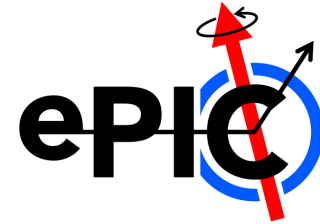
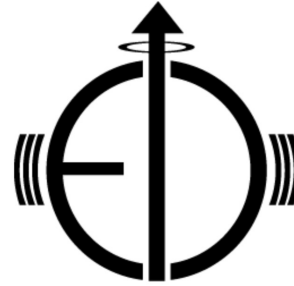




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BIRMINGHAM

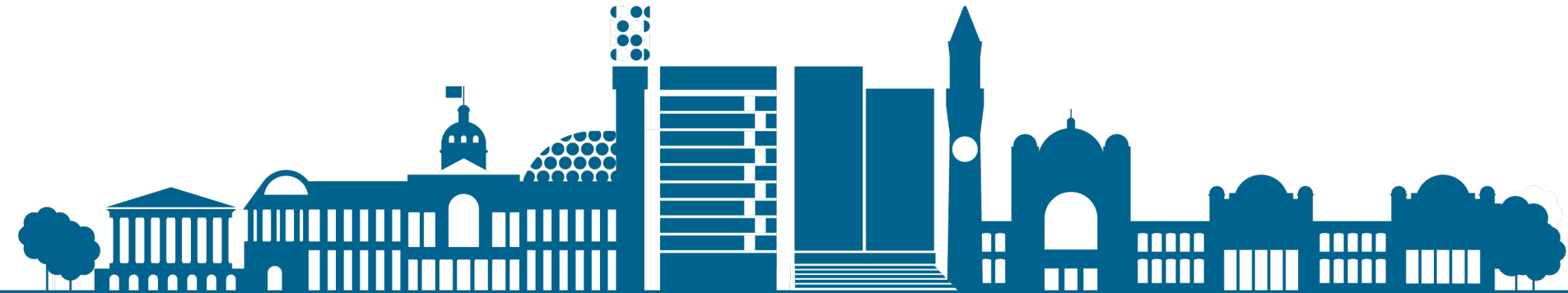


Vertex and Tracking Detector Developments for the Electron-Ion Collider

Laura Gonella

VERTEX 2023

20 October 2023, Sestri Levante



EIC in a nutshell



□ Facility

- The EIC is to be built at the **Brookhaven National Laboratory (BNL)** incorporating the existing Relativistic Heavy Ion Collider

□ Uniqueness

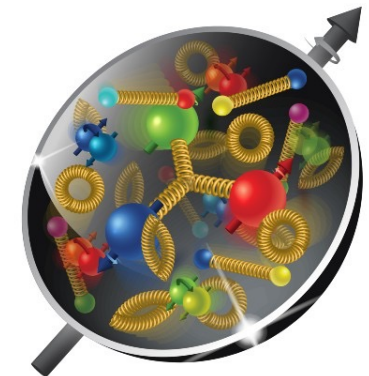
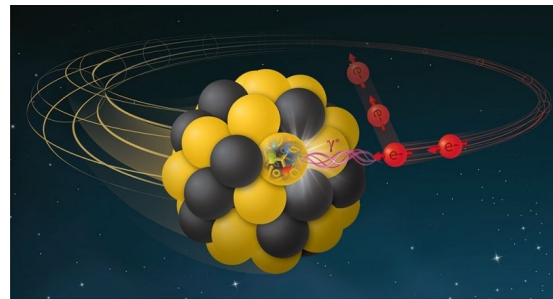
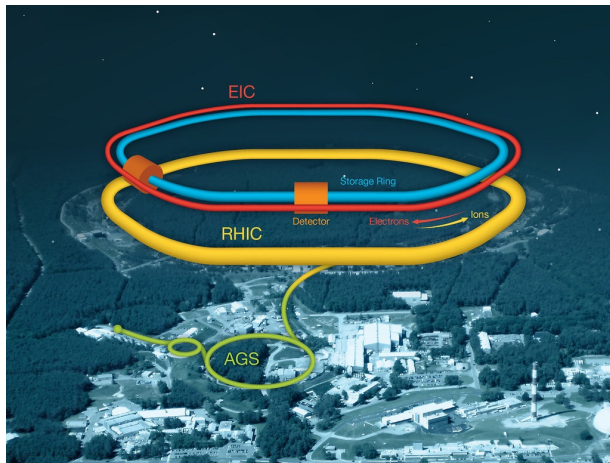
- World's first **polarised electron, polarised proton/light-ion collider**
- World's first **polarised electron, heavy-ion collider**

□ Overarching science questions

- How does **the mass and spin of the nucleon** arise from its constituents?
- What are the emergent **properties of dense systems of gluons?**

□ Timeline

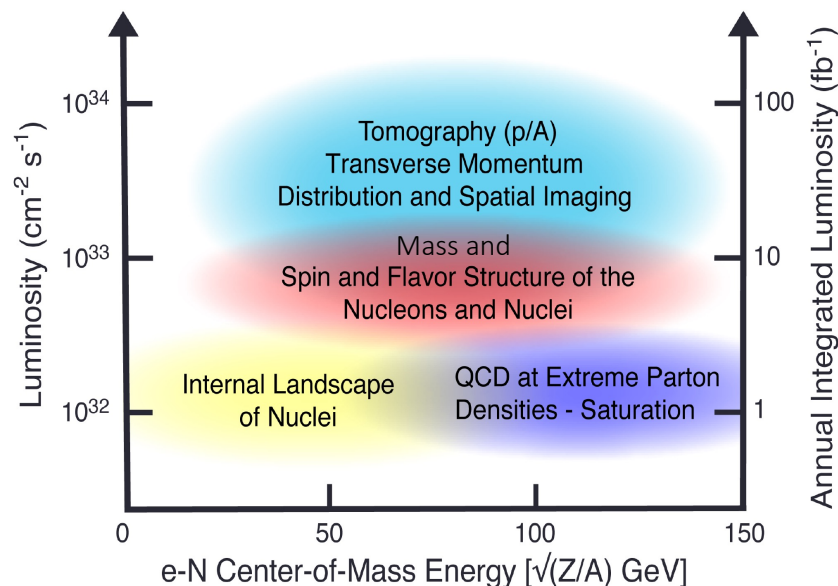
- **Dec 2019: EIC Project approved**
- **Apr 2025: EIC Project Detector TDR**
- **Apr 2032 – Apr 2034: Transition to Operations**



EIC design goals



- High Luminosity: $L = 10^{33} - 10^{34} \text{ cm}^{-2}\text{sec}^{-1}$, 10 – 100 $\text{fb}^{-1}/\text{year}$
- Center of mass energy: 20 – 100 GeV, upgradable to 140 GeV
- Highly Polarized Beams: 70%
- Large Ion Species Range: protons – Uranium
- Large Detector Acceptance and Good Background Conditions
- Accommodate a Second Interaction Region (IR) – The EIC Project covers the accelerator and one detector



EIC project detector requirements



Internal Landscape of Nuclei

QCD at Extreme Parton Densities Saturation

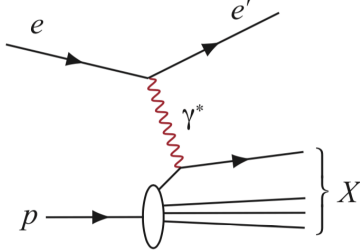
Mass, Spin, Flavor Structure of the Nucleons and Nuclei

Tomography Transverse Momentum Distribution Spatial Imaging

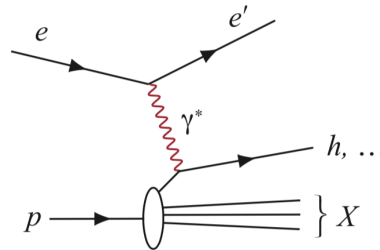
QCD at Extreme Parton Densities Saturation

Tomography Transverse Momentum Distribution Spatial Imaging

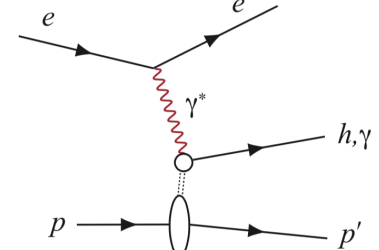
Inclusive DIS



Semi-inclusive DIS



Exclusive DIS



- High performance electron identification and reconstruction

- Tracking and hadronic calorimetry
- Heavy flavors identification from vertexing
- Light flavors from dedicated PID detectors

- Efficient proton tagging
- Cover full acceptance range



Tracking requirements



- Physics derived requirements on precise low momentum particles tracking drive the need for **very high point resolution** and **ultra-low material budget** → **Most challenging requirements**

- High granularity, **low power** active element
- Minimal material** from mechanics, cooling, power and data distribution

Tracking requirements from PWGs						
η			Momentum res.	Material budget	Minimum pT	Transverse pointing res.
-3.5 to -3.0	Central Detector	Backward Detector	$\sigma_{p/p} \sim 0.1\% \times p \oplus 0.5\%$	~5% X0 or less (~MAPS + MPGD trackers)	100-150 MeV/c	dca(xy) ~ 30/pT $\mu\text{m} \oplus 40 \mu\text{m}$
-3.0 to -2.5			100-150 MeV/c			
-2.5 to -2.0			100-150 MeV/c			
-2.0 to -1.5			100-150 MeV/c			
-1.5 to -1.0			100-150 MeV/c			
-1.0 to -0.5		Barrel	$\sigma_{p/p} \sim 0.05\% \times p \oplus 0.5\%$		100-150 MeV/c	dca(xy) ~ 30/pT $\mu\text{m} \oplus 20 \mu\text{m}$
-0.5 to 0			$\sigma_{p/p} \sim 0.05\% \times p \oplus 0.5\%$		100-150 MeV/c	dca(xy) ~ 20/pT $\mu\text{m} \oplus 5 \mu\text{m}$
0 to 0.5						
0.5 to 1.0						
1.0 to 1.5						
1.5 to 2.0						
2.0 to 2.5		Forward Detector	$\sigma_{p/p} \sim 0.05\% \times p \oplus 1\%$		100-150 MeV/c	dca(xy) ~ 30/pT $\mu\text{m} \oplus 20 \mu\text{m}$
2.5 to 3.0			$\sigma_{p/p} \sim 0.1\% \times p \oplus 2\%$		100-150 MeV/c	
3.0 to 3.5					100-150 MeV/c	
	100-150 MeV/c			dca(xy) ~ 30/pT $\mu\text{m} \oplus 60 \mu\text{m}$		

YR Report, Table 11.2



Operational environment

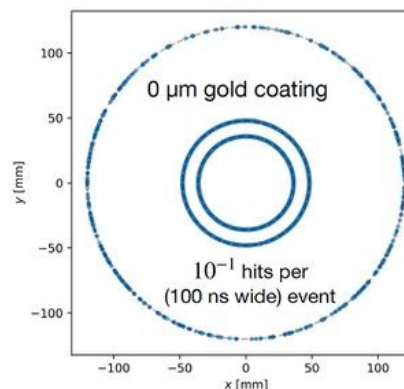


- EIC bunch crossing frequency 98.5 MHz
 - Interaction frequency orders of magnitude lower
- Rates for DIS ep events up to 500 kHz

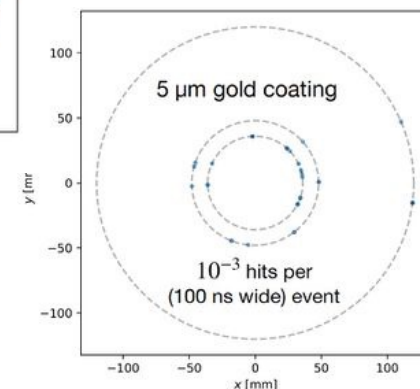
Beam energy [GeV]	5 x 41	5 x 100	10 x 100	10 x 275	18 x 275
L [$10^{33}\text{cm}^{-2}\text{s}^{-1}$]	0.44	3.68	4.48	10	1.54
DIS ep rate [kHz]	12.5	129	184	500	83

[EIC Conceptual Design Report, Table 3.3](#)

- Up to O(MHz) rate for background events
 - Hadron and electron beam gas event rate lowers with improving vacuum condition
 - Synchrotron radiation reduced of two orders of magnitude with 5 μm gold coating of the beam pipe
- Manageable readout frame rate



Scatter plot of SR hits in the innermost silicon tracker layers

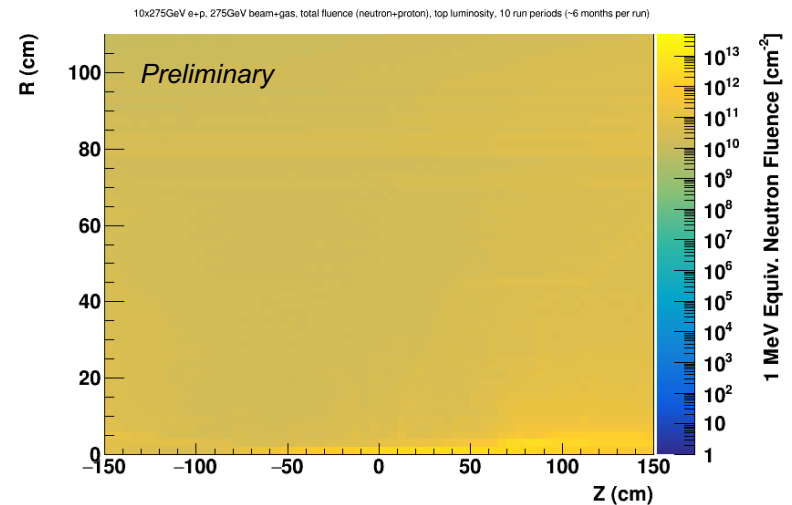
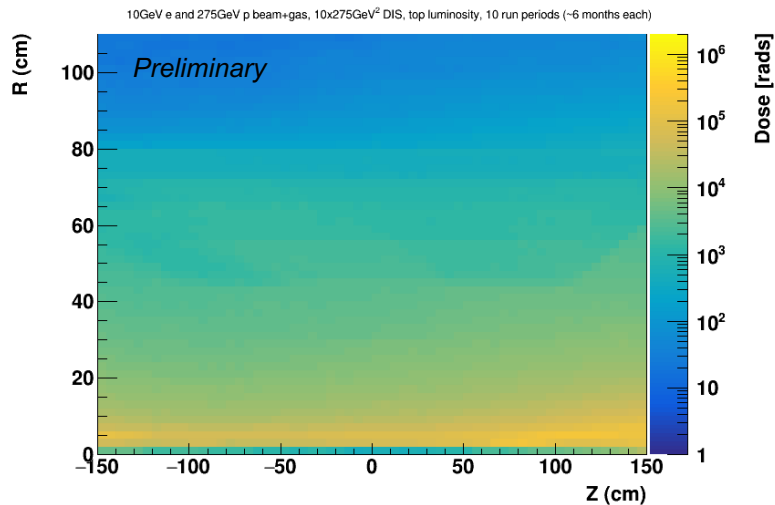


Operational environment



- Low-moderate radiation levels
 - Much lower radiation fluxes than LHC, widens technology options
- Example study: 10 GeV x 275 GeV DIS ep events + beam gas backgrounds
 - Upper bound estimate: top luminosity; 10x 6 months run periods at 100% run time
- Total Ionising Dose below 1 Mrad
- Fluence below $5 \times 10^{13} \text{ n}_{\text{eq}}/\text{cm}^2$

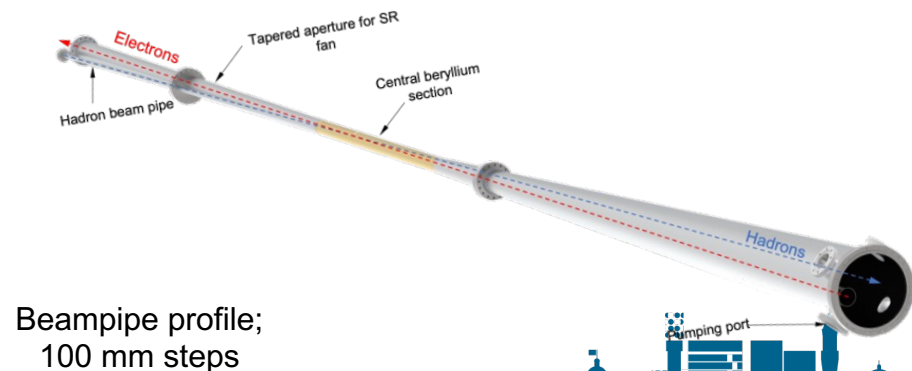
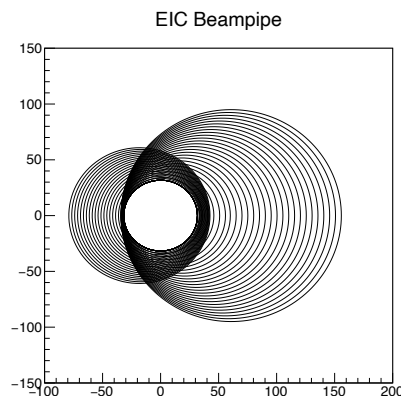
Maps of fluence and dose over the silicon tracker envelop



Integration constraints



- Large beam pipe diameter, **31.8 mm radius**; (more) challenging to reach required vertexing precision
- **Beam pipe diameter increases** away from the interaction point
 - Silicon tracker to be built in two halves clamped around the beam pipe
 - Divergence already in silicon tracker envelop
 - **Complex mechanical support design (local and global) and integration procedure**
- **Beam pipe bake-out** performed with silicon tracker in situ
 - **Demanding cooling requirements** to maximise vertexing capability and acceptance at large eta within material budget

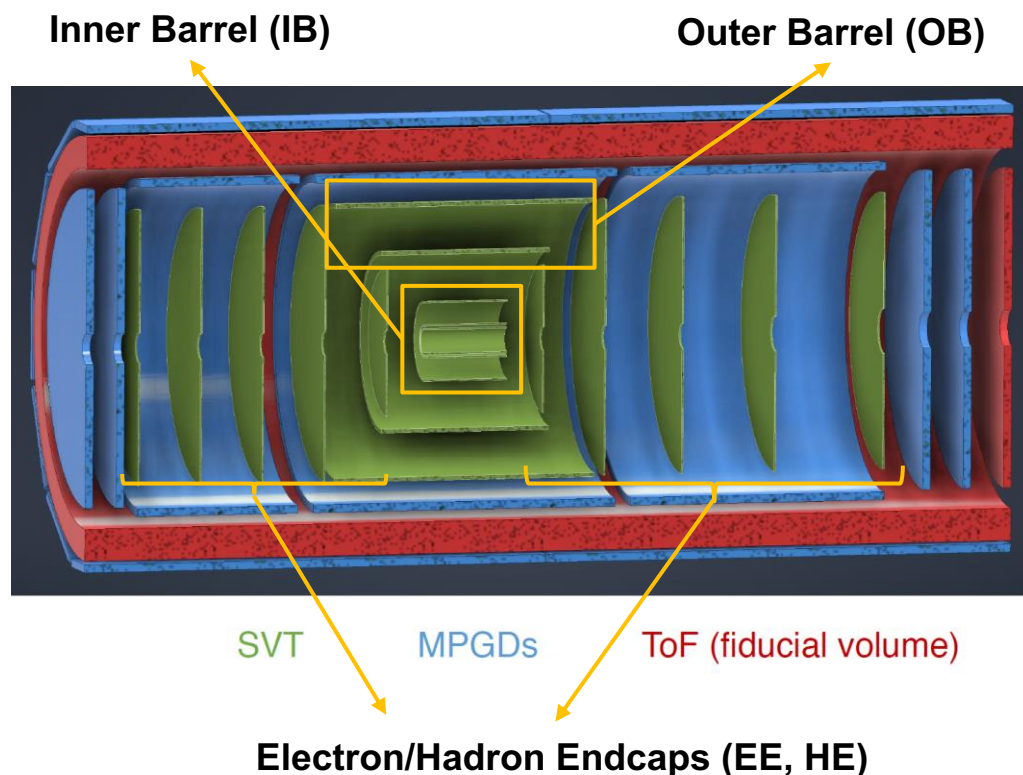


Beampipe profile;
100 mm steps

ePIC Silicon Vertex Tracker (SVT)



- Well integrated, large acceptance, high precision Silicon Vertex Tracker based on large area, low power MAPS in 65 nm CMOS imaging technology



SVT Total (active) area $\sim 8.5 \text{ m}^2$

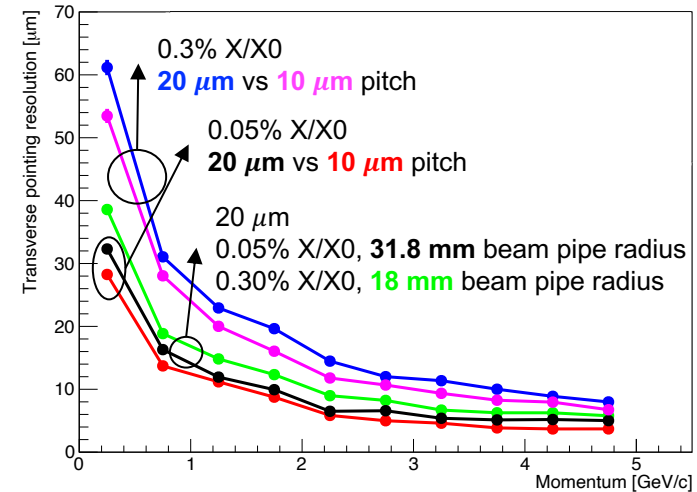
ePIC SVT target specifications	
Spatial resolution	$\sim 5 \text{ um}$
Power	$< 40 \text{ mW/cm}^2$
Frame rate	$\leq 2 \text{ } \mu\text{s}$
Material budget (per layer)	IB: 0.05% X/X_0 OB: 0.25, 0.55% X/X_0 EE/HE: 0.25% X/X_0



Inner barrel

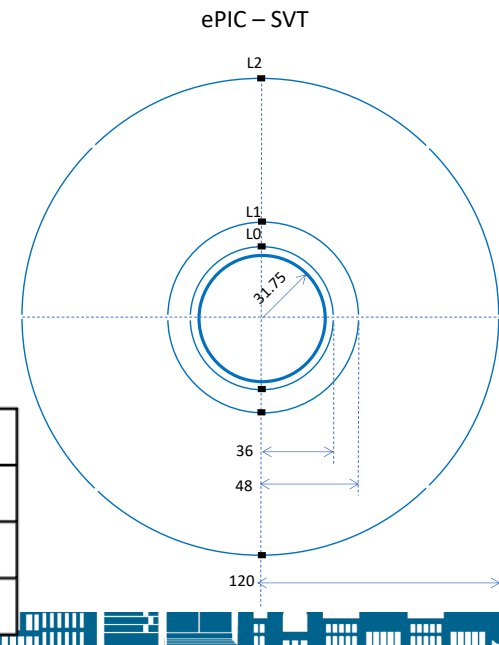


- Transverse pointing resolution is **multiple scattering dominated**
- The IB will adopt the **ALICE ITS3 wafer scale sensor** and **ultra-thin detector concept**
 - Three layers of **thin, bent, silicon sensors**
 - Minimal mechanical support, **air cooling**, no services in active area



- Layers positioned to optimise transverse pointing resolution within **operational constraints**
 - L0, L1: large beam pipe diameter, beam pipe bake-out (5 mm clearance), sensor width
 - L2: $r = 120 \text{ mm}$, dual purpose **vertexing & sagitta layer**, without increase in material

IB	r [mm]	l [mm]	X/X_0 %
L0	36	270	0.05
L1	48	270	0.05
L2	120	270	0.05



Outer barrel and endcaps

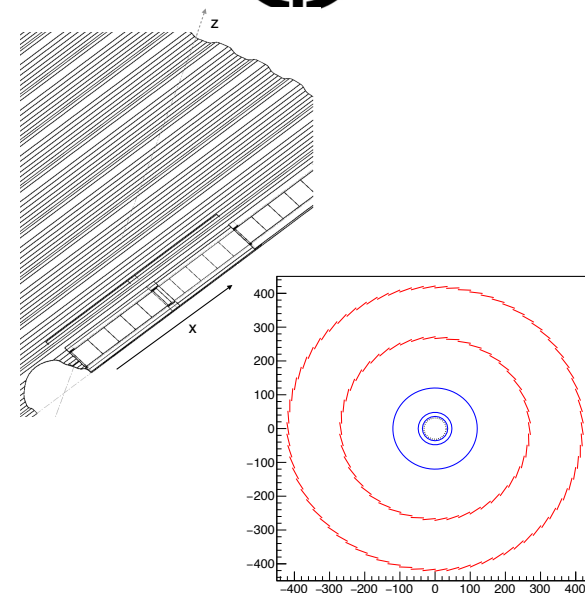


- EIC Large Area Sensor optimised for high yield, low cost, large area coverage
 - Modification of the ITS3 sensor; LAS stitched but not wafer scale; possible modification(s) in the periphery to reduce number of readout links

- Lightweight mechanical supports (staves, disks) with integrated cooling and electrical interfaces

- Large lever arm with high precision measurements
 - Improve momentum resolution
 - Maximise acceptance at high eta

- Disk inner opening defined by beam pipe bake-out constraints and off-centered where beam pipe diverges



BARREL	r [mm]	l [mm]	X/X0 %
Layer 3	270	540	0.25
Layer 4	420	840	0.55

DISKS	+z [mm]	-z [mm]	r_out [mm]	X/X0 %
Disk 0	250	-250	240	0.25
Disk 1	450	-450	420	0.25
Disk 2	700	-650	420	0.25
Disk 3	1000	-850	420	0.25
Disk 4	1350	-1050	420	0.25

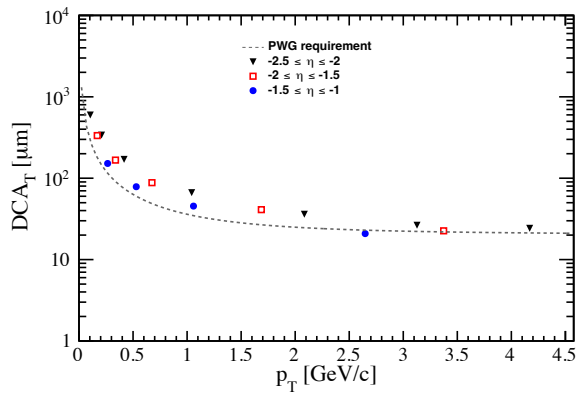


Tracking performance

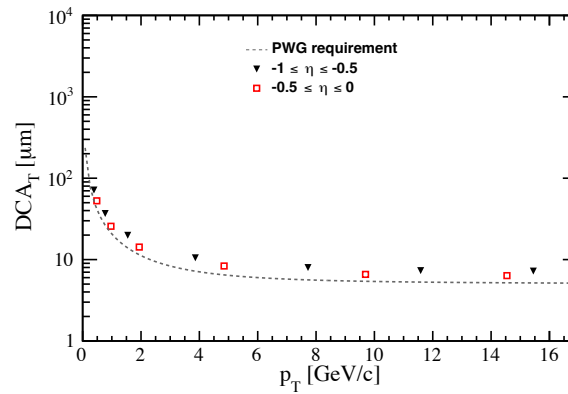


- Requirements on transverse pointing resolution met in the central region and at mid-pseudo rapidity, with good agreement at large eta

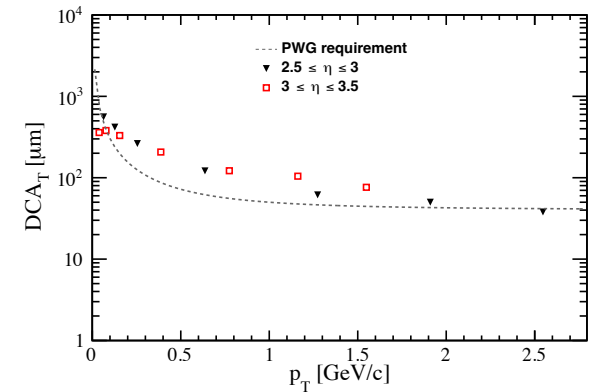
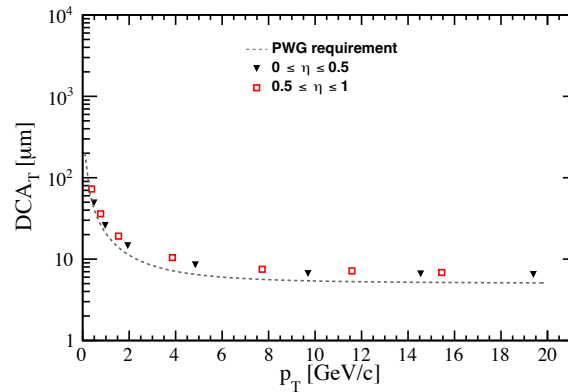
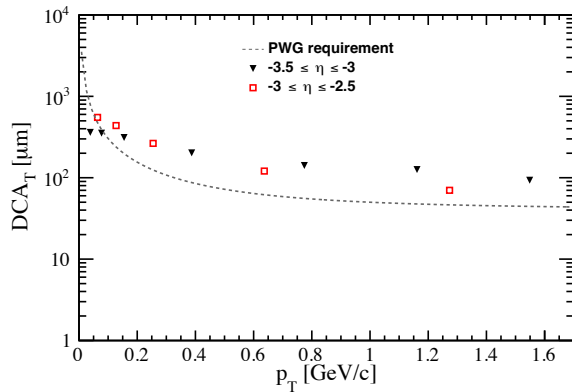
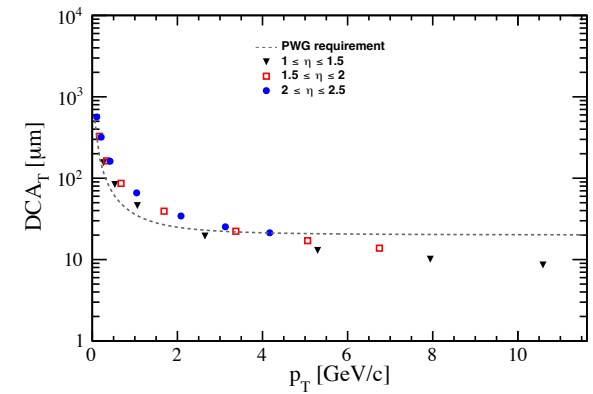
Backward region
(Electron going direction)



Central region



Forward region
(Hadron going direction)



(Single particle, truth seeding)

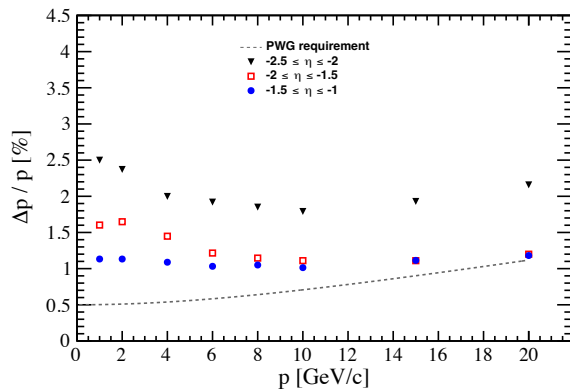


Tracking performance

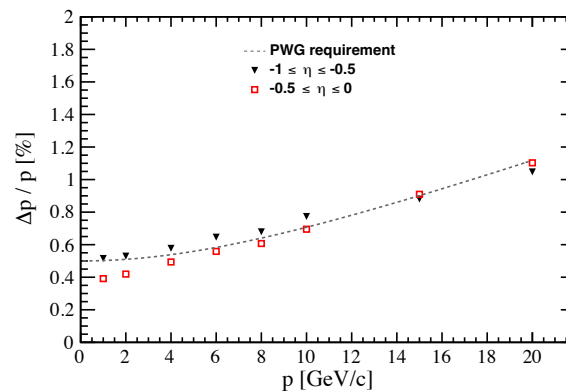


- Requirements on relative momentum resolution met in central and most of the forward region; still challenging in the backward region

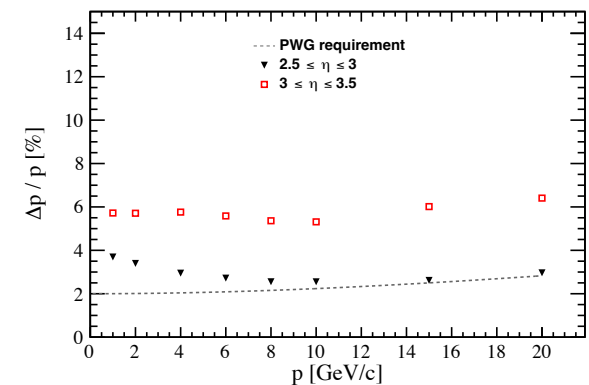
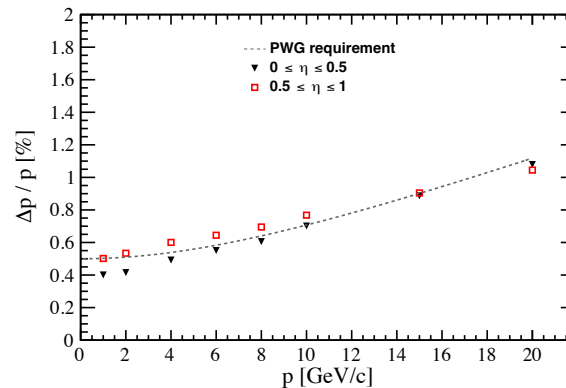
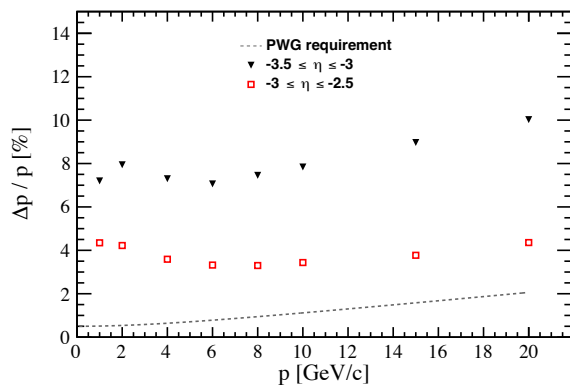
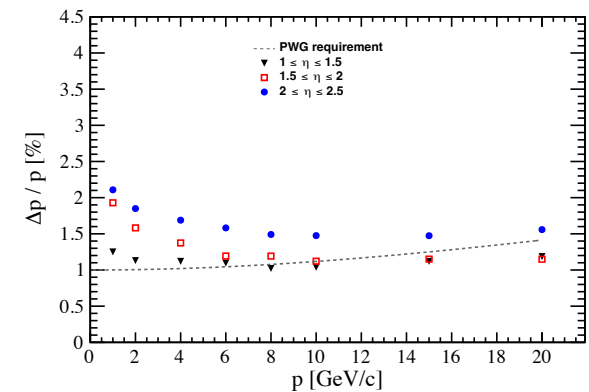
Backward region
(Electron going direction)



Central region



Forward region
(Hadron going direction)



(Single particle, realistic seeding)

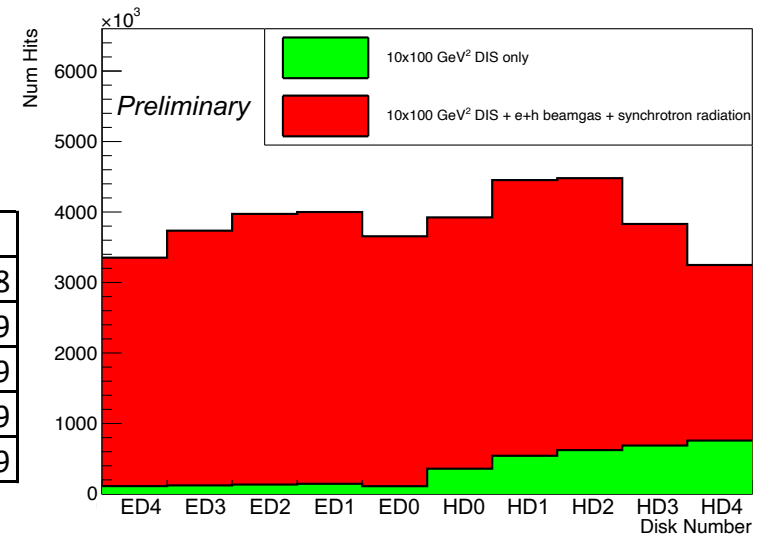
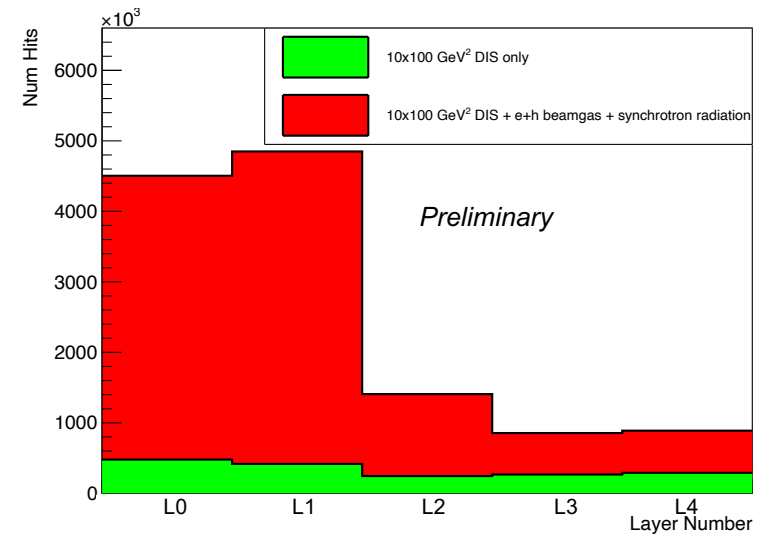


Hit rates in the SVT



- Background events dominate the hit rates in the SVT
- Example study:
 - 10 GeV x 100 GeV DIS ep events
 - 10 GeV electron beam gas and SR, 100 GeV hadron beam gas
 - 20.8 x 22.8 μm^2 pixel, 2 μs frame rate
- 3 - 5 MHz rates in IB and endcaps, ≤ 1 MHz in OB
- Hit occupancy at most $\sim 10^{-7}$ per pixel per frame

	Hits/pixel/frame		Hits/pixel/frame		Hits/pixel/frame
L0	7.00E-08	ED0	1.96E-08	HD0	2.11E-08
L1	5.65E-08	ED1	7.07E-09	HD1	7.87E-09
L2	6.56E-09	ED2	6.81E-09	HD2	7.68E-09
L3	8.85E-10	ED3	6.40E-09	HD3	6.59E-09
L4	3.80E-10	ED4	5.76E-09	HD4	5.62E-09

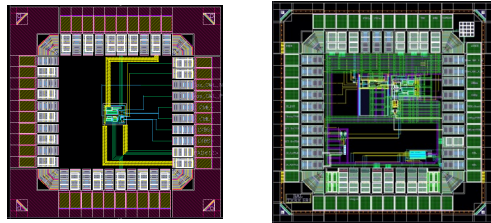


Overview of ongoing R&D activities

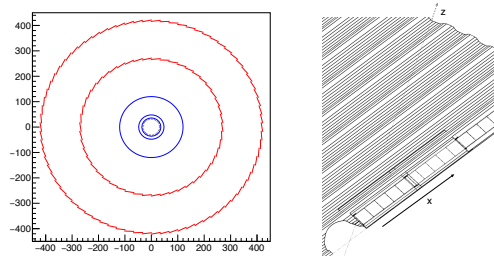


- R&D targets the development of **low mass technological solutions** to satisfy the **physics requirements** and achieve **tight integration** of the different SVT regions

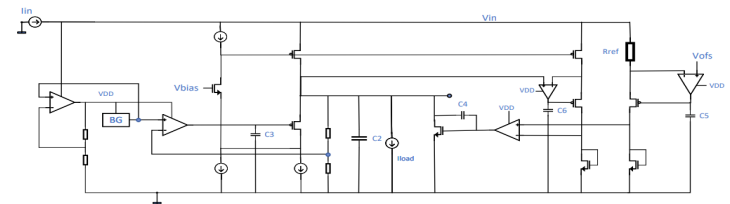
Sensor development (in collaboration with ITS3)



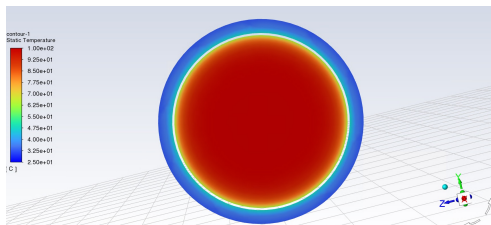
Conceptual design of OB and endcaps



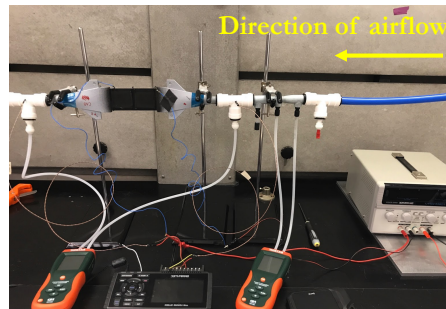
Serial powering



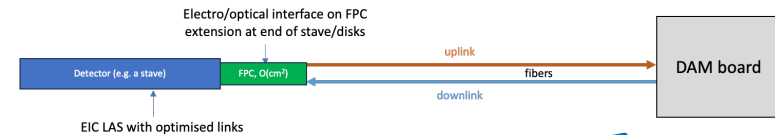
Beam pipe bake-out studies



Air cooling through support structure



Data transmission on optical fibers

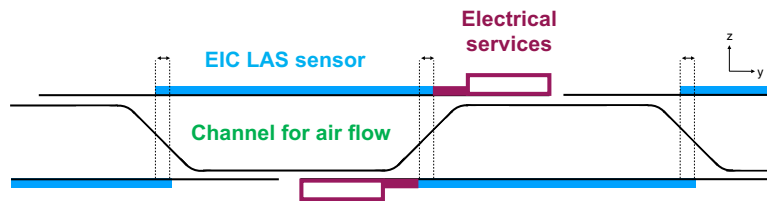
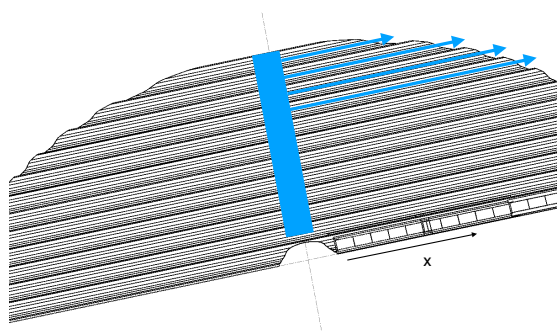


**Selected developments
shown in the next slides**

Integrated mechanics and cooling



- The SVT will operate at **room temperature** with an estimated total sensor power consumption of **~4kW** (excl. overhead for powering and data transmission)
- Preferred cooling solution for the SVT is **air cooling**
 - Baseline for IB, one of the options considered for OB and endcaps
 - Ongoing studies of **airflow internal to the support structure for OB and endcaps**
- **Air flow through corrugated support structure**
 - EIC LAS on both sides of corrugated support structure on carbon fiber sheets
 - Support and space for electrical services between modules; channel for air flow
 - Prototyping of test structure ongoing with available mould; mechanical and thermal tests to follow



Integrated mechanics and cooling

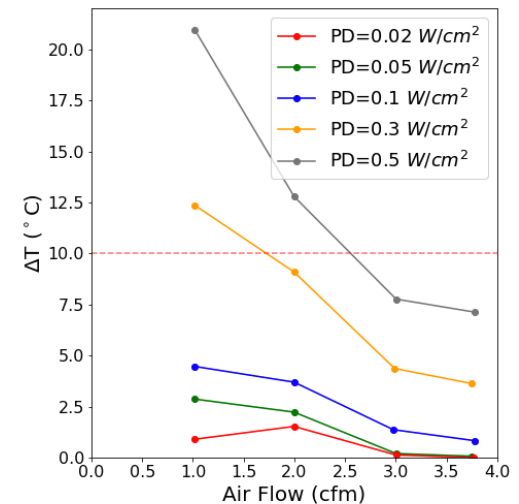


□ Initial testing of air cooling through carbon foam

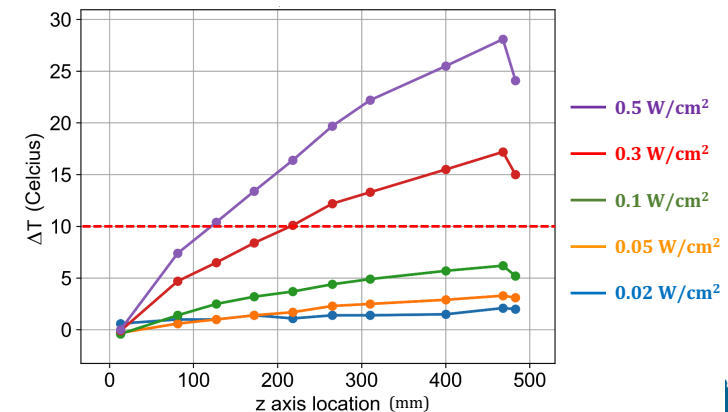
- Small stave structures with different foam type and thickness
- Heat loads to simulate various power densities
- Room temperature air flow
- Goal: $\Delta T < 10C$
- CVD foam meets requirement up to $0.5 W/cm^2$
- RVC foam achieves $\Delta T < 10C$ for power densities $< 0.1 W/cm^2$
- ePIC size staves in fabrication; ongoing improvements to overall setup

□ Air + mono/bi-phase cooling combination also considered, work yet to start

ΔT across 10 cm long, 4 mm thick CVD stave

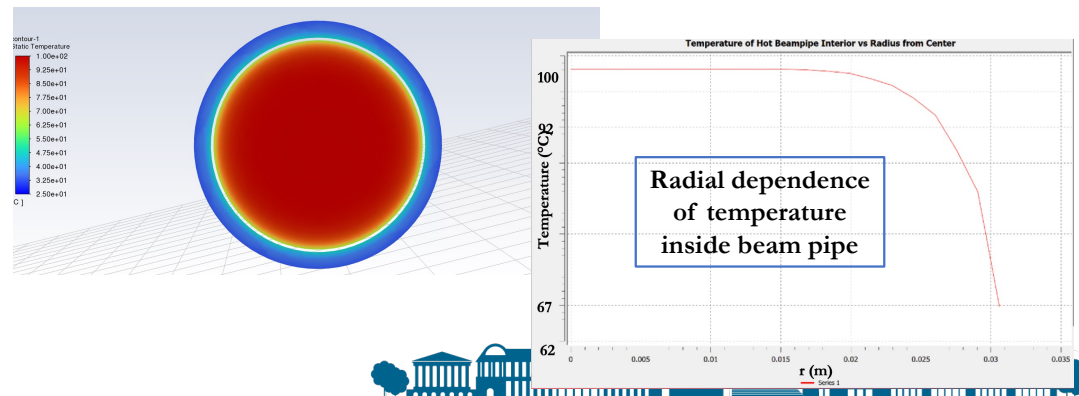
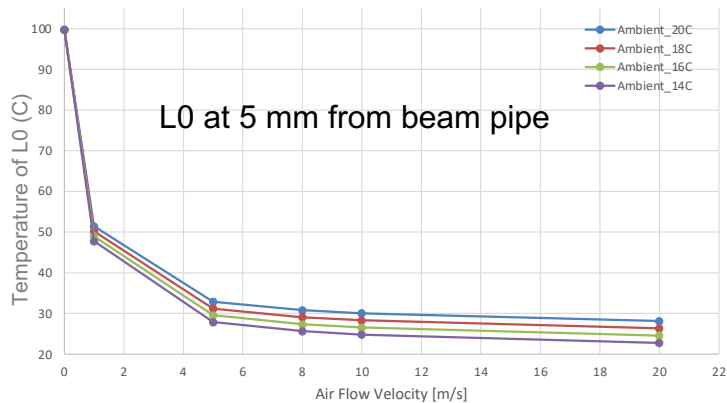


ΔT across 50 cm long, 6 mm thick RVC stave for 3.4 cfm



IB air cooling and beam pipe bake-out

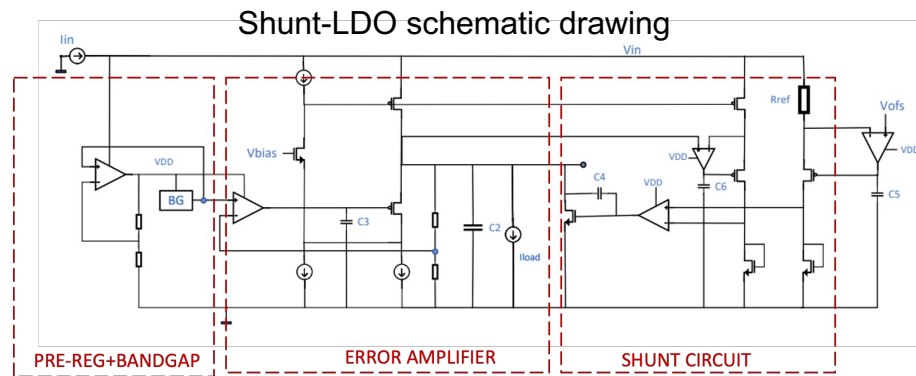
- Beam pipe bakeout performed with IB installed
 - Hot gas pumped into beam pipe at $T \geq 100\text{C}$
 - Target IB temperature during bake-out of 30C
 - Large temperature gradient to accommodate over small volume
- Initial simulations indicated **5 mm spacing** between beam pipe and L0 needed with air flow $T < 20\text{C}$ and 5 mm/s velocity
- However, significant **beam pipe inner surface cooling** from air flow to cool IB ($100\text{C} \rightarrow 67\text{C}$ for air flow $T = 25\text{C}$)
 - Next steps: investigate minimum hot gas temperature to keep inner surface of beam pipe at 100C and study effect on L0 temperature



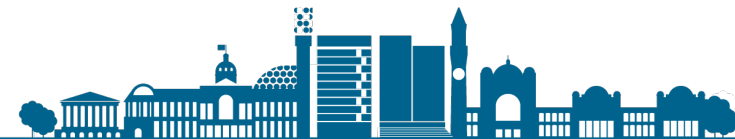
Services material reduction



- **Serial powering** to be implemented for OB and endcaps
 - Current flow between EIC LAS sensors
 - **Shunt-LDO regulator** design to match EIC LAS power specs, ongoing
 - **Aluminium-Kapton flex** for power distribution on stave/disks



- **Readout architecture**
 - **Low radiation levels + IpGBT integrated** in ITS3 sensor periphery → investigate use of **optical fibers for data transmission to/from staves/disks**
 - Electro/optical interface at end of stave/disk; available mechanical support and cooling



Conclusion



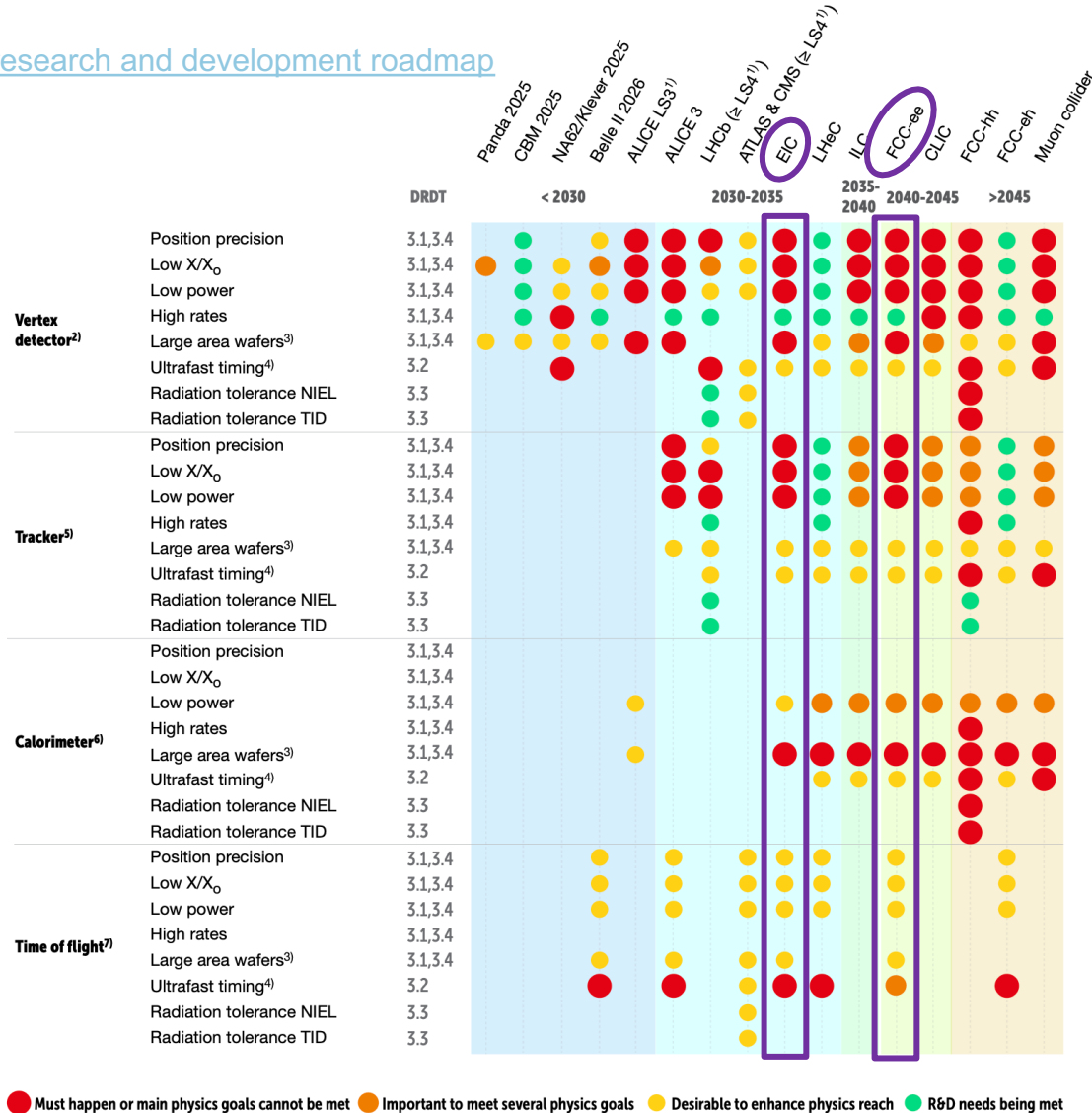
- The EIC will be a **world's unique facility** to continue exploration of strongly interacting matter using DIS, commencing operation in the early 2030s
- The ePIC Silicon Vertex Tracker is a **large, thin, MAPS based detector**, with **very demanding requirements** for precision measurements and integration
- **Synergies with ALICE ITS3** developments + **large programme of dedicated R&D** on lightweight, integrated mechanics, cooling and services

*The ePIC SVT is an **interesting and challenging project**,
and it is not too late to join the effort...*



EIC detector: a technology demonstrator for FCC-ee

The 2021 ECFA detector research and development roadmap



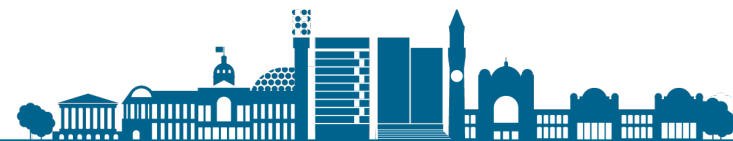
ePIC Silicon Vertex Tracker Detector Subsystem Collaboration



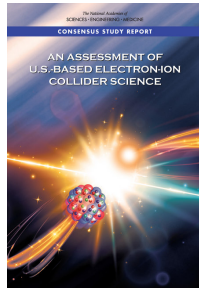
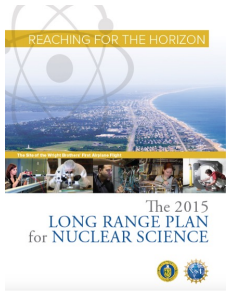
Detector Subsystem Leader: Ernst Sichterman (LBNL)
Detector Subsystem Technical Coordinator: Laura Gonella (Uni Birmingham)



Backup



EIC Project Timeline



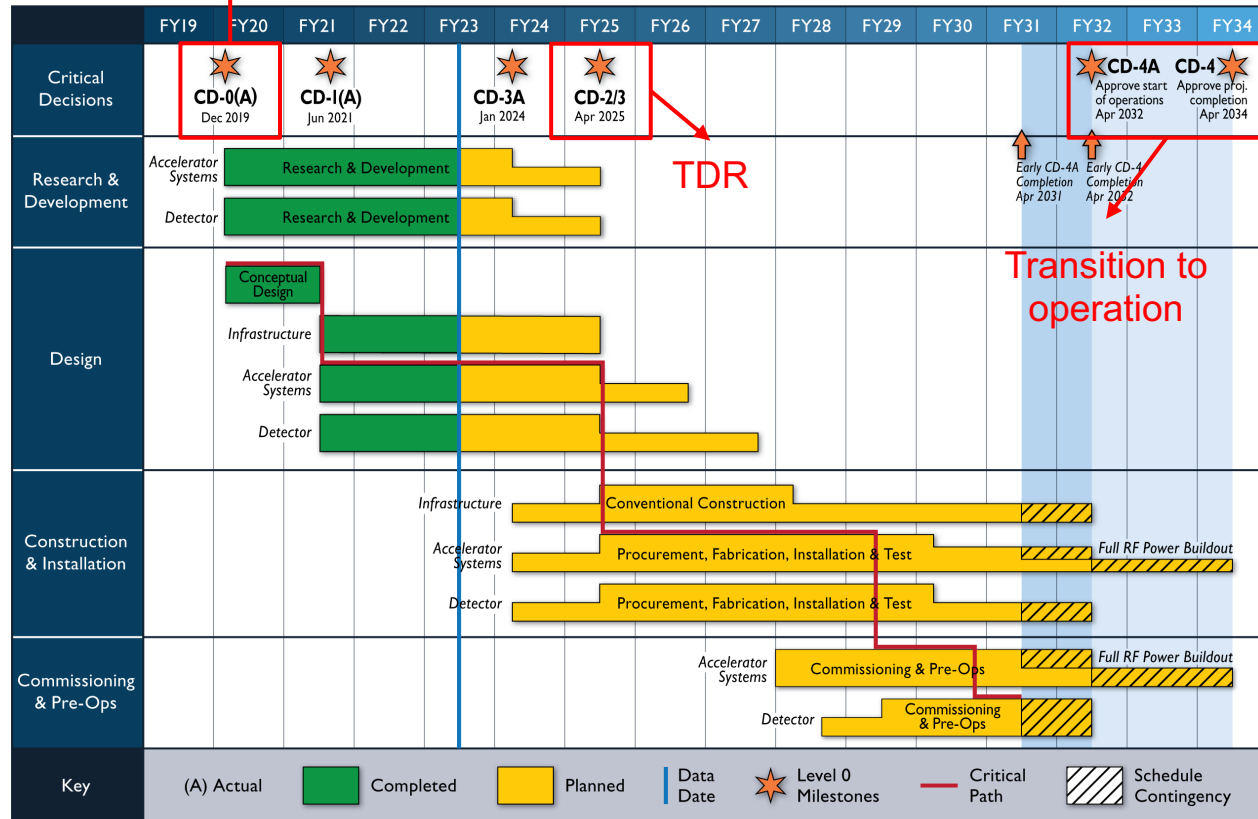
Early endorsement

2015 Long Range Plan for Nuclear Science

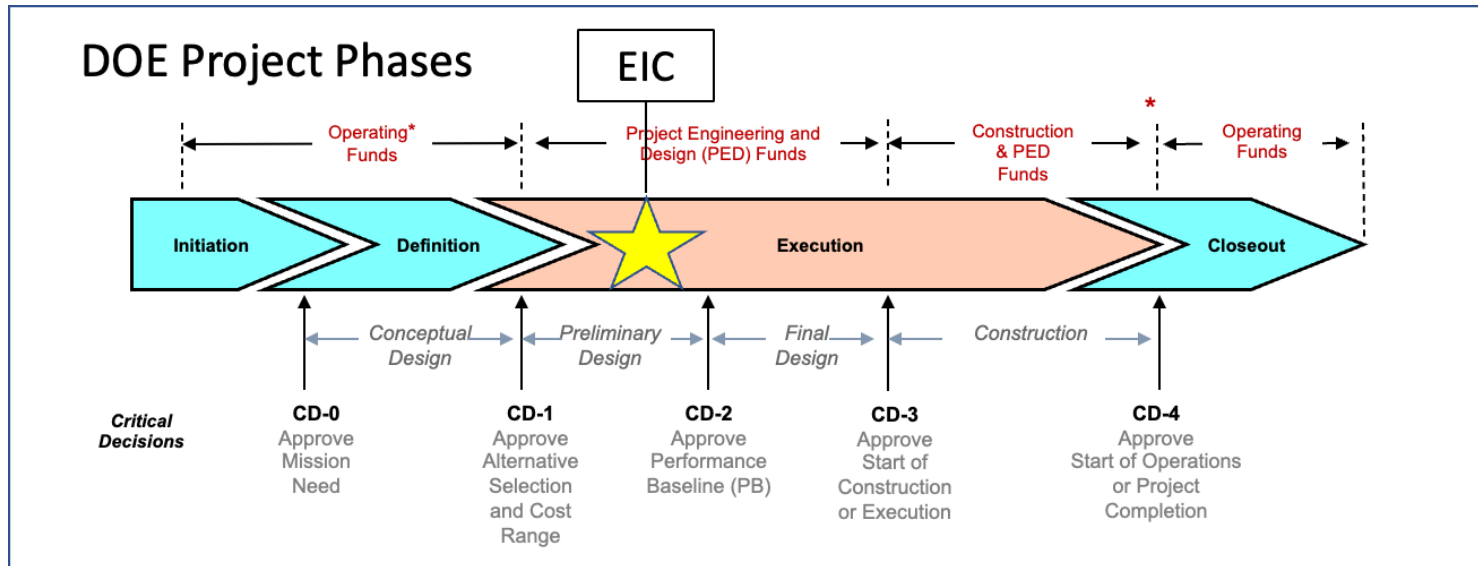
2018 [National Academy of Science Assessment](#)

DOE Project Milestones

Project approved



DOE Project Phases



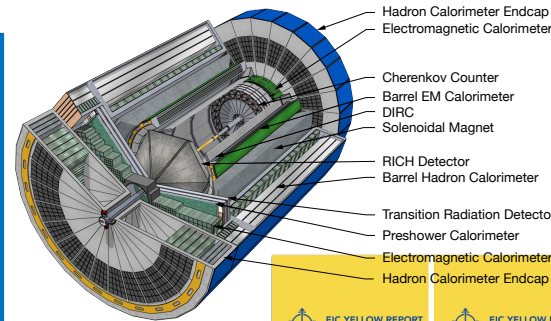
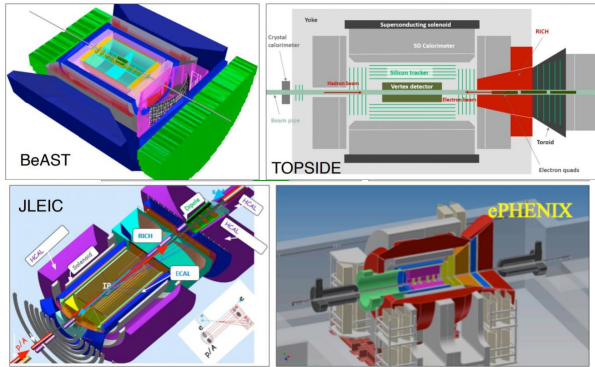
CD-0, Mission Need Approved	December 2019
DOE Site Selection Announced	January 2020
CD-1, Alternative Selection and Cost Range, Approved	June 2021
CD-3A, Long Lead Procurement	January 2024
CD-2/3, Performance Baseline/Construction Start	April 2025
RHIC Shut Down	June 2025



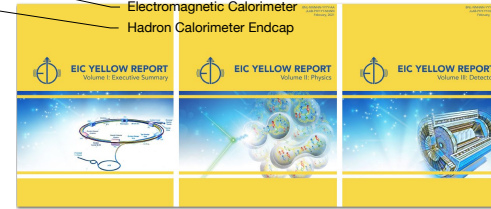
Evolution of EIC Detector Concept



White paper (2012, 2014), initial concepts



Yellow Report
reference detector
(2020), global effort of
the EIC Users Group



Call for Detector proposals (2021)

ATHENA: A Totally Hermetic Electron-Nucleus Apparatus

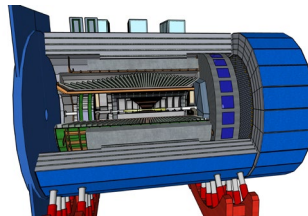
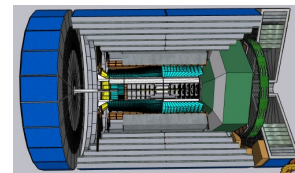
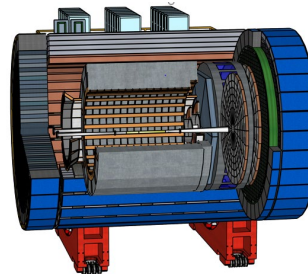
- General purpose detector inspired by YR studies, new central magnet of up to 3T

CORE: COmpact detectoR for the Eic

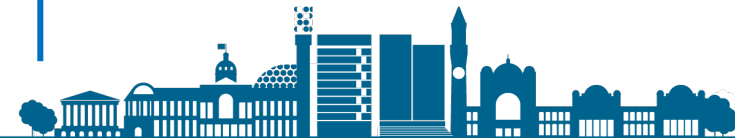
- Nearly hermetic, general purpose compact detector, 2T baseline

ECCE: EIC Comprehensive Chromodynamics Experiment

- General purpose detector, 1.5T BaBar magnet



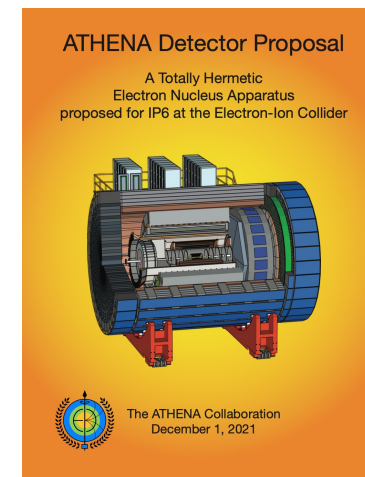
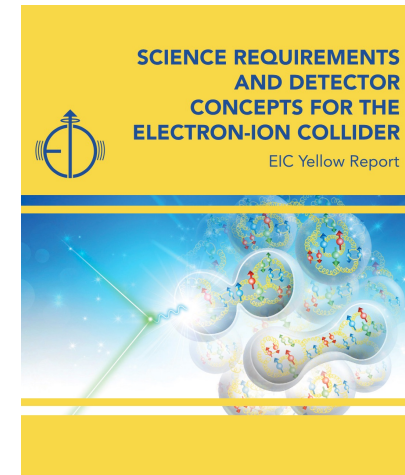
2022: Merging of ECCE and ATHENA proposal strengths forming a new collaboration to deliver the EIC Project Detector
→ **ePIC collaboration** formally established



Evolution of EIC Detector Concept



- 2020: **Yellow Report**
 - Initial requirements, two detector reference designs, further physics opportunities
- 2021: **Call for Detector Proposals**
 - Detector Proposal Advisory Panel (DPAP) reviewed three proposals; **ATHENA, CORE, and ECCE**
 - ATHENA and ECCE fulfil all requirements of the EIC Science Case; ECCE design recommended and adopted as Reference Detector
- 2022: **ATHENA and ECCE merge into the ePIC collaboration to deliver the EIC Project Detector**

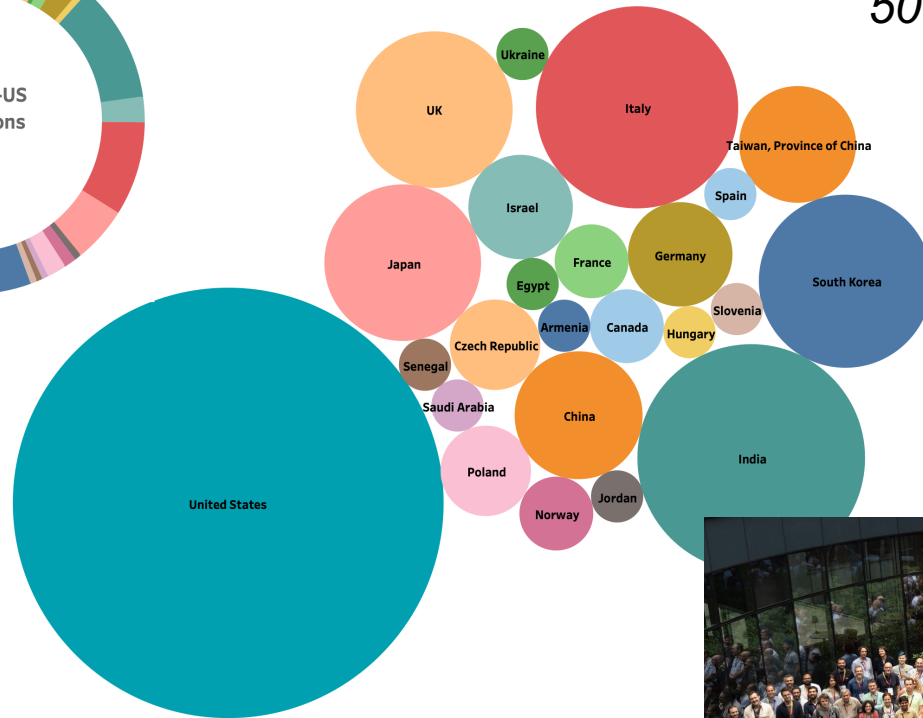
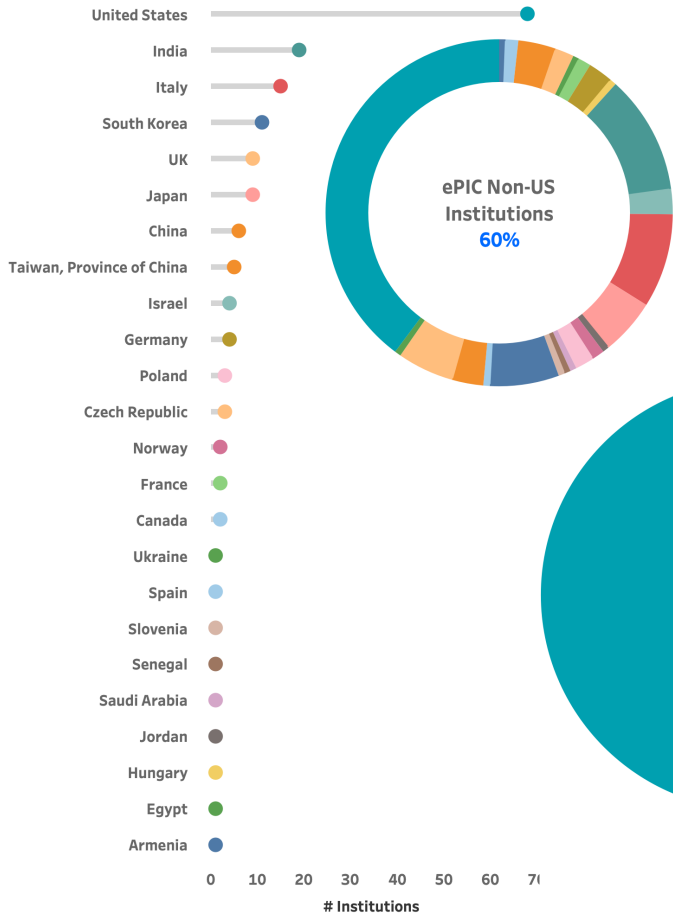


ePIC Collaboration



ePIC ePIC - A **global** pursuit for a new EIC experiment at IP6 at BNL

*171 Institutions
24 countries
500+ participants*



ePIC Detector

Magnet

- New 1.7 T SC solenoid, 2.8 m bore diameter

Tracking

- Si Vertex Tracker MAPS wafer-level stitched sensors (ALICE ITS3)
- Si Tracker MAPS barrel and disks
- Gaseous tracker: MPGDs (μ RWELL, MMG) cylindrical and planar

PID

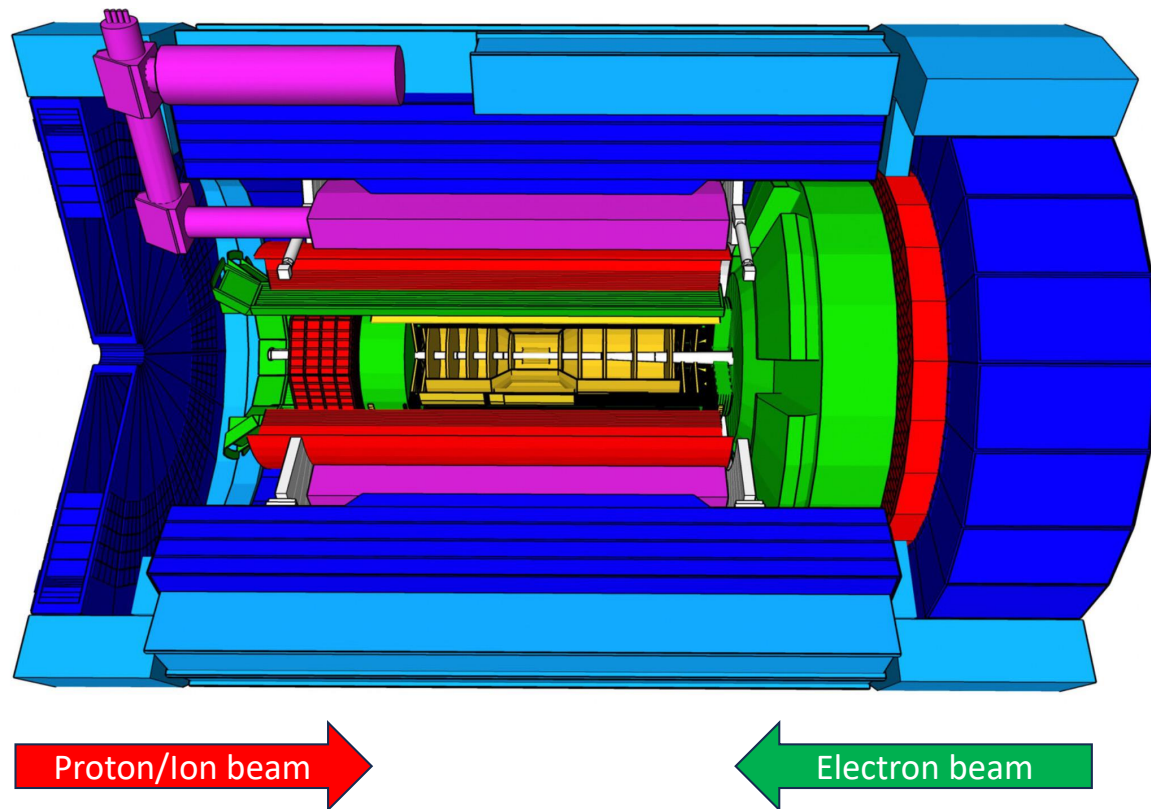
- high performance DIRC (hpDIRC)
- dual RICH (aerogel + gas) (forward)
- proximity focussing RICH (backward)
- ToF using AC-LGAD (barrel+forward)

EM Calorimetry

- imaging EMCal (barrel)
- W-powder/SciFi (forward)
- PbWO_4 crystals (backward)

Hadron calorimetry

- FeSc (barrel, re-used from sPHENIX)
- Steel/Scint – W/Scint (backward/forward)



ePIC Silicon Vertex Tracker (SVT)

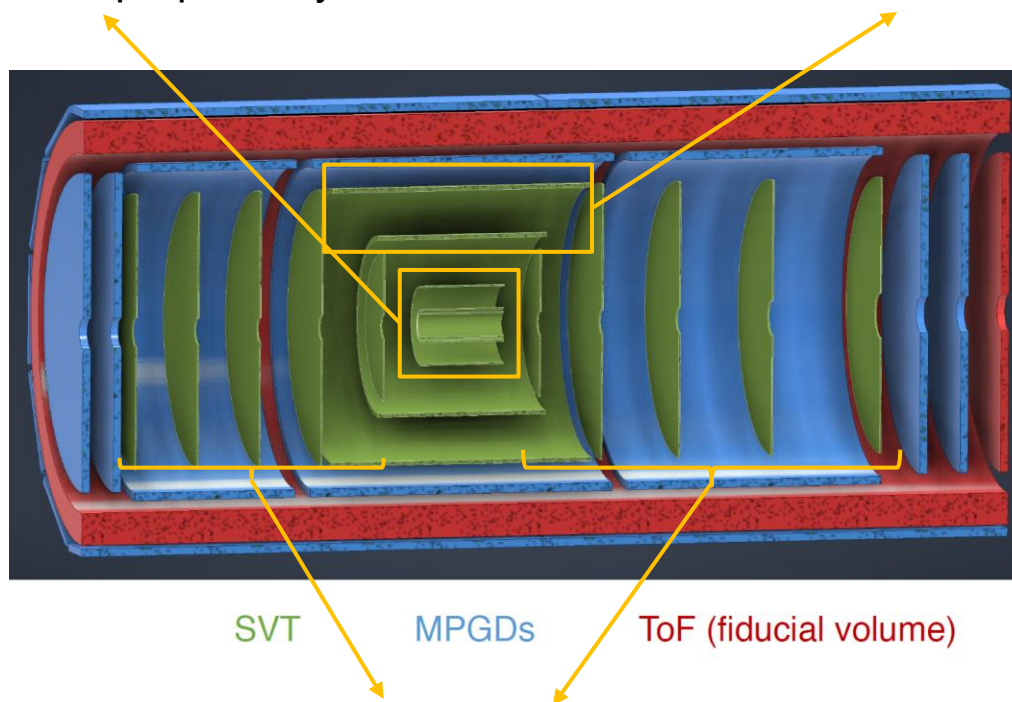


Inner Barrel (IB)

- 2 curved silicon vertex layers
- 1 curved dual-purpose layer

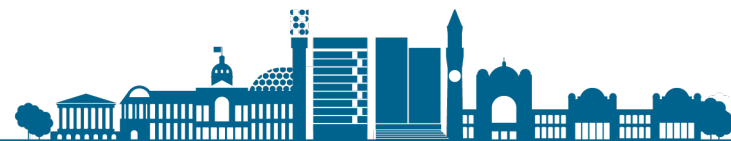
Outer Barrel (OB)

- 1 stave-based sagitta layer
- 1 stave-based outer layer



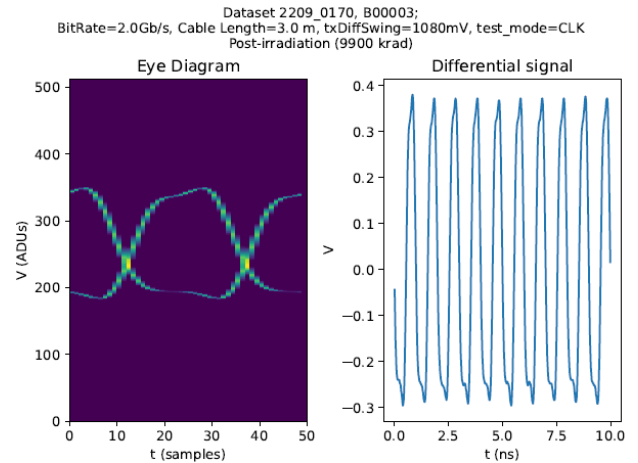
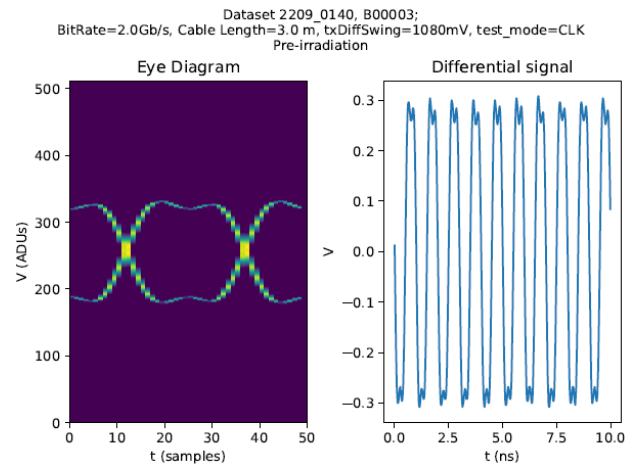
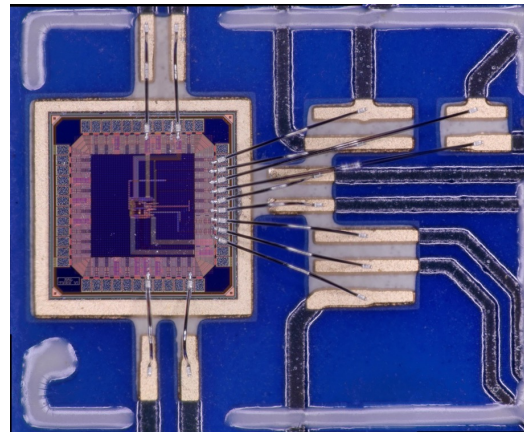
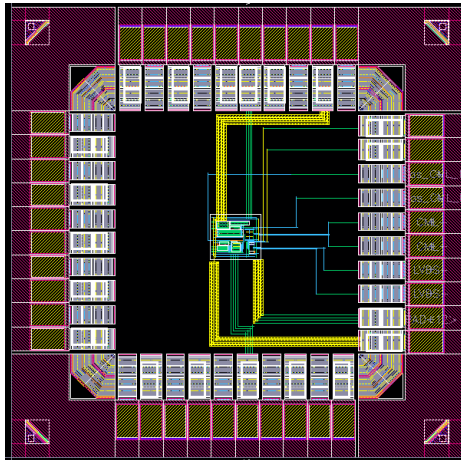
Electron/Hadron Endcaps (EE, HE)

- 5 disks on either side of the IP



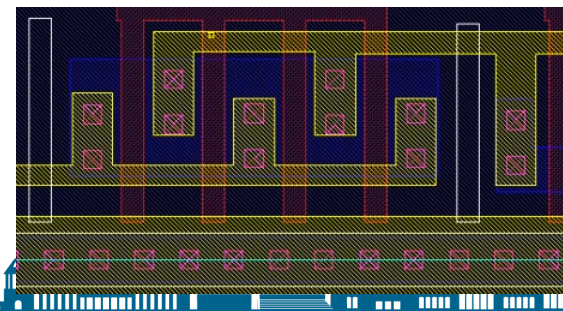
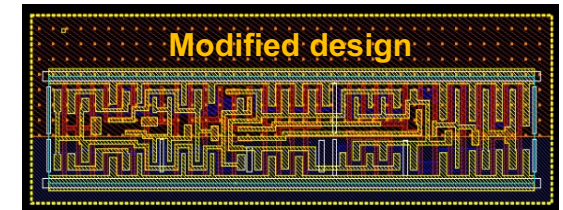
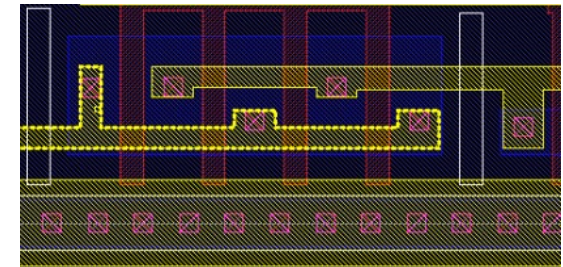
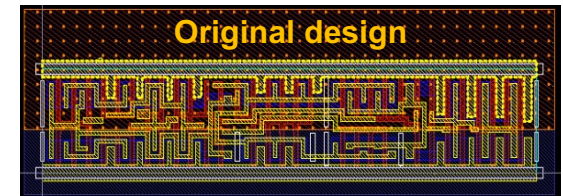
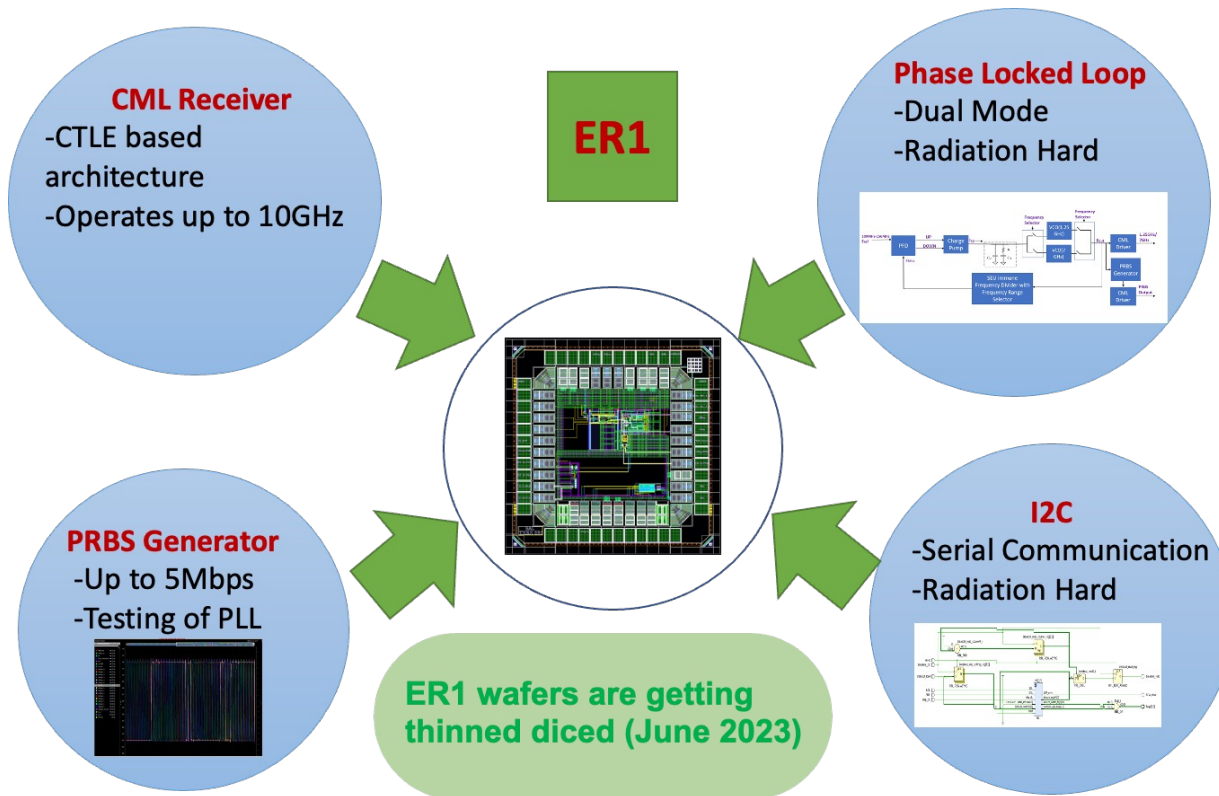
MLR1 design

- High Speed LVDS Receiver + High speed CML Driver
 - Functional up to 2Gbps
 - Tested up to 9900Krad



ER1 designs

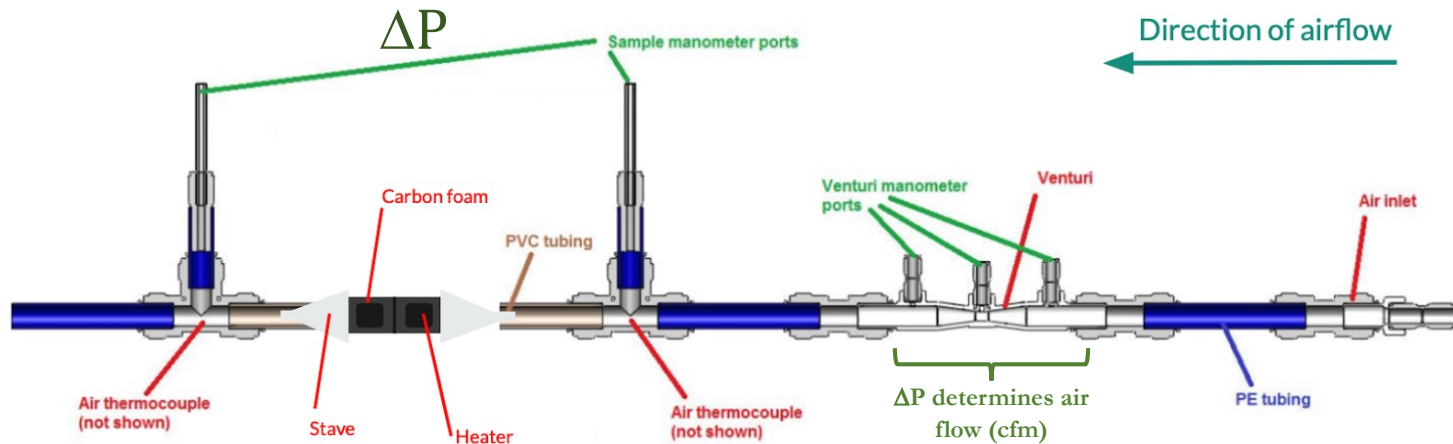
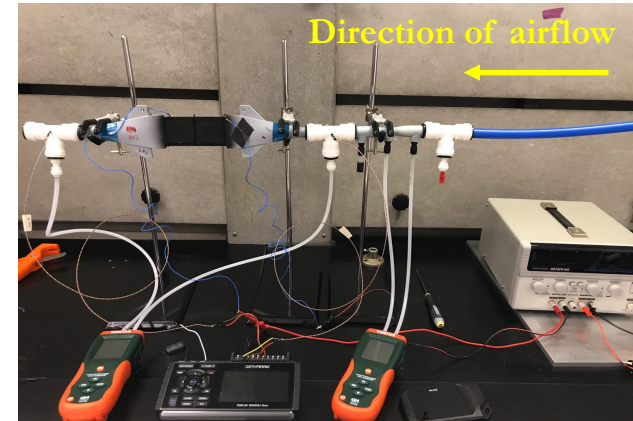
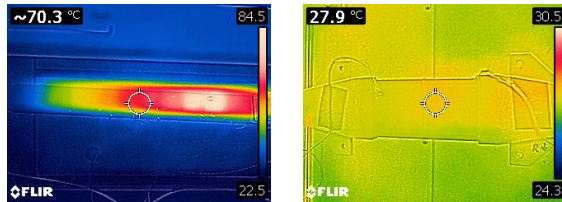
- Functional blocks for data transmission (on- and off-chip)
- Standard cell layout modifications for DFM



Air cooling through carbon foam

Setup

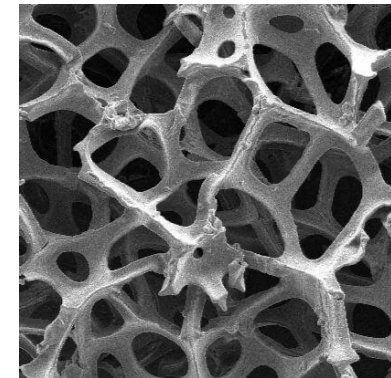
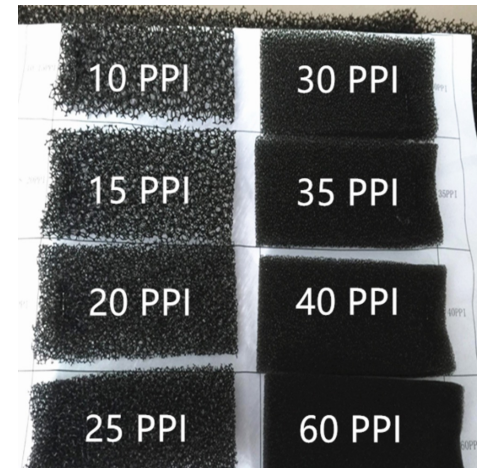
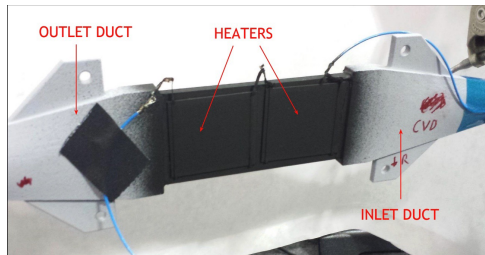
ΔT : “bright” temp – “dark” temp



Air cooling through carbon foam

Stave variations

- Foam types:
 - CVD – conducting, denser than RVC
 - RVC – insulating, lower material budget
- Thicknesses: 4 & 6 mm
- PPI(pores per inch): 30 & 45
- Stave lengths: 100 & 500 mm



Beam pipe bake out

- ❑ No heaters around beampipe due to material budget
- ❑ Pumping ports located ~4.5 m away outside of the detector volume
- ❑ Needed vacuum = 10^{-9} mbar

