UNIVERSITY OF
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Silicon Vertex Tracker for the Electron-Ion-Collider

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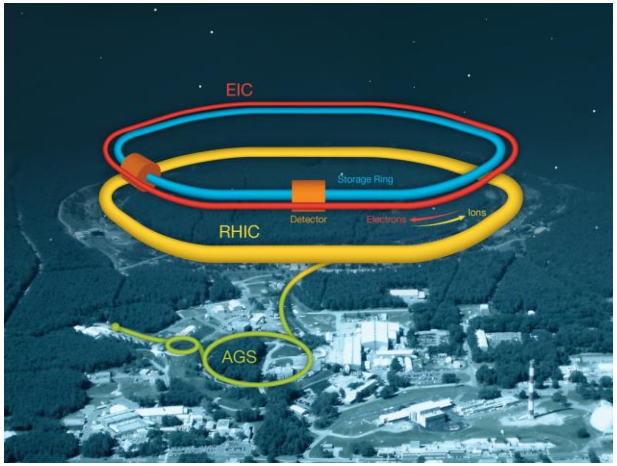
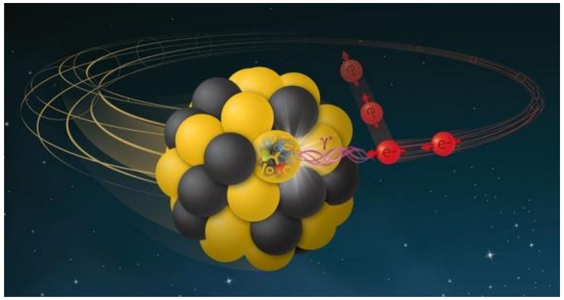
Current and future tracking and vertexing detectors 2023

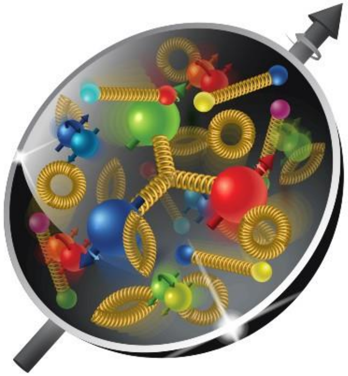
7th November 2023, QMUL

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

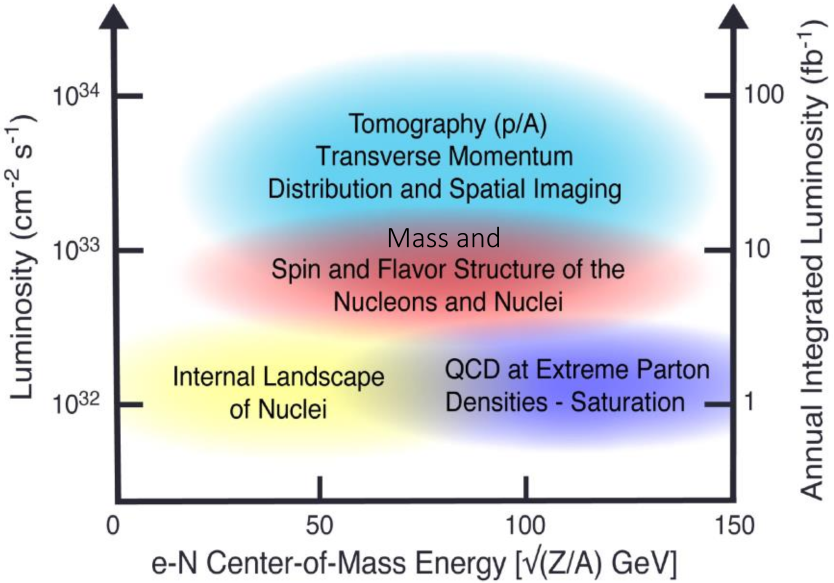






EIC design goals

- ☐ High Luminosity: $L = 10^{33} – 10^{34}$ $cm^{-2}sec^{-1}$, 10 – 100 fb^{-1}/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

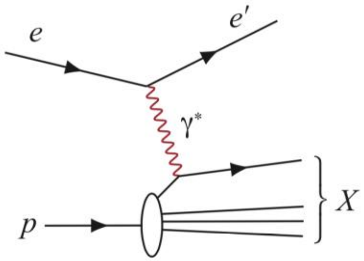
Mass, Spin, Flavor Structure of the Nucleons and Nuclei

Tomography Transverse Momentum Distribution Spatial Imaging

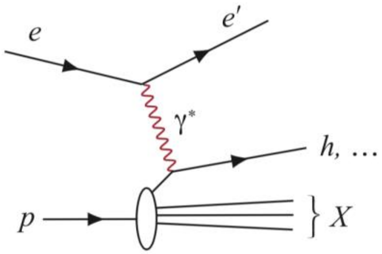
QCD at Extreme Parton Densities Saturation

Tomography Transverse Momentum Distribution Spatial Imaging

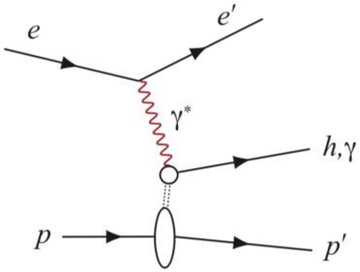
Inclusive DIS



Semi-inclusive DIS



Exclusive DIS

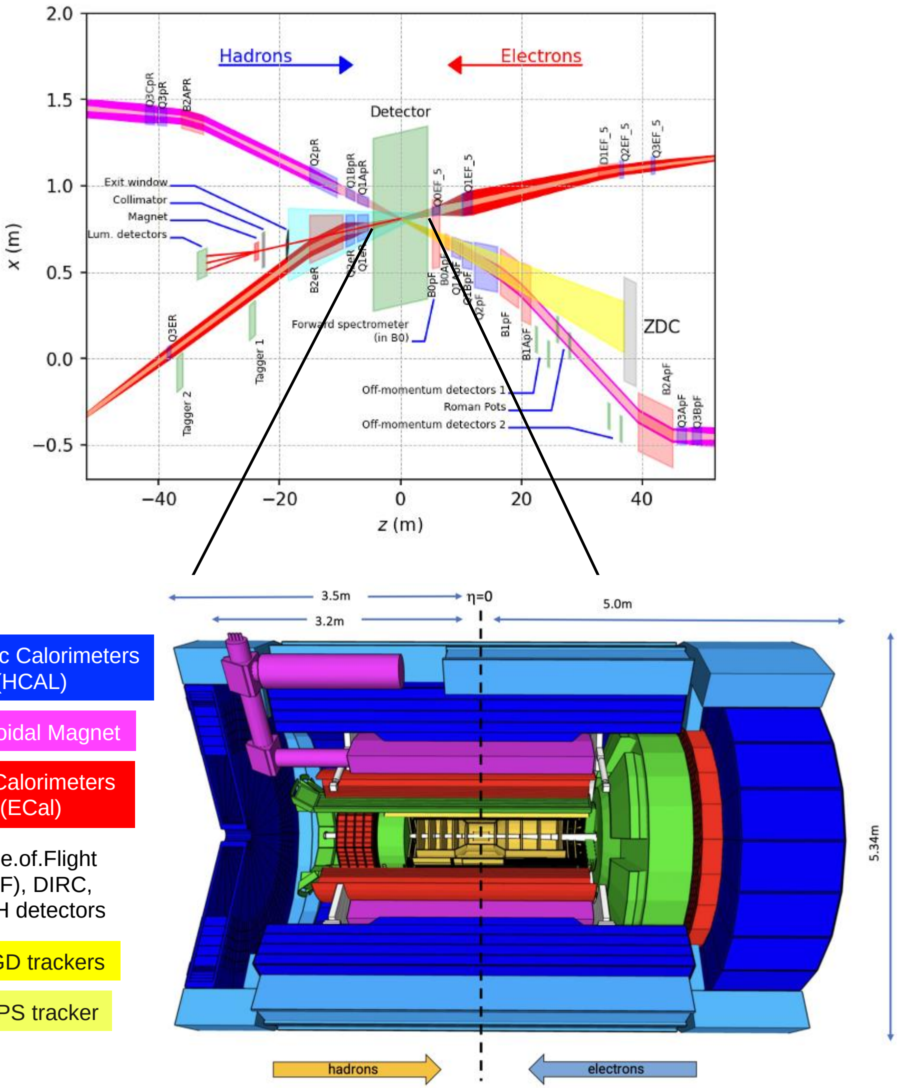


- ☐ High performance electron identification and reconstruction

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

- ☐ Efficient proton tagging
- ☐ Cover full acceptance range

ePIC detector



Hadronic Calorimeters (HCAL)

Solenoidal Magnet

E/M Calorimeters (ECal)

Time.of.Flight (ToF), DIRC, RICH detectors

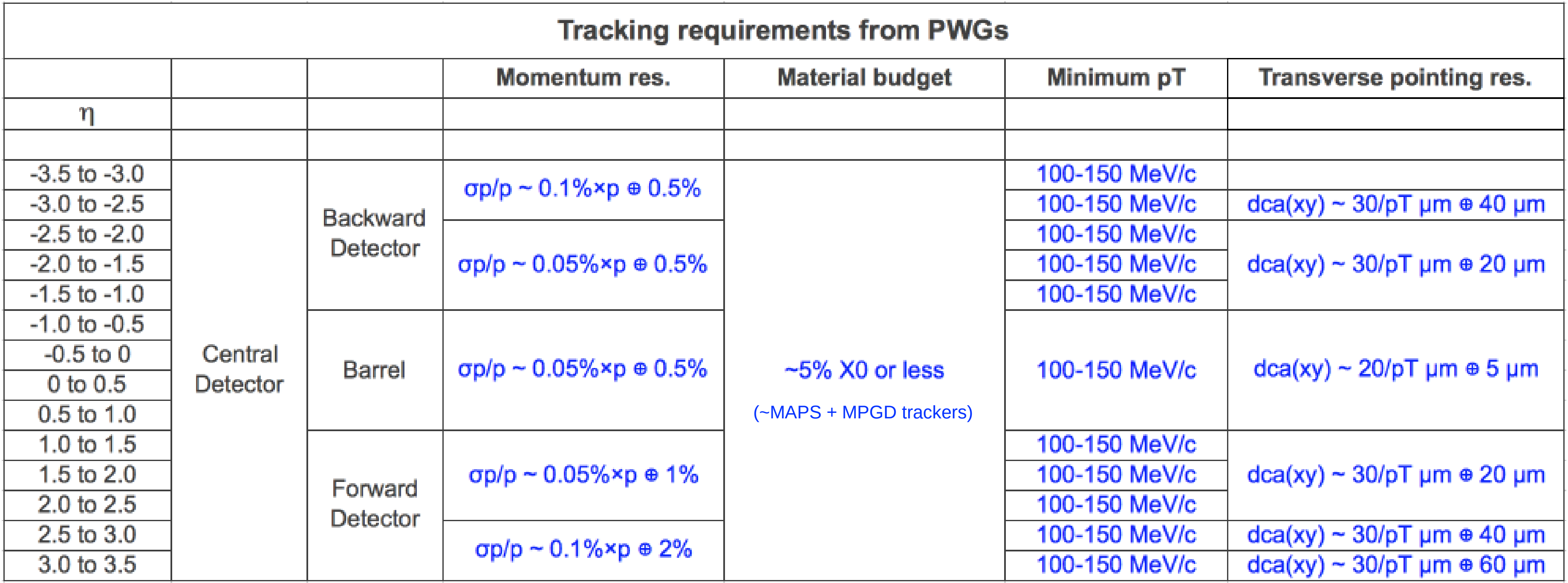
MPGD trackers

MAPS tracker

- ☐ Compact central detector
  - – Combines tracking and vertexing, PID, and EM and hadronic calorimetry
  - – Asymmetric beam energies, different electron and hadron endcaps
- ☐ 1.7 T solenoidal field, ~2.8 m bore
- ☐ Streaming readout approach
- ☐ Extensive beamline instrumentation integral to science programme

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						
			Momentum res.	Material budget	Minimum pT	Transverse pointing res.
η						
-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	
-3.0 to -2.5					100-150 MeV/c	dca(xy) ~ 30/pT μm ⊕ 40 μm
-2.5 to -2.0			$\sigma_p/p \sim 0.05\%\times p \oplus 0.5\%$		100-150 MeV/c	dca(xy) ~ 30/pT μm ⊕ 20 μm
-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) ~ 20/pT μm ⊕ 5 μm
-0.5 to 0						
0 to 0.5						
0.5 to 1.0						
1.0 to 1.5		Forward Detector	$\sigma_p/p \sim 0.05\%\times p \oplus 1\%$		100-150 MeV/c	dca(xy) ~ 30/pT μm ⊕ 20 μm
1.5 to 2.0					100-150 MeV/c	
2.0 to 2.5					100-150 MeV/c	
2.5 to 3.0			$\sigma_p/p \sim 0.1\%\times p \oplus 2\%$		100-150 MeV/c	dca(xy) ~ 30/pT μm ⊕ 40 μm
3.0 to 3.5					100-150 MeV/c	dca(xy) ~ 30/pT μm ⊕ 60 μm

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

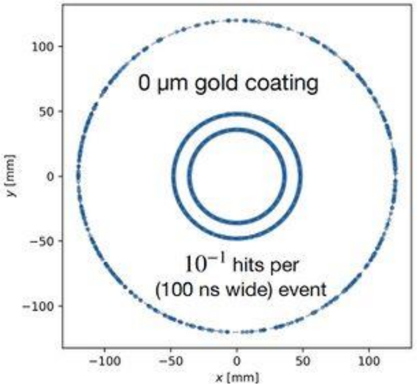
Beam energy [GeV]	5 x 41	5 x 100	10 x 100	10 x 275	18 x 275
L [10^{33}cm^{-2}s^{-1}]	0.44	3.68	4.48	10	1.54
DIS ep rate [kHz]	**12.5**	**129**	**184**	**500**	**83**

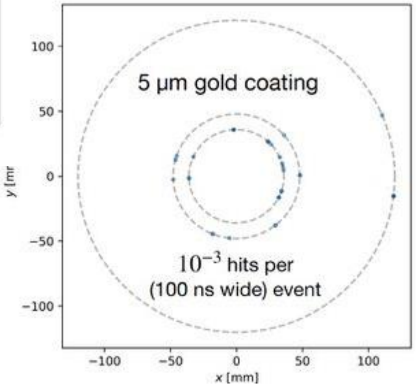
EIC Conceptual Design Report, Table 3.3

- 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



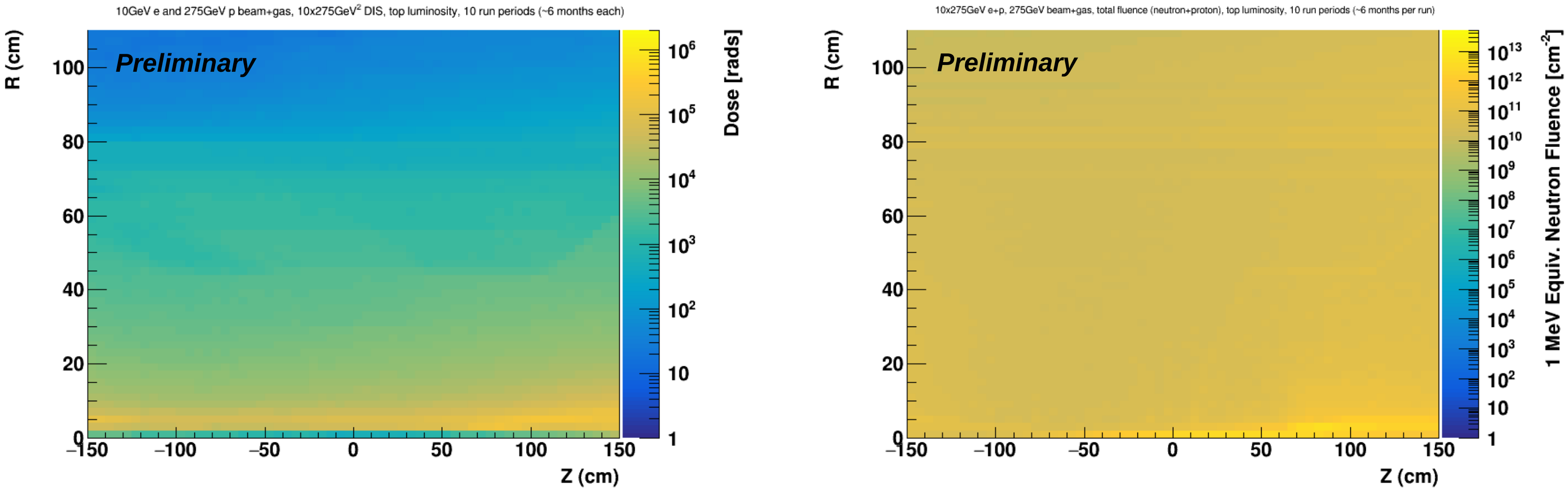


Operational environment

- ☐ 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 5x10^{13} n$_{eq}$/cm^{2}

Maps of fluence and dose over the silicon tracker envelop



10GeV e and 275GeV p beam+gas, 10x275GeV^{2} DIS, top luminosity, 10 run periods (~6 months each)

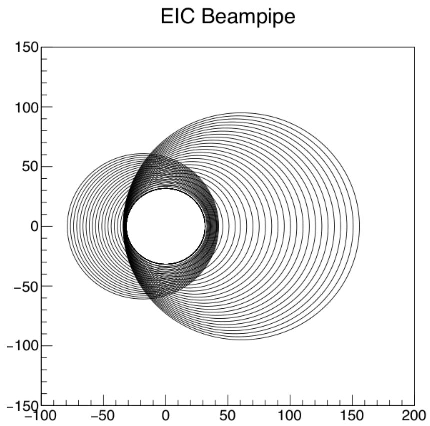
10x275GeV e+p, 275GeV beam+gas, total fluence (neutron+proton), top luminosity, 10 run periods (~6 months per run)

Integration constraints

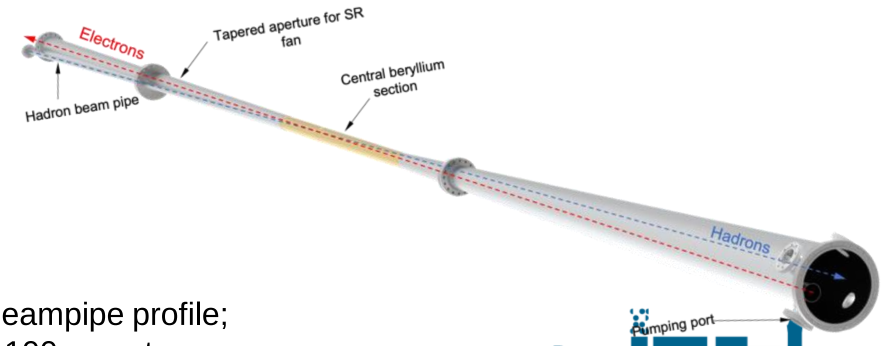
- Large beam pipe diameter, 31.8 mm radius; (more) challenging to reach required vertexing precision

- 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

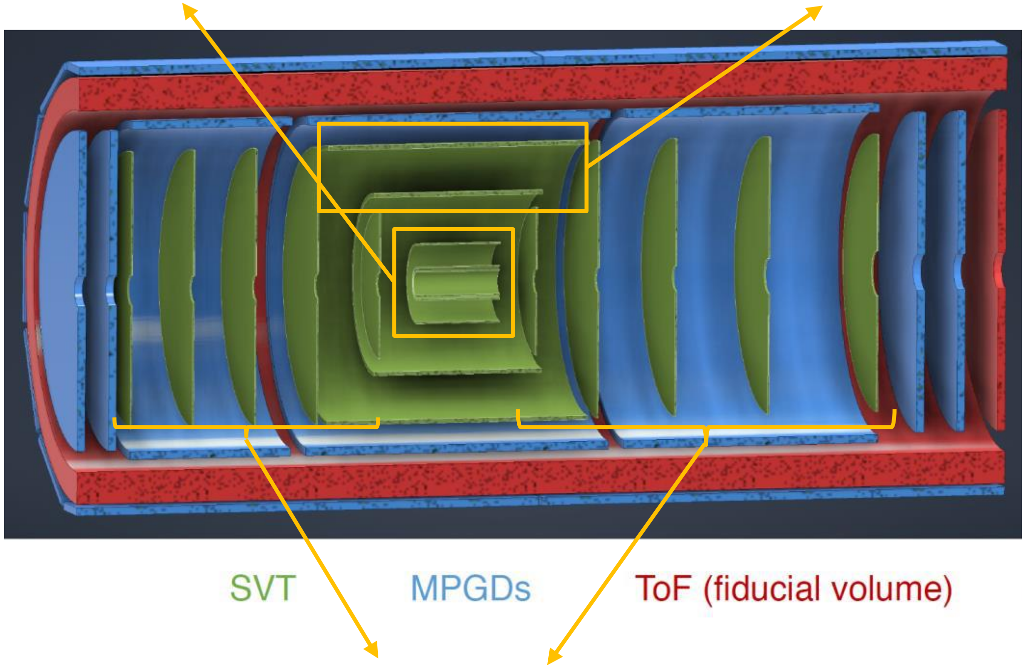


ePIC Silicon Vertex Tracker (SVT)

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

Inner Barrel (IB)

Outer Barrel (OB)



Electron/Hadron Endcaps (EE, HE)

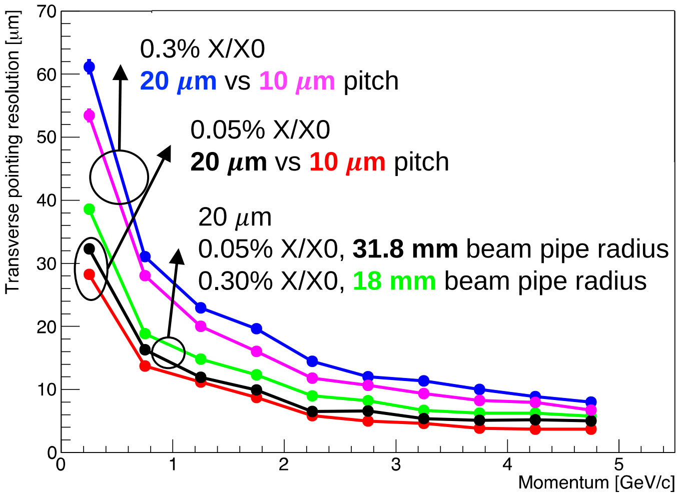
SVT Total (active) area **~ 8.5 m²**

ePIC SVT target specifications	
Spatial resolution	~ 5 um
Power	< 40 mW/cm²
Frame rate	≤ 2 μs
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

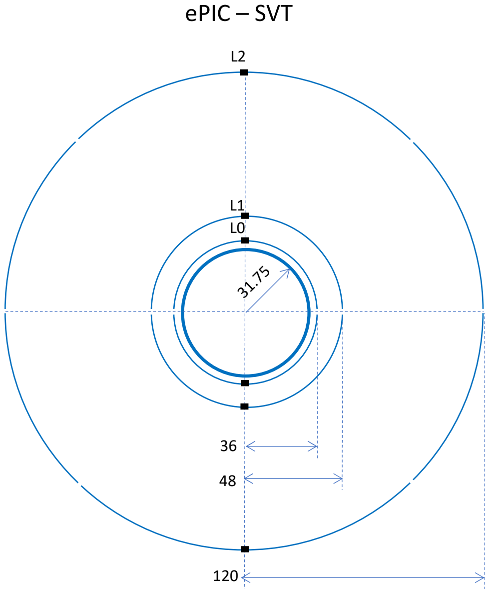
- ☐ Transverse pointing resolution is multiple scattering dominated

- ☐ 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



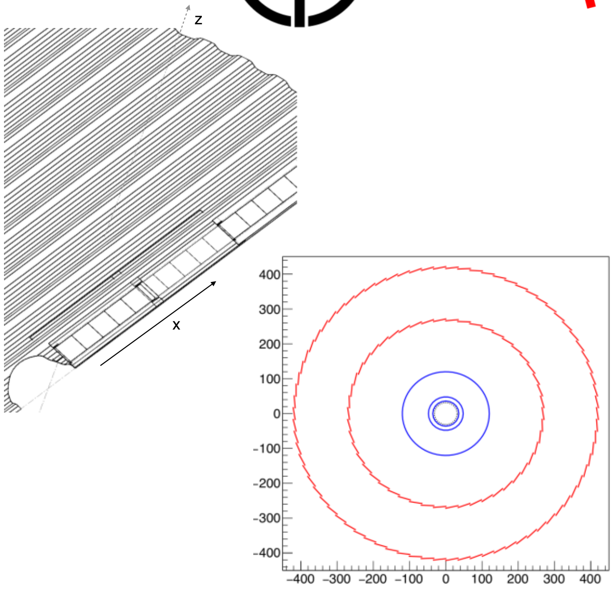
- ☐ Layers positioned to optimise transverse pointing resolution within operational constraints
  - L0, L1: large beam pipe diameter, beam pipe bake-out (5 mm clearance), sensor width
  - L2: r = 120 mm, dual purpose vertexing & sagitta layer, without increase in material

IB	r [mm]	l [mm]	X/X0 %
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

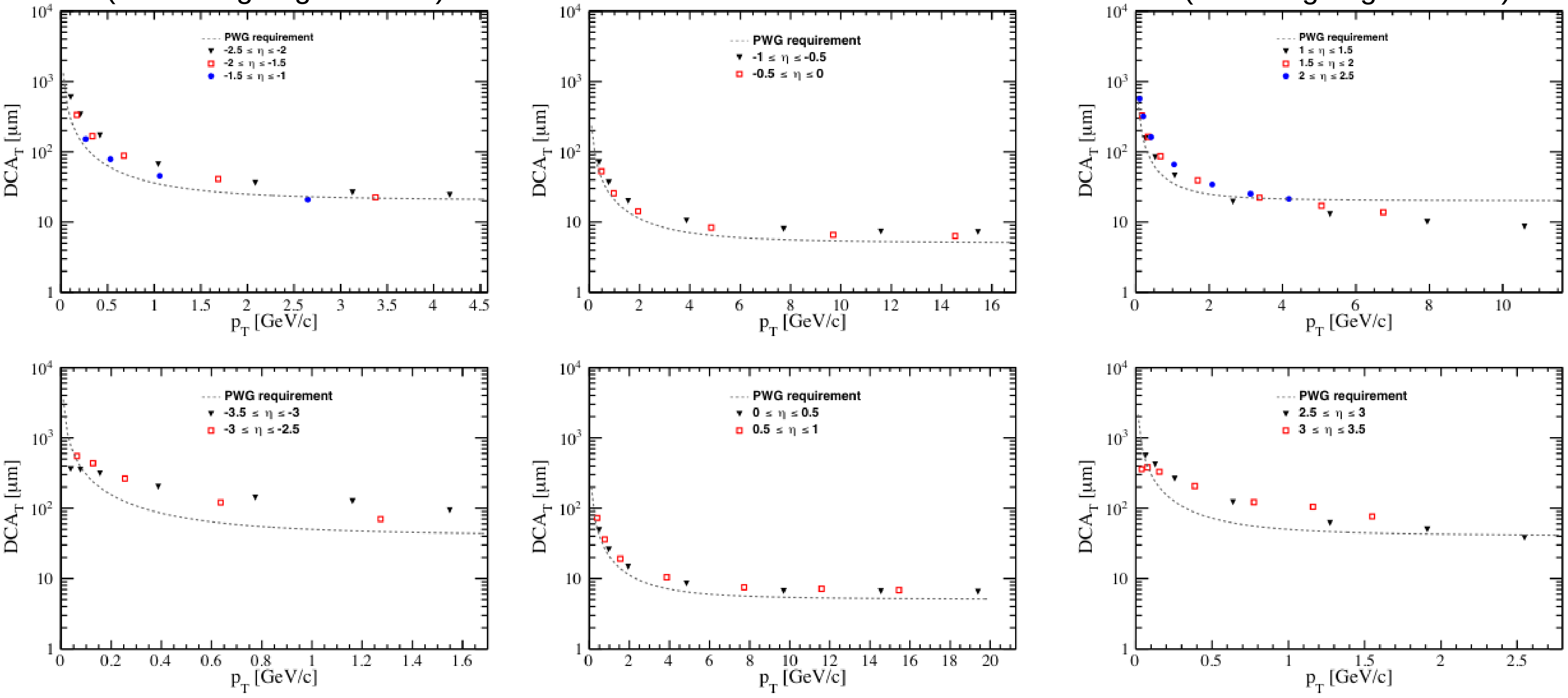


BARREL	r [mm]	l [mm]	X/X0 %
Layer 3	270	540	0.25
Layer 4	420	840	0.55

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

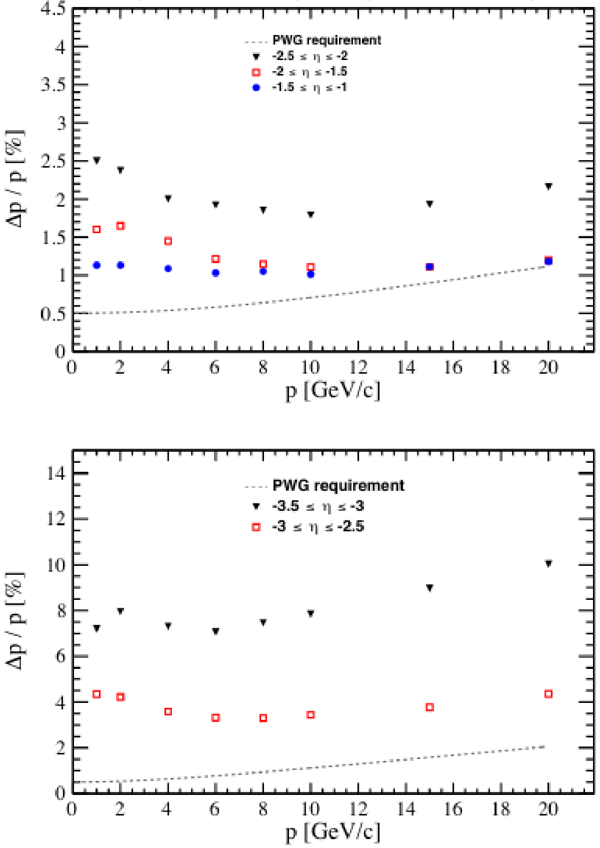
Forward region
(Hadron going direction)

(Single particle, truth seeding)

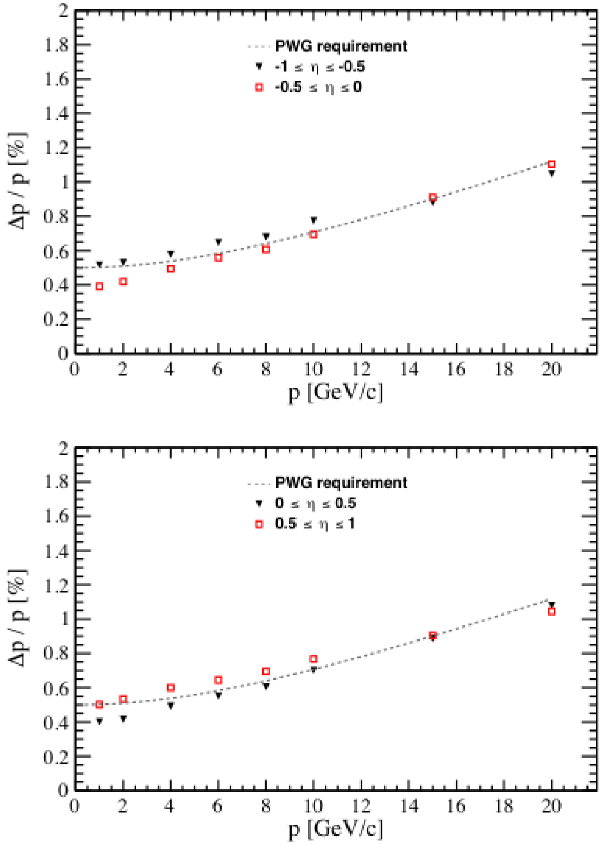
Tracking performance

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

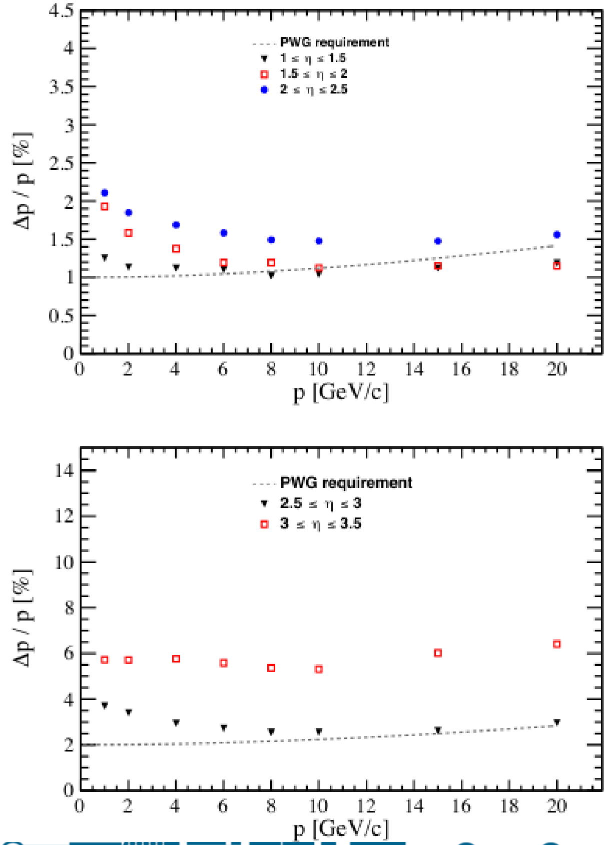
Backward region
(Electron going direction)



Central region



Forward region
(Hadron going direction)

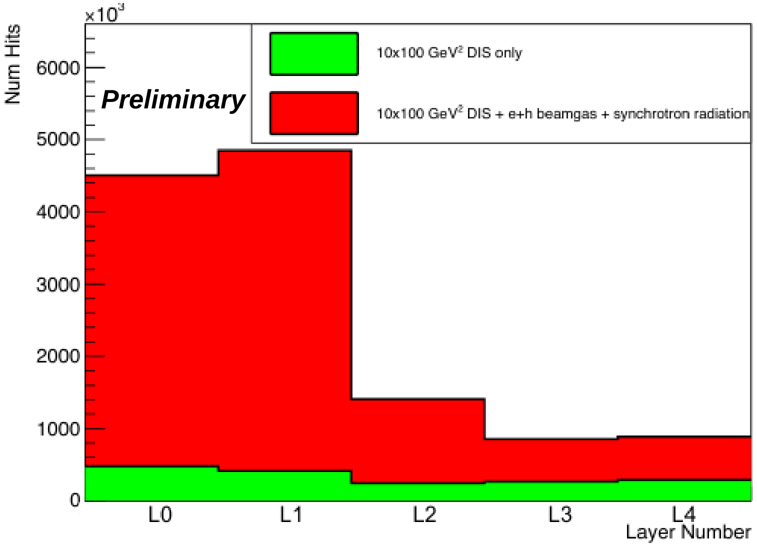


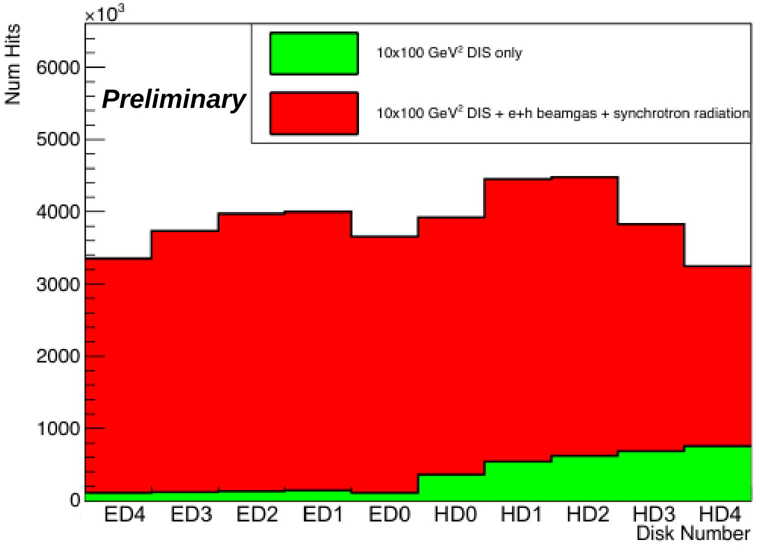
(Single particle, truth seeding)

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 ~ 10^{-9} per pixel per frame

IB, OB	Hits/pix/frame	EE	Hits/pix/frame	HE	Hits/pix/frame
L0	7.00E-10	ED0	1.96E-11	HD0	2.11E-10
L1	5.65E-10	ED1	7.07E-11	HD1	7.87E-11
L2	6.56E-11	ED2	6.81E-11	HD2	7.68E-11
L3	8.85E-12	ED3	6.40E-11	HD3	6.59E-11
L4	3.80E-12	ED4	5.76E-11	HD4	5.62E-11

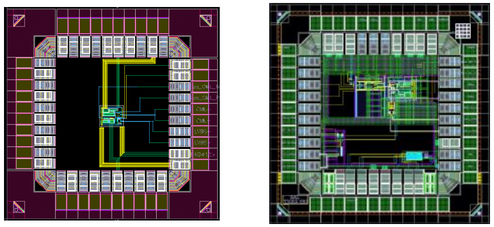




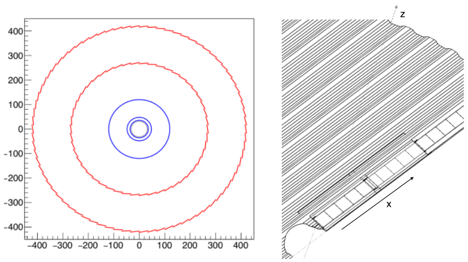
Overview of ongoing R&D activities

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

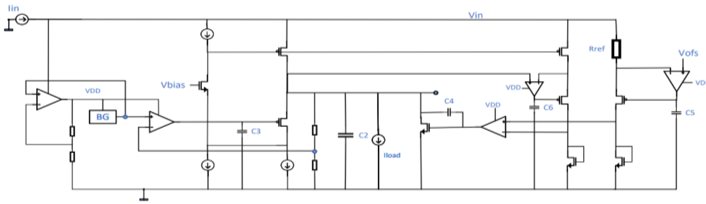
Sensor development
(in collaboration with ITS3)



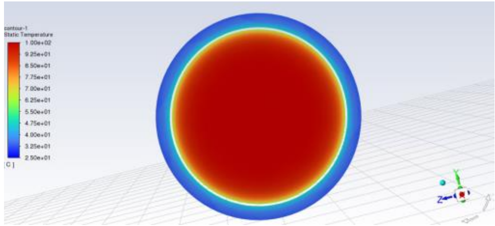
Conceptual design of
OB and endcaps



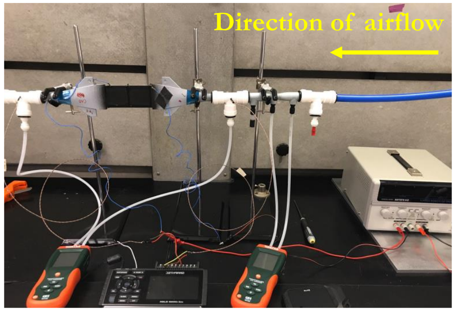
Serial powering



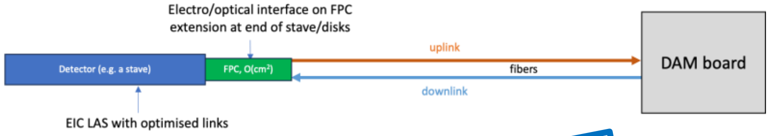
Beam pipe
bake-out studies



Air cooling through
support structure



Data transmission
on optical fibers



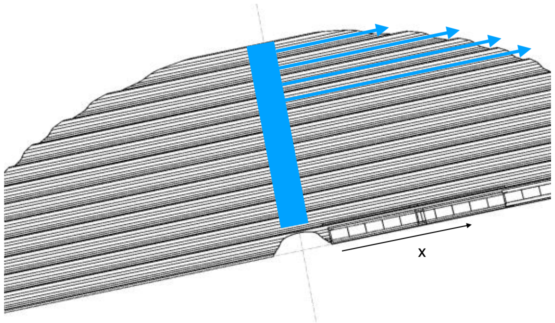
Selected developments
shown in the next slides

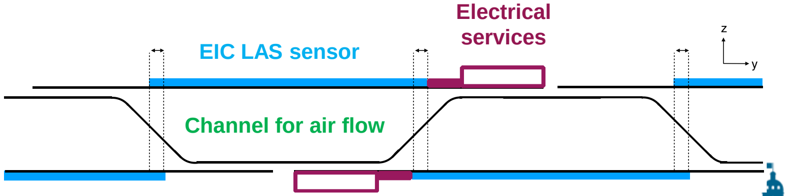
Integrated mechanics and cooling

- ☐ 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





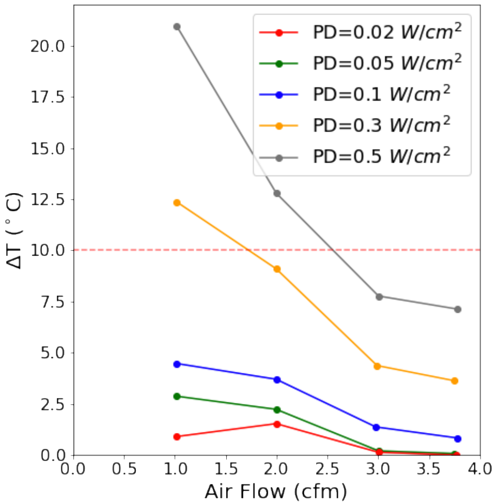

Mould for corrugated structure fabrication

Integrated mechanics and cooling

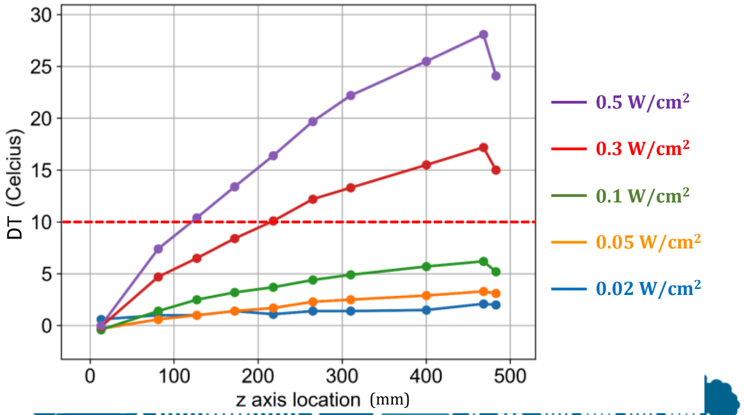
- Initial testing of air cooling through carbon foam
  - Small stave structures with different foam type and thickness
  - Heat loads to simulate various power densities
  - Room temperature air flow
  - Goal: ΔT < 10C
  - CVD foam meets requirement up to 0.5 W/cm^2
  - RVC foam achieves ΔT < 10C for 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



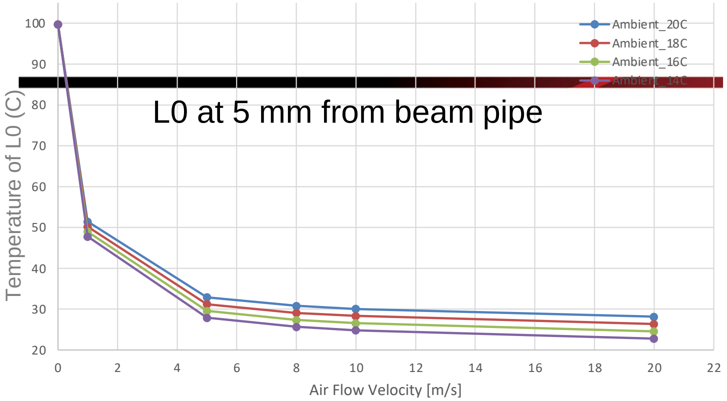
ΔT across 50 cm long, 6 mm thick RVC stave for 3.4 cfm



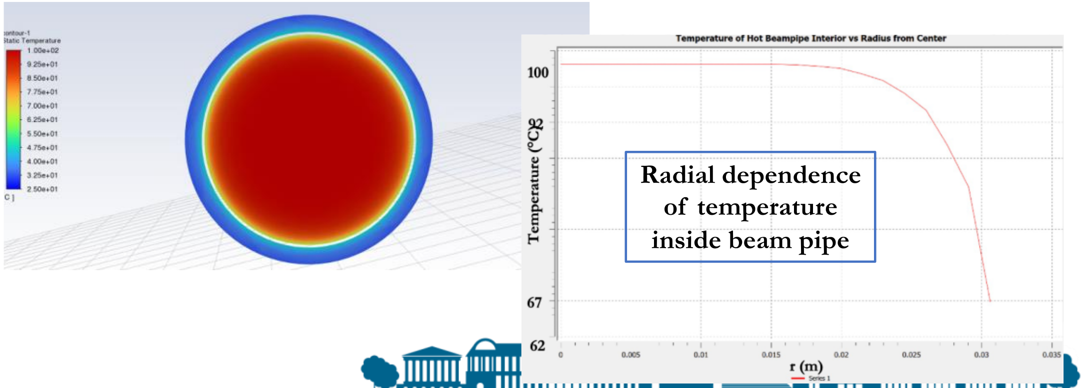
IB air cooling and beam pipe bake-out

- Beam pipe bakeout performed with IB installed
  - Hot gas pumped into beam pipe at T ≥ 100C
  - 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 < 20C and 5 mm/s velocity
- However, significant beam pipe inner surface cooling from air flow to cool IB (100C → 67C for air flow T = 25C)
  - Next steps: investigate minimum hot gas temperature to keep inner surface of beam pipe at 100C and study effect on L0 temperature



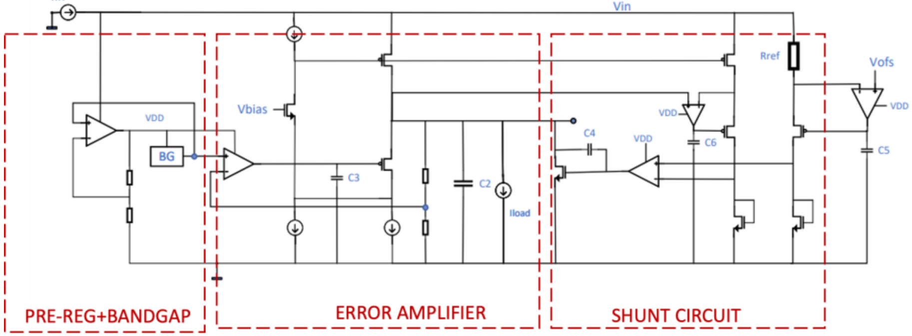
L0 at 5 mm from beam pipe



Radial dependence of temperature inside beam pipe

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



Shunt-LDO schematic drawing

- Readout architecture
  - Low radiation levels + lpGBT 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.

ePIC Silicon Vertex Tracker Detector Subsystem Collaboration

ePIC

UNIVERSITY OF BIRMINGHAM

INFN

BERKELEY LAB

UKRI Science and Technology Facilities Council

Brookhaven National Laboratory

Berkeley UNIVERSITY OF CALIFORNIA

Jefferson Lab

Los Alamos NATIONAL LABORATORY

OAK RIDGE National Laboratory

UNIVERSITY OF LIVERPOOL

UNIVERSITY OF OXFORD

MIT

PURDUE UNIVERSITY

CTU CZECH TECHNICAL UNIVERSITY IN PRAGUE

Brunel University London

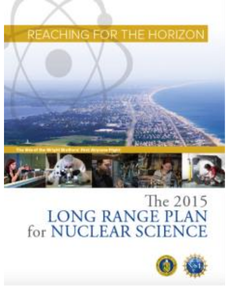
Lancaster University

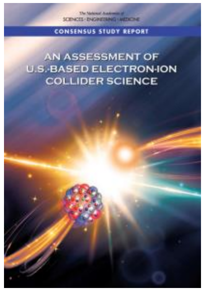
Detector Subsystem Leader: Ernst Sichterman (LBNL)

Detector Subsystem Technical Coordinator: Laura Gonella (Uni Birmingham)

Backup

EIC Project Timeline





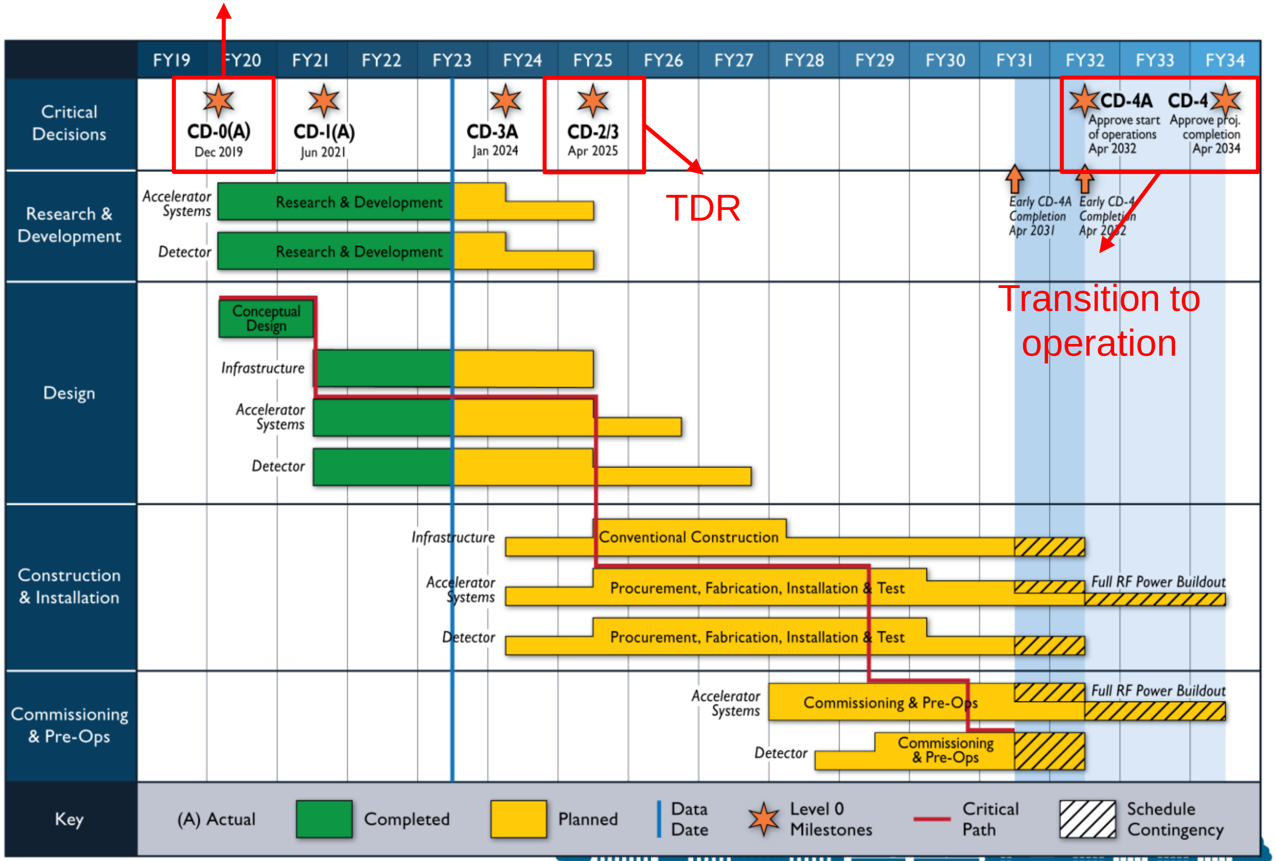
Early endorsement

2015 Long Range Plan for Nuclear Science

2018 National Academy of Science Assessment

DOE Project Milestones

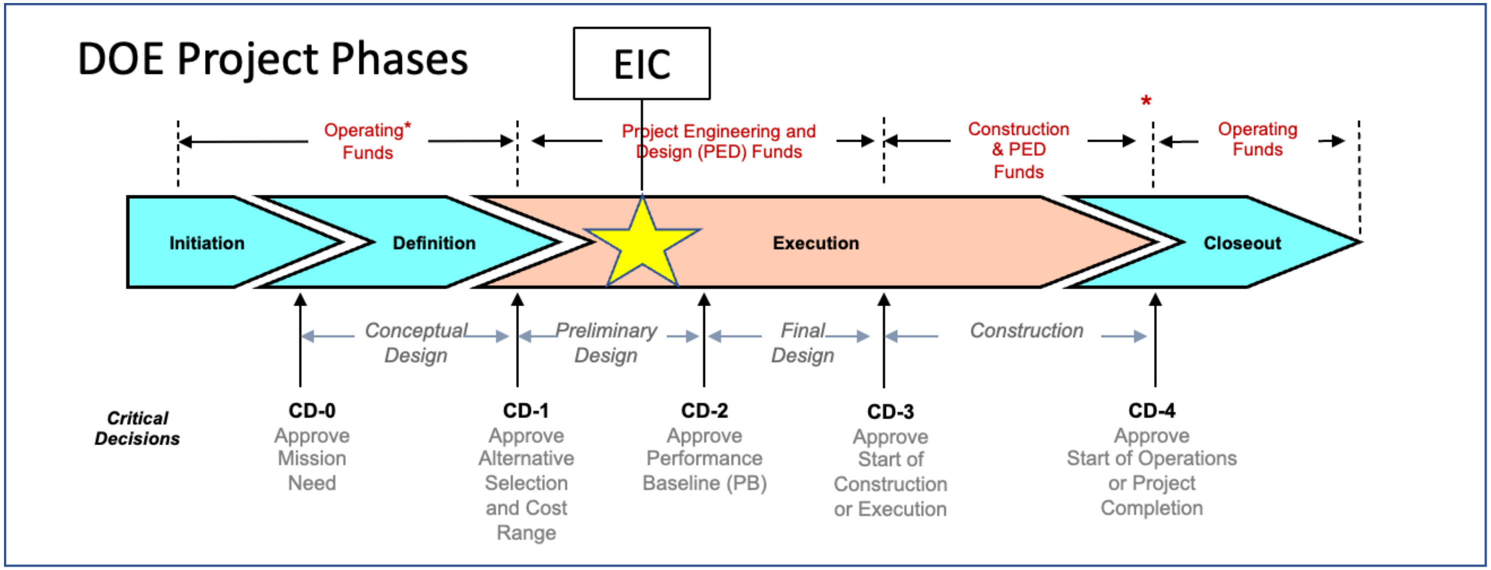
Project approved



TDR

Transition to operation

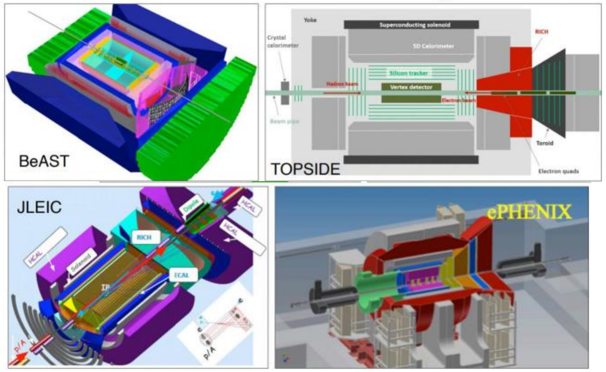
DOE Project Phases

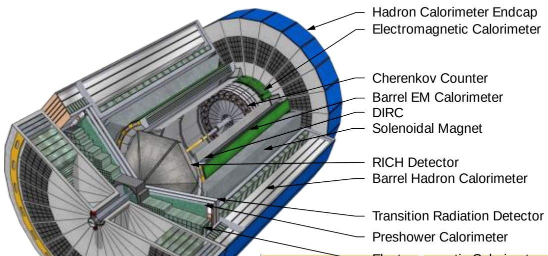


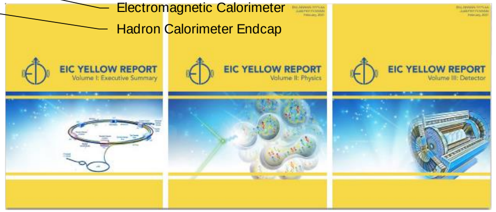
CD-0, Mission Need Approved	December 2019
DOE Site Selection Announced	January 2020
CD-1, Alternative Selection and Cost Range, Approved	June 2021
CD-3A, Long Lead Procurement	**January 2024**
CD-2/3, Performance Baseline/Construction Start	**April 2025**
RHIC Shut Down	**June 2025**

Evolution of EIC Detector Concept

White paper (2012, 2014), initial concepts

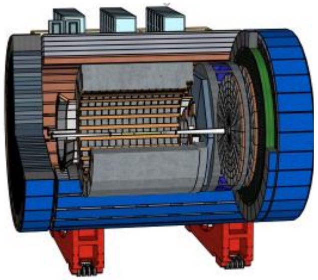






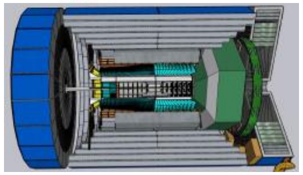
Yellow Report reference detector (2020), global effort of the EIC Users Group

Call for Detector proposals (2021)



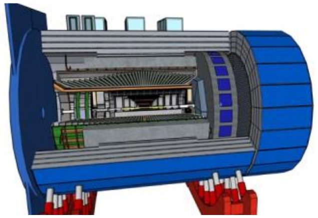
ATHENA: A Totally Hermetic Electron-Nucleus Apparatus

- 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



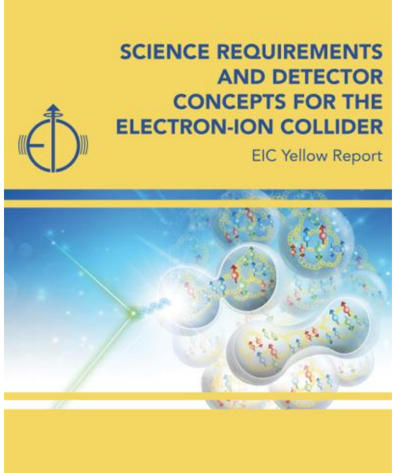
ECCE: EIC Comprehensive Chromodynamics Experiment

- General purpose detector, 1.5T BaBar magnet

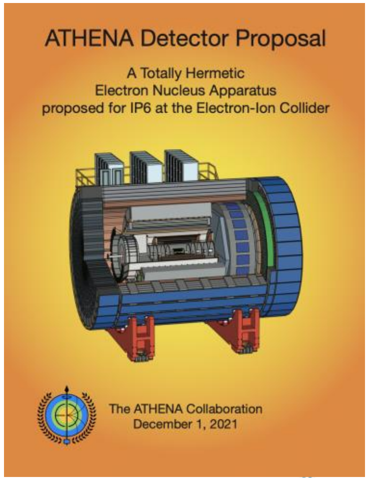
2022: Merging of ECCE and ATHENA proposal strengths forming a new collaboration to deliver the EIC Project Detector → ePIC collaboration formally established

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



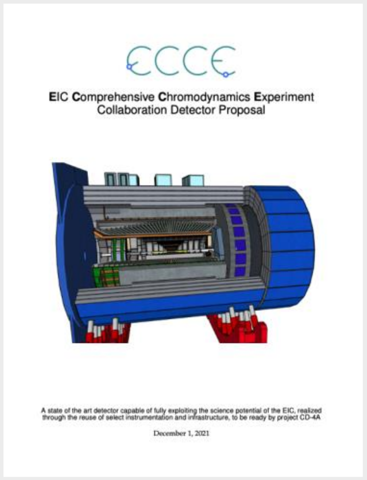
SCIENCE REQUIREMENTS
AND DETECTOR
CONCEPTS FOR THE
ELECTRON-ION COLLIDER
EIC Yellow Report



ATHENA Detector Proposal

A Totally Hermetic
Electron Nucleus Apparatus
proposed for IP6 at the Electron-Ion Collider

The ATHENA Collaboration
December 1, 2021



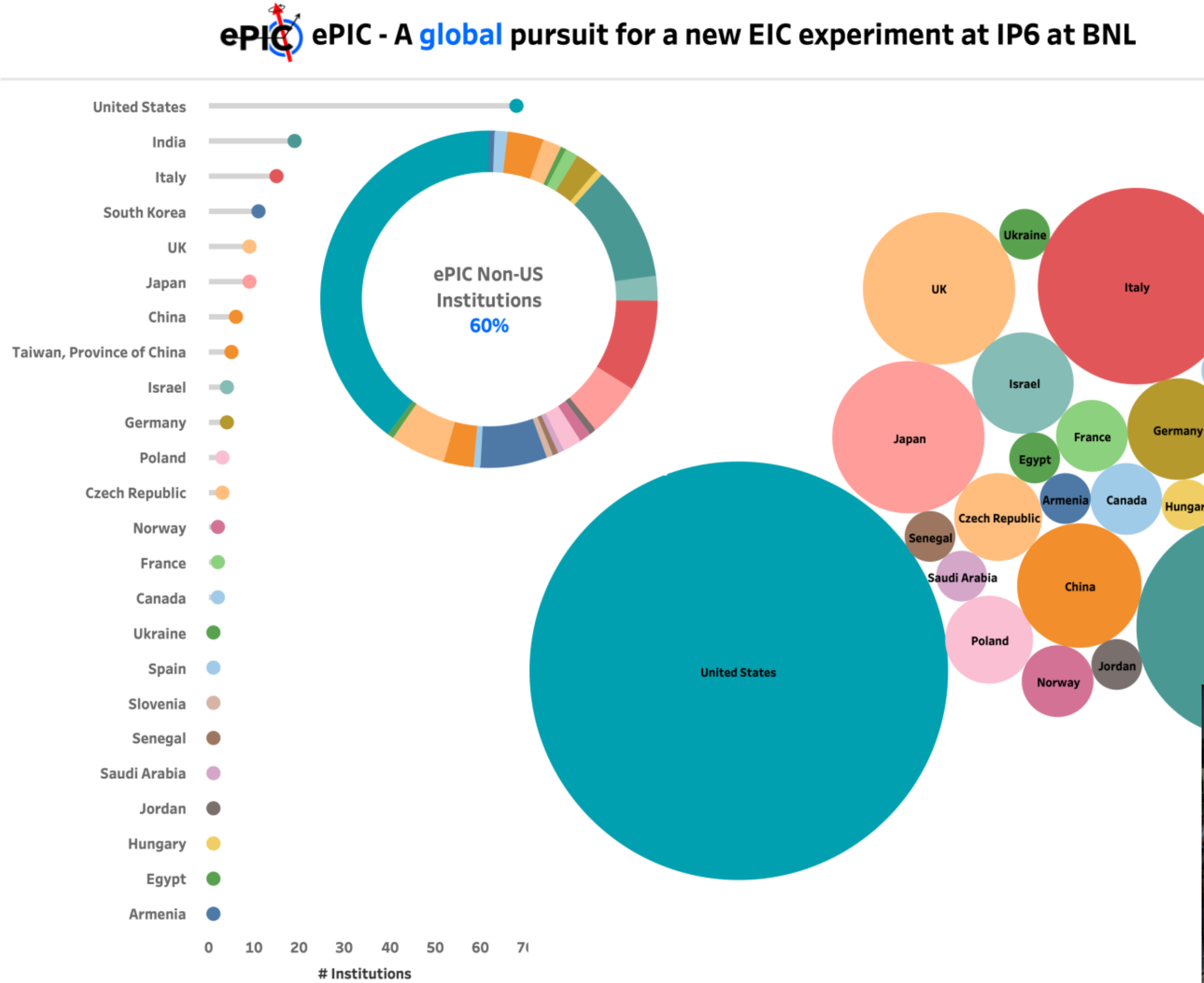
ECCE

EIC Comprehensive Chromodynamics Experiment
Collaboration Detector Proposal

A state of the art detector capable of fully exploiting the science potential of the EIC, realized through the reuse of select instrumentation and infrastructure, to be ready by project CD-4A

December 1, 2021

ePIC Collaboration



171 Institutions
24 countries
500+ participants

ePIC Detector

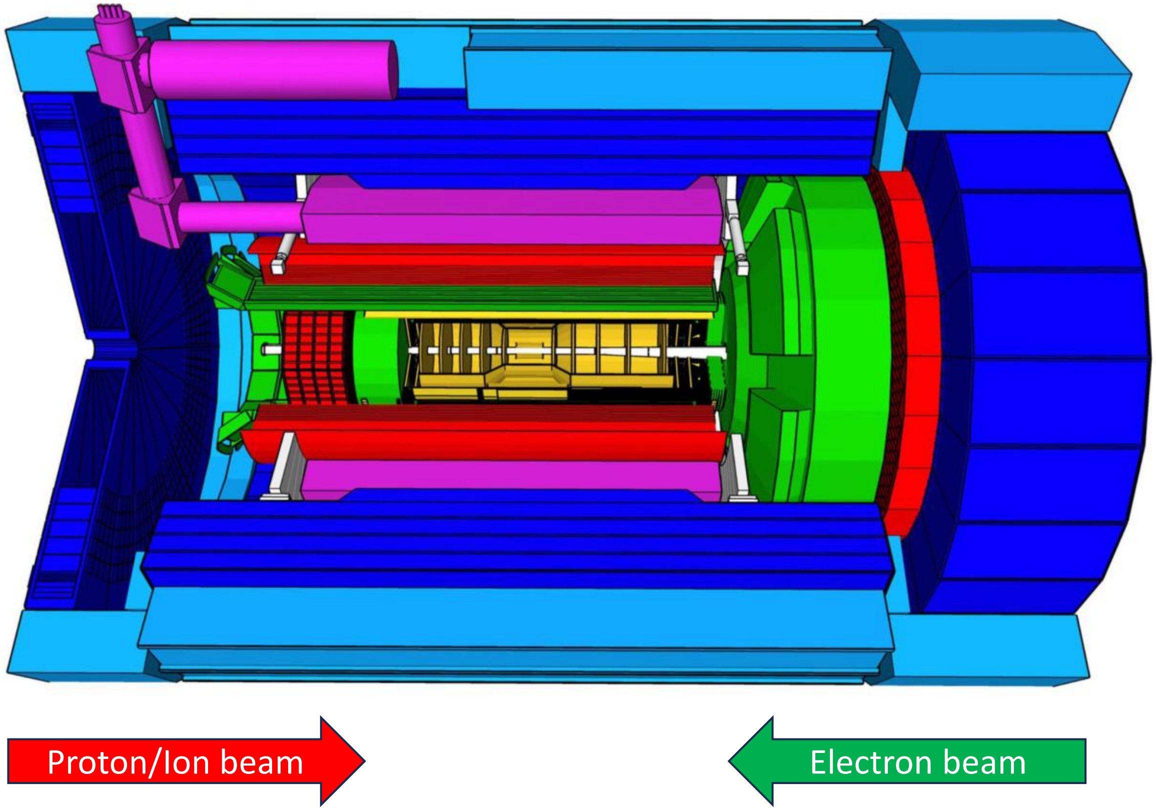
Magnet
- New 1.7 T SC solenoid, 2.8 m bore diameter

Tracking
- Si Vertex Tracker MAPS wafer-level stitched sensors (ALICE ITS3)
- Si Tracker MAPS barrel and disks
- Gaseous tracker: MPGDs (µRWELL, 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)

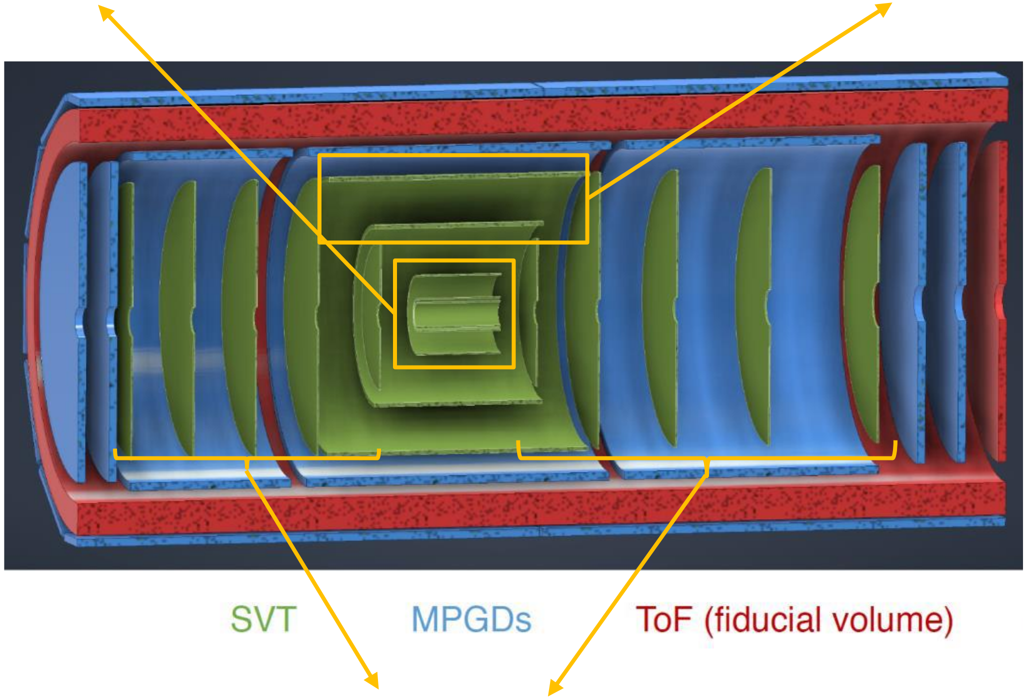
Hadron calorimetry
- FeSc (barrel, re-used from sPHENIX)
- Steel/Scint – W/Scint (backward/forward)



ePIC Silicon Vertex Tracker (SVT)

Inner Barrel (IB)
- 2 curved silicon vertex layers
- 1 curved dual-purpose layer

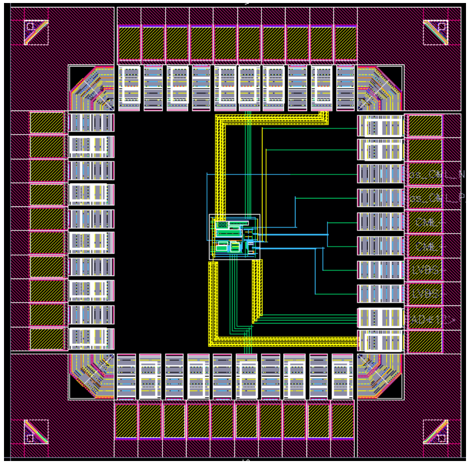
Outer Barrel (OB)
- 1 stave-based sagitta layer
- 1 stave-based outer layer

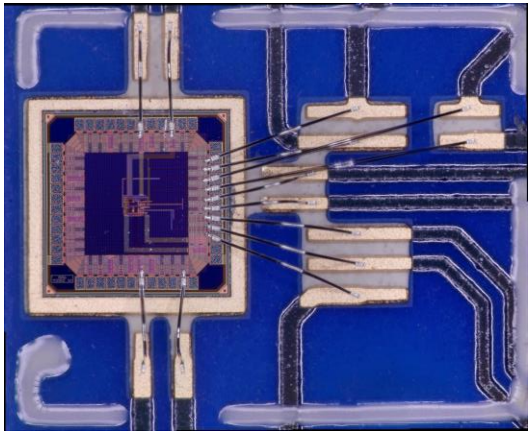


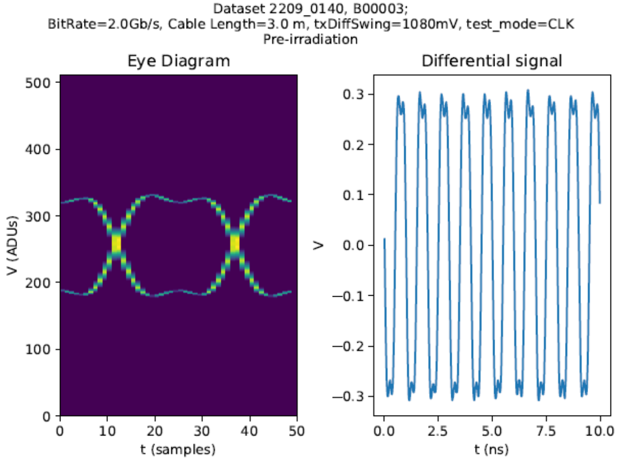
Electron/Hadron Endcaps (EE, HE)
- 5 disks on either side of the IP

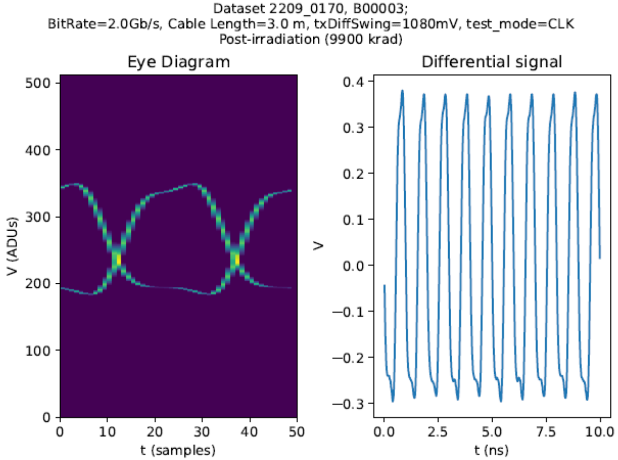
MLR1 design

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



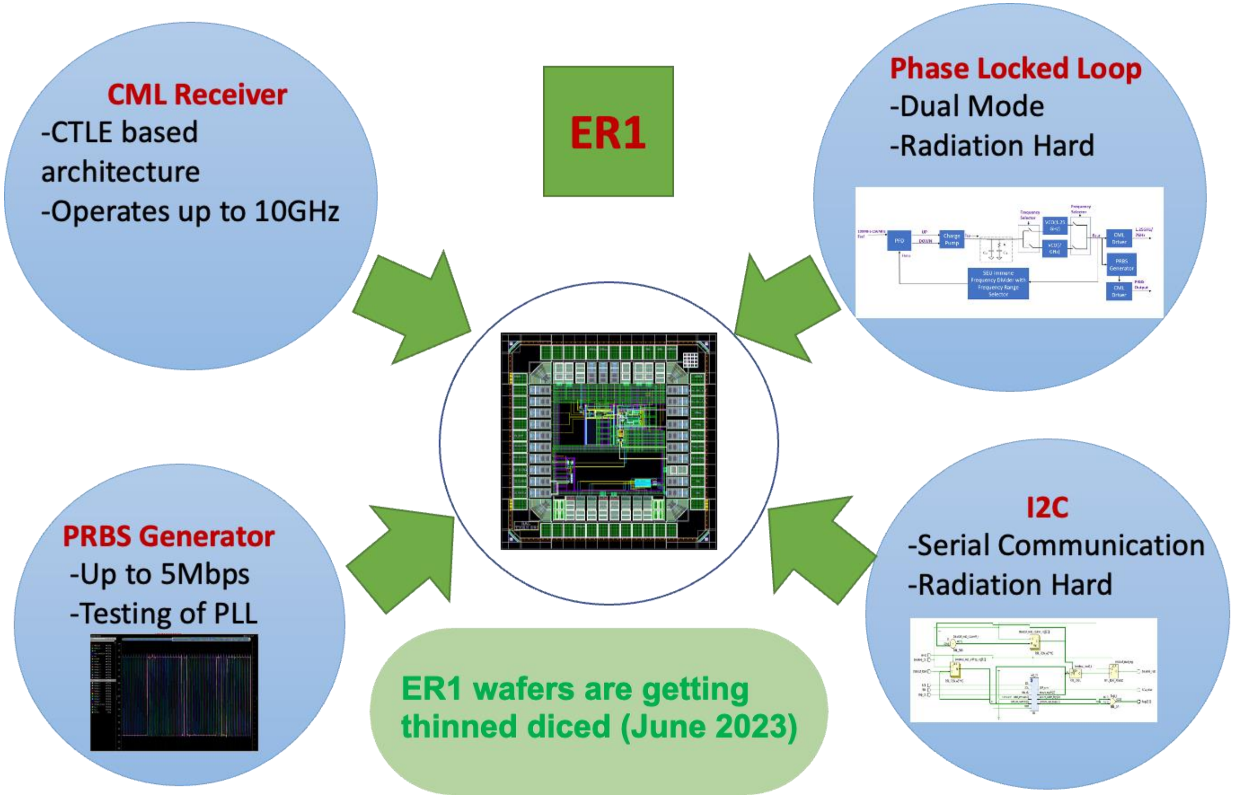






ER1 designs

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



ER1

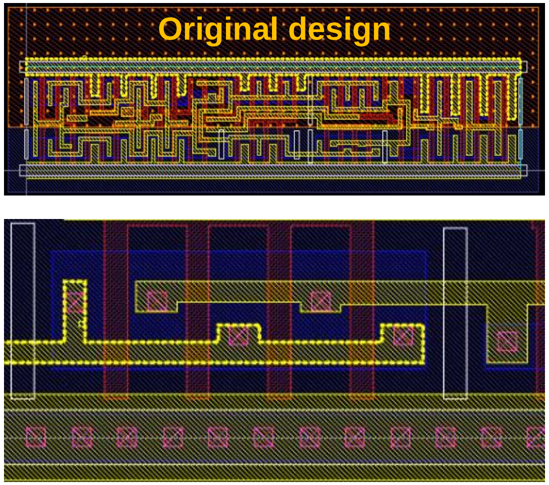
CML Receiver
-CTLE based architecture
-Operates up to 10GHz

Phase Locked Loop
-Dual Mode
-Radiation Hard

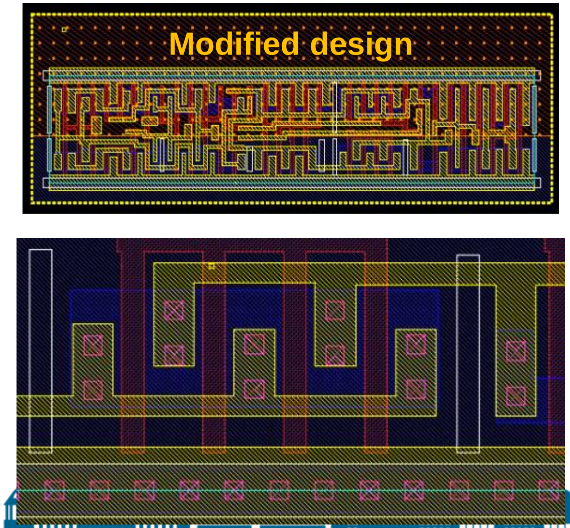
PRBS Generator
-Up to 5Mbps
-Testing of PLL

I2C
-Serial Communication
-Radiation Hard

ER1 wafers are getting thinned diced (June 2023)



Original design

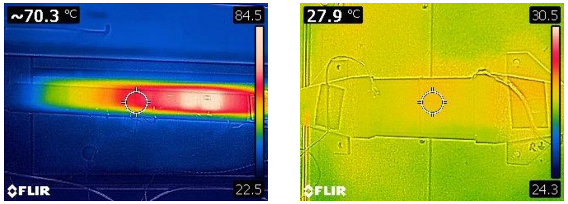


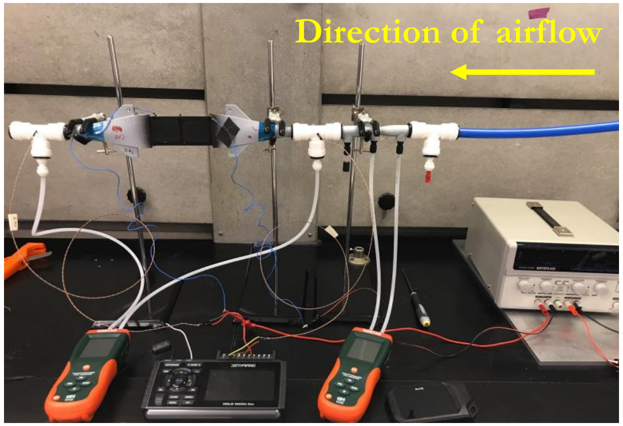
Modified design

Air cooling through carbon foam

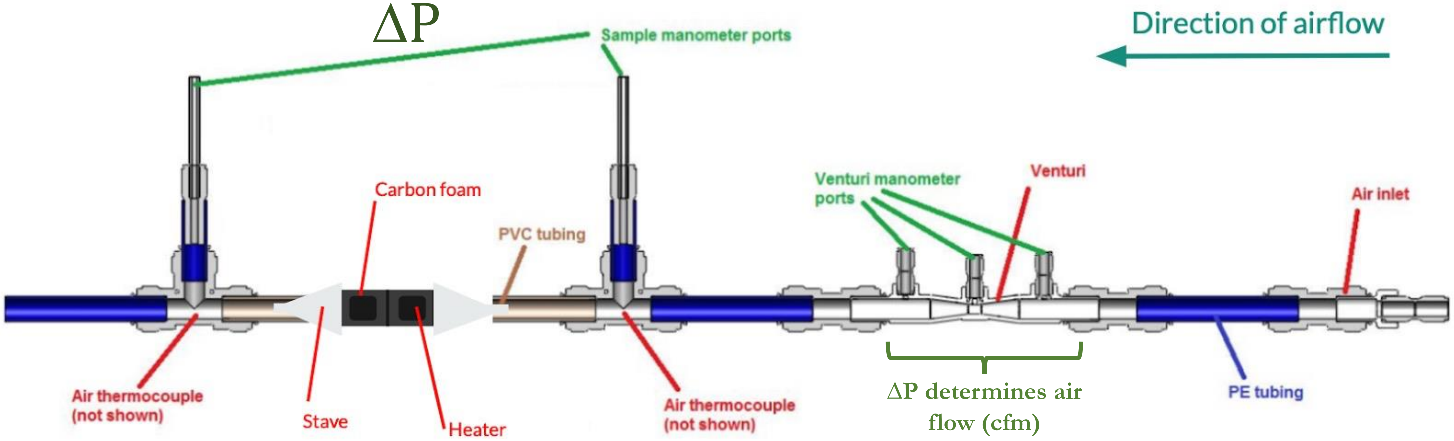
Setup

ΔT: “bright” temp – “dark” temp





ΔP

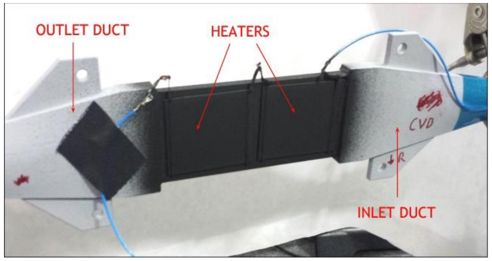


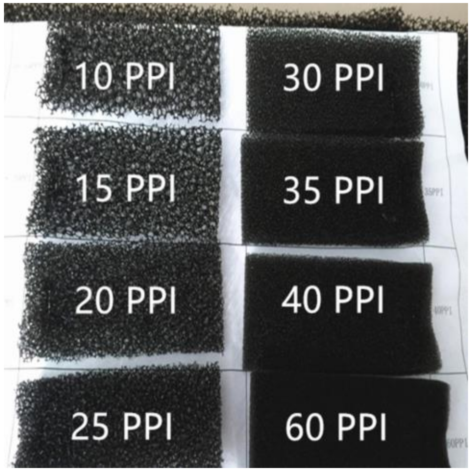
ΔP determines air flow (cfm)

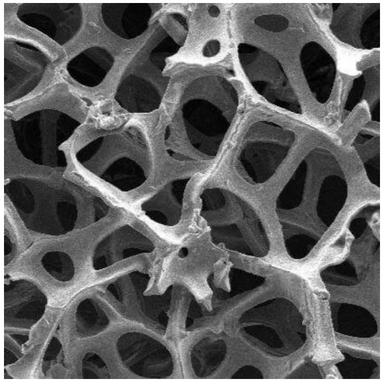
Air cooling through carbon foam

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



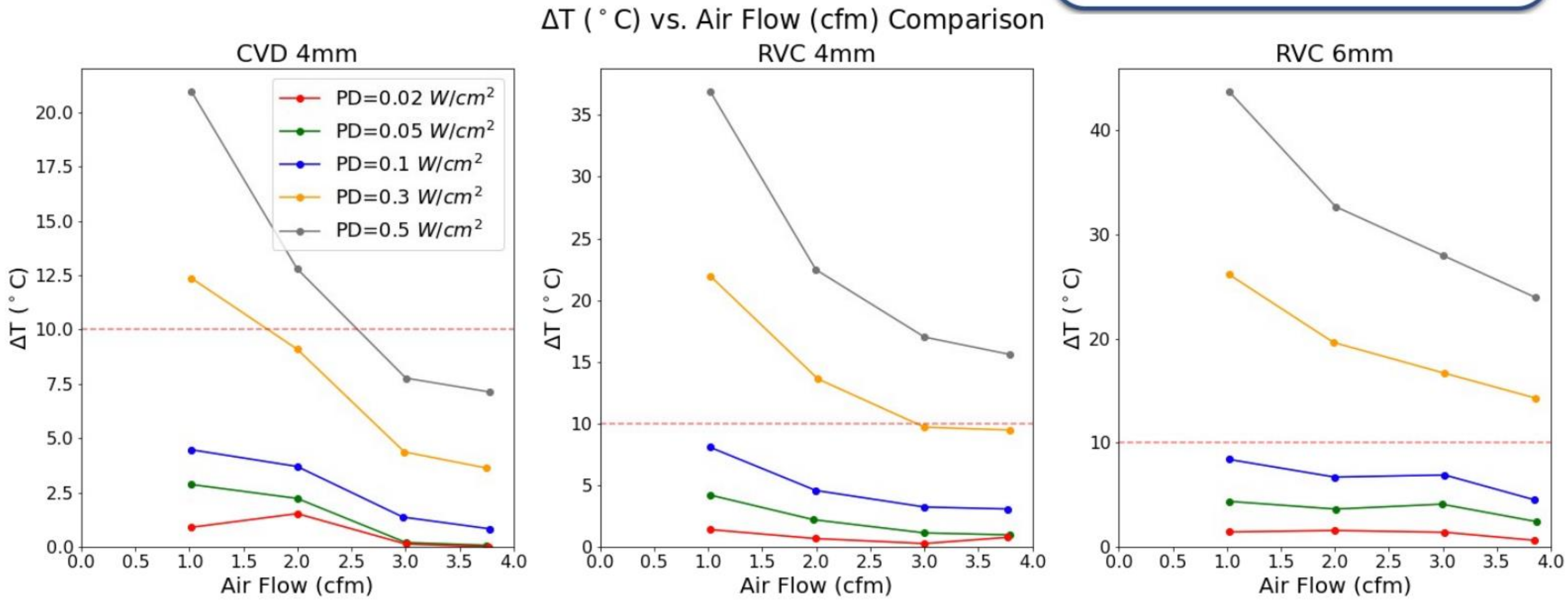




Air cooling through carbon foam

ΔT for different power densities

CVD achieves ΔT for all power densities



Pixel matrix < 0.02 W/cm², periphery > 0.5 W/cm²

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