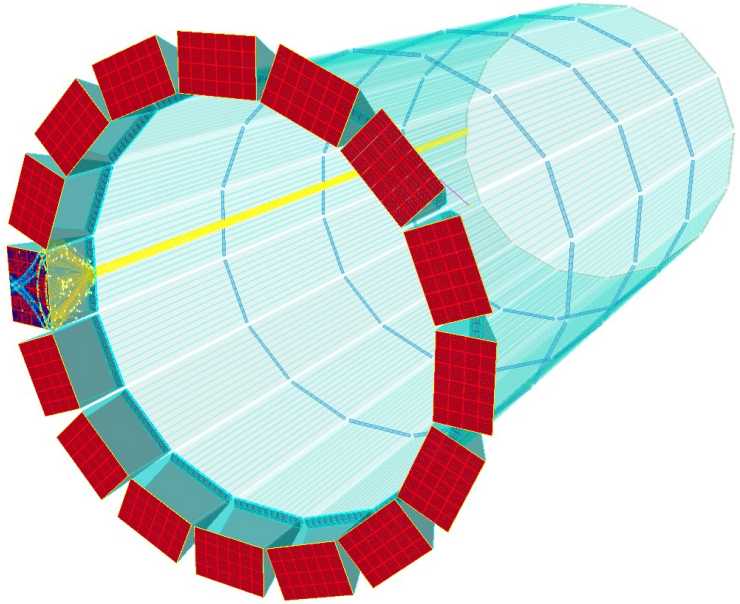
The High-Performance DIRC

Greg Kalicy — CUA

Jochen Schwiening — GSI



- **ATHENA and ECCE Geometries:** almost identical designs, no difficult decisions to make
- **Design details**
- **Key R&D projects:** Test bench tests, and Prototype
- **Photosensors and magnetic field**
- **Simulation in DD4HEP and F4A**

eRD103 hpDIRC Group

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CUA · FAU Friedrich-Alexander Universität Erlangen-Nürnberg · GSI · University of Hawai'i · Jefferson Lab · Old Dominion University · University of South Carolina · Stony Brook University

HPDIRC CONCEPT

Concept:

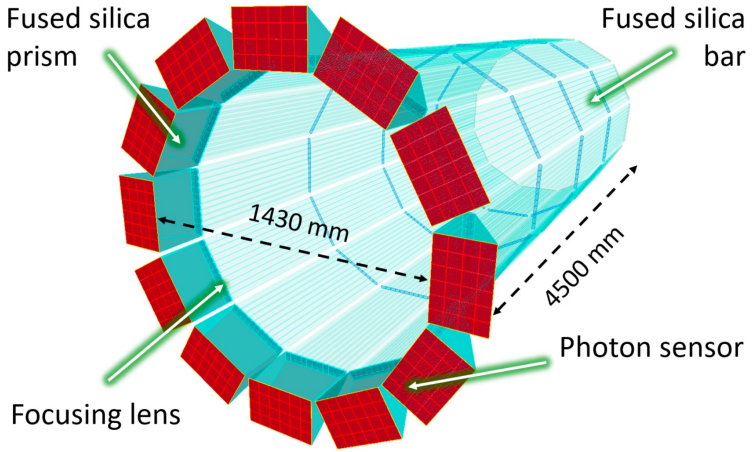
- Fast focusing DIRC, utilizing high-resolution 3D (x,y,t) reconstruction
- Innovative 3-layer spherical lenses, compact fused silica expansion volumes
- Fast photon detection using small-pixel MCP-PMTs *(eRD14)* and high-density readout electronics *(eRD14)*

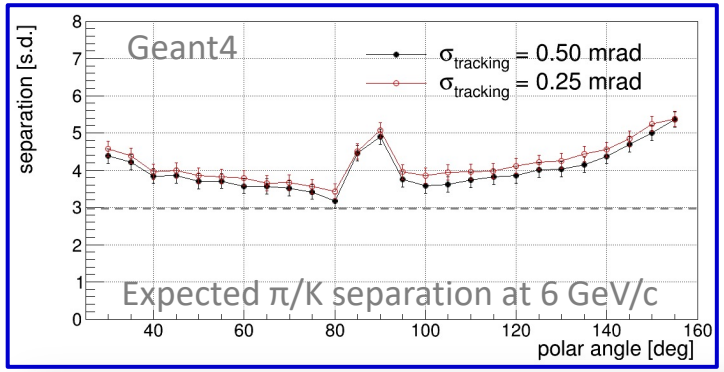
Excellent performance over wide angular range:

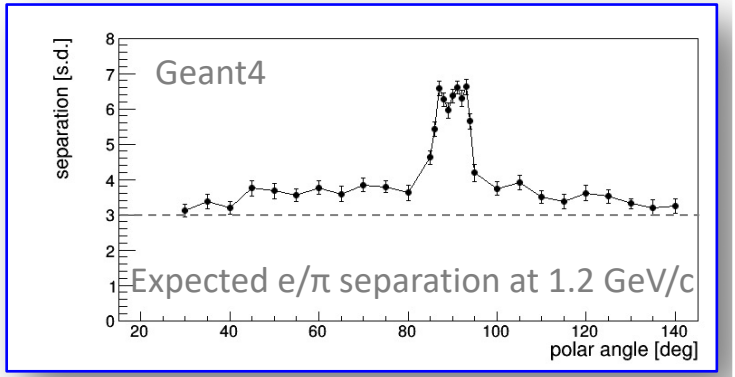
- ≥ 3 s.d. π/K up to 6 GeV/c, ≥ 3 s.d. e/π up to ~1.2 GeV/c
- Low momentum π/K identification in "veto mode" down to 0.2-0.3 GeV/c

Key Features:

- **Radially compact** (~6 cm; impact on cost of post-DIRC systems)
- **Flexible design** (to deal with sensor in B-field and detector integration)
- **Low demand on detector infrastructure** (no cryogenic cooling, no flammable gases)
- **R&D at advanced stage** (PID performance estimate based on test beam results, excellent agreement between detailed simulation and prototype data, fast simulation available)

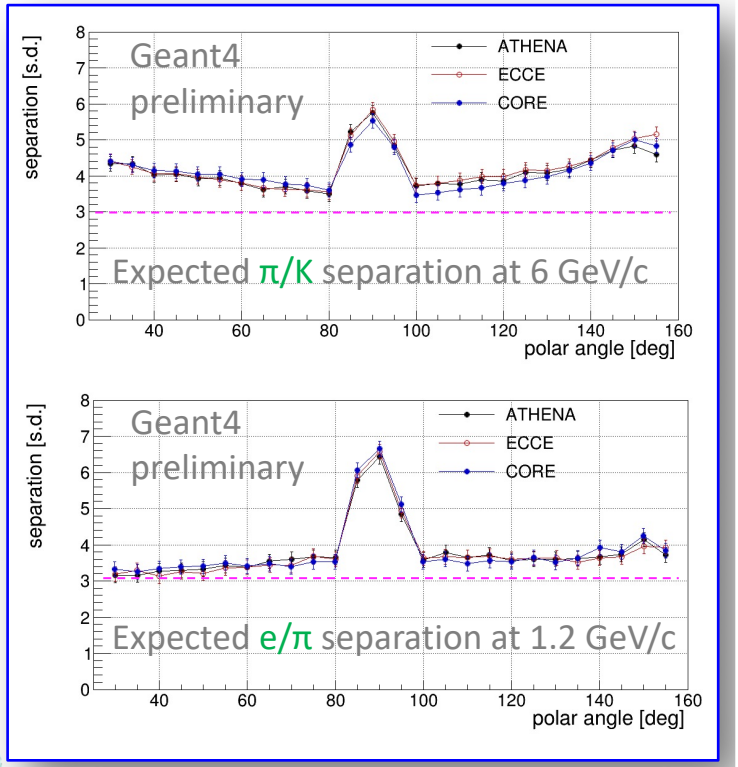


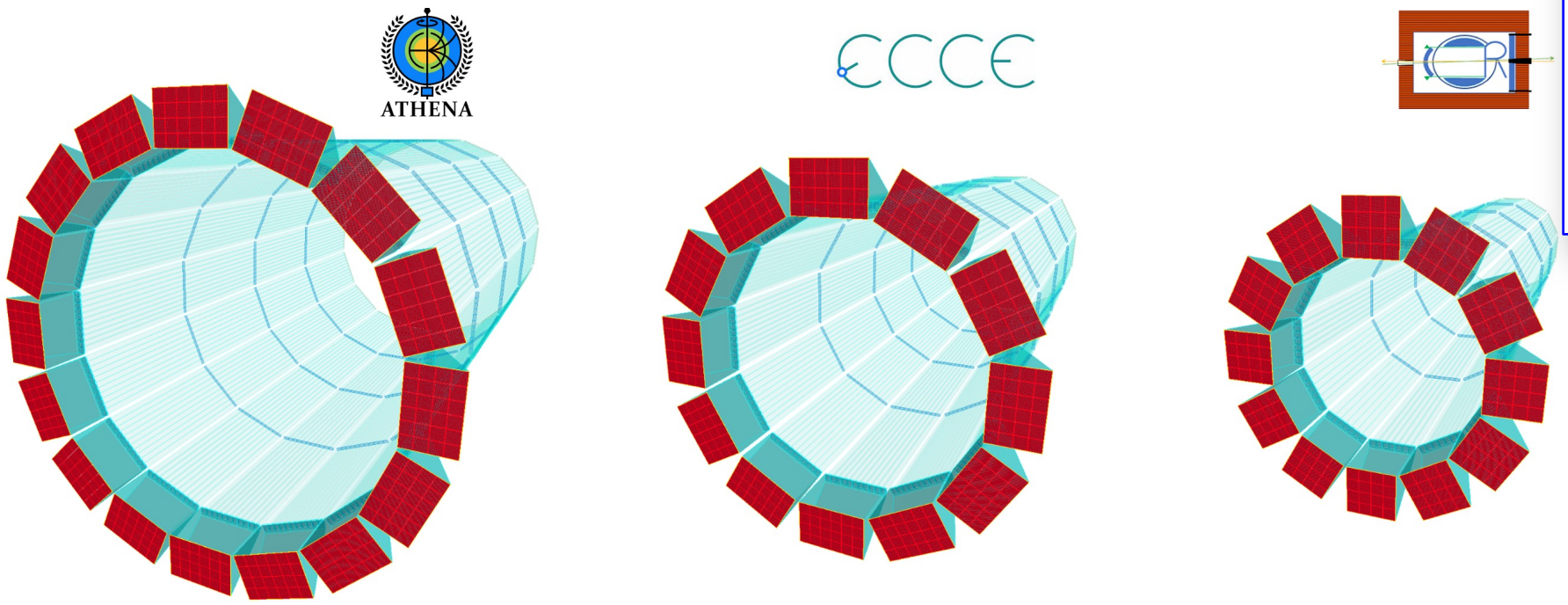




HPDIRC IN PROPOSALS

PID performance largely independent of number of sectors, barrel radius, and bar length!

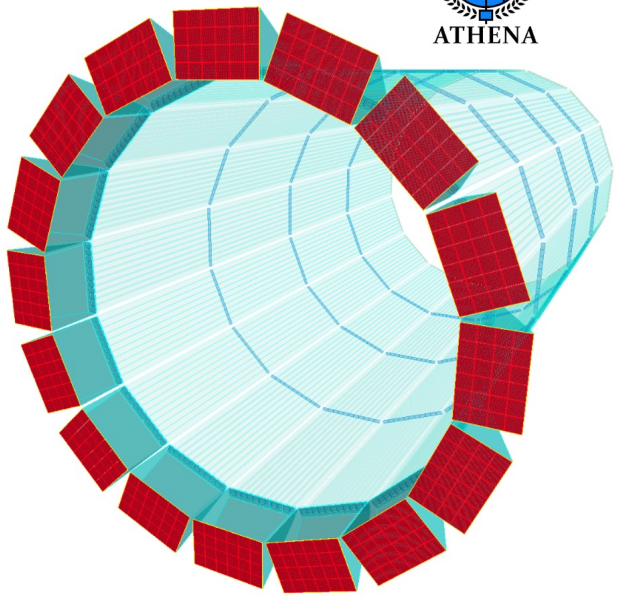




Geant4: hpDIRC designs to scale

HPDIRC IN PROPOSALS

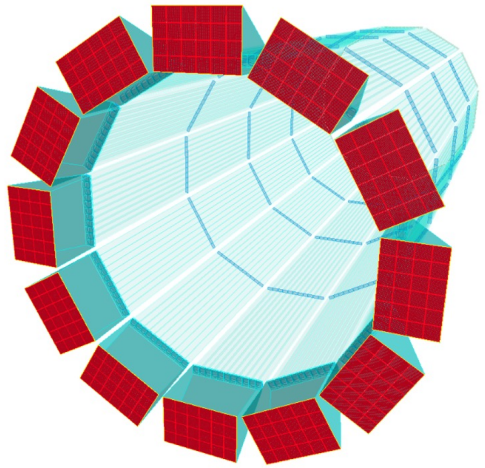
ATHENA



ATHENA Geometry:

- **barrel radius: 964.5 mm**
  (middle of the barbox at 90 degree)
- **number of bar boxes: 16**
- **bar box width: 350 mm**
- bar length: 4400 mm
- number of bars in bar box: 10
- PMT layout: 6x4

ECCE

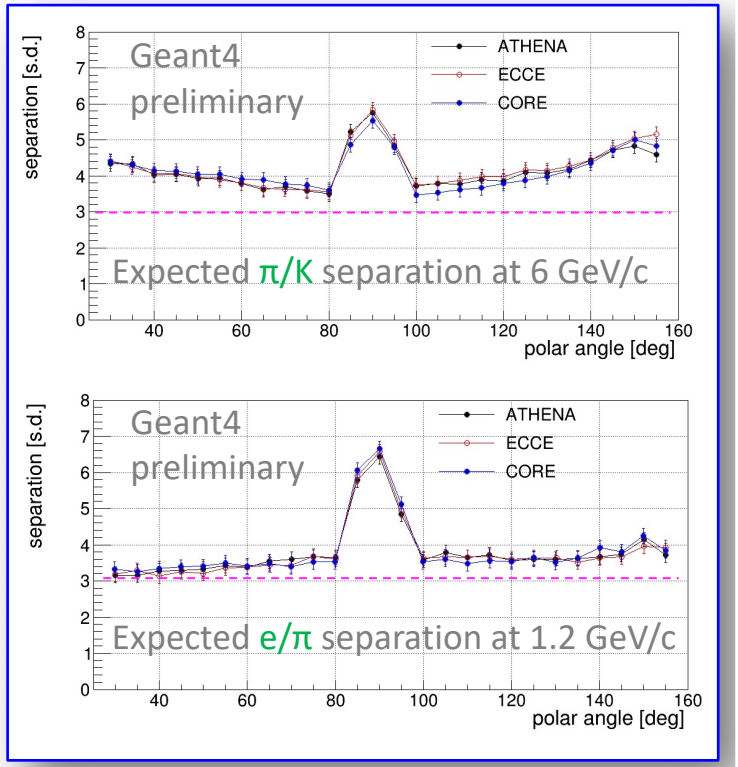


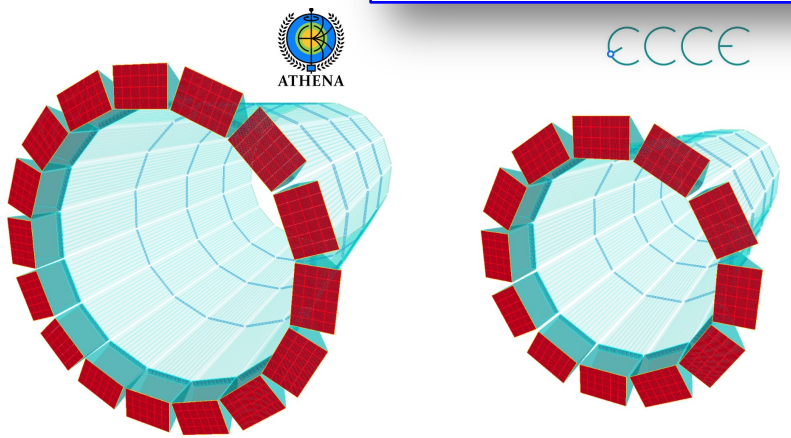
ECCE Geometry:

- **barrel radius: 730 mm**
  (middle of the barbox at 90 degree)
- **number of bar boxes: 12**
- **bar box width: 362 mm**
- bar length: 4200 mm
- number of bars in bar box: 10
- PMT layout: 6x4

HPDIRC IN PROPOSALS

- hpDIRC designs for ATHENA and ECCE are functionally identical
- Both use the same components:
  BaBar DIRC bars, spherical lenses, prisms, sensors, electronics. All those components are interchangeable.
- The only differences are the radius (120 fewer BaBar DIRC bars needed for ECCE) and overall length.
- The only hpDIRC component that needs to be adjusted is the length of the lightguide section of the bar box, coupling the BaBar DIRC bars to the lens and prism
- The remaining R&D is identical for the ATHENA and ECCE designs





Geant4: hpDIRC designs to scale

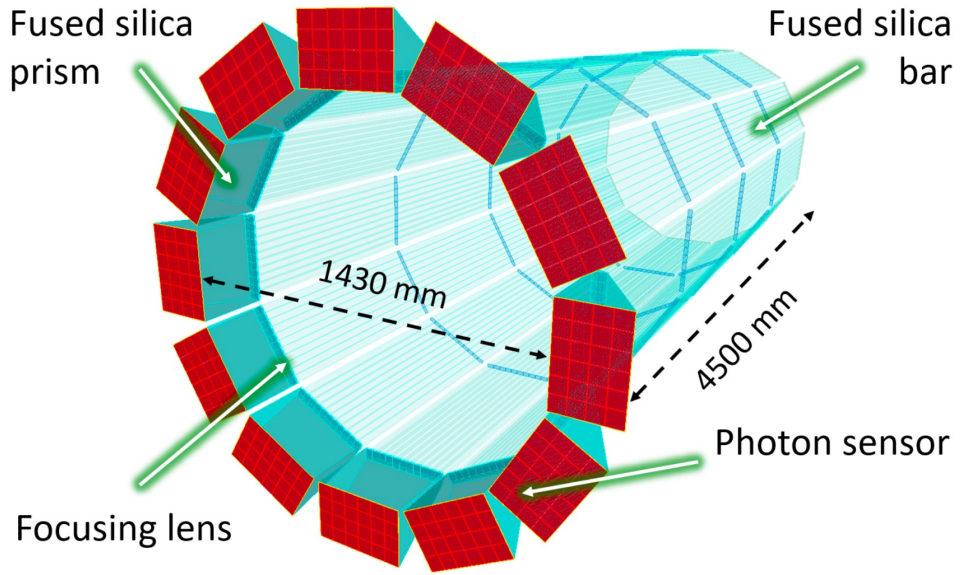
EIC HPDIRC

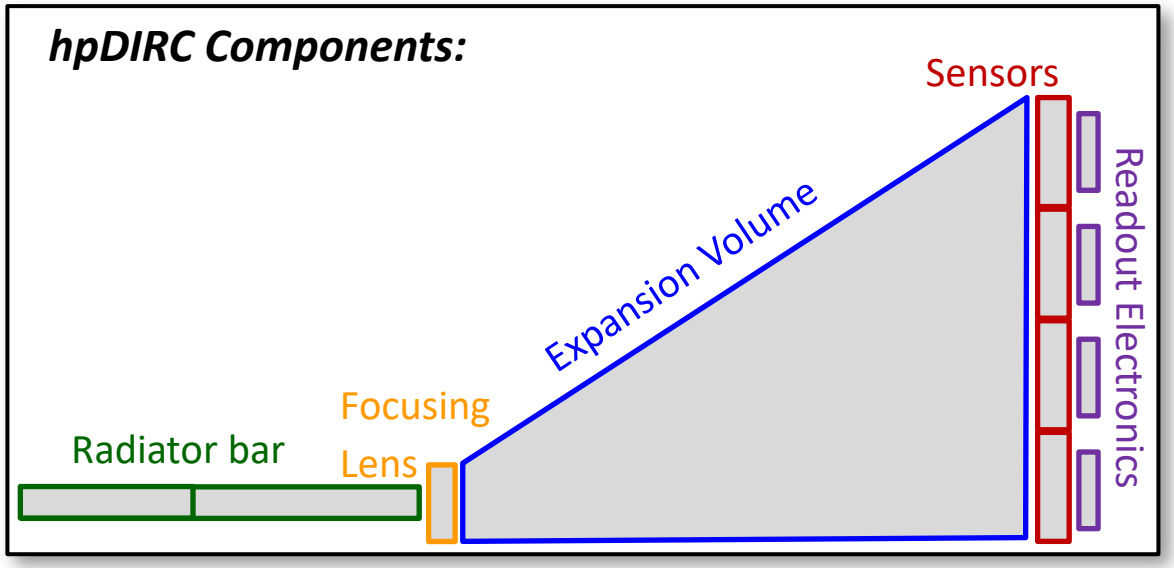
- **Barrel hpDIRC with 72cm radius**
- **Radiator bars:**
  - **420cm bar length** (works with both reused BaBar DIRC bars or new bars)
  - **12 bar boxes**, 10 long bars side-by-side in a bar box, 3 BaBar DIRC bars plus one half BaBar DIRC bar glued to form one long bar (or 3 BaBar DIRC bars plus one new short plate)
- **Focusing optics:**

  Radiation-hard 3-layer spherical lens
- **Expansion volume:**

  Solid fused silica prism: 24 x 36 x 30 cm^3 (H x W x L)
- **Readout:**

  PHOTONIS MCP-PMT Sensors + NALU's ASIC based Readout Electronics





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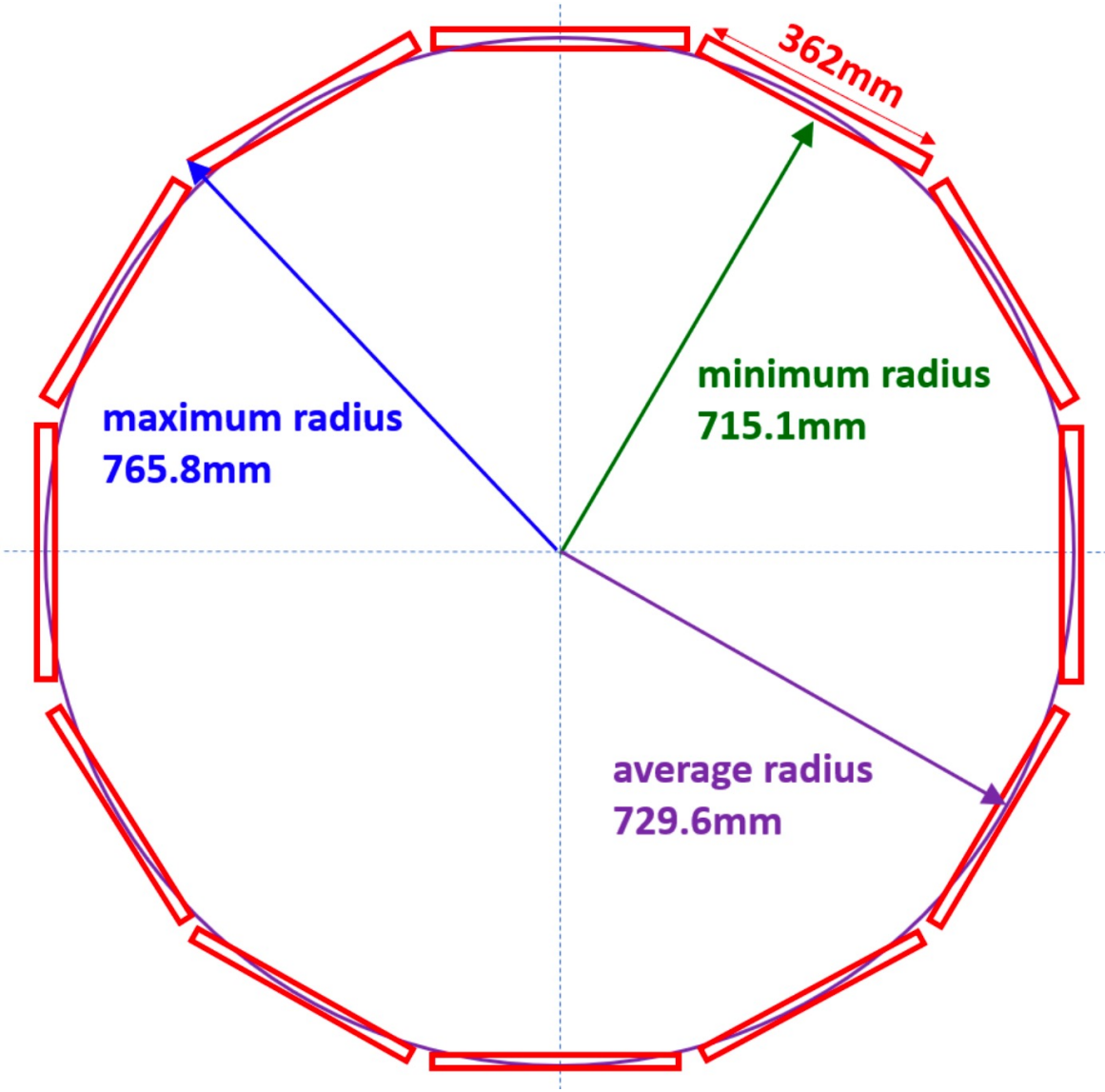

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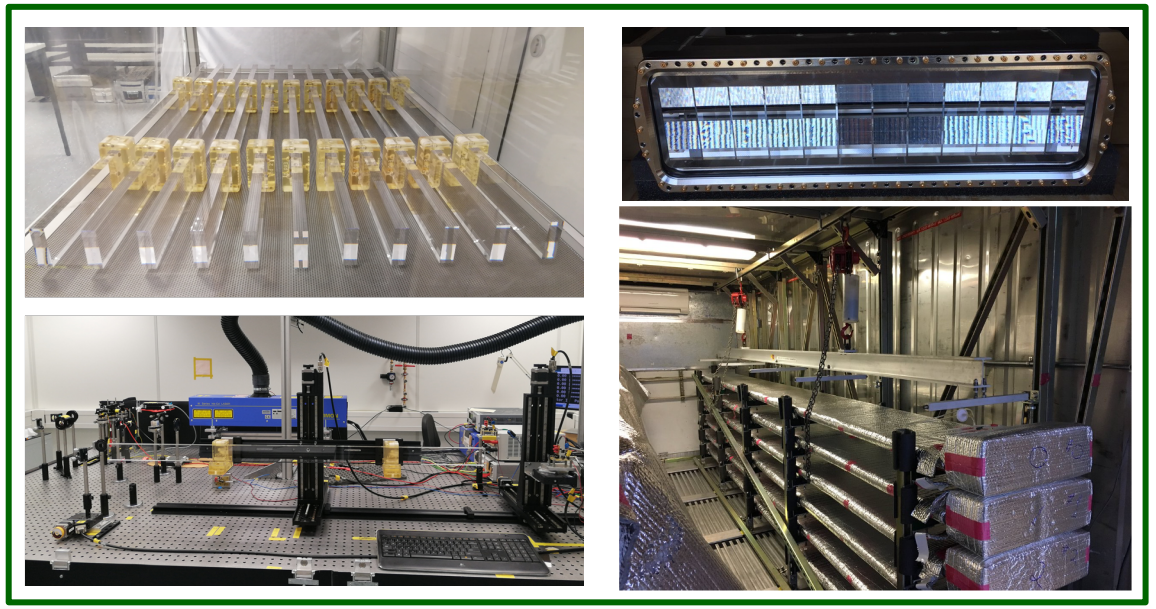

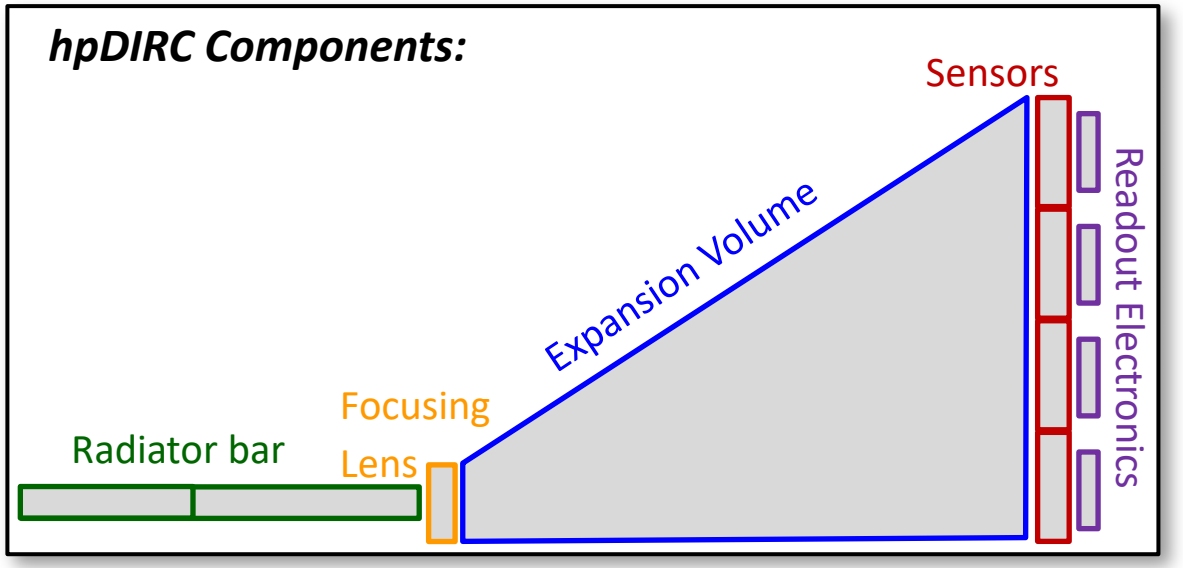

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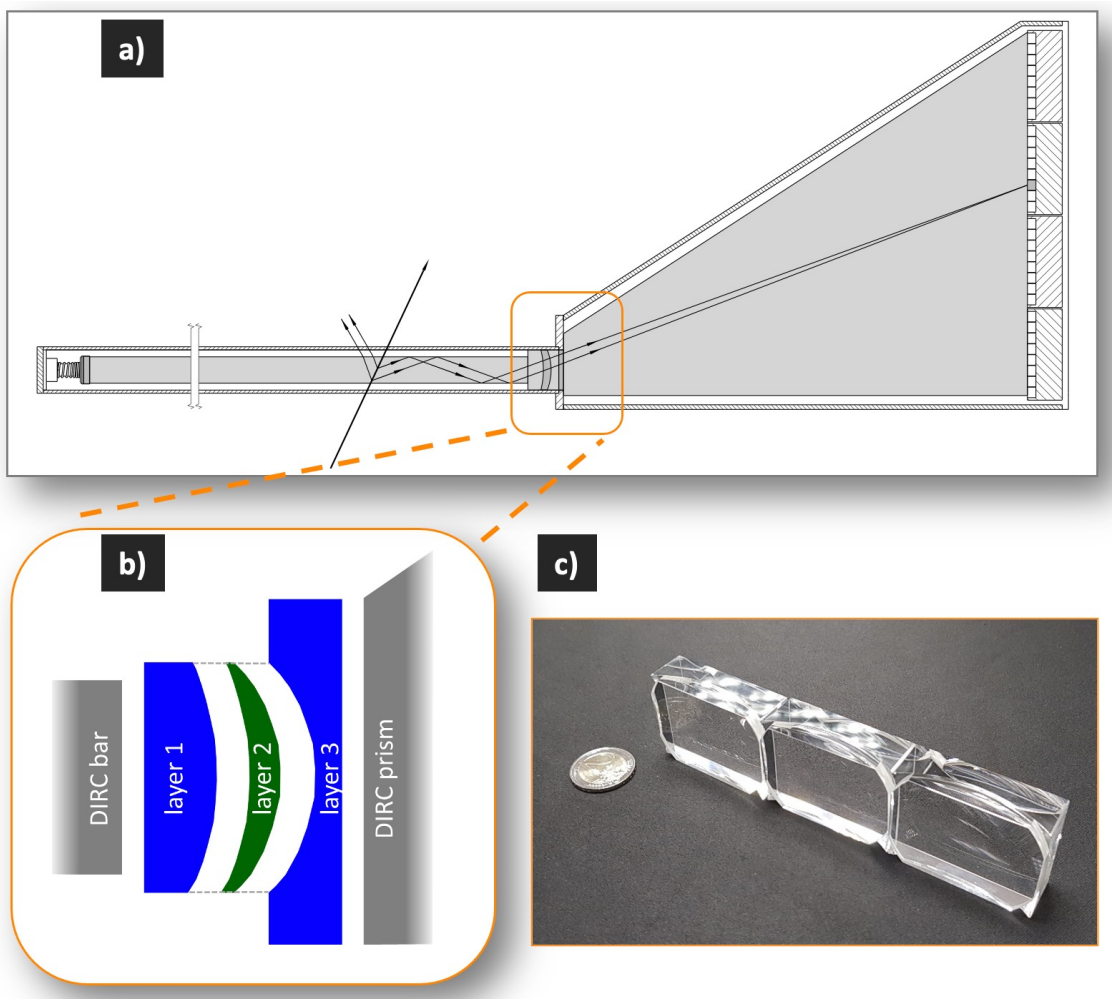

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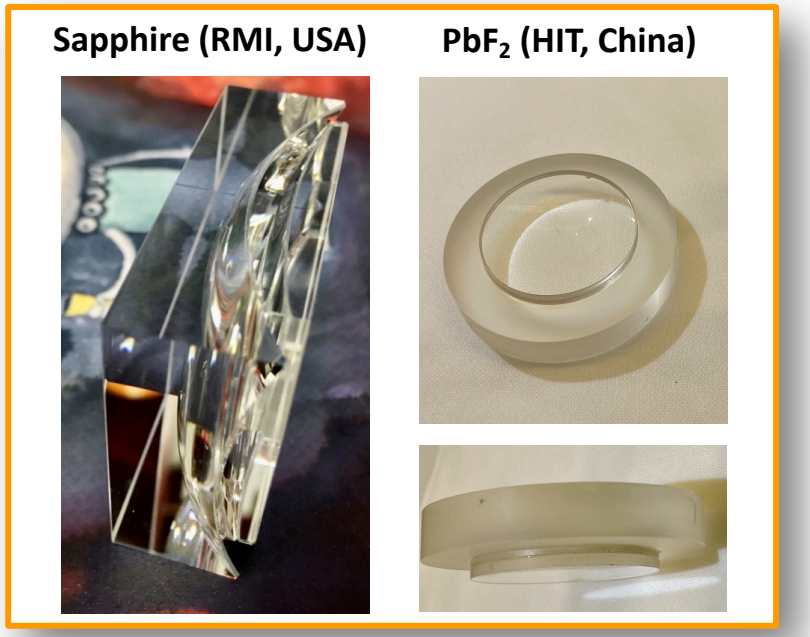

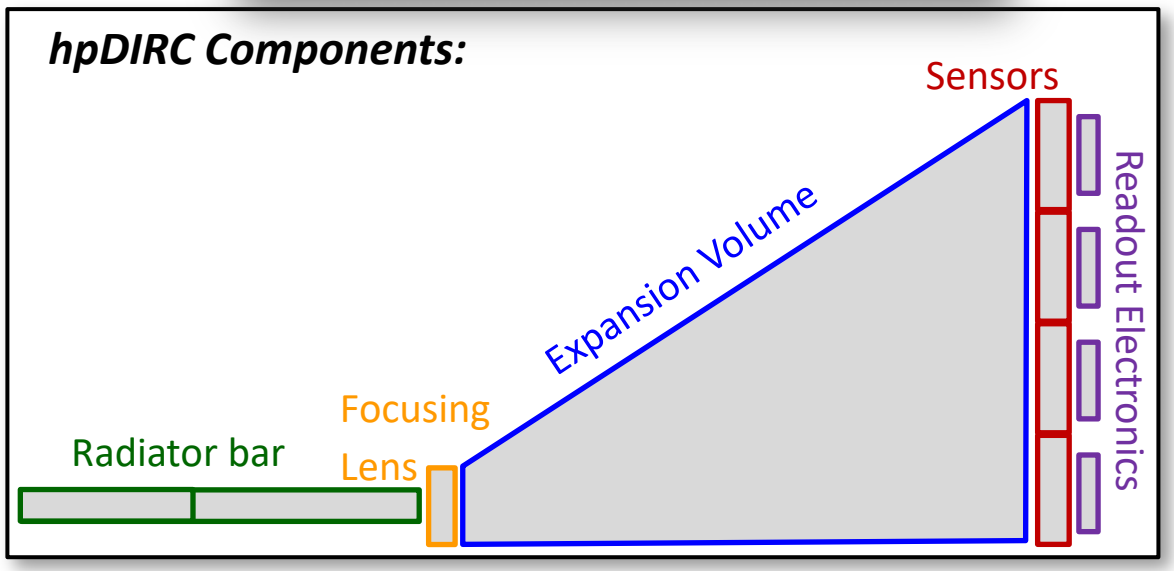

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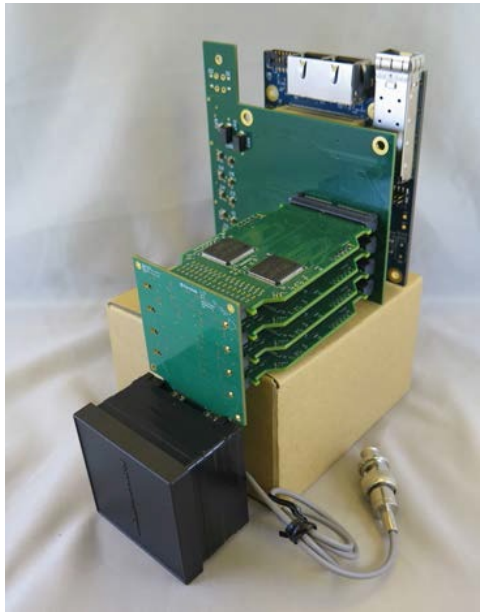
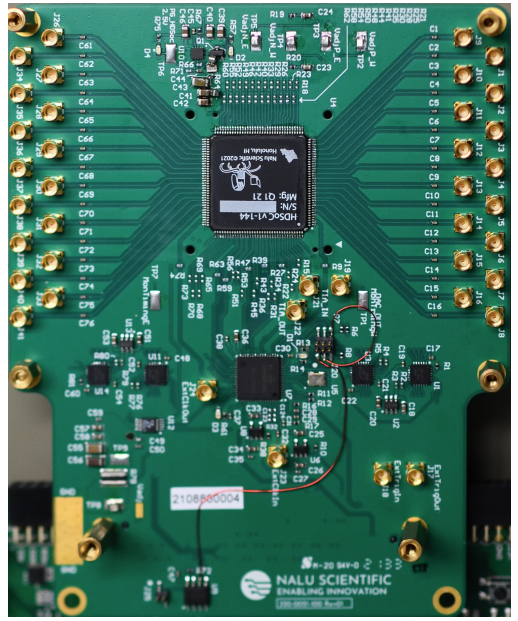
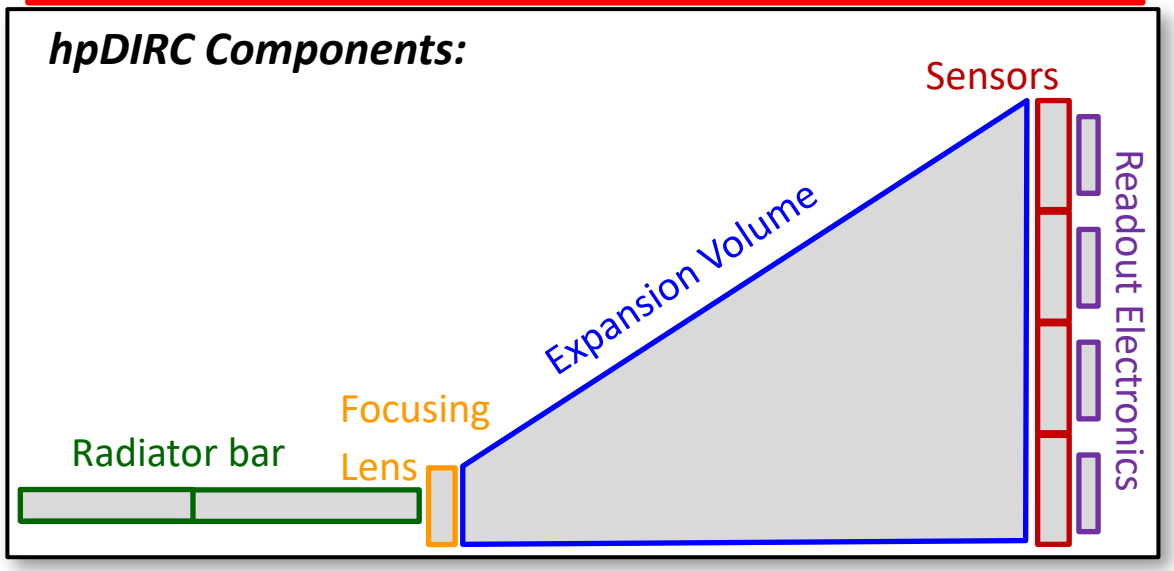


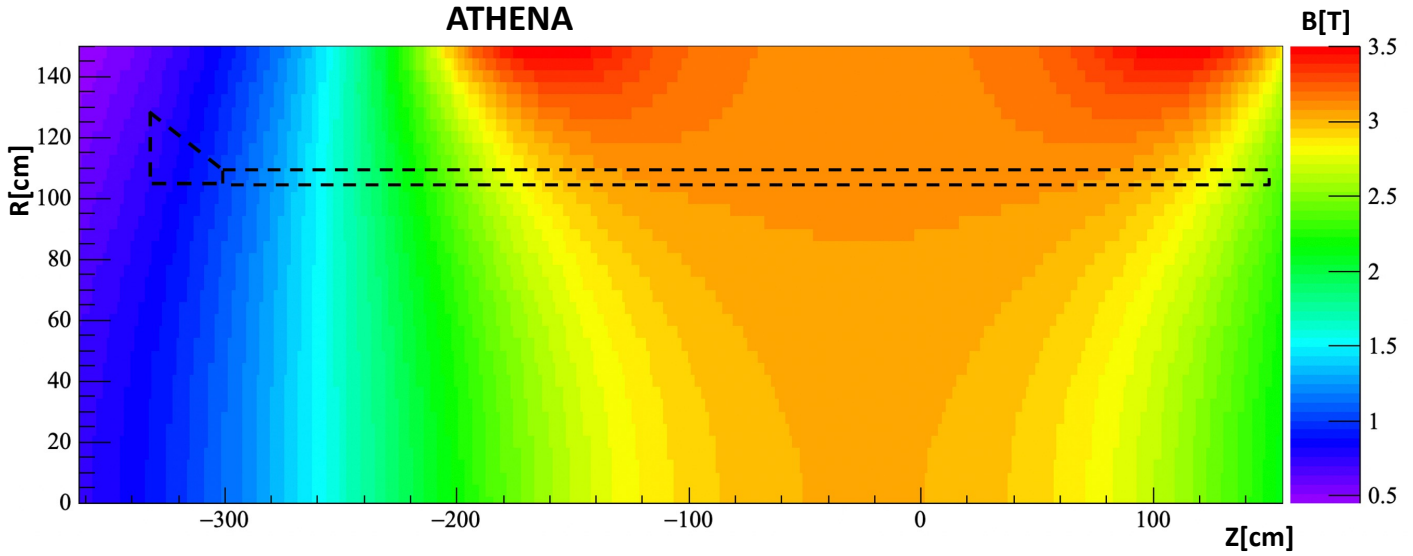


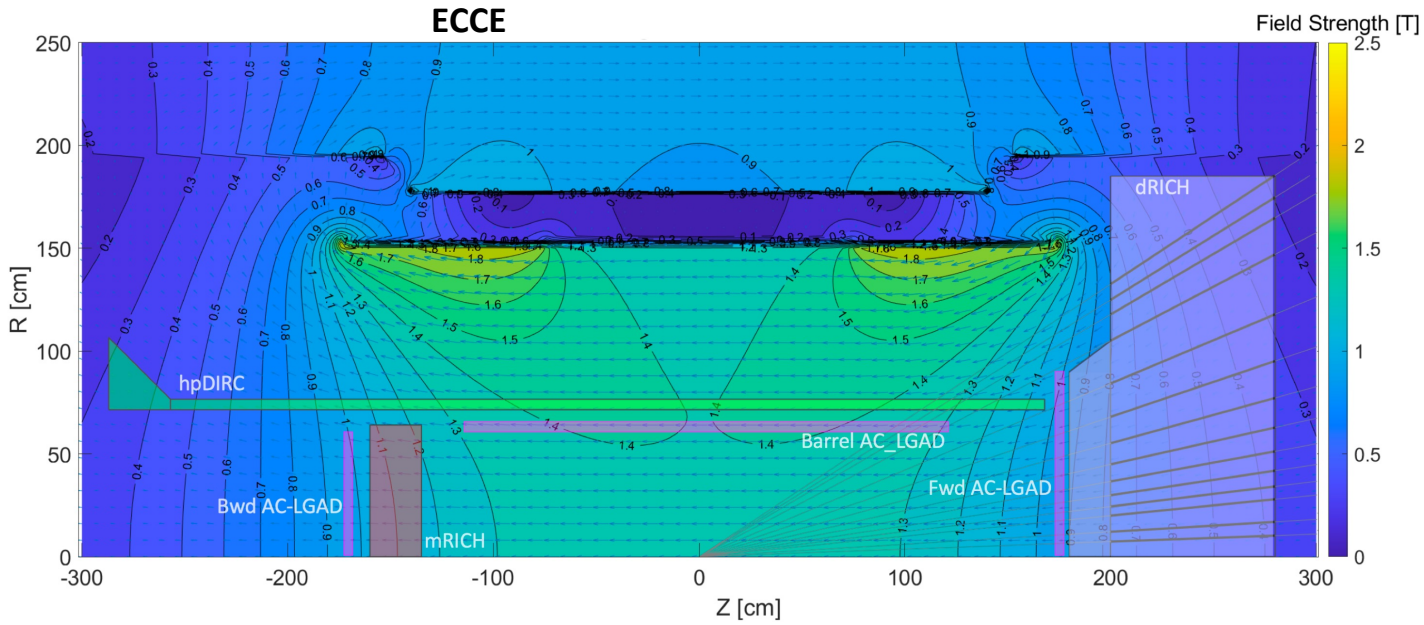


EIC HPDIRC

Photon sensor performance in magnetic field

- Different maturity of sensor development:
  - Established: PHOTONIS XP85122-S
  - Freshly Developed: Photek MAPMT 253
  - Under development: INCOM Gen III HRPPD
- Small-pore MCP-PMTs shown to be OK for fields up to 2 Tesla (see result from A. Lehmann et al. for 6µm-pore 2'' Photek AuraTek MCP-PMT)
- SiPMs as alternative
  (dark noise, radiation damage, cooling, annealing, integration issues)





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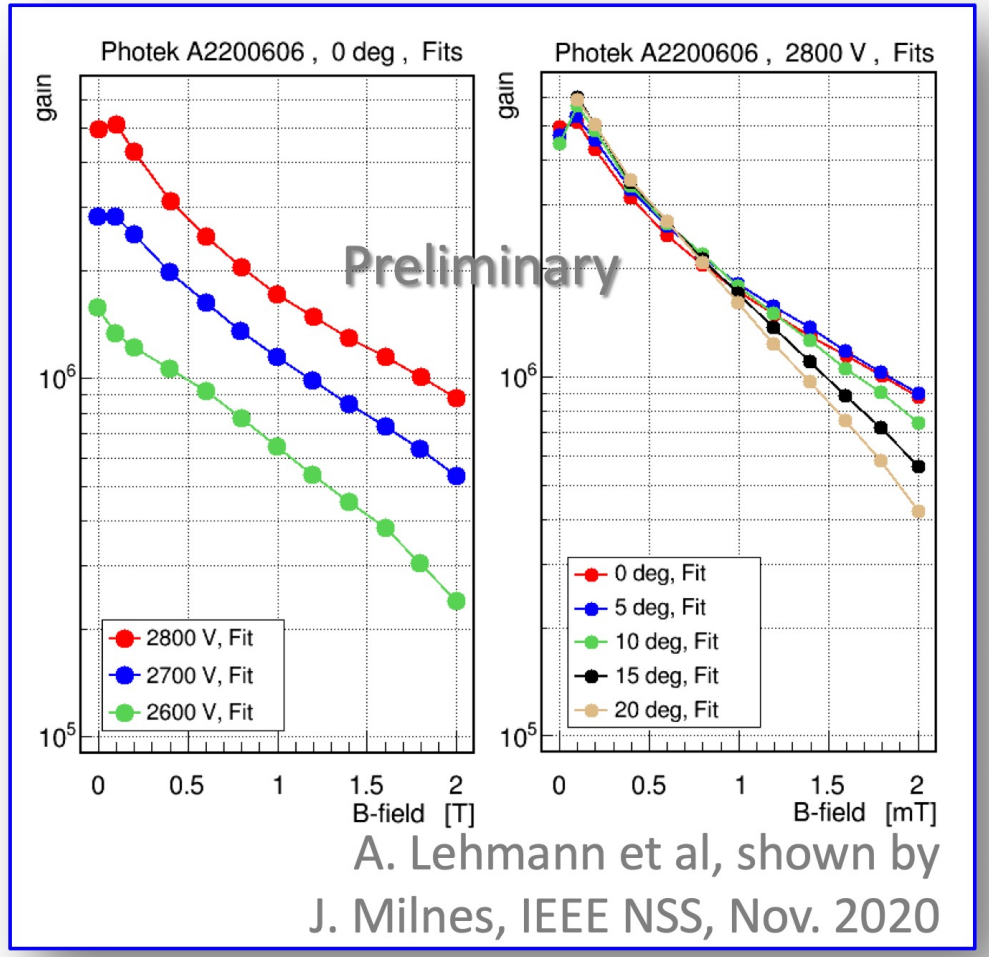
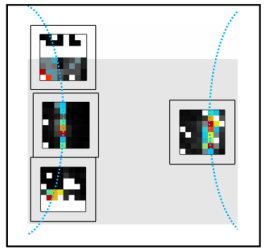
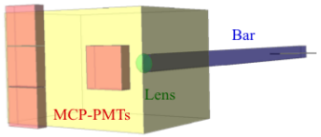
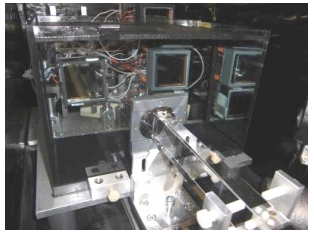


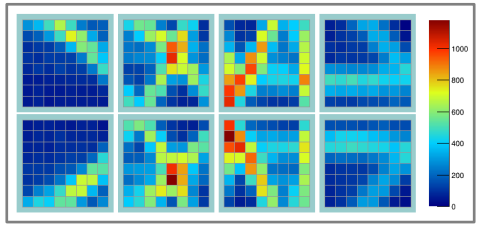
HPDIRC PROTOTYPE PROGRAM



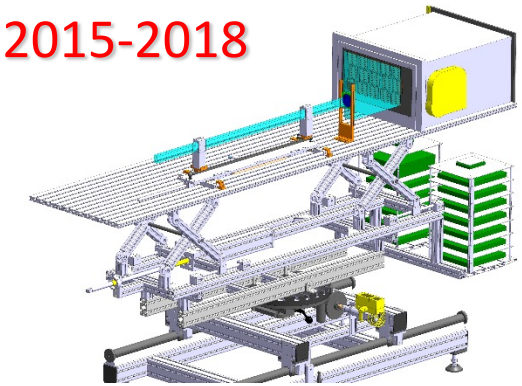


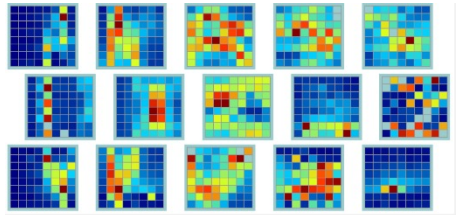
GSI
2008/2009



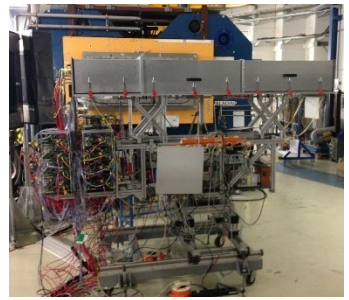


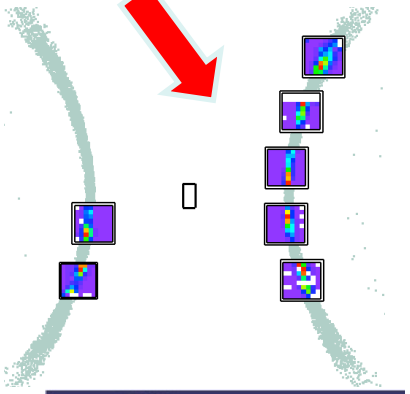
CERN
2015-2018



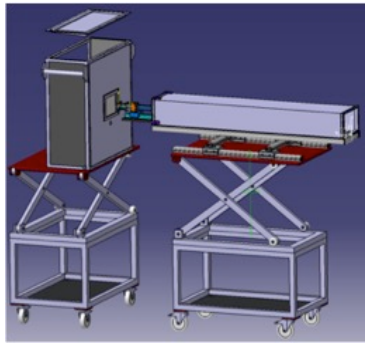


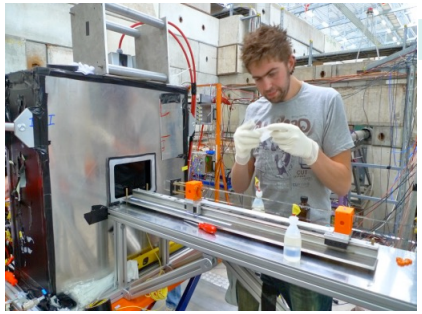
GSI 2014



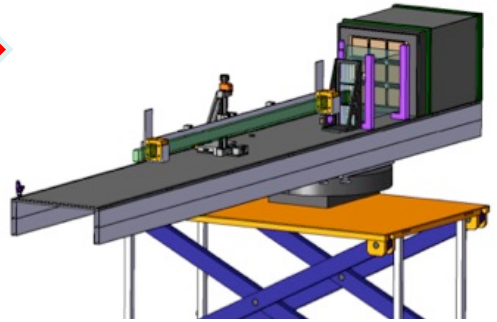


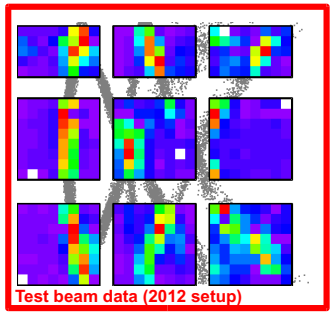
GSI, CERN
2011





CERN
2012





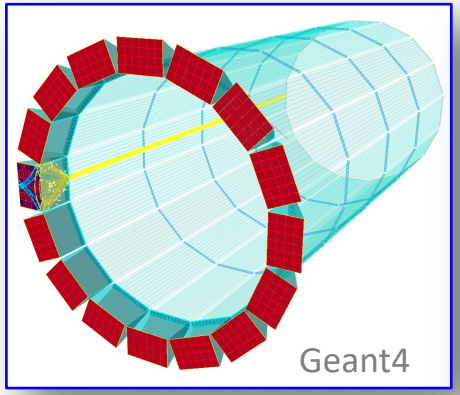
HPDIRC: ACHIEVEMENTS

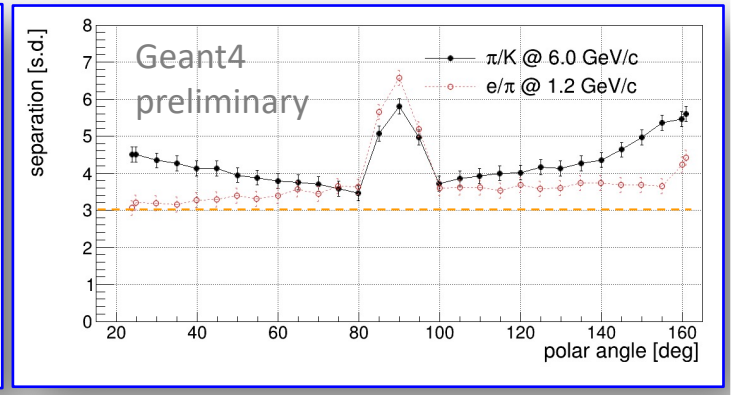
EIC hpDIRC R&D:

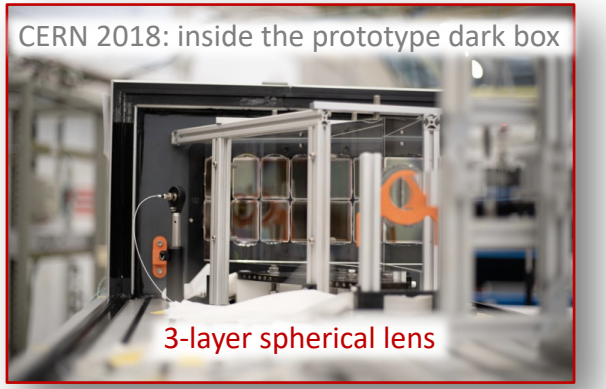
- Collaborative effort since 2011 (eRD4, eRD14, eRD103)

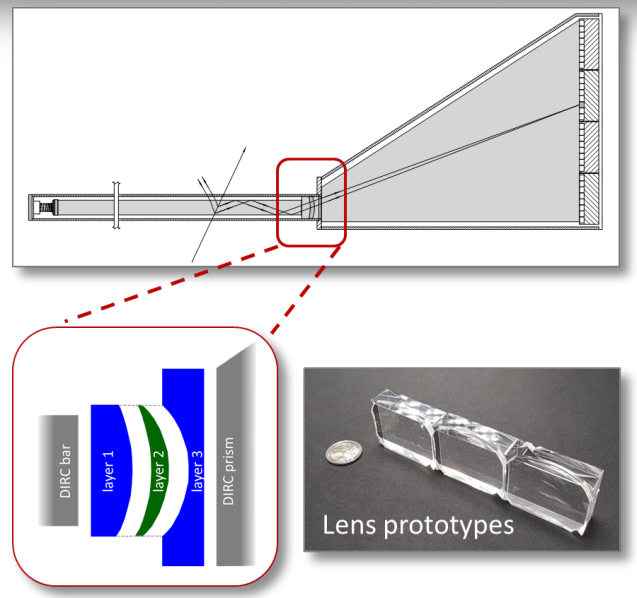
hpDIRC R&D Achievements:

- Developed a very compact barrel EIC PID detector with extended momentum coverage, pushing both the π/K and e/π separation performance well beyond the state-of-the-art for DIRC counters
- Validated performance in detailed Geant4 simulation: 40-120 detected photons per particle, ≥ 3 s.d. π/K at 6 GeV/c
- Developed innovative 3-layer lens, build radiation-hard prototype, and validated properties on testbench and in DIRC prototype with particle beam









HPDIRC: REMAINING R&D

Primary Objectives:

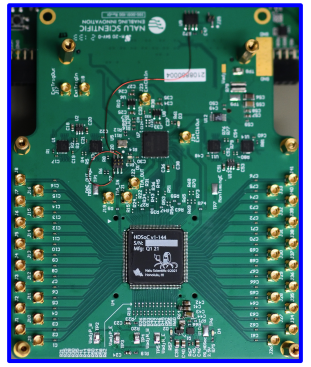
To validate the PID performance of a cost-optimized hpDIRC design for the EIC detector with a vertical-slice prototype in a particle beam by FY24

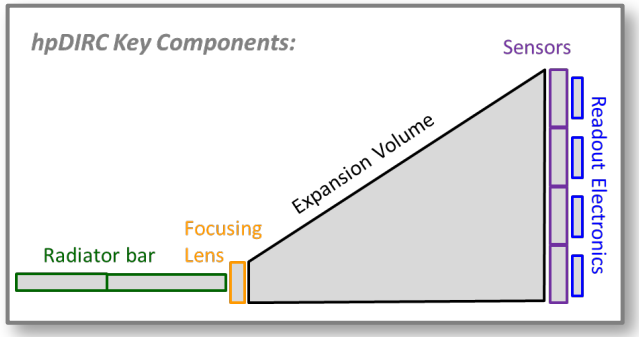
To minimize hpDIRC risks and to realize opportunities:

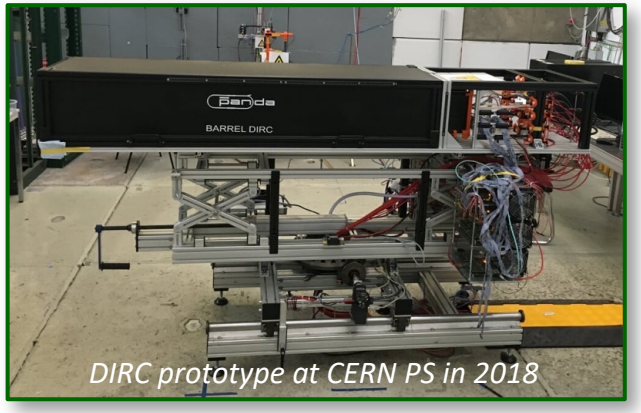
- Technical risk: availability and performance of small-pixel MCP-PMTs and matching fast compact readout electronics
- Technical risk/opportunity: reuse of BaBar DIRC bars
- Technical risk: hpDIRC PID baseline design validation in particle beams
- Technical risk/opportunity: novel hybrid design with narrow bars and wide plate
- Opportunity: cost/performance optimization (simulation and prototype)

Evaluating components and prototypes in DIRC labs (ODU, GSI) and future cosmic ray telescope (SBU), preparing for beam tests at Fermilab

Prototype readout stack at UH/Nalu



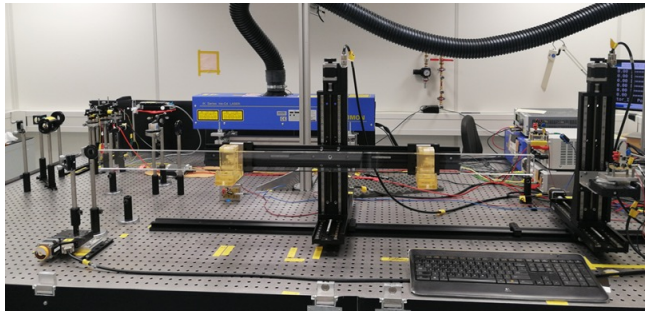


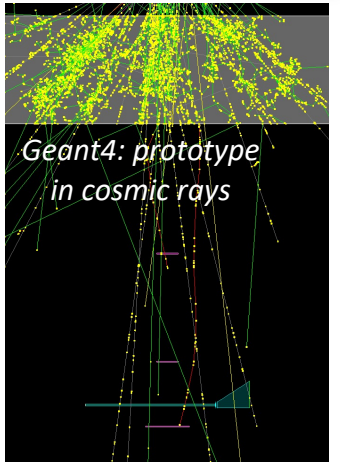


DIRC prototype at CERN PS in 2018

DIRC lab @ ODU

DIRC lab @ GSI



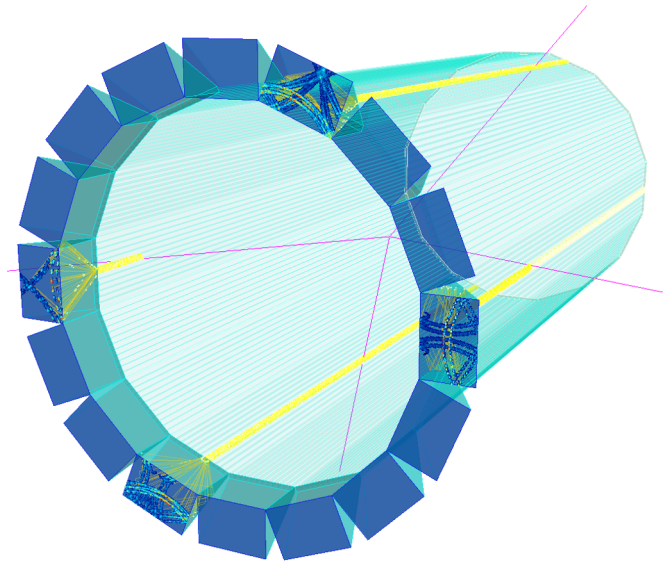


HPDIRC PROTOTYPE: HYBRID RADIATOR DESIGN

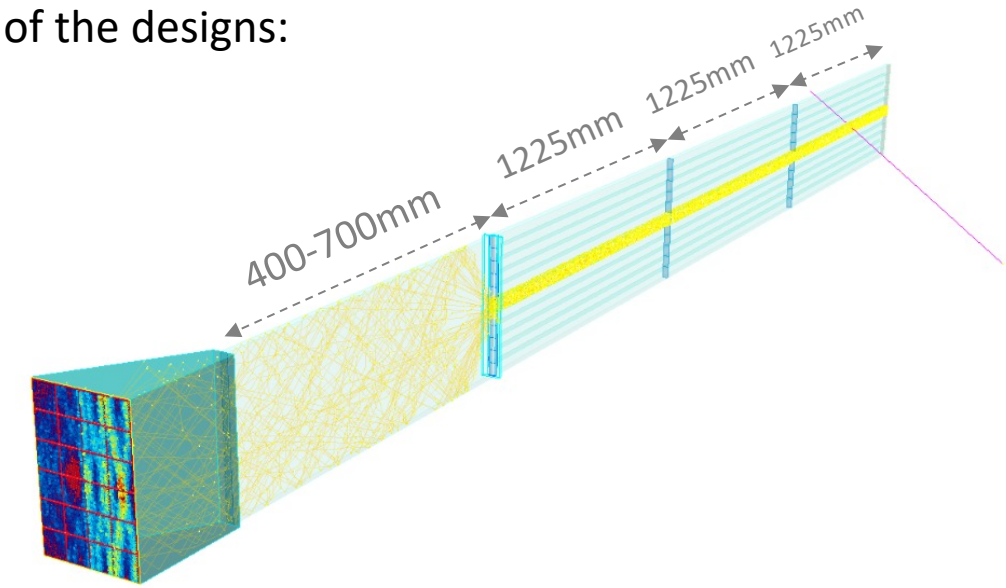
Opportunity: Cost saving and performance improvement

- EIC detector barrel length requires additional fused silica bars or plate to connect BaBar DIRC bars to prism
- Narrow bars could be obtained by cutting and repolishing BaBar DIRC bars or by ordering new bars from industry
- Alternative: use single short wide plate as transition light guide between BaBar DIRC bars and prism
- Would significantly reduce cost compared to new narrow bars and potentially improve hpDIRC performance
- Hybrid designs can be tested in prototype with no investment in new optics (using PANDA DIRC bar, plate and prism)

GEANT4 visualization of the designs:



Narrow bars in each sector



Hybrid of bars and plate in each sector

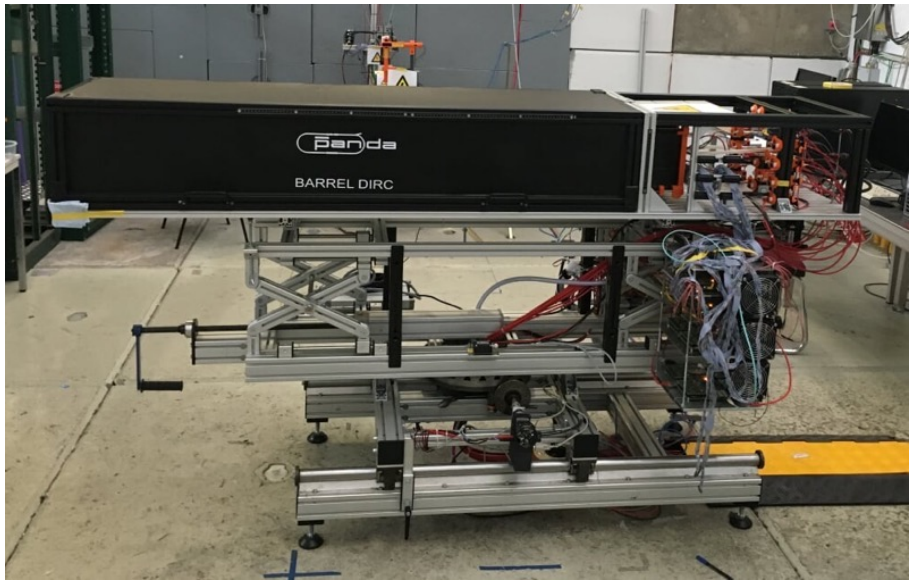
EIC HPDIRC R&D AND QA

Involved Institutions:

- CUA, GSI, ODU, SCU, SBU, JLAB, EU

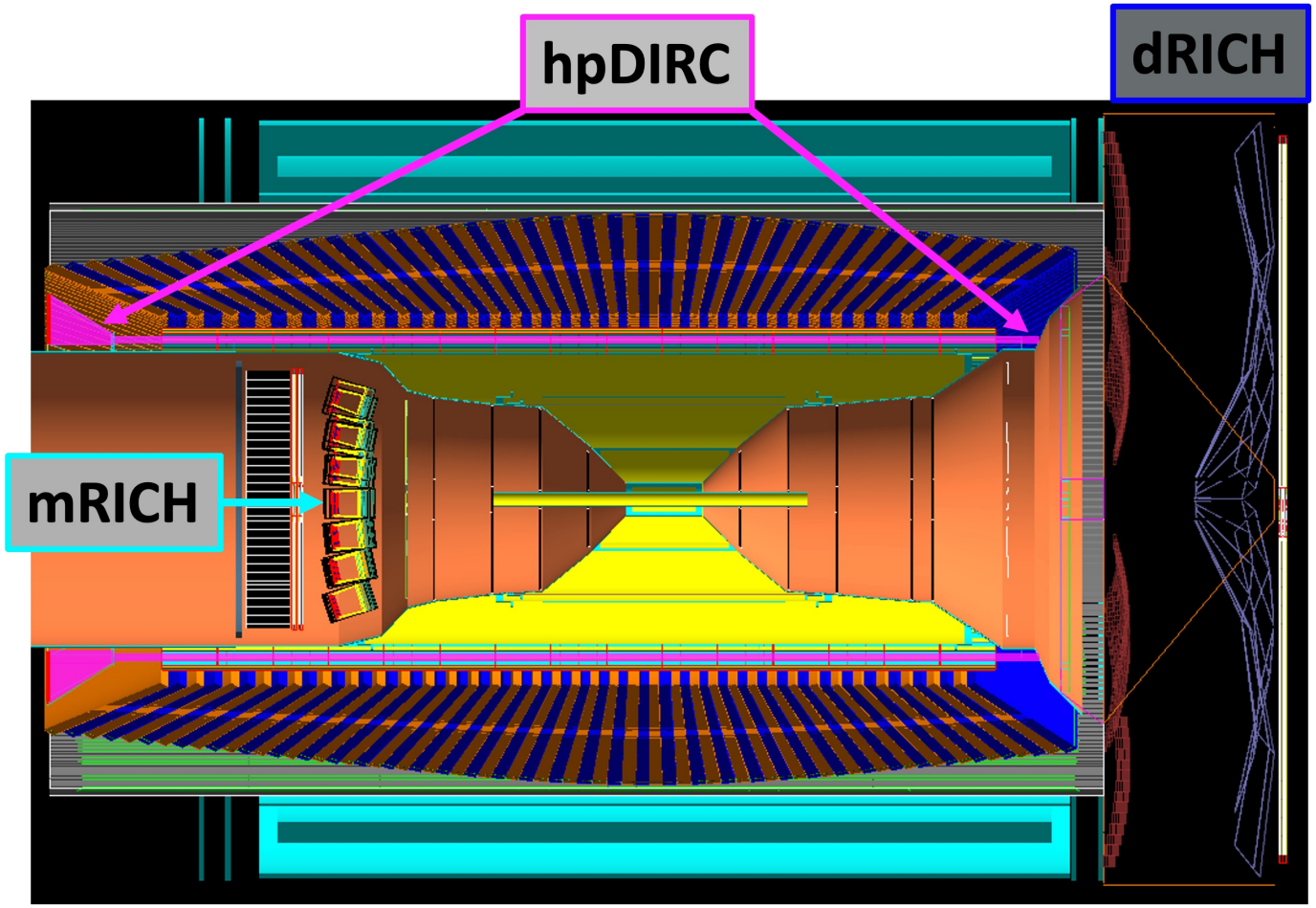
Available Infrastructure:

- Laser lab for lens evaluation at ODU
- HighB Facility in Jlab for sensors studies
- Setup for Bar QA measurements at JLAB or ODU
- Cosmic Ray Telescope (CRT) setup at SBU for prototype development

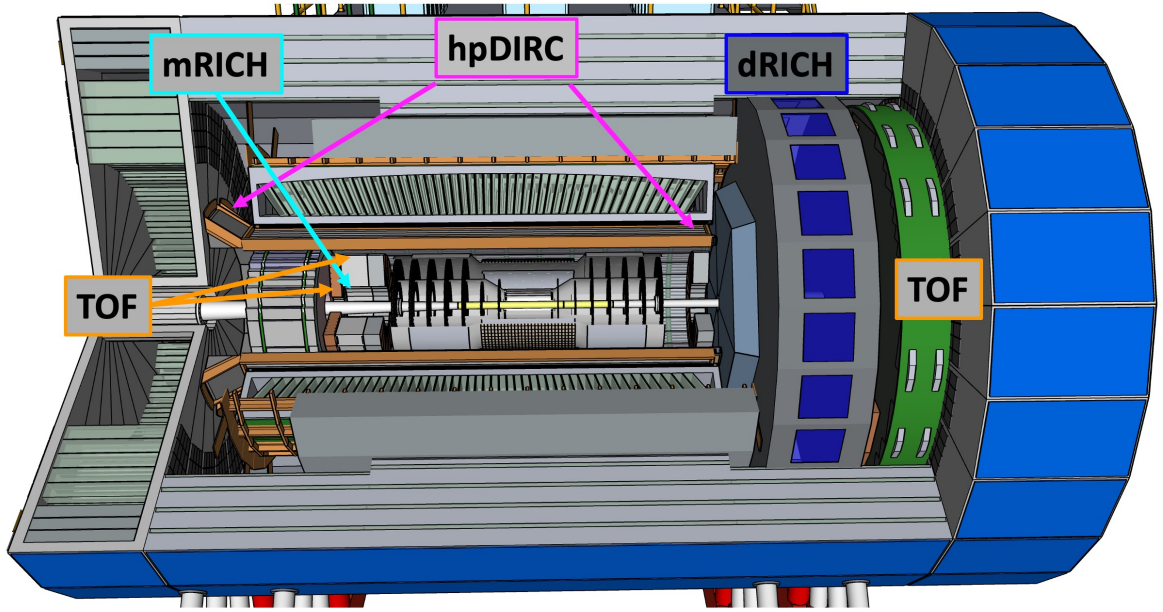


HPDIRC SIMULATION

ECCE Detector F4A Simulation

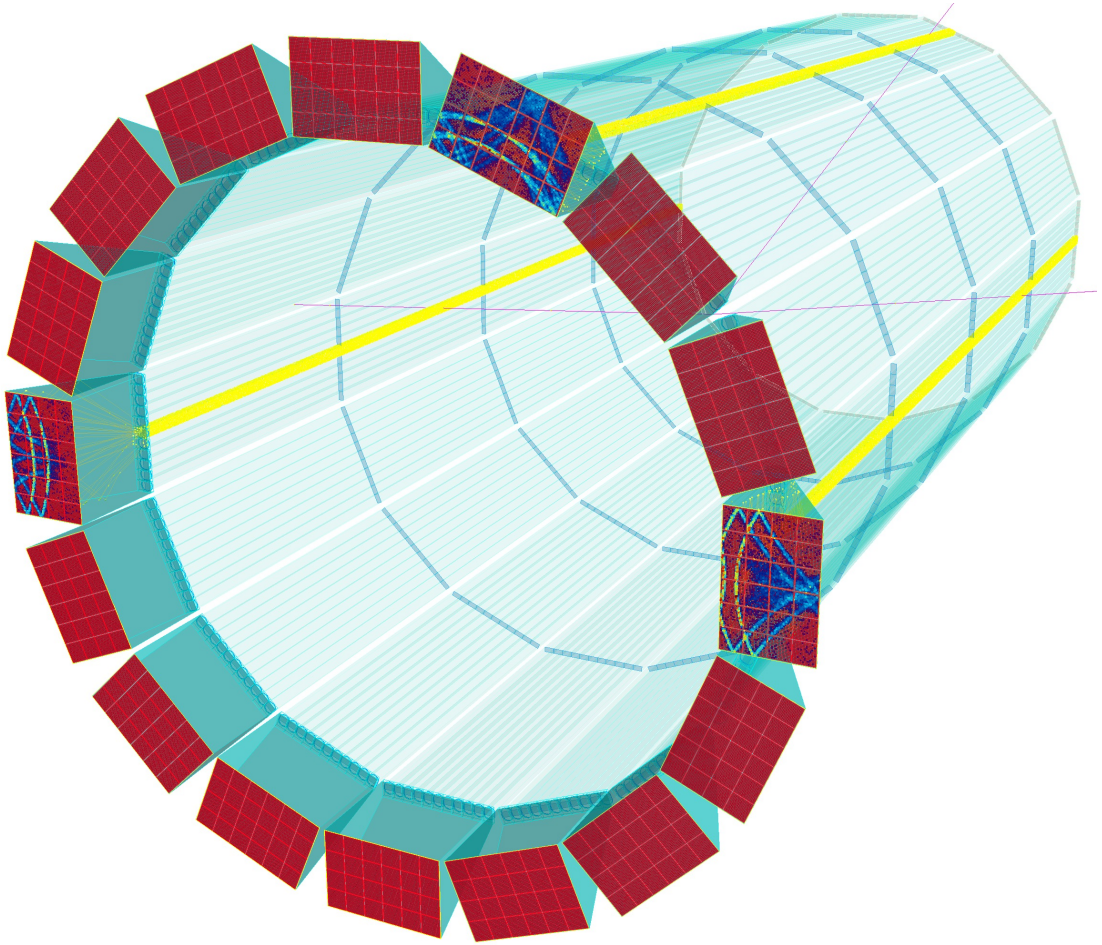


ECCE Detector 3D Model



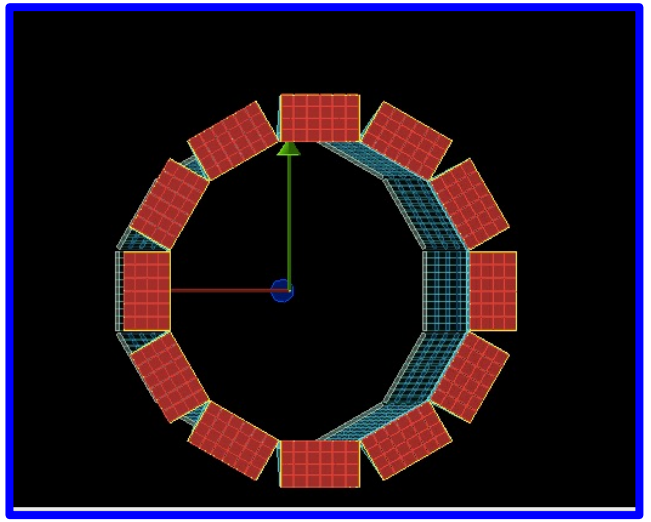
High-performance DIRC: full simulation

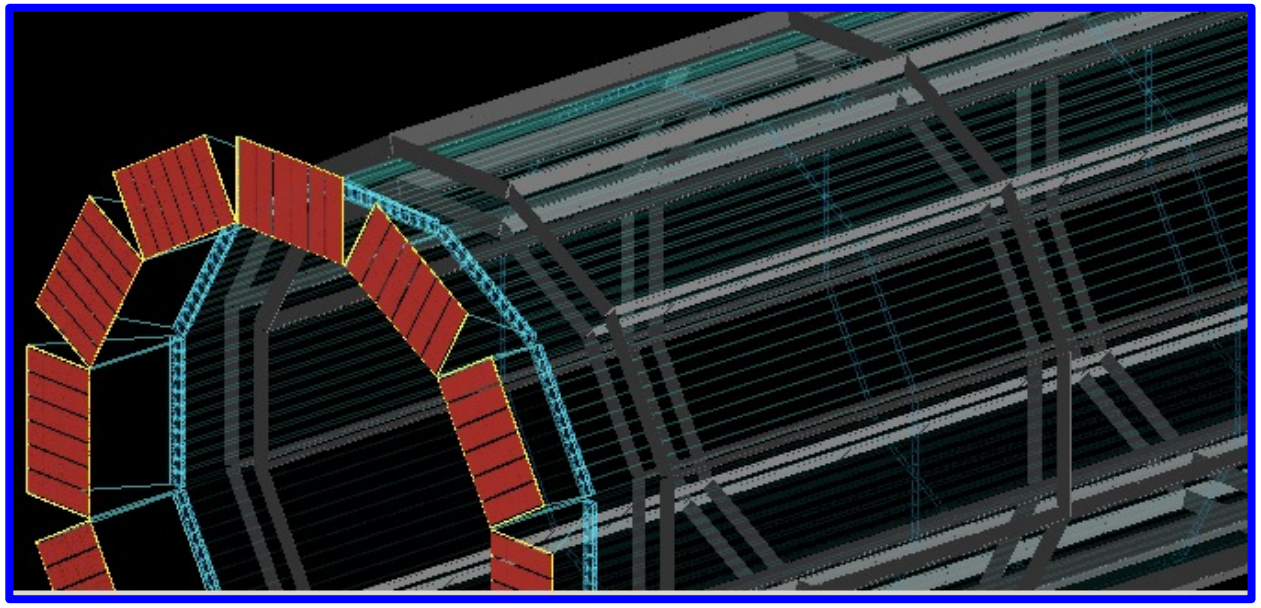
- **Standalone Geant4 simulation**
- **Realistic geometry and material properties based on prototypes**
  - Polished fused silica bars and prism, glue, optical grease
  - 3-layer spherical lens, MCP-PMT, mirror
- **Wavelength-dependent material properties and processes**
  - Refractive index, surface scattering, absorption, reflection
  - Photon transport and detection efficiencies
  - Chromatic dispersion in angle and time
- **Includes all relevant resolution terms**
  - Photon timing precision from MCP-PMT plus readout electronics
  - Tracking resolution
- **Simulation validated with test beam data results**

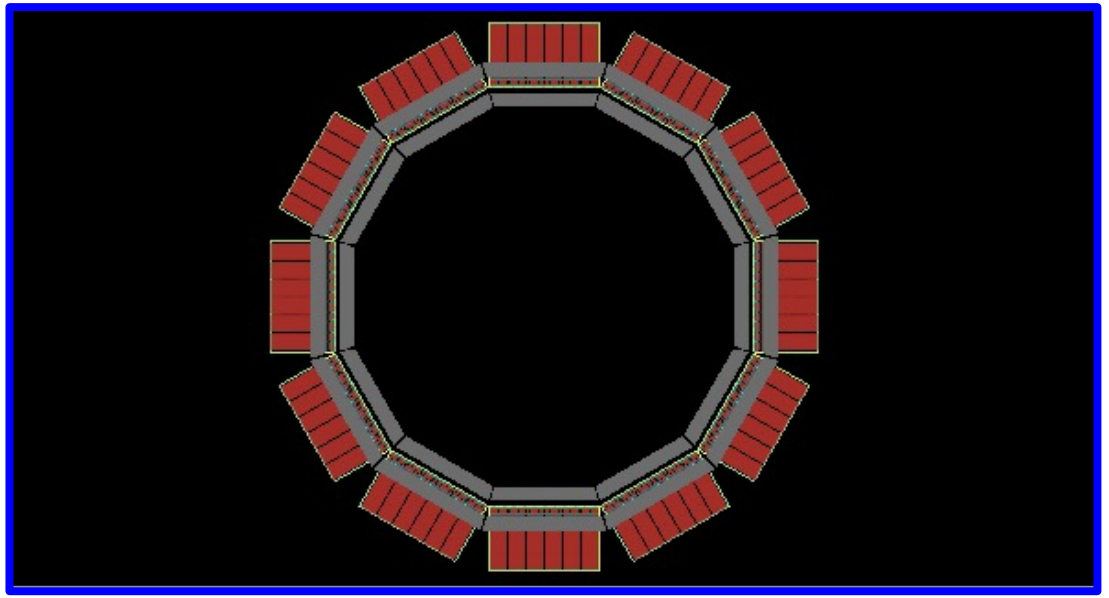


hpDIRC in Fun4All

- Geant4 stand alone hpDIRC fully ported and validated.
- hpDIRC in Fun4All is at an advanced state
- Support structure is part of DIRC class, might needs some improvement.
- Detailed comparison of observables and PID performance to the standalone Geant is ongoing, including the study of the hpDIRC performance in magnetic fields, with physics events (multiple tracks in sectors or bars) and with backgrounds

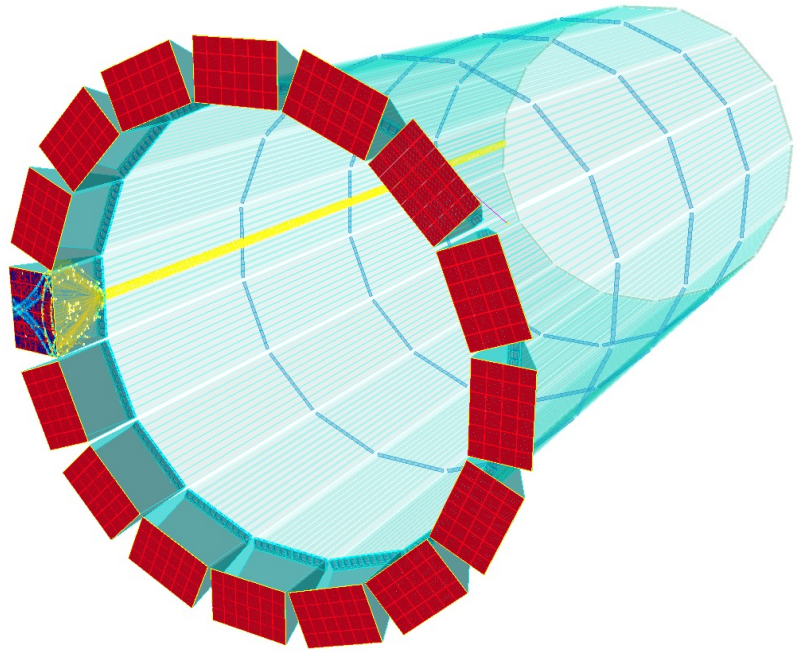






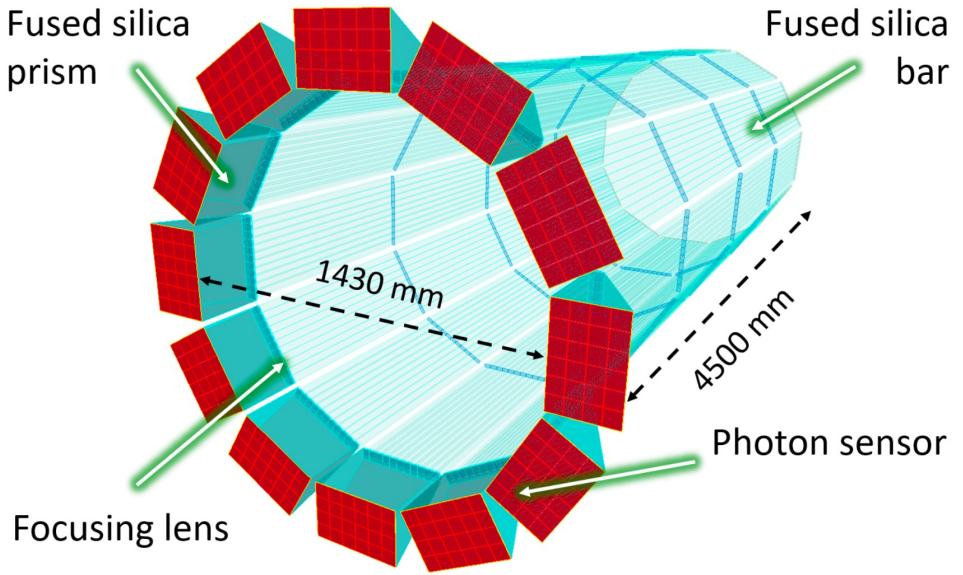
hpDIRC in DD4HEP

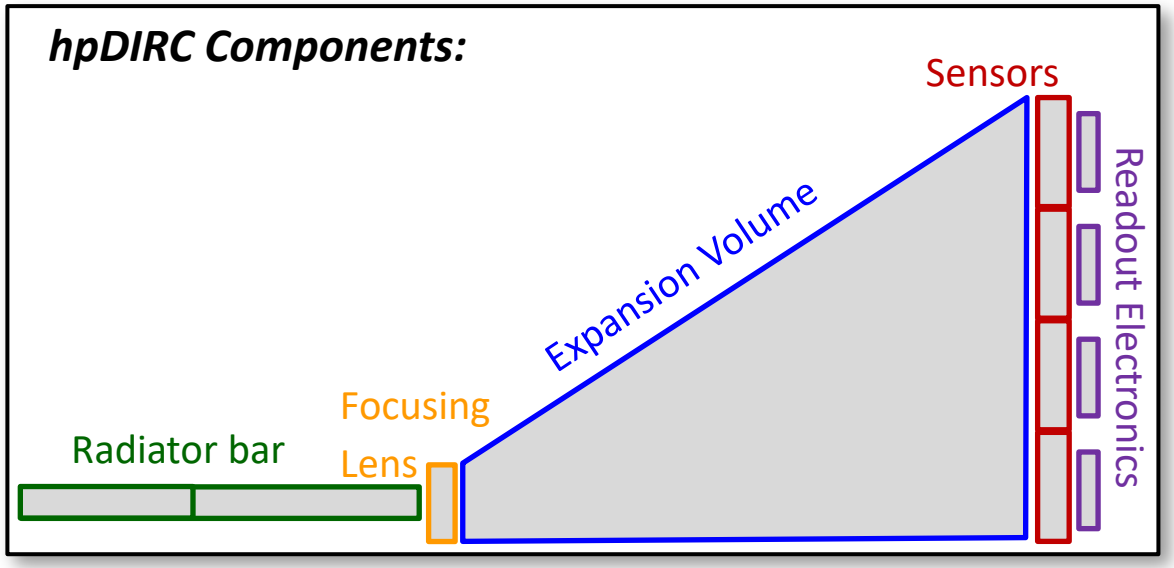
- Most of the initial implementation of the geometry and processes has been performed
  - Copying all relevant code from stand alone repository
  - Resolving some integration coding issues
- Next steps:
  - Performing tests with particle gun and predefined particle parameters (momentum, incidence angle, hit position)
  - Number of observables to look at to make sure geometry is correct, understand parameters and their definition
  - Validating particle transport and digitization with performance observables

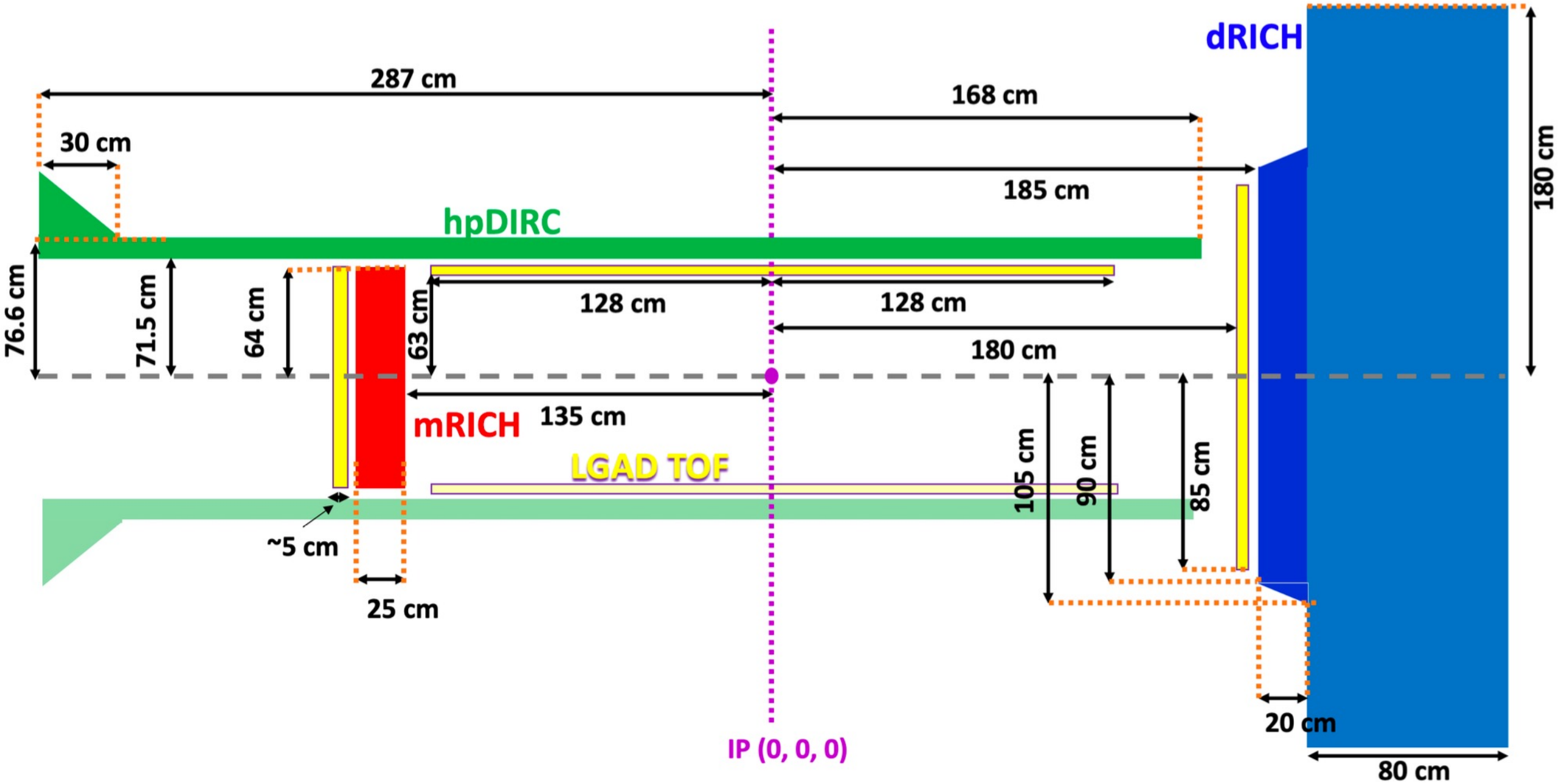


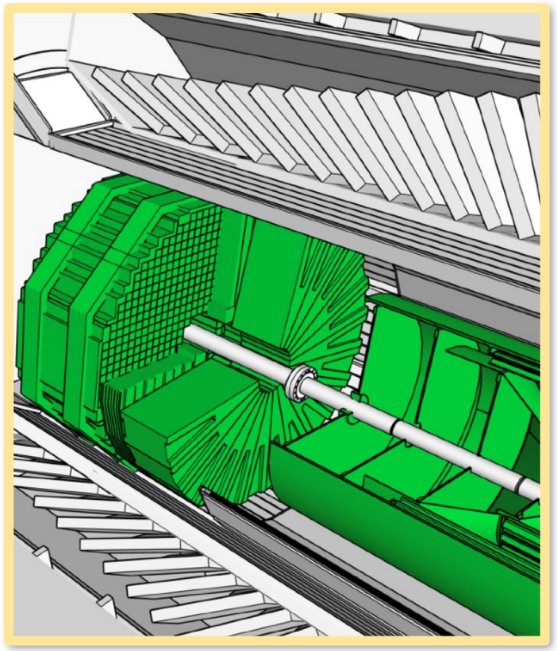
SUMMARY

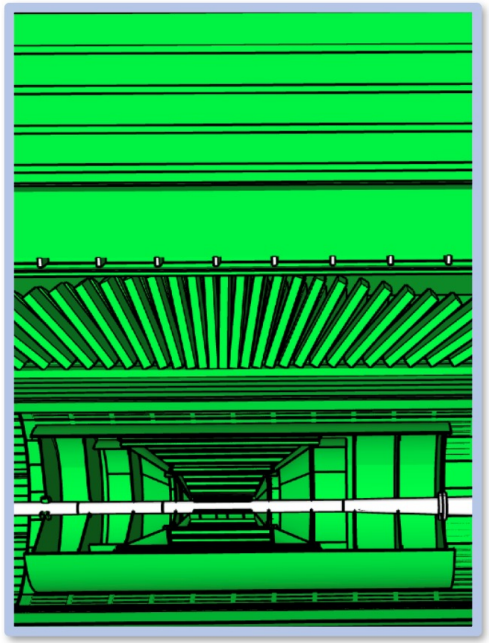
- Barrel hpDIRC almost identical ATHENA and ECCE designs with the same components and no different R&D plans
- The proof of principle, validation of stand alone simulation software, and initial component tests were done in particle beam tests with PANDA DIRC group
- The lens radiation hardness issue solved, prototypes build and tested
- The magnetic field strength for the BaBar magnet is suitable for the use of MCP-PMTs
- Fully implemented in F4A, started implementation in DD4HEP
- Remaining R&D focused on reuse of BaBar radiator bars and prototype program in CRT and particle beam

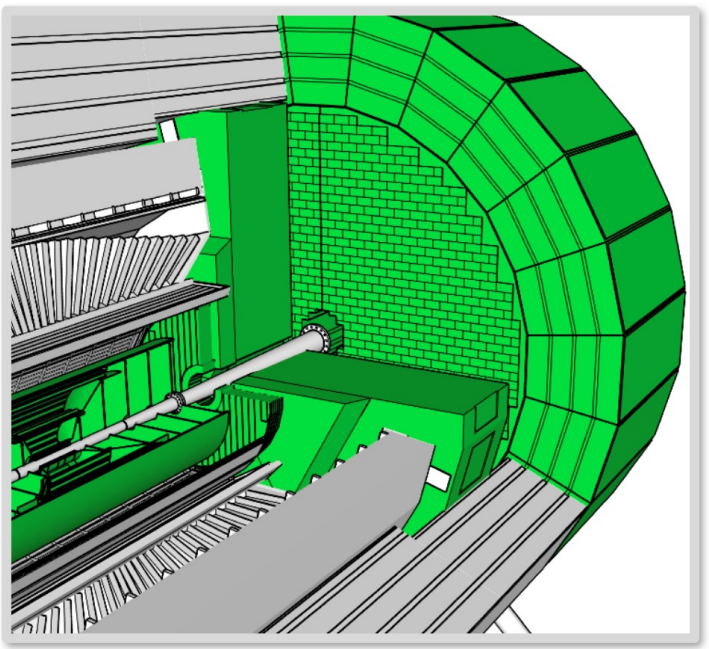





dRICH
287 cm
168 cm
30 cm
185 cm
hpDIRC
180 cm
76.6 cm
71.5 cm
64 cm
63 cm
128 cm
128 cm
180 cm
mRICH
135 cm
LGAD TOF
105 cm
90 cm
85 cm
~5 cm
25 cm
20 cm
80 cm
IP (0, 0, 0)







Backward Endcap

Tracking:
- ITS3 MAPS Si discs (x4)
- AC-LGAD

PID:
- mRICH
- AC-LGAD TOF
- $PbWO_4$ EM Calorimeter (EEMC)

Barrel

Tracking:
- ITS3 MAPS Si (vertex x3; sagitta x2)
- µRWell outer layer (x2)
- AC-LGAD (before hpDIRC)
- µRWell (after hpDIRC)

h-PID:
- AC-LGAD TOF
- hpDIRC

Electron ID:
- SciGlass EM Cal (BEMC)

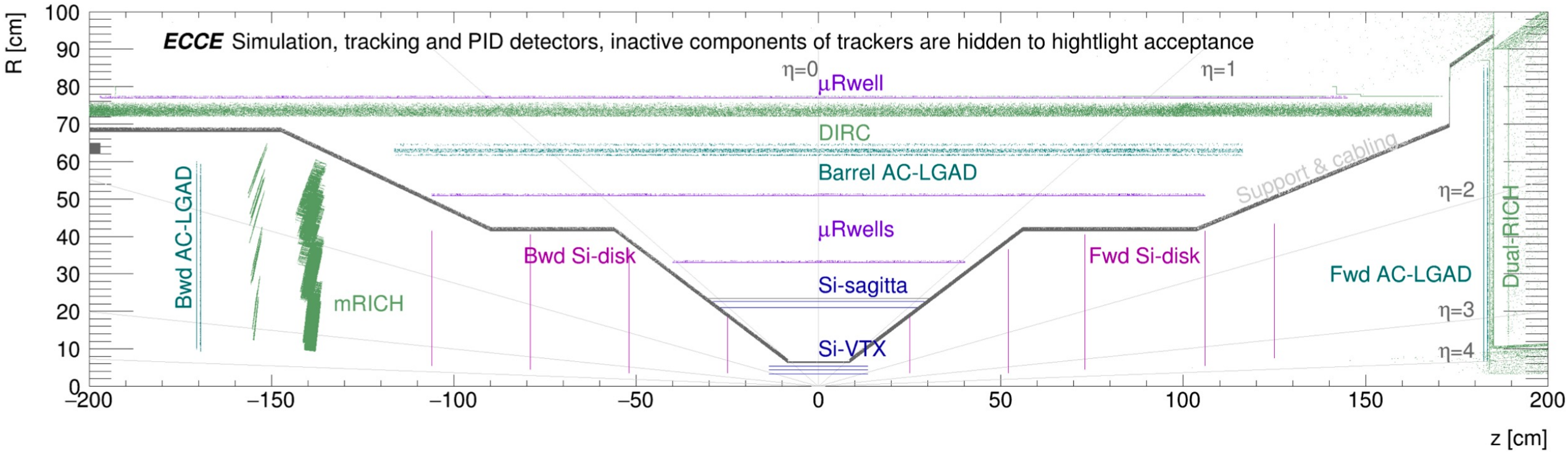
Hadron calorimetry:
- Outer Fe/Sc Calorimeter (oHCAL)
- Instrumented frame (iHCAL)

Forward Endcap

Tracking:
- ITS3 MAPS Si discs (x5)
- AC-LGAD

PID:
- dRICH
- AC-LGAD TOF

Calorimetry:
- Pb/ScFi shashlik (FEMC)
- Longitudinally separated hadronic calorimeter (LHFCAL)


ECCE Simulation, tracking and PID detectors, inactive components of trackers are hidden to hightlight acceptance
R [cm]
z [cm]
η=0
η=1
η=2
η=3
η=4
μRwell
DIRC
Barrel AC-LGAD
μRwells
Si-sagitta
Si-VTX
Support & cabling
Bwd AC-LGAD
mRICH
Bwd Si-disk
Fwd Si-disk
Fwd AC-LGAD
Dual-RICH

EIC HPDIRC R&D

FY22:

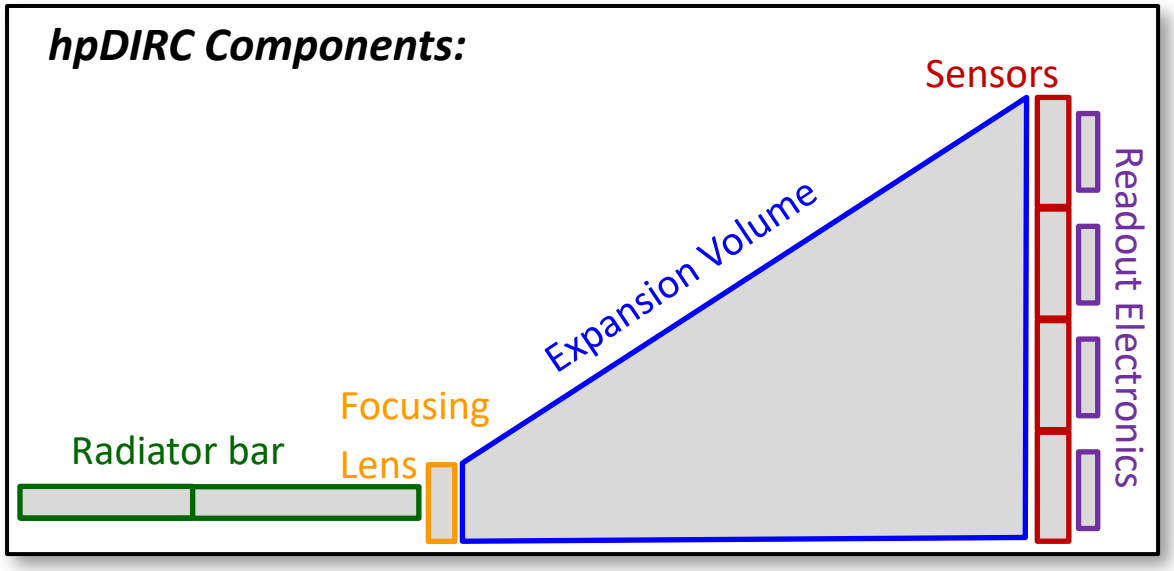
- Validation of BaBar DIRC radiator bars reuse option
- Disassembly and QA of remaining BaBar bars
- Lens prototypes validation

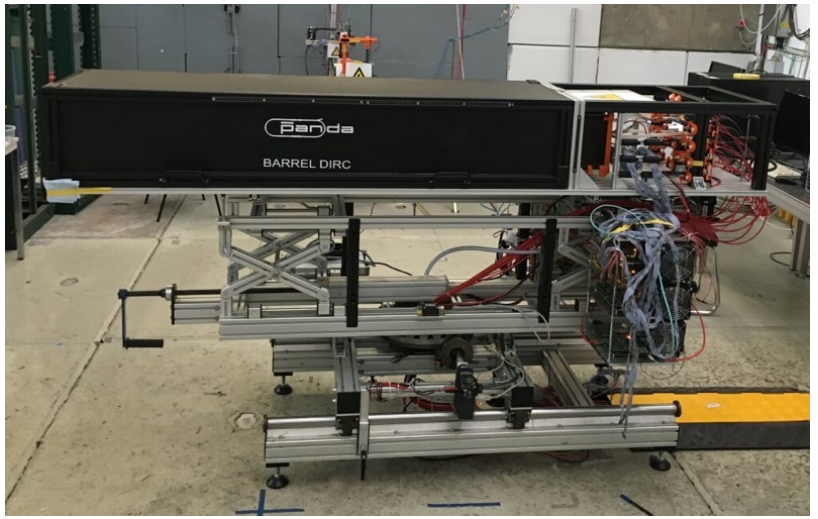
FY23:

- Development and adaptation of Readout Electronics
- Evaluation of Sensors and Readout Electronics in hpDIRC prototype
- MCP-PMT sensors selection

FY24:

- Evaluation of the optimized sensor arrangement
- Validation of new focusing lens approach (Radiator bar hybrid design, combining a narrow bar and a wide plate)
- Conclusion of prototype program with final cost/performance optimized design





EIC HPDIRC

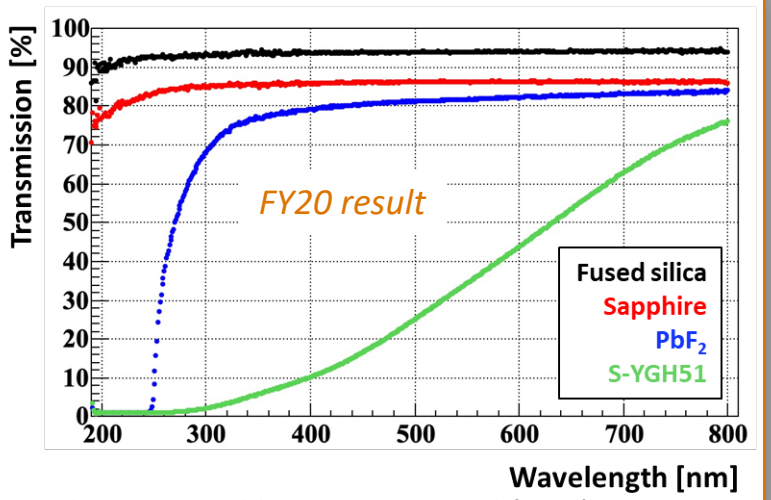
Technical risk: hpDIRC PID components validation

- Radiation hardness and focusing performance of 3-layer lens

hpDIRC R&D activities:

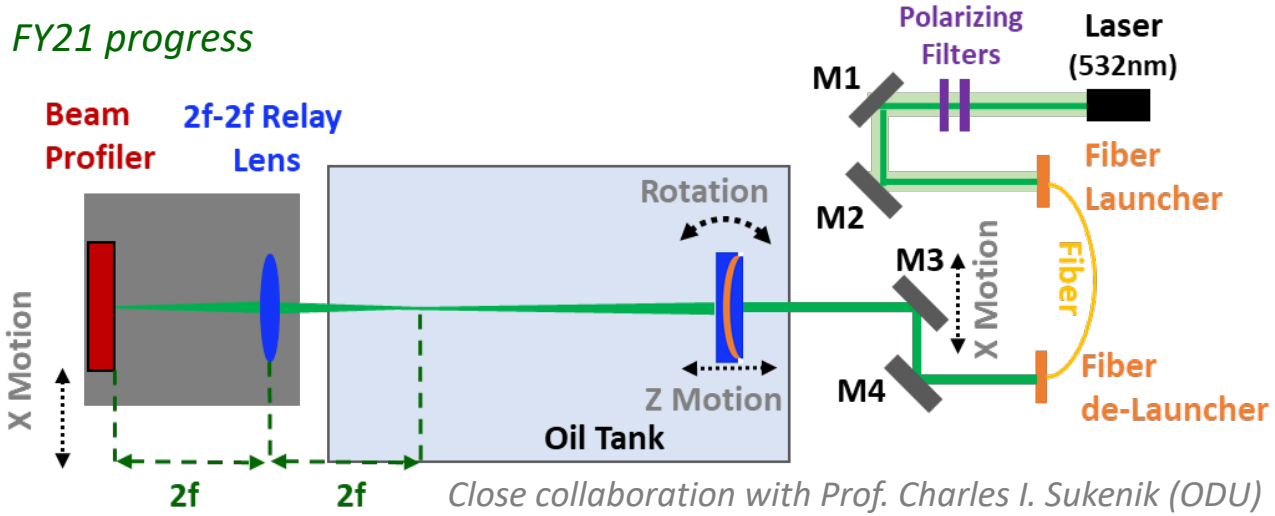
- Identify radiation-hard material for middle layer (^{60}Co study complete, neutrons next)
- Demonstrate that rad-hard material is suitable for lens fabrication by industry
  (New sapphire and PbF_2 lens prototypes produced, ready for tests)
- Validate focusing properties/flat focal plane
  → completed upgrade of laser setup at ODU in FY21, lens scans in progress

Transmission after 2Mrad dose (^{60}Co source)

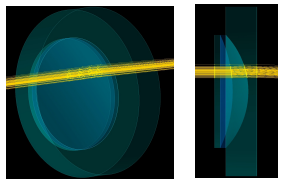


Work supported by Jim Kierstead (BNL)

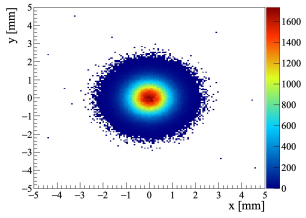
FY21 progress



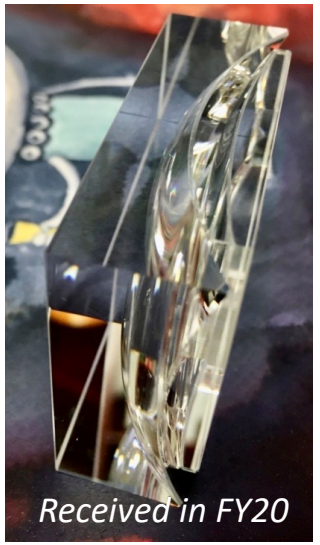
Close collaboration with Prof. Charles I. Sukenik (ODU)



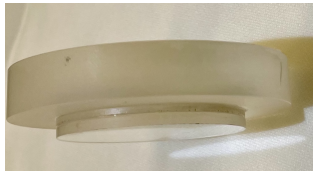
Geant4 simulation



Sapphire (RMI, USA)



PbF_2 (HIT, China)



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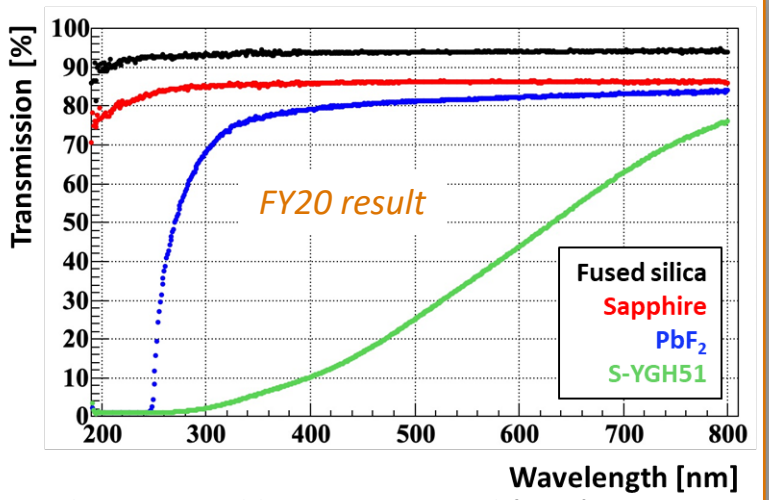

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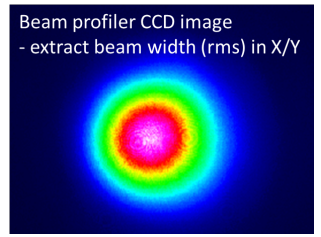
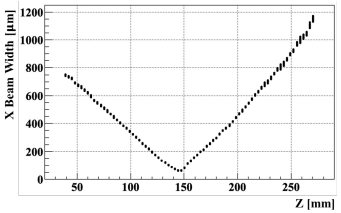
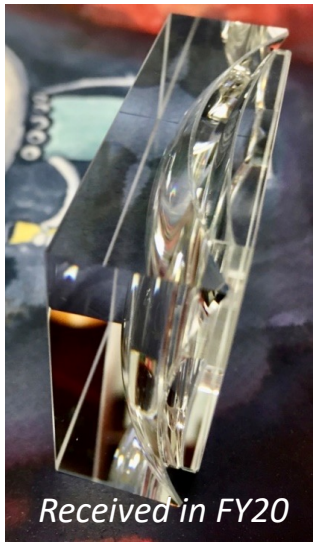
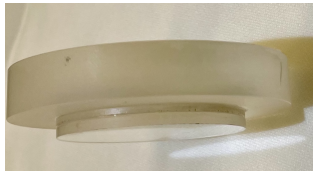




Sapphire (RMI, USA)



PbF_2 (HIT, China)



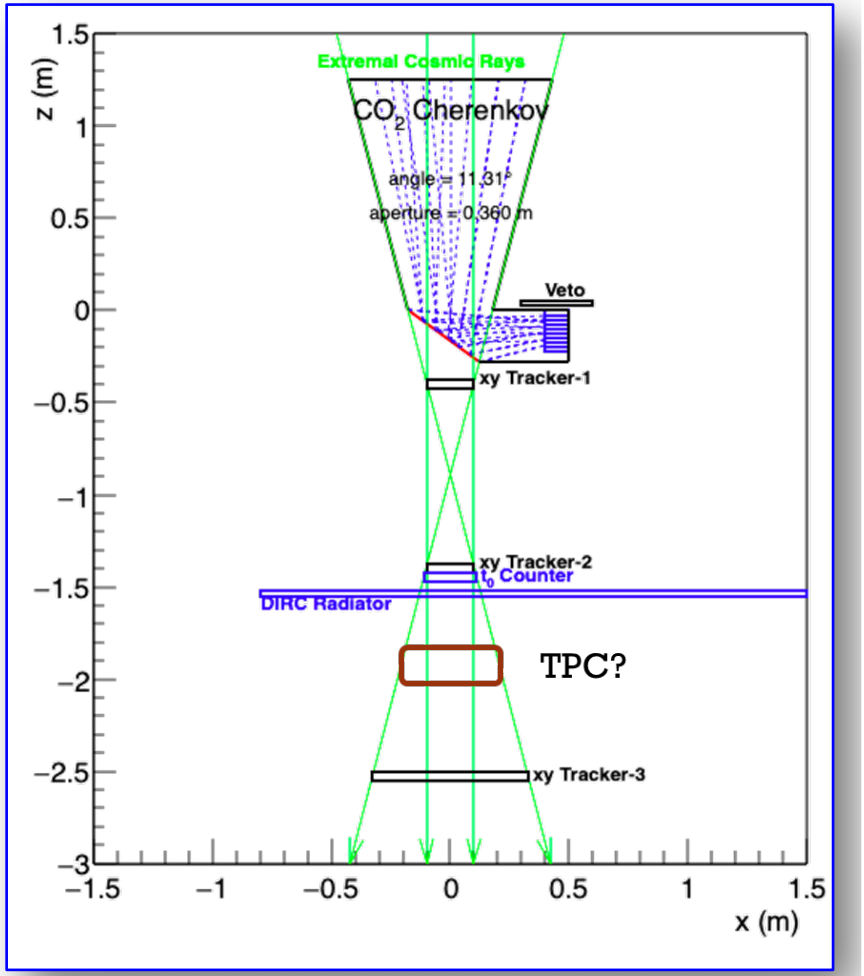
HPDIRC PROTOTYPE: CRT

Opportunity: Preparation of Tests of DIRC Prototype with Cosmic Rays

- Crowded beam test schedules – validate hpDIRC with cosmic muons
- Work on mechanical and readout aspects of hpDIRC prototype
- Collaboration of CUA – GSI – ODU – SBU to develop cosmic ray telescope (CRT) design and measurement plan

Current design:

- Momentum selection: new CO_2 Cherenkov threshold tagger (> ~3.5 GeV/c)
- 3D tracking: two GEM tracker stations (from sPHENIX) above and below DIRC bar, potentially combined with TPC prototype
- Shower rejection: scintillator plates as veto counters
- T_0 start counter: MCP-PMT/LAPPD or PICOSEC-Micromegas counter
- Mechanical design progressing, prototype polar angle rotation foreseen
- Geant simulation package in preparation



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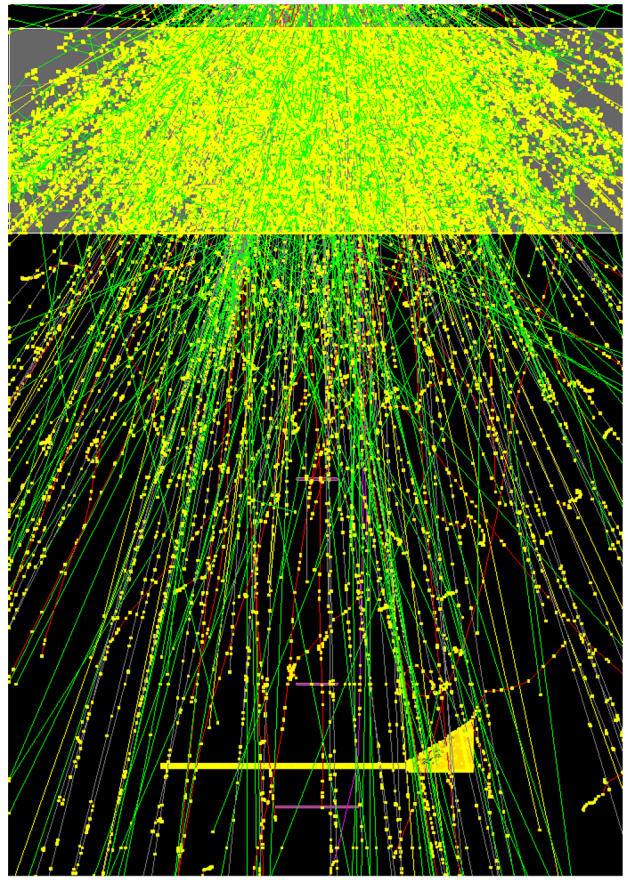
Geant: ~10 seconds of real time



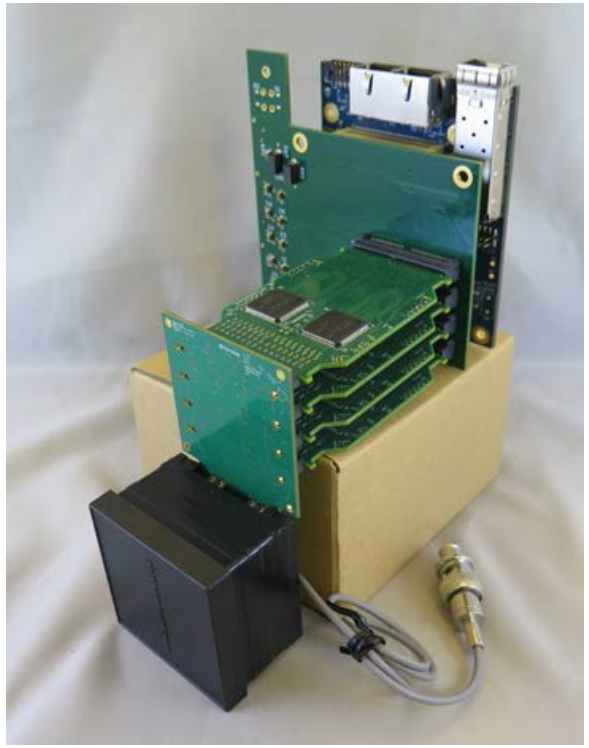
HPDIRC SCHEDULE

Activity ID	Activity Name	Start	Finish	Duration
ECE06.10.04.01.01.03	**Barrel PID - hpDIRC Final Design**	**11-Feb-26**	**07-Aug-26**	**125**
EIC1920	Optics assembly design	11-Feb-26	06-May-26	60
EIC1930	Readout Design	07-May-26	31-Jul-26	60
EIC1940	Mechanical Design	07-May-26	31-Jul-26	60
EIC1942	Final Design Review	03-Aug-26	07-Aug-26	5
EIC1950	Milestone: hpDIRC Design Complete		07-Aug-26	0
ECE06.10.04.01.01.04	**Barrel PID - hpDIRC Procurement and Subcomponent Assembly**	**15-Dec-22**	**08-Oct-25**	**711**
EIC1964	Obtain Radiator Bars (In-Kind Contribution)	15-Dec-22	09-Feb-23	40
EIC1970	BaBar Boxes disassembly	10-Feb-23	08-Aug-23	125
EIC1980	Bars QA scan	10-Feb-23	07-Feb-24	250
EIC1982	Short bars repolish/new plates	08-Feb-24	05-Aug-24	125
EIC1990	Barbox assembly tooling, tables	08-Feb-24	04-Apr-24	40
EIC2010	Lenses procurement	02-Jul-24	30-Jun-25	250
EIC2020	Mirrors procurement	02-Jul-24	30-Jul-24	20
EIC2030	Prisms procurement	02-Jul-24	30-Jun-25	250
EIC2040	Sensors Procurement	02-Jul-24	31-Dec-24	125
EIC2050	Readout electronics (Check with Chris!) (Cost moved to Electronics)	02-Jul-24	31-Dec-24	125
EIC2060	Lenses and Prisms QA	02-Jul-24	15-Jul-25	260
EIC2061	Barboxes assembly	05-Apr-24	17-Apr-25	260
EIC2062	Sensors QA	02-Jul-24	15-Jul-25	260
EIC2070	Electronics and readout assembly (Cost moved to Electronics)	02-Jul-24	10-Sep-25	300
EIC2080	Mechanical System, Calibration, Misc.	11-Sep-25	08-Oct-25	20
EIC2084	Milestone: hpDIRC Procurement and Subcomponent Assembly Complete		08-Oct-25	0
ECE06.10.04.01.01.05	**Barrel PID - hpDIRC System Assembly and Installation**	**09-Oct-25**	**03-Feb-31**	**1336**
EIC2120	hpDIRC components delivery to BNL	09-Oct-25	20-Nov-25	30
EIC2130	hpDIRC installation in the hall	06-Aug-29	17-Sep-29	30
EIC2140	Cosmic tests of full detector	18-Sep-29	30-Oct-29	30
EIC2142	Milestone: PID hpDIRC System Assembly and Installation Complete		03-Feb-31	0
EIC2144	Milestone: PID hpDIRC Execution Complete		30-Oct-29	0

READOUT ELECTRONICS

hpDIRC unique readout requirements:

- All three leading sensor candidates (MCP-PMT, MAPMT, SiPM) share:
  - Large number of small pixels
  - Fast single photon timing
  - Relatively high photon rates and sensor occupancies
- Readout electronics must maintain 60-100ps timing resolution, matching sensors
- Performance requirements for e.g. triggerless streaming, data reduction, bandwidth, latency and throughput must be achieved while simultaneously meeting technical requirements for other critical factors such as e.g. power consumption, integration issues at the detector front end along with robust electromechanical sensor interfaces and biasing
- There is **NOTHING** on the market that meets all requirements and scales well
- Test all sensors with minimal effort on electronics and a common readout solution



Requesting funding for 50% PostDoc and fabrication cost at UH and equipment and engineering support from Nalu.

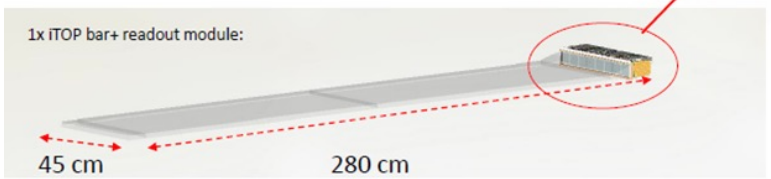
READOUT ELECTRONICS

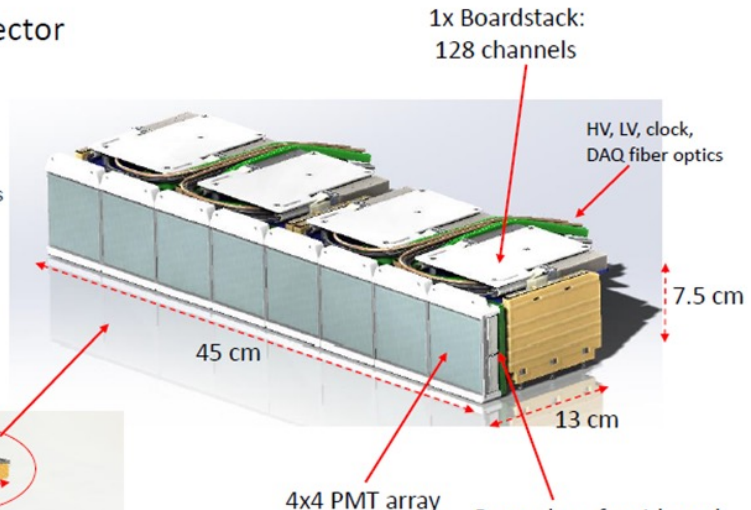
The close collaboration between Nalu and UH was established several years ago in the design, fabrication and deployment of the Belle II DIRC TOP detector (below left), which shares many similarities to the hpDIRC.

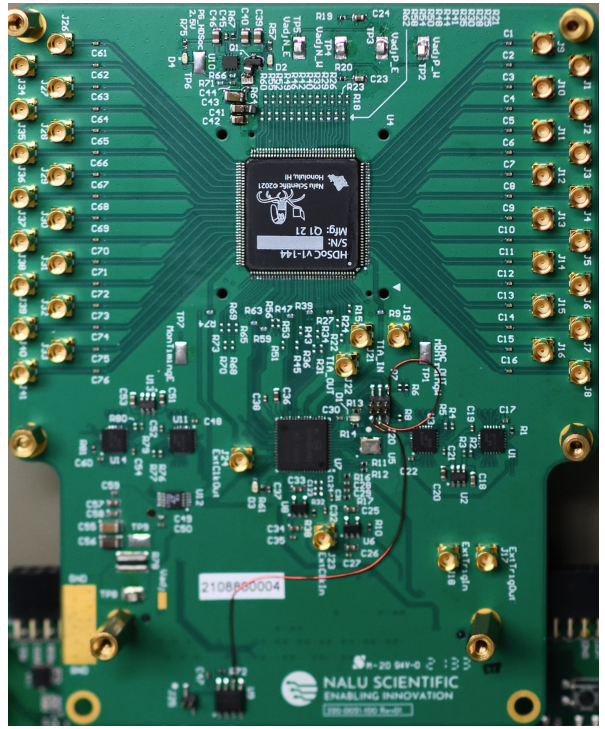
The TOP project was awarded the DOE's Project Management Achievement Award in 2017, and was completed two months ahead of schedule and under budget while meeting or exceeding all objective Key Performance Parameters.

Nalu's HDSoC ASIC (32-chnl test board below right), currently under development with a DOE Phase II SBIR, is well matched to EIC-PID's performance and technical requirements and the plan is to continue to evolve the platform to systematically address the challenges inherent in ultimately bringing the full EIC detector(s) online and ready for physics data-taking.

- 8192 channels of readout for iTOP subdetector
- 16 quartz bars, 1x module/bar
  - 1x readout module:
    - Photons in, DAQ data out
    - PMTs, interconnectes, amps, ASICs, FPGAs, heatsinks
    - 45 cm x 7.5 cm x 13 cm
    - 512 channels
    - Dense and compact- operates inside magnet
- All modules installed in detector







READOUT ELECTRONICS

FY'22- Develop and de-risk electronics

- Use 32ch HDSoC eval card as a building block to readout a subset of channels of various sensors (Photonis, HRPPD, Photek…)
- Nalu will provide 32 ch HDSoC eval board+engineering knowhow and FW/SW customization
- UH will provide post-doc and lab for testing and data analysis - prepare for cosmic telescope testing (for 32 or 64ch)
- Nalu will develop and fab the 64 channel HDSoC using Phase II SBIR funds
- Preliminary design for a modular integrated readout solution.

FY'23 - Prepare for summer '23 beam tests

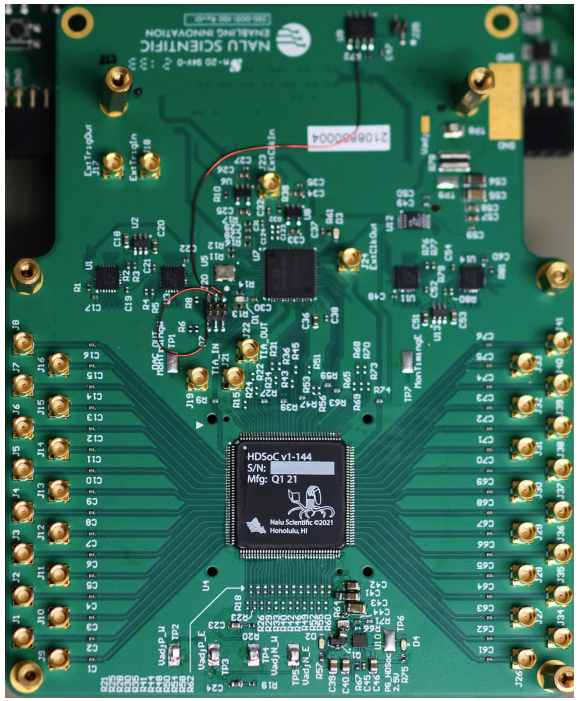
- Design and fab sensor specific 4-6k channel electro-mechanically integrated readout based on 64ch HDSoC (with design reuse in mind) and prepare for beam tests - contingent on proper budget allocation and prompt start on day one of FY23.
- Perform beam tests, analyze data and present results
- Perform a study on ASIC customization for various subdetectors (SBIR funds slightly more generic R&D than detector specific work).

FY'24-25- ASIC and electronic customization

- Customize HDSoC for speed (60ps resolution), data rates, processing capacity of each detector.
- Fab, package, test and qualify - rather low risk given underlying ASIC is mature
- Design high channel count subdetectors using customized ASICs.

FY'26-27 - Mass production

- Design for cost, dedicated ASIC fab and packaging.
- Board level designs tweaked for cost and sent to contract fab/assy houses
- Calibration, qualification, installation.



Readout electronics schedule matches hpDIRC timeline

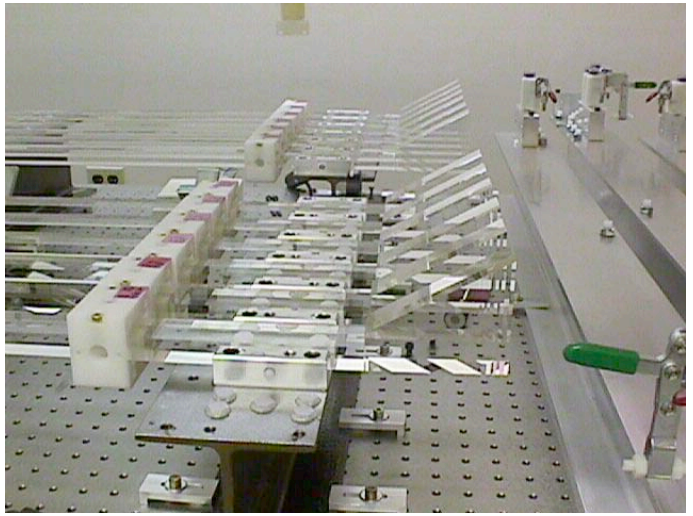
DIRC Simulation Assumptions

Bar Material	Synthetic fused silica, polished to 0.5 nm *rms* surface roughness, transmission and reflection coefficient based on PANDA DIRC bar measurements
Bar Dimension	1.7 x 3.5 cm^2 bar cross-section (the BaBar DIRC bar box reuse)
Focusing System	3-layer spherical lens (hpDIRC), optical properties based on tested prototypes
Mirror	Front-coated mirror, reflectivity based on BaBar DIRC mirror measurement
Glue	Epotek 301-2, transmission based on BaBar DIRC measurements
Optical Cookies	RTV, transmission based on GlueX DIRC measurements
Sensors	MCP-PMTs, 3 x 3 mm^2 pixel size, CE/QE/PDE based on PANDA DIRC measurements
Mechanical System	All DIRC components made from aluminum alloy or CFRP (PANDA DIRC)
Readout Electronics	Assume 100 ps timing precision per photon (sensor, electronics, synchronization) Readout boards and cables not included in Geant simulation
Background	Random dark noise background, based on PANDA DIRC measurements
Tracking	0.5 mrad polar angle resolution, no post-DIRC tracking assumed
Particle Generation	Standalone Geant4, single tracks, no magnetic field

QA of Disassembled Bars

Technical risk: QA of the disassembled bars in laser setup:

- BaBar DIRC bars were produced with 0.3-0.5nm surface optical finish
- Loss of optical quality would cause loss of photon yield and drop in PID performance
- Carefully evaluate all bars from first bar box, decide if disassembly strategy (decoupling into single bars) works or should be changed (keeping longer bar units)
- Expect to perform full scans on at least 10% of bars



BaBar DIRC bars in SLAC lab (~1997)

PANDA Barrel DIRC bars in GSI lab (2021)