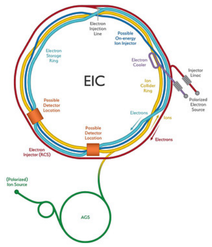


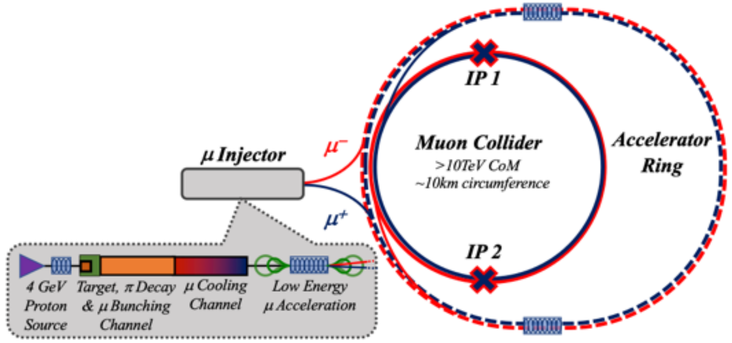
Status of Future Collider Projects

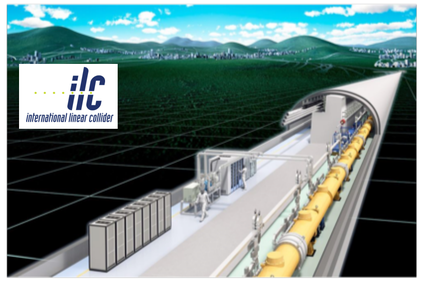
Hwidong Yoo (Yonsei Univ.)

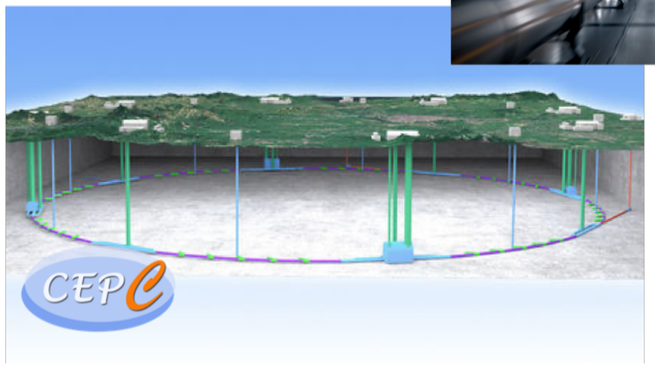
CPNR workshop,
October 25, 2025

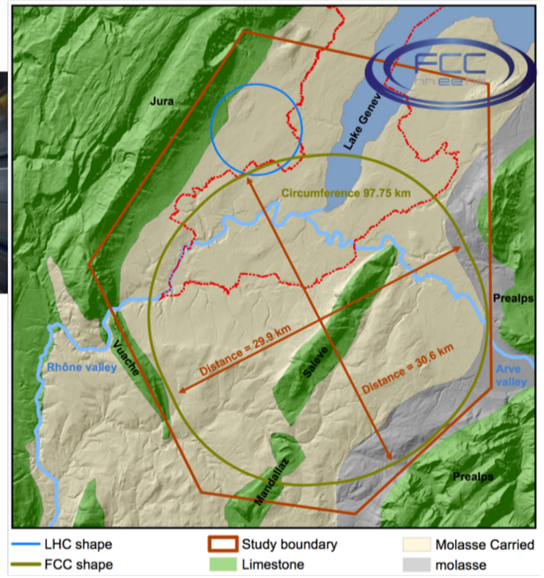
Future Collider Projects in HEP

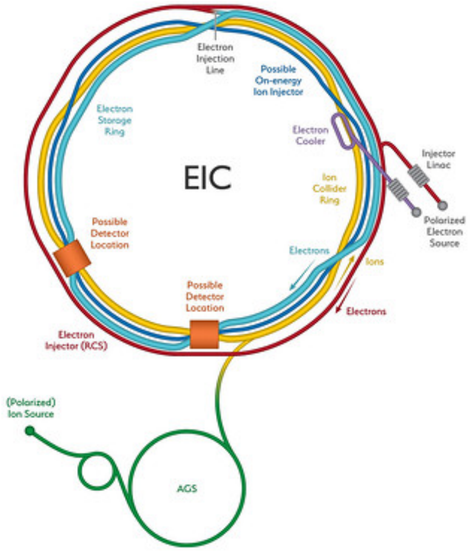
- Many next generation experiments are under discussion
  - Linear colliders: ILC (Japan), CLIC (CERN)
  - Circular colliders: **FCC-ee**/eh/hh, muon collider (CERN, US), **CEPC**/SPPC (China)
  - HI colliders: **EIC** (US)











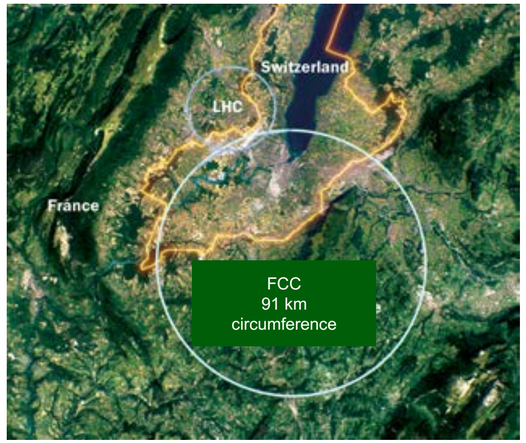
Most slides from Open Symposium European Strategy for Particle Physics (23-27 June 2025), link

From CERN

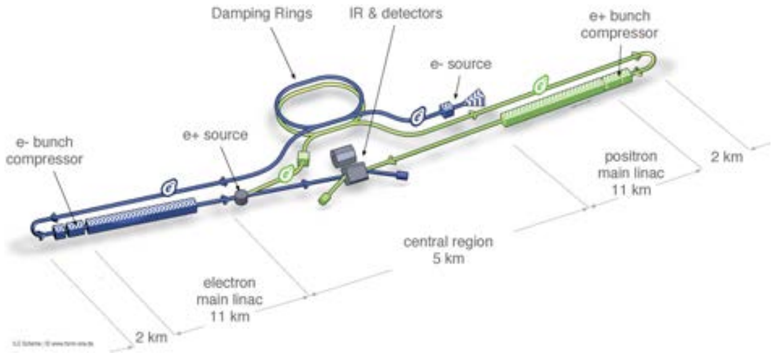
Proposed Large-Scale Projects at CERN (~2045)

e^+e^- colliders
("Higgs factories")

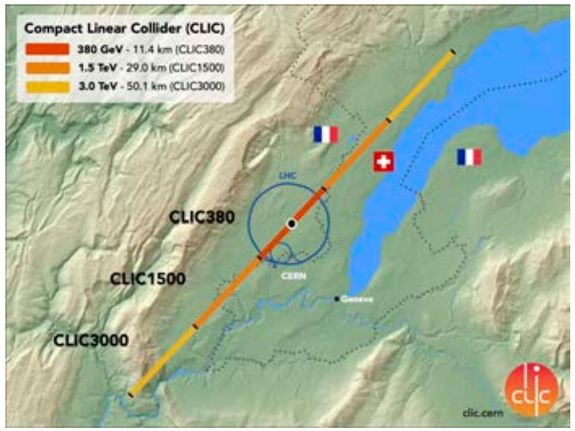
FCC-ee (e^+e^-, circular, 91 – 365 GeV)



LCF (e^+e^-, linear, 91 – 240, 550 GeV)



CLIC (e^+e^-, linear, 380 GeV, 1.5 TeV)

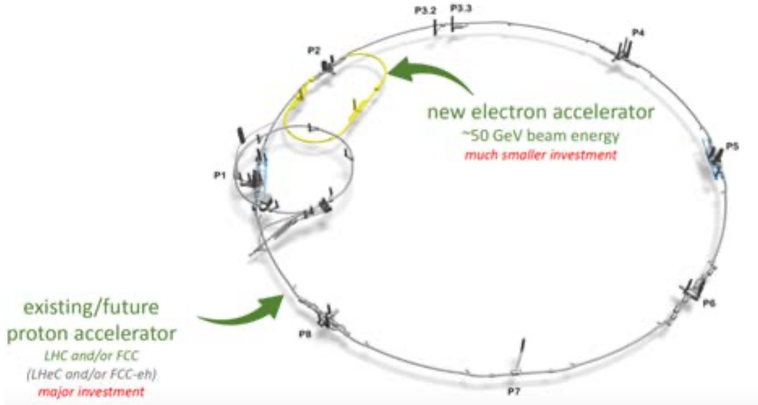


Intermediate projects

(Leave room (time, budget, resources) for further development of THE machine that can probe directly the energy frontier at the 10 TeV parton scale)

LEP3 (e^+e^-, circular, 91 – 230 GeV)

LHeC (ep, circular, electron ERL, 50 GeV e^-, > 1 TeV ep collisions)



The Vision by CERN Council

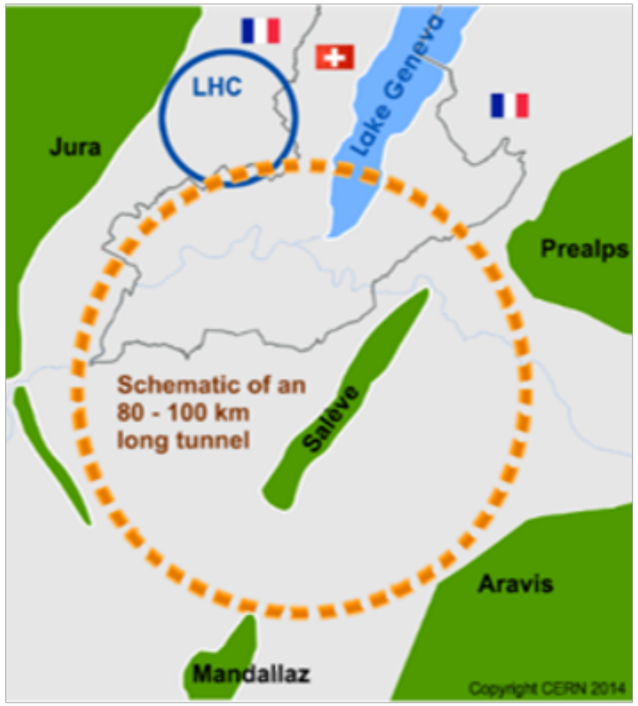
*"The aim of the Strategy update should be to develop a **visionary and concrete plan** that greatly advances human knowledge in fundamental physics through the **realisation of the next flagship project at CERN**. This plan should attract and value **international collaboration** and should **allow Europe to continue to play a leading role in the field.**"*

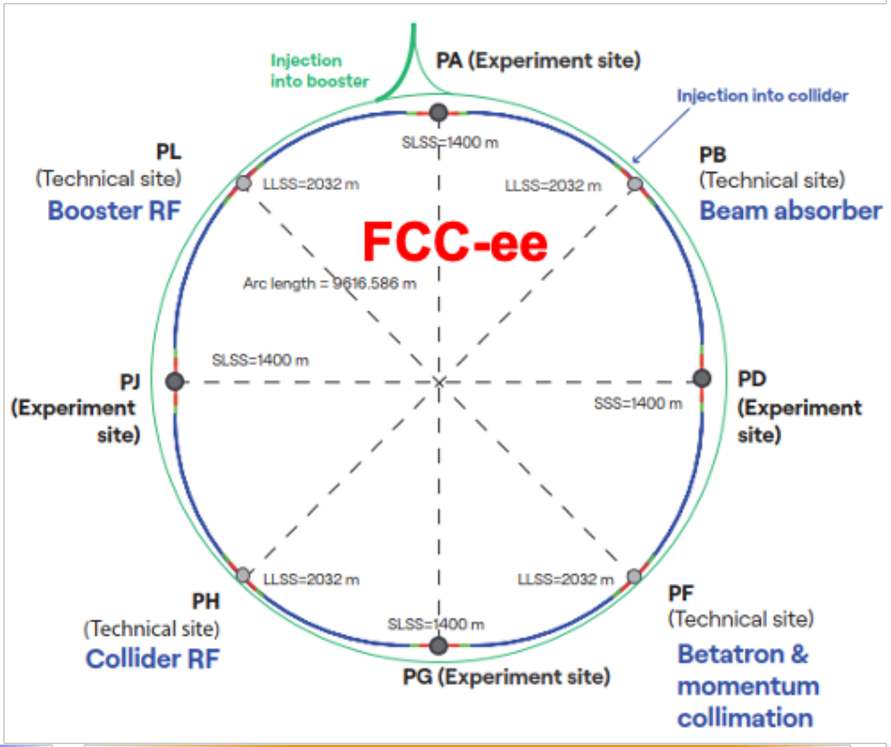
This vision is strongly echoed by the High-Energy Physics communities in Europe and beyond, as testified by the input received from the **national HEP communities**

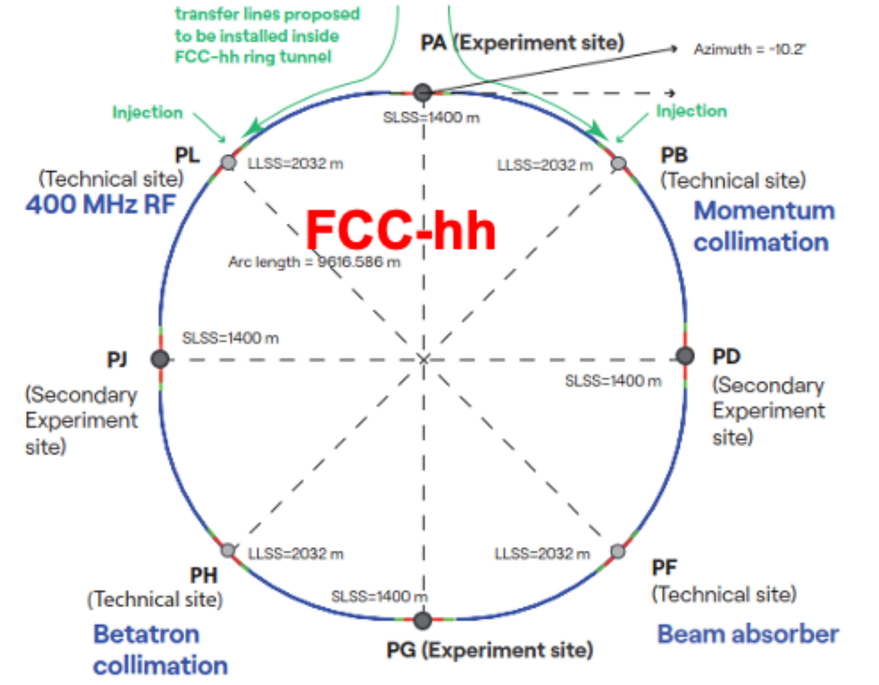
Many HEP communities support a forward-looking European strategy that **maintains CERN as the global centre for collider physics** and ensures a balanced, ambitious, and innovative research programme.

FCC Project

- FCC-ee/hh project: CERN
  - stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities
  - stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, pp & AA collisions; e-$_h$ option





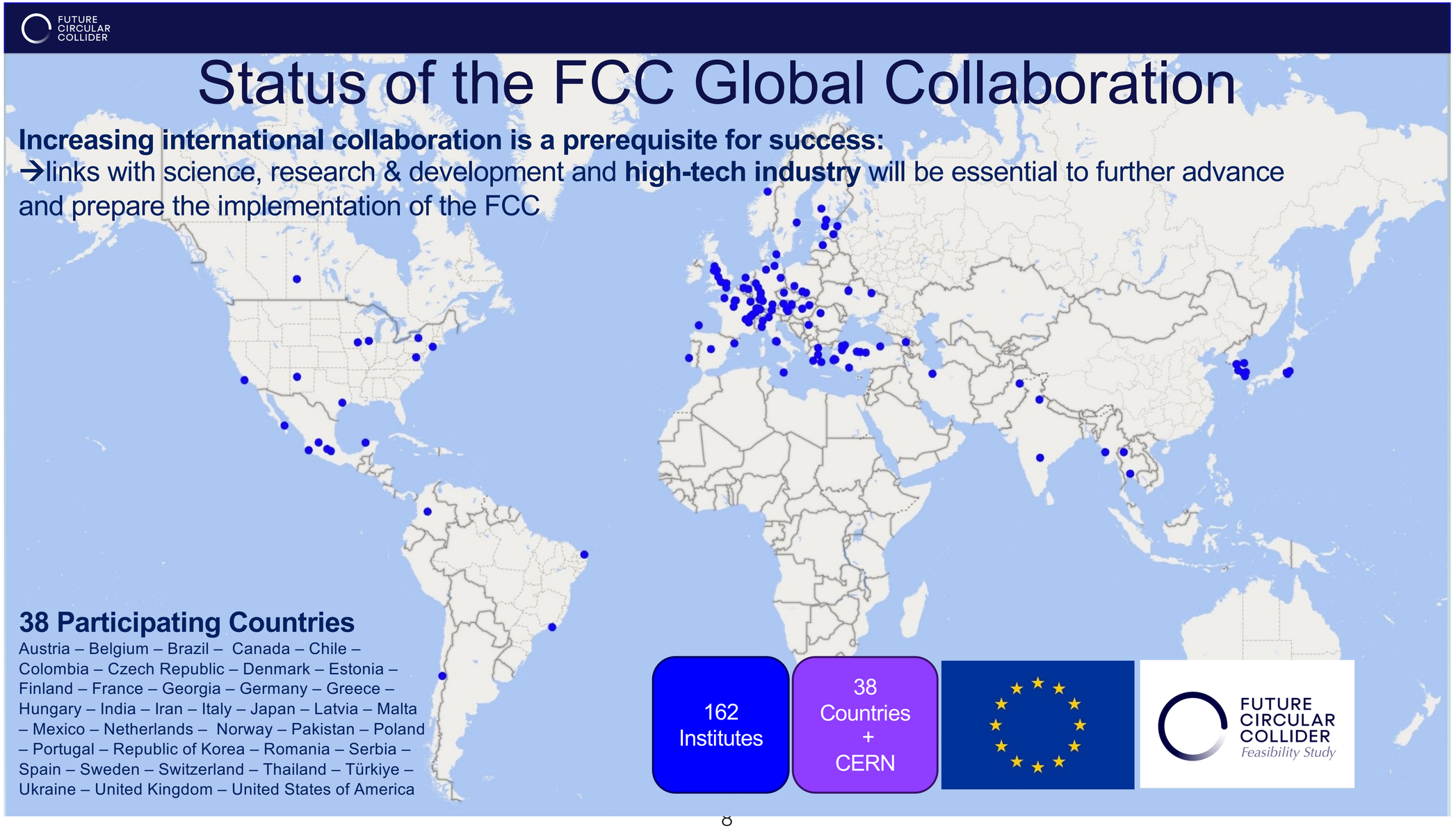


2020 - 2045 | **2046 - 2065** | **2070 - 2100**

FCC-ee Main Parameters and Operation Plan

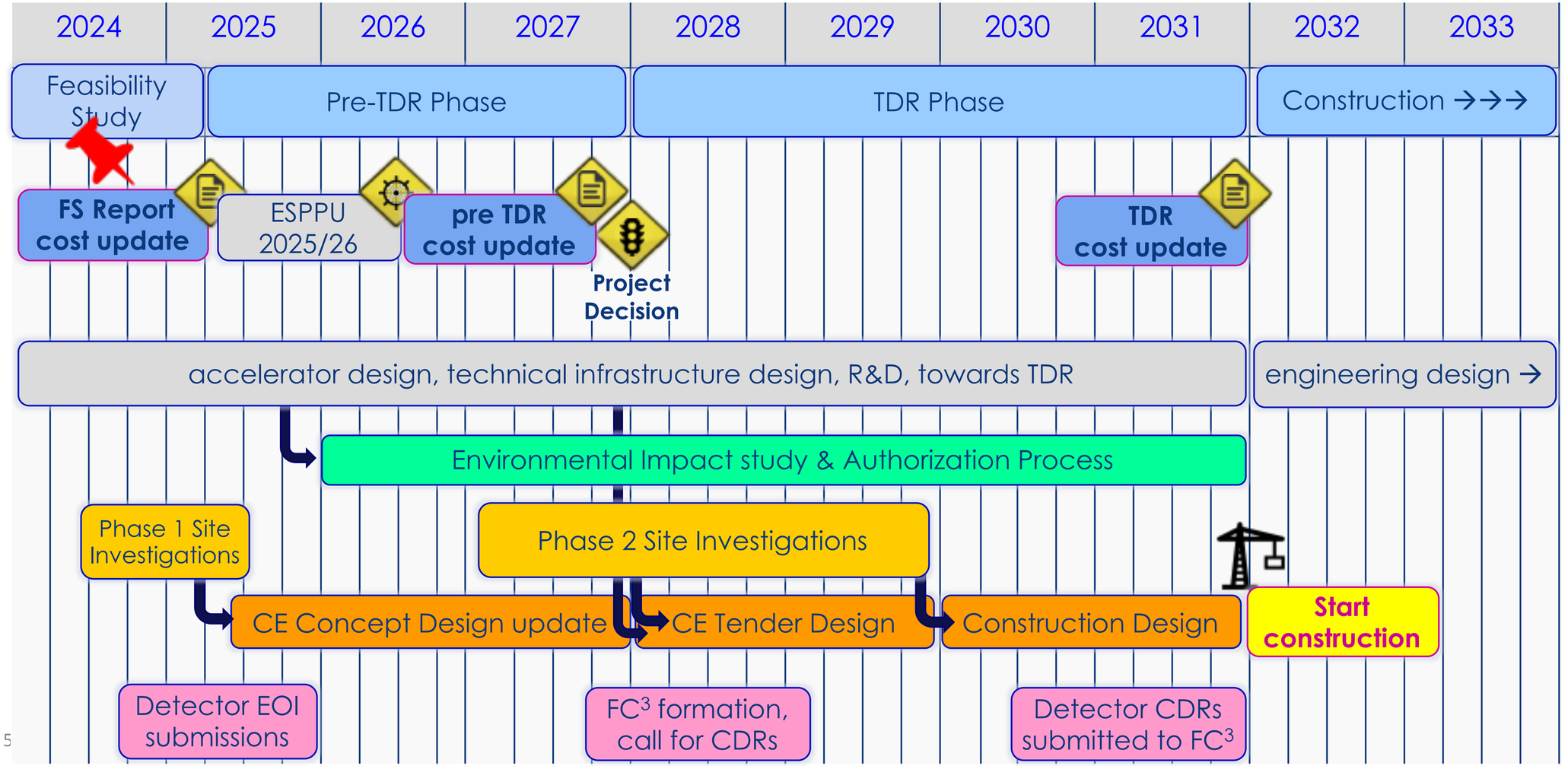
parameter	Z	WW	H (ZH)	tt	
Collision energy √s [GeV]	88, 91, 94	157, 163	240	340-350	365
synchrotron radiation/beam [MW]	50	50	50	50	50
beam current [mA]	1294	135	26.8	6.0	5.1
number bunches / beam	11200	1852	300	70	64
total RF voltage 400 / 800 MHz [GV]	0.08 / 0	1.0 / 0	2.1 / 0	2.1 / 7.4	2.1 / 9.2
luminosity / IP [10^{34} $cm^{-2}s^{-1}$]	144	20	7.5	1.8	1.4
luminosity / year [ab^{-1}]	68	9.6	3.6	0.83	0.67
run time (including lumi ramp-up) [years]	4	2	3	1	4
total integrated luminosity [ab^{-1}]	205	19.2	10.8	0.4	2.7
total number of events	$6x10^{12}$ Z	$2.4x10^{8}$ WW (incl. WW at higher √s)	$2.2x10^{6}$ ZH 65k WW → H	$2x10^{6}$ tt + 370k ZH + 92k WW → H	

FCC Glocal Collaboration



FCC Project Timeline

- Technical timeline before construction



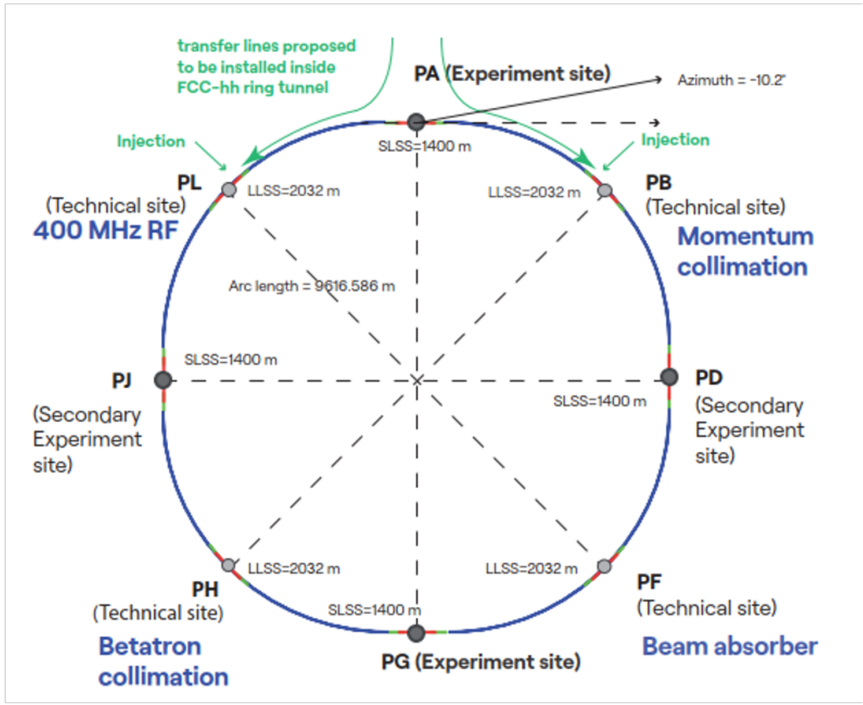
Status of FCC-hh

- Parameter optimization to lower electricity consumption (~max. consumption of FCC-ee)
- Magnetic field considered realistic with current technologies (Nb_3Sn, ~14T, 1.9 K)

Main parameters FSR 2025

parameter	FCC-hh	FCC-hh CDR	HL-LHC
collision energy cms [TeV]	85	100	14
dipole field [T]	14	16	8.33
circumference [km]	90.7	97.8	26.7
beam current [A]	0.5	0.5	1.1
synchr. rad. per ring [kW]	1200	2400	7.3
peak luminos. [10^{34} $cm^{-2}s^{-1}$]	30	30	5 (lev.)
events/bunch crossing	1000	1000	132
stored energy/beam [GJ]	6.5	8.3	0.7
integr. luminosity / IP [fb^{-1}]	20000	20000	3000

FCC-hh functional layout



FCC-hh Timeline Scenarios

Milestone	Date
Conceptual design study	2014-18
Definition of placement scenario	2022
Feasibility Report ready	2025
Main technologies R&D completion	**2054**
Technical Design Report ready	2054
Latest Project Approval	**2054**
Environmental evaluation & project authorization processes	2054-2058
Industrialisation & magnet production	2054-2069
Civil engineering – collider	2060-2068
FCC-ee dismantling	2063-2064
TI installation – collider	2065-2069
Accelerator installation – collider	2068-2072
HW commissioning – collider	2071-2073
Beam commissioning – collider	2073
Physics operation start	**2074**

FCC-hh timeline as a second phase after FCC-ee.

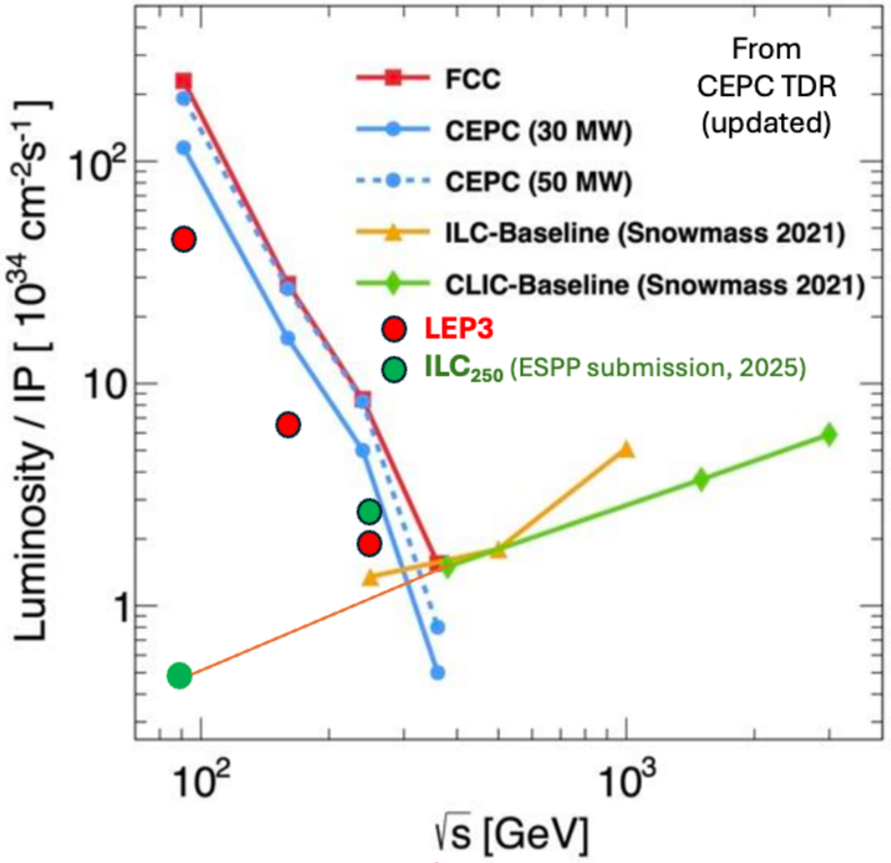
Milestone	Date
Conceptual design study	2014-18
Definition of placement scenario	2022
Feasibility Report ready	2025
Latest Project Approval	**2033**
Environmental evaluation & project authorization processes	2026-35
Main technologies R&D completion	**2037**
Technical Design Report ready	2037
Industrialisation & magnet production	2038-2053
Civil engineering – collider	2037-2046
TI installation – collider	2043-2050
Accelerator installation – collider	2046-2052
HW commissioning – collider	2049-2053
Beam commissioning – collider	2054
Physics operation start	**2055**

Fastest possible FCC-hh timeline as a stand-alone project.

LEP3 and LHeC

LEP3: Run at √s =230 GeV

- Only 10% higher energy than LEP.
- 18% lower synchrotron power loss at √s=230 GeV compared with 240 GeV.



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

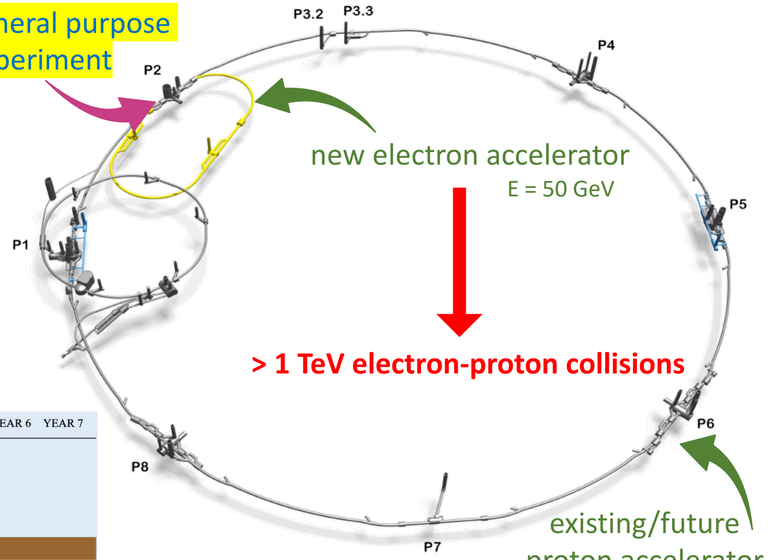
LHeC FCC hh ee he

802.5MHz, 20MV/m in CW, 6x25mA in SRF
ERL 3-turns, 50 GeV (1/3 of LHC circumference)
Start operation after HL-LHC (>2041)
Luminosity above 10^{34} $cm^{-2}s^{-1}$
6 years of operation, 1 ab^{-1} (e.g. 2043-2048)
120MW from HL-LHC + 100MW from e-beam

LHeC construction planning	YEAR 1	YEAR 2	YEAR 3	YEAR 4	YEAR 5	YEAR 6	YEAR 7
Land negotiations							
Environmental Impact Study							
Building permits							
Detailed design & tendering							
Construction							

for example 2034 → 2041

one general purpose experiment

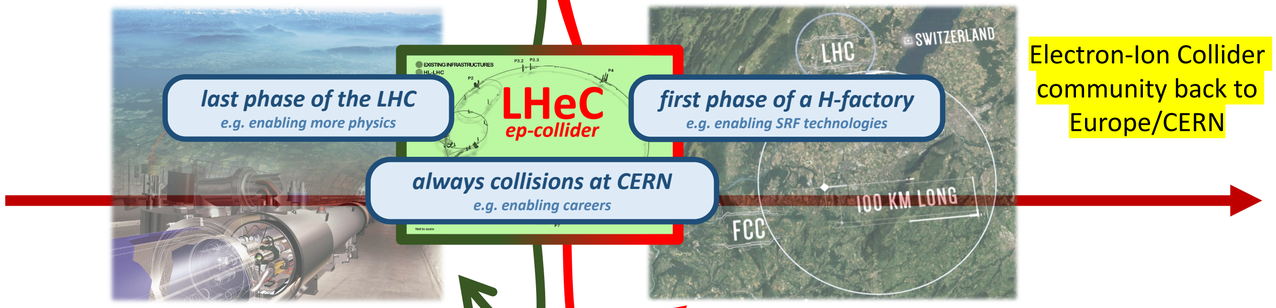


ultimate upgrade of the LHC physics reach

cost-effective inves…

re-use injector

essential enabler for the physics at any new high-energy hadron collider



Electron-Ion Collider community back to Europe/CERN

fast-track to new and impactful opportunities at colliders for attractive SM & BSM physics

fast-track to the optimal SRF performance of a H-factory & cost/risk reduction for SRF at FCC-ee/LEP3

~ 4 x10^5 H bosons for LEP3 and LC, and 22 x10^5 H bosons for FCC-ee (240 only) i.e. ratio of 1:1:~5.5

Cost Estimations

FCC-ee cost estimate (FSR 2025)

Capital cost (2024 CHF) for construction of the FCC-ee is summarised below. This cost includes construction of the entire new infrastructure and all equipment for operation at the Z, WW and ZH working points.

FCC-ee

Domain	Cost [MCHF]
Civil engineering	6,160
Technical infrastructures	2,840
Injectors and transfer lines	590
Booster and collider	4,140
CERN contribution to four experiments	290
FCC-ee total	**14,020**
+ four experiments (non-CERN part)	1,300
FCC-ee total incl. four experiments	**15,320**

Note: Upgrade of SRF (800 MHz) & cryogenics for ttbar operation corresponds to additional cost of 1,260 MCHF

LCF CLIC

Unit: MCHF	LCF 250 (LP)	Δ LCF 550 (FP)	CLIC 380	Δ CLIC 1500
Collider	3864	4204	2471	4684
Main Beam inj./transfer	1181	86	1046	23
Drivebeam inj./transfer	-	-	1060	302
Civil Engineering	2338	0	1403	703
Technical Infrastructure	1109	1174	1361	1404
Sum	**8492**	**5464**	**7341**	**7116**

LEP3

Cost Element	2 new Xpts	2 Exist Xpts
Accelerator	2705	2705
Injectors and Transfer Lines	295	295
Technical Infrastructures	435	435
Experiments	130	60
Civil Engineering	165	165
LHC Removal/LEP3 Installation	140	140
Total CERN (MCHF)	**3870**	**3800**
Experiments non-CERN part	900	270

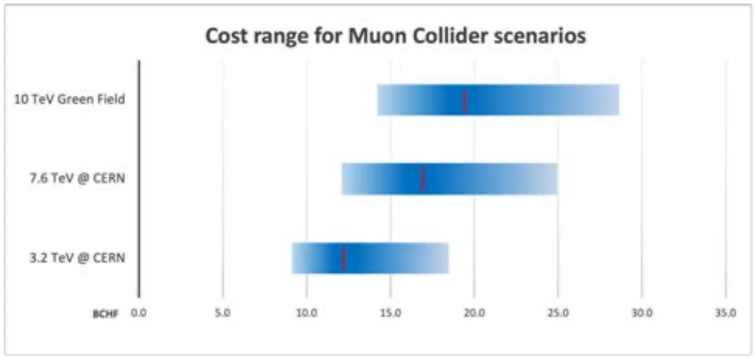
Cost summary table in 2024 MCHF for the construction of FCC-hh.

FCC-hh
(after FCC-ee)

Domain	FCC-hh Cost [MCHF]
FCC-ee dismantling	200
Collider*	13400
Injectors and transfer linear	1000
Civil Engineering	520
Technical infrastructures	3960
Experiments	N/A
Total	**19080**

*target price of 2.0 MCHF per 14.3 m long magnet with 1.0 MCHF of conductor, 0.5 MCHF for assembly, and 0.5 MCHF for components

Muon Collider



LHeC (cost estimate 2018, 60 GeV e-)

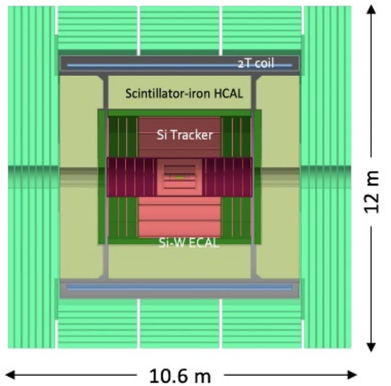
Budget Item	Cost
SRF System	805MCHF
SRF R&D and Proto Typing	31MCHF
Injector	40MCHF
Magnet and Vacuum System	215MCHF
SC IR magnets	105MCHF
Dump System and Source	5MCHF
Cryogenic Infrastructure	100MCHF
General Infrastructure and installation	69MCHF
Civil Engineering	386MCHF
Total	1756MCHF

→ ~2 BCHF (2025)

FCC-ee Detector Concept

- Three detector concepts are proposed for FCC-ee so far
- Korean team has led the design and core R&Ds of the Dual-Readout Calorimeter (DRC) for IDEA detector
- Included in the CDRs of both FCC-ee and CEPC, published at the end of 2018

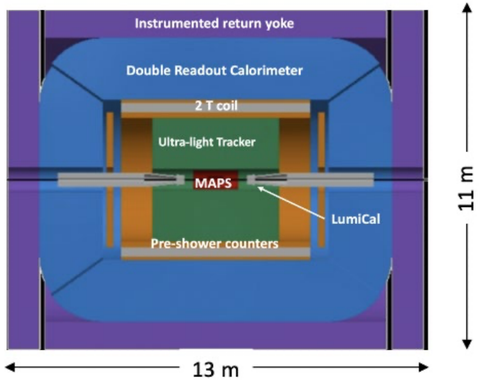
CLD



- Well established design
  - ILC -> CLIC detector -> CLD
- Full Si vtx + tracker
- CALICE-like calorimetry;
- Large coil, muon system
- Engineering still needed for operation with continuous beam (no power pulsing)
  - Cooling of Si-sensors & calorimeters
- Possible detector optimizations
  - σ_p/p, σ_E/E
  - PID ($\mathcal{O}$(10 ps) timing and/or RICH)?

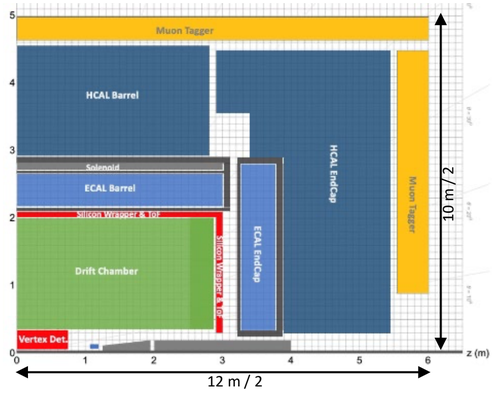
CDR

IDEA



- A bit less established design
  - But still ~15y history
- Si vtx detector; ultra light drift chamber with powerful PID; compact, light coil;
- Monolithic dual readout calorimeter;
  - Possibly augmented by crystal ECAL
- Muon system
- Very active community
  - Prototype designs, test beam campaigns, …

ALLEGRO



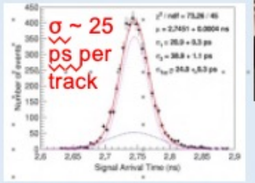
- The “new kid on the block”
- Si vtx det., ultra light drift chamber (or Si)
- High granularity Noble Liquid ECAL as core
  - Pb/W+LAr (or denser W+LKr)
- CALICE-like or TileCal-like HCAL;
- Coil inside same cryostat as LAr, outside ECAL
- Muon system.
- Very active Noble Liquid R&D team
  - Readout electrodes, feed-throughs, electronics, light cryostat, …
  - Software & performance studies

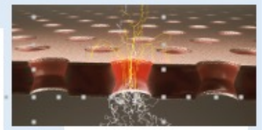
R&D on Detector Technologies

Implemented through Detector R&D (DRD) collaborations hosted at CERN, with review and oversight provided by DRD Committee (DRDC) and ECFA Detector Panel

DRD1: Gaseous Detectors

Large · Fast · eco-friendly gases · MPGD, e.g. GEMs

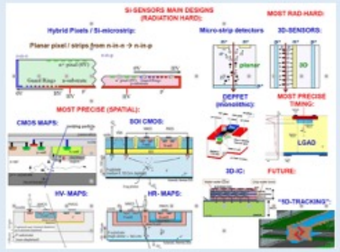




PICOSEC: NIMA903 (2018) 317

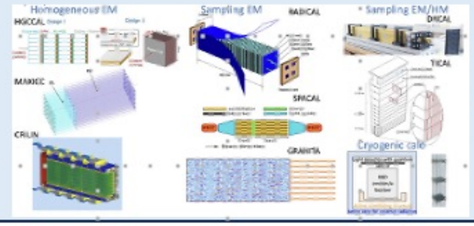
DRD3: Semiconductor Det.

Monolithic CMOS · LGADs · radiation hardness · interconns.



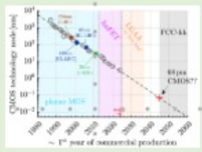
DRD6: Calorimetry

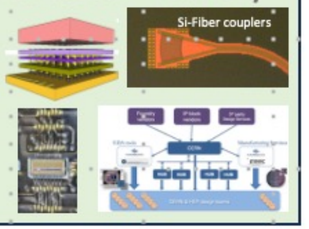
Energy resolution · High granularity · dual readout · particle flow · sandwich · optical



DRD7: Electronics

ADC/TDC IP Blocks · Opto-electronics · packaging · power · extreme environments · COTS · intelligence on detector · foundry access

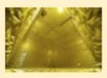


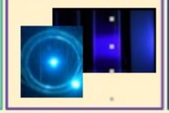


DRD2: Liquid Detectors

for Neutrinos · Dark Matter · 0vbb

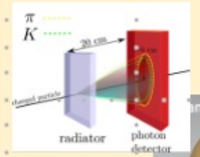
Noble Elements	Liquid Scintillators	Water Cherenkov
• Argon & Xenon • Ionisation charge & transport • VUV Sciptillation, light propagation & detection	• Visible Scintillation, light propagation • Scintillator properties • Isotope loading	• Cherenkov light, light propagation • Doping for n-capture

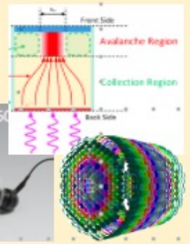




DRD4: Photon detectors

vacuum, solid-state (SiPM), hybrid single-photon and SciFi detectors · applications in PID and RICH

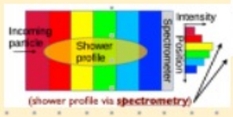


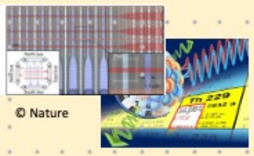


DRD5: Quantum Sensors

Quantum dots · superconduct. nanowires · bolometers · TES · MMC · nuclear clocks

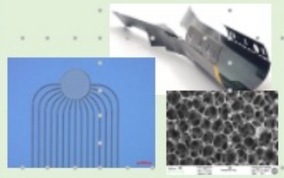
First applications for DM, first projects in HEPP happening

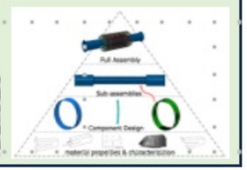




DRD8: Mechanics

Ultra-thin beam pipes · CF foam and new materials · curved, retractable sensors · air & micro-channel cooling · eco-friendly cooling fluids · robots · augmented reality





Courtesy T. Bergauer

Status of Participations in Korea

	Institute	PI
DRD1	Osong Medical Innovation Foundation	Won-Kyu Lee
	DGIST	Gain Kim
	Hanyang University	Tae Jeong Kim
	Seoul National University	Do Won Kim
	University of Seoul	Jason Lee
	Yonsei Cancer Center	Dong Wook Kim
DRD3	Kyungpook National University	Chang Seong Moon
DRD6	Gangneung-Wonju National University	Minsuk Kim
	Hanyang University	Byunggu Chun
	Korea University	Jae Hyeok Yoo
	Kyungpook National University	Sehwook Lee
	Pusan National University	Sanghoon Lim
	Sungkyunkwan University	Beomkyu Kim
	University of Seoul	Jason Lee
	Yonsei Cancer Center	Dong Wook Kim
	Yonsei University	Hwidong Yoo

DRD-Calo Activities in Korea

- Huge participation in the DRD-Calo collaboration from the beginning

ECFA

DRD Calo - Proposal Team

European Strategy Update

Coordinators: Roberto Ferrari, Gabriella Gaudio (INFN-Pavia), R.P. (IJCLab)

Representative from ECFA Detector R&D Roadmap Coordination Team: Felix Sefkow (DESY)

WP 1: Sandwich calorimeters with fully embedded Electronics – Main and forward calorimeters
Conveners: Adrian Irles (IFIC, adrian.irles@ific.uv.es), Frank Simon
(KIT, frank.simon@kit.edu), Jim Brau (University of Oregon, jimbrau@uoregon.edu),
Wataru Ootani (University of Tokyo, wataru@icepp.s.u-tokyo.ac.jp), Imad Laktineh (I2PI, imad.laktineh@in2p3.fr)

WP 2: Liquified Noble Gas Calorimeters
Conveners: Martin Aleksa (CERN, martin.aleksa@cern.ch), Nicolas
Morange (IJCLab, nicolas.morange@ijclab.in2p3.fr), Marc-Andre Pleier (mpleier@bnl.gov)

WP 3: Optical calorimeters: Scintillating based sampling and homogenous calorimeters
Conveners: Etiennette Auffray (CERN, etiennette.auffray@cern.ch),
Macro Lucchini (University and INFN Milano-Bicocca, marco.toliman.lucchini@cern.ch),
Philipp Roloff (CERN, philipp.roloff@cern.ch), Sarah Eno (University of Maryland, eno@umd.edu),
Hwidong Yoo (Yonsei University, hdyoo@cern.ch)

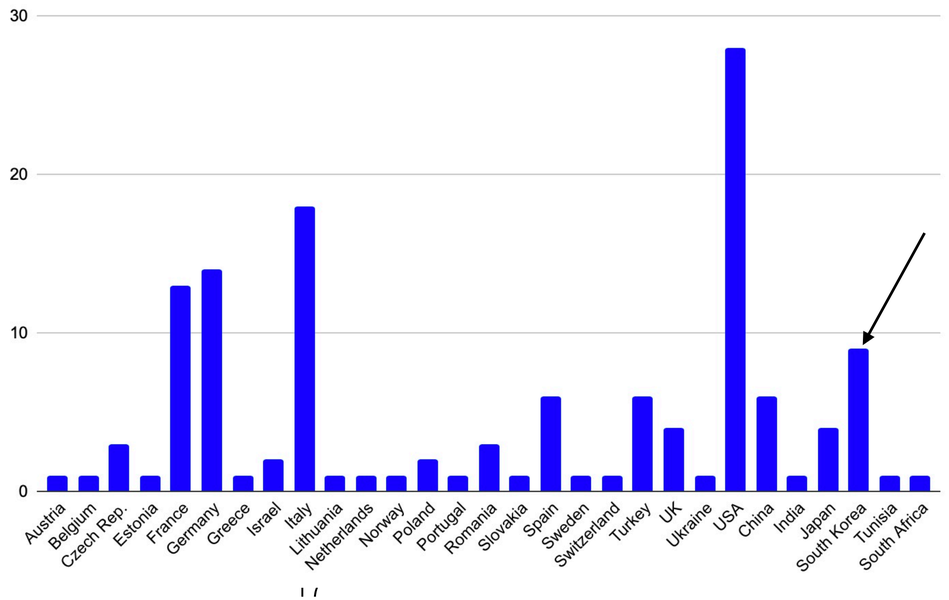
WP 4: Electronics and DAQ
Christophe de la Taille (OMEGA, taille@in2p3.fr)

Transversal Activitiies
Photodetectors: Alberto Gola (FBK, gola@fbk.eu)

Proto-CB Meeting – Jan. 2024

1st collaboration meeting (4/9-11, 2024)

Institutes per Countries



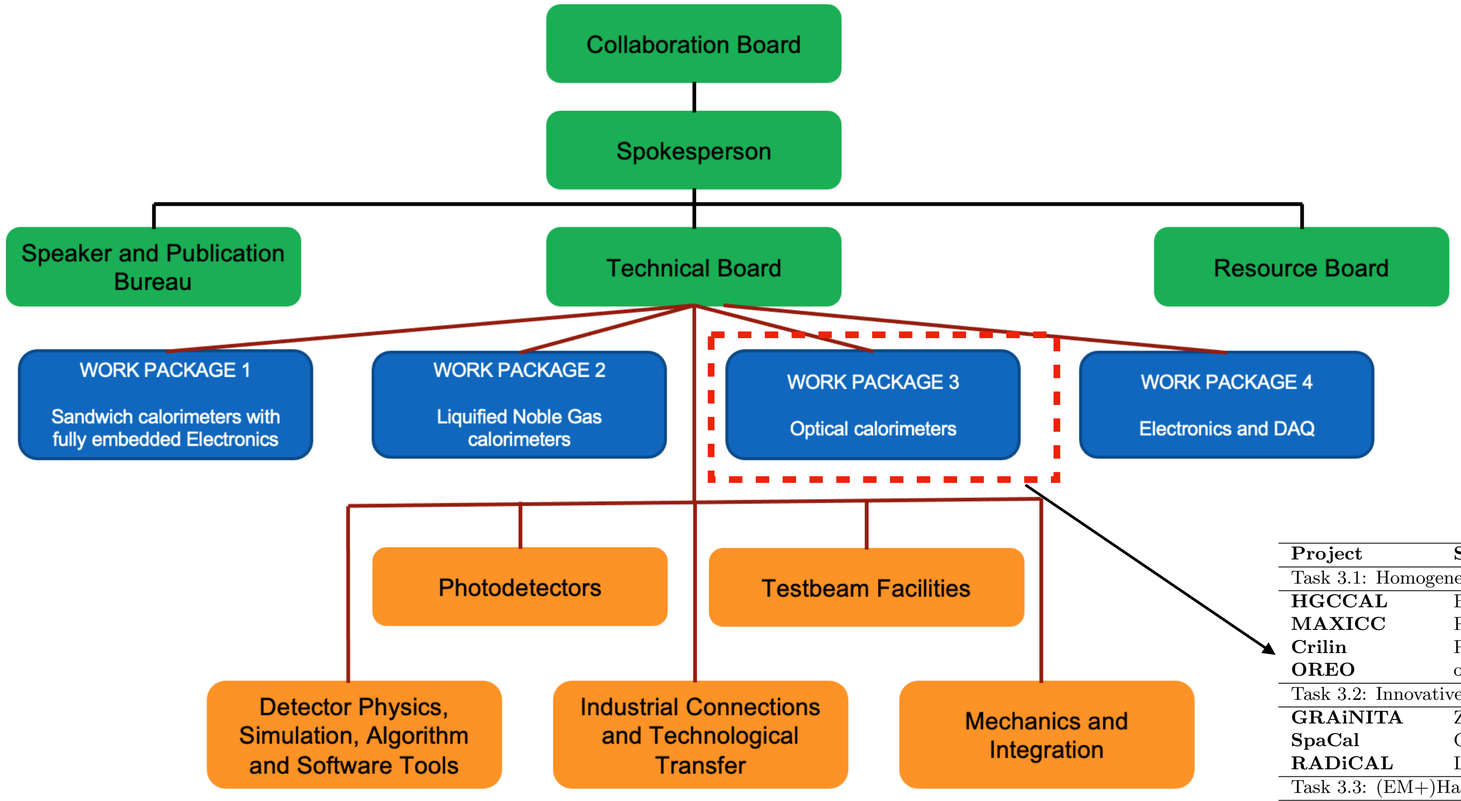
DRD-Calo Activities in Korea

- Hwidong Yoo has been elected as next WP3 coordinator

MANAGEMENT:

WORK PACKAGES:

WORKING GROUPS:



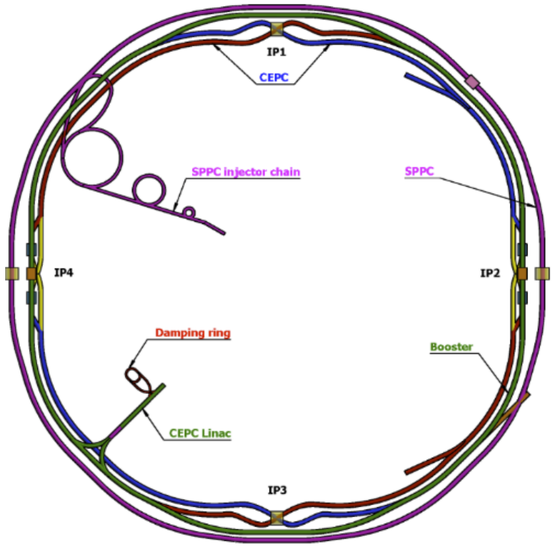
Project	Scintillator/WLS	Photodetector	DRDTs	Target
Task 3.1: Homogeneous and quasi-homogeneous EM calorimeters				
HGCCAL	BGO, LYSO	SiPMs	6.1, 6.2	e^+e^-
MAXICC	PWO, BGO, BSO	SiPMs	6.1, 6.2	e^+e^-
Crilin	PbF_2, PWO-UF	SiPMs	6.2, 6.3	$\mu^+\mu^-$
OREO	oriented PWO-UF	SiPMs	6.2, 6.3	$e^+e^-/\mu^+\mu^-$
Task 3.2: Innovative Sampling EM calorimeters				
GRAiNITA	$ZnWO_4$, BGO	SiPMs	6.1, 6.2	e^+e^-
SpaCal	GAGG, organic	MCD-PMTs,SiPMs	6.1, 6.3	e^+e^-/hh
RADiCAL	LYSO, LuAG	SiPMs	6.1, 6.2, 6.3	e^+e^-/hh
Task 3.3: (EM+)Hadronic sampling calorimeters				
DRCal	PMMA, plastic	SiPMs, MCP	6.2	e^+e^-
TileCal	PEN, PET	SiPMs	6.2, 6.3	e^+e^-/hh
Task 3.4: Materials				
ScintCal	-	-	6.1, 6.2, 6.3	$e^+e^-/\mu^+\mu^-$/hh
CryoDBD Cal	TeO, ZnSe, LiMoO NaMoO, ZnMoO	n.a.	-	DBD experiments

Table 2: Overview of R&D activities on optical calorimeter concepts.

From China

CEPC/SPPC Project

- 100km circumference
- Compatible tunnel for CEPC and SPPC
- Baseline: 100 km, 30 MW;
  Upgradeable to 50 MW, High Lumi Z, ttbar
- Switchable operation: Higgs, W/Z, top
- A very high energy Synchrotron radiation facility



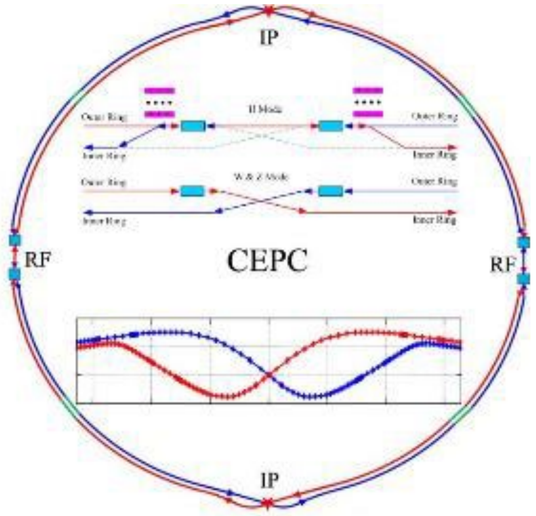
High Energy Photon Source (HEPS)

Operation Plan

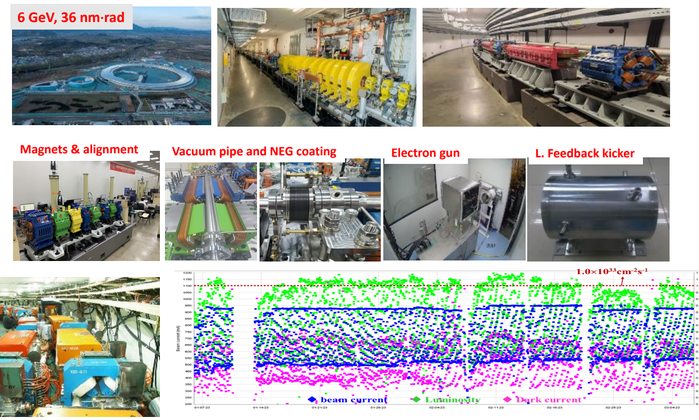
* Higgs is the top priority. The CEPC will commence its operation with a focus on Higgs

Particle	$E_{c.m.}$ (GeV)	Years	SR Power (MW)	Lumi. /IP ($10^{34}cm^{-2}s^{-1}$)	Integrated Lumi. /yr (ab^{-1}, 2 IPs)	Total Integrated L (ab^{-1}, 2 IPs)	Total no. of events
H*	240	10	50	8.3	2.2	21.6	4.3×10^6
			30****	5	1.3	13	2.6×10^6
Z	91	2	50	192**	50	100	4.1×10^{12}
			30****	115**	30	60	2.5×10^{12}
W	160	1	50	26.7	6.9	6.9	2.1×10^8
			30****	16	4.2	4.2	1.3×10^8
$t\bar{t}$	360	5	50	0.8	0.2	1.0	0.6×10^6
			30****	0.5	0.13	0.65	0.4×10^6

** Detector solenoid field is 2 Tesla during Z operation, 3Tesla for all other energies.
*** Calculated using 3,600 hours per year for data collection.
**** 30 MW leaves room for international in-kind contributions



Experience at HEPS/BEPCII



Accelerator TDR Published

Accelerator TDR Review
June 12-16, 2023, Hong Kong

Accelerator TDR Cost Review
Sept. 11-15, 2023, Hong Kong

Domestic Civil Engineering
Cost Review, June 26, 2023, IHEP

9th CEPC IAC 2023 Meeting
Oct. 30-31, 2023, IHEP

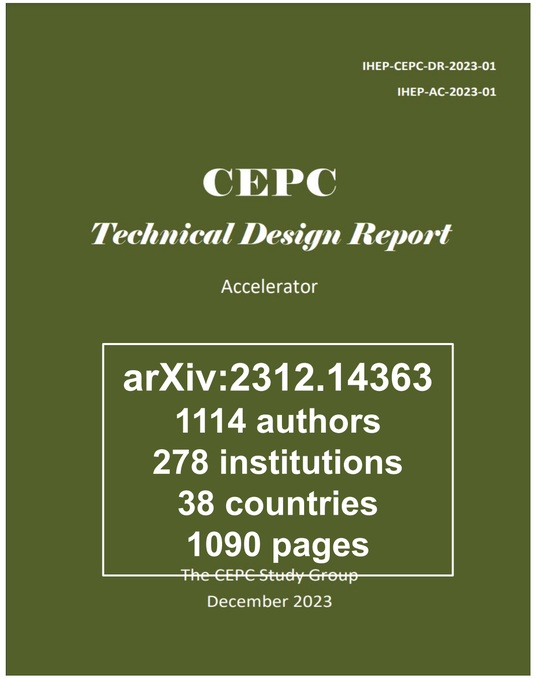
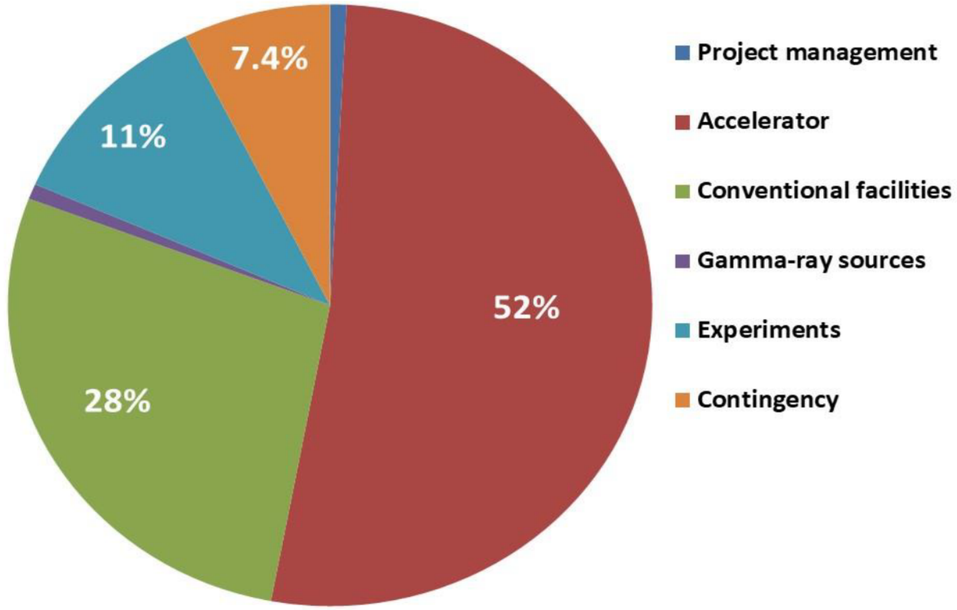


Table 12.1.2: CEPC project cost breakdown, (Unit: 100,000,000 yuan)

Total	**364**	**100%**
Project management	3	0.8%
Accelerator	190	52%
Conventional facilities	101	28%
Gamma-ray beam lines	3	0.8%
Experiments	40	11%
Contingency (8%)	27	7.4%

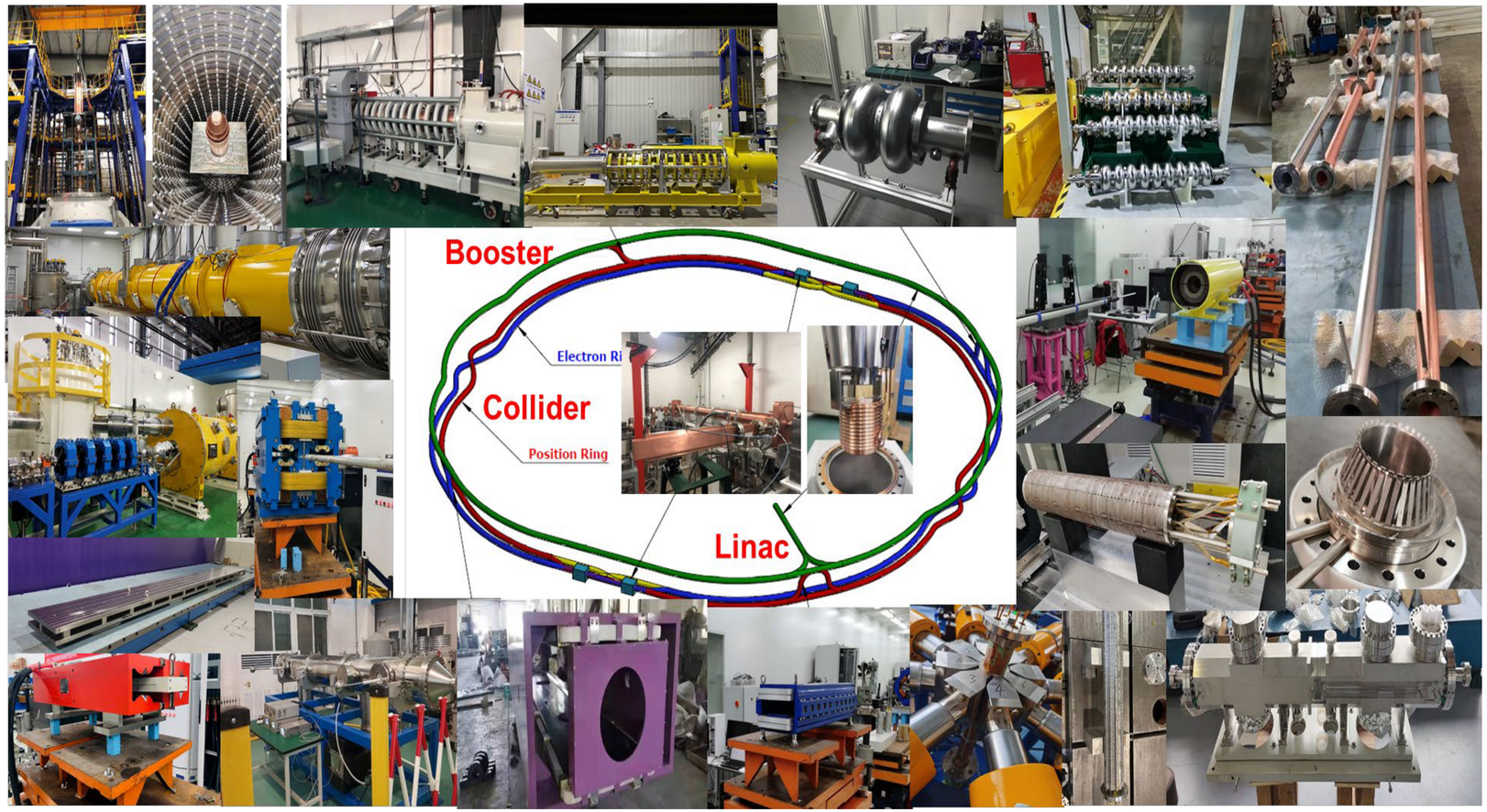


CEPC accelerator TDR link: (arXiv: 2312.14363)
CEPC accelerator TDR releasing news:
http://english.ihep.cas.cn/nw/han/y23/202312/t20231229_654555.html

total TDR cost of **36.4B RMB (~ 5B €)**

Key Technologies R&D are on-going

- Key technologies R&D span over all components listed in CDR/TDR
- About 10% remaining (eg. RF power source, control, alignment, SC magnets, machine integration) to be completed by 2026.



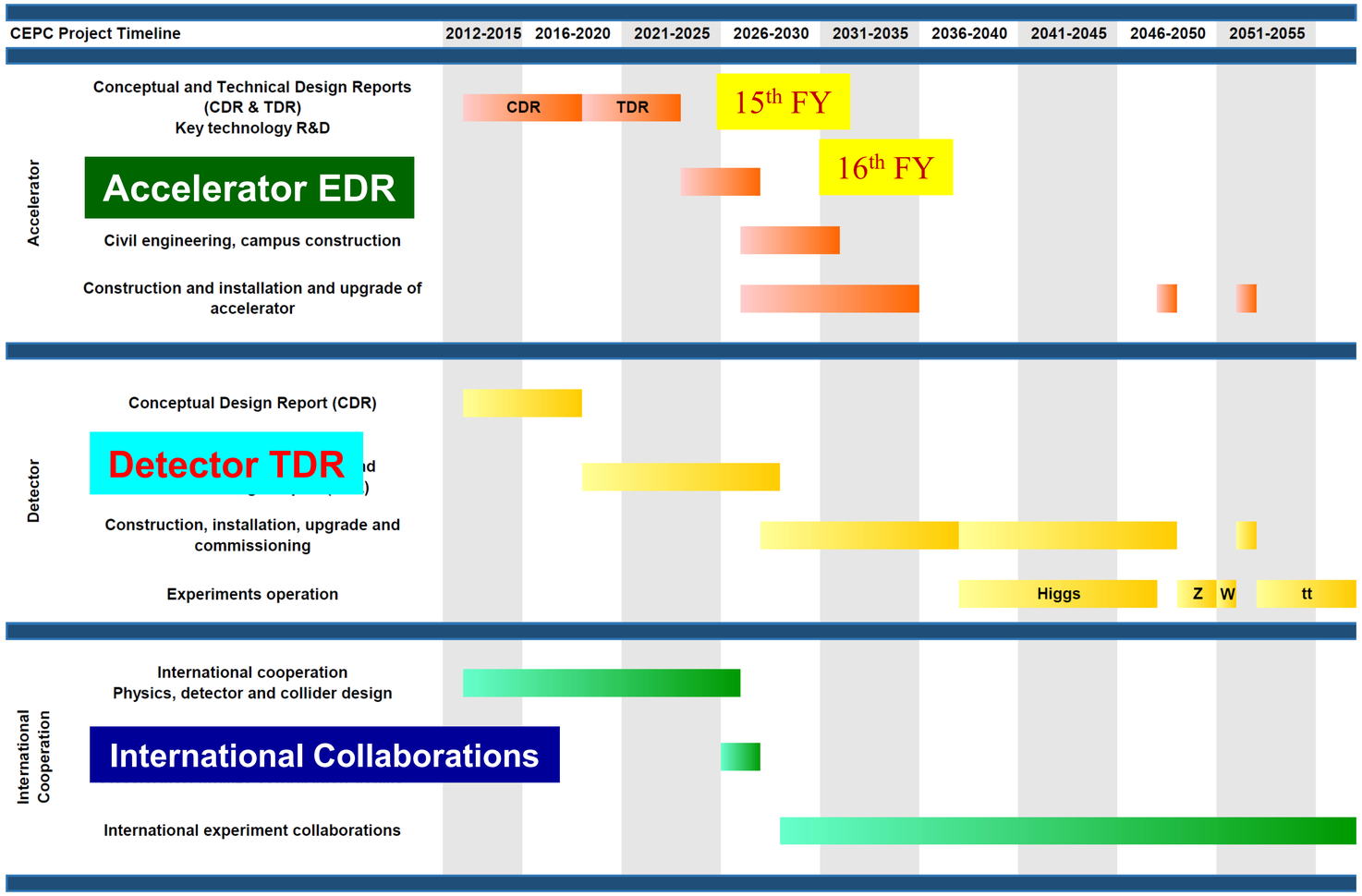
✔ **Specification Met**

✔ **Prototype Manufactured**

Accelerator	Fraction
✔ Magnets	27.3%
✔ Vacuum	18.3%
✔ RF power source	9.1%
✔ Mechanics	7.6%
✔ Magnet power supplies	7.0%
✔ SC RF	7.1%
✔ Cryogenics	6.5%
✔ Linac and sources	5.5%
✔ Instrumentation	5.3%
✔ Control	2.4%
✔ Survey and alignment	2.4%
✔ Radiation protection	1.0%
✔ SC magnets	0.4%
✔ Damping ring	0.2%

CEPC Planning and Schedule

TDR (2023), EDR(2027), start of construction (~2027)

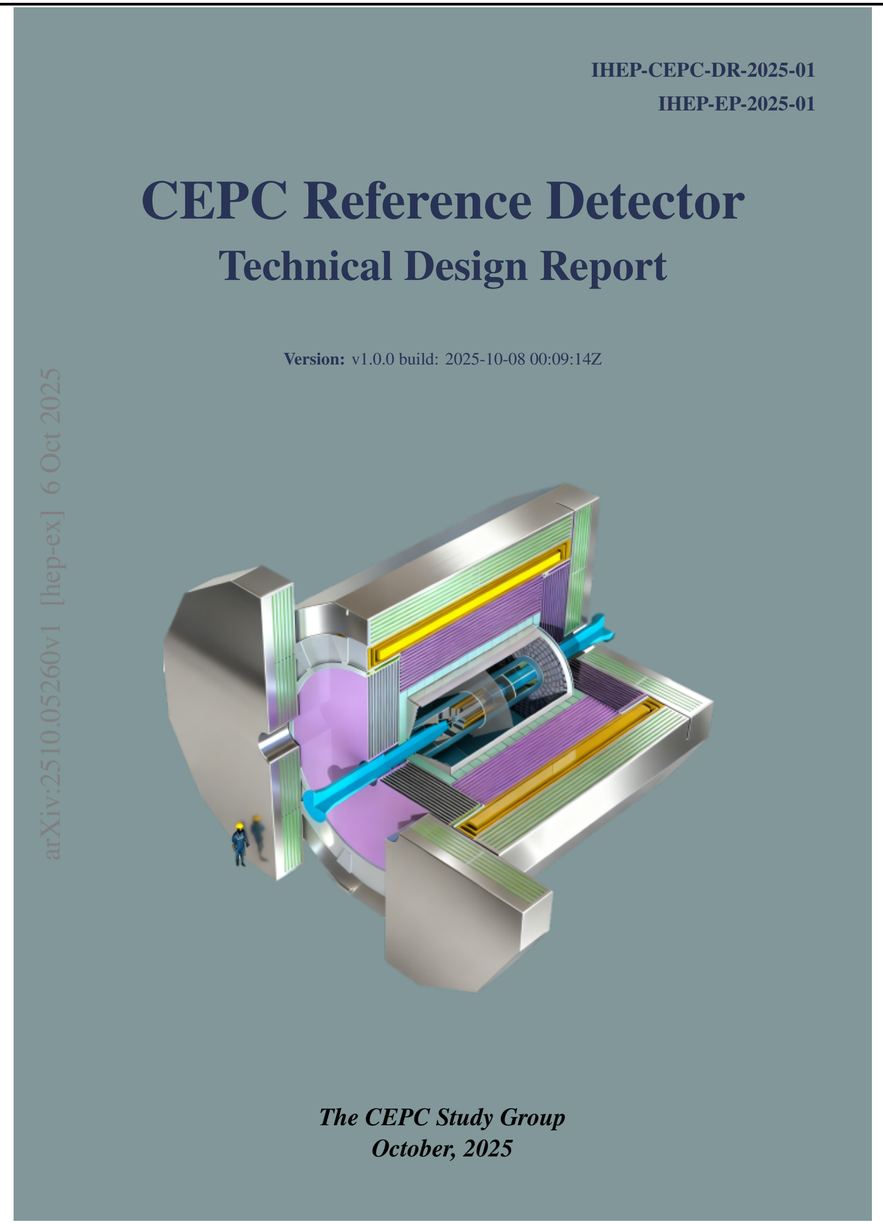


- CEPC plans to submit the proposal to the central government(NDRC) within the "15th five year plan"
- For this purpose, CAS organized studies and reviews
- CEPC was ranked by CAS as the No. 1 for HEP & NP, and No.2 for Basic Science
- We are waiting for the 2nd review by CAS later this year
- Waiting for the "call for proposals" by NDRC by the end of this year

NDRC: National Development and Reform commission

CEPC Detector: Reference Detector TDR

- International collaboration may only be established after the CEPC project is approved by the Chinese government
- For the approval, a design and budget is needed
- Solution: A reference TDR to demonstrate a working design, the feasibility, technologies, budget, etc.
  - CEPC international advisory committee suggested and approved this plan
- An international review of the Ref-TDR held in April 14-16
- TDR will be released in the mid of this year, after being reviewed by the International Detector Review Committee



arXiv:2510.05260

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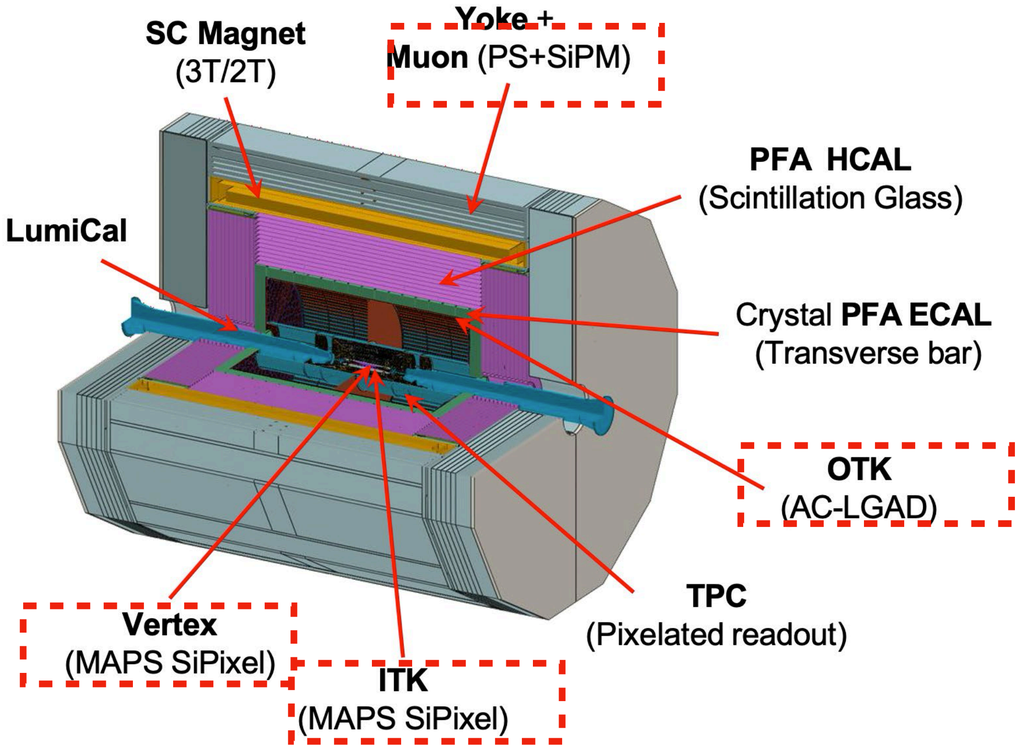
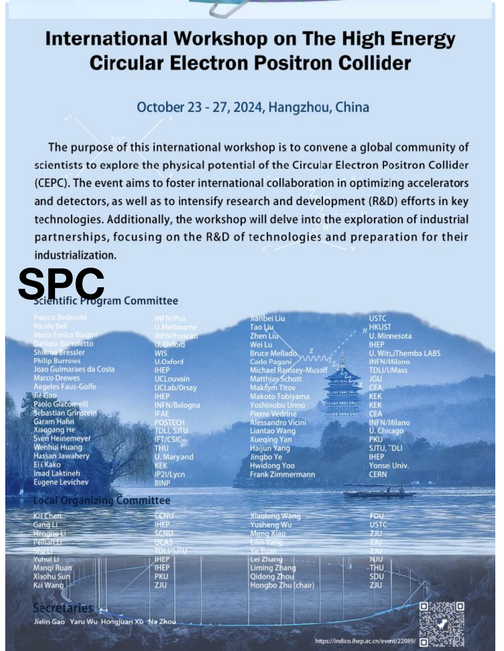


arXiv:2510.05260

CEPC Activities in Korea



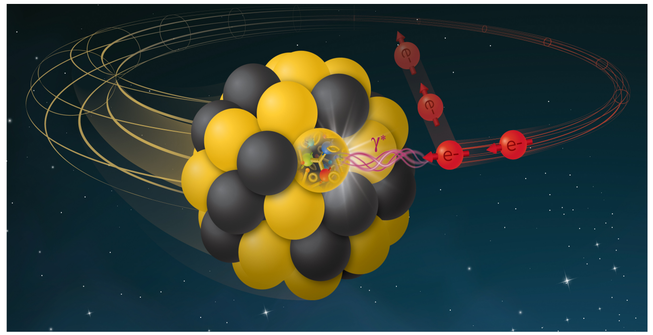
Dual-Readout Calorimeter Activities in Asia

Hwidong Yoo (Yonsei Univ.)

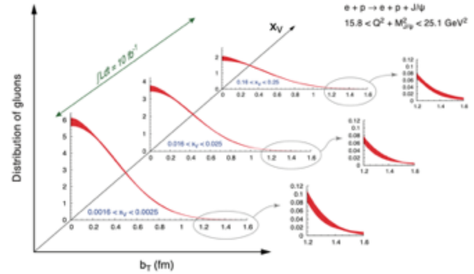
CEPC workshop,
October 23, 2024

From US

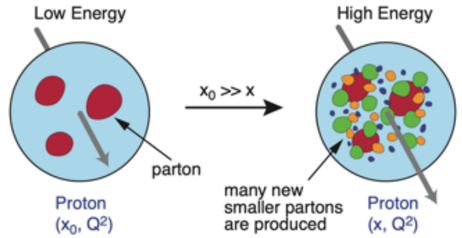
Electron-Ion Collider



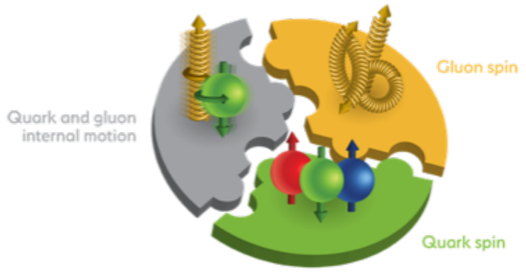
3D structure of protons and nuclei



Gluon saturation

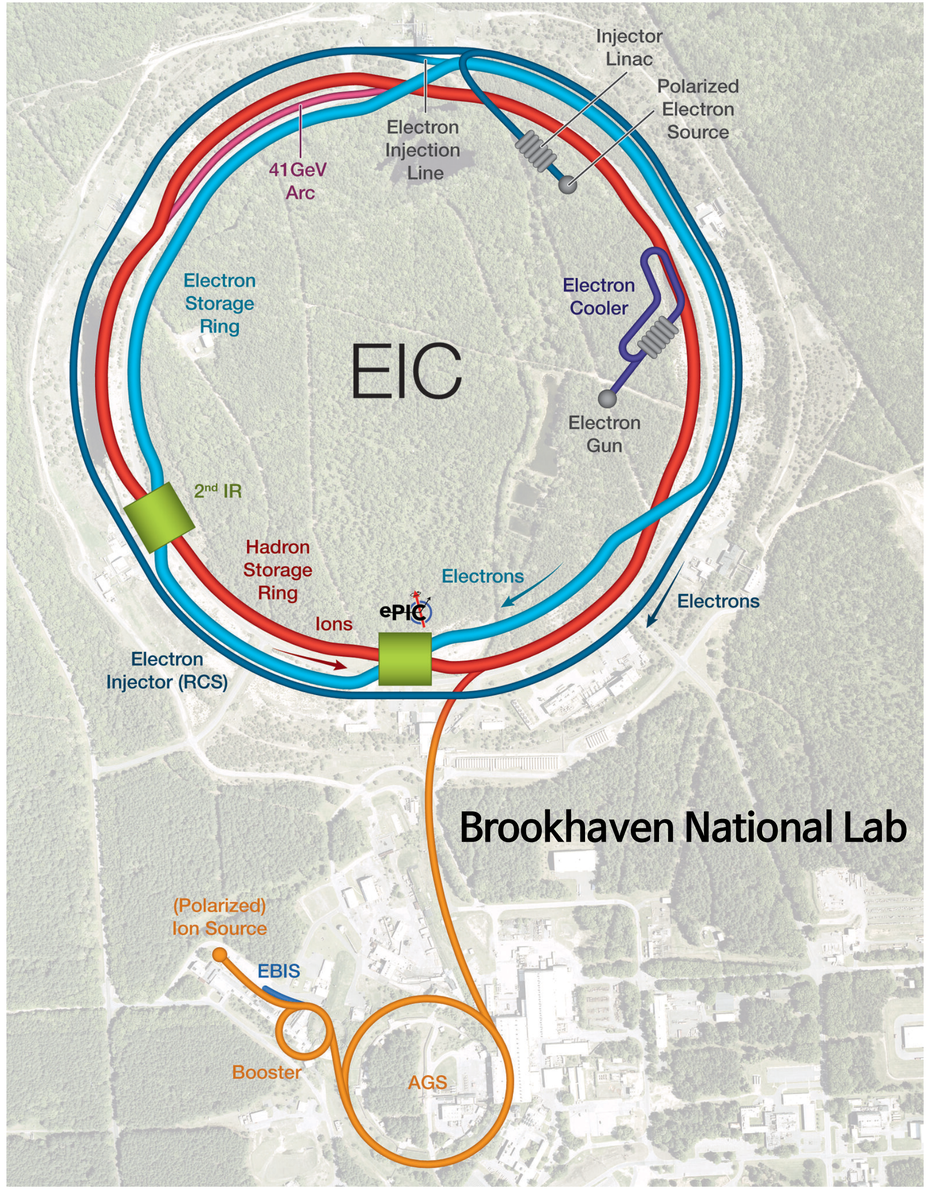


Proton spin puzzle

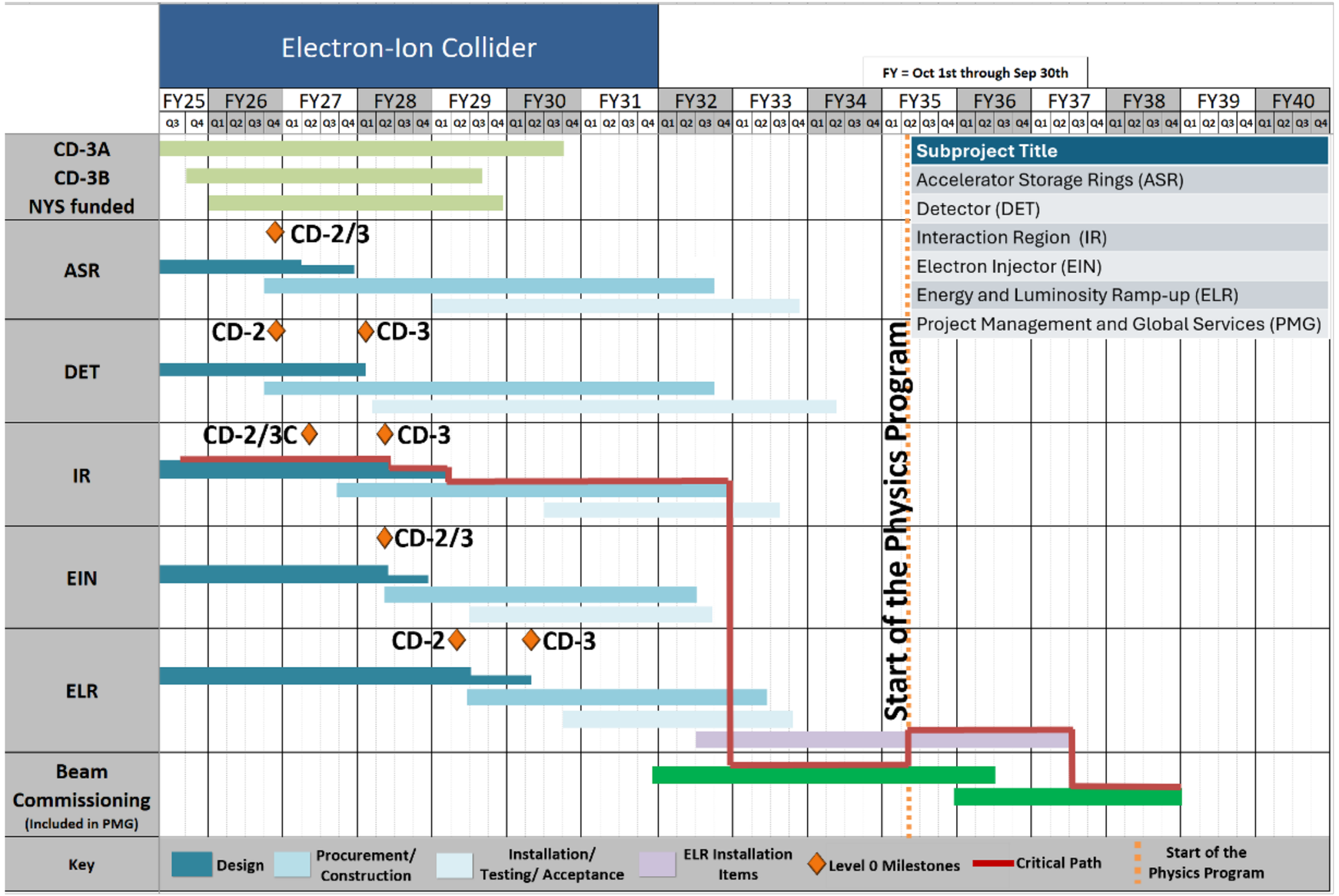


Quark gluon confinement

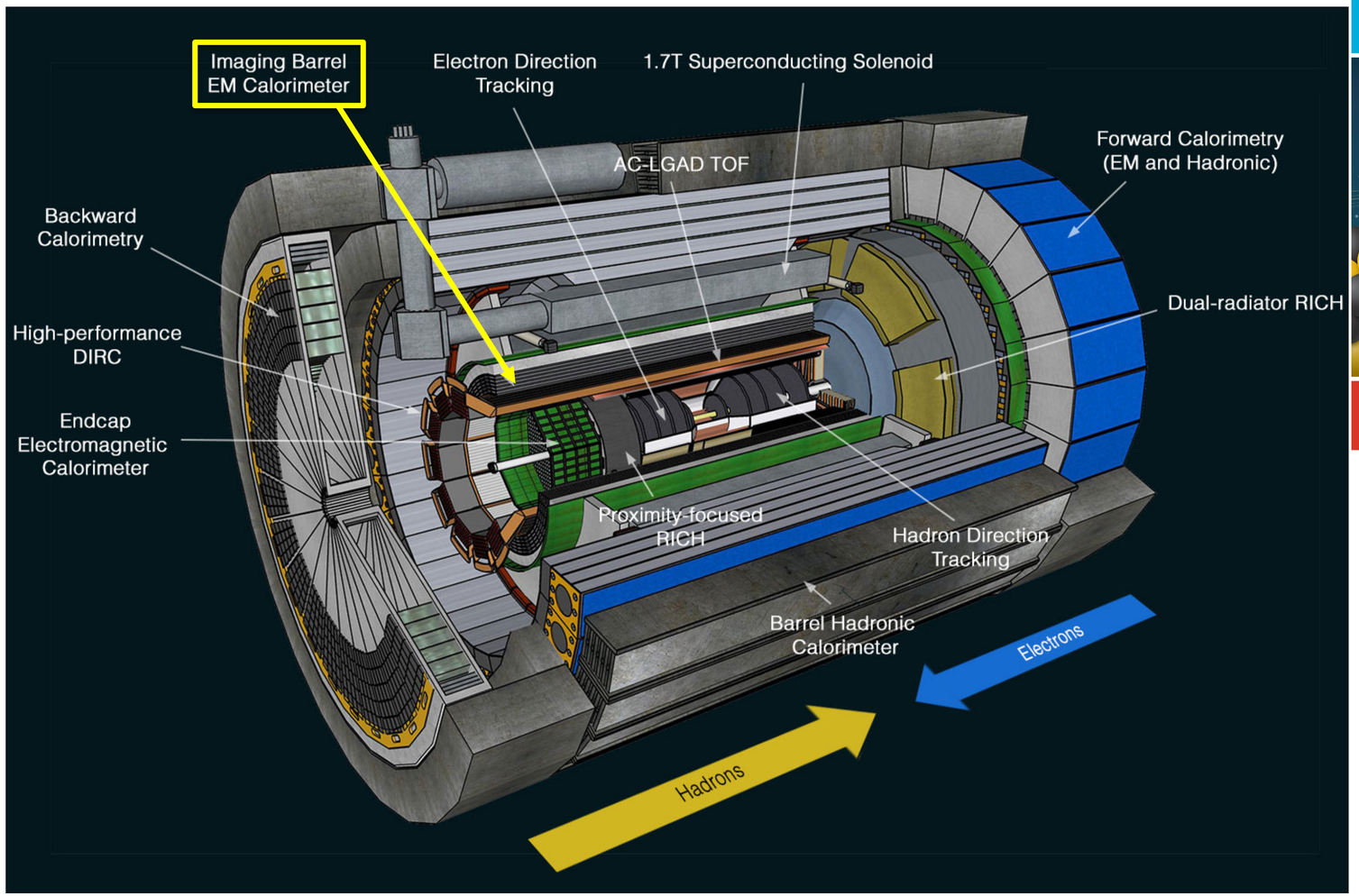
41 GeV, 100 to 275 GeV	p/A beam →	← e beam	5 GeV to 18 GeV



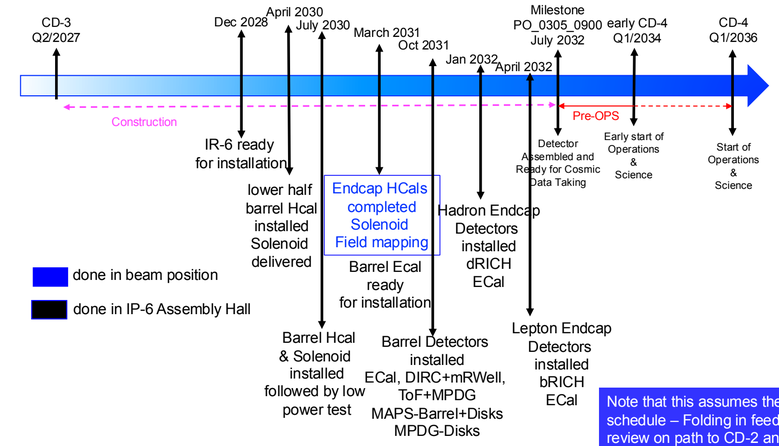
EIC Schedule



ePIC Detector



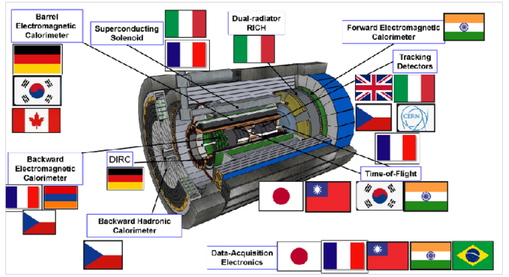
Current High Level Installation Schedule

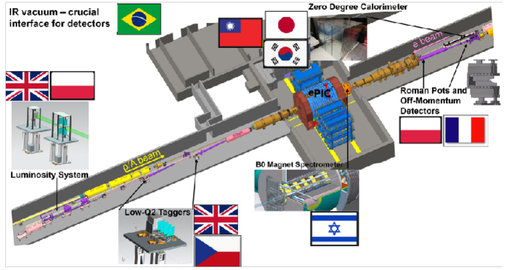


Note that this assumes the present best-known schedule – Folding in feedback from this OPA-DOE review on path to CD-2 and CD-3, and the implementation of subprojects, dates may shift slightly.

Overview of IKC for Detector Subproject

- Italy and France IKCs for the Detector Solenoid magnet, procurement and design respectively.
- UK, Italy, France, Korea, Canada, and Japan have identified scope for IKCs in several Detector areas.
- Other IKCs are being discussed with India, Israel, Taiwan and potentially others could follow.





ePIC Collaboration

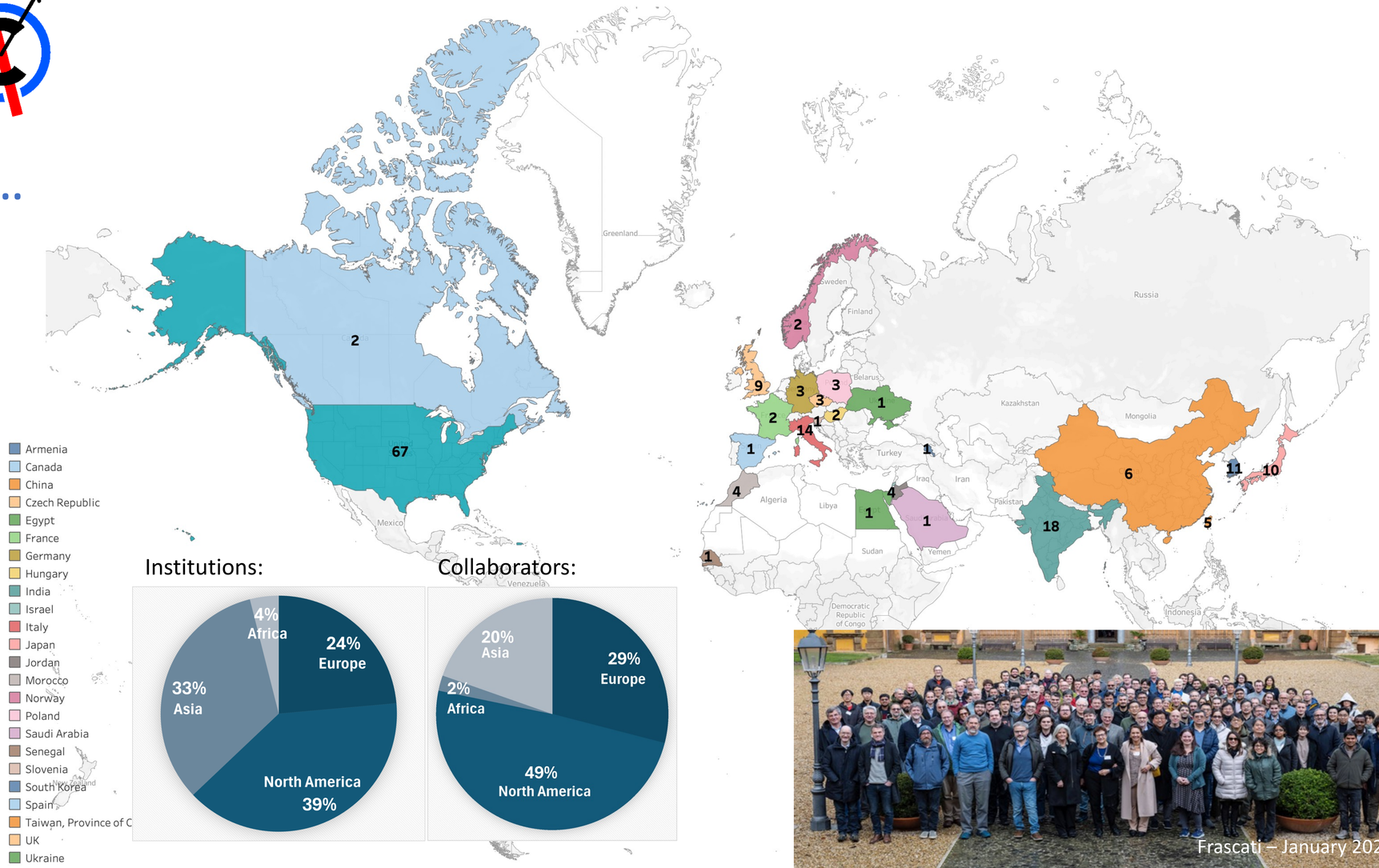
By the numbers…

Currently: >1000 collaborators from 2025 survey

ePIC Institutions
180

ePIC Countries
25

ePIC World Region
4

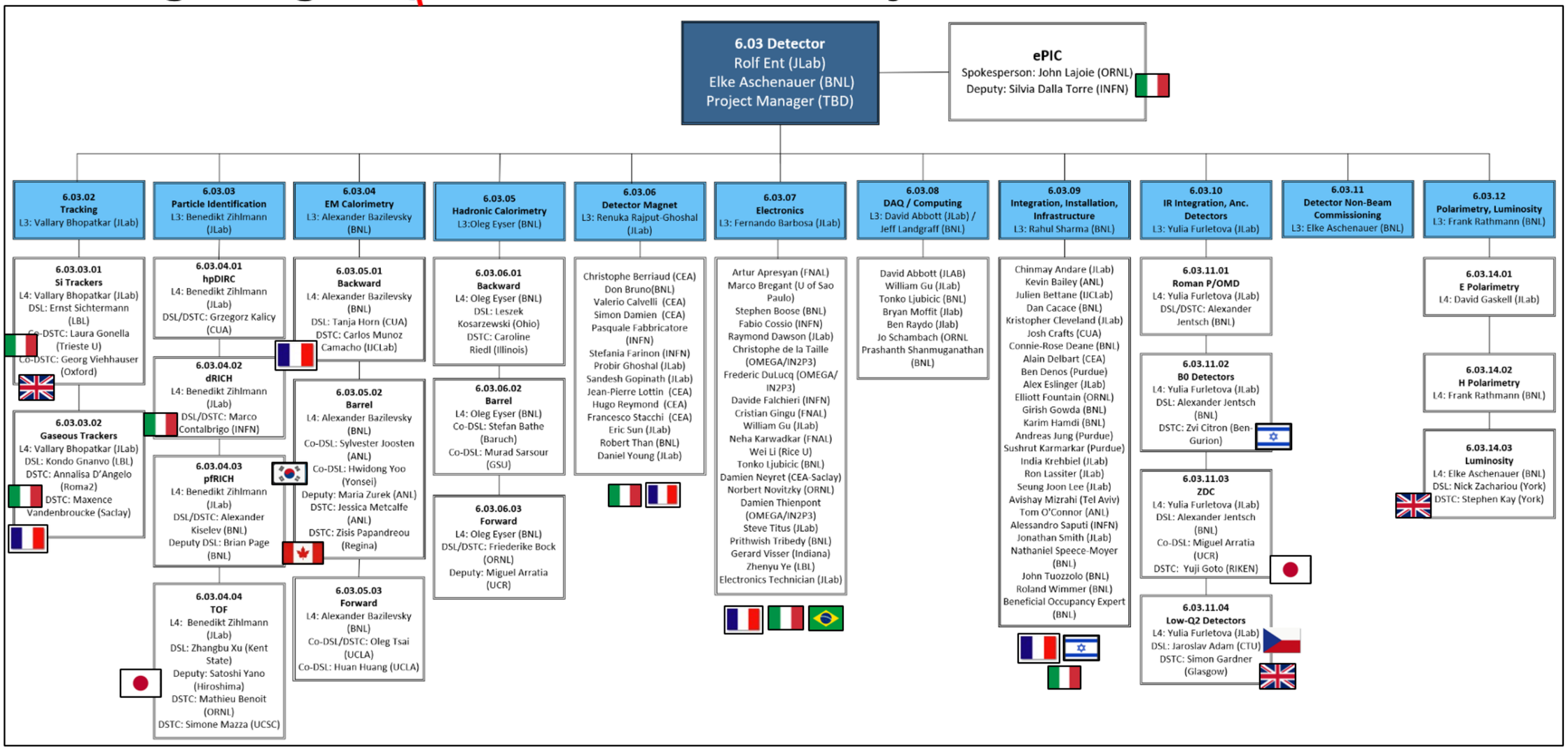


Institutions:

Collaborators:

ePIC Collaboration Organization

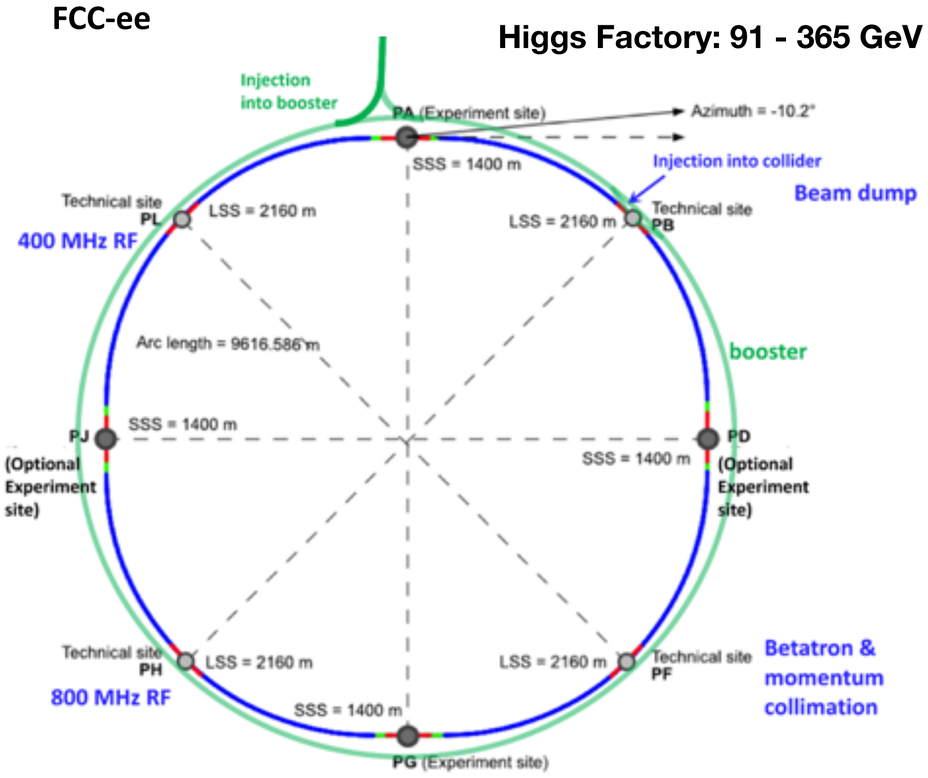
Integrating ePIC collaboration in Project WBS

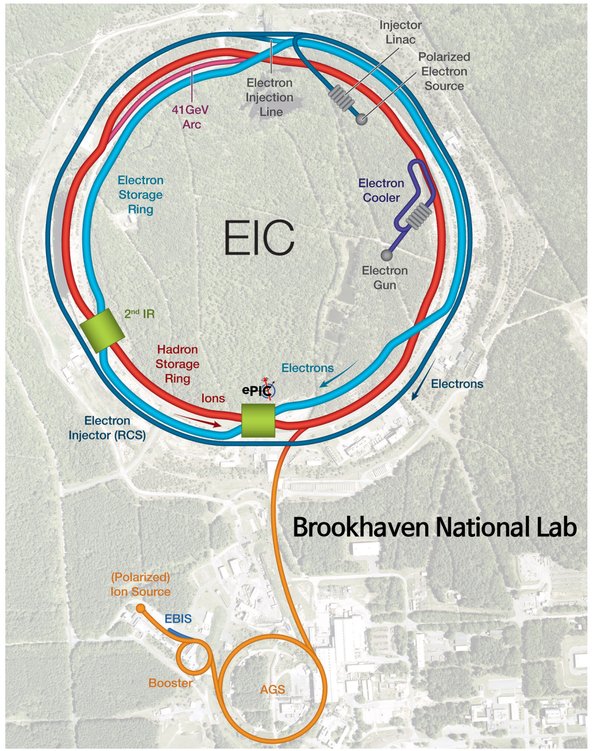


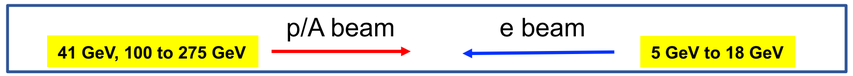
From Korea

Two Main Activities: FCC-ee/CEPC and EIC

- Calorimeter R&D projects in Korea: optical fiber-based calorimeter
  - FCC-ee (+CEPC) IDEA detector: Dual-Readout Calorimeter
  - EIC ePIC detector: Barrel Imaging Calorimeter







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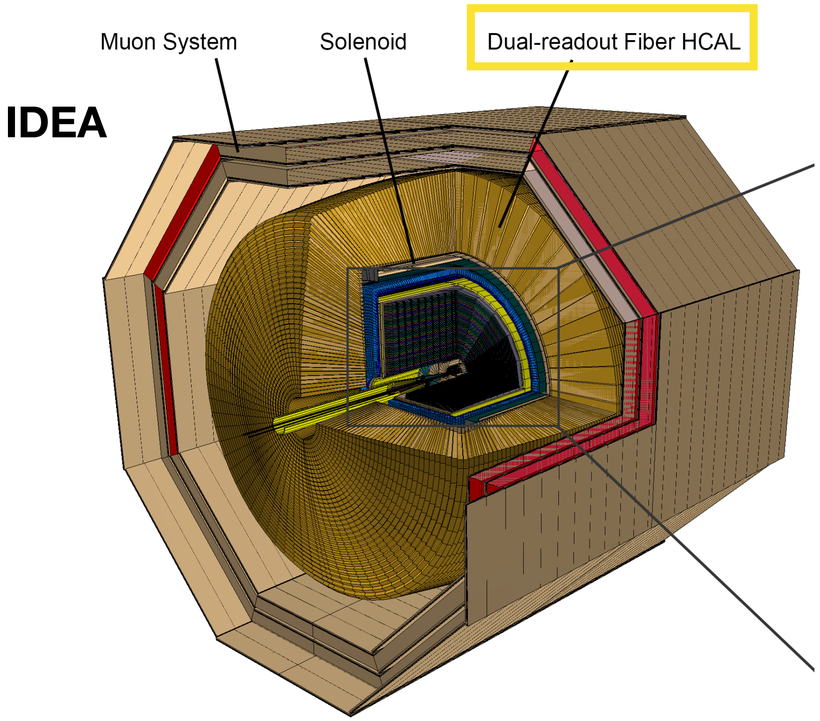
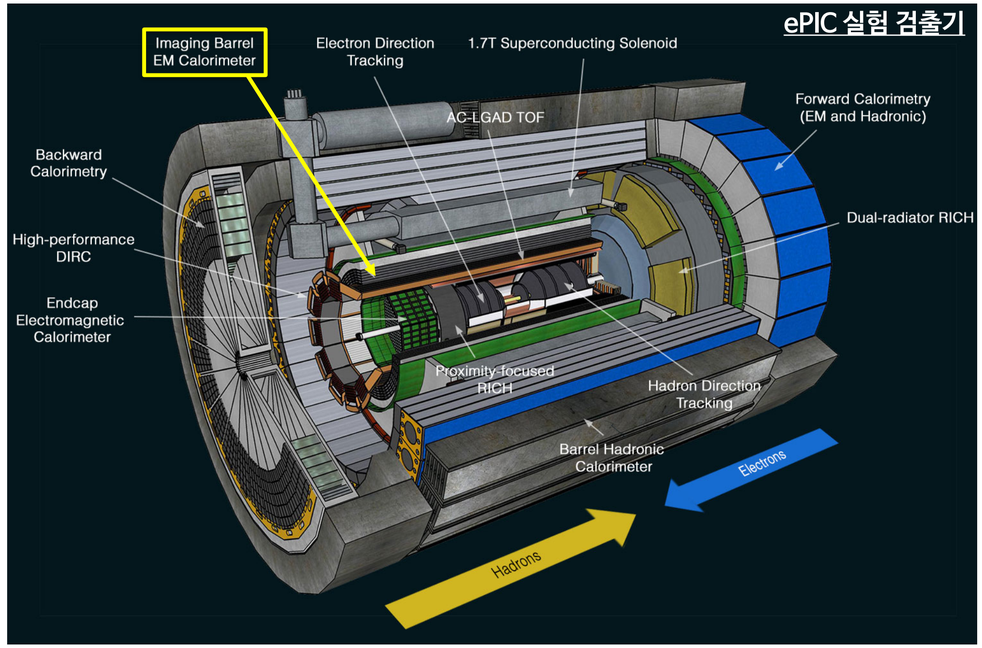
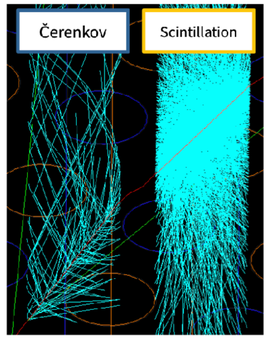
  - EIC ePIC detector: Barrel Imaging Calorimeter



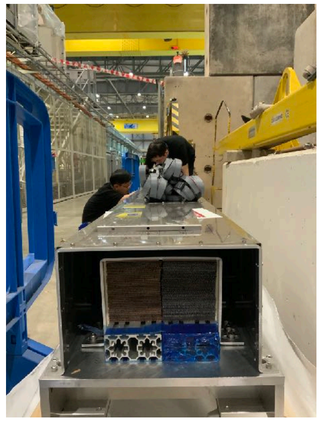


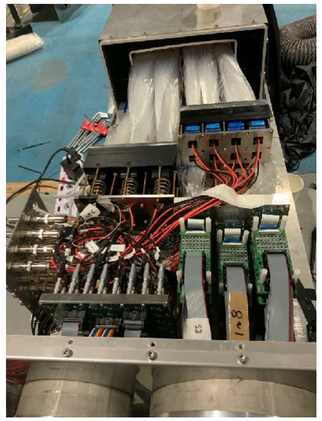
Dual-Readout Calorimeter (DRC) R&D

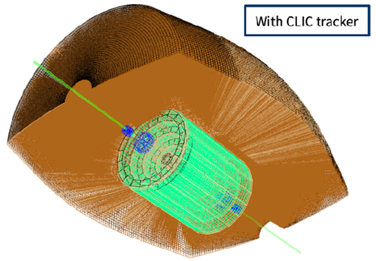
- We are doing all aspects of the dual-readout calorimeter R&D
  - Module building
  - Electronics system
  - DAQ system
  - Data analysis framework
  - Test-beam experiments at CERN
  - Full/fast GEANT4 simulation framework (standalone, key4hep)
  - Performance studies using simulation
- We expand our activities to barrel ECAL construction for Electron-Ion Collider project (BNL)



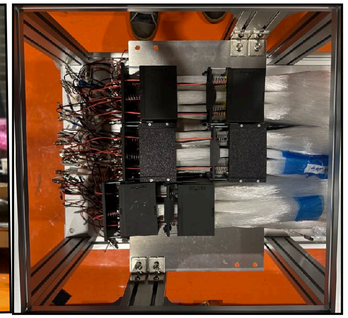
Important for a longitudinally unsegmented calorimeter







With CLIC tracker



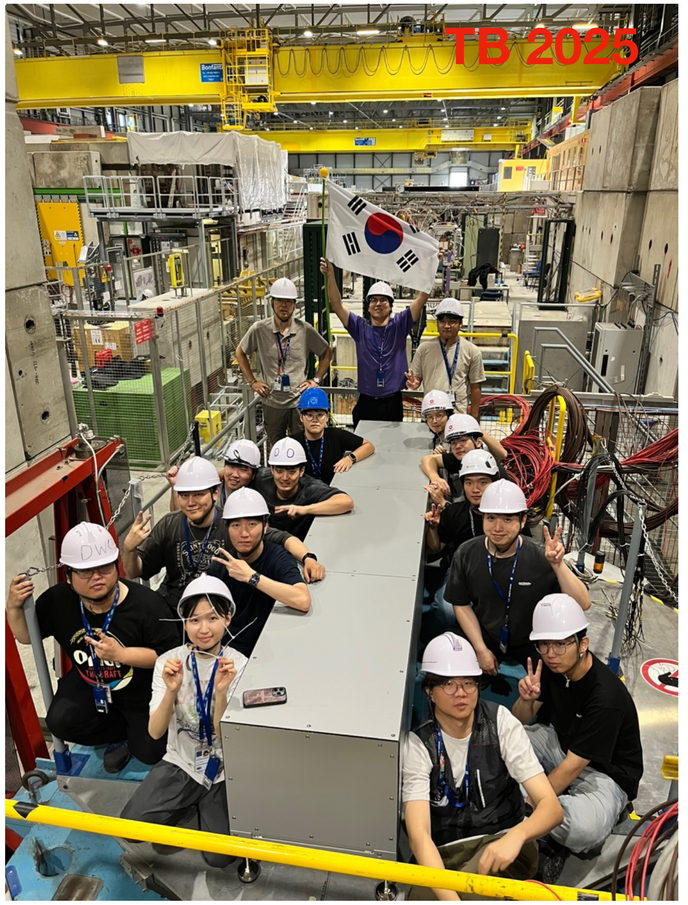
Test-beam Experiments (2022-2025)

- 9 Institutes, 11 faculties, more than 30 researchers and graduate students: most of members are young generation! (9 times since 2022)

	Date	Duration (week)	Facility	e Energy (GeV)	Detector Type	Module Size (cm3)	Weight (kg)
CERN	08/17/2022	1	SPS	10 - 120	DRC	10x20x250	300
	07/05/2023	1	PS	0.5 - 5	DRC	10x10x50	30
	08/07/2024	1	PS	0.5 - 3	BIC	15x9x32	15
	08/07/2024	3	SPS	10 - 120	DRC	30x30x250	1500
	07/23/2025	1	PS	0.5 - 5	BIC	32x15x24	30
	08/06/2025	1	SPS	10 - 120	DRC	30x30x250	1500
KEK	03/19/2025	1	PF-AR	0.5 - 5	BIC	32x12x24	30
	06/12/2025	1	PF-AR	0.5 - 5	BIC	32x15x24	30
	11/28/2025	1	PF-AR	0.5 - 5	DRC	15x15x50	70

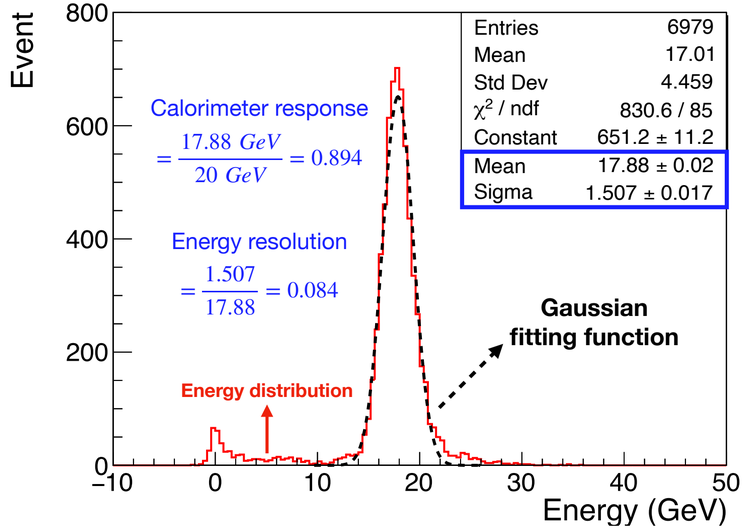
Test-beam Experiments (2022-2025)

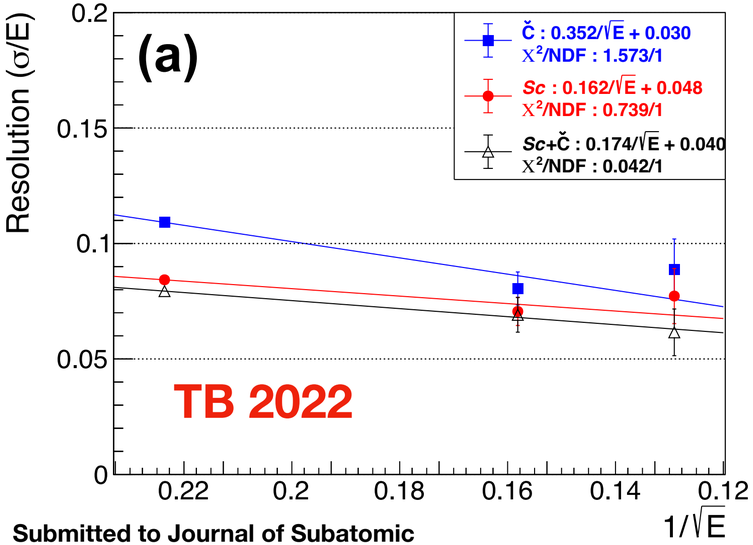
- 9 Institutes, 11 faculties, more than 30 researchers and graduate students: most of members are young generation!



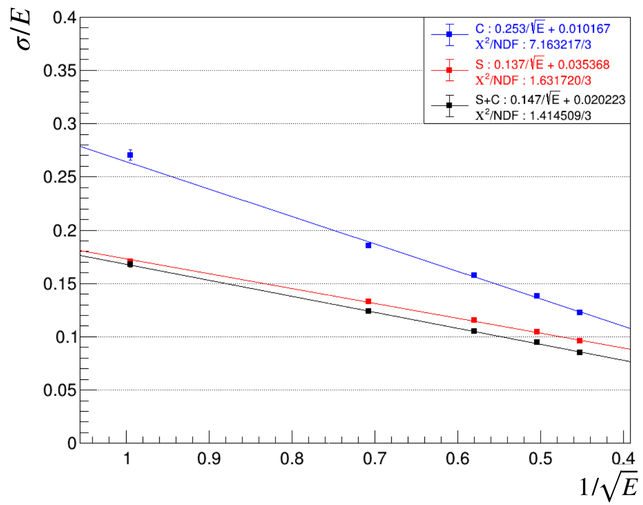
Results of Test-beam Experiments

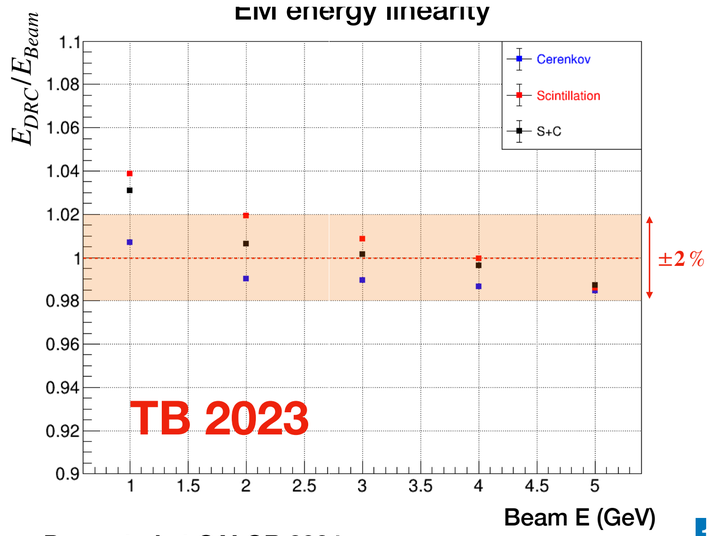
- Analyses and paper preparations are on-going



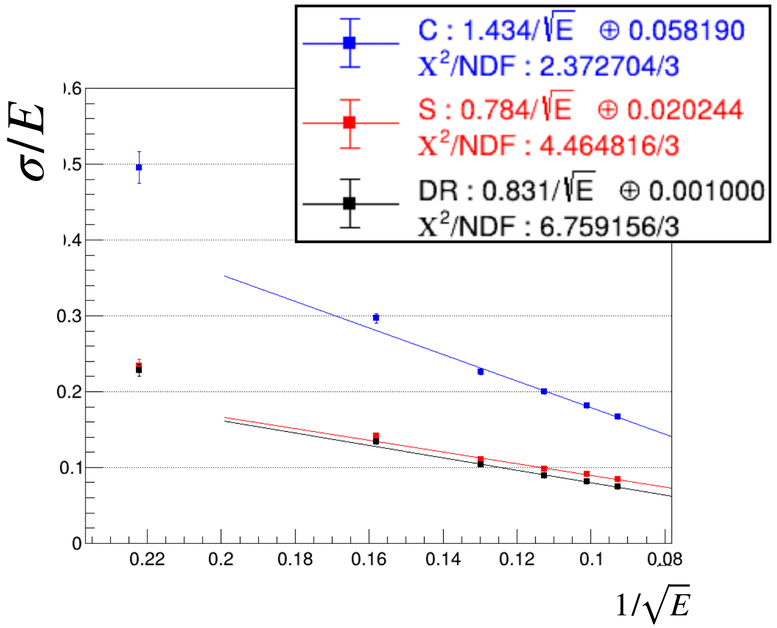


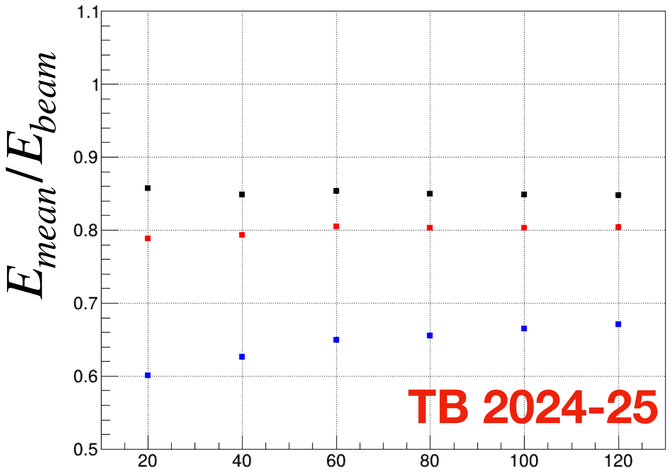
Submitted to Journal of Subatomic Particles and Cosmology (Elsevier)





Presented at CALOR 2024

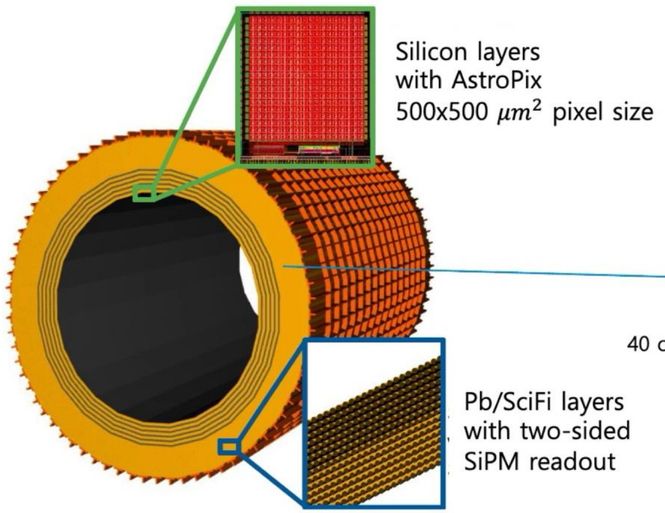




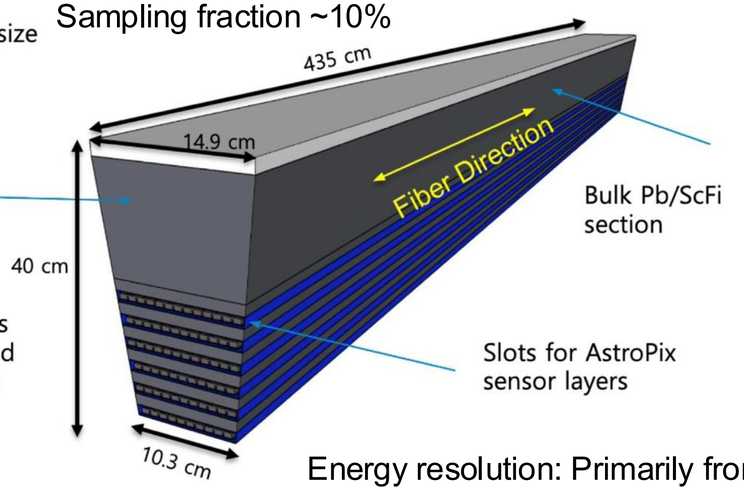
Presented at KPS 2025 Fall

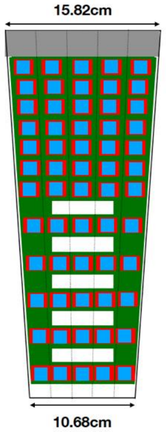
EIC: Barrel Imaging Calorimeter (BIC) R&D

- Korea-EIC group will construct 50% of BIC detector



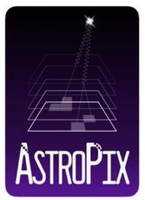
4(+2) layers of imaging Si sensor interleaved with 5 Pb/SciFi layers
Followed by a bulk section of Pb/SciFi sections
Total radiation thickness ~17.1 X_0
Sampling fraction ~10%

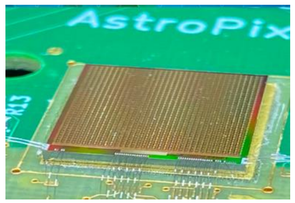


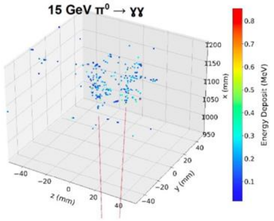


Position resolution: Primarily from Imaging layers
(+2-side Pb/SciFi readout and radial segmentation)

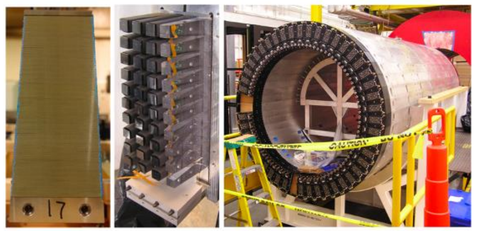
Energy resolution: Primarily from Pb/SciFi layers
(+ Imaging pixels energy information)







AstroPix tracking layers to capture 3D image of shower development
NASA AMIGO-X mission



GlueX Pb/SciFi sampling calorimeter

BIC Collaboration

USA

- Argonne National Laboratory
- NASA Goddard Space Flight Center
- Oklahome State University
- University of Connecticut
- University of California Santa Cruz

Canada

- University of Manitoba
- University of Regina
- Mount Allison University
- NSERC
- Canada Fund for Innovation

Korea

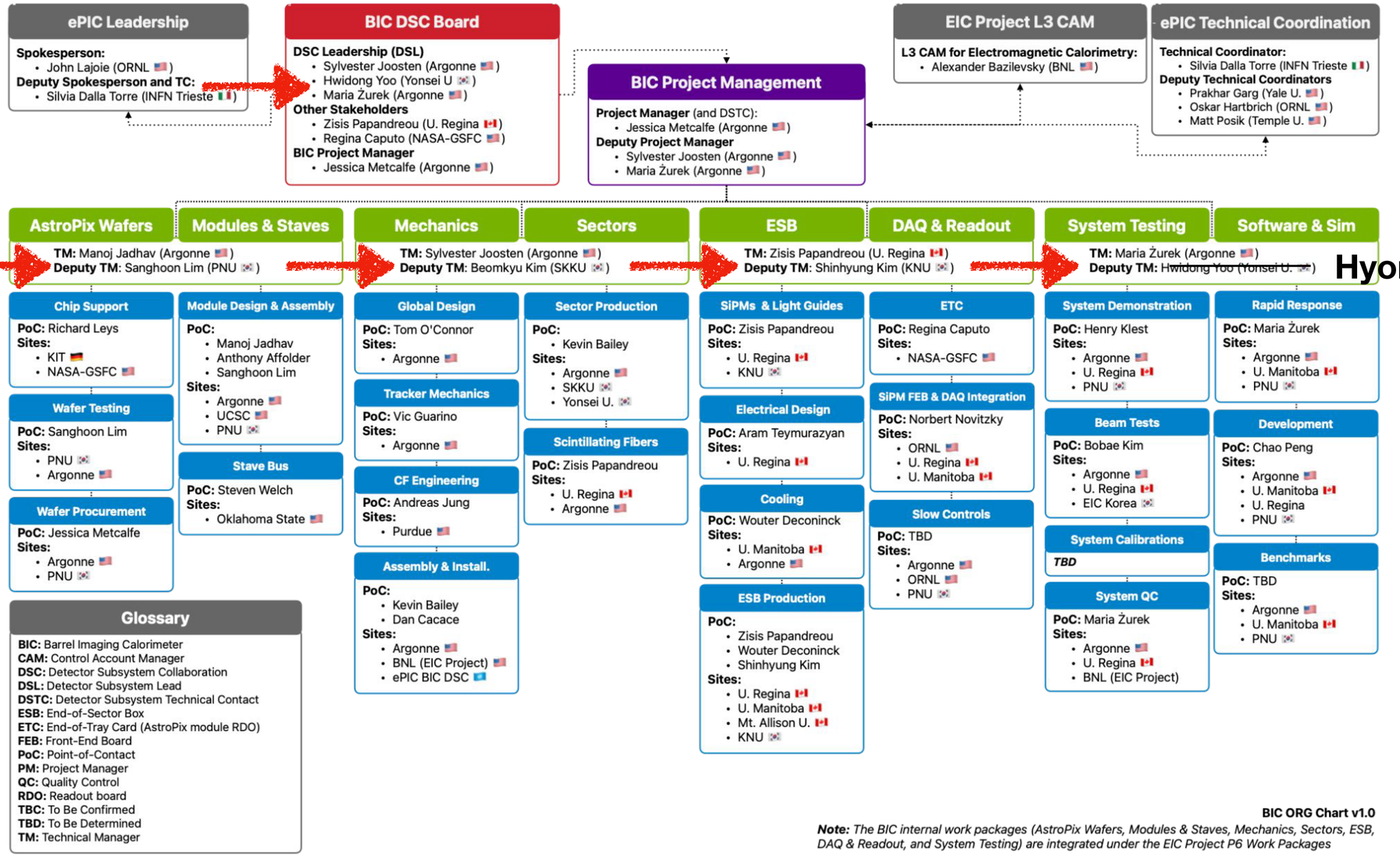
- Kyungpook National University
- Yonsei University
- University of Seoul
- Pusan National University
- Korea University
- Sungkyunkwan University
- Hanyang University
- Gangneung-Wonju National University

Germany

- Karlsruhe Institute of Technology
- University of Giessen

ePIC BIC Detector Subsystem Collaboration

BIC Organization Chart



Activities for BIC R&D in Korea with US team

Sectors and Mechanics

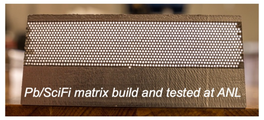
Green Team Leader: Sylvester Joosten, Deputy: Beomkyu Kim

Design constraints defined and mostly frozen; geometries and envelopes documented; BIC and Project engineers aligned.

Design challenges: self-supporting sector with ePIC integration; FEA in progress using delamination data at CF–Pb and Pb/SciFi interfaces.

Sector test articles:

- 0.5 m GlueX-style matrix reproduction completed, critical equipment commissioned. SciFi QC produce established.
- Short bulk Pb/SciFi with GlueX fibers and CF-frame integration ongoing
- Long 3 m article next; full-scale 4.35 m sector for prepoduction targeted for 2026



First tracker test article - module base with stave like railing

AstroPix tracker mechanics: staves integrated into trays → modules slide onto trays → trays slide into sector drawer/slot.

- First extruded-aluminum mechanical article built and tested for tolerances and stability

Mechanical risks are under active test with a defined path to full-scale sector in 2026. First test articles of tracker support and SciFi matrix tested.

See S. Joosten, Sectors & Mechanical Design talk and Z. Papandreou, Scintillating Fibers talk

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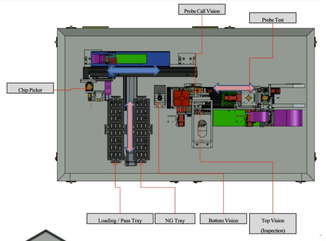
Wafers and Modules

Green Team Leader: Manoj Jadhav, Deputy: Sanghoon Lim

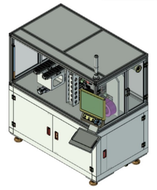
Chip testing scope

- **Scale:** 31,104 modules, 279,936 AstroPix chips.
- **Need:** automated chip-level testing before module assembly with established QC procedures.
  QC coverage: sensor bias with HV, analog and digital checks, injection scans for relative energy calibration.



v3 Pilot (this fall → 2025 Q4)

- **Probe card:** simple v3 card for the carrier board, built with a Korean manufacturer; uses validated GECCO + FPGA setup; leverages ALICE experience
- **Throughput target:** validate the QC flow on ~80 v3 chips this fall
- **Automation:** single-chip v3 test machine from C-ON Tech due 2025 Q4 to run initial validation, refine the test flow, document the full chain, and deliver qualified v3 chips for prototype modules



Single-chip v3 machine is un production by tech in Korea

Preproduction (v5/v6, FY26-FY27)

- **Design update:** v5 ready in FY26 for preproduction
- **Process readiness:** finalize procedures and acceptance criteria

We are moving from a validated v3 pilot to a preproduction workflow for v5/v6, establishing throughput, traceability, and acceptance criteria needed to de-risk delivery of 280k+ chips for 31k modules.

See S. Lim, AstroPix Wafers talk

System Testing

Green Team Leader: Maria Zurek, Deputy: Hyon-Suk Jo

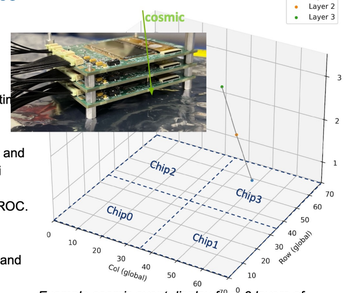
Function: validate system-level performance and design, establish system-level QC/QA procedures.

AstroPix imaging layers: multichip and multilayer test articles to demonstrate daisy-chaining, synchronization, and energy, position, and ti response; bench and beam tests completed.

Pb/SciFi calorimetry: Bulk (~15.5 X_0) and SFILs (~1.5 X_0) tested with e and π beams, validating energy response and e/π separation in the Pb/SciFi section; simulations benchmarked.

- **ANL-built SFILs:** first units show good MIP response with HGCROC.

Large-scale integration (PED, PREP): readout and large test article integration under way to validate system-level performance, calibration, and QC/QA at AstroPix Tray and Sector level; outputs will inform also component-level QC procedures.



Example cosmic event display from 3 layers of daisy-chained AstroPix v3 quad chips

The testing program de-risks the design and defines system QC/QA for production; current validations confirm calorimeter energy performance and rate capability, and validate the simulation against data.

See B. Kim *Multichip Design Demonstrations*, J. Bok *AstroPix System Testing*, H. Klest *SciFi & System Testing*

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Wafers and Modules

Green Team Leader: Manoj Jadhav, Deputy: Sanghoon Lim

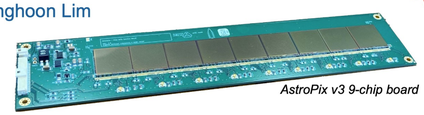
Scope: single-flavor module for more than 30,000 units

AstroLinx (PCB): optimized for module performance, meets required operation specs; first design completed and reviewed. Expected this fall; another iteration anticipated.

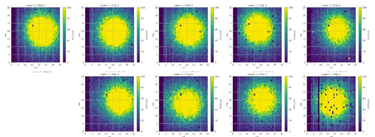
9-chip PCB test article: In hand to mock up AstroLinx, verify power-distribution stability and daisy-chain readout. Successfully tested on a bench with sources.

Module builds: plan to assemble about six prototypes this fall using extruded aluminum base, AstroPix v3, and AstroLinx; test PCB designed to validate electrical performance; initial base-plate prototype produced to define assembly steps.

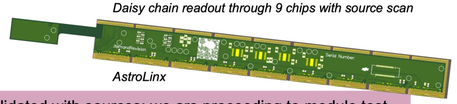
Open design items: base-plate locking mechanism, adhesive selection, flex-PCB connector finalization



AstroPix v3 9-chip board



Daisy chain readout through 9 chips with source scan



AstroLinx

AstroLinx has been reviewed and the 9-chip PCB validated with sources; we are proceeding to module test articles to lock performance and assembly while closing the few remaining design choices for preproduction.

See M. Jadhav, *AstroPix Modules* talk and B. Kim, *Multichip Design Demonstration* talk

24

ESB (End of Sector Box) and DAQ

Green Team Leader: Zisis Papandreou, Deputy: Shin Hyung Kim

Function: on-detector power distribution and data collection. Encloses cooling and provides mechanical protection.

Interfaces with ePIC: integration procedure nearly final; service requirements provided (electrical cabling, cooling, DAQ).

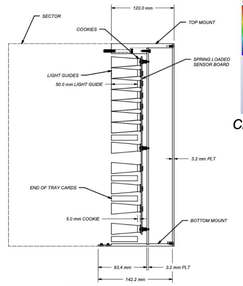
Thermal/mechanical validation: Ongoing: development and construction of PCB (thermal) test article to validate CFD calculations.

SiPM readout path: CALOROC → common RDO → FELIX.

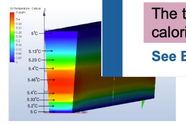
- Lightguides design complete, geometry fixed.
- CALOROC design under submission; evolution of HGCROC with CMS and ALICE heritage.
- SiPMs passed FDR at CD-3a/3b.

AstroPix readout path: End-of-Tray Card (ETC) → FELIX.

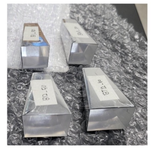
- ETC to be designed by NASA GSFC; start pending contract processing; leverages existing AstroPix FPGA board designs.



ESB Envelope



CFD Calculations Performed



LG test articles validated

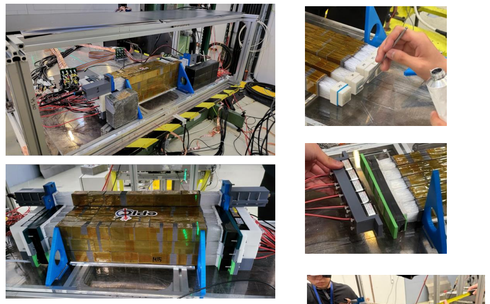
ESB envelope and interfaces nearly finalized; CALOROC at submission; ETC awaits contract start, with existing designs reducing risk. SiPM design completed. Lightguides and cookies nearly finalized.

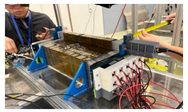
See S-H. Kim *ESB Talk* and N. Novitzky *Readout DAQ Talk*

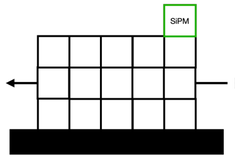
25

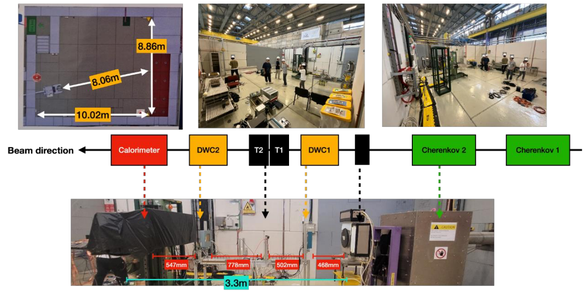
Test-beams for BIC R&D

- Four times of test-beams have been done at CERN and KEK since 2024.7

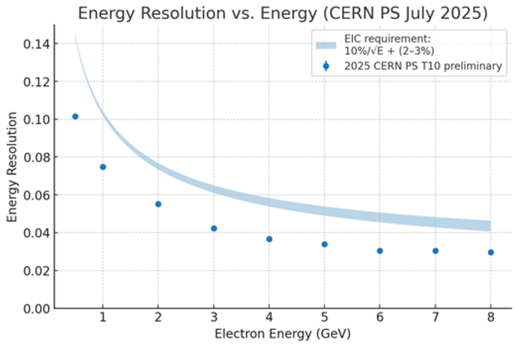




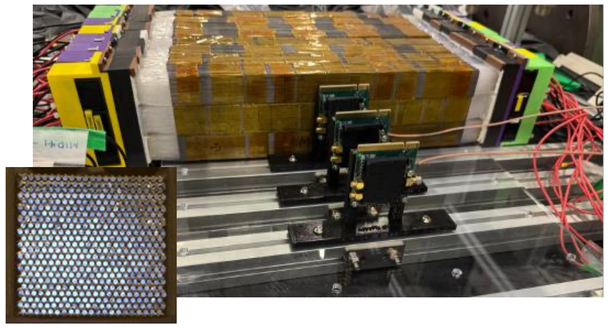




- Beam test of a test article at CERN PS T10 using electron/pion beam.
  - No glue, PMT readout



- Total dimension of the test article is 32(w)x9(h)x24(d) cm^3
- Pb : SciFi : Air = 40:43:17, X_0= 1.38cm
  - Total depth is **17.4 X_0**

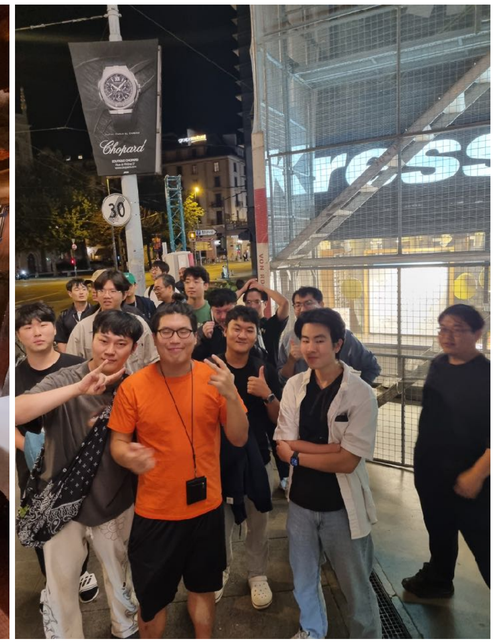


Even with less optimal construction technique, Electron energy resolution still fulfills the minimum requirement for EIC Barrel ECal

Summary

- Various future collider projects are actively on-going world-wide and decisions will be started in near future
- Dual-Readout Calorimeter R&Ds for FCC-ee and CEPC in Korea have shown the performance of the world leading class
  - All aspects of the DRC detector R&D have been done for both HW and SW
  - Training next generation of calorimeter experts
- Expand our activities to barrel ECAL construction for Electron-Ion Collider project (BNL)

TB dinner at Le Coq Rouge (25.8)

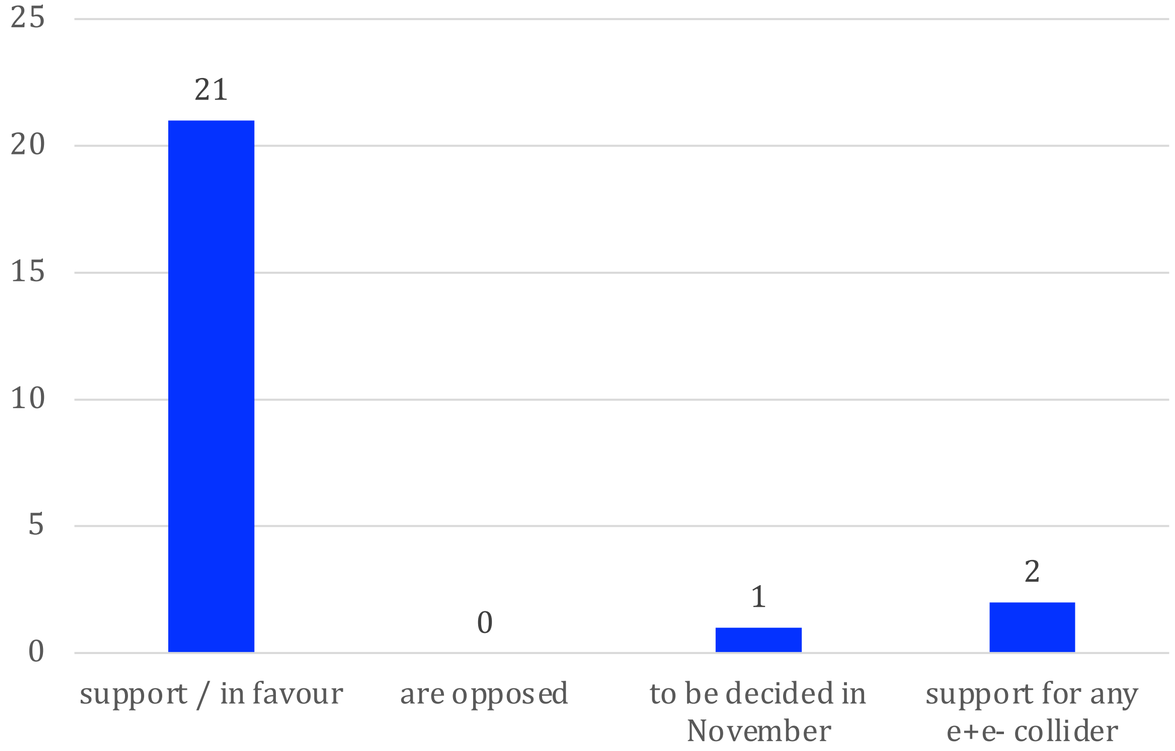


TB dinner at Les Armures Geneva (24.8)

Back Up

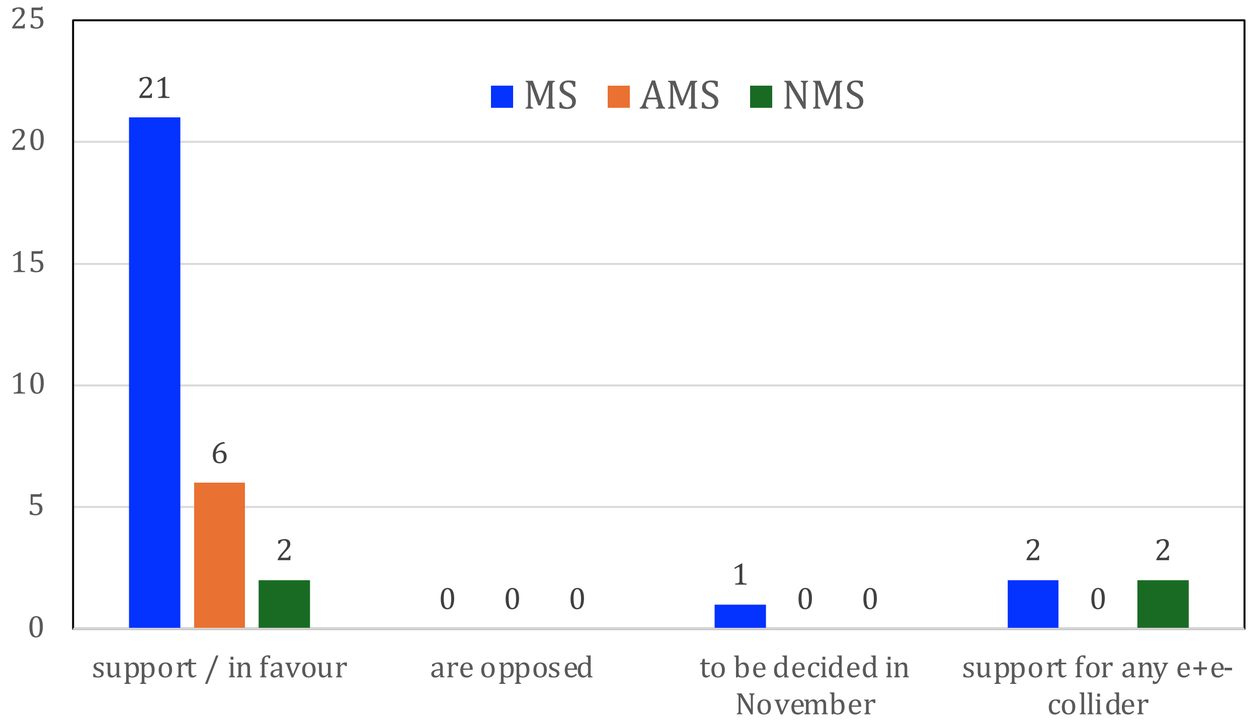
a) Which is the preferred next major/flagship collider project for CERN?

- **Broad consensus** among CERN Member States in support of the Future Circular Collider (FCC) as a key long-term project to maintain Europe's leadership in particle physics.



Support for FCC	Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Israel, Italy, Norway, Poland, Portugal, Romania, Serbia, Slovak Republic, Spain, Sweden, Switzerland, United Kingdom
Opposed	None
To be finalized in November	Netherlands
Support for any e^+e^- collider	Austria, Bulgaria

a) Which is the preferred next major/flagship collider project for CERN?



Support for FCC	MS: Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Israel, Italy, Norway, Poland, Portugal, Romania, Serbia, Slovak Republic, Spain, Sweden, Switzerland, United Kingdom
	AMS: Brazil, Croatia, Lithuania, Pakistan, Slovenia, Ukraine
	NMS: Canada, United States of America (The U.S. supports FCC-ee as the next major flagship project at CERN)
Opposed	None
To be finalized in November	Netherlands
Support for any e^+e^- collider	MS: Austria, Bulgaria; NMS: Australia, Japan

c) Should CERN/Europe proceed with the preferred option set out in (a) or should alternative options be considered.

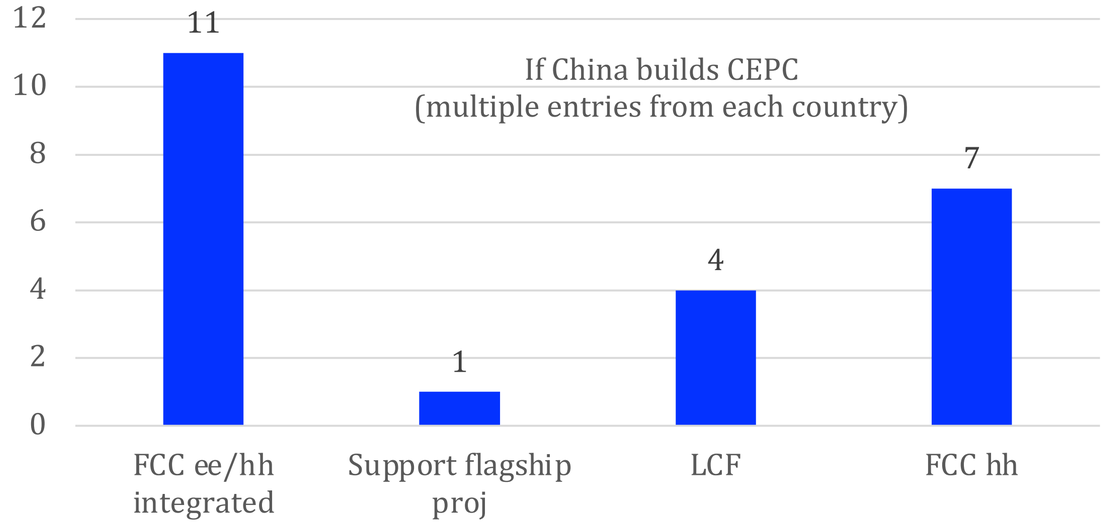
i. If Japan proceeds with the ILC in a timely way

National inputs that consider a potential ILC in Japan, consistently favour maintaining the FCC project.
The ILC is generally seen as having less physics potential and offering only a medium-term scientific perspective.
Several countries recall that a commitment from Japan has not yet been made.

ii. If China proceeds with the CEPC on the announced timescale

There's no unanimous view among the national inputs.
The largest set of inputs suggest sticking with the FCC-ee/hh integrated project.
Of the ones who suggest a switch, the majority shift focus to the FCC-hh, likely limited to 85-90 TeV due to technology limits. Only one input proposes dropping the FCC altogether.

FCC ee/hh integrated	BE, CH, DK, FI, FR, GR, HU, IT, PL, PT, SE
Support flagship	ES
LCF	DE, FR, NO, PT
FCC hh	AT, CZ, DE, FI, FR, PT, RS, UK



c) Should CERN/Europe proceed with the preferred option set out in (a) or should alternative options be considered.

iii. If the US proceeds with a muon collider

A muon collider faces higher technical risks and a longer development timeline.

By and large, national MS HEP community inputs see no reason to change the choice of preferred collider.

The P5 has suggested budget scenarios where both the muon collider demonstrator and the FCC-ee could be accommodated with minimal conflicts expected. A potential U.S. hosted muon collider will likely follow the completion of the FCC-ee construction. Given this, a planned muon collider effort in the U.S. should not influence the decision to move forward with the FCC-ee program at CERN.

At the request of the DOE and the NSF, the National Academies conducted a study to explore the long-term goals and future ambitions for particle physics. The recently-released study also envisions a dedicated U.S. national R&D program, with international coordination, including a muon collider technology demonstrator within the next 20 years as well as participation in the international Future Circular Collider Higgs factory currently under study at CERN.

iv. If there are major new (unexpected) results from the HL-LHC or other HEP experiments

Although some Member States acknowledge that the HL-LHC or other experiments might yield surprises and consider a possible extension of the HL-LHC, there is a strong agreement that any delay would be detrimental to the overall scientific program of CERN.

d) Beyond the preferred option, what other accelerator R&D topics?

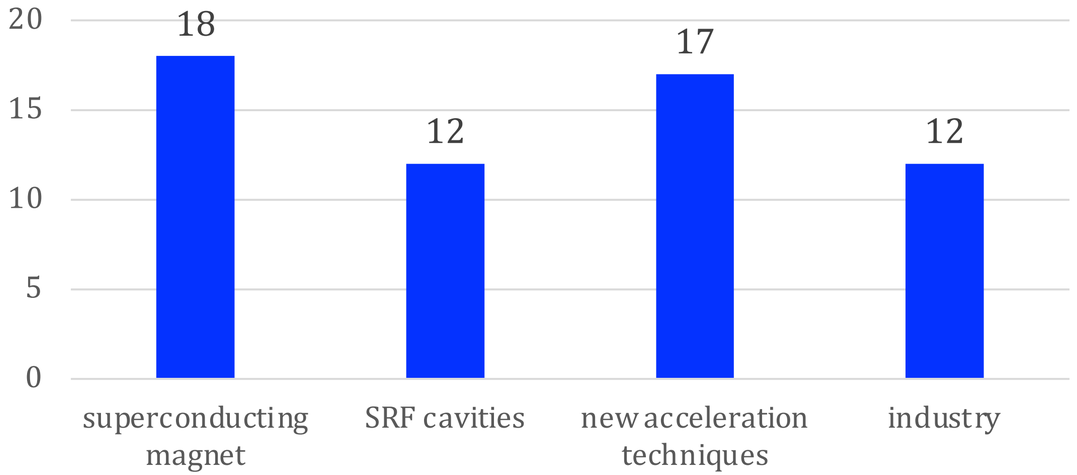
- Continued innovation in **superconducting magnet technology**, especially using HTS, is deemed essential for collider performance limits to be pushed.

- **High-performance SRF cavities** are regarded as foundational for linear and circular accelerators, with research targeted at higher gradients and quality factors and industrial application transition.

- **Groundbreaking methods** such as Plasma Wakefield Acceleration, Muon Acceleration and Cooling, Energy Recovery Linacs, and Terahertz Acceleration are to be invested in, requiring extensive R&D and demonstration facilities.

- **Industry engagement** is to be strengthened to accelerate technology transfer and innovation. Accelerator R&D benefits beyond particle physics - to medicine, energy, and other infrastructures - are to be highlighted to support investment.

Superconducting magnet technology	AT, BE, CH, DE, DK, ES, FI, FR, GR IT, NL,PL, PT, RO, RS, SE, SK, UK
SRF cavities	AT, BE, DE, ES, FI, FR, GR, IT, PL, RO, RS, UK
New acceleration techniques	AT, BE, DE, DK, EE, ES, FR, GR, IT, NL, PL, PT, RO, RS, SE, SK, UK
Industry engagement	AT, BE, DE, ES, FR, IT, NL, PL, RO, RS, SE, UK



- Among the accelerator R&D priorities, the U.S. has focused on superconducting magnet technology, high-performance SRF cavities, and new acceleration techniques. (not counted in the histogram)

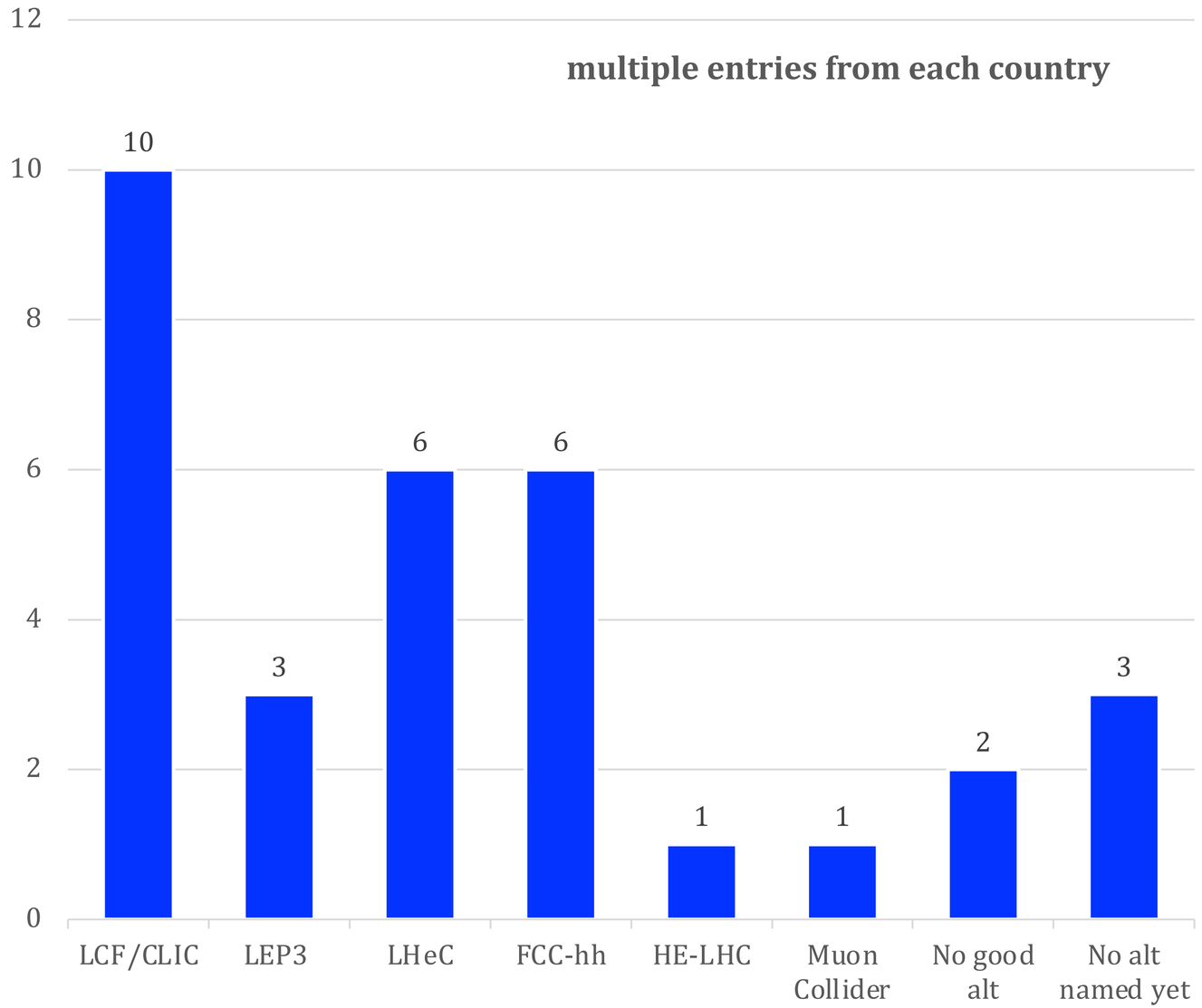
e) What is the prioritised list of alternative options if the preferred option is not feasible?

- Ten countries (DE, ES, FI, FR, NO, PL, PT, SE, RS, SK) list a linear collider at CERN as the second-best choice, with one (FI) mentioning the need for it to be affordable and another (UK) highlighting it as a viable strategic alternative. Two (DE, ES) of these countries highlight the benefits of polarized beams, the potential for two interaction points, and its ability to be upgraded.

- Two countries (CH, HU) see no reason for another option, as they would be equally costly.

- Three countries (BE, GR, UK) mention LEP3 as a genuinely less costly alternative to the FCC-ee.

- No prioritised alternatives have been named yet by three other countries (CZ, DK, SK). The U.S. national input did not express a prioritized list.



e) What is the prioritised list of alternative options if the preferred option is not feasible?

- Two countries (AT, NL) aren't yet committed to a preferred option. One country (NL) suggests a feasibility study for at least one alternative to the FCC-ee.
- A muon collider would be the top alternative for one country (GR), and an option for later consideration for two others (RS, NO). For other countries, it's seen as interesting but not yet ready.
- Six countries (BE, DE, FR, NL, SE, UK) support the LHeC, mostly as an intermediate project.
- Hadron collider options are also mentioned by five other countries (DE, IT, RS, GR, UK). One country (RO) brings up a lower energy hadron collider with an ep collision option.