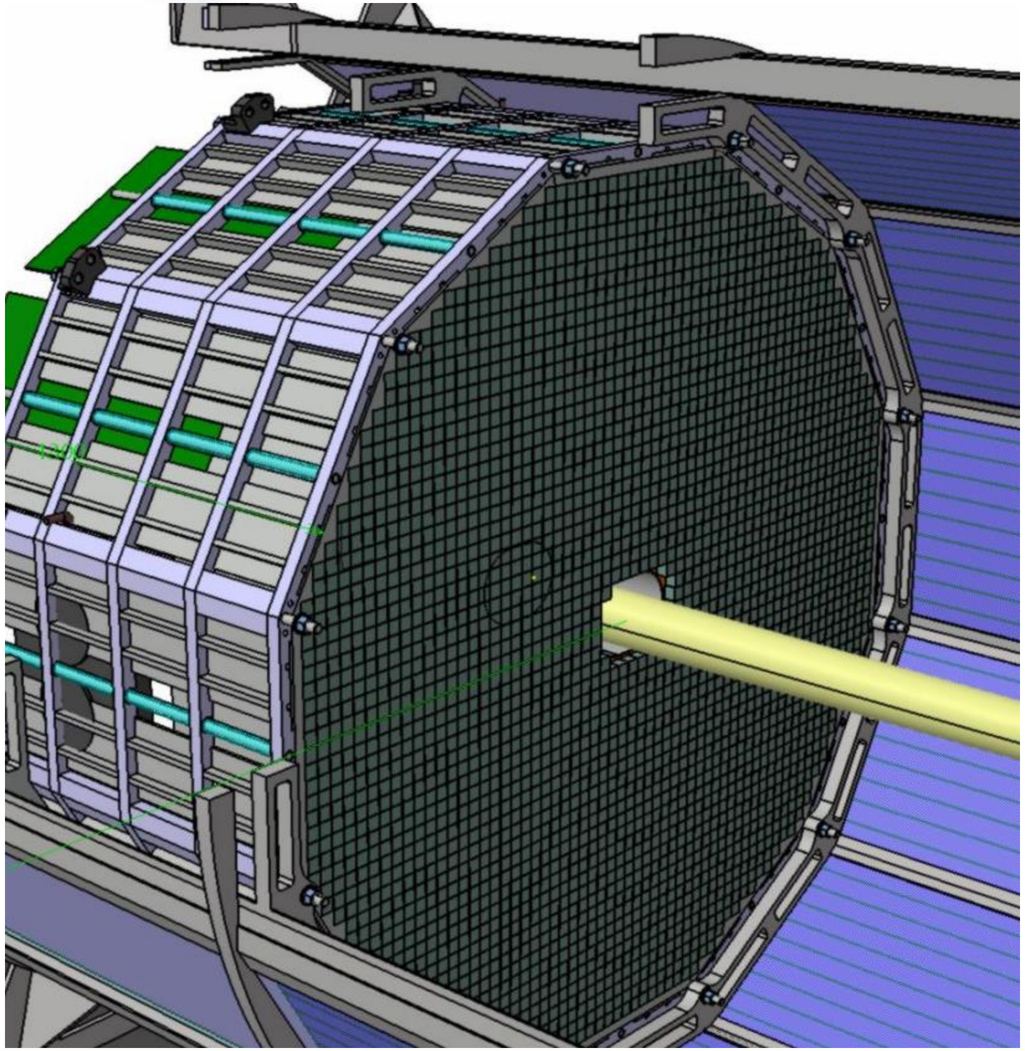


Electromagnetic calorimetry for EIC

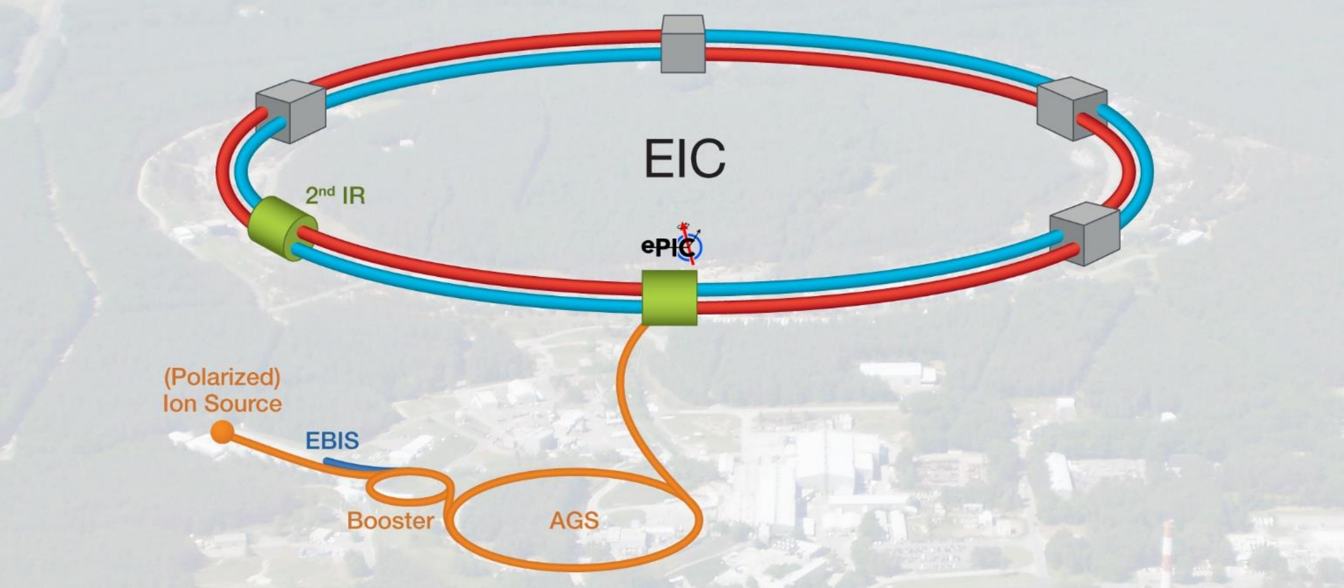
R&D: SiPM readout of PWO crystals

Carlos Muñoz Camacho

AG GDR GI2I, June 24 (2024)

The EIC facility

- Highly polarized electron / Highly polarized proton and light ions /Unpolarized heavy ions
- CME: ~ 20–140 GeV
- Luminosity: ~ $10^{33\text{-}34}$ $cm^{-2}s^{-1}$

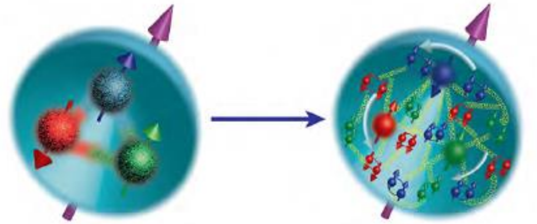


- Polarized electron source and 400 MeV injector linac to feed a rapid cycling synchrotron design to avoid depolarizing resonances up to the maximum e-beam energy of 18 GeV
- Polarized proton beams and ion beams based on existing RHIC facility
- 2 detector interaction points capability in the design

Motivation – the EIC science program

Origin of spin:

How does the spin-1/2 of the nucleon arise from the spin of quarks, gluons and their orbital angular momenta?

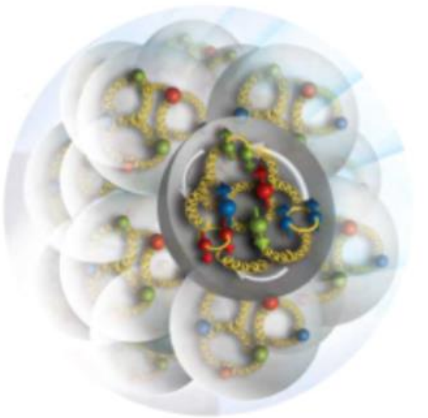


Origin of mass:

How do massless gluons make up for most of the nucleon mass?

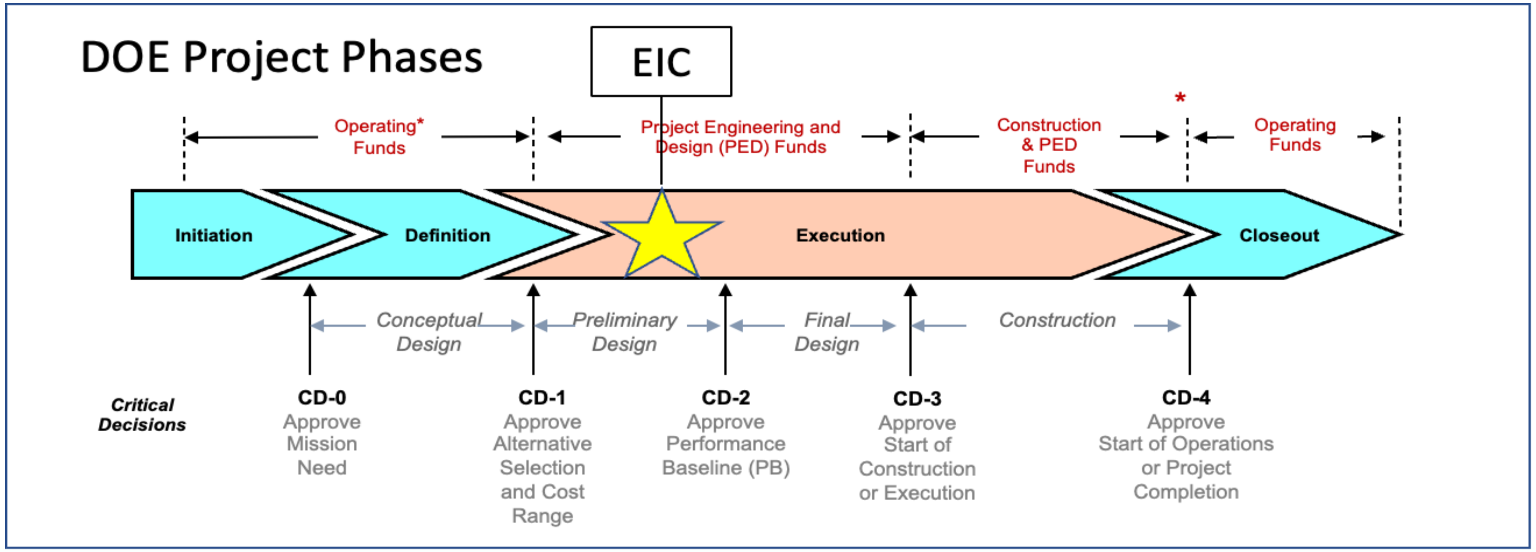
Gluons in nuclei:

Does gluon density saturate at high energy giving rise to a new regime of matter?



EIC project timeline

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 Approved	**March 2024**
CD-3B, Long-Lead Procurement Planned Approval	**March 2025**
CD-2/3, Performance Baseline/Construction Start Plan	**End 2025**



Project cost

- EIC detector: $300M ($200M DoE; $100M in-kind)
- EIC accelerator: $1.3B ($1.25B DoE; $50M in-kind)
- Other: management ($200M), infrastructure ($250M), pre-ops ($50M), contingency…

EIC detector milestones

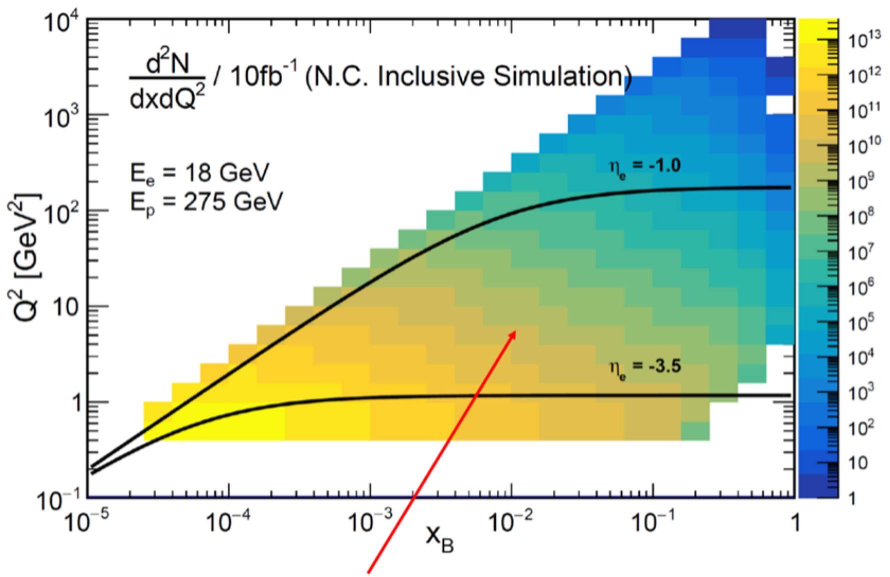
- **Dec 2021:** Detector design
- *Currently: Detector R&D*
- End 2025: TDR completed (CD-3), start of construction
- 2030: Detector commissioning
- 2031: Pre-ops
- 2034: Start of physics program (CD-4)

Backward Ecal at EIC

Electromagnetic (EM) calorimetry is key to any EIC detector concept

- Almost every channel needs to measured the scattered electron
- EM e-endcap calorimeter :

$-3.5 < \eta < -1$



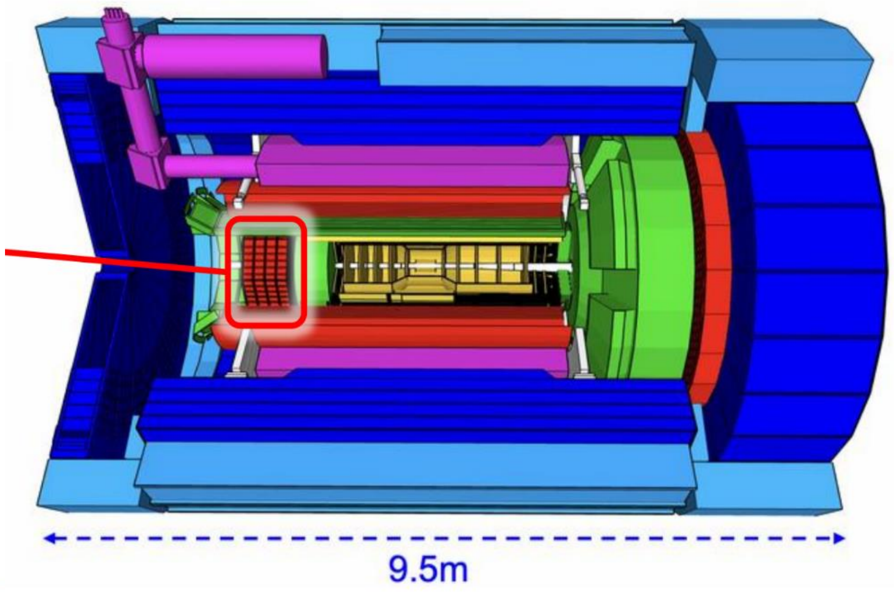
Region of physics enabled by the EEEMCal

High resolution in the forward region (endcap) can only be achieved with homogeneous materials, such as crystals

Requirements:

- Energy resolution: 2%/√E + (1-3)%
- Pion suppression: 1:10^4
- Minimum detection energy: > 50 MeV

Backward ECal

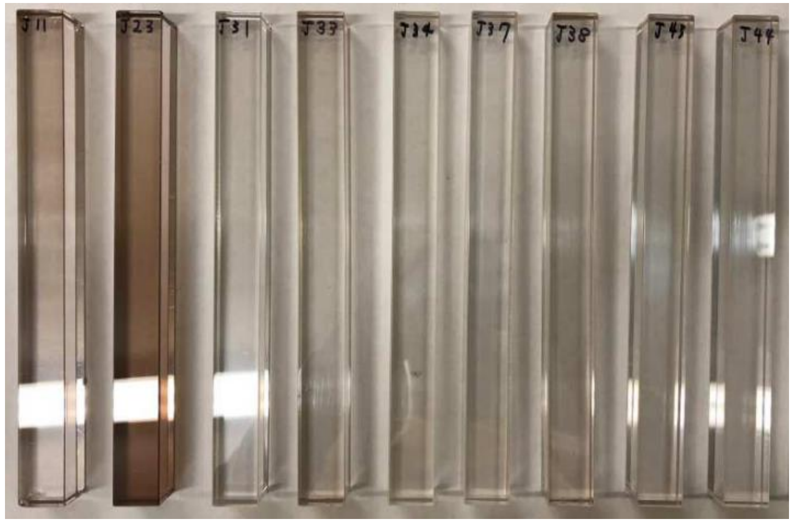


Technology choice: PWO crystals (2x2 cm^2) with high density SiPM (16 3x3 mm^2 or 4 6x6 mm^2 per crystal)

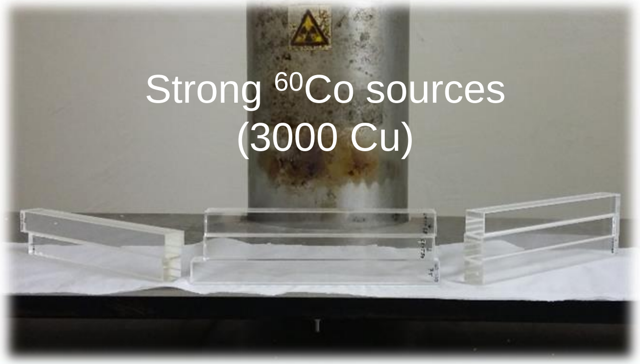
Lead tungsten crystals (PWO)

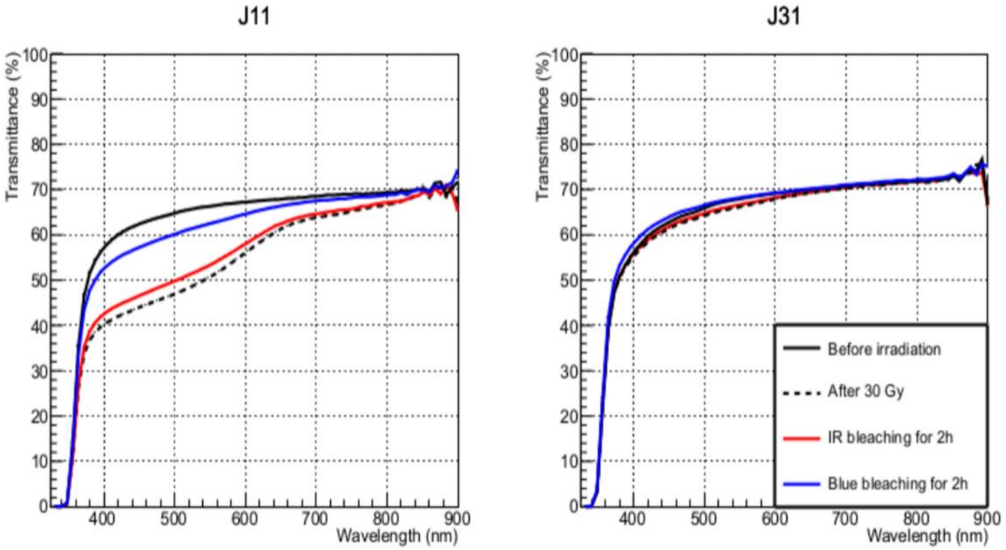
R&D carried out in ~2015-2020 to evaluate PWO worldwide suppliers of PWO (SICCAS & CRYTUR) after BTCP (main CMS provider) closed

- SICCAS showed poor quality control
- CRYTUR (new provider of PWO) produces now high quality crystals after several years of development.



Radiation hardness
(in collaboration with LCP)

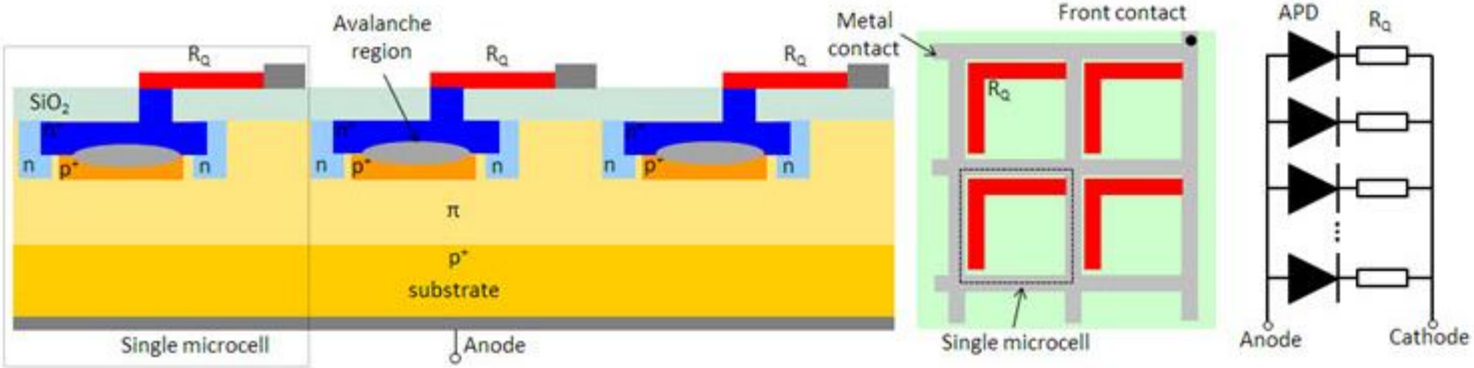




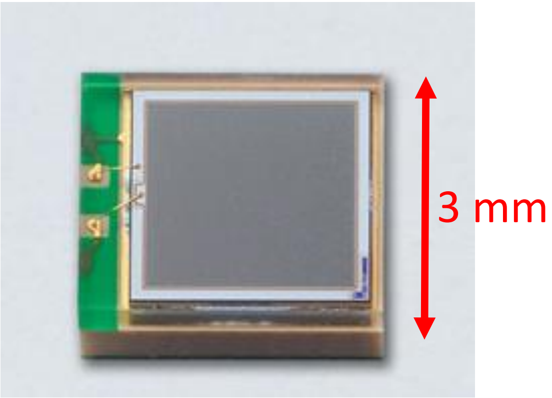
- Optical transmittance, light yield homogeneity, radiation hardness studies done at IPN/IJCLab
- Optical bleaching successfully implemented to cure radiation damage effects (particularly relevant for high luminosity facilities like Jefferson Lab)

Nucl. Instrum. Meth. A956 (2020) 163375. ArXiv: 1911.11577

SiPM readout



- Solid-state photodetector
- Current pulse of 20-50ns with 10^5-10^6 electrons (i.e. gain similar to a PMT)
- Insensitive to magnetic fields



- Small size
- Linearity/dynamic range
- Significant dark noise
- Not very radiation hard

➢ With PWO, readout (few p-e) requires analog amplification
➢ For calorimetry at EIC, large dynamic range needed (~5 MeV – 15 GeV)

Collaboration with INFN, BNL, JLab

SiPM models under study

HAMAMATSU
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PRELIMINARY

MPPC

Feb. 3, 2022

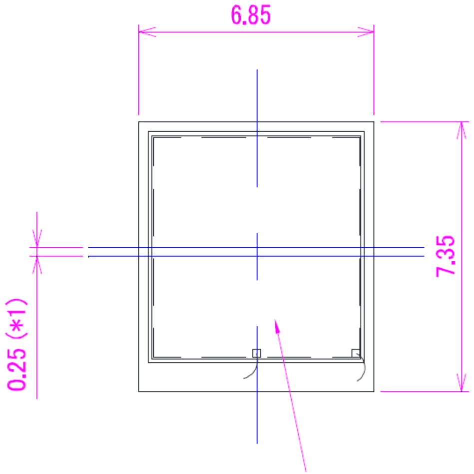
SPECIFICATION SHEET S14160-6010PS/6015PS

■ Structure

Parameters	S14160-6010PS	S14160-6015PS	Unit
Effective photosensitive area	6.0 × 6.0		mm^2
Pixel pitch	10	15	μm
Number of pixels	359011	159565	-
Window	Silicone resin		-
Window refractive index	1.57		-
Package	Surface mount type		-

■ Electrical and optical characteristics (Typical value, Ta = 25 deg C, Vr = Vop unless otherwise noted)

Parameters	Symbol	S14160-6010PS	S14160-6015PS	Unit
Spectral response range	λ	290 to 900		nm
Peak sensitivity wavelength	λp	460		nm
Photon detection efficiency at λp *2	PDE	18	32	%
Breakdown voltage	Vbr	38 +/- 3		V
Recommended operating voltage *3	Vop	Vbr + 5.0	Vbr + 4.0	V
Dark count rate	DCR	Typ. 3.0 / Max. 10		Mcps
Terminal capacitance at Vop	Ct	2500		pF
Gain	M	1.8×10^5	3.6×10^5	-
Temperature coefficient of Vop	ΔTVop	34		mV/°C



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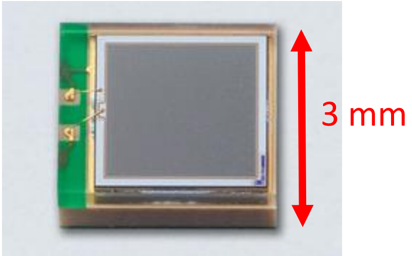
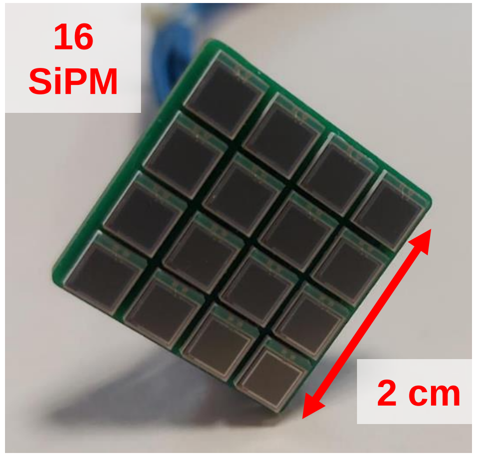
MPPC

S14160-3010PS





SiPM specifications for backward ECAL

SiPM

SiPM Size	6x6 mm2
Voltage	40-46 V
Array of SiPM (summing)	2x2
Capacitance/ channel	2.5 nF
Pixel/channel	160-360k
Dynamic range	10-10,000pC

SiPM stability

Overvoltage	+5 V
Stability required [mV]	TBD
Bias voltage accuracy	TBD
Bias voltage current	TBD
Temperature compensation	Bias voltage temperature compensation would be preferred

Pre-amp

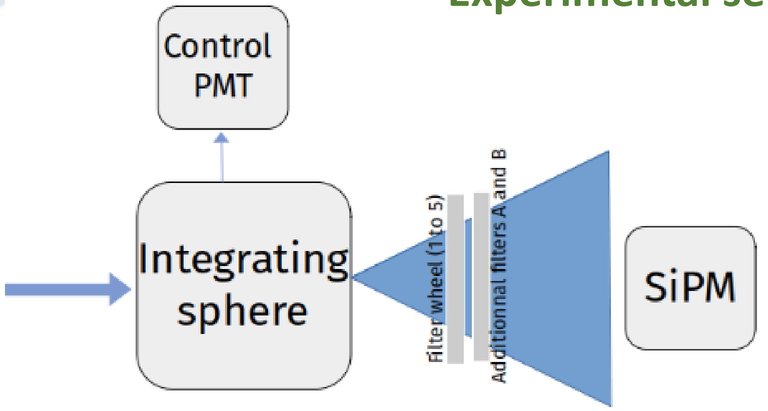
Linearity	< 0.5 %
Gain stability	< 0.5 %
Peak time	20 ns
Charge resolution	14-bit
Time-hit resolution	(TBD) 5 ns
Double pulse resolving	10 ns(?)

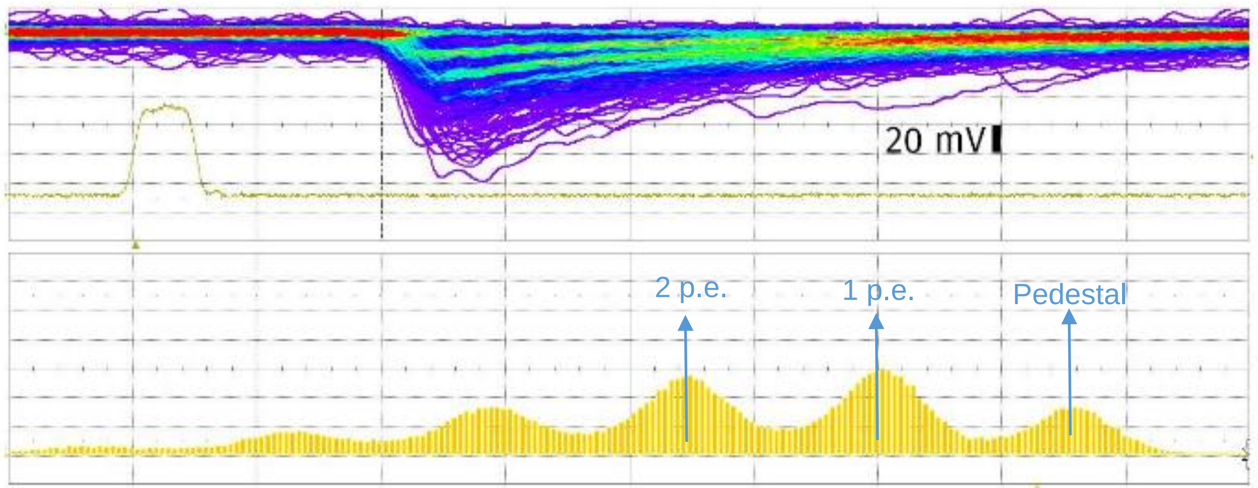
FEB, RDO

SiPM bias monitoring	Yes
Temperature monitoring	Yes
FEB on detector	Yes
FEB accessibility	Between runs
FEB-RDO distance	3-5m
RDO on detector	No
RDO location	TBD

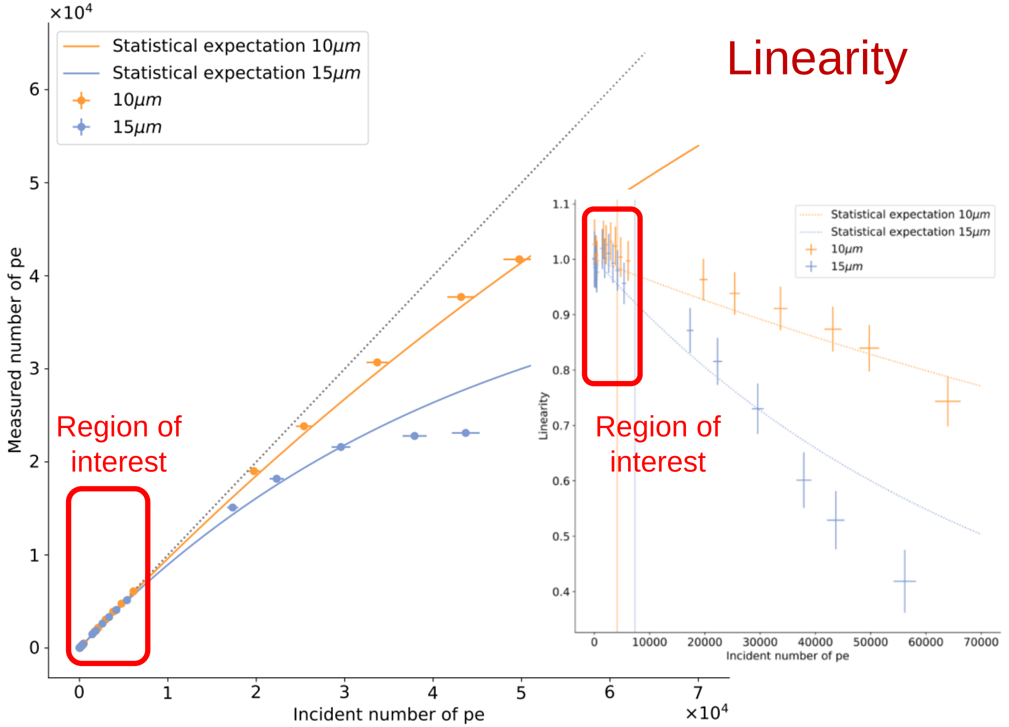
Measurements at IJCLab

Experimental setup:





Waveform (top) and integrated signal (below) showing single p.e. signals in Hamamatsu S14160-6015, produced with a low-intensity LED.



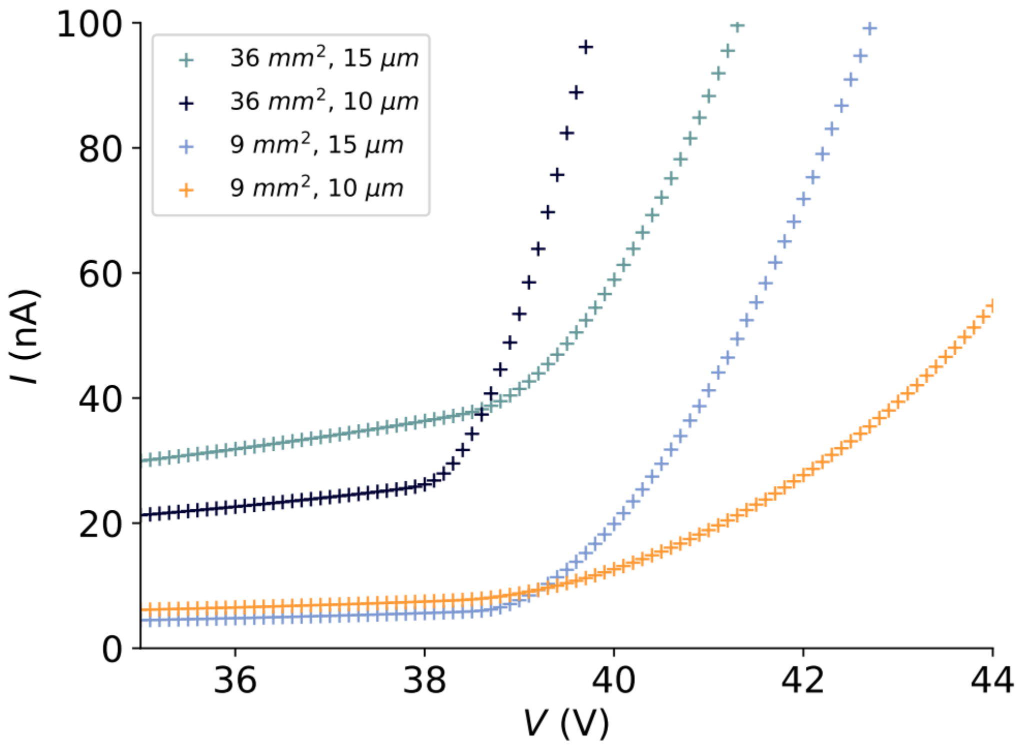
- Linearity better than 3% in the region of interest
- Deviation compatible with statistical expectation (i.e. number of pixels)
- Low dark current: very small signal detectable (close to single photo-electron)

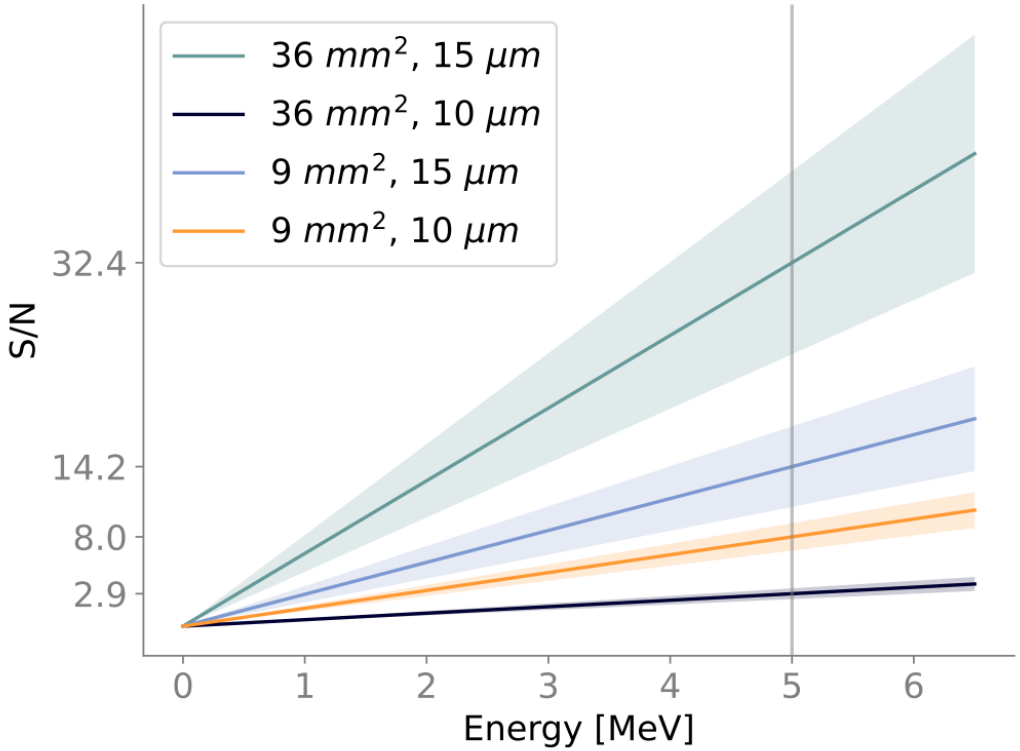
V. Chaumat, N. Pilleux (PhD student)

Low energy reach

Requirement: down to ~5 MeV in a crystal (~50 MeV cluster)

- Limited by dark current rate of SiPM
- Measurements of several high density models by Hamamatsu

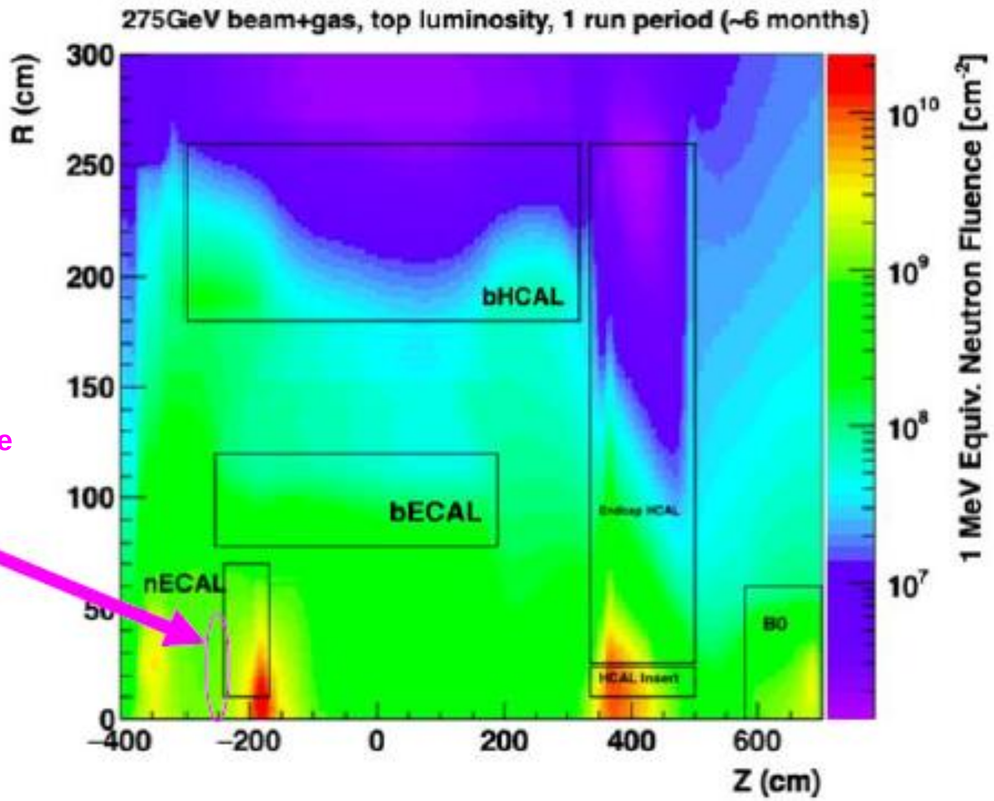




SiPM size (mm^2)	Pixel size (μm)	pe at 5 MeV	S/N at 5 MeV
9	10	$\simeq 1.4$	8.0 ± 1.2
9	15	$\simeq 2.5$	14.2 ± 3.6
36	10	$\simeq 5.5$	2.9 ± 0.5
36	15	$\simeq 9.8$	32.4 ± 8.2

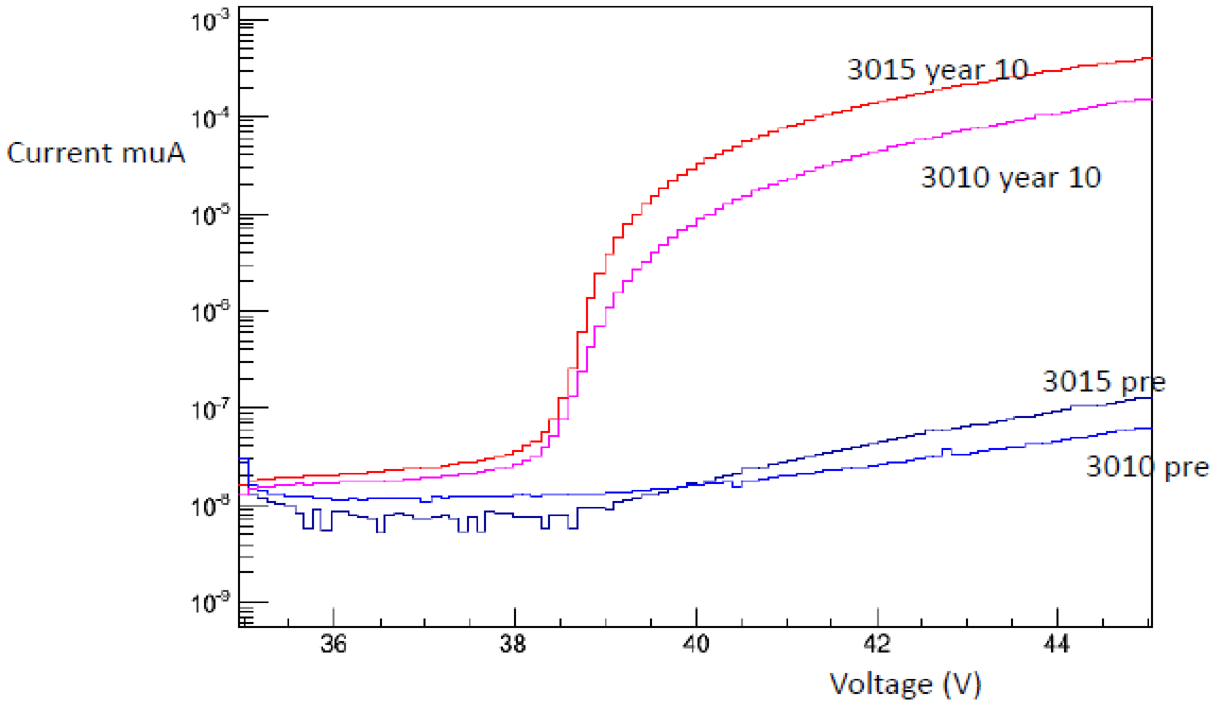
V. Chaumat, N. Pilleux (PhD student)

Radiation damage



Selected dose rate for innermost crystals

Irradiation tests at UCDavis (proton) beam (60 MeV), May 2024

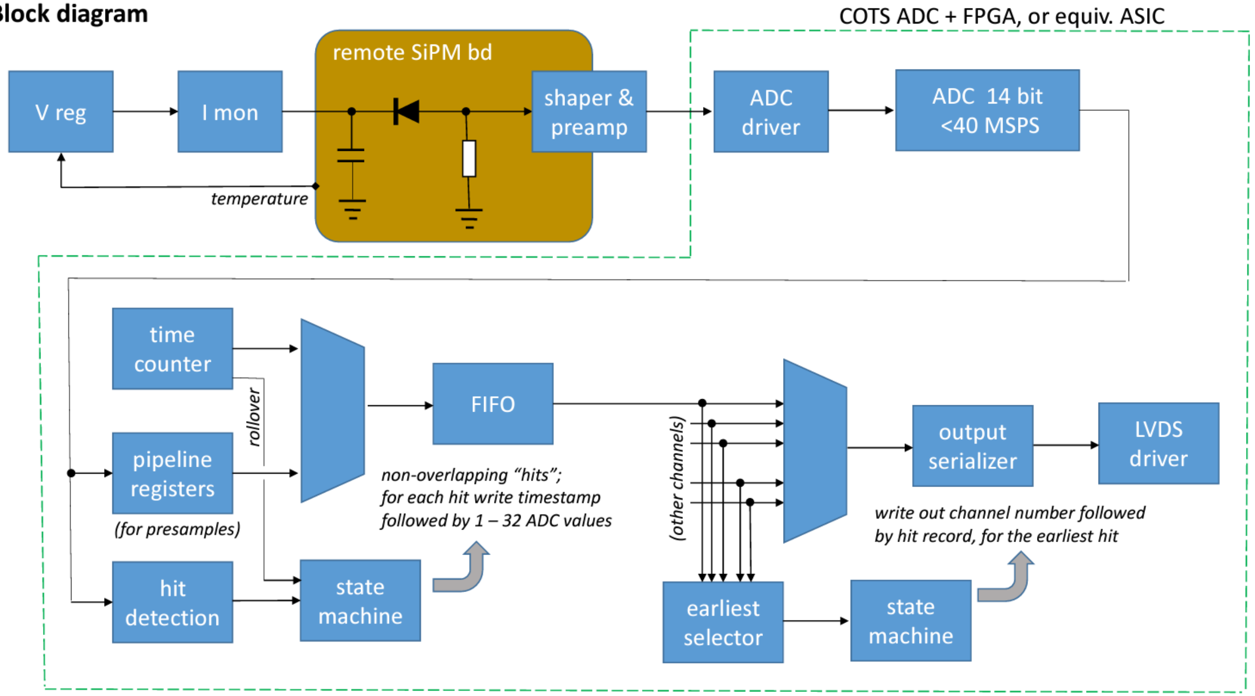


- All SiPM models behave similar
- Innermost SiPMs may need recovery mechanism (or replacement) to maintain the low energy reach of the detector

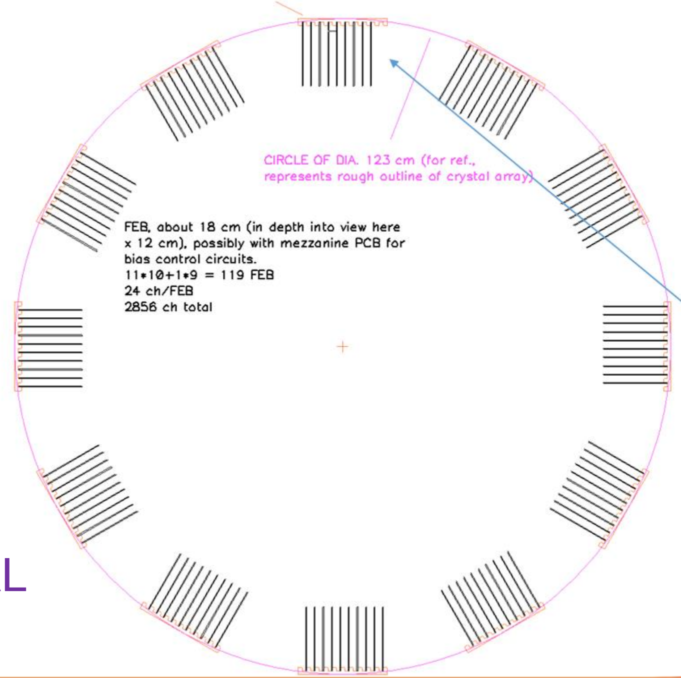
Backward ECAL: front-end electronics

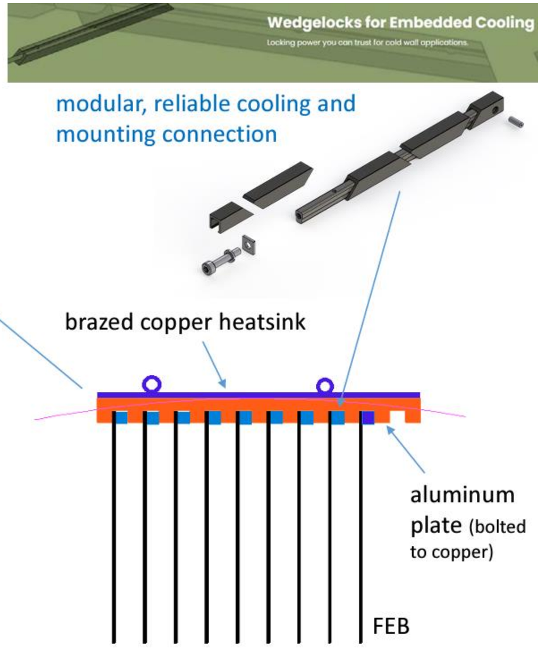
Proposal A: discrete electronics

Block diagram



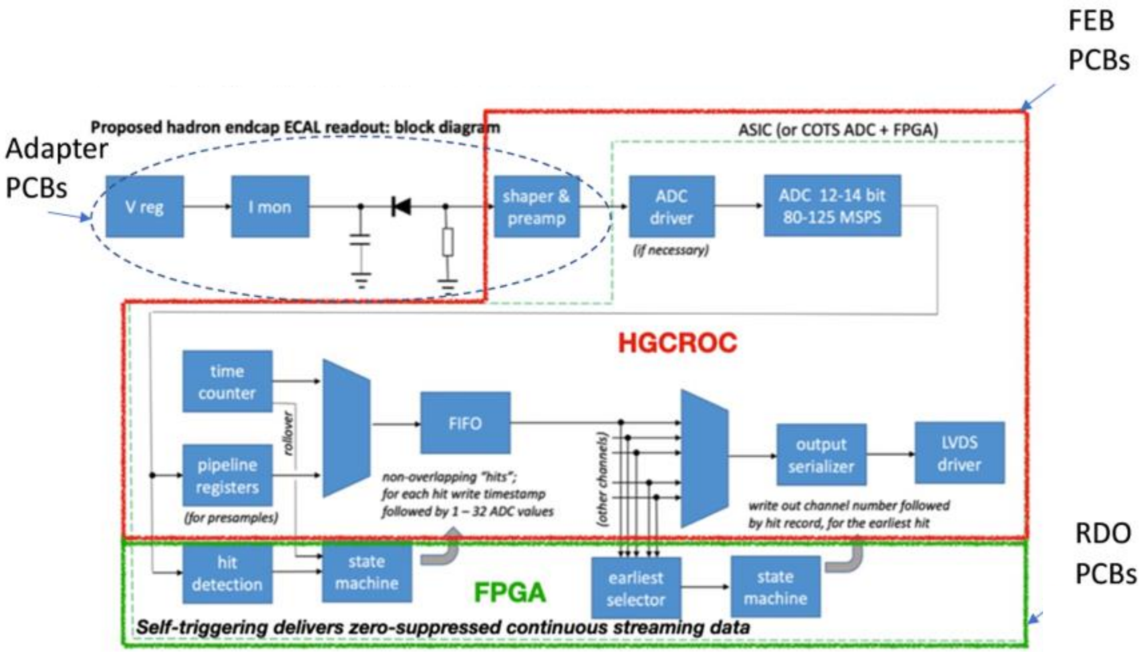
STAR FCS waveform readout (remote preamp/shaper), 32 ch/board





Concept for backward ECAL
(G. Visser, Indiana U.)

Proposal B: H2GCROC chip (OMEGA)



Many advantages:

- ➢ Lower power dissipation (by at least 1 order of magnitude)
- ➢ Input DAC to tune input voltage to compensate for breakdown voltage fluctuation
- ➢ Much lower cost

Several challenges:

- ➢ Very large capacitance SiPM for backward ECAL
- ➢ Stringent requirements on gain stability and linearity (<0,5%)

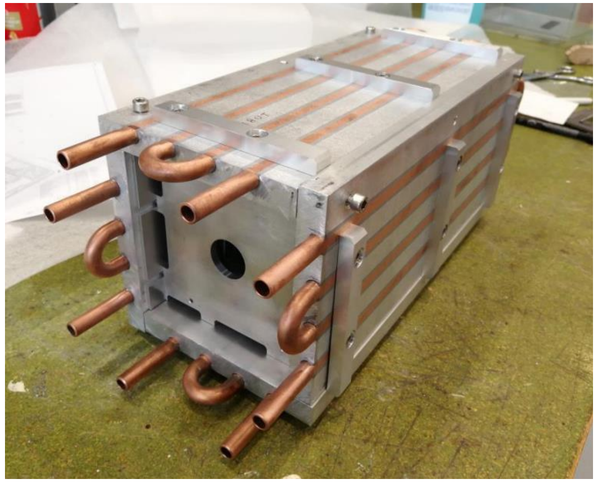
New PhD thesis started for EIC ASIC developements
(Pedro Dumas, OMEGA)

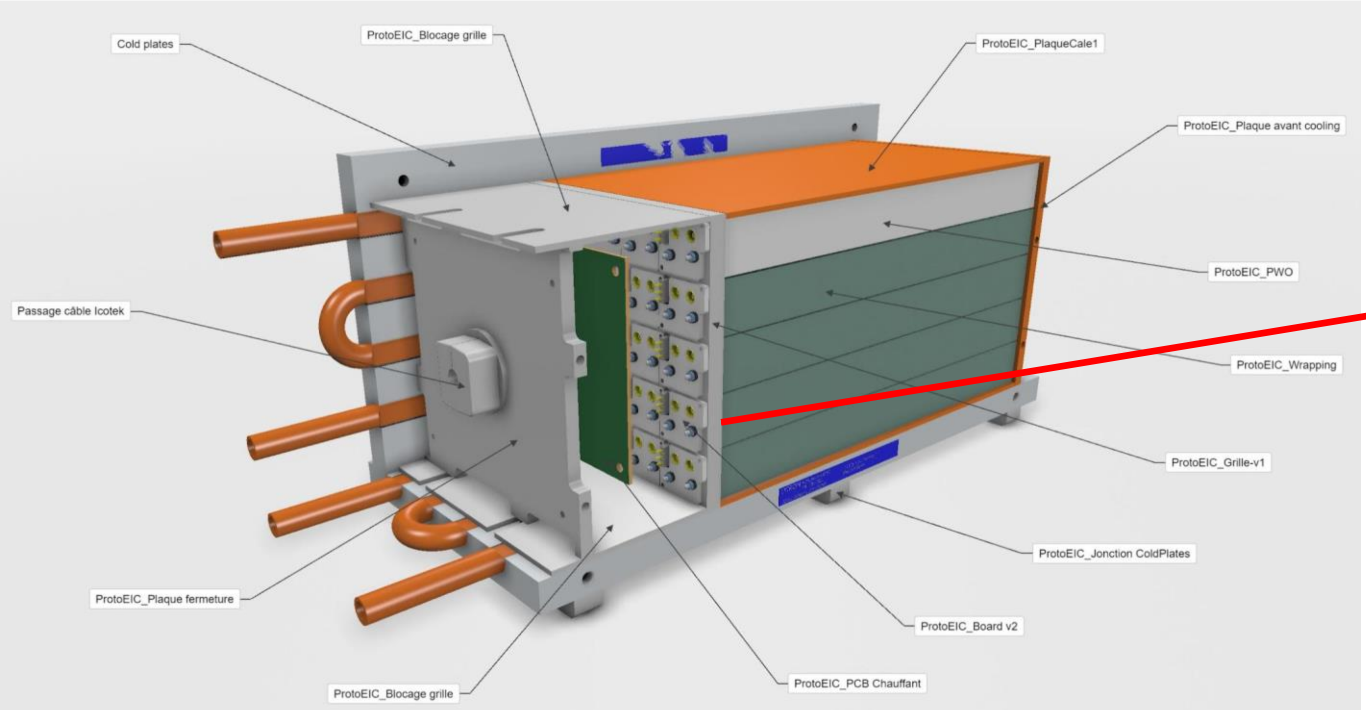
In collaboration with LLR (M. Nguyen, O. Le Dortz, L. Kalipoliti)

Beam-test prototype

- **Next milestone:** energy resolution measurements in beam

- Beam test in August 2024 at CERN (4 instrumented channels) and October 2024 (DESY) with the fully instrumented prototype (25 channels)
- Progress on the mechanical design of a 5x5 prototype
- Different readout (16: 3×3 mm^2 / 4: 6×6 mm^2 SiPM)
- Compatible with different front-end electronics (discrete/ASIC)





Mechanical design: J. Bettane (IJCLab)

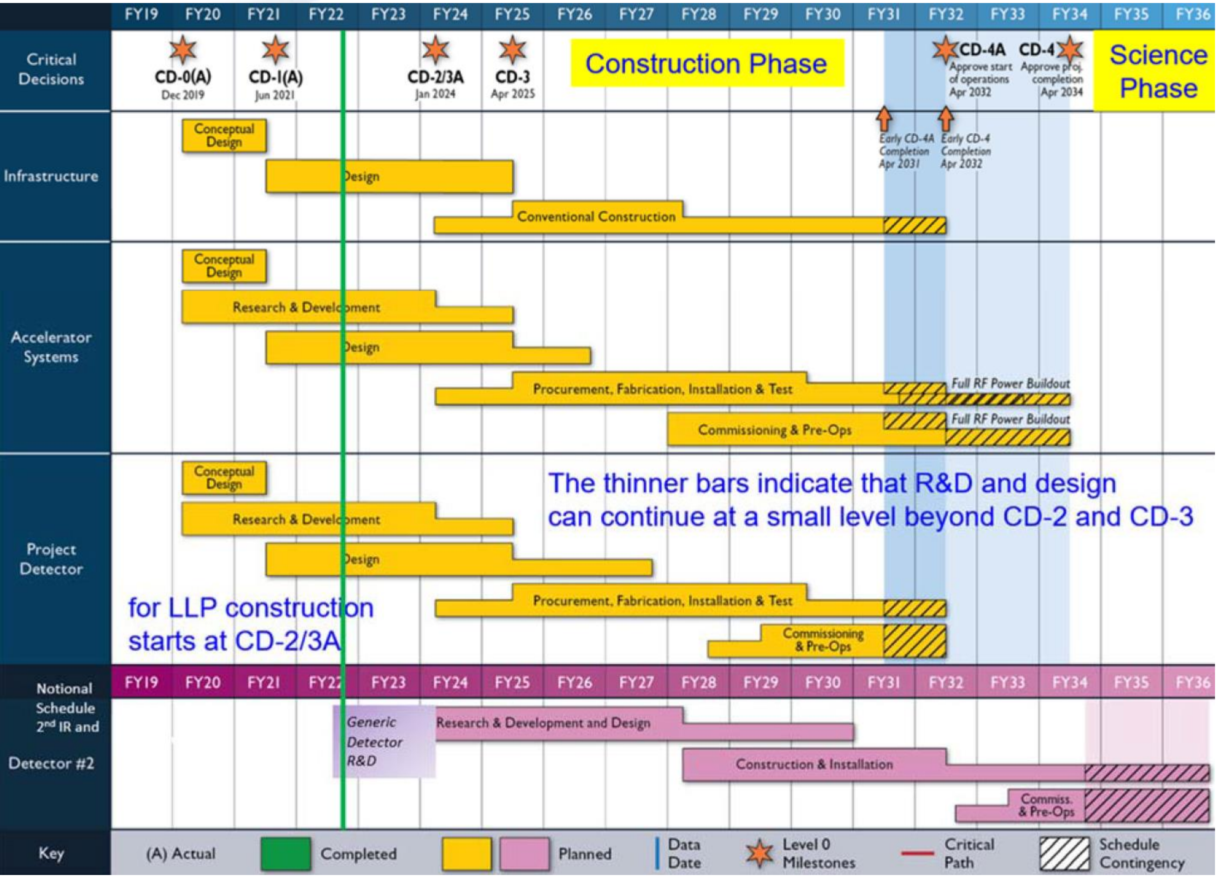
SiPM PCB design: Thi Nguyen-Trung (IJCLab)

Summary

- Readout of PWO crystals with SiPM will be first implemented at EIC
- Several challenges for high resolution EM calorimetry:
  - Large dynamic range
  - Small energy reach
  - Dark current, radiation damage
- Readout solution with HGCROC ASIC underway
- Upcoming beam test to evaluate performance
- Start of construction: ~2026

Back up

News from the EIC project



EIC detector milestones

- **Dec 2021:** Detector design
- Jan 2024: R&D completed (CD-2)
- Apr 2025: TDR completed (CD-3), start of construction
- 2030: Detector commissioning
- 2031: Pre-ops
- 2034: Start of physics program (CD-4)

Recent news

- **PbWO4 Final Design Review :** July 21 2023
- **SiPM Final Design Review:** September 14, 2023

Long term procurement of PWO crytals and SiPM can start

- **2023 NSAC Long-Range Plan:** October 4, 2023

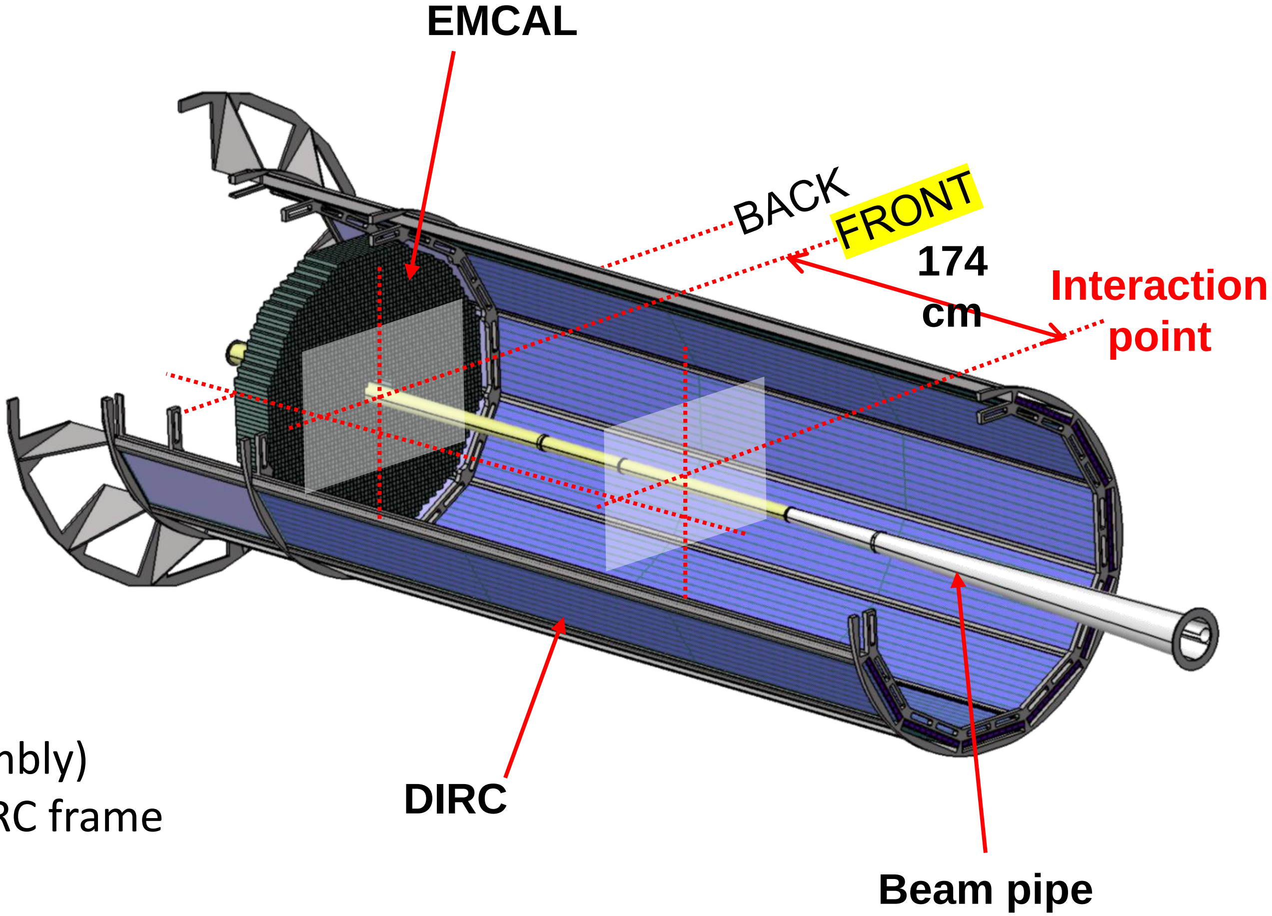
Recommendation 3: EIC construction

Requirements

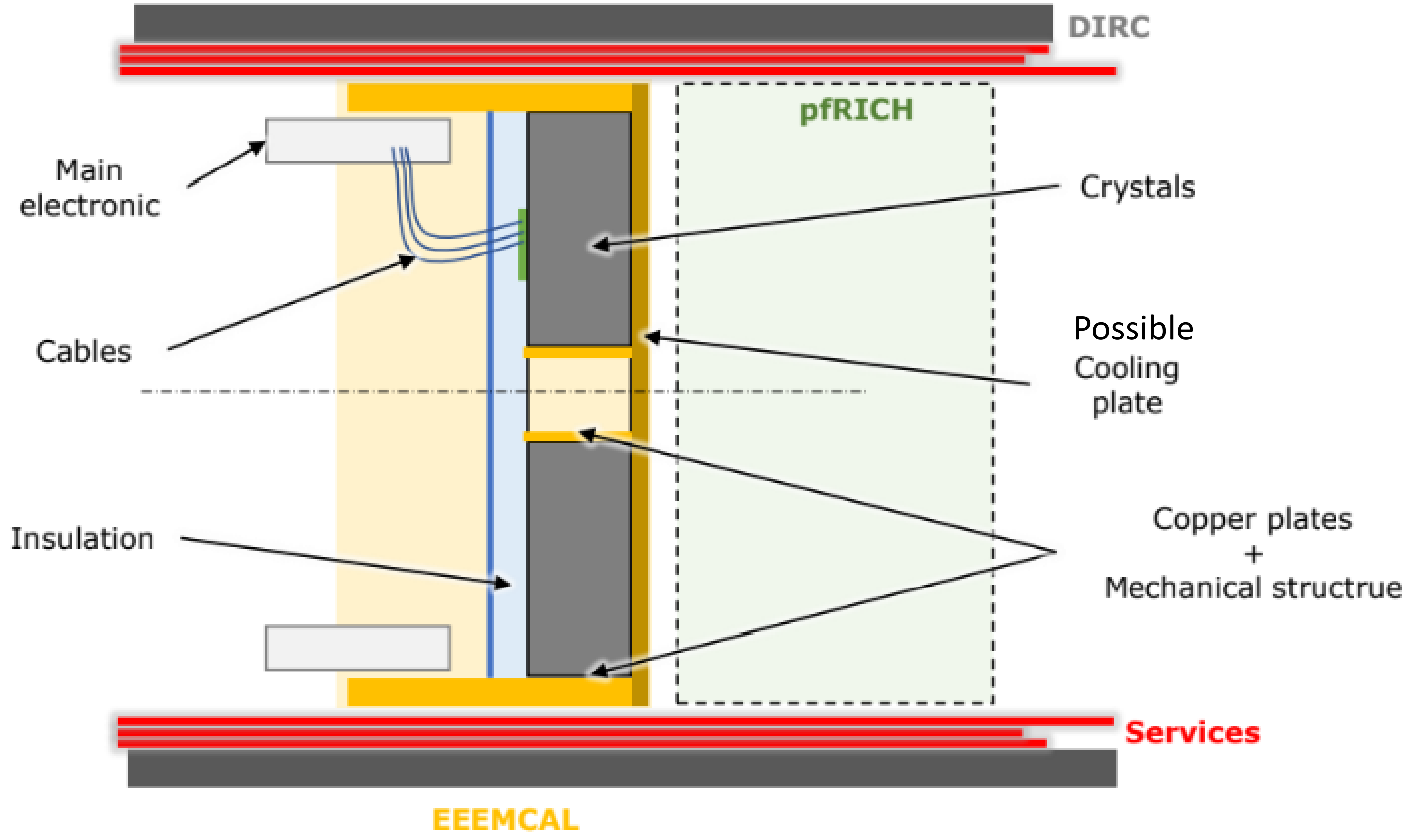
❑ Physics:
- Minimize the material & space between crystals
- Minimize material in front of the detector
- To be as close as possible to the beampipe
- Gain monitoring system (1 fiber/crystal)

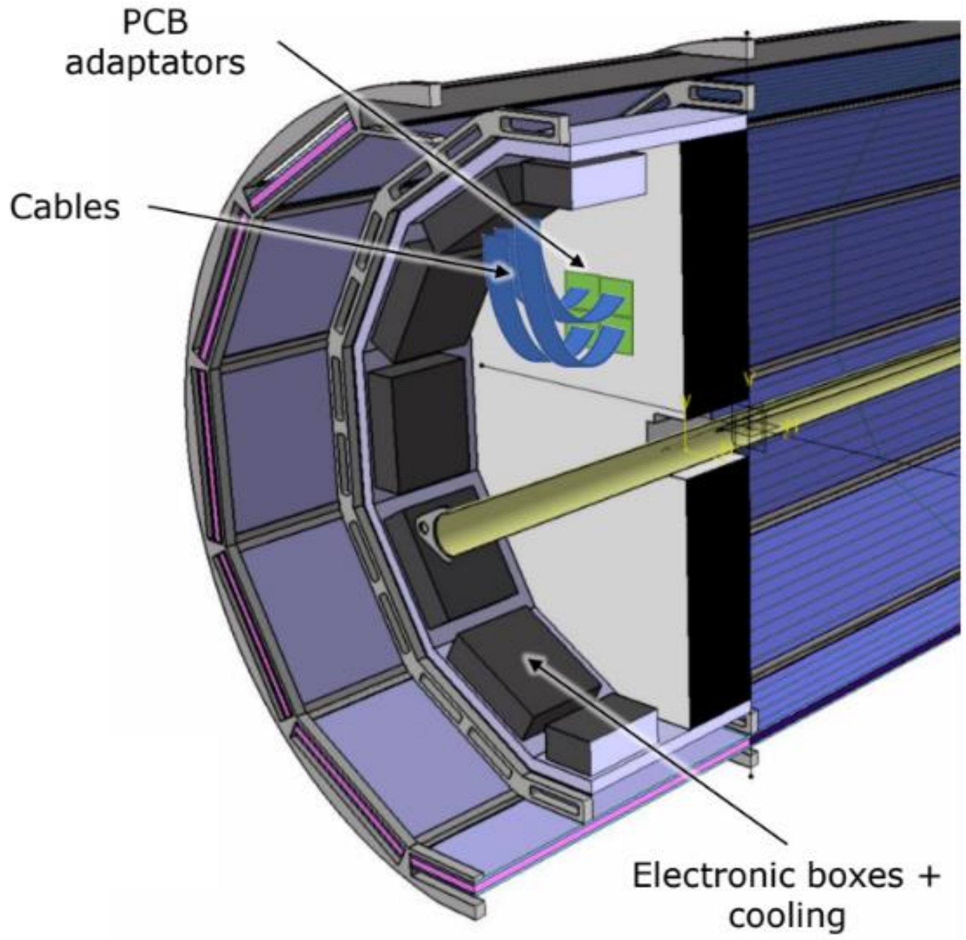
❑ Thermal:
- Operation at 20°C (room temp)
- Required stability on crystal temperature: +/- 0.1°C

❑ Installation:
- Removal of the detector in one block (without disassembly)
- Clearance of 5 mm between the beam pipe and the DIRC frame



Front-end electronics and cooling





The EEEMCal consortium

US

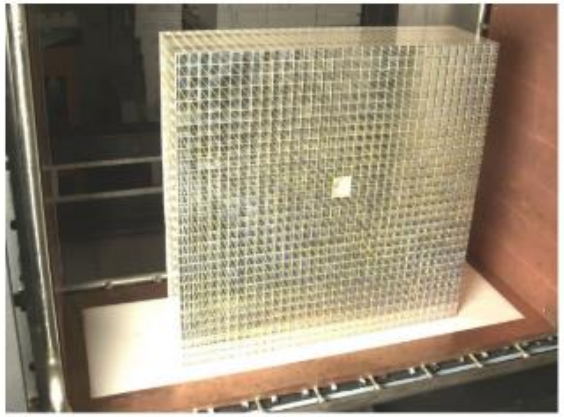
- The Catholic University of America (contact: Tanja Horn, hornt@cua.edu)
- Lehigh University (contact: Rosi Reed, rosijreed@lehigh.edu)
- University of Kentucky (contact: Renee Fatemi, renee.fatemi@uky.edu)
- MIT and MIT-Bates Research and Engineering Center (contact: Richard Milner, milner@mit.edu)
- Florida International University (contact: Lei Guo, leguo@fiu.edu)
- James Madison U. (contact: Gabriel Niculescu, gabriel@jlab.org)
- Abilene Christian University (contact: Larry Isenhower, ldi00a@acu.edu)
- Ohio University (contact: Justin Frantz, frantz@ohio.edu)
- College of William & Mary (contact: Cristiano Fanelli, cfanelli@wm.edu)

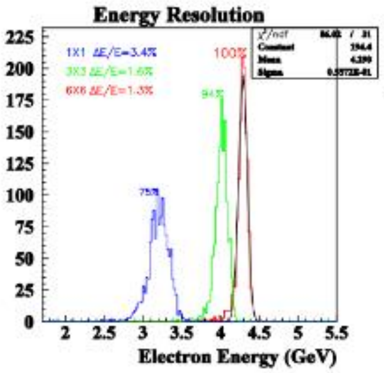
International

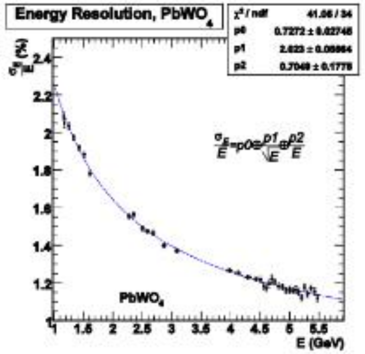
- AANL, Armenia (contact: Ani Aprahamian, aapraham@nd.edu)
- Charles University Prague, Czech Republic (contact: Miroslav Finger, Miroslav.finger@cern.ch)
- IJCLab-Orsay, France (contact: Carlos Munoz-Camacho, munoz@jlab.org)

Prototype Beam Test Campaigns

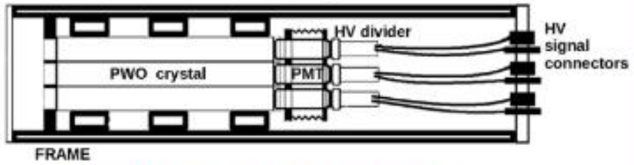
HyCal (pre-2014)
1152 $PbWO_4$ crystals (PWO-I)
SICCAS/China

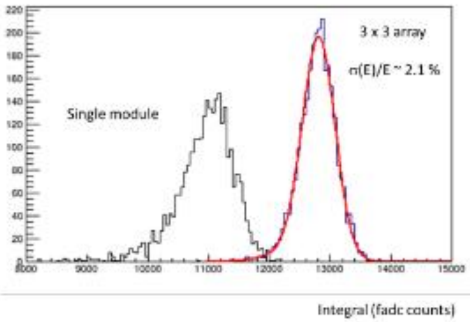






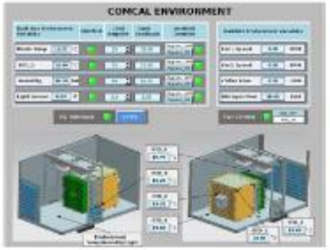
3x3 prototypes (2018/19)
9 $PbWO_4$ (PWO-II) crystals
CRYTUR/Czech Rep.

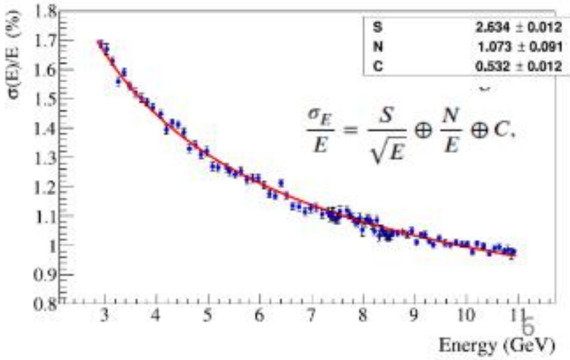




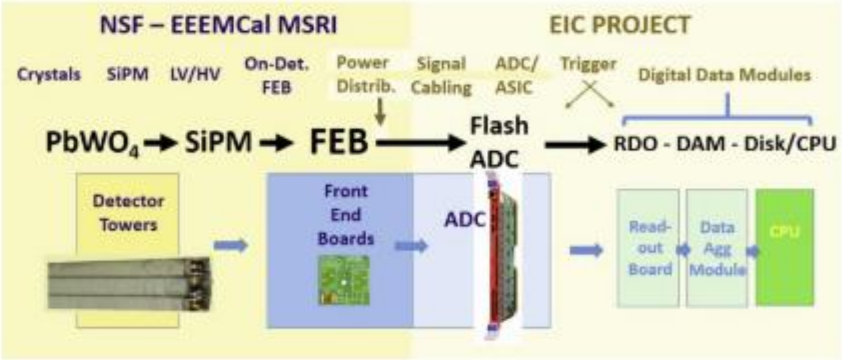
12x12 prototypes (2019)
144 $PbWO_4$ (PWO-II) crystals
CRYTUR/Czech Rep/

ComCal/
FCAL





Work Breakdown Structure



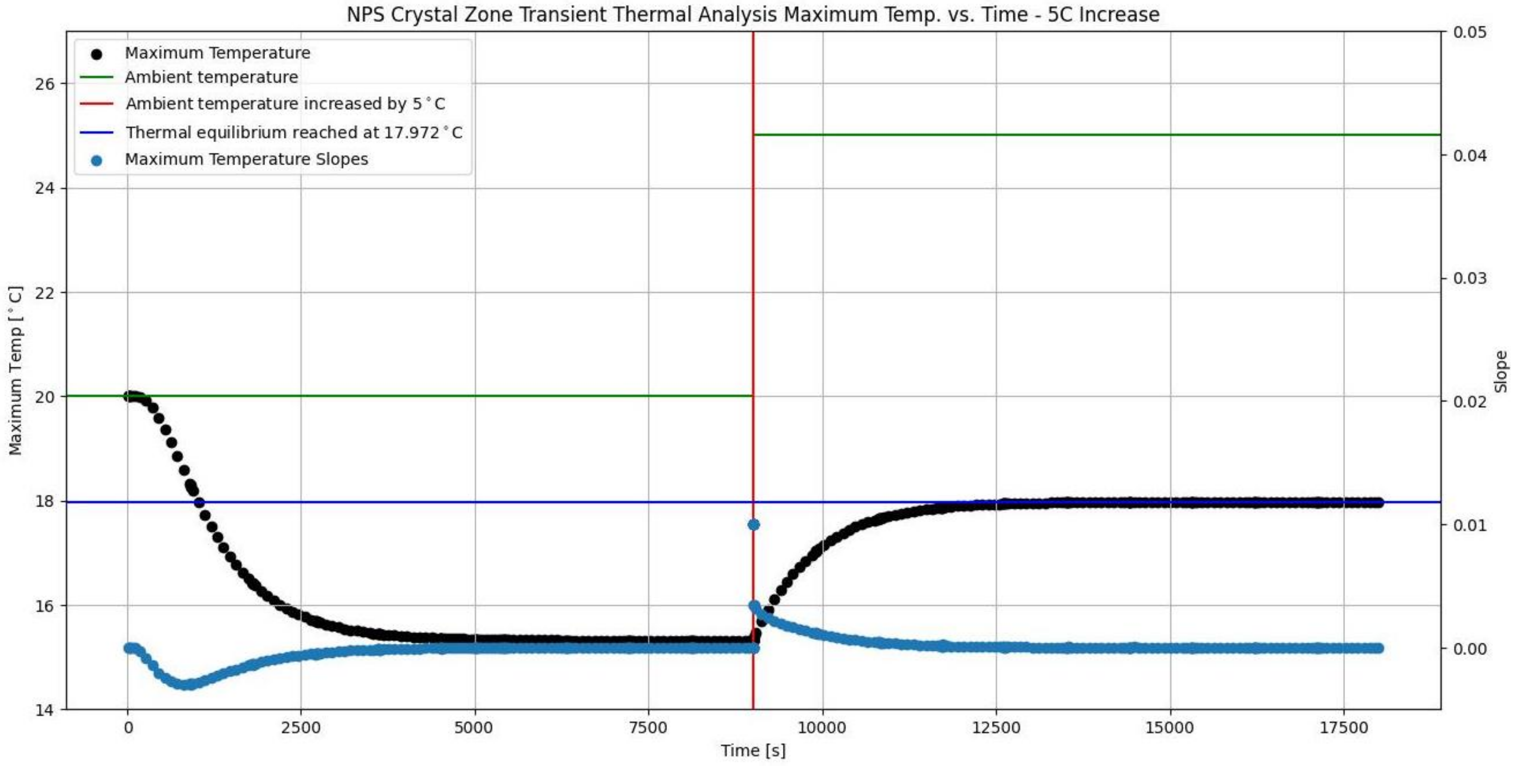
If ASICs will be used this would basically be "FEE" with contributors: OMEGA, Laboratoire Leprince-Ringuet (LLR)

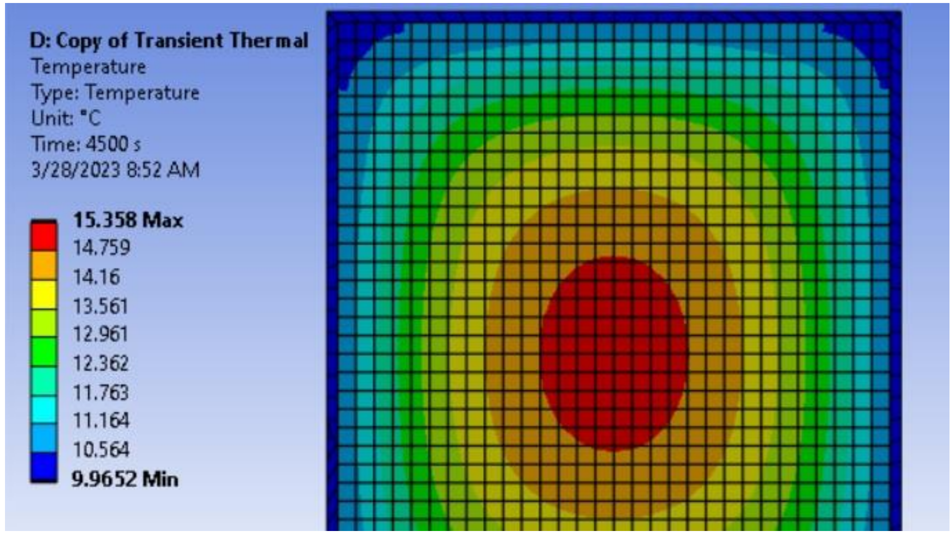
WBS Title	EIC WBS	WBS Dictionary Description	
EEEMCAL Project	6.10.05.01	Construction of the EEEMCAL. The EEEMCAL is an electromagnetic calorimeter for measurement of the inclusive processes physics in the electron-going direction at the EIC	
Radiator	6.10.05.01.01	Radiation detectors consisting of scintillating crystals (PWO) and thin reflector sheets. These provide the detection of energetic electrons	CUA, Kentucky, JMU, AANL, Charles U.
Photosensors	6.10.05.01.02	Photosensors consisting of multi-pixel photon counters (MPPC) grouped into an array to maximize surface coverage of the PWO blocks, along with printed circuit boards to which the MPPC are also attached for analog readout.	OU, Lehigh, ACU
Mechanical Structure	6.10.05.01.03	Mechanical structure including installation fixtures and a cooling system providing thermal stabilization, which is important for crystal performance.	IJCLab, MIT
Signal Processing/DAQ	6.10.05.01.04	Signal Processing/DAQ providing the electronics to transmit the signals to the data analysis modules.	FIU
Simulations/Software	6.10.05.01.05	Software libraries and infrastructure foundation for analyzing the EEEMCAL detector data and simulating it.	W&M

Ansys Transient Thermal Analysis

Studies by the JLab DSG for the NPS setup

- Copper shell temp: 10°C (constant)
- Q = 0.3 W per crystal
- Ambient temp: 20°C





- ➢ Temperature stabilization has a **long time constant:** it takes >1h to reach equilibrium after a change
- ➢ Working with Ansys to understand the stabilization temperature (disagreement with previous steady-state simulations)

The EIC project detector: ePIC

Tracking:
- New 1.7T solenoid
- Si MAPS Tracker
- MPGDs (μRWELL/μMegas)

PID:
- hpDIRC
- mRICH/pfRICH
- dRICH
- AC-LGAD (~30ps TOF)

Calorimetry:
- SciGlass/Imaging Barrel EMCal
- $PbWO_4$ EMCal in backward direction
- Finely segmented EMCal +HCal in forward direction
- Outer HCal (sPHENIX re-use)

hadronic calorimeters

Solenoidal Magnet

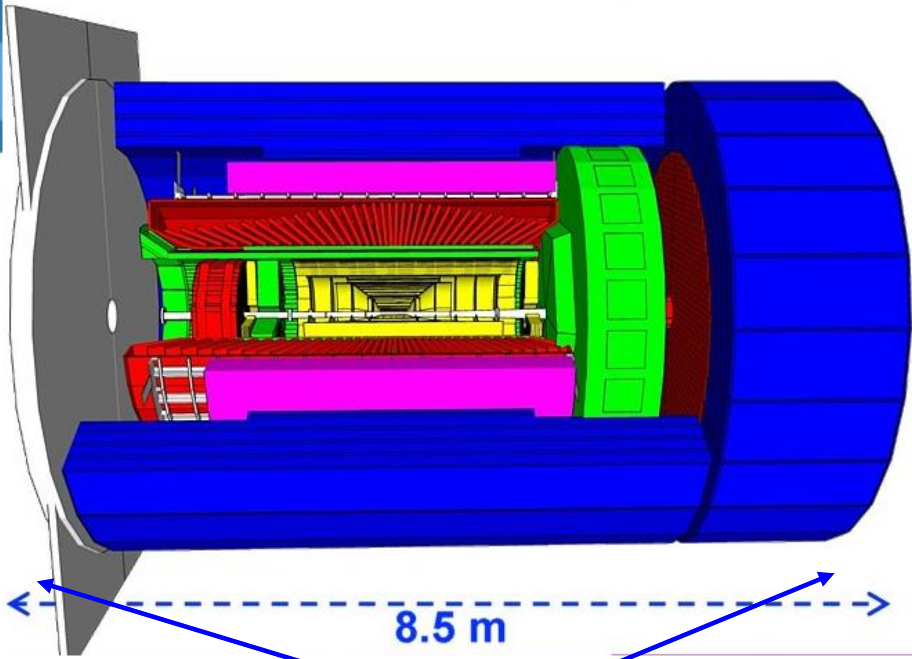
e/m calorimeters

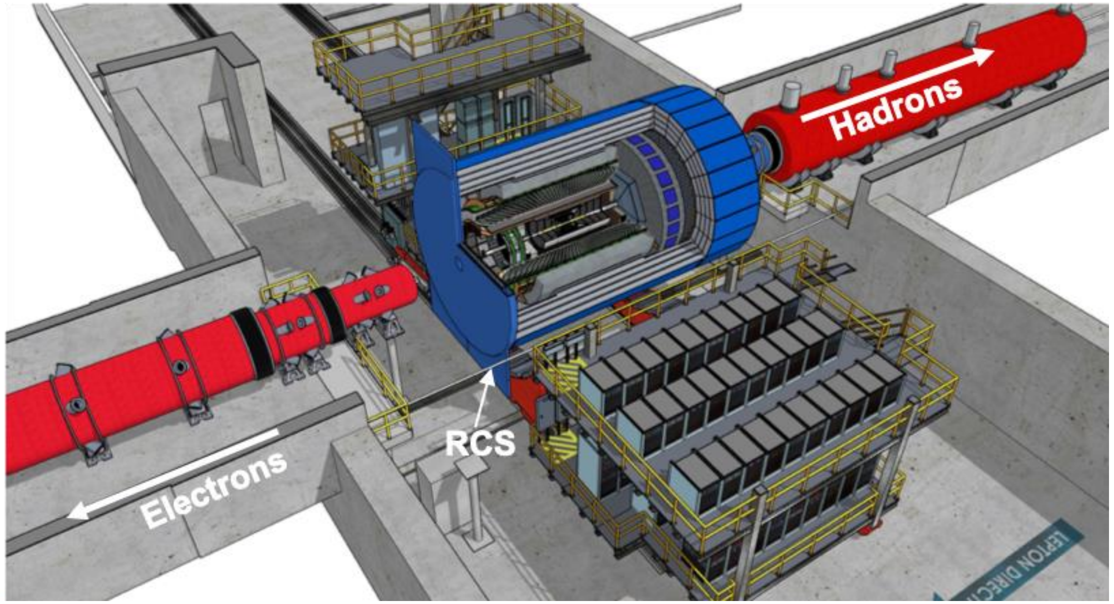
ToF, DIRC, RICH detectors

MPG trackers

MAPS tracker

25 subdetectors incl. polarimeters





Far-Backward Detectors:
- Luminosity monitor.
- Low-Q^2 Tagger

Far-Forward Detectors:
- B0 Tracking and Photon Detection
- Roman Pots and Off-Momentum Detectors.
- Zero-Degree Calorimeter