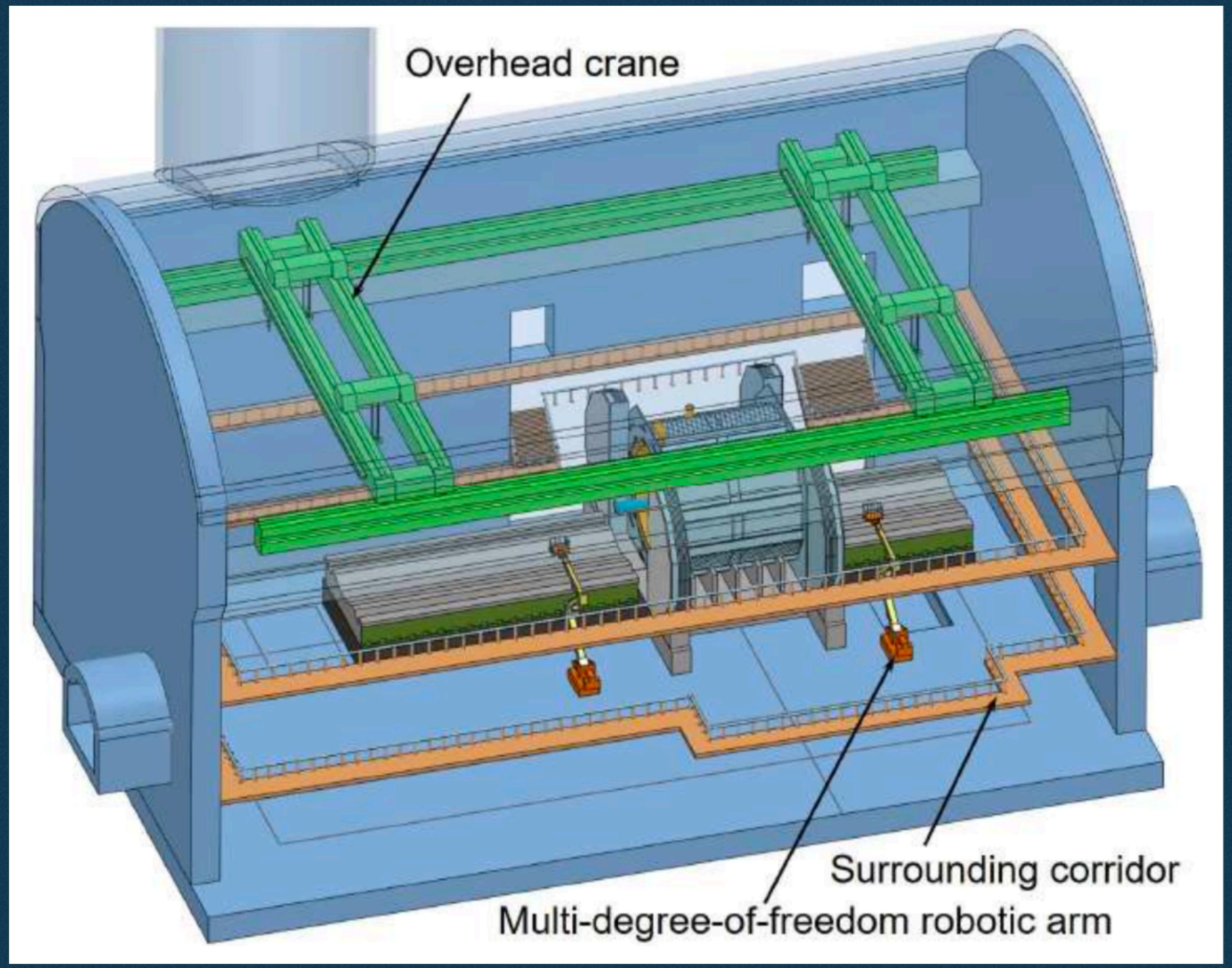
Mechanics and Integration

Installation will proceed from outside inwards

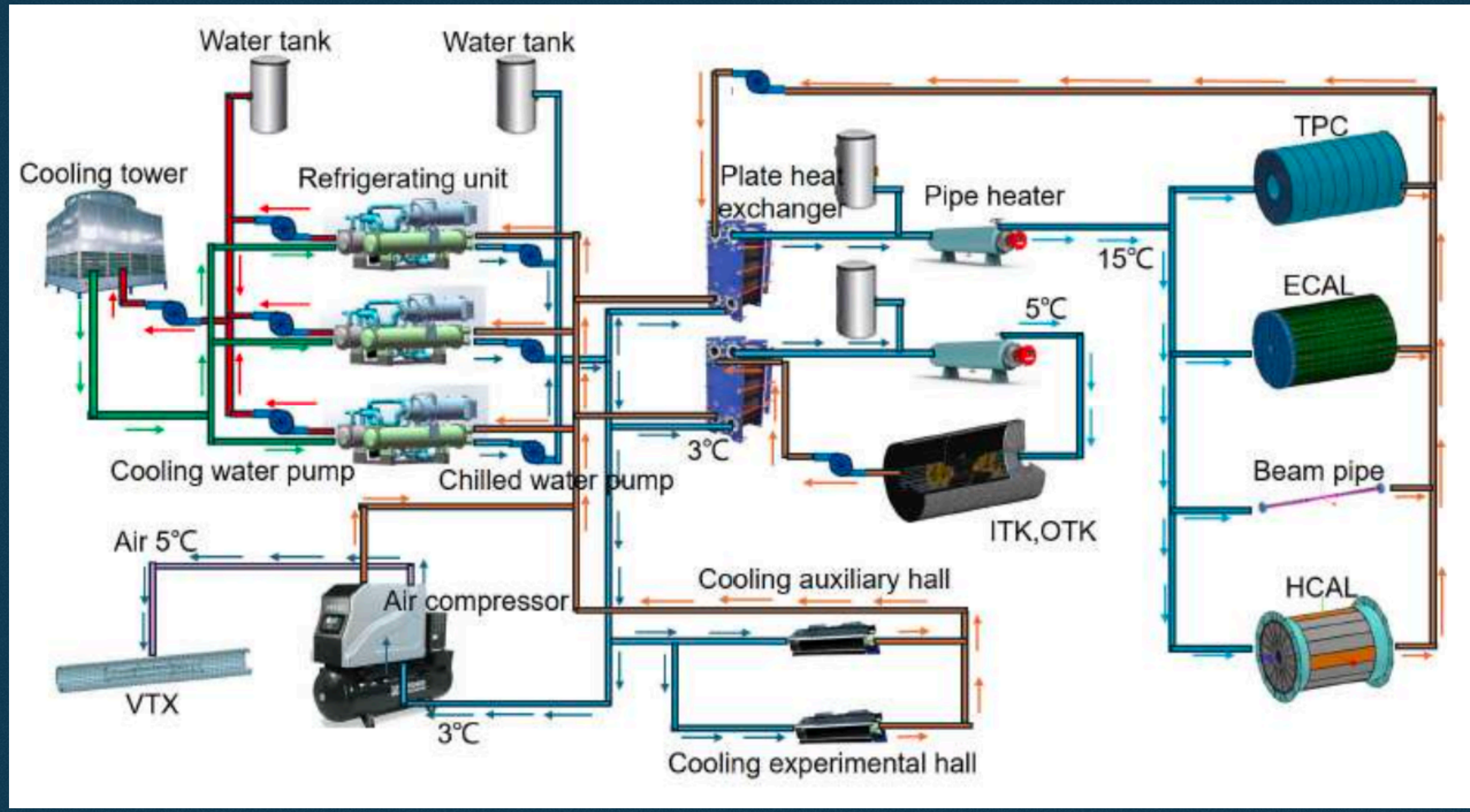
Mechanics and Integration

Layout of underground halls

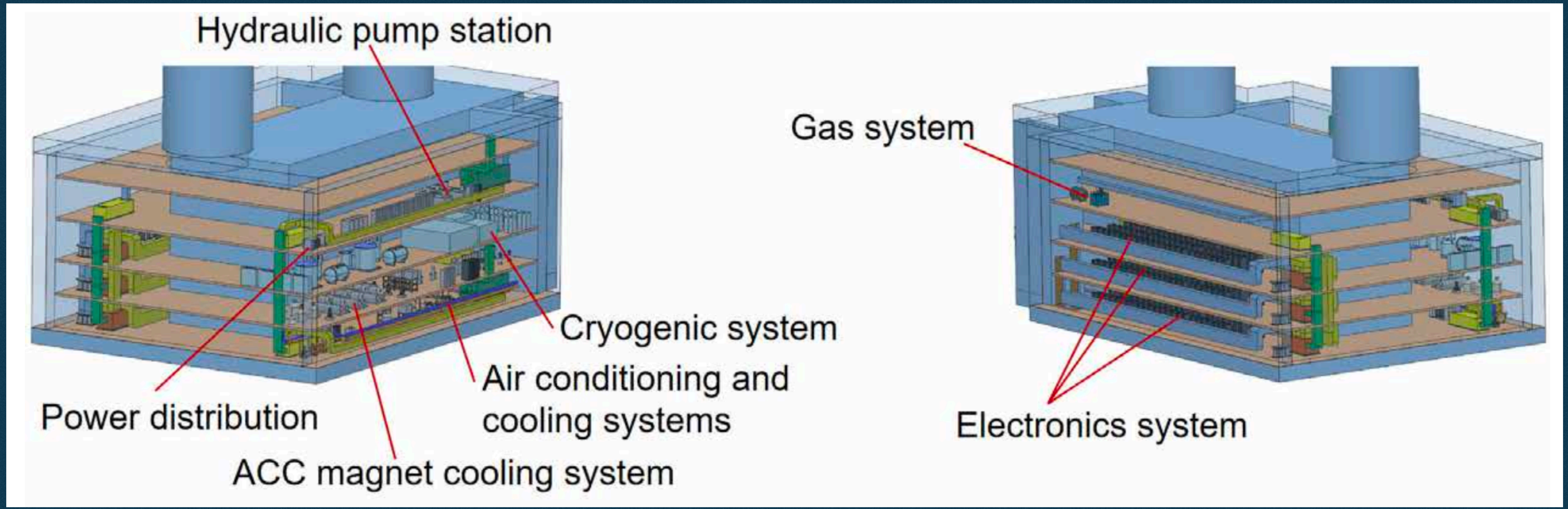
Collision hall



Cooling system



Auxiliary halls and facilities



Detector International Review Committee (IDRC)

International Committee composed of 19 experts in detector physics

Name	Affiliation	Country/Region
Daniela Bortoletto (chair)	Oxford	UK
Colin Gay	UBC	Canada
Bob Kowalewski	U Victoria	Canada
Burkhard Schmidt	CERN	CERN
Liang Han	USTC	China
Paul Colas	Saclay	France
Christophe De La Taille	OMEGA, CNRS	France
Cristinel Diaconu	CPPM	France
Roman Poeschl	IJCLab	France
Maxim Titov	Saclay	France

Name	Affiliation	Country/Region
Frank Gaede	DESY	Germany
Anna Colaleo	INFN, Bari	Italy
Tommaso Tabarelli de Fatis	INFN Milano-Bicocca	Italy
Roberto Tenchini	INFN, Pisa	Italy
Akira Yamamoto	KEK	Japan
Hitoshi Yamamoto	Tohoku U., Valencia	Japan
Gregor Kramberger	IJS	Slovenia
Ivan Villa Alvarez	Santander	Spain
James Brau	Oregon	USA

Three review meetings were held from October 2024 to September 2025

Detector International Review Committee (IDRC)

Final report outcome

In summary, the CEPC detector programme is entering a decisive stage. A significant portion of the technical groundwork is complete, but the coming years must consolidate the design through focused R&D, integrated prototyping, and system validation. By sustaining momentum in innovation while deepening international cooperation, the collaboration will be well positioned to deliver a technically mature and scientifically powerful detector system—one capable of serving as the basis for the two international experiments that will define the CEPC physics era.

Readiness for construction after R&D and engineering preparations

With sector/module demonstrators, thermal and mechanical mock-ups, full DAQ chains, and formal design/production reviews (FDR/PRR), the project can credibly achieve production readiness. The Ref-TDR supports early industrial engagement; remaining work is system-level validation and final down-selection on an agreed schedule.

Detector Cost

- **Detector total cost estimate: 333 MCHF**
  - Includes 3% installation cost, but no contingency
  - Includes projection for cost evolution in next 5-10 years

System	Cost (MCHF)
The Reference Detector	333.3
Machine detector interface and luminosity measurement	1.8
Vertex detector	4.5
Silicon tracker	29.7
Time projection chamber	6.2
Electronmagnetic calorimeter	115.0
Hadron calorimeter	68.3
Muon detector	2.5
Detector magnet system	22.0
Readout electronics	19.3
Trigger and data acquisition	12.2
Offline software and computing	23.1
Mechanics and integration	28.9

Cost drivers

1. Crystal calorimeter
2. Hadronic calorimeter
3. Silicon tracker

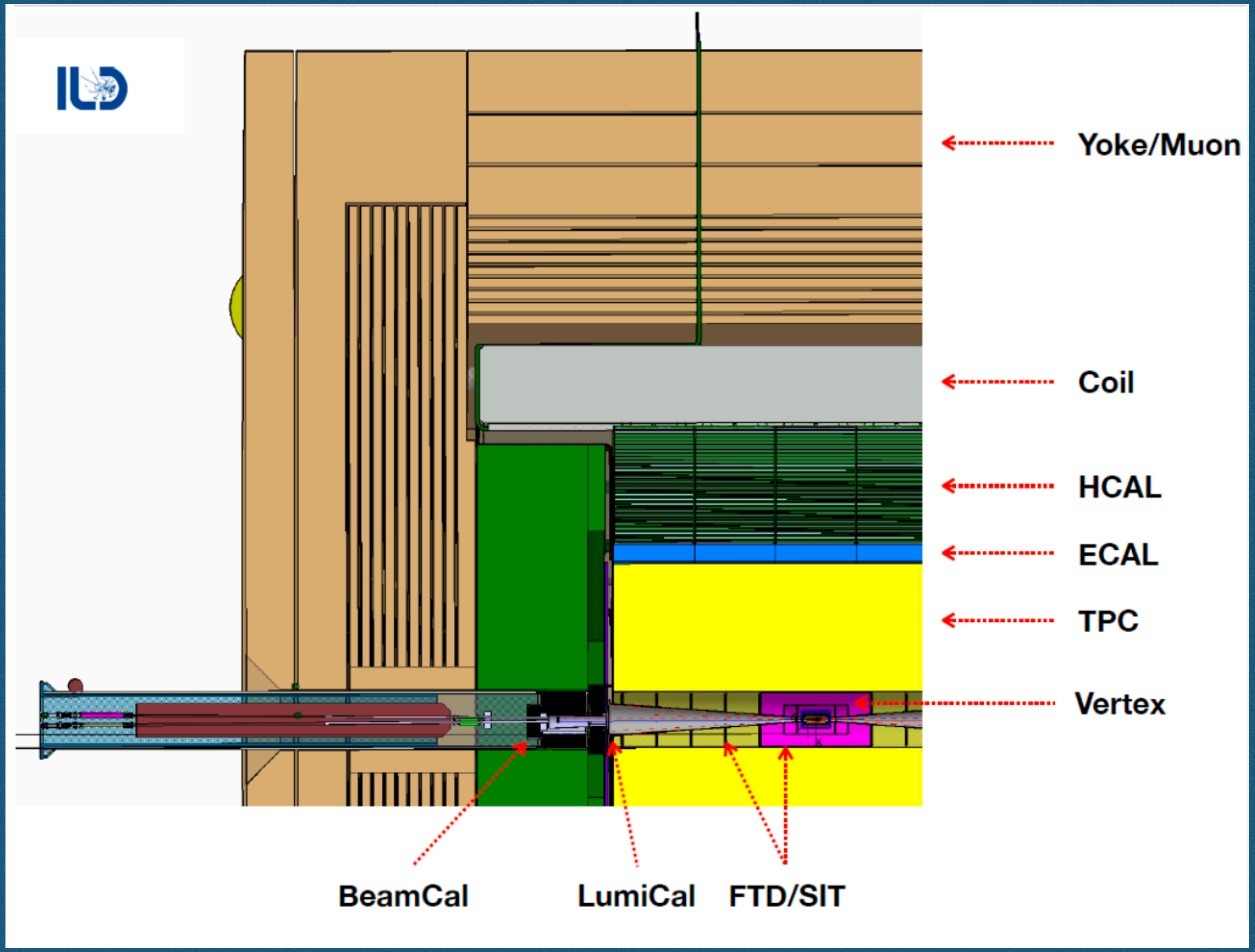
Review by IDRC

The cost evaluation for the reference detector to be **well structured**, **robust**, and consistent with **comparable assessments** from other large-scale experimental projects

Alternative Detector Concepts in the TDR

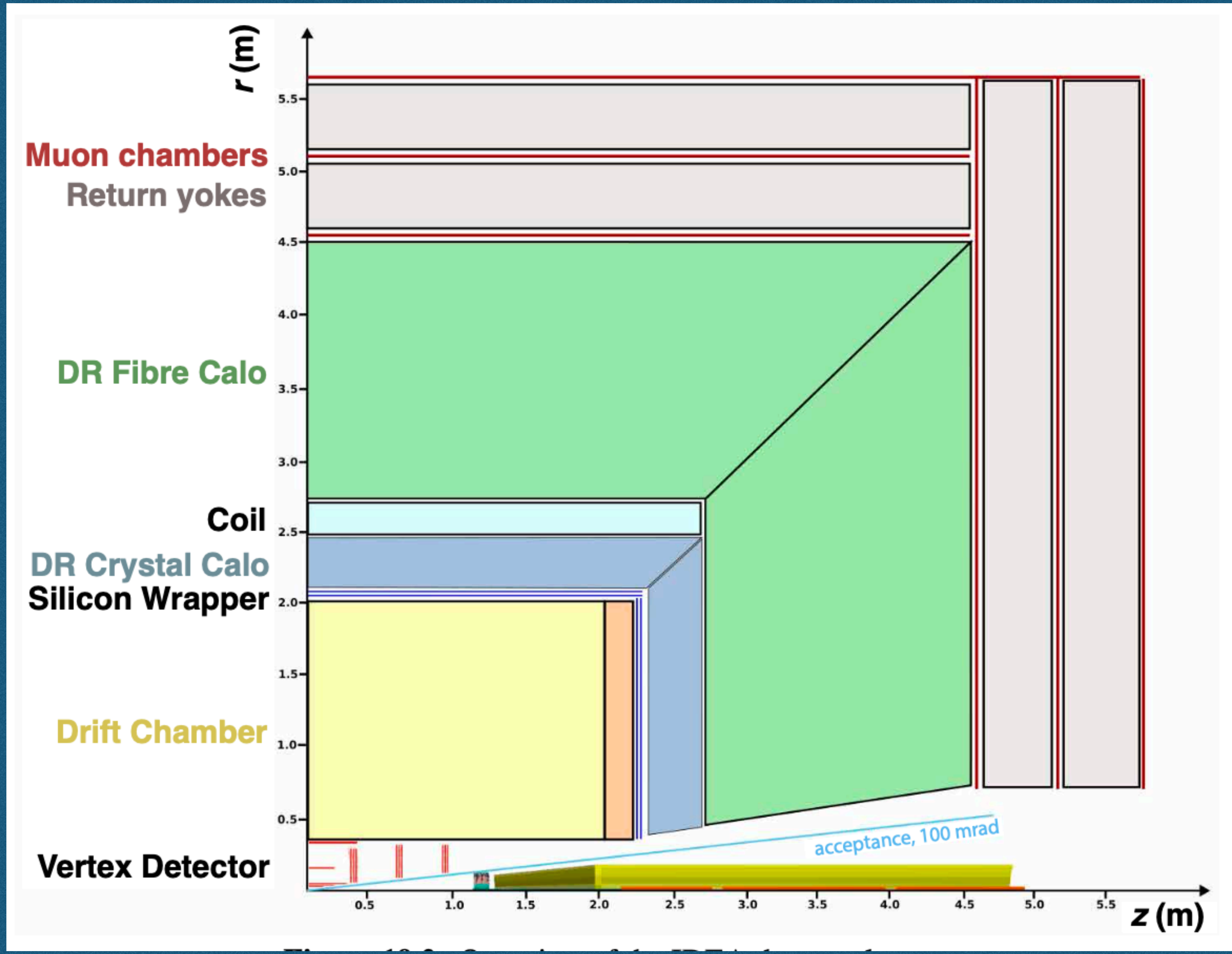
(not reviewed by IDRC)

ILD: International Large Detector



Chapter 18

IDEA: Innovative Detector for Electron-positron Accelerator



Chapter 19

Final two detectors will result from international proposals

Final remarks

The Reference Detector TDR was finished mid October 2025

The Detector is a innovative, but challenging concept, capable of delivering the CEPC physics

The technical design of each sub-system is well advanced although some R&D remains necessary

Focus will shift into consolidating the designs and validation with large scale prototypes and mechanical mock-ups

CEPC community remains committed to international collaboration

Engagement between research communities of different future projects will highly benefit everyone who has the goal to continue exploring the high-energy frontier

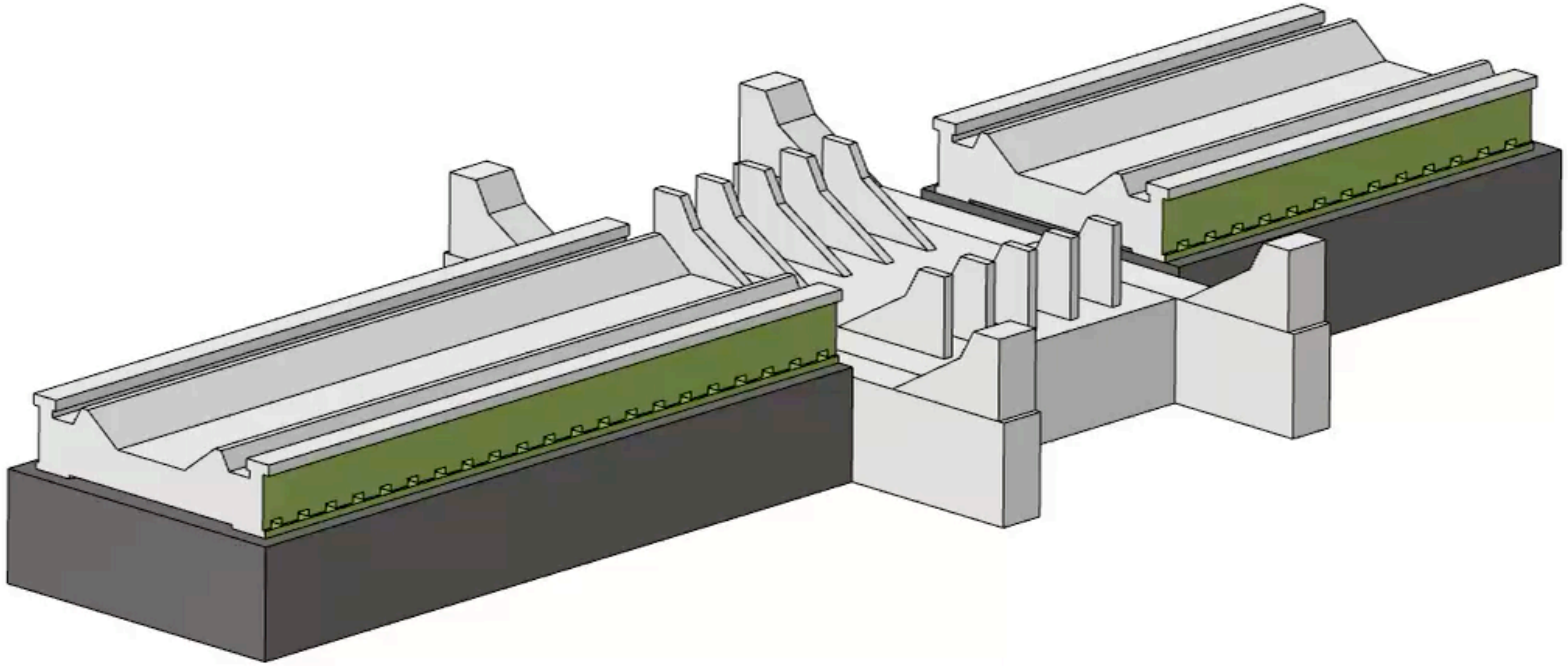
Next CEPC Workshop: Lisbon (April 7-11, 2026)

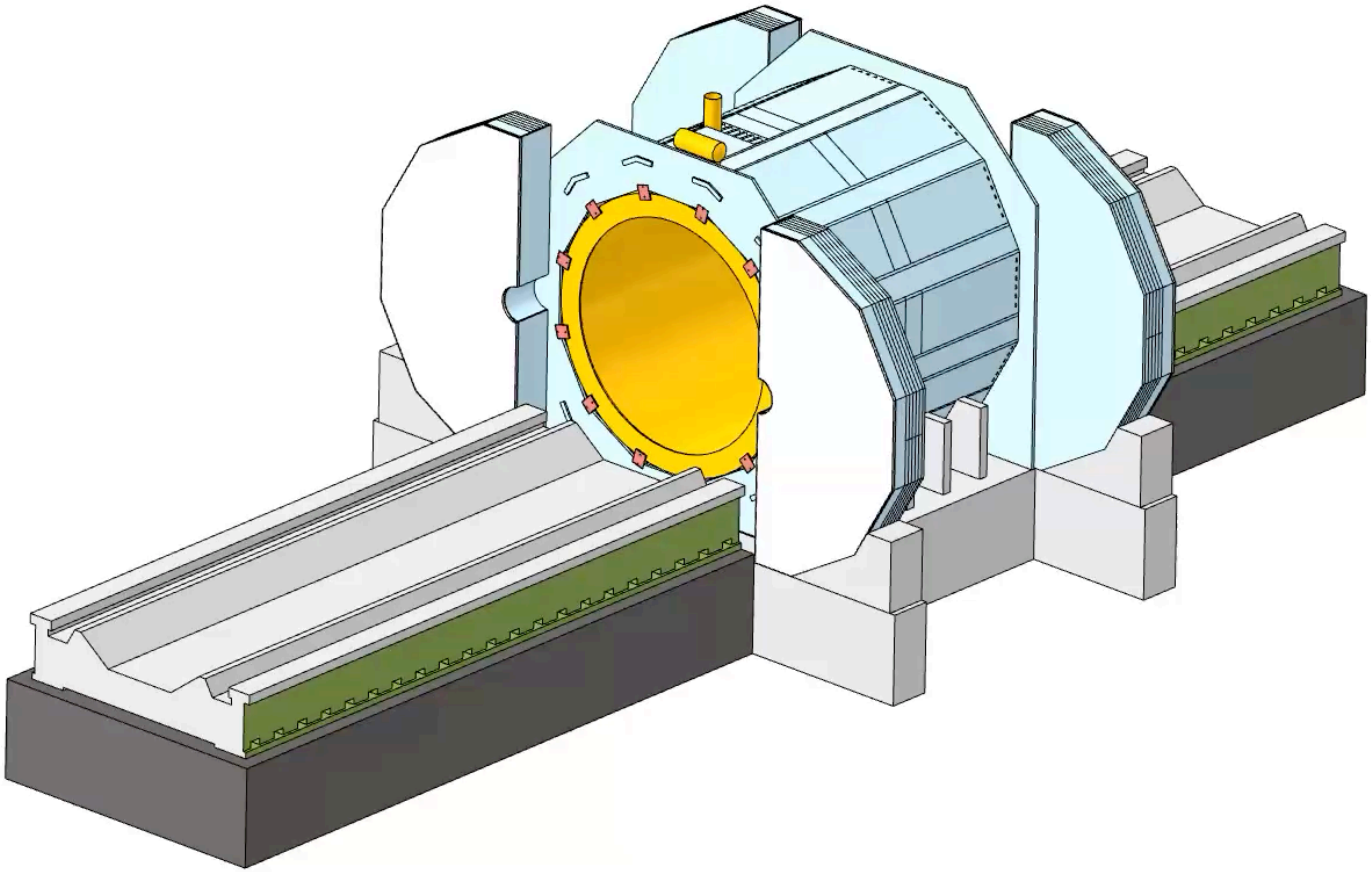
https://indico.cern.ch/event/1598929/

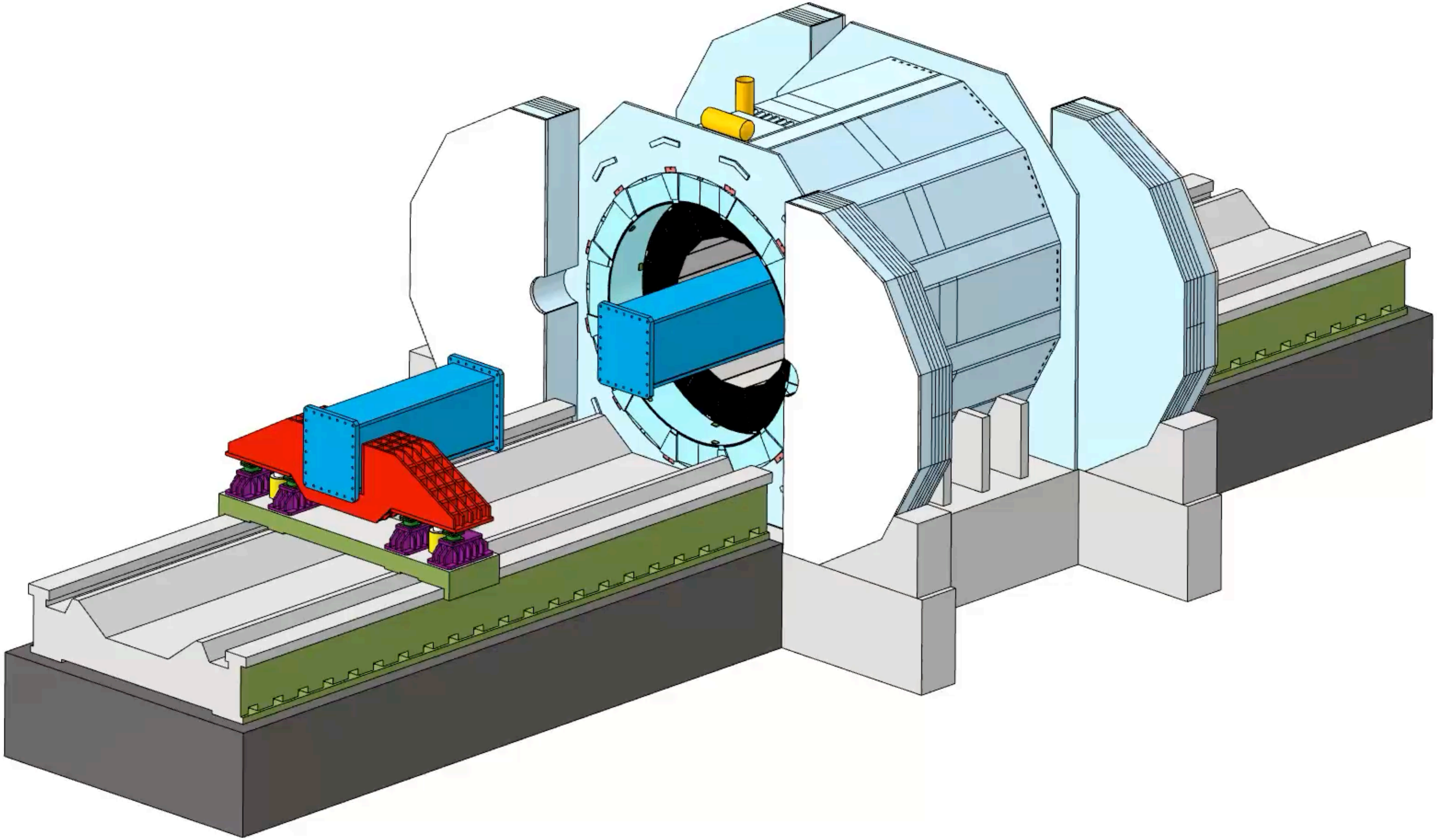
https://indico.cern.ch/e/CEPC2026EU

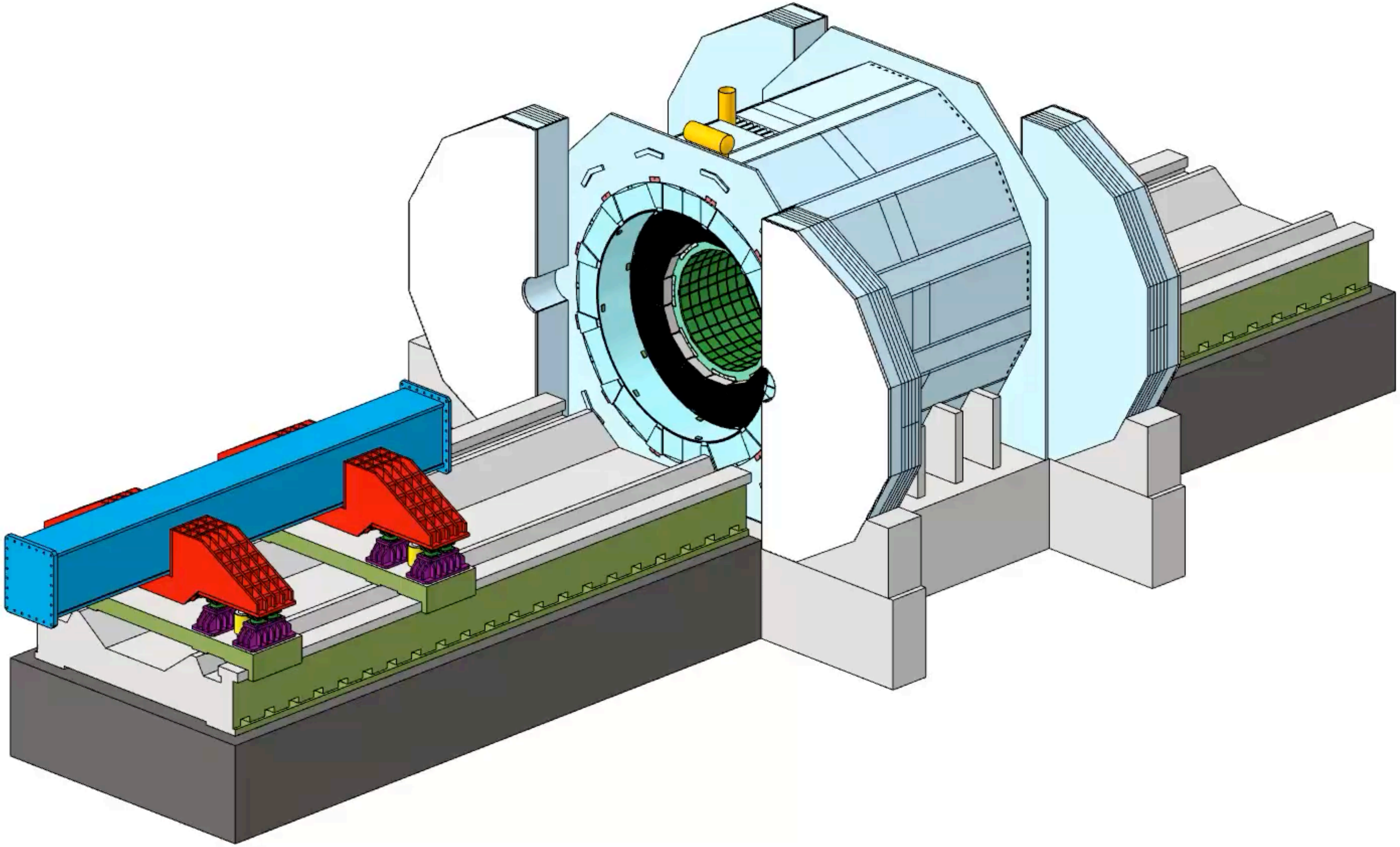
The end

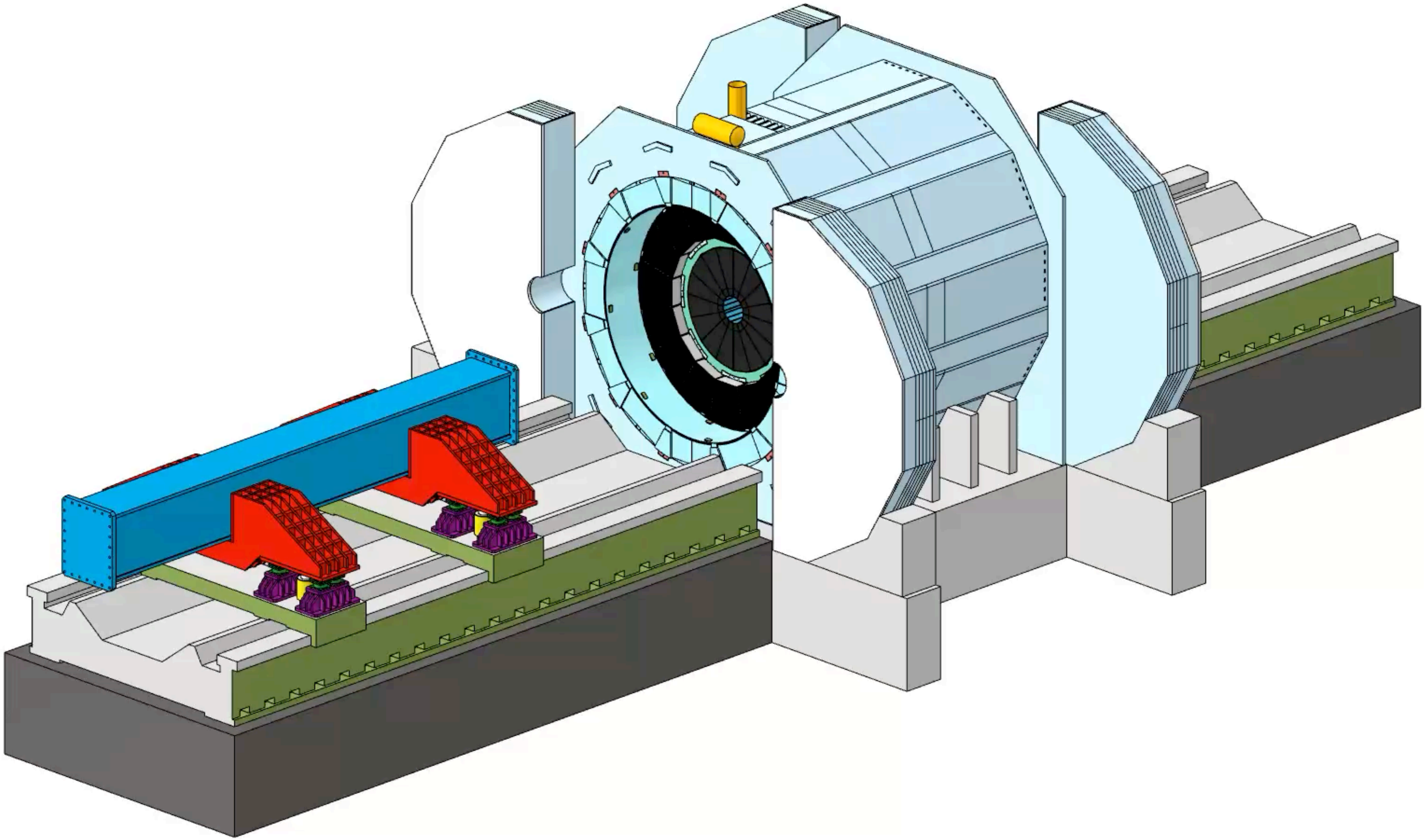
CEPC Reference Detector Installation

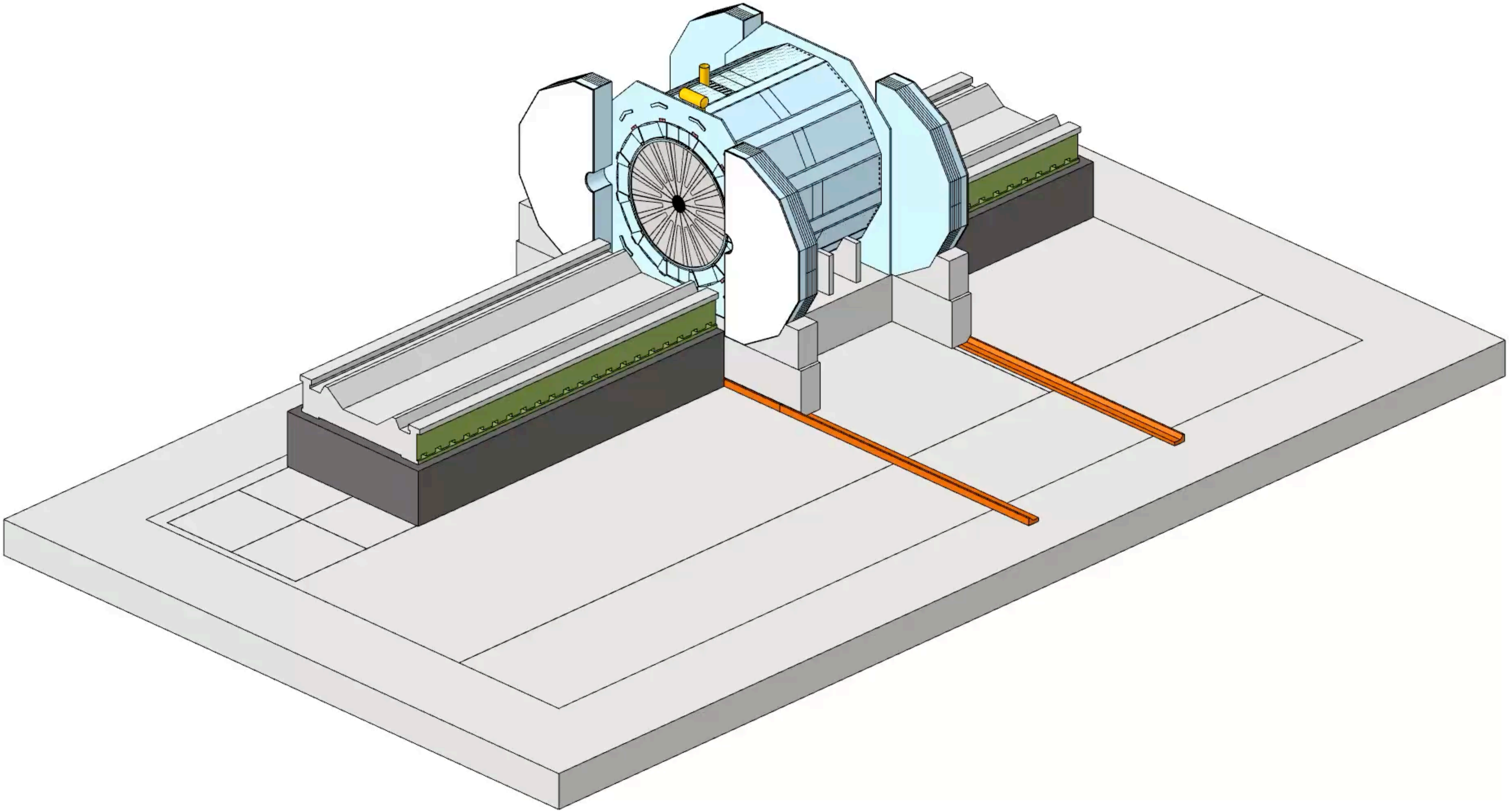












Reference Detector Layout and Key Technologies

Detector	Technology	In (mm)	Out (mm)	Comment
Vertex	Silicon pixel	$r_{in} = 11.1$	$r_{out} = 47.9$	4 single, 2 double layers
ITK (barrel)	Silicon pixel	$r_{in} = 235.0$	$r_{out} = 555.6$	3 layers
ITK (endcap)	Silicon pixel	$\|z_{in}\| = 505.0$	$\|z_{out}\| = 1489$	4 disks
LumiCAL (front)	Silicon pixel	$r_{in} = 12$ $\|z\| = 560$	$r_{out} = 42$	1 double layer disk
LumiCAL (back)	Silicon pixel	$r_{in} = 12$ $\|z\| = 640$	$r_{out} = 51$	1 double layer disk
OTK (barrel)	Silicon microstrip	$r = 1800$ $\|z\| \leq 2840$		1 layer
OTK (endcap)	Silicon microstrip	$r_{in} = 406$ $\|z\| = 2910$	$r_{out} = 1816$	1 disk
TPC	Gaseous tracking	$r_{in} = 600$ $\|z\| \leq 2900$	$r_{out} = 1800$	MPGD high-granularity readout
ECAL (barrel)	Crystal + SiPM	$r_{in} = 1830$ $\|z\| \leq 2900$	$r_{out} = 2130$	18 layers, 32 sectors
ECAL (endcap)	Crystal + SiPM	$r_{in} = 350$ $\|z_{in}\| = 2930$	$r_{out} = 2130$ $\|z_{out}\| = 3230$	$1.5 \times 1.5 \times 3$ cm^3 3D granularity 18 layers, 24 X_0, 1.2 λ_I
LumiCAL (front)	LYSO + SiPM	$r_{in} = 12$ $\|z_{in}\| = 647$	$r_{out} = 56$ $\|z_{out}\| = 670$	14 layers 2 X_0
LumiCAL (back)	LYSO + SiPM	$r_{in} = 12$ $\|z_{in}\| = 800$	$r_{out} = 110$ $\|z_{out}\| = 950$	10 layers 13.4 X_0
HCAL (barrel)	Glass scintillator + SiPM	$r_{in} = 2140$ $\|z\| \leq 3230$	$r_{out} = 3455$	48 layers, 16 sectors
HCAL (endcap)	Glass scintillator + SiPM	$r_{in} = 400$ $\|z_{in}\| = 3260$	$r_{out} = 3385$ $\|z_{out}\| = 4575$	$4 \times 4 \times 1$ cm^3 pixel 48 layers, 6 λ_I
Muon (barrel)	Plastic scintillator + SiPM	$r_{in} = 4245$ $\|z\| \leq 4475$	$r_{out} = 5185$	6 layers, 12 sectors
Muon (endcap)	Plastic scintillator + SiPM	$r_{in} = 550$ $\|z_{in}\| = 4635$	$r_{out} = 5085$ $\|z_{out}\| = 5875$	

Reference Detector - Performance Requirements

Physics objects	Measurands	Detector subsystem	Performance requirement
Tracking	Coverage Recon. efficiency Resolution in barrel Resolution in endcap	Tracker	$\lvert\cos\theta\rvert \leq 0.99$ $\geq 99\%$ ($p_T > 1$ GeV/c) $\sigma_{p_T}/p_T < 0.3\%$ ($\lvert\cos\theta\rvert \leq 0.85$) $\sigma_{p_T}/p_T < 3\%$ ($\lvert\cos\theta\rvert > 0.85$)
Leptons (e, μ)	PID efficiency Mis-ID rate	Tracker, ECAL HCAL, Muon	$\geq 99\%$ ($p > 5$ GeV/c, isolated) $\leq 2\%$ ($p > 5$ GeV/c, isolated)
Photons	PID efficiency Mis-ID rate Energy resolution	ECAL, HCAL	$\geq 95\%$ ($E > 3$ GeV, isolated) $\leq 5\%$ ($E > 3$ GeV, isolated) $\sigma_E/E \leq 3\%/\sqrt{E(\mathrm{GeV})} \oplus 1\%$
Vertex	Position resolution	Vertex	$\sigma_{r\phi} = 5 \oplus \frac{10}{p(\mathrm{GeV})\times\sin^{3/2}\theta}$ (μm)
Hadronic jets	Energy resolution Mass resolution	Tracker ECAL, HCAL	$\sigma_E/E \sim 30\%/\sqrt{E(\mathrm{GeV})} \oplus 4\%$ BMR $\leq 4\%$
Jet flavor tagging	b-tagging efficiency c-tagging efficiency	Full detector	$\sim 80\%$, mis-ID of uds $< 0.3\%$ $\sim 50\%$, mis-ID of uds $< 1\%$
Charged kaon	PID efficiency, purity	Tracker, TOF	$\geq 90\%$ (inclusive Z sample)

Tracking System Parameters and Layout

Components		Radius R [mm]		$\pm z$ [mm]	Material [X_0]	σ_ϕ [µm]	σ_t [ns]
Beam pipe		10.55		85.0	0.454%	—	—
VTX	Layer 1	11.1		80.7	0.067%	5	100
	Layer 2	16.6		121.1	0.059%	5	100
	Layer 3	22.1		161.5	0.058%	5	100
	Layer 4	27.6		201.9	0.061%	5	100
	Layer 5	39.5		341.0	0.280%	5	100
	Layer 6	47.9		341.0	0.280%	5	100
Beam pipe protective cylinder		66.3		462.0	0.19%	—	—
ITK Barrel	Layer 1 (ITKB1)	235.0		493.3	0.68%	8	3–5
	Layer 2 (ITKB2)	345.0		704.8	0.68%	8	3–5
	Layer 3 (ITKB3)	555.6		986.6	0.68%	8	3–5
OTK Barrel	Layer 4 (OTKB)	1,800.0		2,840.0	1.58%	10	0.05
TPC	Inner wall	600.0		2,900.0	0.45%	—	—
	Gas	605.4–1,779.6		2,750.0	1.00%	110–144	—
	Outer wall	1,800.0		2,900.0	0.69%	—	—
		R_{in}	R_{out}				
ITK Endcap	Disk 1 (ITKE1)	82.5	244.7	505.0	0.76%	8	3–5
	Disk 2 (ITKE2)	110.5	353.7	718.5	0.76%	8	3–5
	Disk 3 (ITKE3)	160.5	564.0	1,000.0	0.76%	8	3–5
	Disk 4 (ITKE4)	220.3	564.0	1,489.0	0.76%	8	3–5
OTK Endcap	Disk 5 (OTKE)	406.0	1,816.0	2,910.0	1.37%	10	0.05