CEPC Detector R&D Progress

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Outline

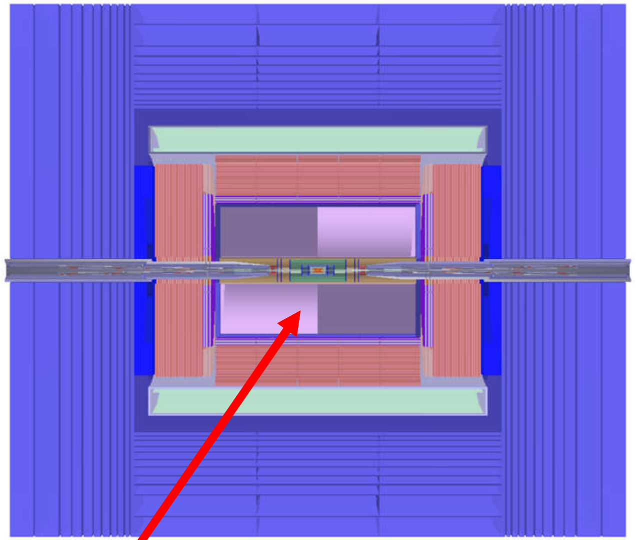
- Detector concepts in CDR
- R&D for the CDR detectors
- The forth detector concept: more physics requirements and motivations
- Mechanical design
- Challenges from enhanced collider luminosities
- Summary

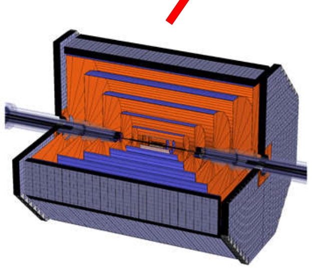
Many slides are courtesy of Joao and Jianchun

CEPC Detector Concepts

Baseline : PFA approach
(derived from ILD)

Silicon + TPC + PFA-ECAL&HCAL
+ Solenoid (2/3T) + Muon

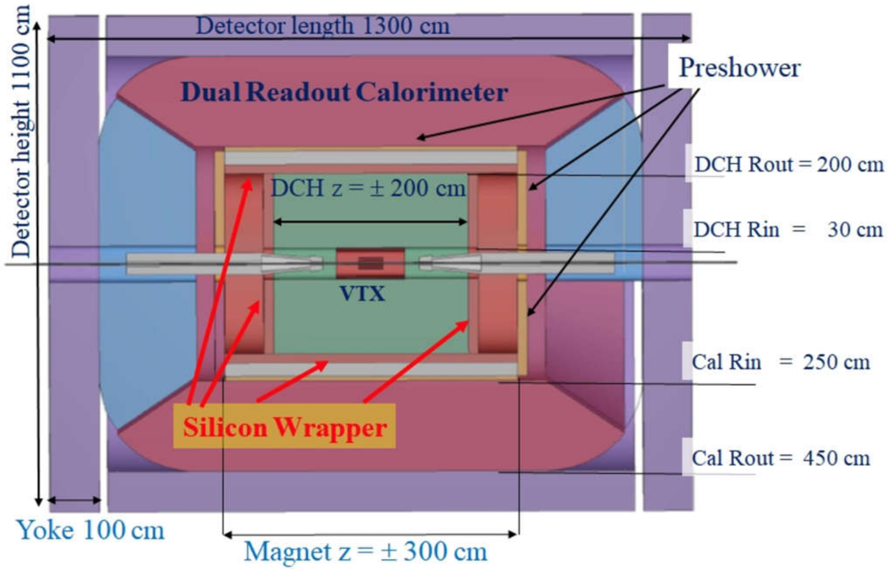




Another tracker option
with full-silicon

Alternative : IDEA
(low magnetic field)

Silicon + Drift Chamber + Solenoid(2T)
+ Dual-readout calorimeter + Muon



Three detector concepts in CDR

- PFA with TPC
- PFA with full silicon
- IDEA with DRC

CMOS Pixel Sensors

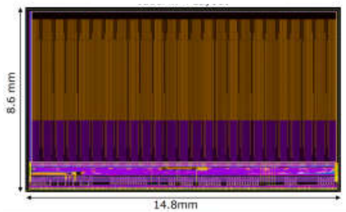
	JadePix1 2015	JadePix2 2017	MIC4	JadePix3 2019
Architecture	Roll. Shutter + Analog output	Roll. Shutter + In pixel discri.	Data-driven r.o. + In pixel discri.	Roll. shutter + end of col. priority encoder
Pitch (μm²)	33 × 33 /16 × 16	22 × 22	25 × 25	16 × 26 16 × 23.11
Power con. (mW/cm²)	--	--	150	~ 55* / <100
Integration time (μs)*	--	40-50	~3	~100
Prototype size (mm²)	3.9 × 7.9 (36 individual r.o)	3 × 3.3	3.1 × 4.6	10.4 × 6.1
Main goals	Sensor optimization	Small binary pixel	Small pixel + Fast readout+ nearly full functional	Smaller pixel + Low power + fully functional

* Assuming a matrix of 512 × 1024 pixels

All prototypes in TowerJazz 180 nm process

JadePix1 (IHEP) JadePix2 (IHEP) MIC4 (CCNU & IHEP) JadePix3 (IHEP, CCNU, Dalian Minzu Unv., SDU)

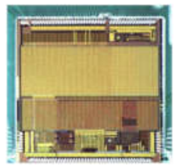
JadePix4



	S.P. resolution	Integration time	Average power
JadePix-4	<5 μm	~1 μs	< 100 mW/cm²
JadePix-3	<3 μm	<100 μs	< 100 mW/cm²

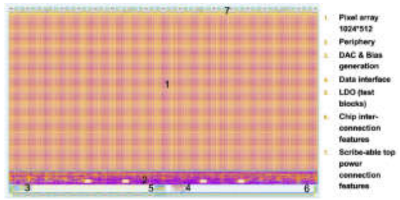
Optimized for fast readout

Taichupix1 Taichupix2



Chip size: 5 mm × 5 mm
Pixel size: 25 μm × 25 μm

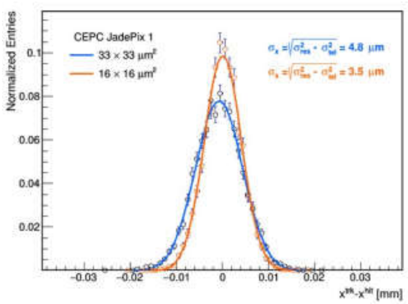
Full-size Taichupix



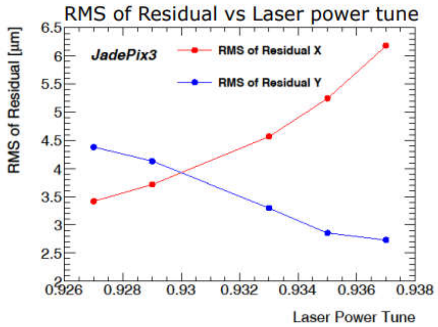
1024*512 pixel array, FE-I3-like

High speed, deadtime~50ns@40MHz, time stamp precision 25/50ns

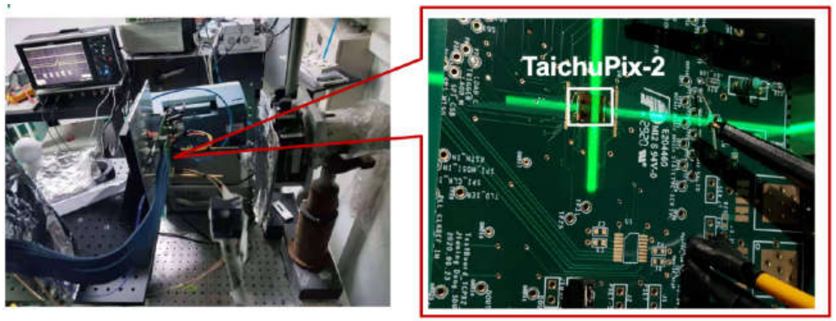
Beam test



Laser test



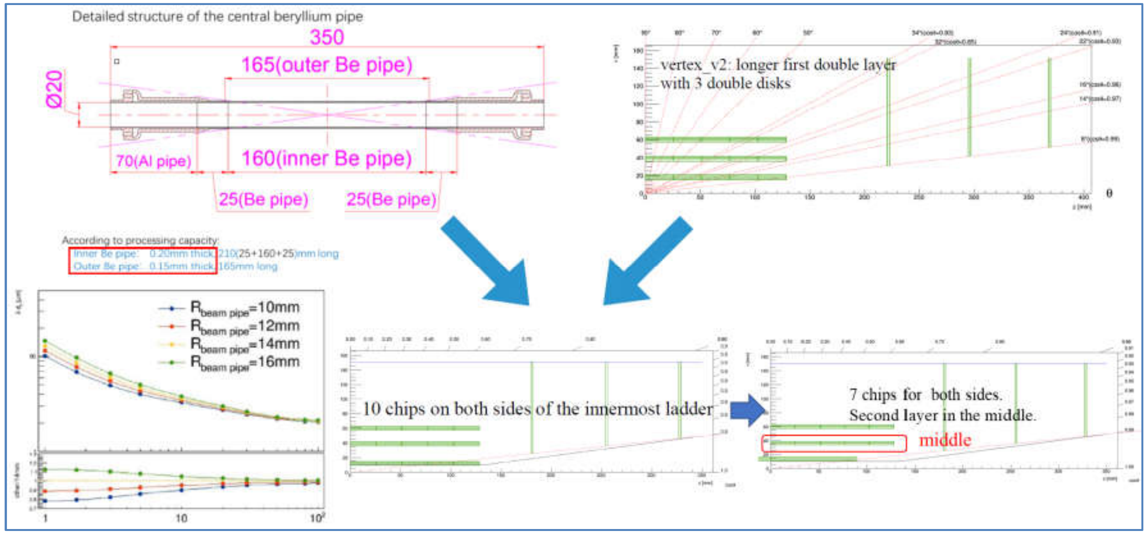
Radiation test



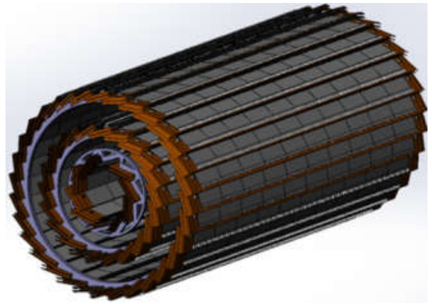
TaichuPix-2 exposed to 6 keV X-ray up to 2.5 Mrad and beyond

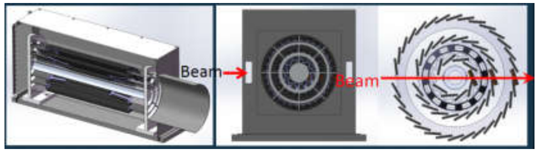
Vertex Detector

Vertex detector layout optimization



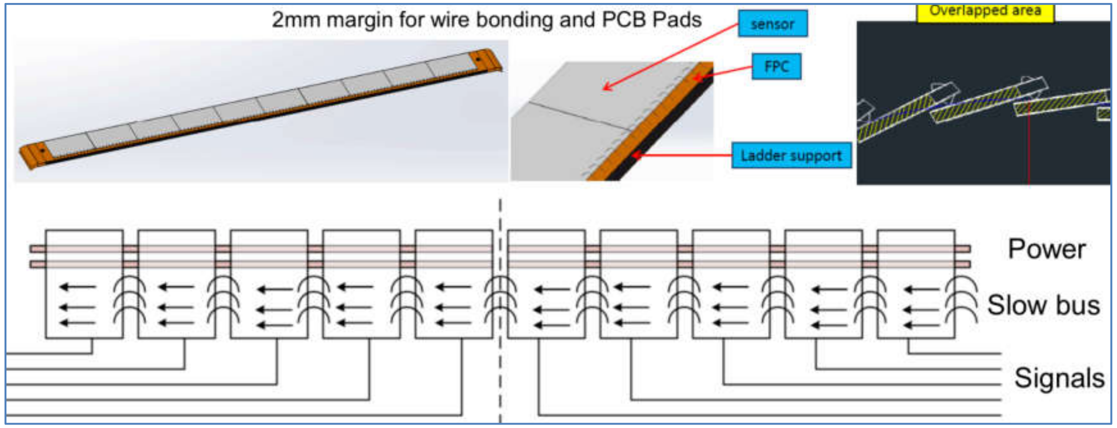
Vertex detector prototype





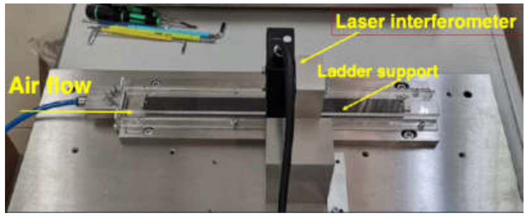
Engineering design and tooling design for assembling

Vertex detector ladder design



New idea: inter-chip connection

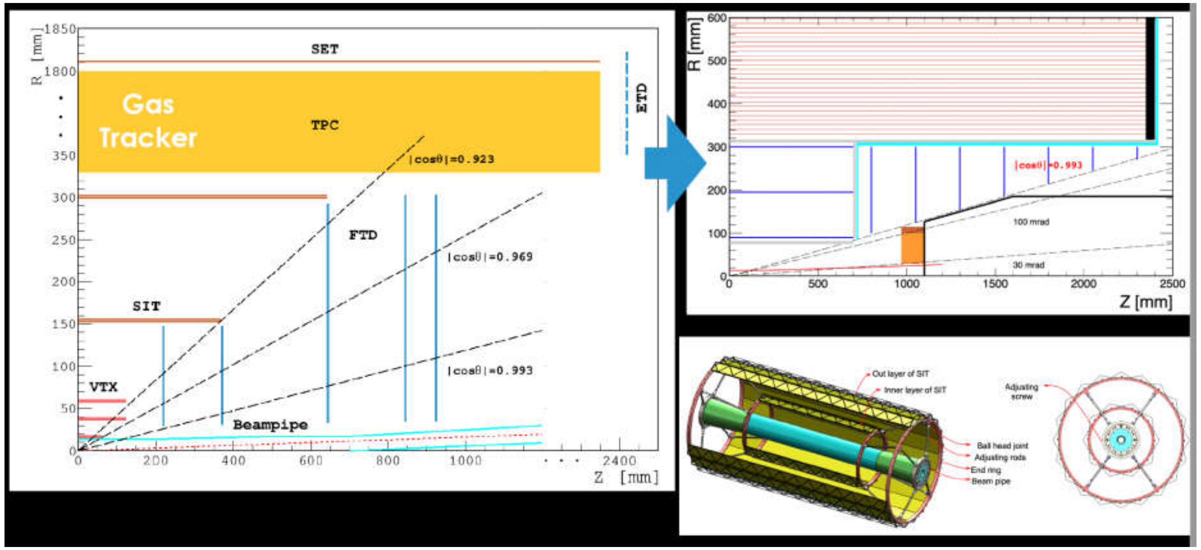
Air cooling testing



Max temperature of ladder (℃) (air temperature 5 ℃)					
Power Dissipation (mW/cm2) \ Air speed (m/s)	5	4	3	2	1
100	19.6	21.8	25.0	30.6	43.4
150	26.9	30.1	35	43.4	62.6
200	34.2	38.6	45.1	56.2	81.8

Silicon Tracker

Silicon tracker layout optimization and structure design

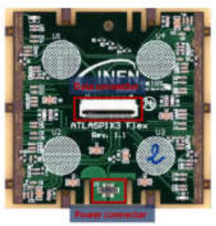


A big international effort

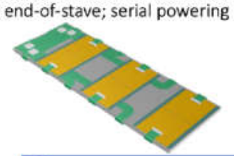
- Australia
  - University of Adelaide
- China
  - Harbin Institute of Technology
  - Institute of High Energy Physics, CAS
  - Northwestern Polytechnical University
  - Shandong University
  - T. D. Lee Institute – Shanghai Jiao Tong University
  - University of Science and Technology of China
  - University of South China
  - Zhejiang University
- Germany
  - Karlsruhe Institute für Technologie
- Italy
  - INFN Sezione di Milano, Università degli Studi di Milano e Università degli Studi dell'Insubria
  - INFN Sezione die Pisa e Università di Pisa
  - INFN Sezione di Torino e Università degli Studi di Torino
- UK
  - Lancaster University
  - Queen Mary University of London
  - STFC – Daresbury Laboratory
  - STFC – Rutherford Appleton Laboratory
  - University of Bristol
  - University of Edinburg
  - University of Liverpool
  - University of Oxford
  - University of Sheffield
  - University of Warwick

Demonstrator (Short Stave)

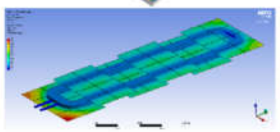
QuadModule Concept



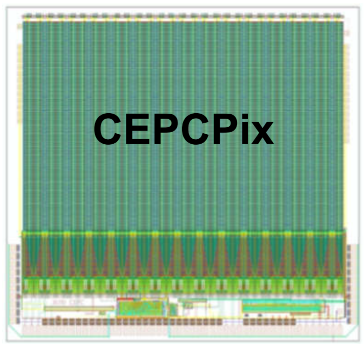
- Multiple modules on light composite support
  - Alternate tile pattern for hermeticity
  - Aggregation of data/optical conversion at the end-of-stave; serial powering



- Readout unit based on 4 chips
  - Shared services among 4 sensors by common power connections and configuration lines
  - Benefits of in-chip regulators to reduce connections



TSI 180 nm HV-CMOS



- Smaller pixel size (25μm) in φ direction
- Lower capacitance
- Amplifier and comparator design
- Electronics in pixel or periphery
- Daisy chain of readout

55 nm HV-CMOS

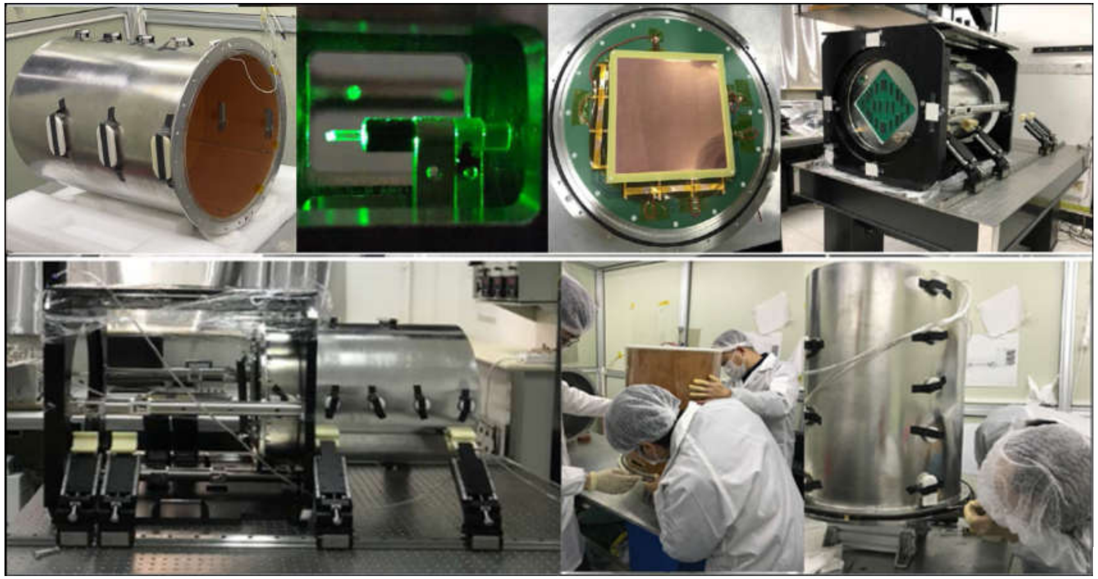
华虹集团 HUAHONG GROUP

上海华力 HLMC

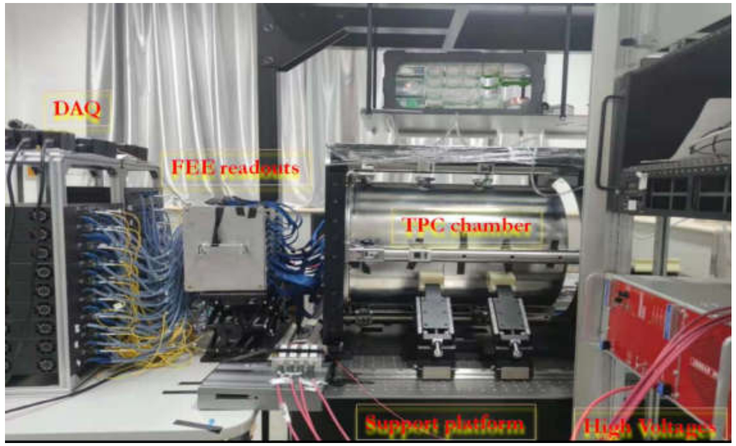
A Chinese foundry

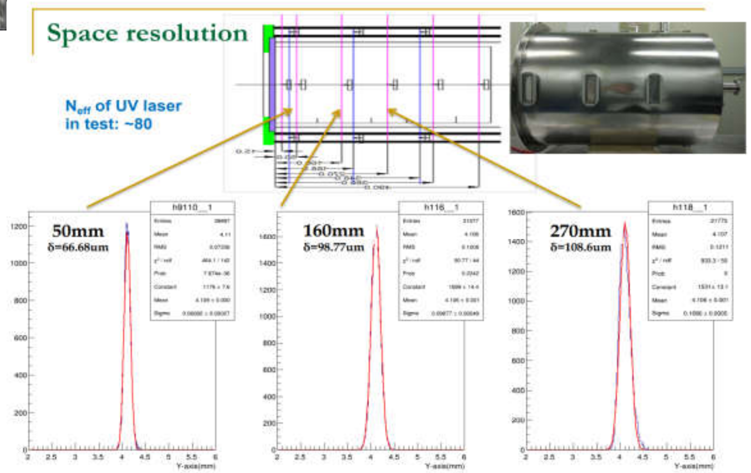
TPC Tracker

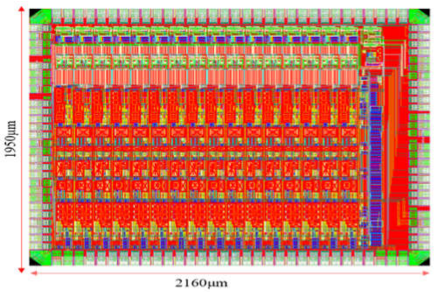
A 50cm-long TPC prototype read out with GEM+MM was developed

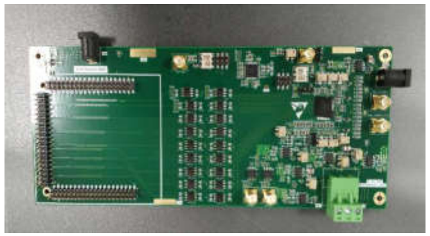


Tested with UV laser





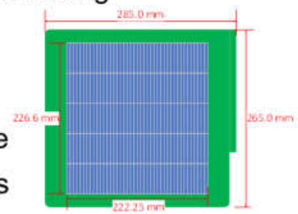


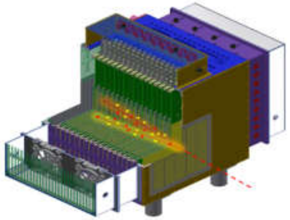


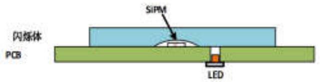
Low power readout ASIC chip developed with 65 nm CMOS process. 16 chs/chip, 2mW/ch

PFA ECAL Prototype

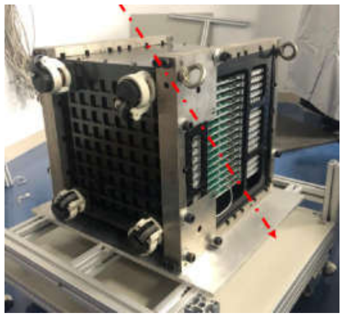
- 16 super-layers with each super-layer consisting of 2 EBUs and 2 tungsten layers.
- The total radiation length ~ 23.4 X_0
- Scintillator strips (45mm*5mm*2mm) are arranged in alternating orthogonal layers and read out with SiPM
- 210 channels per EBU
- 12 fans at two ends for air cooling



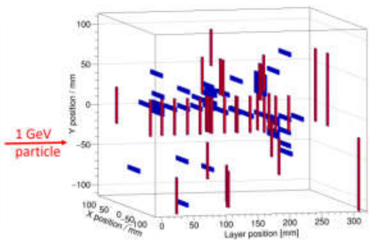


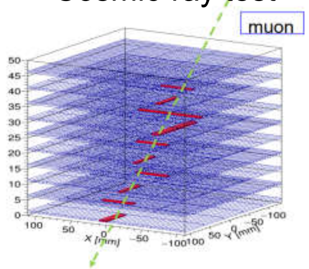


Beam test at IHEP



Cosmic-ray test

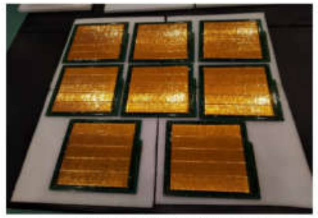




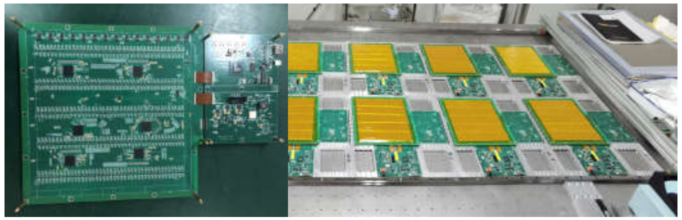
质量检查

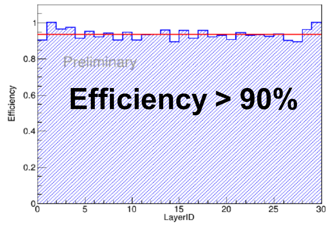
部件清洗

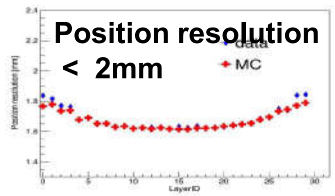
单元组装



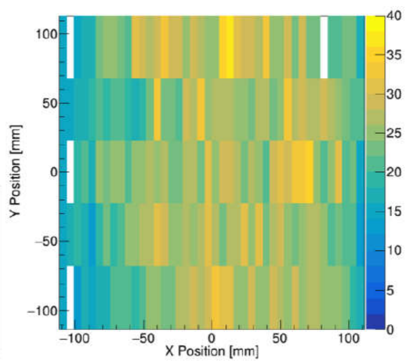
探测器与电子学集成







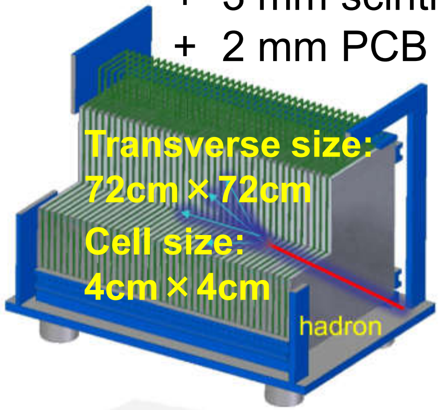
Light yield ~ 20 ph.e./MIP



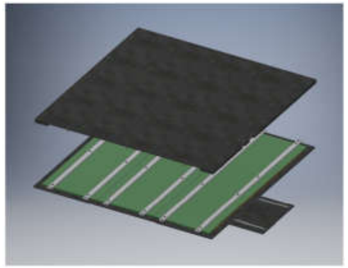
PFA HCAL

A full-size AHCAL prototype is being built

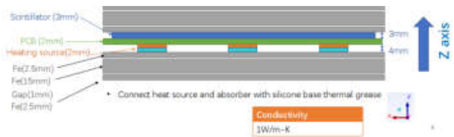
40 layers of 20 mm steel
+ 3 mm scintillator
+ 2 mm PCB



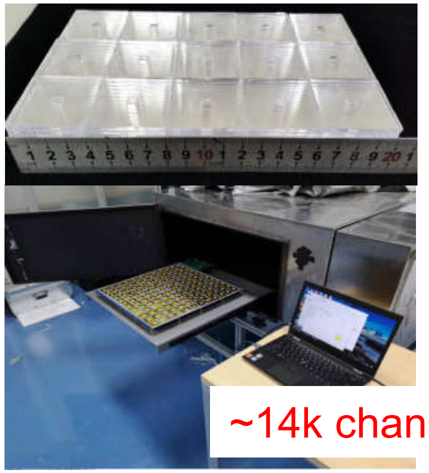
Mechanical design



Cooling design and simulation

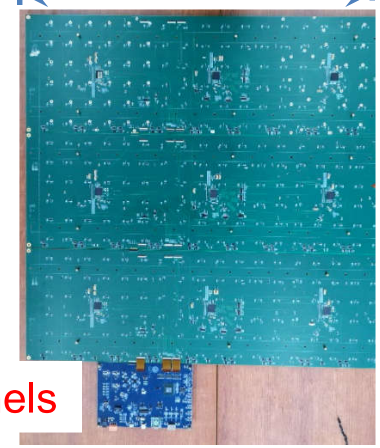


Scintillator tiles production and quality control



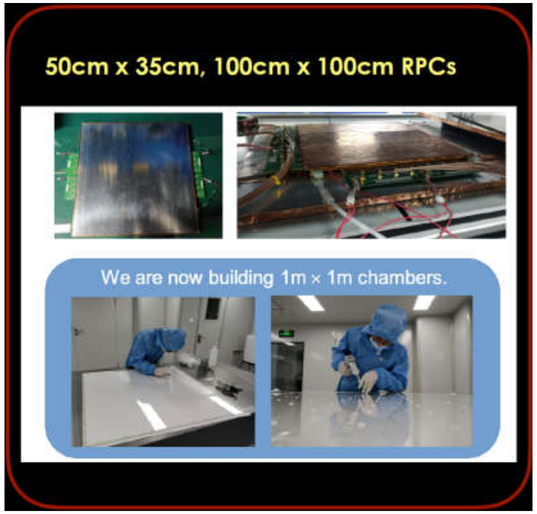
Readout board development

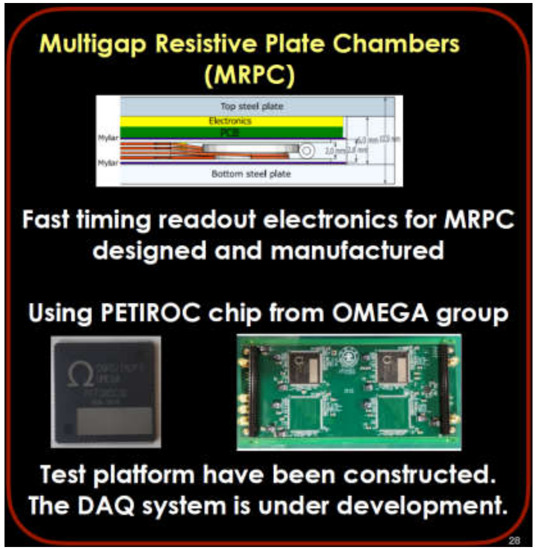
72 cm



~14k channels

RPC-SDHCAL





Dual Readout Calorimeter

International collaboration has been formed

Korea

Prof. Hyonsuk Jo (KNU)
Prof. Yongsun Kim (Sejong U.)
Prof. Jason Lee (UoS)
Prof. Sehwook Lee (KNU)
Prof. Sanghoon Lim (PNU)
Prof. Hwidong Yoo (YU)

Taiwan

Prof. Rong-Shyang Lu
Prof. Chia Ming Kuo

Japan

Prof. Yuji Enari
(Active from 2021)

USA

Prof. Sarah Eno
Prof. Chris Tully
Prof. Richard Wigmans
Prof. John Hauptman

Europe

Prof. Paolo Giacomelli (Bologna)
Prof. Romualdo Santoro (Insubria)
Prof. Roberto Ferrari (Pavia)
Prof. Franco Bedeschi (Pisa)
Prof. Iacopo Vivarelli
Prof. Valery Chmill

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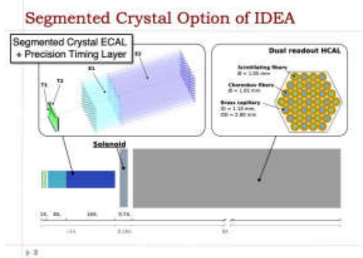
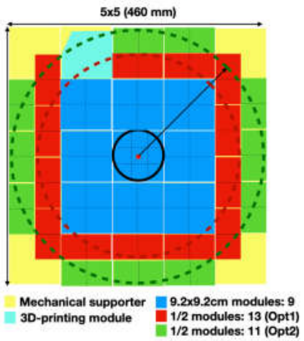
DREAM FOR FUTURE

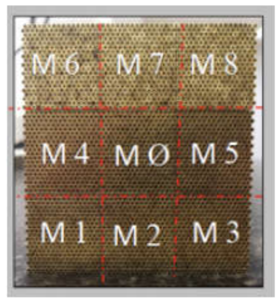
DRC with crystal



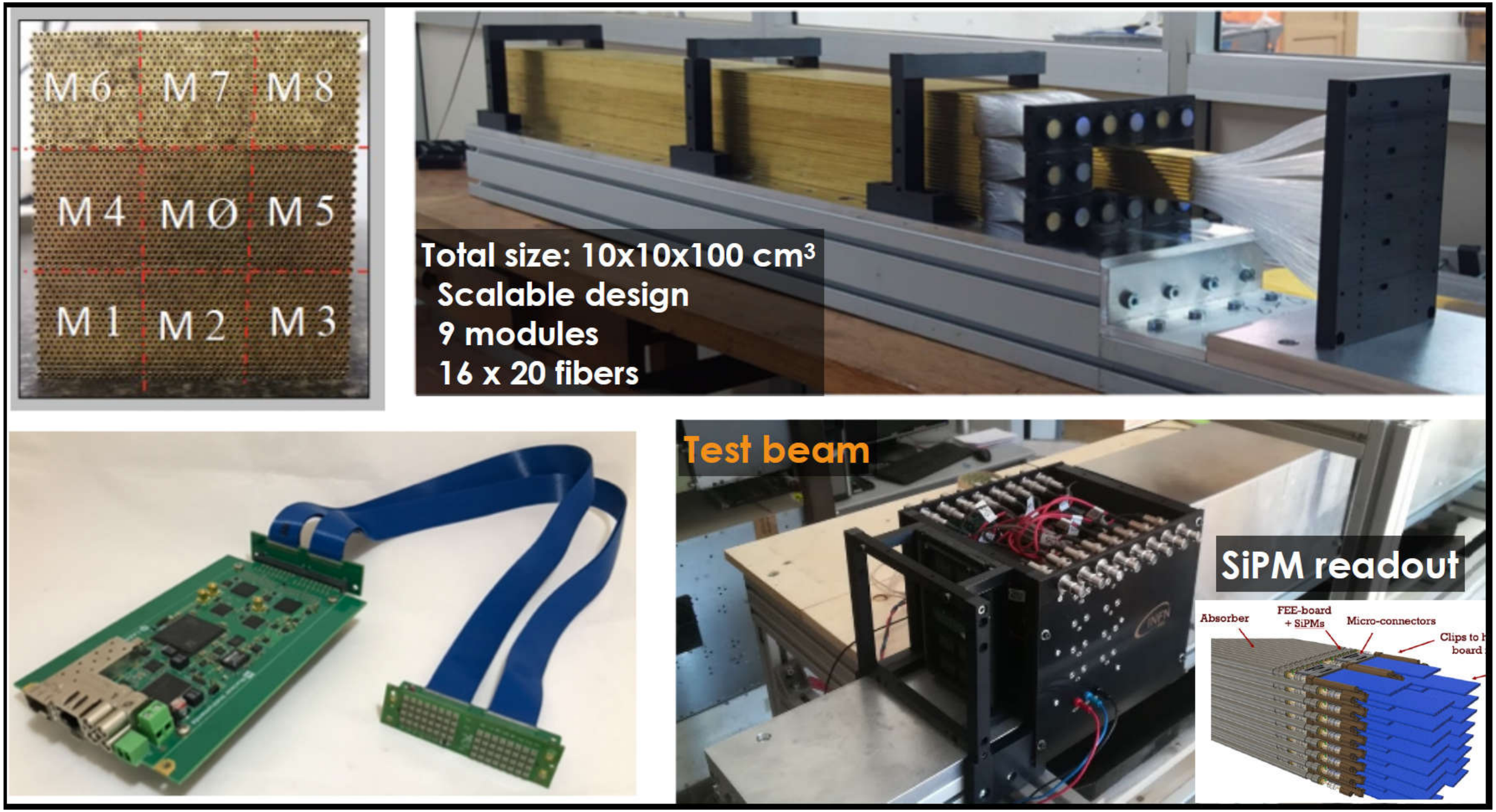
Full-size prototype detector



Bucatini prototype



Bucatini DRC Prototype



Korea DRC Prototype

Primary goal: build a prototype detector for the detector design of CEPC experiment

- **5 year (2020.Mar. - 2025.Feb.) R&D funding** supported by Korea NRF ($~0.4M/year, total **$~2M** for 5 years) => 2nd year in this program
- Contain almost (97.5%) full hadronic shower energy
- Demonstrate engineering aspects for full geometry detector

- Secondary goal: train next generations as experts of the (DRC) detector

WE ARE HERE

2017-9	2020-1	2022-5	TBD
Design	R&D	Prototype	Production

Stage	Topic
Design	Propose a design of Dual-Readout Calorimeter to IDEA detector concept
R&D	Perform R&D (including engineering aspects) based on HW & SW
Prototype	Build 4x4 detector and perform test beams
Production	TBD

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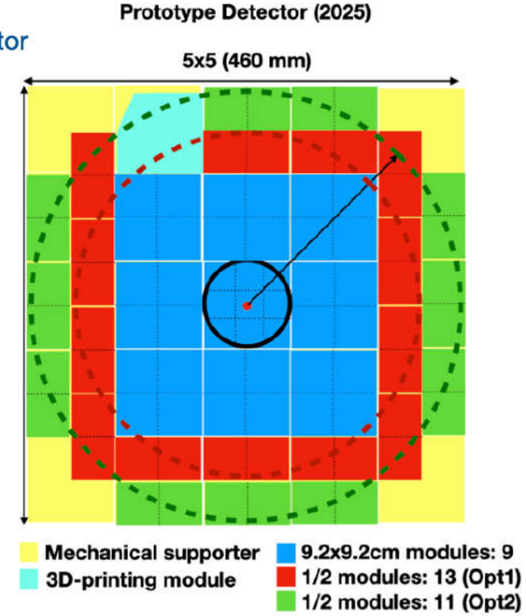
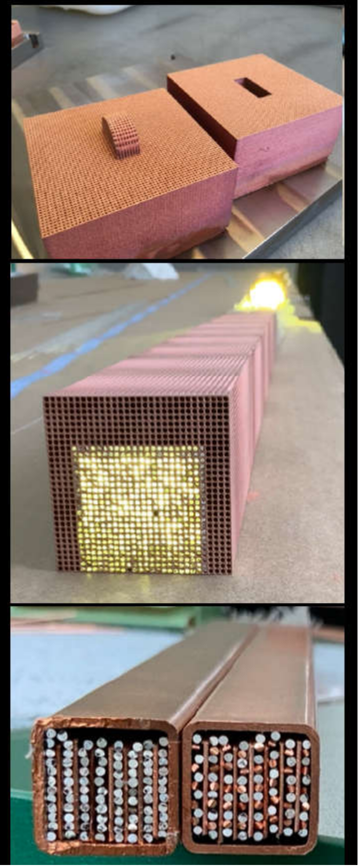
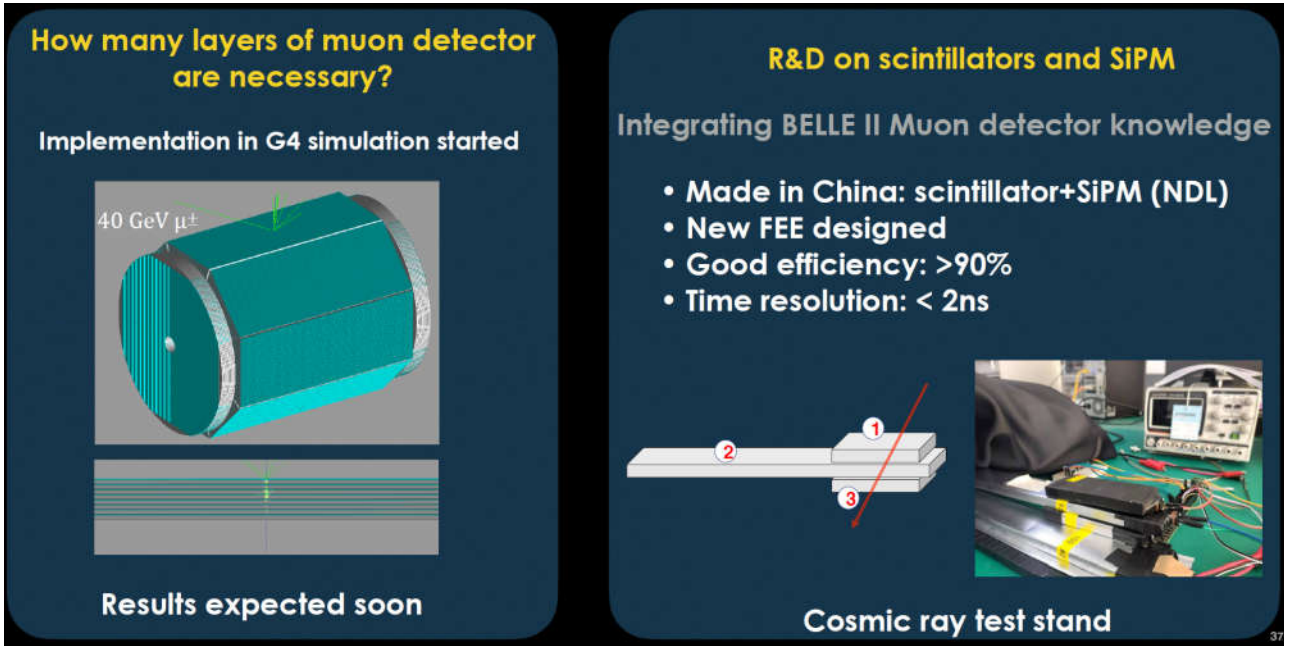


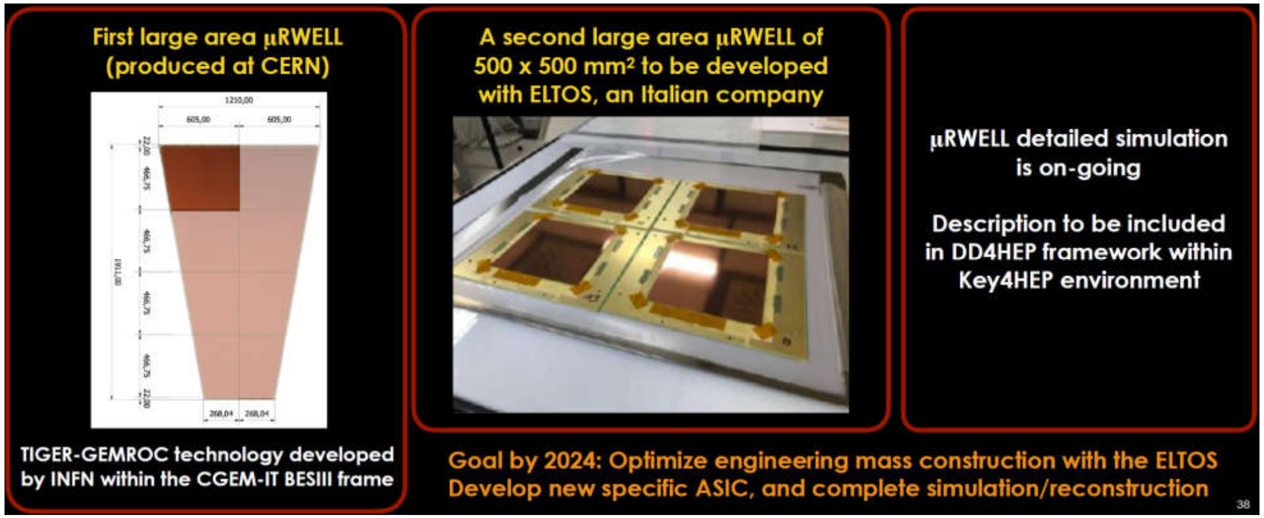


Muon Detector



Option1 : scintillator strips + SiPM

Option 2: uRWELL MPGD technology

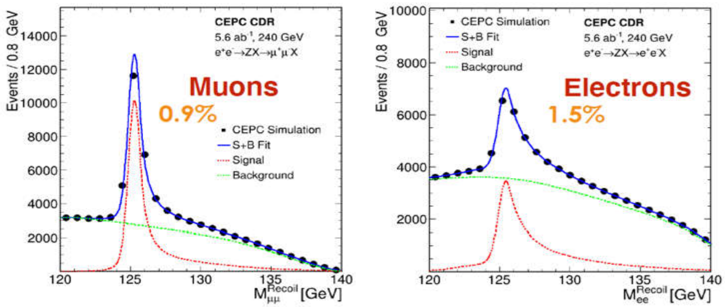


More Physics Requirements

Detector performance requirements in CDR

Physics process	Measurands	Detector subsystem	Performance requirement
$ZH, Z \to e^+e^-, \mu^+\mu^-$ $H \to \mu^+\mu^-$	$m_H, \sigma(ZH)$ $\mathrm{BR}(H \to \mu^+\mu^-)$	Tracker	$\Delta(1/p_T) =$ $2 \times 10^{-5} \oplus \frac{0.001}{p(\mathrm{GeV}) \sin^{3/2}\theta}$
$H \to b\bar{b}/c\bar{c}/gg$	$\mathrm{BR}(H \to b\bar{b}/c\bar{c}/gg)$	Vertex	$\sigma_{r\phi} =$ $5 \oplus \frac{10}{p(\mathrm{GeV}) \times \sin^{3/2}\theta} (\mu\mathrm{m})$
$H \to q\bar{q}, WW^*, ZZ^*$	$\mathrm{BR}(H \to q\bar{q}, WW^*, ZZ^*)$	ECAL HCAL	$\sigma_E^{\mathrm{jet}}/E =$ $3 \sim 4\%$ at 100 GeV
$H \to \gamma\gamma$	$\mathrm{BR}(H \to \gamma\gamma)$	ECAL	$\Delta E/E =$ $\frac{0.20}{\sqrt{E(\mathrm{GeV})}} \oplus 0.01$

Good EM energy resolution is required for bremsstrahlung radiation recovery



ee → HZ(→ee/μμ), recoil mass against Z boson

EWK physics:
Precise EM measurement

Flavor physics:
Precise EM measurement
Dedicated hadron identification

The 4th Detector Concept

Scint Glass PFA HCAL

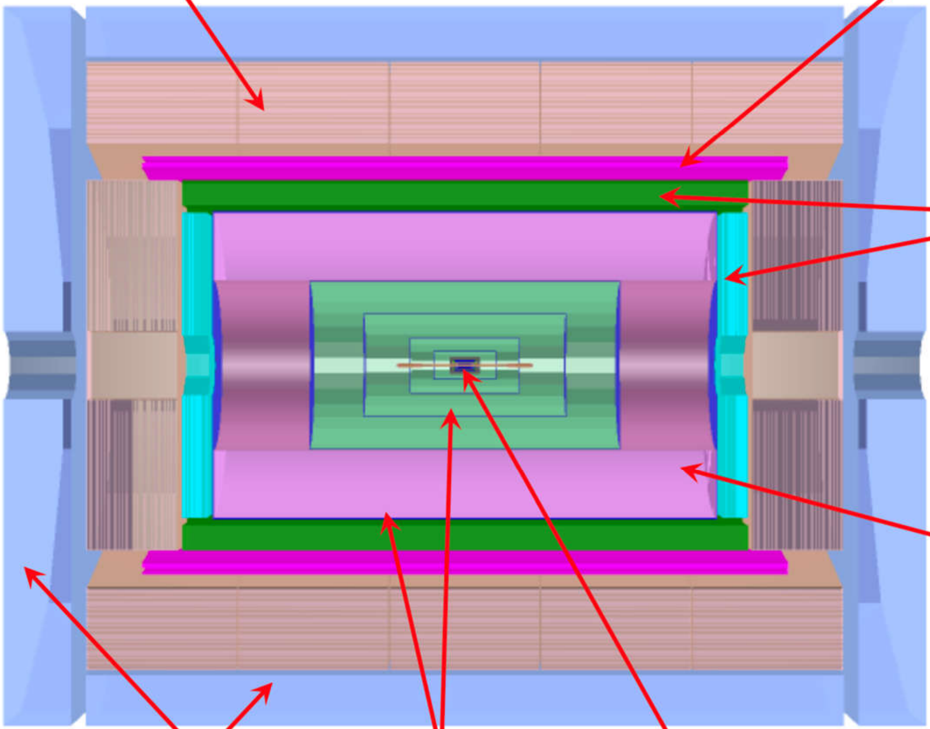
Advantage: Cost efficient, high density

Challenges: Light yield, transparency, massive production.

Solenoid Magnet (3T / 2T) Between HCAL & ECAL

Advantage: the HCAL absorbers act as part of the magnet return yoke.

Challenges: thin enough not to affect the jet resolution (e.g. BMR); stability.



Muon+Yoke **Si Tracker** **Si Vertex**

Transverse Crystal bar ECAL

Advantage: better π^0/γ reconstruction.

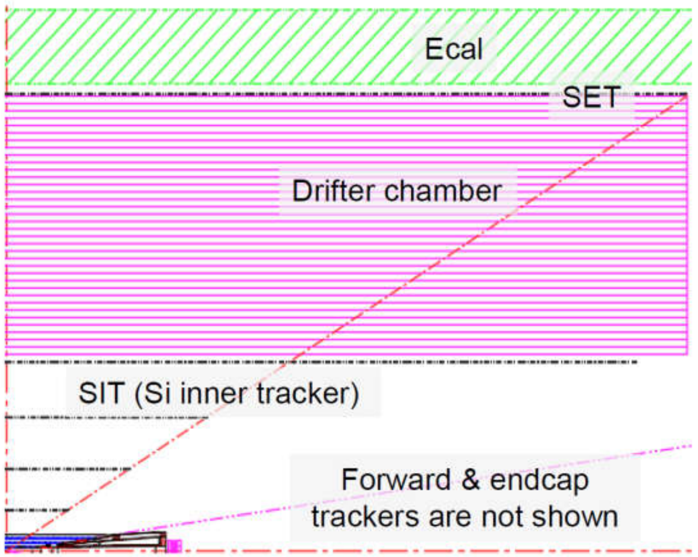
Challenges: minimum number of readout channels; compatible with PFA calorimeter; maintain good jet resolution.

A Drift chamber that is optimized for PID

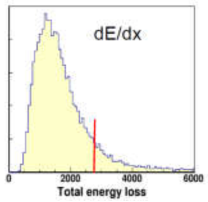
Advantage: Work at high luminosity Z runs

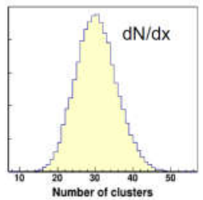
Challenges: sufficient PID power; thin enough not to affect the moment resolution.

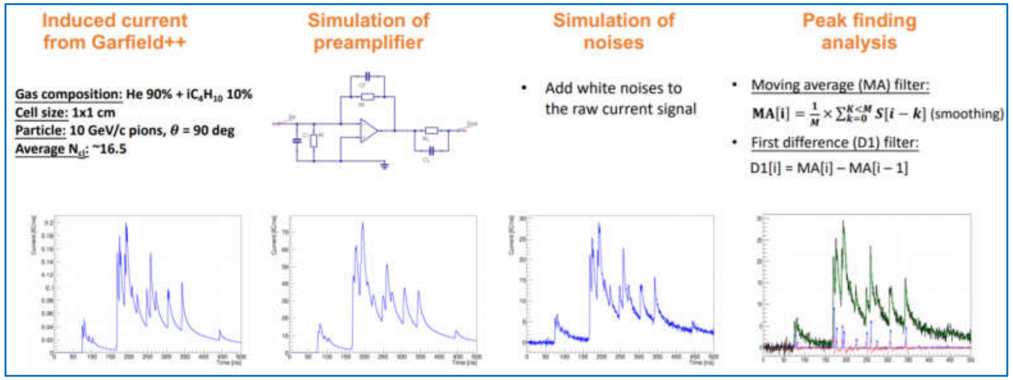
Drift Chamber



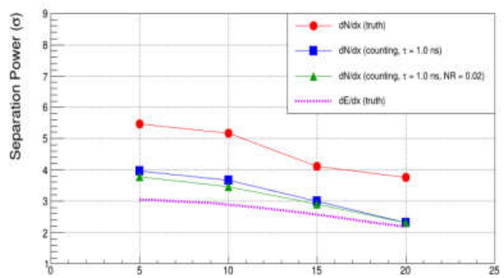
Explore the full PID potential of a drift chamber by counting primary ionization clusters







100 layers (R_{DC} from 0.8 to 1.8m)



2-σ π/K separation @ 20 GeV/c

Cell size: 1cm ×1cm,
Gas mixture: 90% He + 10% iC4H10
Sampling frequency : 2GHz

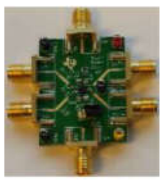
Elements being optimized

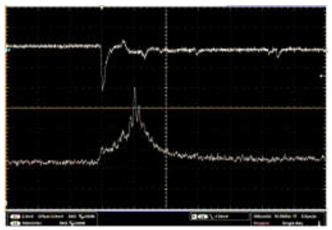
- Cell size, number of layers
- Working gas (drift velocity, primary ionization)
- Sampling frequency

Test with radiation source

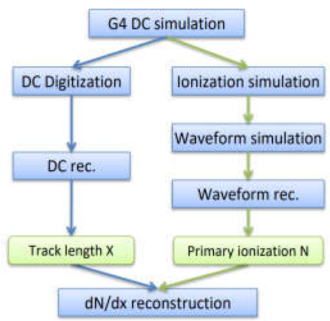
Proportional tube (φ32mm)

Preamplifier
GBP: 8 GHz



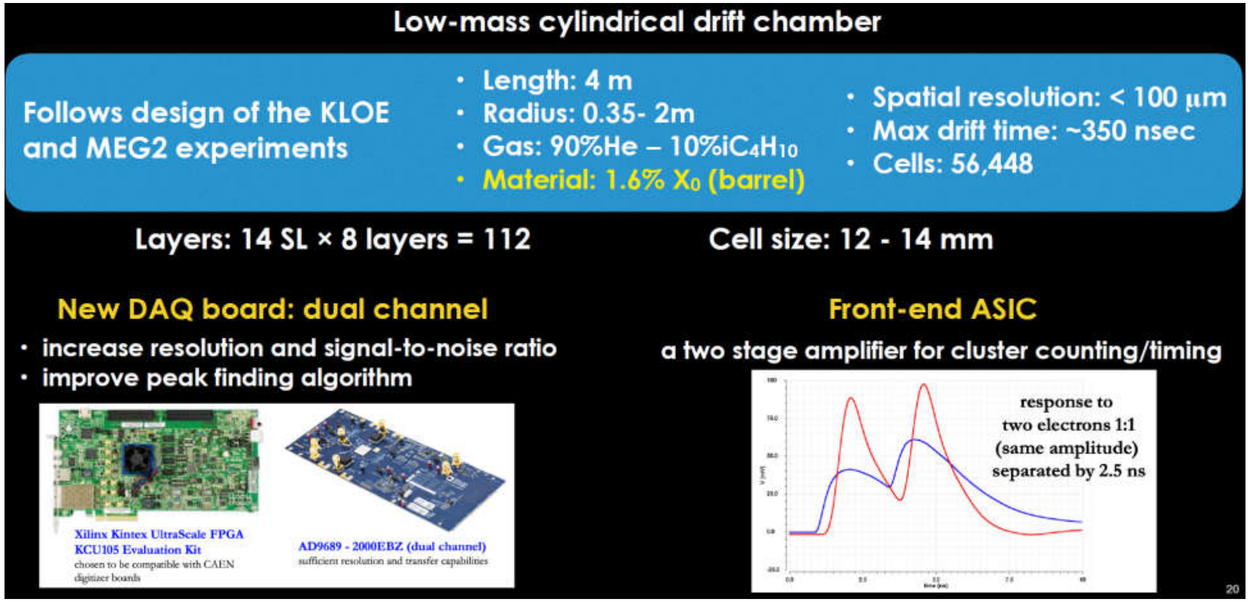


Software development

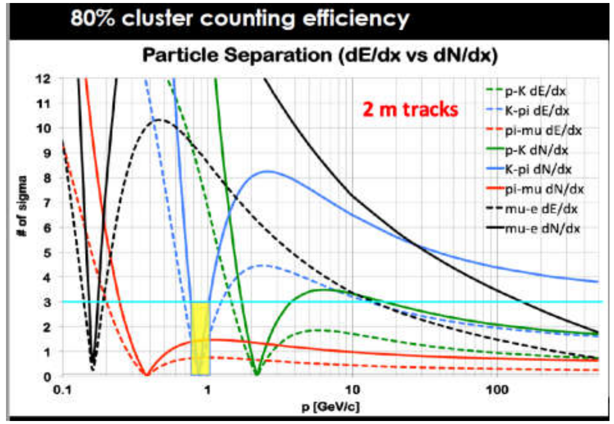


- CEPCSW
  - Gaudi based framework
  - External libraries and tools
- Geometry and field map
  - DD4hep
  - Non-uniform magnetic field: done
- Data model
  - EDM4hep and FWCore
  - dN/dx event model: in progress
- Drift chamber
  - DC Simulation: done
  - DC Digitization: done
  - dN/dx simulation: in progress
  - dN/dx reconstruction: in progress
  - Track fitting with measurement: done

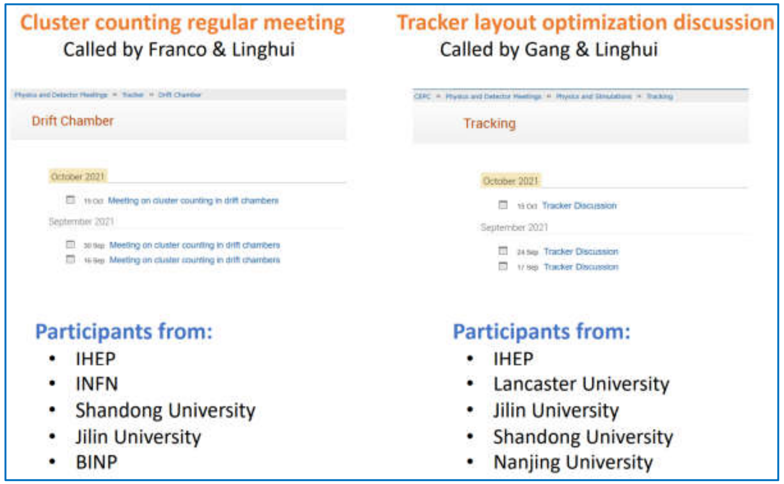
Drift Chamber



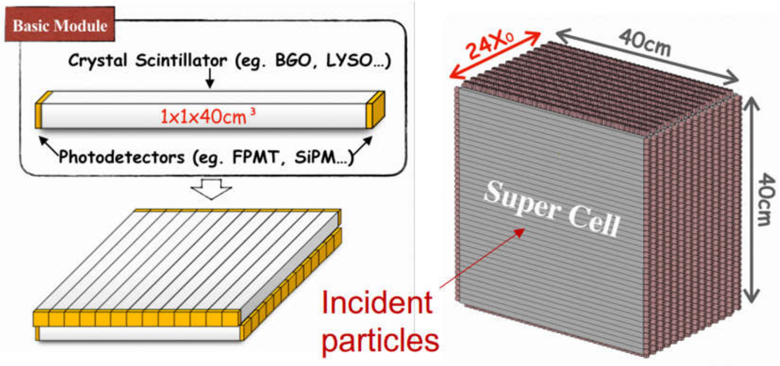
IDEA drift chamber

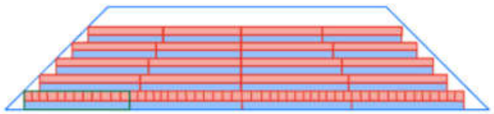


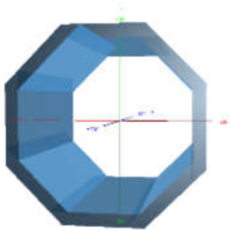
- A lot of synergy between IDEA and 4th Concept on the drift chamber
- Collaboration on drift chamber and tracking



Crystal ECAL





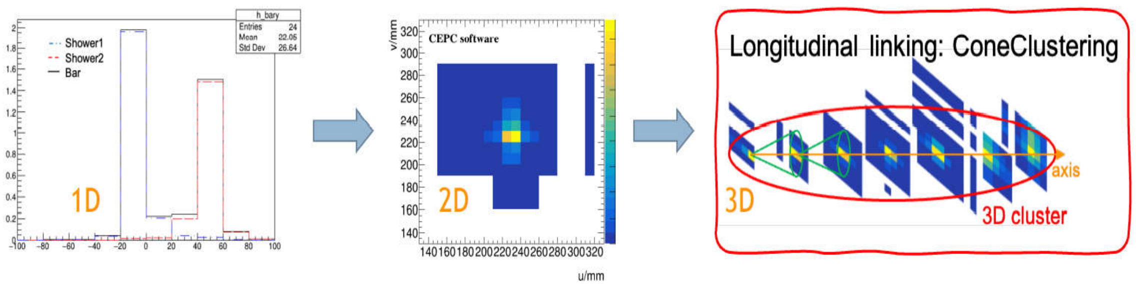


8 trapezoidal staves

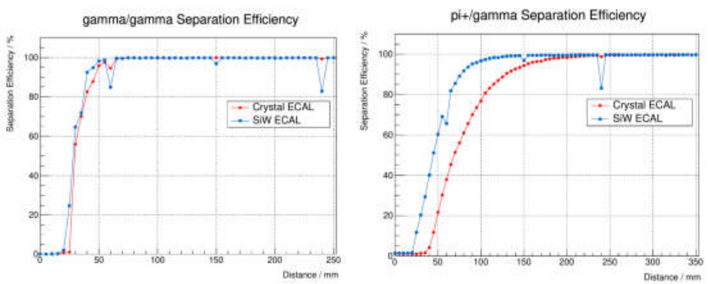
R=1.8m, L=4.6m, H=28cm

- A crystal bar ECAL
  - Homogeneous BGO crystal.
  - Bar size ~$40 \times 1 \times 1$ cm^3, time measurements at two ends for position along the bar.
  - Crossed arrangement in adjacent layers. Two layers form a super cell module: ~$40 \times 40 \times 2$ cm^3.
  - Reduce readout channels, minimize dead materials.
- Key issues:
  - Ambiguity caused by 2D measurements (**ghost hit**).
  - Identification of energy deposits from individual particles (**confusion**).
- Ongoing work:
  - Use ArborPFA software & crystal cubes of 1 cm^3 in size to study PFA performance, compare with SiW ECAL.
  - Develop a proto-PFA new software that has separation capability of multiple incident particles.
  - Bench test of crystal bars.

Reconstruction



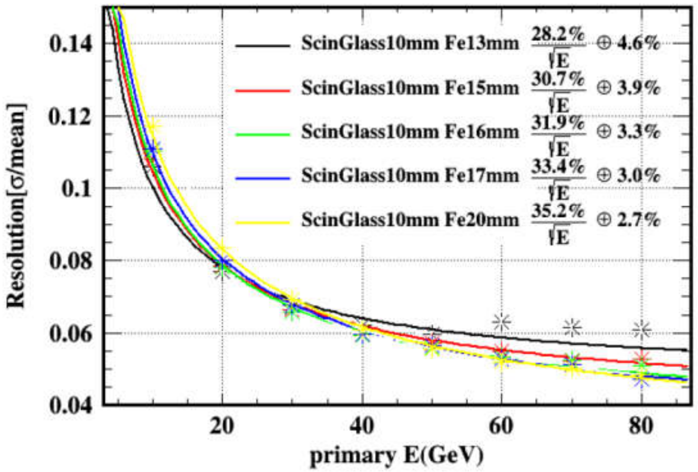
PFA performance



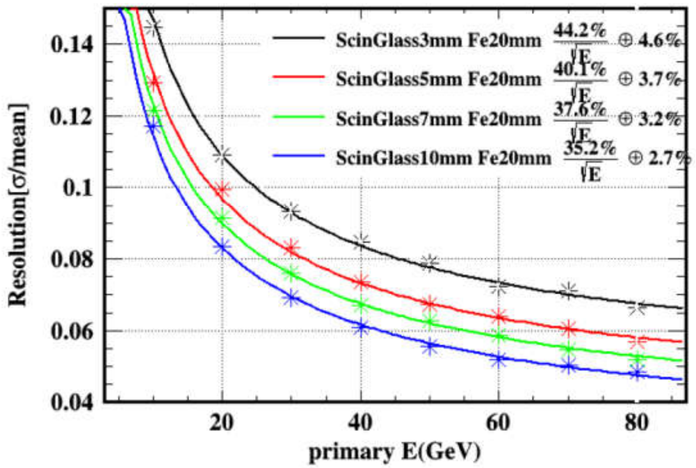
Scintillator Glass HCAL

Sample nos.	Molar compositions	Density (g/cm^3)	Radiation length (cm)	Integrated light yield (% of BGO)
S0	$20SiO_2–35B_2O_3–15BaF_2–15Lu_2O_3–15Gd_2O_3$	5.6	–	–
S1	$20SiO_2–38B_2O_3–15BaF_2–15Lu_2O_3–10Gd_2O_3–2CeF_3$	5.2	1.81	54
S2	$20SiO_2–33B_2O_3–15BaF_2–15Lu_2O_3–15Gd_2O_3–2CeF_3$	5.6	1.67	87
S3	$20SiO_2–28B_2O_3–15BaF_2–15Lu_2O_3–20Gd_2O_3–2CeF_3$	6.0	1.56	58
S4	$20SiO_2–38B_2O_3–15BaF_2–10Lu_2O_3–15Gd_2O_3–2CeF_3$	5.1	1.89	81
S5	$20SiO_2–28B_2O_3–15BaF_2–20Lu_2O_3–15Gd_2O_3–2CeF_3$	6.2	1.48	86

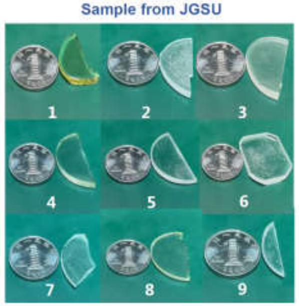
Varying thickness of Steel



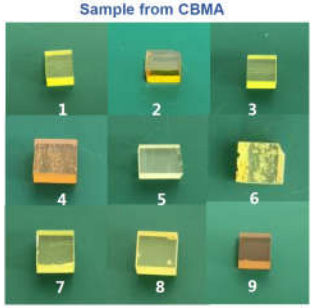
Varying thickness of ScintGlass

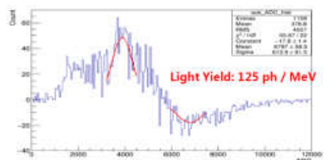


Sample from JGSU

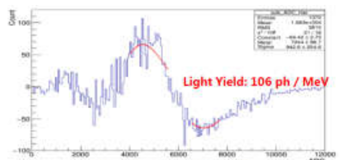


Sample from CBMA

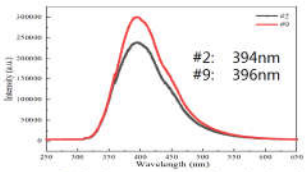




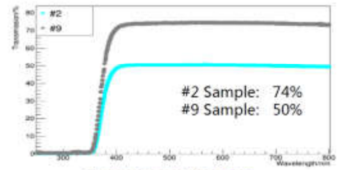
Energy Spectrum of #2



Energy Spectrum of #9

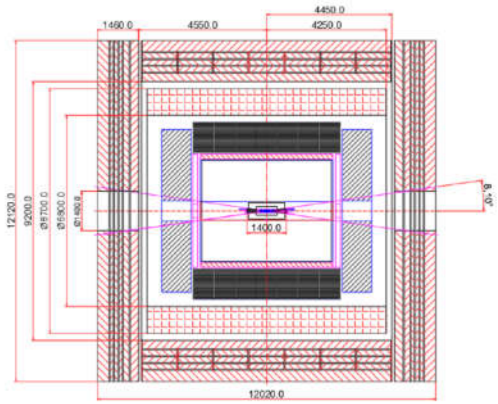


Emission spectra of X-ray induced

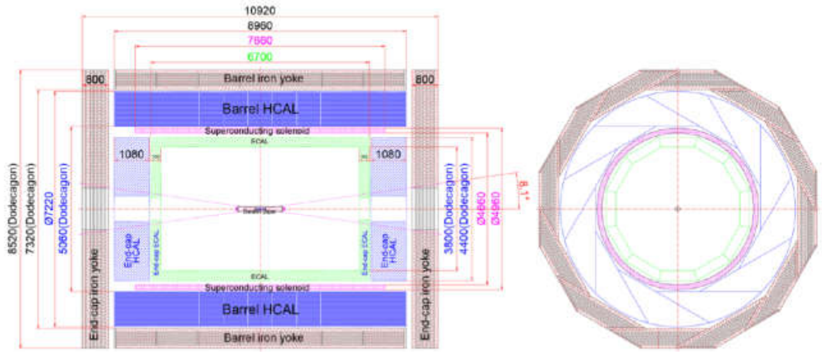


Transmission Spectrum

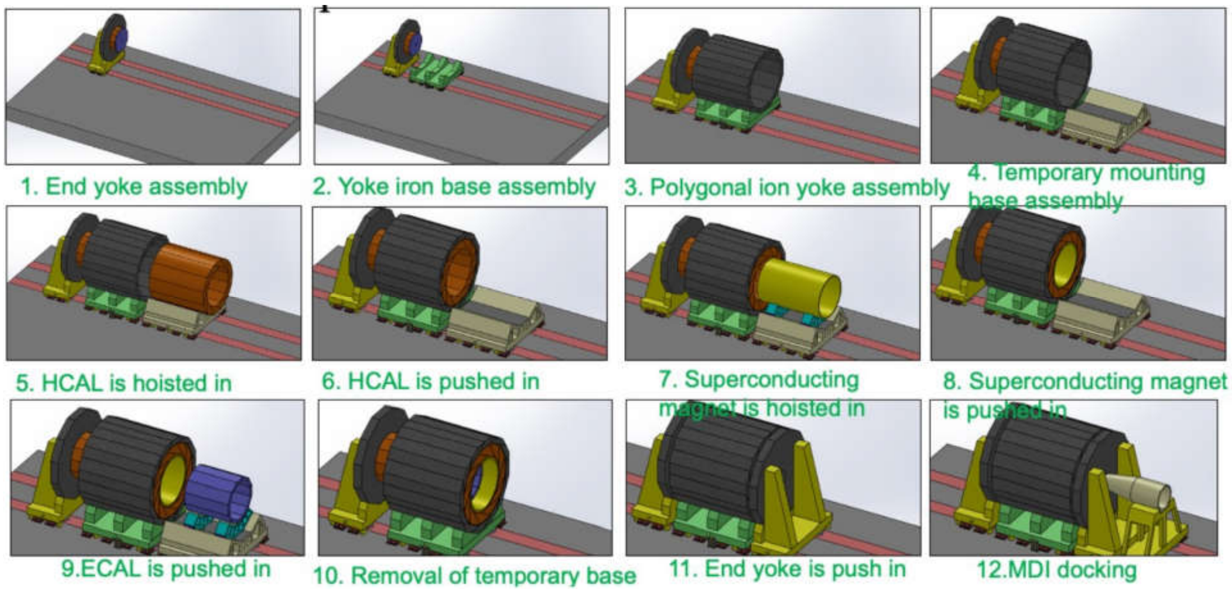
Mechanical Design



A detector layout in the [Mechanics Workshop 2020] by Quan Ji (IHEP)



A new detector layout in the [Yangzhou Joint Workshop 2021] by Quan Ji (IHEP)



https://indico.ihep.ac.cn/event/14392/other-view?view=standard

CEPC Luminosity Enhancement

2018 CDR Baseline Design

	Higgs	W	Z (3T)	Z (2T)
Number of IPs	2			
Beam energy (GeV)	120	80	45.5	
Circumference (km)	100			
Synchrotron radiation loss/turn (GeV)	1.73	0.34	0.036	
Crossing angle at IP (mrad)	16.5 × 2			
Piwinski angle	3.48	7.0	23.8	
Particles /bunch N_e (10^{10})	15.0	12.0	8.0	
Bunch number	242	1524	12000 (10% gap)	
Bunch spacing (ns)	680	210	25	
Beam current (mA)	17.4	87.9	461.0	
Synch. radiation power (MW)	30	30	16.5	
Bending radius (km)	10.7			
Momentum compaction (10^{-5})	1.11			
β function at IP β_x^* / β_y^* (m)	0.36/0.0015	0.36/0.0015	0.2/0.0015	0.2/0.001
Emittance x/y (nm)	1.21/0.0024	0.54/0.0016	0.18/0.004	0.18/0.0016
Beam size at IP σ_x/σ_y (μm)	20.9/0.06	13.9/0.049	6.0/0.078	6.0/0.04
Beam-beam parameters ξ_x/ξ_y	0.018/0.109	0.013/0.123	0.004/0.06	0.004/0.079
RF voltage V_{RF} (GV)	2.17	0.47	0.10	
RF frequency f_{RF} (MHz)	650			
Harmonic number	216816			
Natural bunch length σ_z (mm)	2.72	[illegible]	[illegible]	
Bunch length σ_z (mm)	4.4	[illegible]	[illegible]	
Damping time $\tau_x/\tau_y/\tau_E$ (ms)	[illegible]	[illegible]	[illegible]/849.5/425.0	
Natural Chromaticity	[illegible]	[illegible]	-491/-1161	-513/-1594
Betatr[illegible]	363.10 / 365.22			
S[illegible]	0.065	0.040	0.028	
H[illegible] (2 cell) (k[illegible]	0.46	0.75	1.94	
Natural energy spread (%)	0.100	0.066	0.038	
Energy spread (%)	0.134	0.098	0.080	
Energy acceptance requirement (%)	1.35	0.90	0.49	
Energy acceptance by RF (%)	2.06	1.47	1.70	
Photon number due to beamstrahlung	0.082	0.050	0.023	
Beamstruhlung lifetime /quantum lifetime† (min)	80/80	>400		
Lifetime (hour)	0.43	1.4	4.6	2.5
F (hour glass)	0.89	0.94	0.99	
Luminosity/IP (10^{34} cm^{-2}s^{-1})	3	10	17	32

† include beam-beam simulation and real lattice

2021 Improved Design

	ttbar	Higgs	W	Z
Number of Ips		2		
Circumference [km]		100.0		
SR power per beam [MW]		30		
Half crossing angle at IP [mrad]		16.5		
Bending radius [km]		10.7		
Energy [GeV]	180	120	80	45.5
Energy loss per turn [GeV]	9.1	1.8	0.357	0.037
Piwinski angle	1.21	5.94	6.08	24.68
Bunch number	35	249	1297	11951
Bunch population [10^10]	20	14	13.5	14
Beam current [mA]	3.3	16.7	84.1	803.5
Momentum compaction [10^-5]	0.71	0.71	1.43	1.43
Beta functions at IP (bx/by) [m/mm]	1.04/2.7	0.33/1	0.21/1	0.13/0.9
Emittance (ex/ey) [nm/pm]	1.4/4.7	0.64/1.3	0.87/1.7	[illegible]7/1.4
Beam size at IP (sigx/sigy) [um/nm]	39/113	15/36	[illegible]	[illegible]/35
Bunch length (SR/total) [mm]	2.2/2.9	[illegible]	[illegible]	2.5/8.7
Energy spread (SR/total) [%]	[illegible]	[illegible]	[illegible]07/0.14	0.04/0.13
Energy acceptance (DA/RF) [%]	[illegible]	[illegible]/2.2	1.2/2.5	1.3/1.7
Beam-beam parameters (ksix/ksiy)	[illegible]	0.015/0.11	0.012/0.113	0.004/0.127
RF voltage [GV]	10	2.2	0.7	0.12
RF frequency [MHz]	650	650	650	650
HOM power per cavity (5/2/1cell)[kw]	0.4/0.2/0.1	1/0.4/0.2	-/1.8/0.9	-/-/5.8
Qx/Qy/Qs	0.12/0.22/0.078	0.12/0.22/0.049	0.12/0.22/	0.12/0.22/
Beam lifetime (bb/bs)[min]	81/23	39/18	60/717	80/182202
Beam lifetime [min]	18	12.3	55	80
Hour glass Factor	0.89	0.9	0.9	0.97
Luminosity per IP[1e34/cm^2/s]	0.5	5.0	16	115

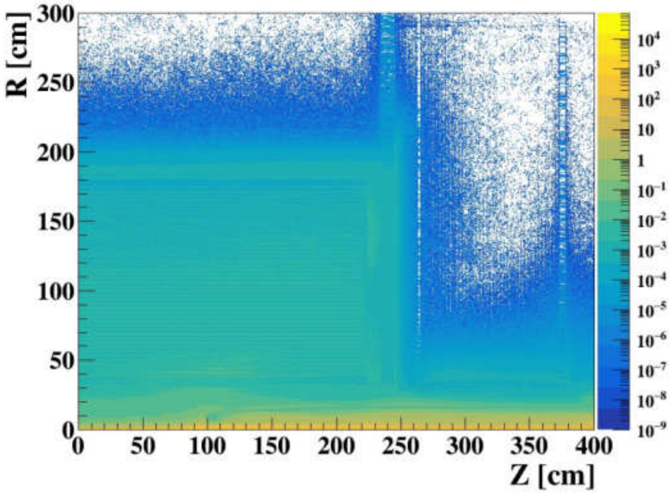
67%⇑ (Higgs) **259%⇑** (Z)

Beam Background

Background on inner most layer

Background	Hit Density($cm^{-2} \cdot BX^{-1}$)			TID($Mrad \cdot yr^{-1}$)			1 MeV equivalent neutron fluence ($n_{eq} \times 10^{12} \cdot cm^{-2} \cdot yr^{-1}$)		
	Higgs	W	Z	Higgs	W	Z	Higgs	W	Z
Pair production	1.8	1.2	0.4	0.50	2.1	5.6	1.0	3.8	10.6
Beam Gas	0.4	0.4	0.2	0.36	1.3	4.1	1.0	3.6	11.1
Beam Thermal Photon	0.1	0.1	0.03	0.07	0.3	0.8	0.2	0.7	1.9
Total	2.3	1.7	0.63	0.93	3.7	10.5	2.2	8.1	23.6
Lifetime		-			31.21			70.7	
Total_oCDR	2.4	2.3	0.25	0.93	2.9	3.4	2.1	5.5	6.2

Background on sub-detectors



Name	Position in R	Hit/cm²/BX	Hit/cm²/s
VTX	15 mm	~2.3	~3.33e7
SIT	15 cm	~0.01	~14507
TPC	50 cm	~0.005	~7253
Ecal	200 cm	~1e-4	~145
Hcal	220 cm	~2e-6	~2.9

Impacts of enhanced luminosities on detectors need to be carefully assessed.

Summary

- Active and intense R&D work across all sub-detectors targeting key technologies.
- A lot of progress has been made and several R&D projects have reached a success.
- A new detector concept to address precise EM measurement and PID has been proposed with dedicated R&D already ongoing.
- Still a lot of room for improvement and innovation.

- Back up