ATHENA Proposal
Risk, R&D Needs, and Upgrade Path

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on behalf of the ATHENA collaboration

ATHENA

EIC Detector Proposal Advisory Panel Meeting, December 13–15, 2021

ATHENA's Subsystems in Past R&D

- Many ATHENA subsystems were developed and improved in the **Generic EIC Detector R&D Program**
- Program was supported through funds provided to BNL by the DOE Office of Nuclear Physics and was running for 10 years (2011 - 2021)
- FY21: 281 participants from 75 institutions (37 non-US)
- Many PIs and participants of this program now active in ATHENA detector working groups
- R&D program made good progress on many components vital for ATHENA
- The status of R&D on the various subsystems was taken into account in the design of the ATHENA detector

ATHENA subsystems that were part of this effort:

Project	Topic
eRD1	WSciFi and SciGlass electromagnetic calorimetry
eRD3	MMG, GEM, and μRWell MPGD technologies
eRD6	Lightweight GEM tracker miniTPC* for PID in barrel through dE/dx MMG, GEM, and μRWell MPGD
eRD12	Auxiliary detectors: low-Q^2 tagger, far forward tracker (Roman Pots), luminosity measurement
eRD14	DIRC, dRICH, Photosensors, LAPPDs
eRD16	Forward and backward MAPS tracker disks

Tracking | PID | Calorimetry | Simulations | DAQ/Electronics

Project	Topic
eRD18	Barrel: main and vertex MAPS tracker
eRD22	TRD in forward region for enhanced e/h
eRD23	Streaming DAQ
eRD24	AC-LGAD sensors for Roman Pots and B0
eRD25	Merger of eRD16 and eRD18 covering main ATHENA Si tracker
eRD27	High Resolution ZDC
eRD29	AC-LGAD barrel ToF for enhanced PID

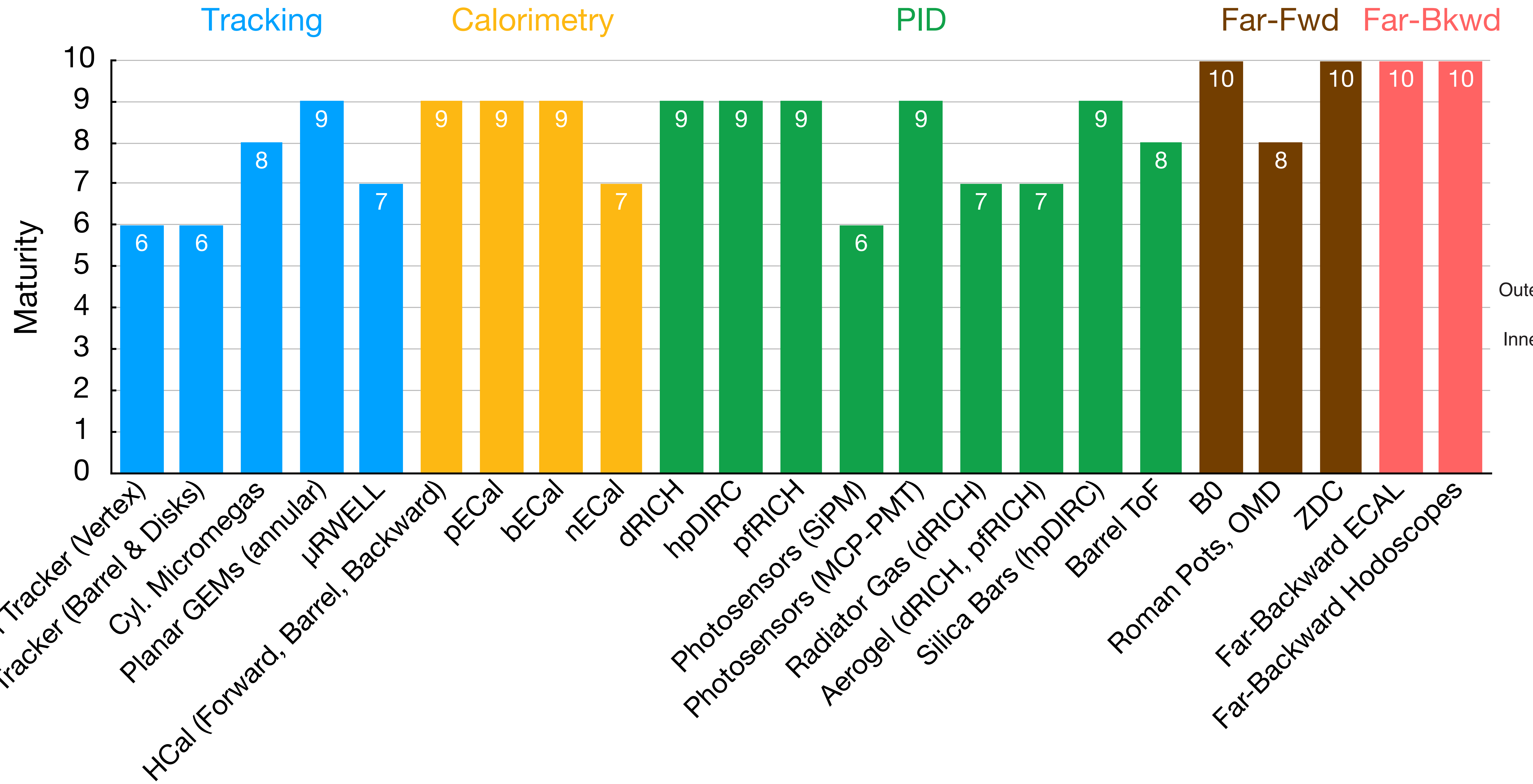
ATHENA’s Subsystems in Present R&D

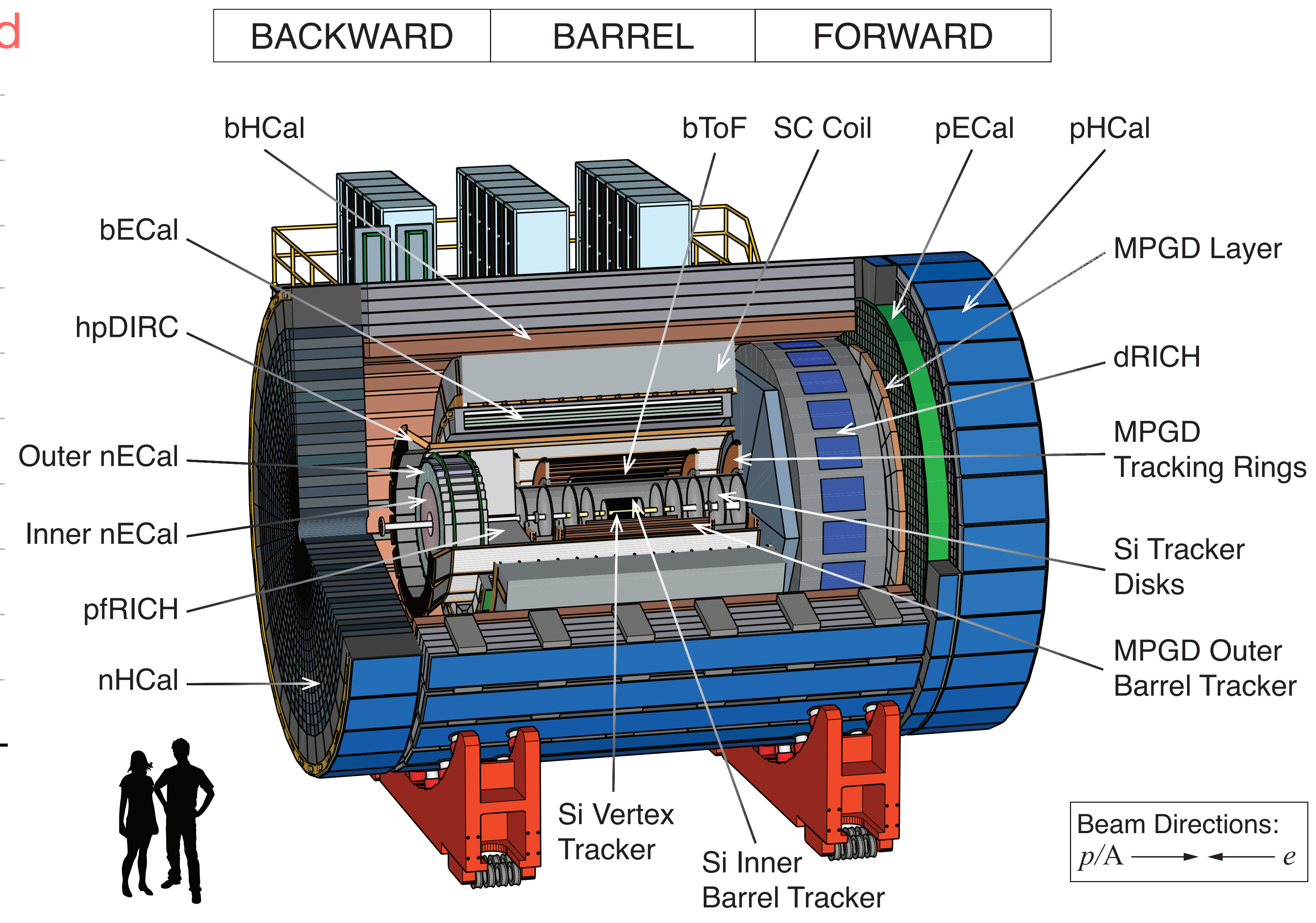
ATHENA

- **Project R&D** aims at achieving the maturity required to carry out final design and construction
- While this program is *not specific to any proto-collaboration at this time* many detector components of the ATHENA baseline design are covered in this R&D program (FY22):
  - eRD102: Dual radiator RICH (dRICH)
  - eRD103: High performance DIRC (hpDIRC)
  - eRD104: Service reduction (power and data)
  - eRD105: SciGlass
  - eRD106: Forward EMCAL
  - eRD107: Forward HCAL
  - eRD108: Cylindrical Micromegas layers and planar MPGDs (GEM and μRWell)
  - eRD110: Photosensors for RICH detectors and calorimeters
  - eRD111: Si-Tracker
  - eRD112: AC-LGAD (incl. ASIC)

Tracking | PID | Calorimetry | Sensors

Maturity Level of ATHENA Subsystems



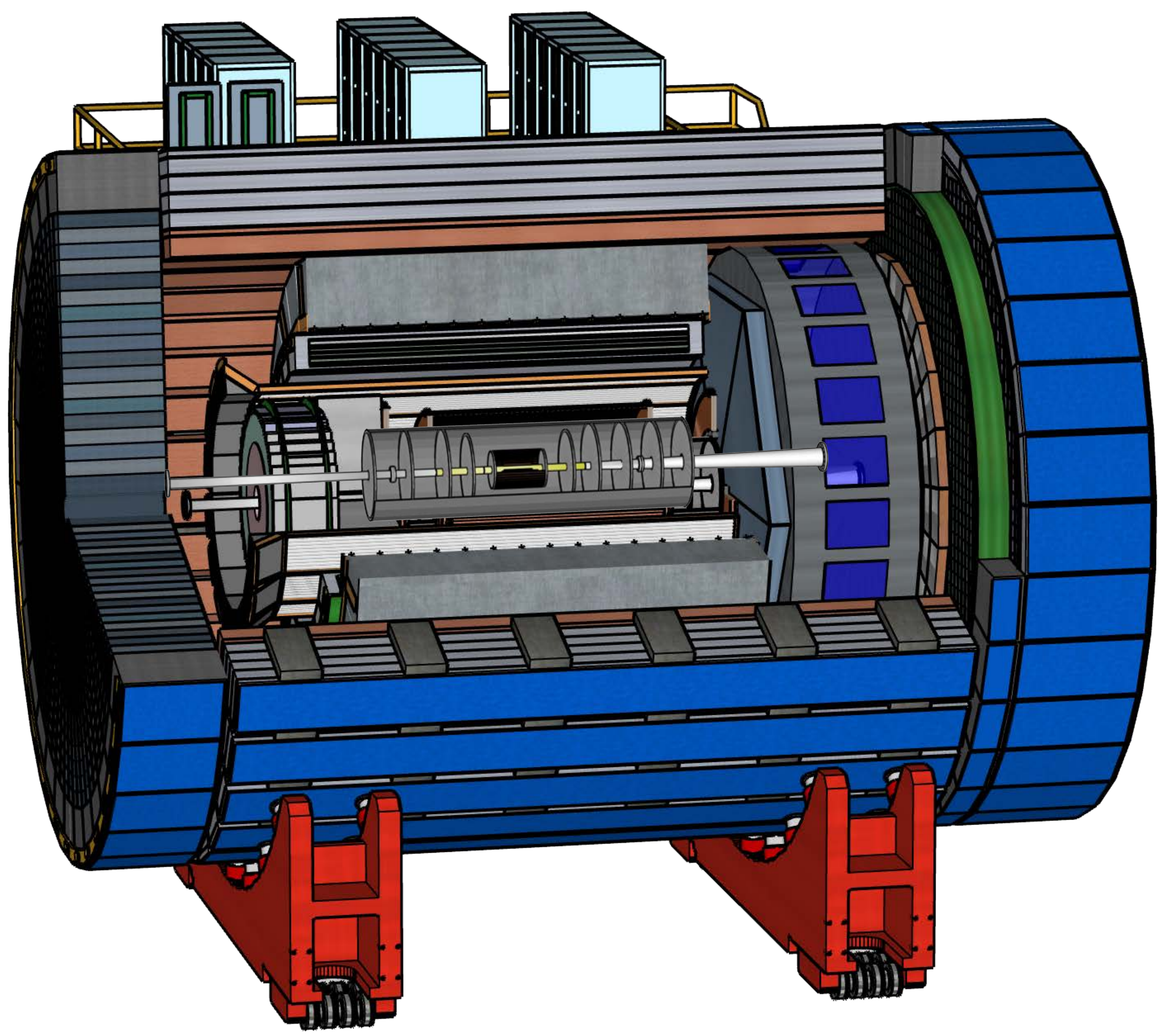


- ATHENA conducted careful evaluation of risks associated with the selected technologies
- We ranked technological maturity on a scale of 0-10, where 10 = fully developed technology
- Mitigation strategies are in place minimizing the overall risk to the detector

ATHENA R&D Needs

- During generic R&D program several subsystems matured to levels where little basic R&D remains
  - ➢ Focus is shifting to the construction and testing of full chain prototypes (detector, electronics, supplies, and DAQ) in test beams
  - ➢ These developments will be supported by EIC project funded R&D
  - ➢ Project funds will also support R&D of components that have not reached their full potential yet and need further optimization.
- Only limited number of technologies still need appreciable R&D and have been selected because of the exceptional performance benefits they would bring

Example 1: MAPS for Si-Trackers



Parameter	ALPIDE (existing)	Wafer-scale sensor (this proposal)
Technology node	180 nm	65 nm
Silicon thickness	50 μm	20-40 μm
Pixel size	27 x 29 μm	O(10 x 10 μm)
Chip dimensions	1.5 x 3.0 cm	scalable up to 28 x 10 cm
Front-end pulse duration	~ 5 μs	~ 200 ns
Time resolution	~ 1 μs	< 100 ns (option: <10ns)
Max particle fluence	100 MHz/cm^2	100 MHz/cm^2
Max particle readout rate	10 MHz/cm^2	100 MHz/cm^2
Power Consumption	40 mW/cm^2	< 20 mW/cm^2 (pixel matrix)
Detection efficiency	> 99%	> 99%
Fake hit rate	< 10^{-7} event/pixel	< 10^{-7} event/pixel
NIEL radiation tolerance	~3 x 10^{13} 1 MeV n_{eq}/cm^2	10^{14} 1 MeV n_{eq}/cm^2
TID radiation tolerance	3 MRad	10 MRad

- Vertex layers made of large-area, wafer-scale, stitched sensors bent around beam pipe
- Barrel layers comprise more traditional stave design that uses smaller stitched sensors.
- ATHENA plans to use the same sensor (ITS3) in all parts of its silicon tracker
- ITS3: Latest 65 nm MAPS technology currently being developed for an upgrade of the inner tracking system of the ALICE experiment at CERN
- Close collaboration with ITS3 collaboration to develop MAPS sensors leveraging efforts at CERN

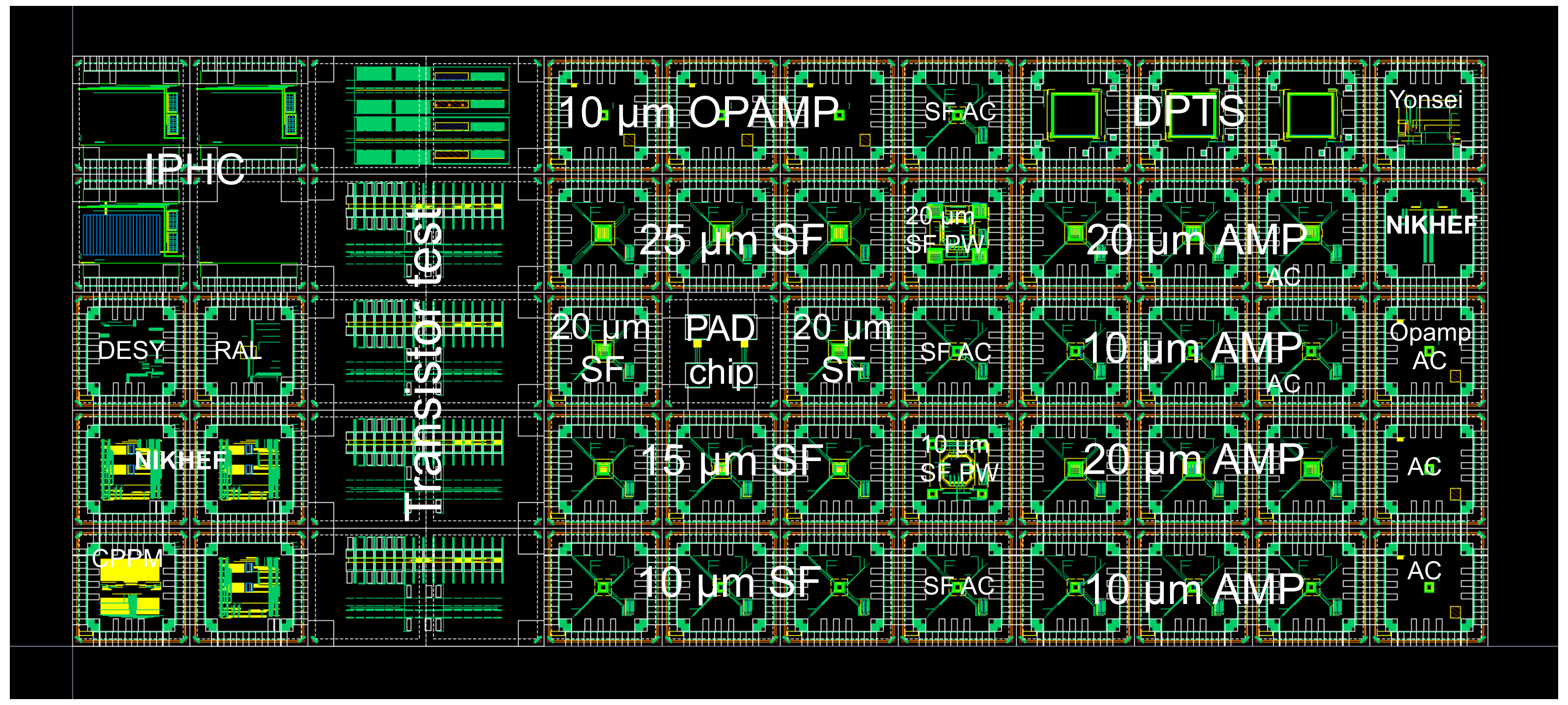
BNL, Birmingham, Brunel, CCNU Wuhan, CTU Prague, CUTN, Daresbury, Goa U., IIT Madras, INFN, LANL, LBNL, Lancaster, Liverpool, NISER, NPI Czech Acad., RAL, U. Jammu, U. Michigan, UC Berkeley, UC Davis

Example 1: MAPS for Si-Trackers

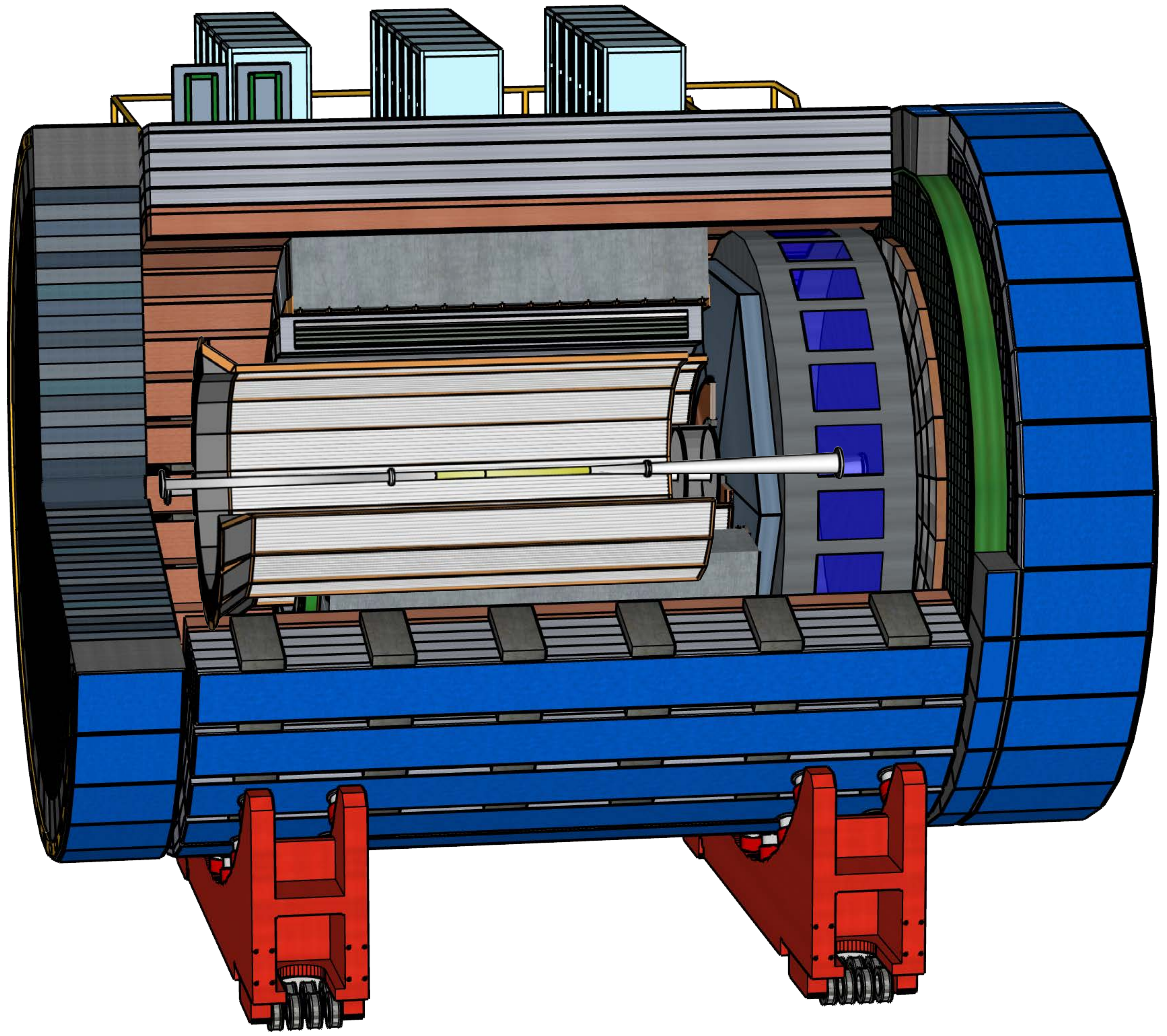
- **Challenges & Observations**
  - ➢ Highly innovative new sensor in development
- **Mitigation/Fallback Solutions**:
  - ➢ New sensor in 180 nm technology, with pixel pitch and power specifications close to the 65 nm sensor (ITS3 fallback solution).
  - ➢ In case of delays of both ATHENA will start with ALPIDE and upgrade to a new sensor as soon as possible. Higher power consumption of the ALPIDE implies more material that, combined with the larger pixel pitch, will degrade vertex resolution and $\delta p/p$ (forward and backward).

- **R&D Needs**
  - ➢ Develop full detector infrastructure in parallel with sensor development
  - ➢ eRD111: forming modules from sensors and developing infrastructure required to produce staves and disks, mechanical support structures and cooling.
  - ➢ eRD104: carries out R&D into services reduction, powering, and readout

Successful MLR1 submission/performance



Example 2: hpDIRC

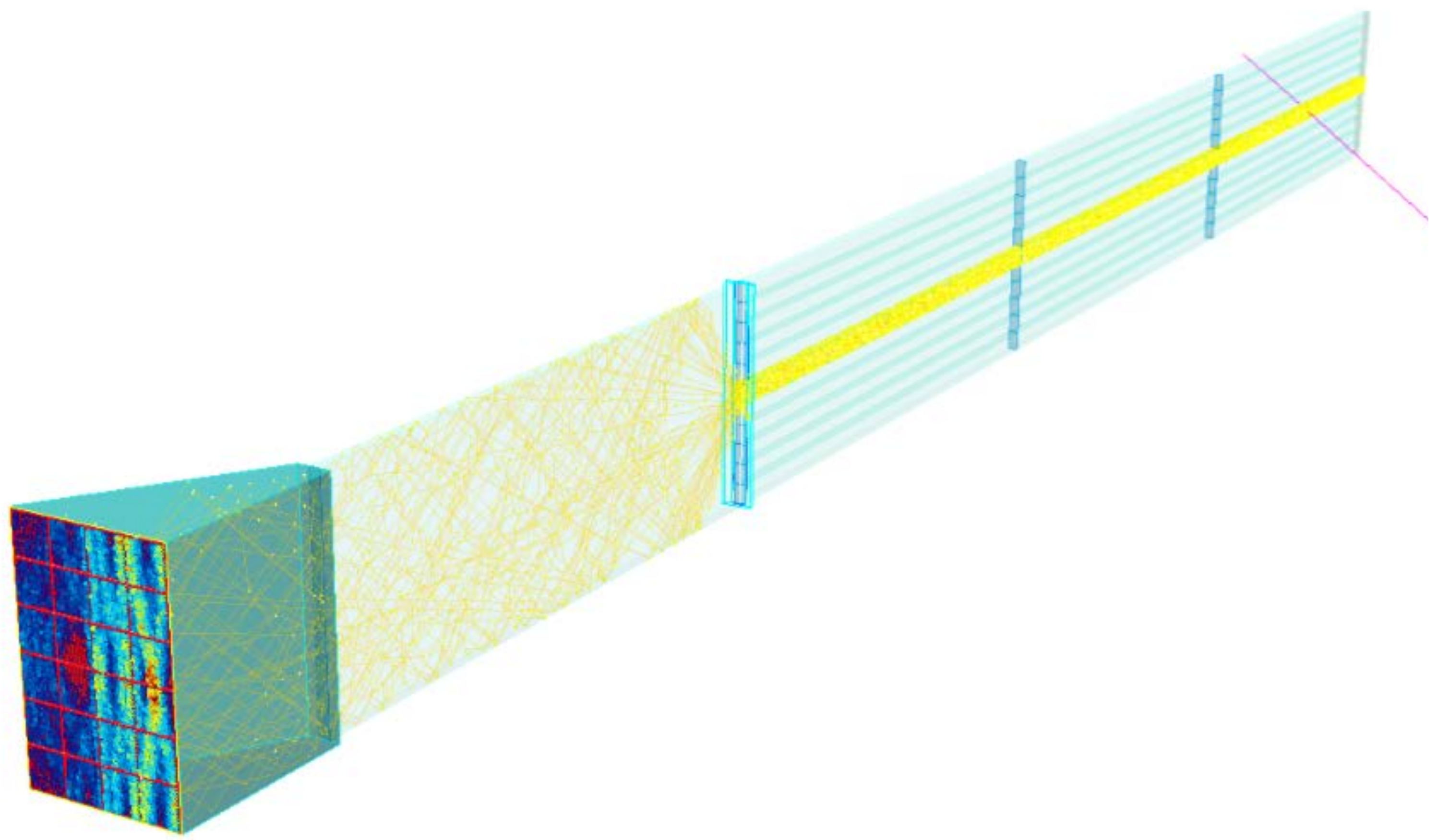


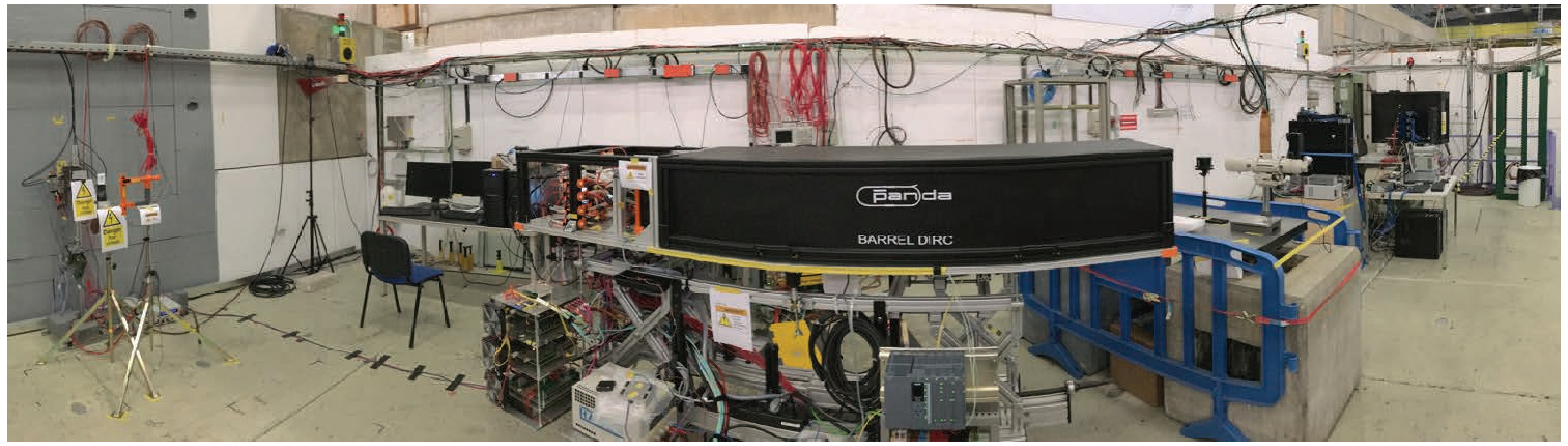
- Develop fast, compact, focusing DIRC with π/K separation up to 6 GeV/c
- Pushing the performance well beyond the state-of-the-art for DIRC counters.
- **Challenges & Observations**
  - ➢ Similar focusing DIRC extensively developed and confirmed by test beam for PANDA at GSI.
  - ➢ Principle of hpDIRC (more refined focusing by lenses) demonstrated with optical studies.
  - ➢ Confirmation of the performance of hpDIRC needed.
- **Mitigation**
  - ➢ Completion of the ongoing studies by prototyping and test beam exercises.

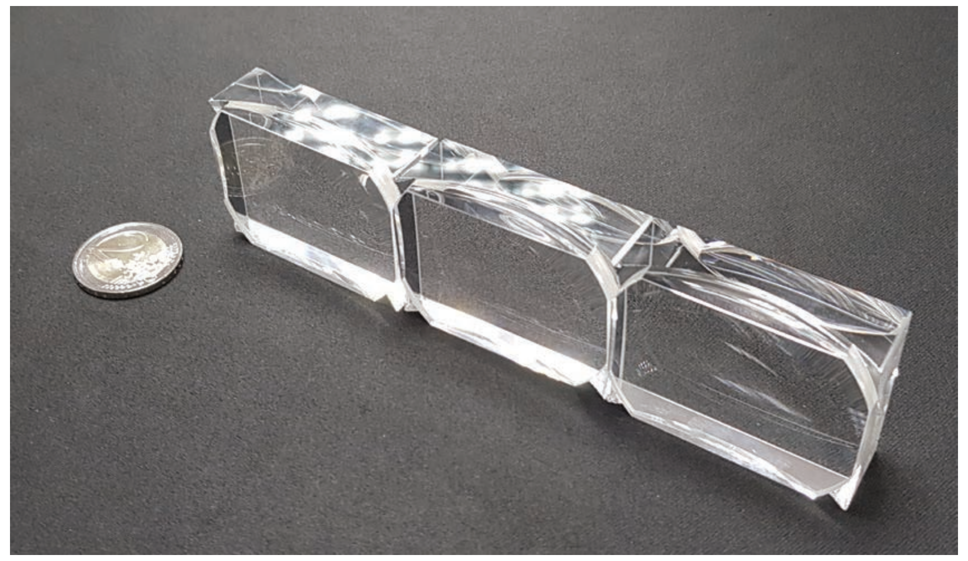
Banaras U., BNL, CUA, GSI, Mississipi State, NISER, Stony Brook

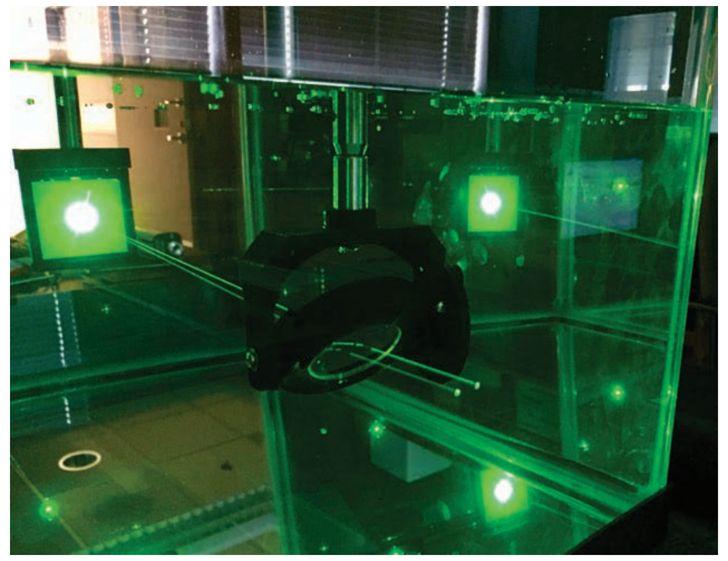
Example 2: hpDIRC

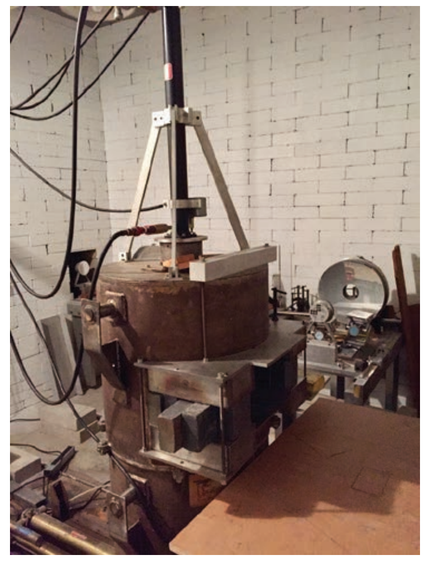
- **R&D Priorities**
  - ➢ Baseline design validation ➟ prototype
  - ➢ Cost/performance optimization
  - ➢ Opportunity: Reuse of BaBar DIRC bars
    - ◉ Bars moving to East Coast soon for validation of reuse
    - ◉ Alternative: new narrow bars with wide plate hybrid design



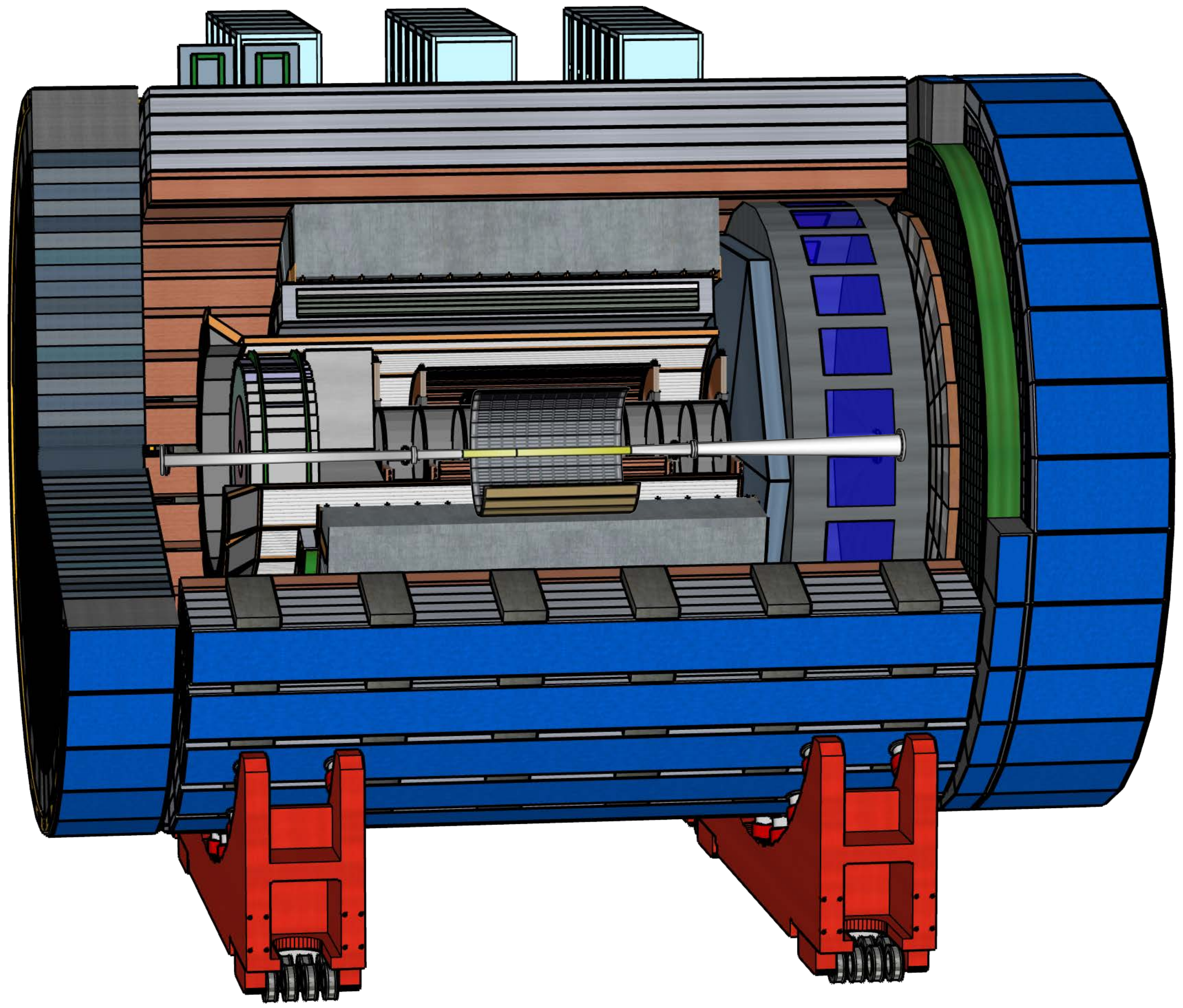


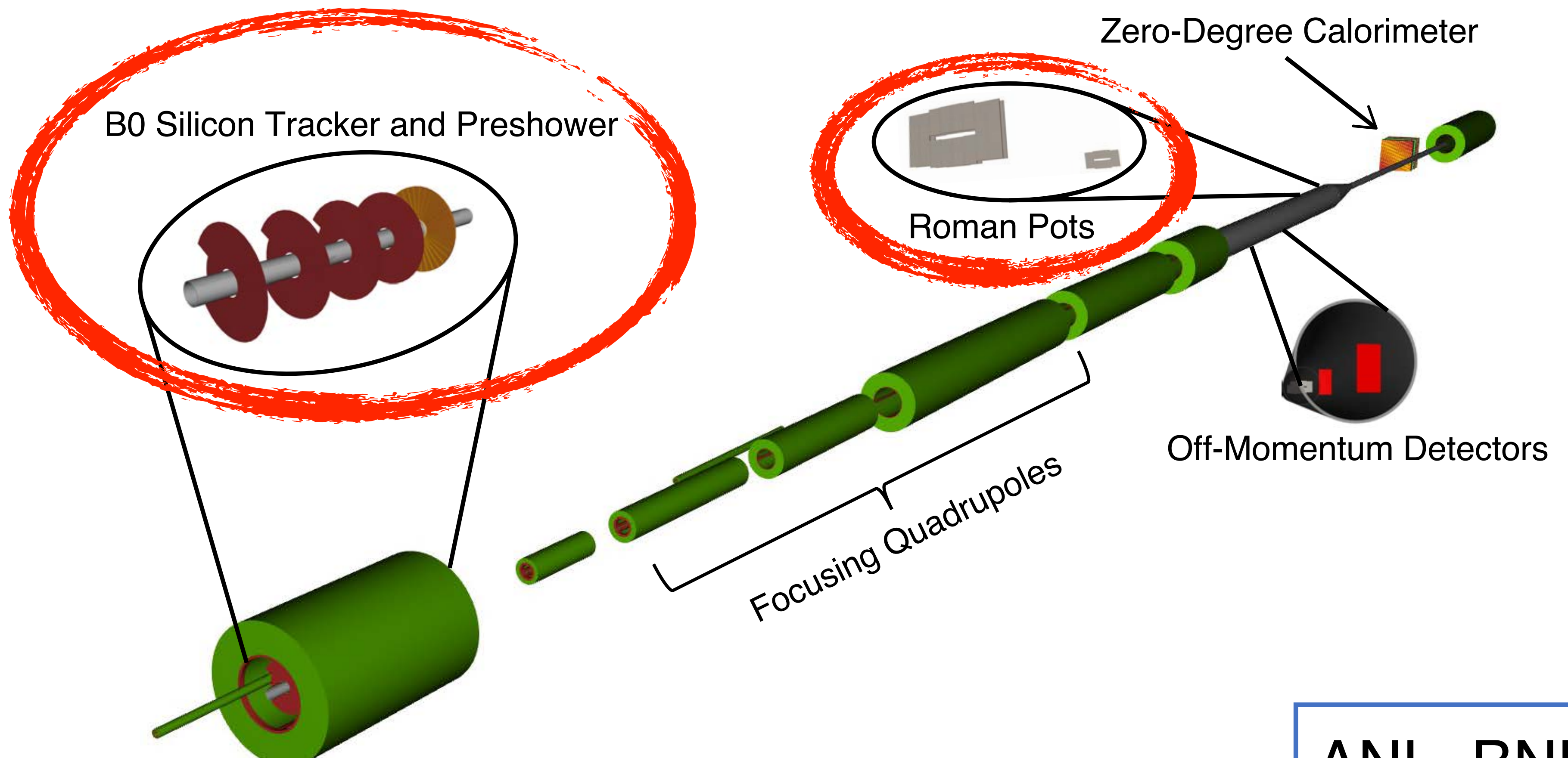






Example 3: AC-LGAD





- AC-LGAD delivers excellent time resolution (< 30 ps/layer) and good spatial resolution
- Use of AC-LGAD sensors in:
  - ➢ Auxiliary detectors (timing: Roman Pots, Off-Momentum Detectors, spatial resolution for B0)
  - ➢ Polarimetry
  - ➢ bToF
    - Common issue of thickness and heat dissipation compensated by pixel ➟ strips
- Common designs in sensor, ASIC where possible, combine R&D efforts
- Synergies with other proposed applications: ATLAS RP for HL-LHC, LHCb upgrade, ALICE3, NA62, CERN, PIENUX, TRIUMF and space missions PAN.

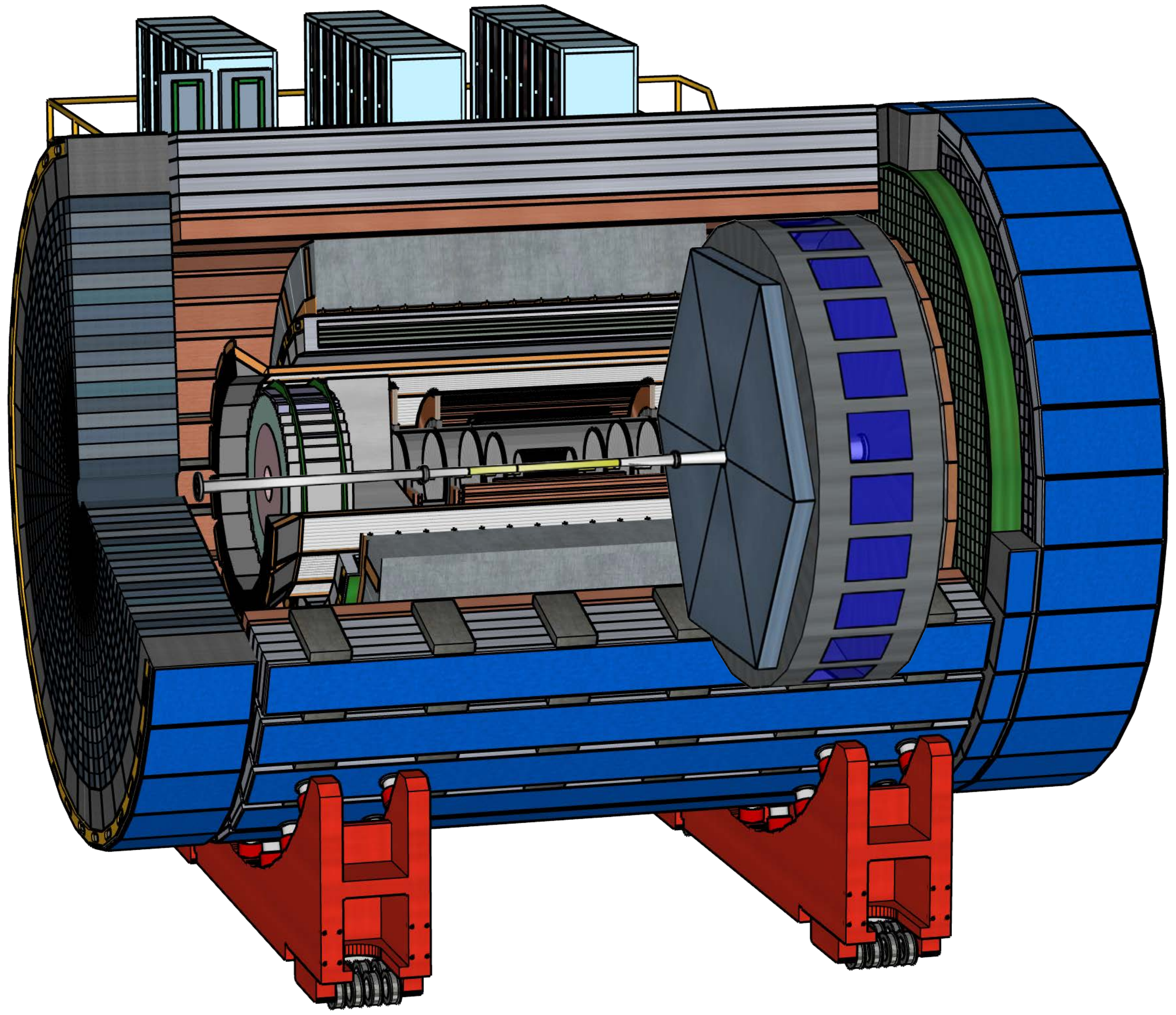
ANL, BNL, UI Chicago, Rice, UT Austin, Saclay/IJCLAB/ Omega, IISRE, NCKU

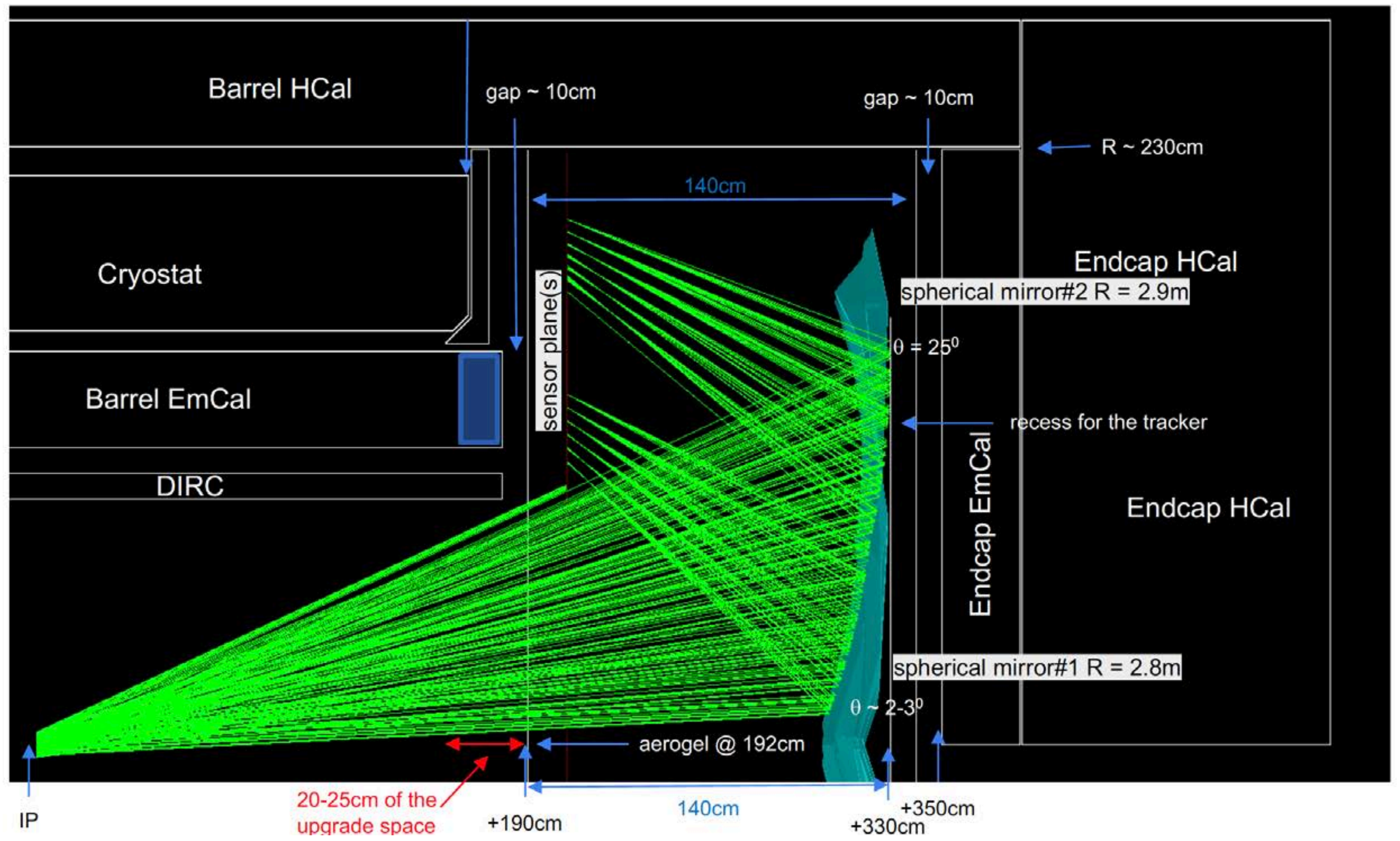
Example 3: AC-LGAD

- **Challenges & Observations**
  - Development advanced at present time
  - Sensor:
    - minimal readout channel density for reduced power and material: long strip, rectangular pixel
    - Goal: $\delta t/t$ = 15-20 ps, $\delta x/x$ = 5-50 μm
  - ASIC
    - 15-20 ps jitter
    - minimal power consumption (1-2 mW/ch)
- **Mitigation & Alternatives**
  - Forward Detectors: use MAPS + timing layer
  - for PID at low momenta to complement PID by DIRC in the barrel: R&D dedicated to a miniTPC with sensors by GridPix technology
- **R&D Needs**
  - Sensor
    - Produce and test sensors with thin active volume to achieve $\delta t/t$
    - Optimize implantation parameters and AC-pad segmentation through simulation and real device studies
  - ASIC
    - Continue the ASIC prototyping effort for RPs by Saclay/IJCLAB/Omega (1st submission in FY22 funded externally)
    - Utilize the design and experience in ASICs for fast-timing detectors from ATLAS and CMS
    - Investigate common ASIC design and development for RPs and ToF

Substantial synergy with AC-LGAD efforts in HEP → LGAD Consortium

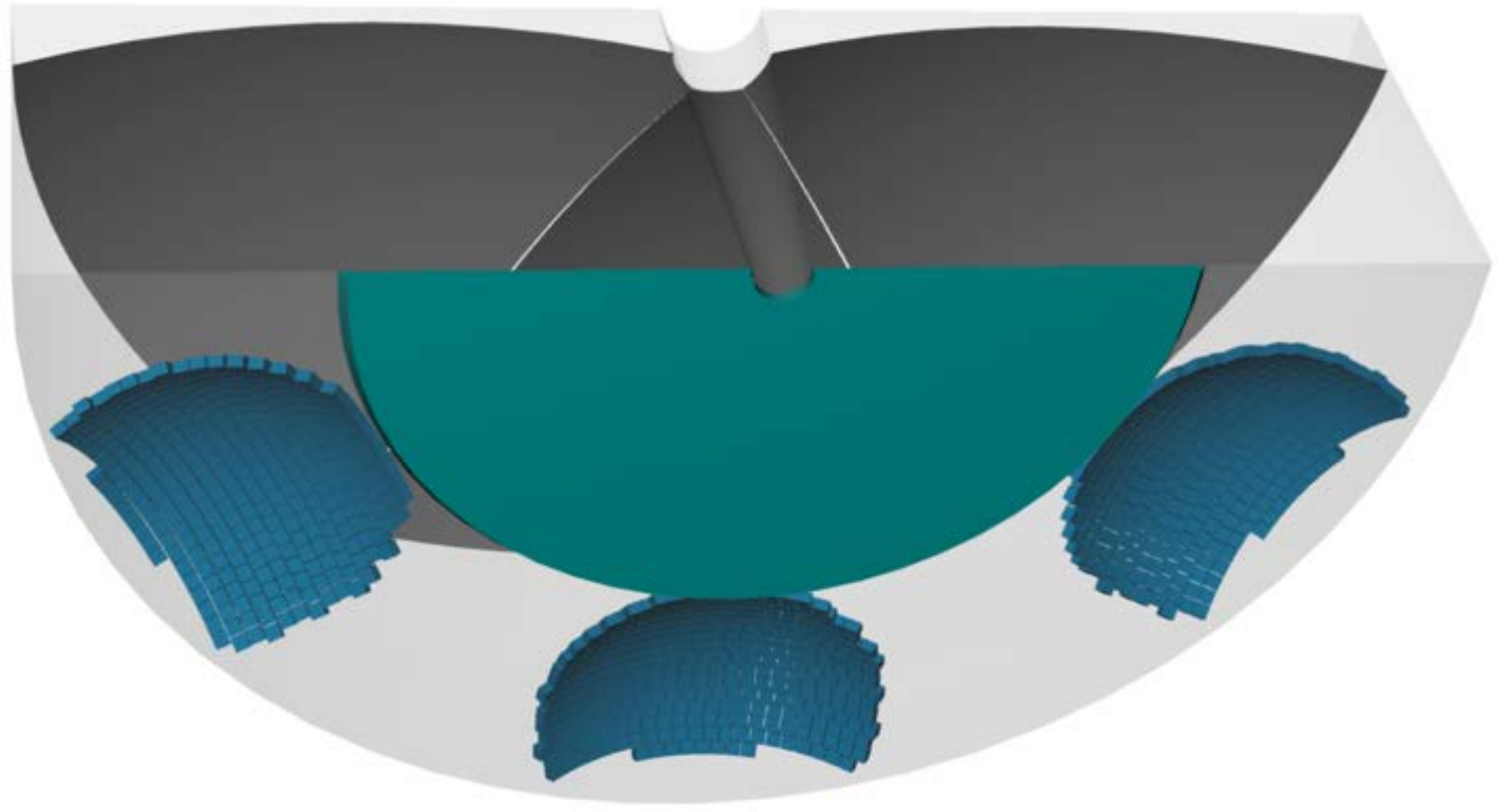
Example 4: dRICH





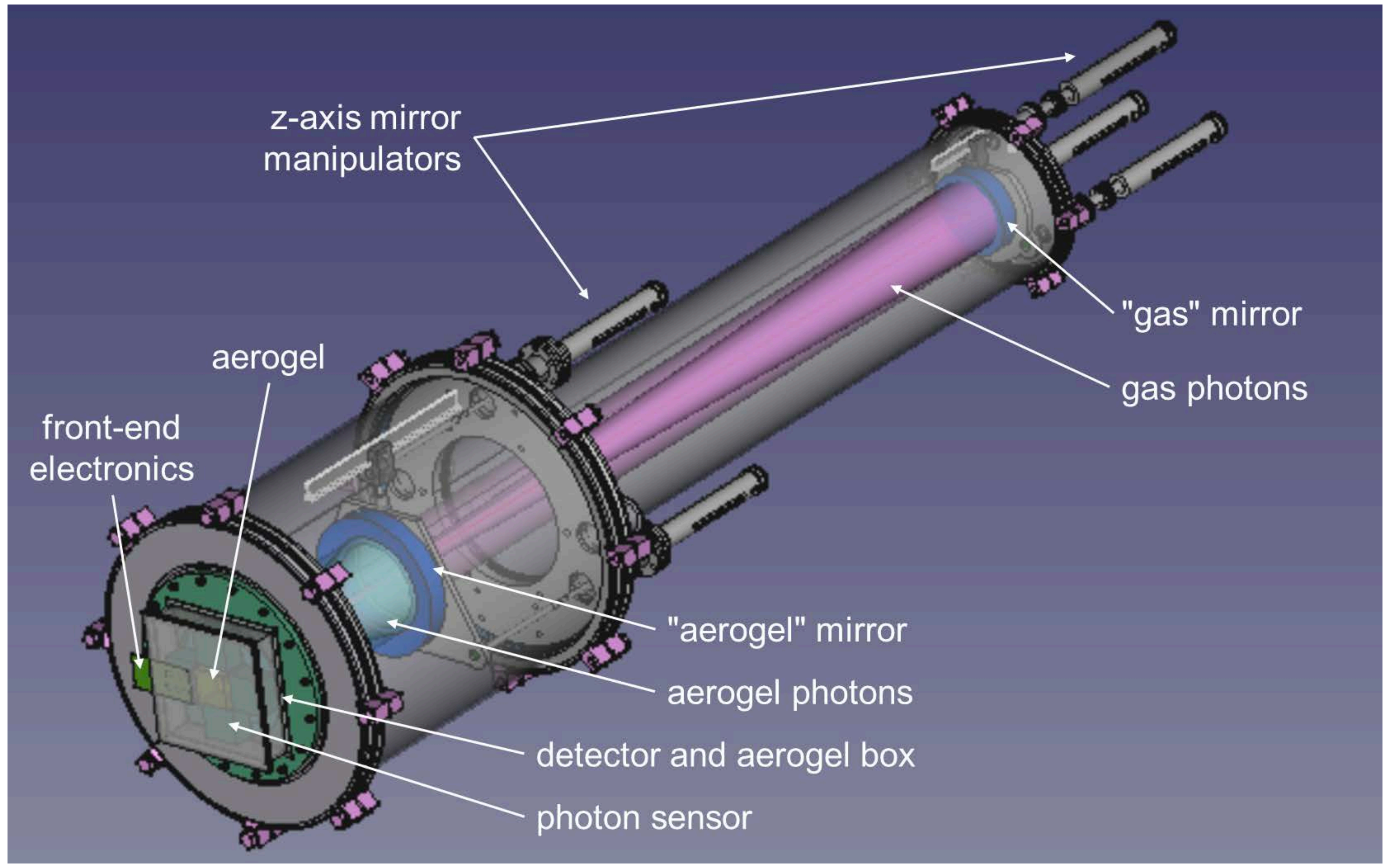
- First dRICH for use in solenoidal field
- Performance optimization ongoing
- Combination of C_2F_6 gas and n=1.02 aerogel
- Outward-reflecting mirrors reduce backgrounds and (UV) scattering in aerogel
- Sophisticated 3D focusing to reduce photosensor area

Banaras, Duke, GSU, INFN, NISER, Stony Brook, U of Massachusetts



Example 4: dRICH

- **Challenges & Observations**
  - ➢ The radiator combination in relation with the expected environment at EIC to be validated
  - ➢ Two-radiator RICHs already operated in experiments (HERMES, LHCb)
- **Mitigation**
  - ➢ Completion of the ongoing studies by prototyping and test beam runs.
- **R&D Needs**
  - ➢ FY22: Preparation of the basic version of the dRICH prototype and first test beams at CERN.
    - Tests are organized in synergy with ALICE
    - Study of the single-photon response of SiPM coupled to ALCOR readout
    - Comparative use of Russian, Japanese, and US aerogel
  - ➢ FY23/FY24: optimization of technical specifications and matching to EIC-driven (developed by other EIC R&D) photosensors and readout electronics

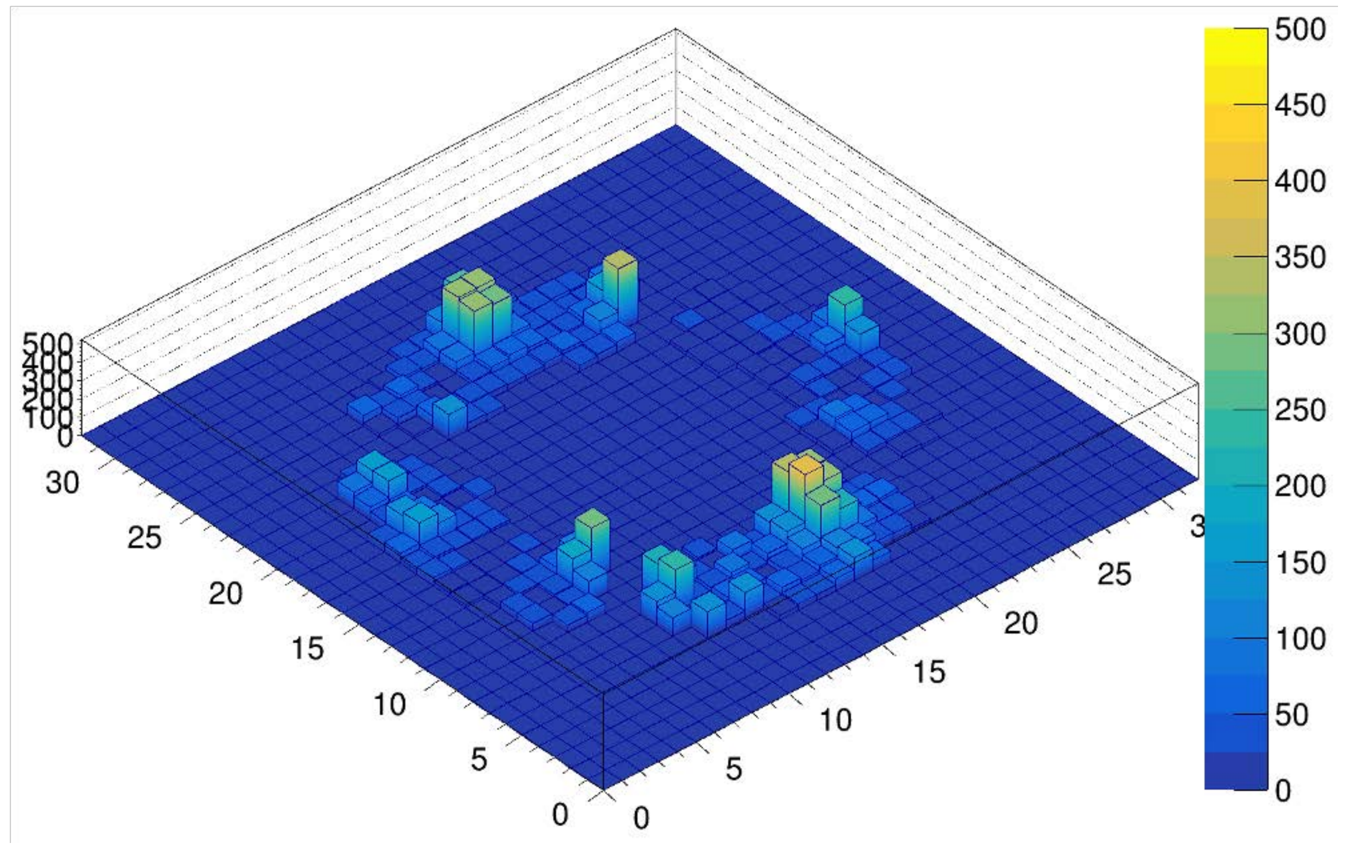


Example 5: Photosensors

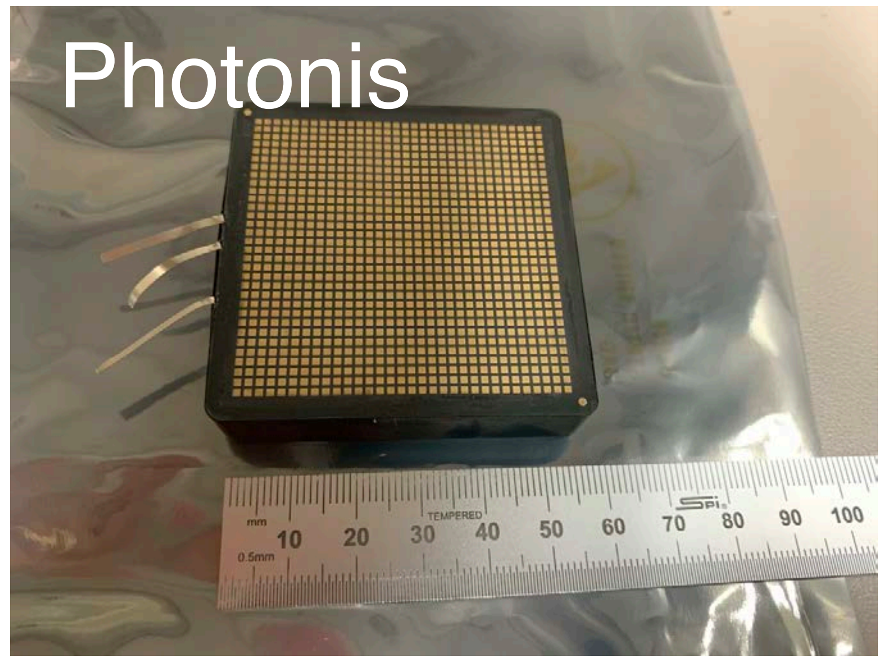
- **R&D Goal**: Reduce current risk associated with reliable highly pixilated photodetectors working at 1-3 T for PID and calorimetry
- On the market, but need development
  - ➢ SiPMs - radiation damage mitigation
  - ➢ Incom LAPPD - pixelation
- In development by manufacturer
  - ➢ Incom HRPPD (multi-anode direct readout)
- Already on the market
  - ➢ Photonis (most mature, multi-anode MCP PMT)
  - ➢ Photek (new, multi-anode MCP PMT)

Recall:
hpDIRC ➟ MCP-PMTs
dRICH, pfRICH, Calorimetry ➟ SiPMs

Pixelated Gen II LAPPD



Single event with multiple photon clusters

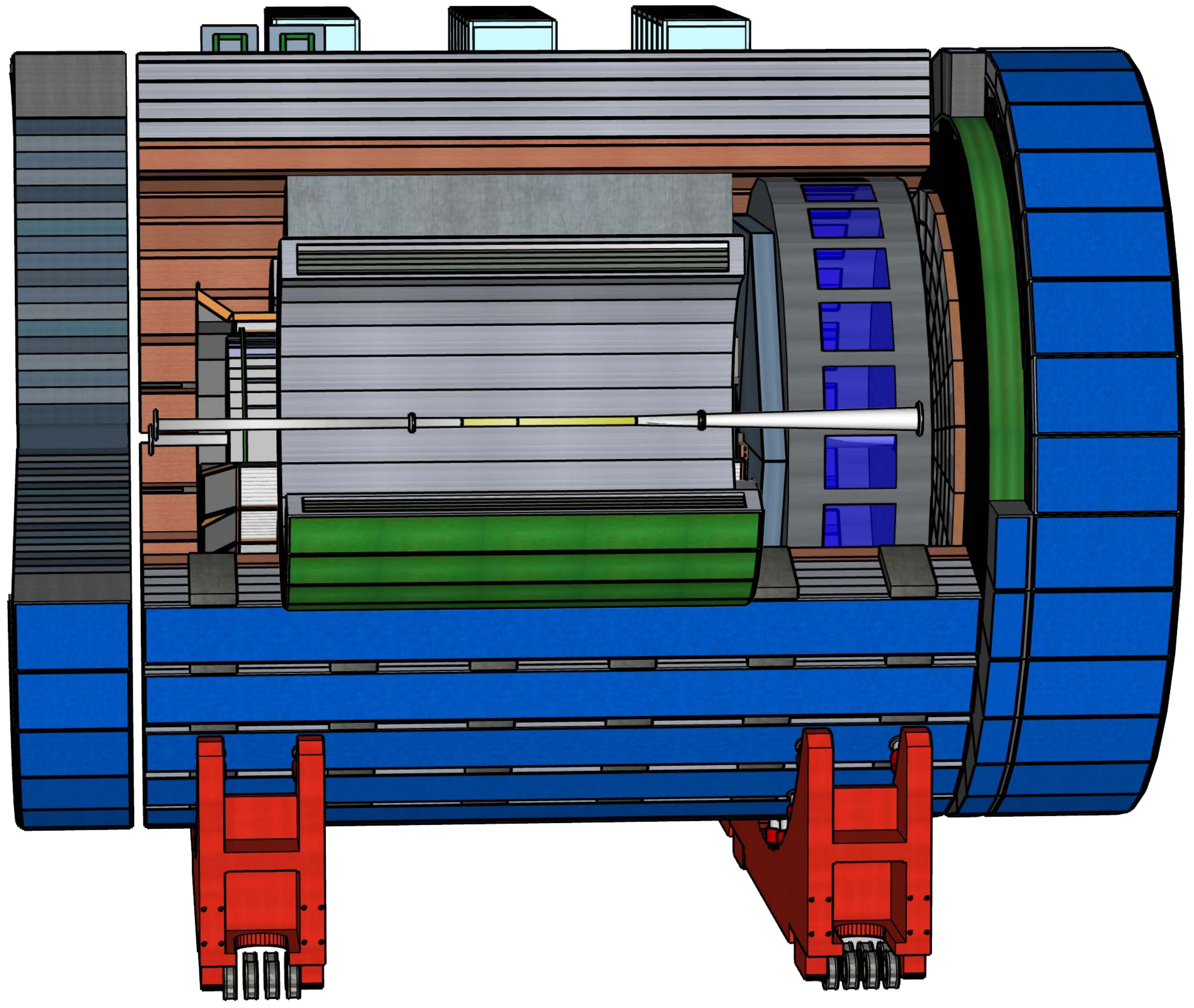


ANL, BNL, CUA, JLab, Mississippi State, Stony Brook, UCLA, GSI, INFN: Bologna, Ferrara, Trieste, Torino

Example 5: Photosensors

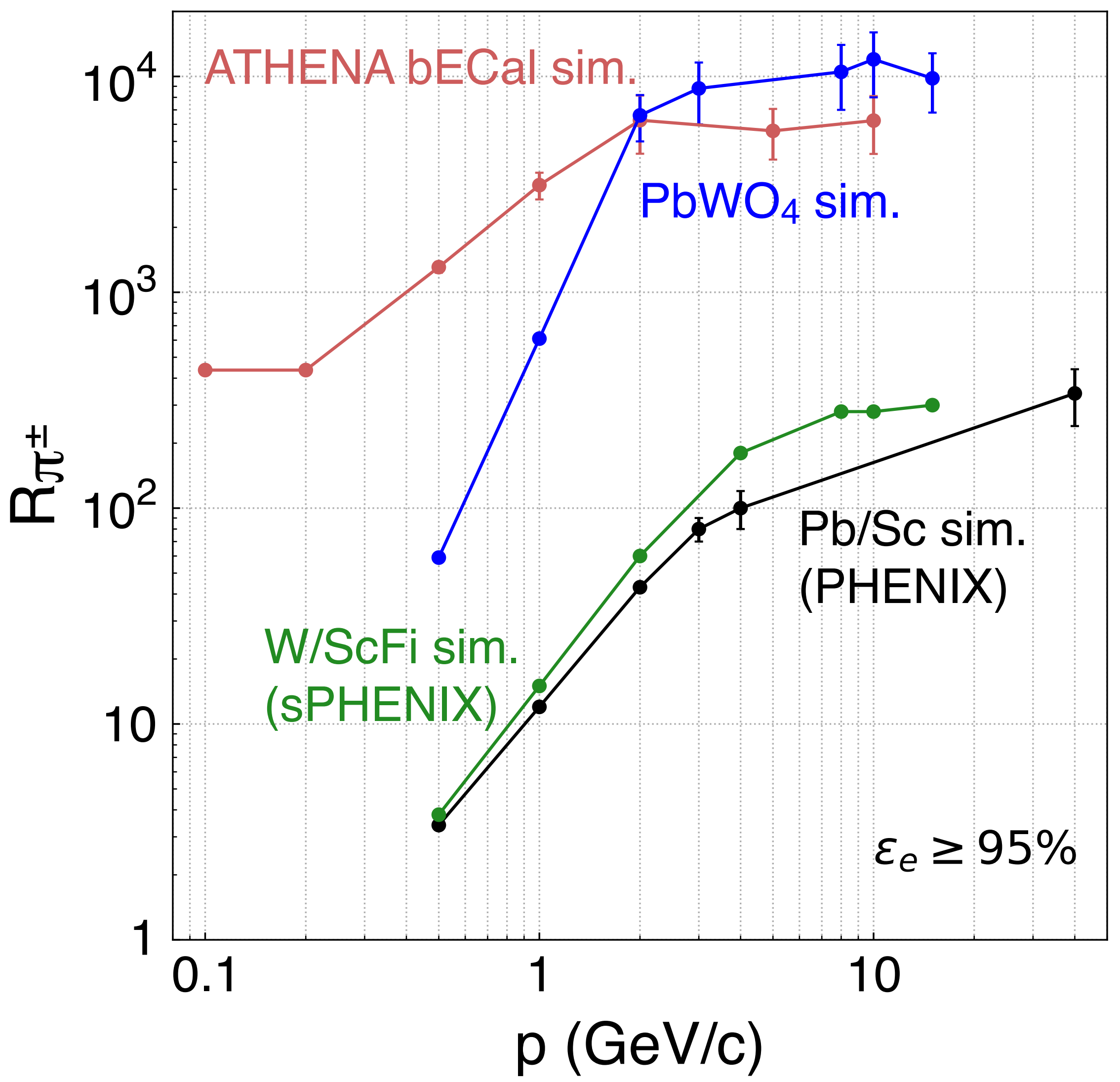
- **Challenges SiPM**
  - Evaluation of dark current vs irradiation dose and vs repeated thermal annealing cycles
  - Variations in devices from different providers ➟ detailed characterization
- **Mitigation SiPM**
  - Alternative: Pixelized LAPPDs (are not established yet). This item requires management attention, adequate support and investment
- **Challenges MCP-PMT**
  - Production rate and cost.
  - Further confirmation that gain loss in high field (affecting the time resolution) is acceptable
- **Mitigation MCP-PMT**
  - Early purchasing procedure.
  - Further studies of performance in realistic magnetic field. Fallback option: continue pursuing the development of an alternative approach (LAPPD).
- **R&D Program eRD110**
  - Characterization of Photek/Photonis MCP-PMTs
  - Pixelization and improvement of field resilience of LAPPDs & HRPPDs
  - Improvement of the radiation hardness of SiPMs and the optimization of the sustainability of their proper temperature treatment in collaboration with various manufacturers.

Example 6: Barrel EMCal (bECal)



- Innovative design
  - ➢ Hybrid calorimeter with front imaging layers using AstroPix sensor alternated with Pb/SciFi layer followed by a set of Pb/SciFi layers
- Provides tracking layer after hpDIRC for MS corrections
- Exceptional pion rejection power

KIT, ANL, NASA
Derived from ATLASPix



ANL, University of Massachusetts Amherst, Yerevan Physics Institute

Example 6: Barrel EMCal (bECal)

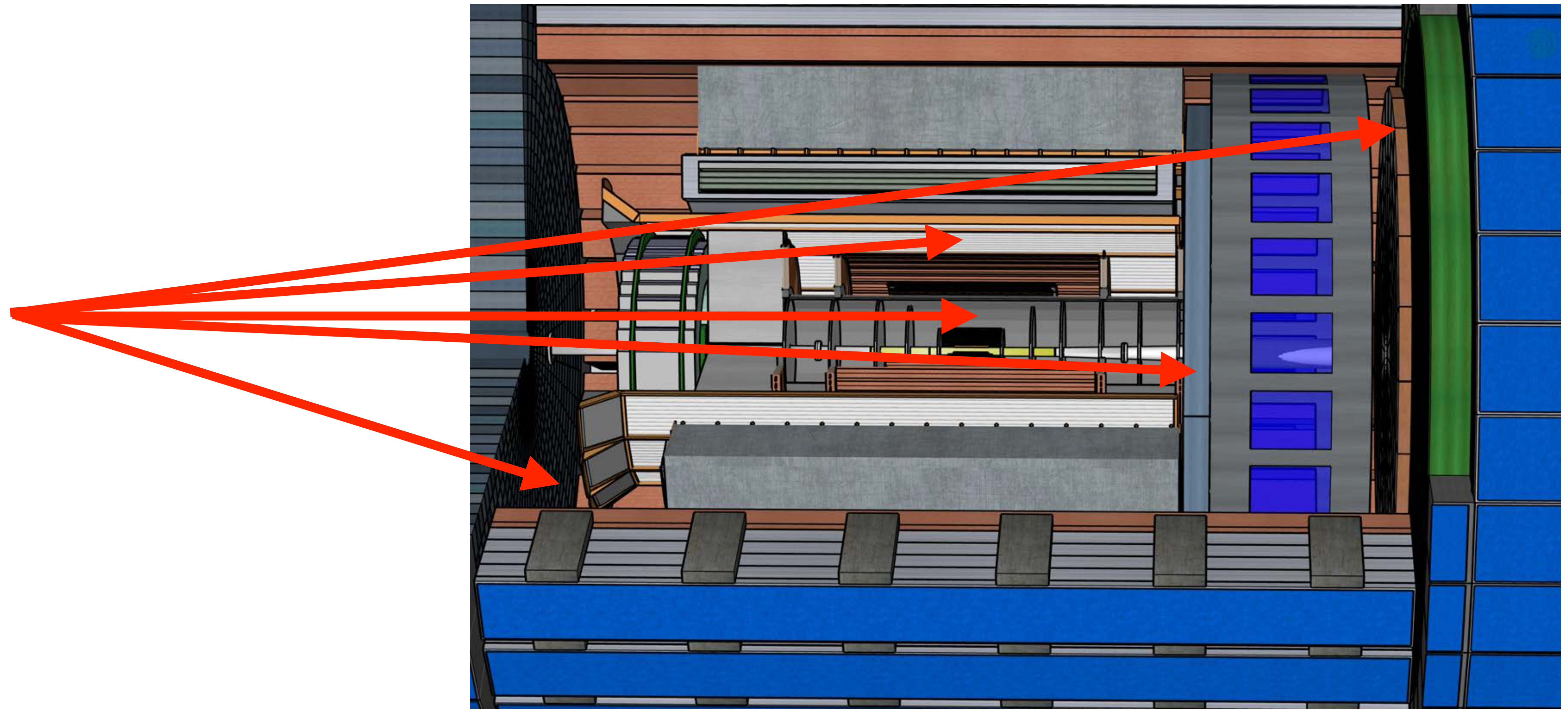
ATHENA

- **Challenges & Observations**
  - ➢ Pb/SciFi (most recently: GLUEX) and AstroPix, are established technologies
  - ➢ Performance and interplay between the ECal and HCal to be better understood
- **Mitigations**
  - ➢ Further studies to confirm performance needed.
- **R&D Need**
  - ➢ Construction of a smaller prototype to validate the Monte Carlo simulations of the device is imperative. AstroPix sensors used in the prototype should be recovered for use in the full scale electromagnetic calorimeter.
- **Other Calorimeter R&D**
  - ➢ eRD105 for development of high-resolution electromagnetic calorimeters based on scintillating glass (nECal)
  - ➢ eRD106 and eRD107 for development of a very compact, high-resolution hadron endcap system (pECal, pHCal)
  - ➢ eRD110 for studies of the impact on calorimeter performances due to radiation damage of the SiPMs.
  - ➢ The ATHENA hadron calorimeters for the barrel and negative endcap do not require R&D.

Upgrade Paths

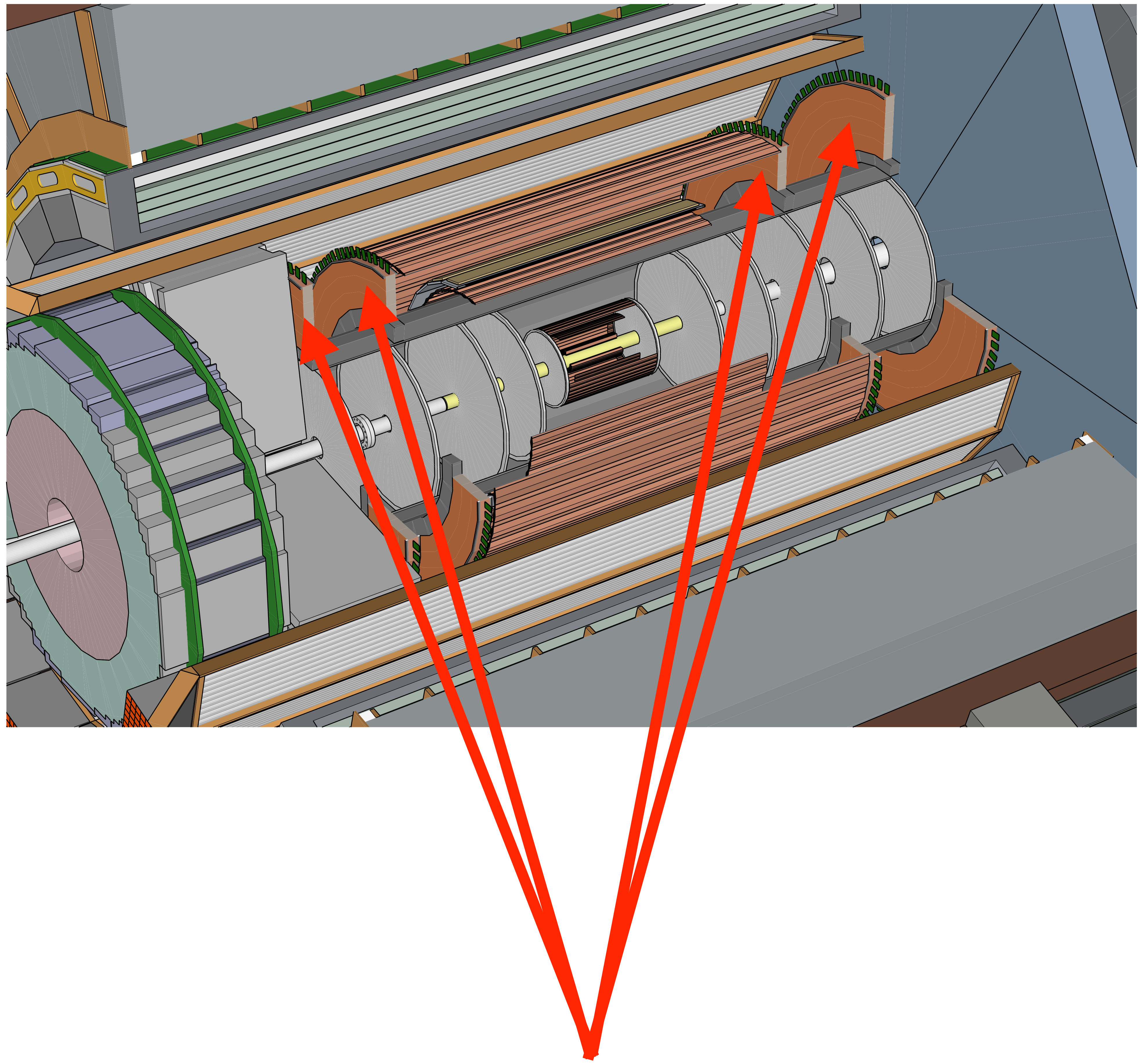
- Upgrade paths considered are strictly related to ongoing R&D activities
- Distinguish:
  - ➢ Improvements of the baseline detector described in this proposal by alternative techniques offering performance or cost advantages that can become mature in the near future
  - ➢ Upgrades that can be implemented after a few years of data taking, informed by the experience gained with the initial detector configuration (not discussed here)

ATHENA reserved intentionally several areas for upgrades possible thanks to large bore of magnet



Upgrade Path (I)

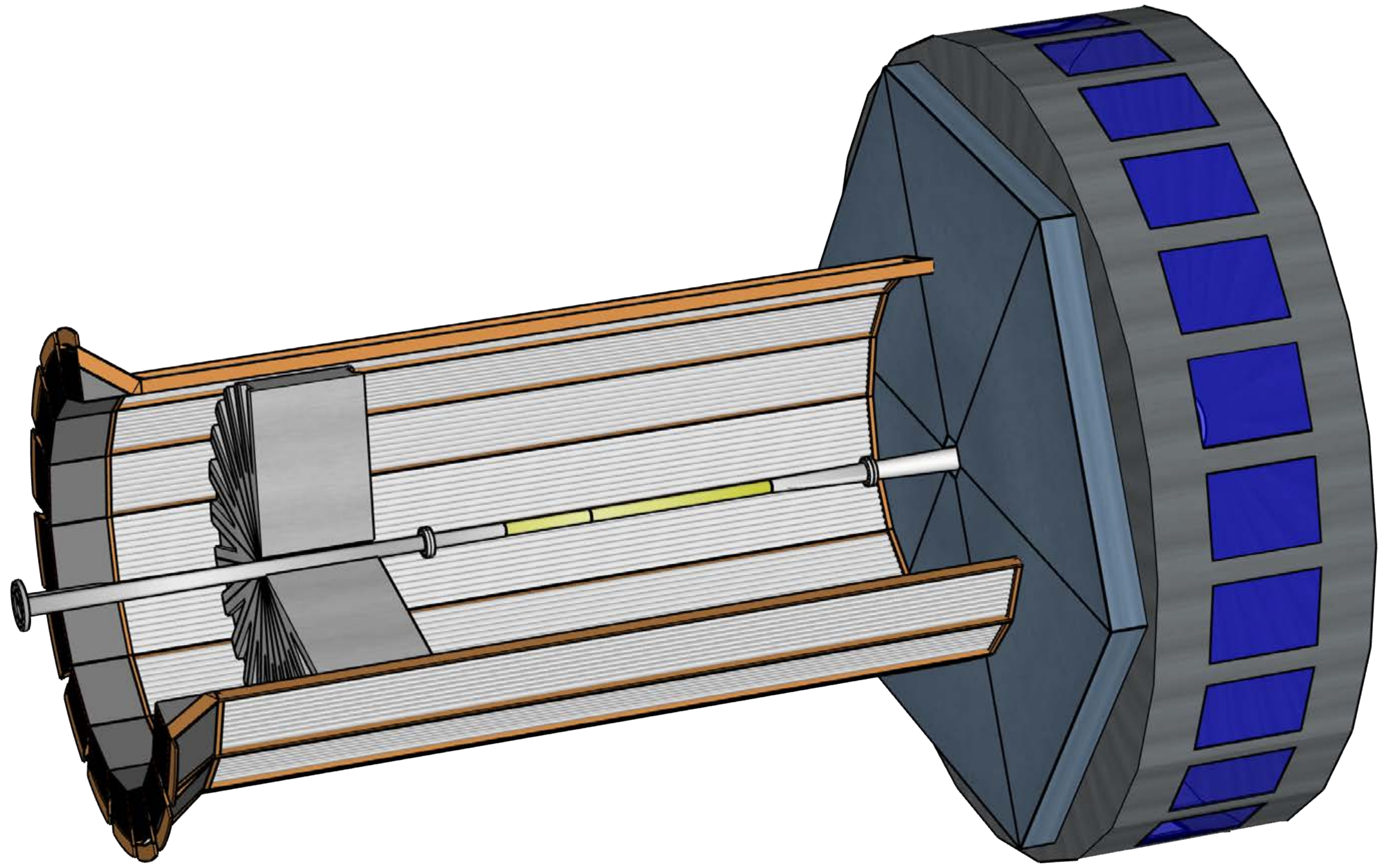
- **μRWell**
  - ➢ μRWell instead of GEMs for gaseous detectors in the endcap regions of the central detector
    - easier detector construction,
    - lower material budget
    - save around 25% in material cost.
  - ➢ μRWell technology is recent development
  - ➢ Has not yet been adopted in any experiment.
  - ➢ This upgrade option during the ATHENA design phase requires finalizing the R&D of this novel technology.



GEM technology, including large-size chambers, is well established

Upgrade Path (II)

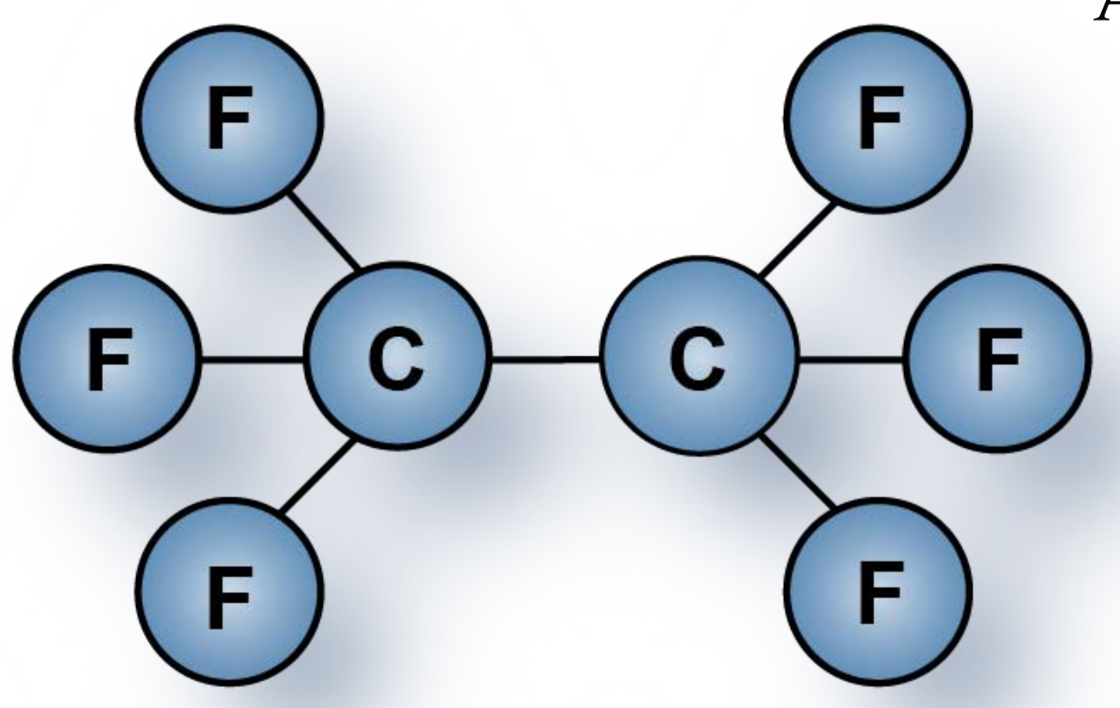
- **Photosensors**
  - ➢ Major challenge are the photosensors for the Cherenkov devices
  - ➢ The baseline design
    - commercial MCP-PMTs for the hpDIRC ➟ cost
    - SiPMs for the dRICH and the pfRICH ➟ cooling



- **LAPPDs**
  - ➢ Offering reduced cost for the hpDIRC & fallback solution for the dRICH and pfRICH
  - ➢ Sensor could provide ToF information (~10 ps) through the photons produced in the sensor window by the charged particles
  - ➢ In spite of significant progress
    - pixelized versions of these detectors are not sufficiently mature yet
    - in-field performance needs further improvement

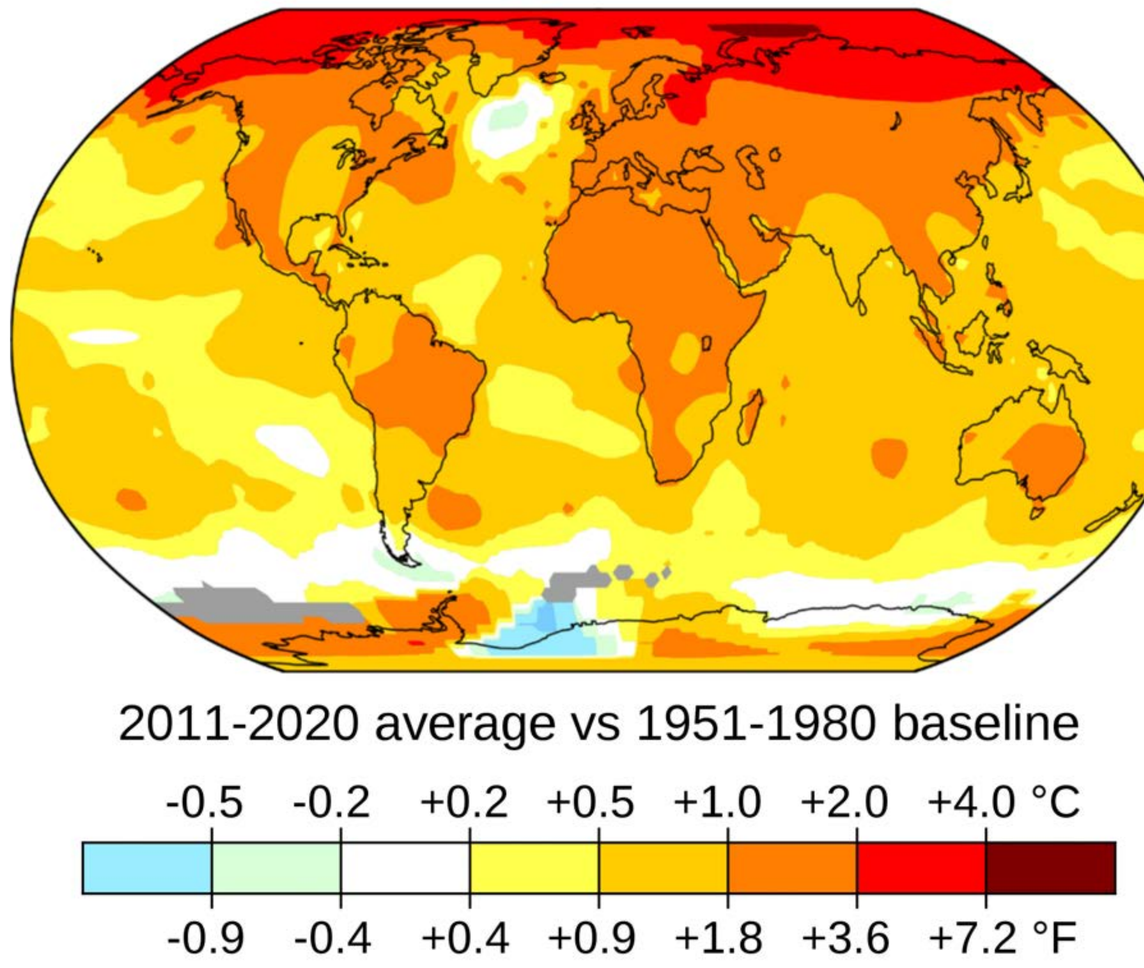
Upgrade Path (III)

- **Radiator Gases:**
  - ➢ Radiator gases for dRICH and pfRICH are fluorocarbons that exhibit extremely high Global Warming Power (GWP)
  - ➢ Increasingly prohibited across the world
  - ➢ Where used
    - ◉ complex and expensive close circulation systems needed
    - ◉ increasing procurement issues expected
  - ➢ RICH performance is preserved when fluorocarbons at atmospheric pressure are replaced with argon pressurized at a few bar
  - ➢ The challenge is to design vessel that allows
    - ◉ safe high-pressure operation
    - ◉ minimizing its impact on the overall detector material budget.



Formula	Name	Lifetime years	Global Warming Potential (GWP) 100-yr horizon	100-yr horizon	500-year horizon
			(SAR[a])	(AR4[b])	(AR4)
CF_4	PFC-14	50 000	6500	7390	11 200
C_2F_6	PFC-116	10 000	9200	12 200	18 200
C_3F_8	PFC-218	2600	7000	8830	12 500

Temperature change in the last 50 years



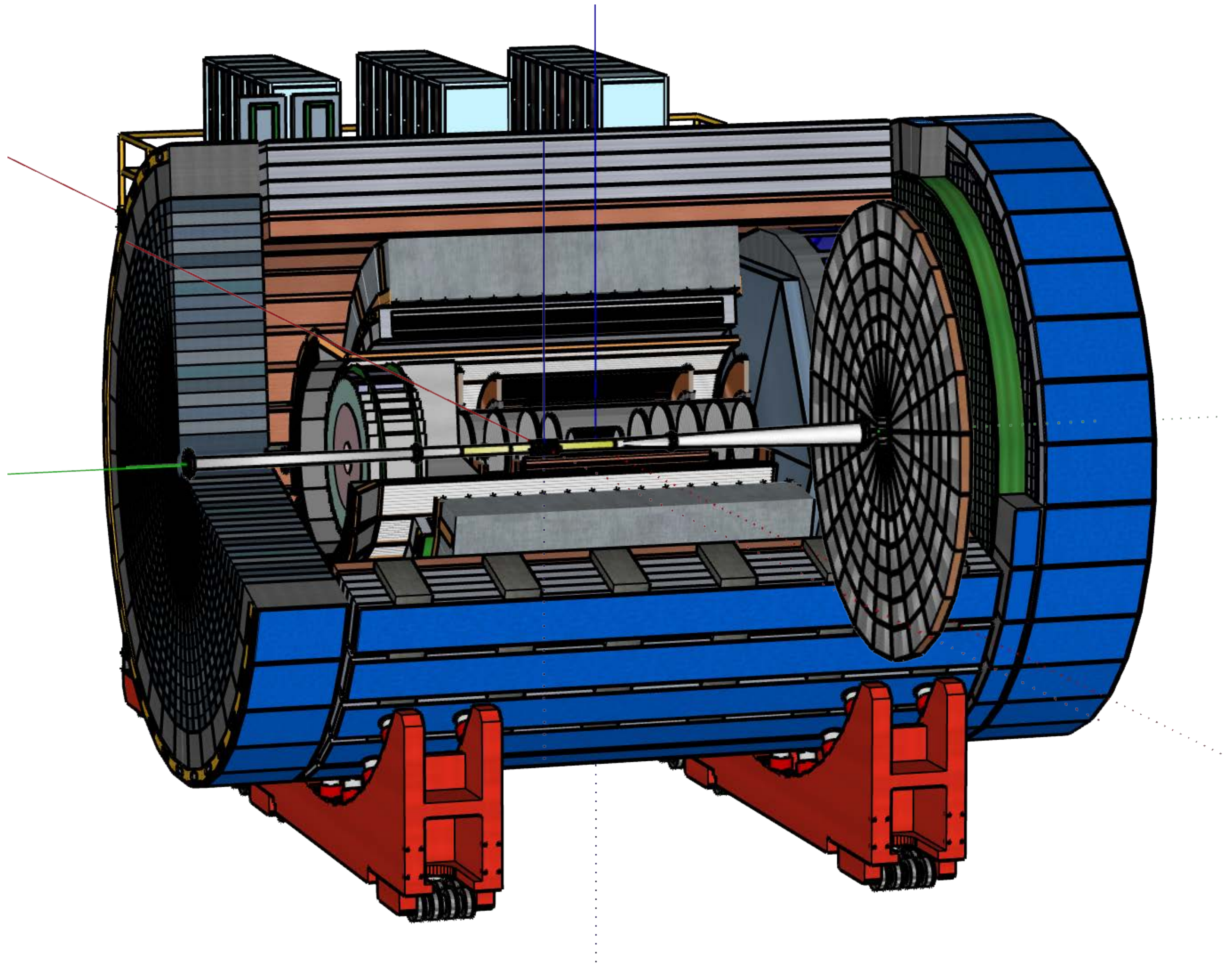
Take Away Message

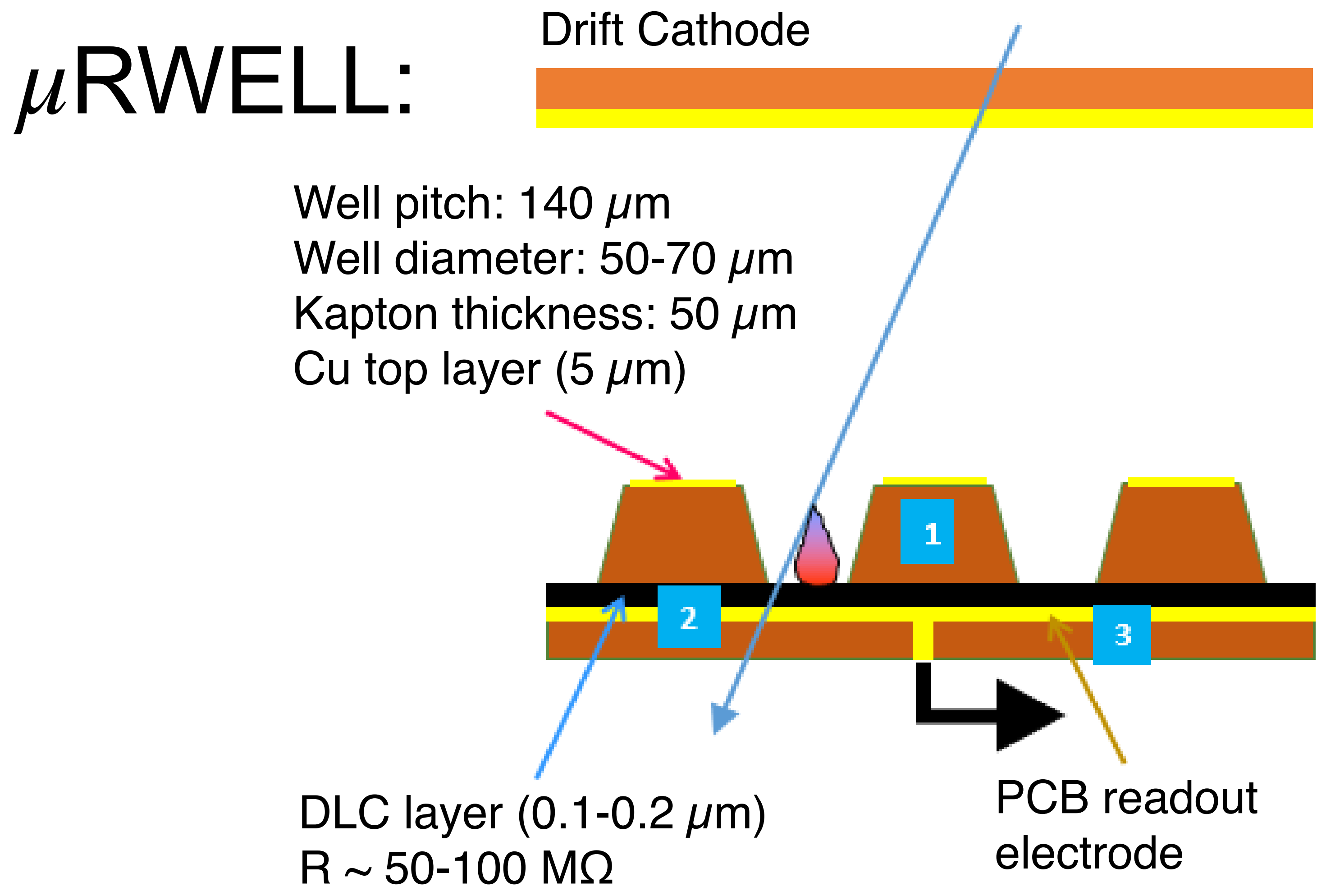
- Most ATHENA subsystems were participating in generic R&D program (2011-2021)
- Subsystems with larger risk have alternatives in place and are part of project funded rigorous R&D program
- Overall maturity level of detector at this time is already high
- Upgrade path in place with ample room for new technologies
- ATHENA is designed to be ready for data taking at CD-4A

Backup Slides

Example 7: Forward MPGD Tracking Layer

ATHENA

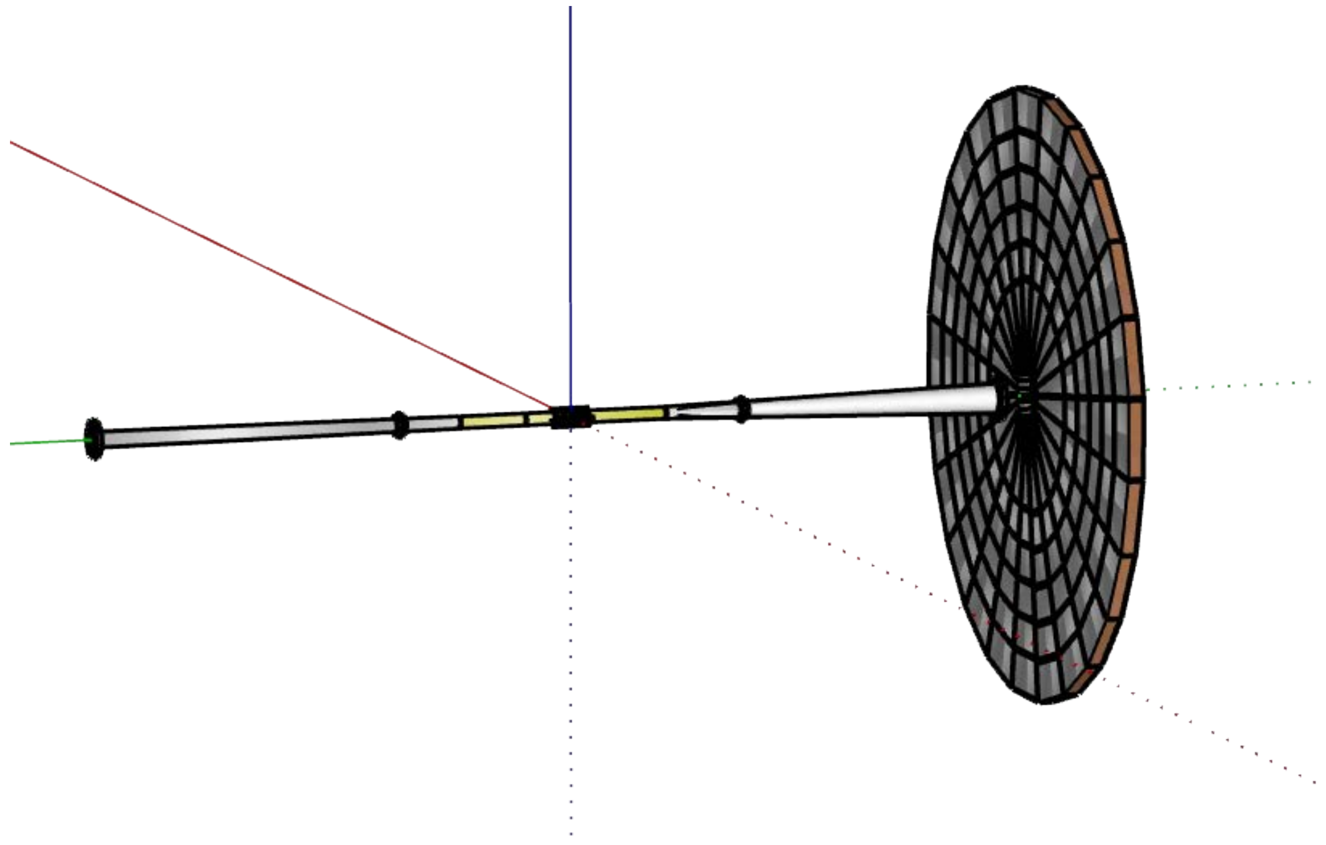




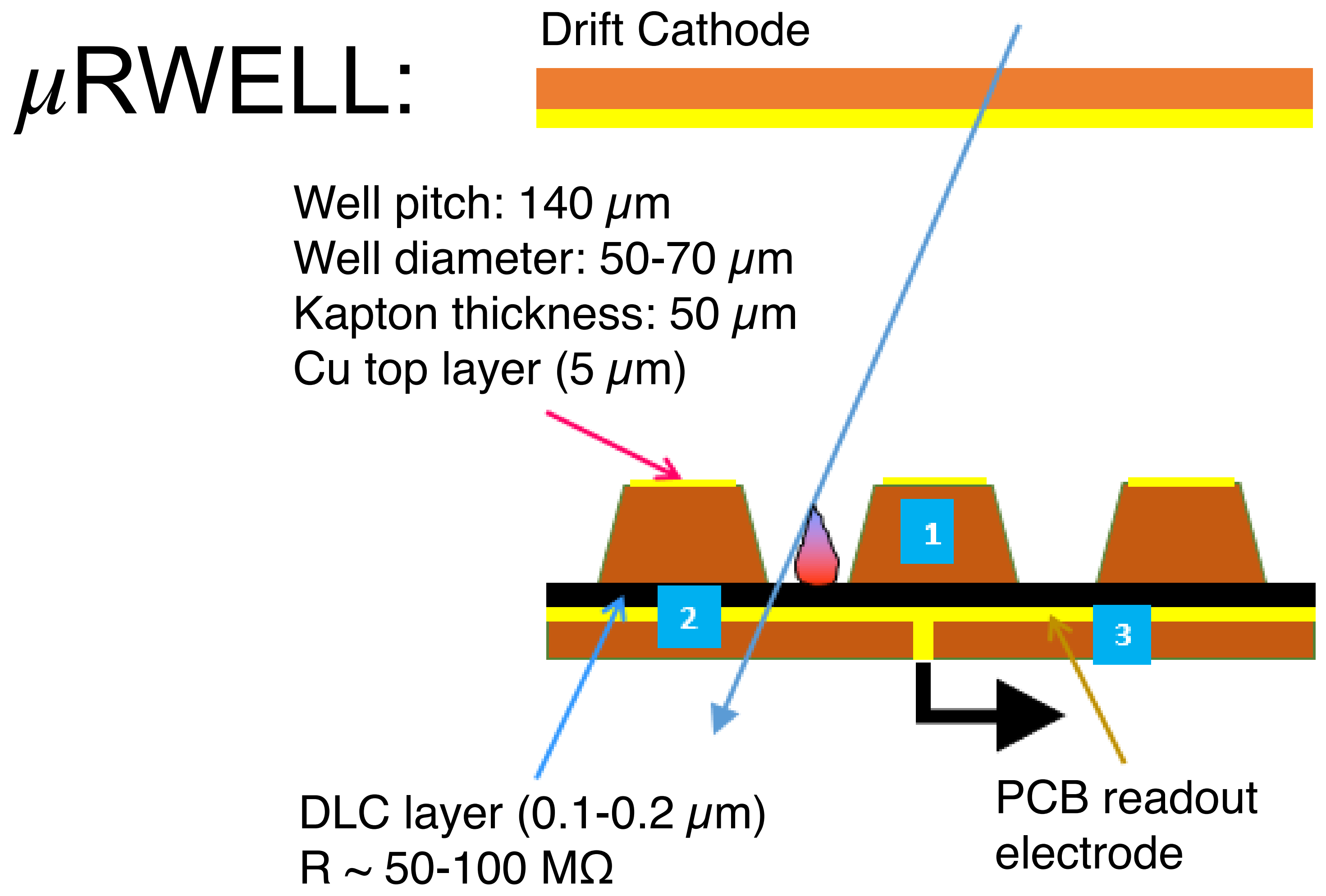
- Using μRWell detectors instead of GEM detectors in the endcap reduces material budget, simplify construction, and lower cost for the overall endcap tracker.
- **Challenge**
  - ➢ μRWELL never used in an experiment
    - foreseen in LHCb upgrade
    - considered also for SOLID
    - CLAS12 upgrade at JLab
  - ➢ Maturity Level of the Technology: 7
- **Alternatives & Mitigation**
  - ➢ Different gaseous detector technologies: GEM, MICROMEGAS, sTGC

FIT, Institute of Physics, CEA-Saclay, JLAB, NISER, Rama. College, Temple University, Yale University

Example 7: Forward MPGD Tracking Layer

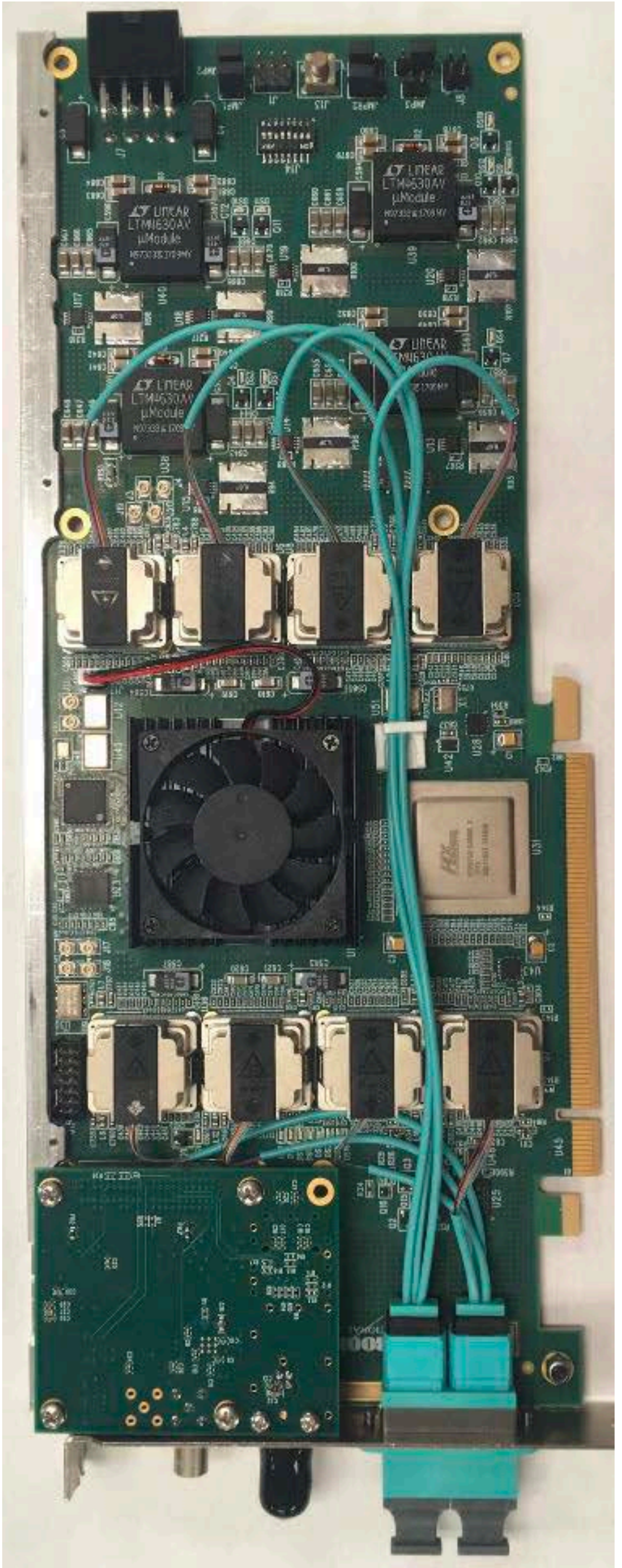


- R&D was already conducted in eRD6
- More R&D needed to build and test a large μRWell prototype
  - ➢ See eRD108 EIC R&D project



Upgrade Path (IV)

- **DAQ:**
  - ➢ In the present design FELIX boards using the GBTx fiber protocol are used
    - as interface between the FEB and the DAQ computers
    - for data aggregation
    - for front end data processing
- Development of a dedicated generic aggregation board consisting of a simplified FELIX-like design to save costs while maintaining the data interface, timing interface and potential trigger capabilities of the board
  - ➢ less expensive FPGA
  - ➢ fiber interface with less stringent radiation-hard requirements
  - ➢ consider the need for the PCIe interface



Examples of Potential Long Term Upgrades

- **GEM-based TRD**
  - ➢ Space is available to introduce a GEM-based TRD in front of dRICH
  - ➢ Enhanced e−h separation power in the forward direction
  - ➢ Intense R&D ongoing to establish the technology to construct a large-scale detector (see Suppl. Mat.).
- **AC-LGAD ToF in Endcaps**
  - ➢ ToF layers by AC-LGAD downstream of the pfRICH and upstream or downstream of the dRICH
  - ➢ Increase of the e-h separation power and h-PID capabilities at low momenta in the endcaps,
- **GridPIX miniTPC**
  - ➢ Could be installed at radii between 20–45 cm.
  - ➢ GridPIX provides spatial and energy measurements with fine-space granularity.
  - ➢ Extend the identified particle reach down to 100 MeV/c through dE/dx and provide tracking information.
- **ZDC**
  - ➢ The ZDC hadronic calorimeter could be improved by adding another interaction length (an additional 17 layers), and a tail-catcher (independent readout of the final few layers) to further improve energy resolution for neutrons at high energies.
- **pHCal**
  - ➢ A region of the pHCal close to the beam pipe has a potential upgrade path to replace scintillation tiles with Si sensors.
- **Nanowire-based RPs**
  - ➢ Superconducting nanowire particle detectors are under development for the EIC (eRD28) and might provide an upgrade for the RP silicon sensor technology.
  - ➢ Excellent position and time resolution, radiation hard, and can operate in high magnetic fields (5T).