Lead Tungstate Calorimeter of the Jefferson Lab Eta Factory Experiment

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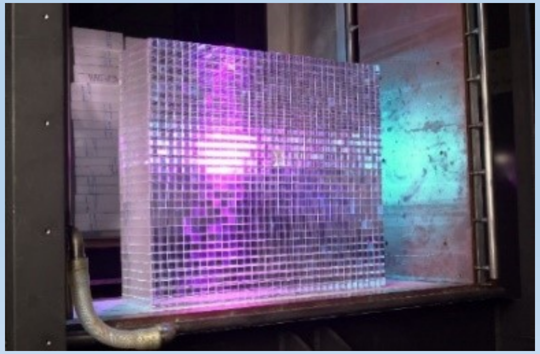
on behalf of the JEF working group

10th International conference on calorimetry in particle physics

Tsukuba, Japan, May 19 – 24, 2024



Overview

- GlueX detector in Hall *D* at Jefferson Lab
- Jefferson Lab Eta Factory (JEF) experiment
- Upgrade of the GlueX forward calorimeter
- Lead tungstate calorimeter (ECAL)

  - module design, testing, and fabrication

  - calorimeter installation in Hall D

  - light monitoring system

  - readout electronics and trigger

  - shower reconstruction

  - performance of the large scale prototype

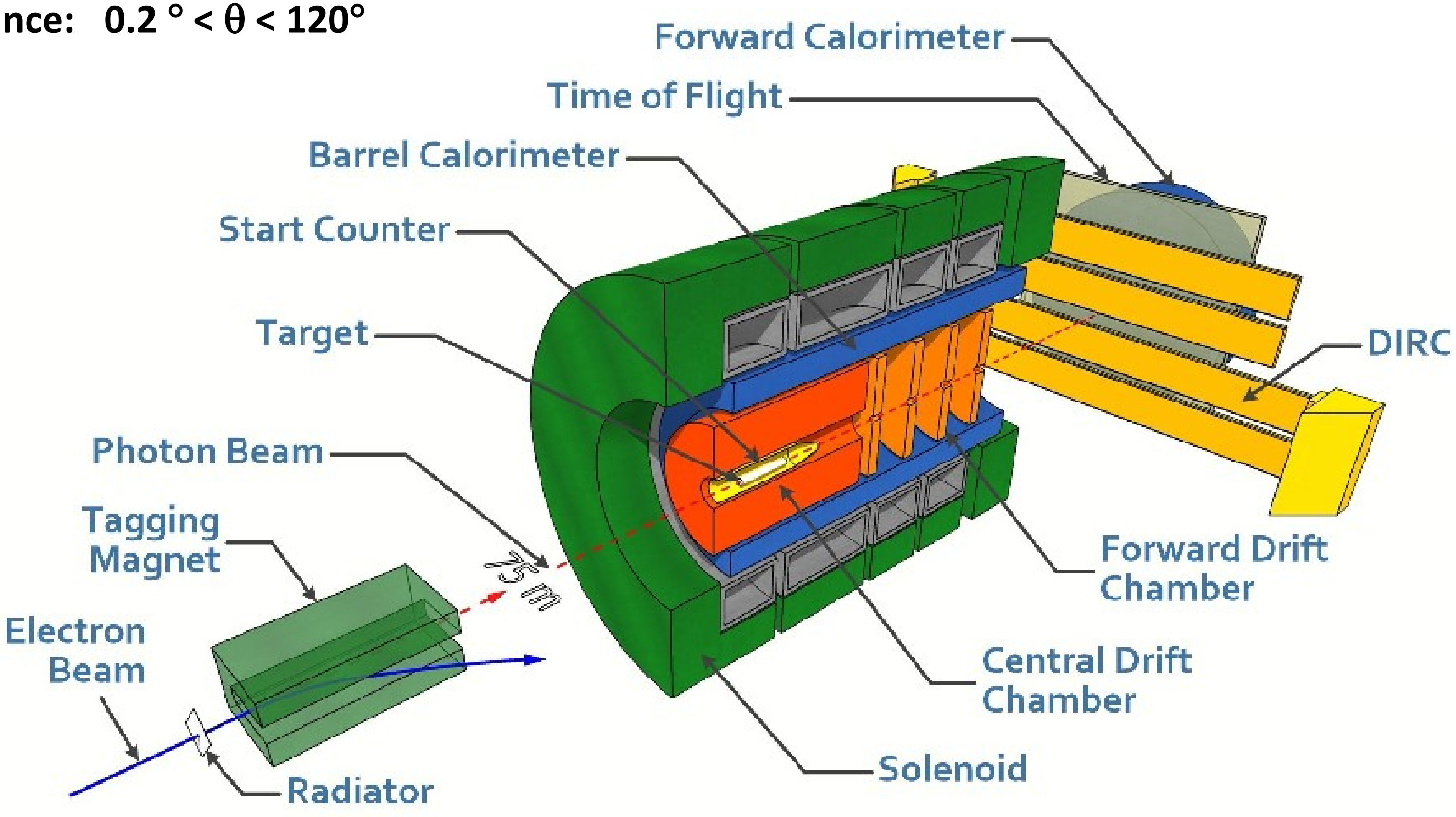
GlueX Detector in Hall *D* at Jefferson Lab

Photons: $\sigma_E / E \sim 6\,\% / \sqrt{E} \oplus 2.0\,\%$

Tracks: $\sigma_p / p \sim 2 – 5\,\%$

Acceptance: $0.2\,° < \theta < 120°$

Nucl. Instrum. Meth. A 987, 164807 (2021)



Experiments:

- Search for mesons with exotic quantum numbers
- Study of meson and baryon decays to strange final states
- Measurement of η radiative decay width via the Primakoff effect
- Measurement of pion polarizability
- Study short range correlations
- Study $\eta^{(')}$ decays (JEF)
- Measurement of high energy contribution to the GDH sun rule
- Strange hadron spectroscopy with KL beam

- Beam of photons with the energy of up to 12 GeV, linear polarization
- The detector design is optimized to detect multi-particle final states
- The detector was commissioned in 2016. Several experiments have been carried out since then

Physics Program of the Jefferson Lab Eta Factory (JEF) Experiment

Upgrade the Forward Calorimeter

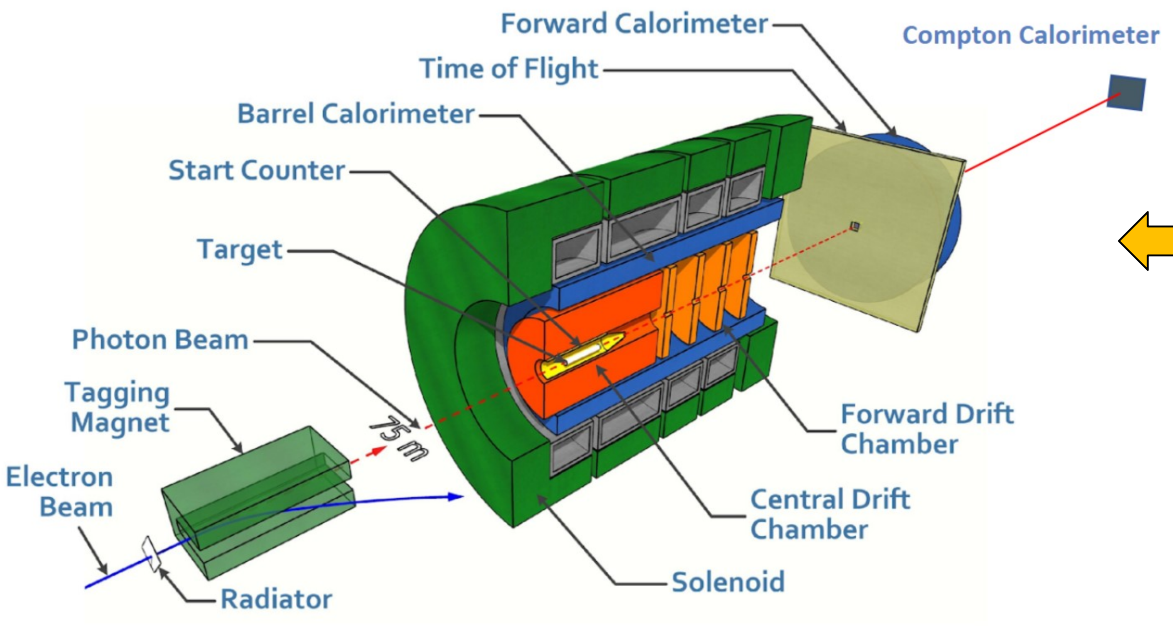
Mode	Branching Ratio	Physics Highlight	Photons
priority:			
$\pi^0 2\gamma$	$(2.7 \pm 0.5) \times 10^{-4}$	χPTh at $\mathcal{O}(p^6)$	4
$\gamma + B$	beyond SM	leptophobic dark boson	4
$3\pi^0$	$(32.6 \pm 0.2)\%$	$m_u - m_d$	6
$\pi^+\pi^-\pi^0$	$(22.7 \pm 0.3)\%$	$m_u - m_d$, CV	2
3γ	$< 1.6 \times 10^{-5}$	CV, CPV	3
ancillary:			
4γ	$< 2.8 \times 10^{-4}$	$< 10^{-11}$[112]	4
$2\pi^0$	$< 3.5 \times 10^{-4}$	CPV, PV	4
$2\pi^0\gamma$	$< 5 \times 10^{-4}$	CV, CPV	5
$3\pi^0\gamma$	$< 6 \times 10^{-5}$	CV, CPV	6
$4\pi^0$	$< 6.9 \times 10^{-7}$	CPV, PV	8
$\pi^0\gamma$	$< 9 \times 10^{-5}$	CV, Ang. Mom. viol.	3
normalization:			
2γ	$(39.3 \pm 0.2)\%$	anomaly, η-η' mixing PR12-10-011	2

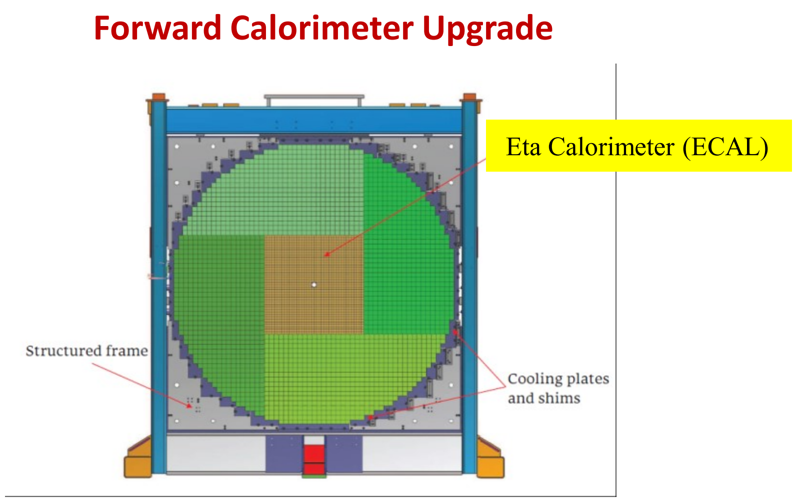
4

Main physics topics:

1. Test of low-energy QCD
2. Search for dark matter
3. Directly constrain CVPC new physics
4. Constrain the light quark mass ratio

JEF Experiment using GlueX Detector





- Upgrade the inner part of the lead glass Forward Calorimeter with high-granularity high-resolution **$PbWO_4$** crystals to improve reconstruction of multi-photon final states
- Produce η / η′ using a beam of tagged photons with the energy between 8.4 - 11.7 GeV
- Reconstruct η / η′ in exclusive reactions:

$$\gamma + p \rightarrow \eta/\eta' + p \qquad \eta/\eta' \rightarrow \gamma\gamma,\ \pi^0\gamma\gamma,\ \ldots$$

- Run in parallel with other GlueX experiments: collect large data set of η / η′ mesons

Forward Calorimeter Upgrade

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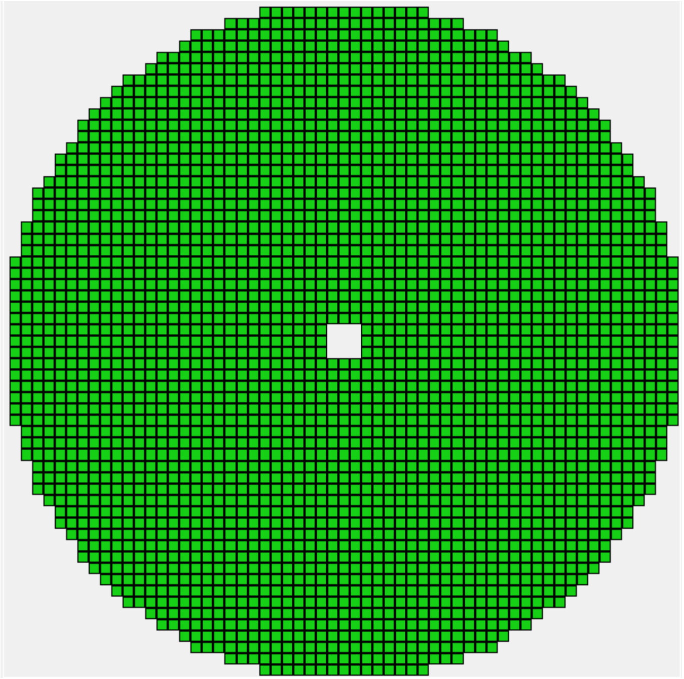
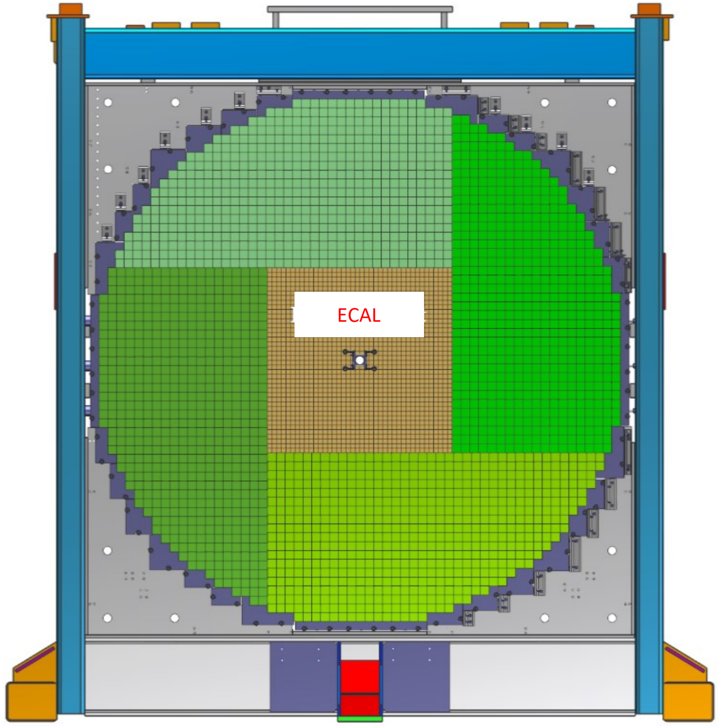


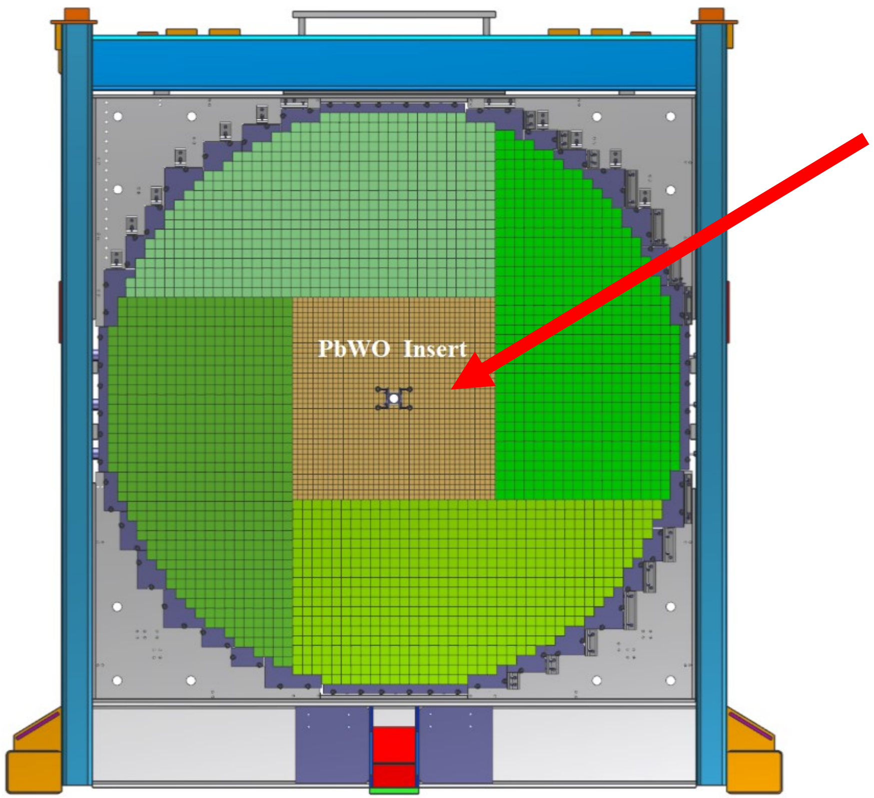


- 2800 lead glass modules (taken from E852 experiment at BNL)
  - lead glass block size: 4 cm x 4 cm x 45 cm
- Photodetectors: FEU 84-3 PMTs with Cockroft-Walton bases
- The energy resolution: $\frac{\sigma(E)}{E}(\%) = \frac{6.2}{\sqrt{E}} \oplus 4.7$

- Replace lead glass modules in the inner part of the detector with high-granularity high-resolution lead tungstate scintillating crystals

Eta Calorimeter (ECAL)

Lead Tungstate Eta Calorimeter (ECAL)



- ECAL consists of an array of 40 x 40 $PbWO_4$ (1596) modules

  - 2 cm x 2 cm x 20 cm $PbWO_4$ crystal
  - 4 cm x 4 cm x 45 cm   lead glass block

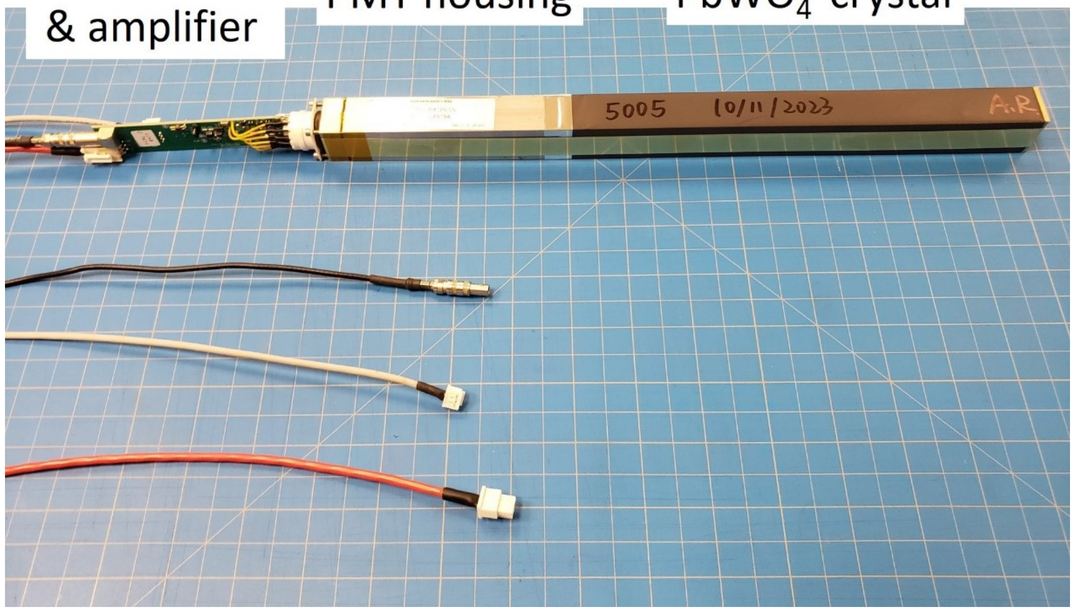
Lead Glass & $PbWO_4$ modules

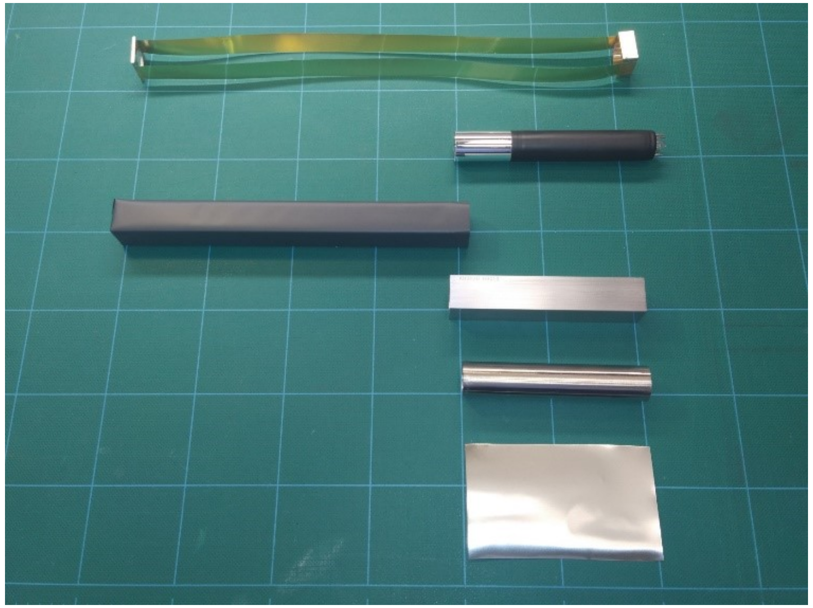
- A factor of 4 better detector granularity
  - significantly improve shower separation
- Improves the energy and position resolutions by about a factor of 2

ECAL installation required:

- removing all lead glass blocks
- modifying the detector mounting frame, installing cooling blocks
- installing lead glass and lead tungstate modules
- the construction of the ECAL has started in 2022, the installation will be completed in July 2024

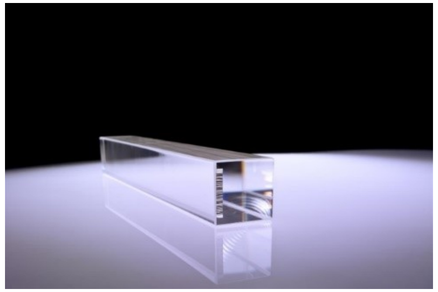
ECAL Module Design





- $PbWO_4$ crystal wrapped with the 65 μm thick ESR reflective foil and light-tight Tedlar
- Hamamatsu R4125 PMT placed inside the 350 μm and 50 μm mu-metal cylinders and soft iron housing
- 3.5 cm long light guide (18.5 mm diameter) is glued to the PMT and coupled to the crystal using a silicon cookie
- PMT divider attached to the socket

Lead Tungstate Crystals

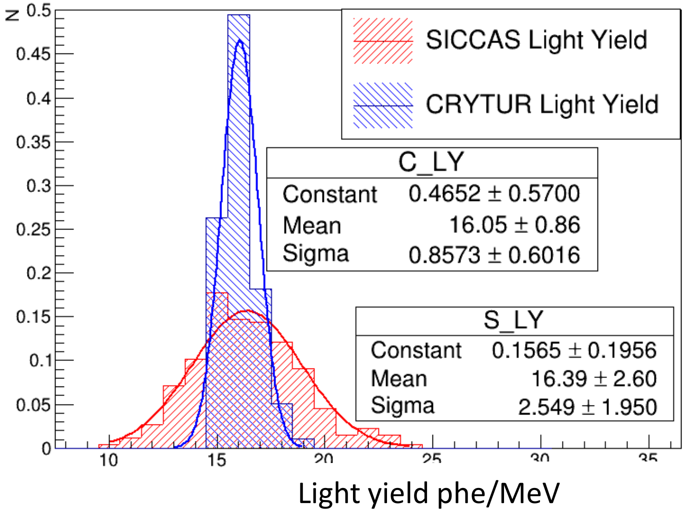


- ECAL consists of 1596 crystals (Type II) forming an array of 40 x 40
- Crystal dimensions: 20.5 x 20.5 x 200 mm^3 (22 R.L.)
- Crystals procured from two vendors: 900 crystals from CRYTUR in the Czech Republic
  700 crystals from SICCAS in China
- Performed quality assurance of crystals used in the ECAL

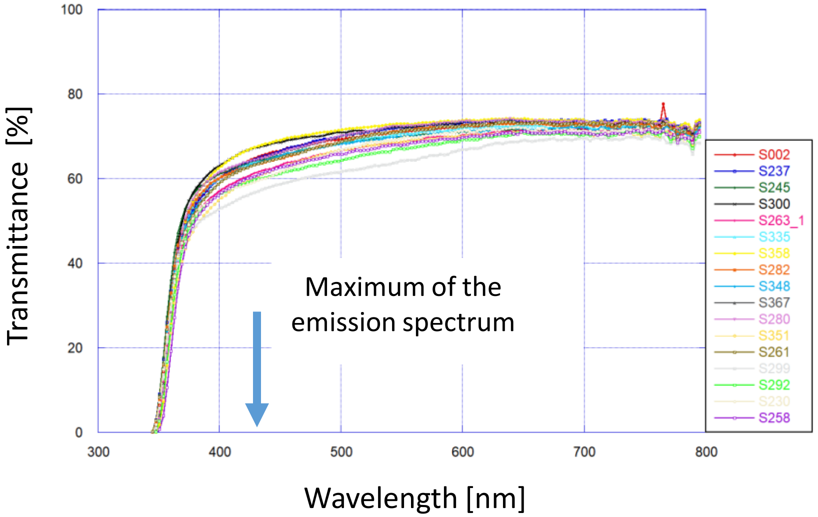
  - longitudinal optical transmittances of crystal
    360 nm: 29 % (SICCAS) 45 % (CRYTUR)
    420 nm: 64 % (SICCAS) 69 % (CRYTUR)

NIM A 956 (2020) 163375

Light yield

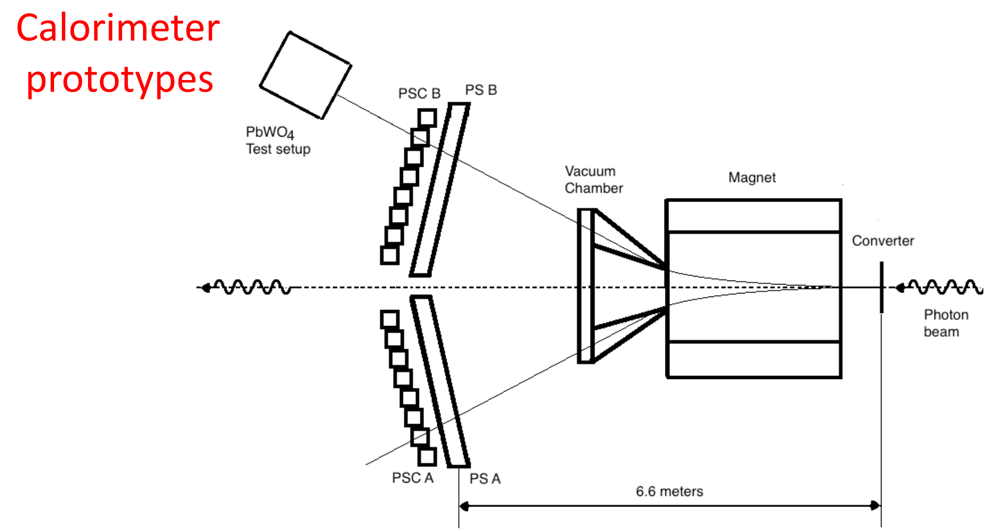


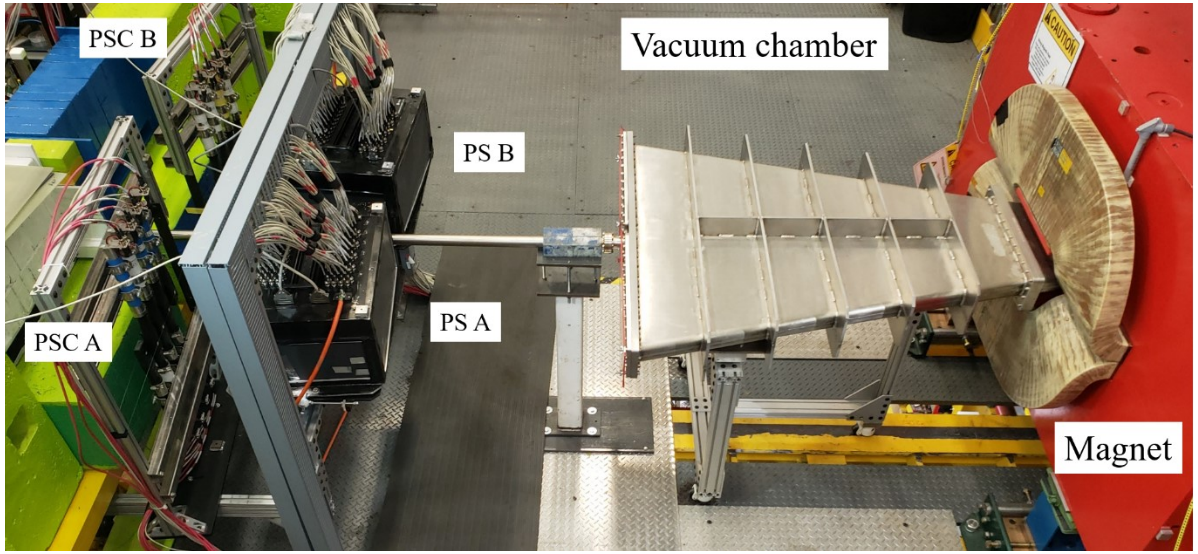
Light transmittance



Calorimeter Testing Facility in Hall D

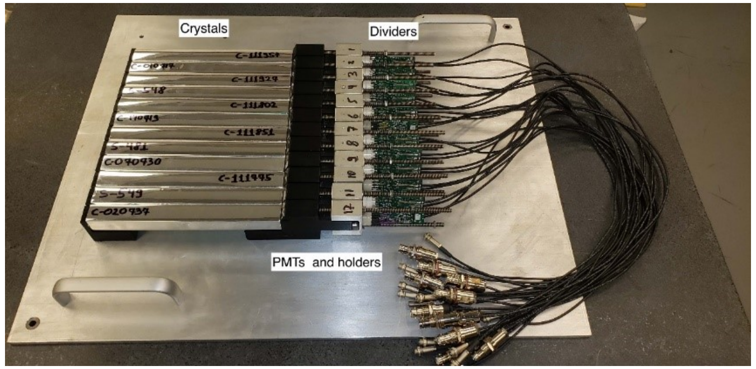
NIM A 795 (2015) 376-380



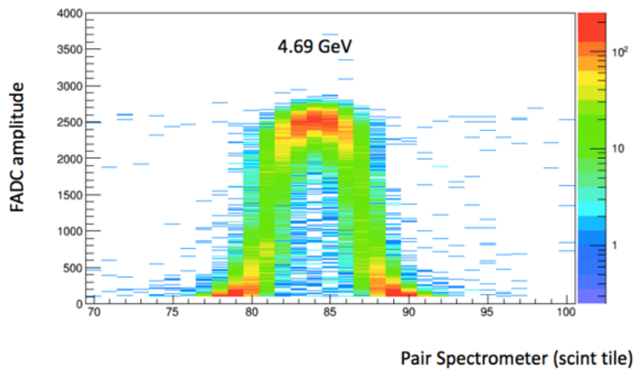


- Position various detector prototypes downstream the PS
- Beam of electrons and positrons with known energy
  - the energy range between 3 GeV and 6 GeV
- Perform tests in parallel with GlueX data taking
  - trigger provided by the PS
  - can use flash ADCs, and TDCs; readout integrated into the GlueX DAQ

Testing modules for Hall D ECAL



Pulse amplitude as a function of the hit position

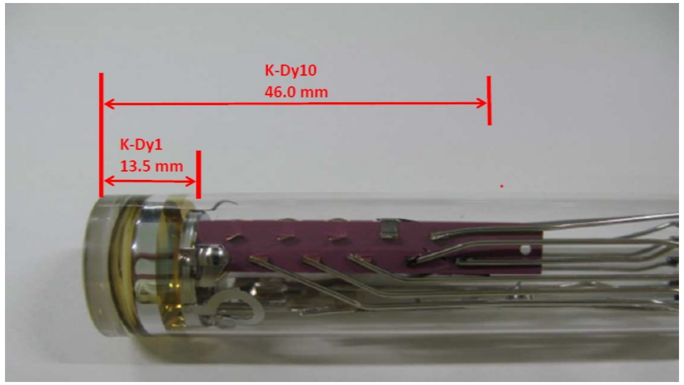


Magnetic Shielding for Hamamatsu R4125 PMT

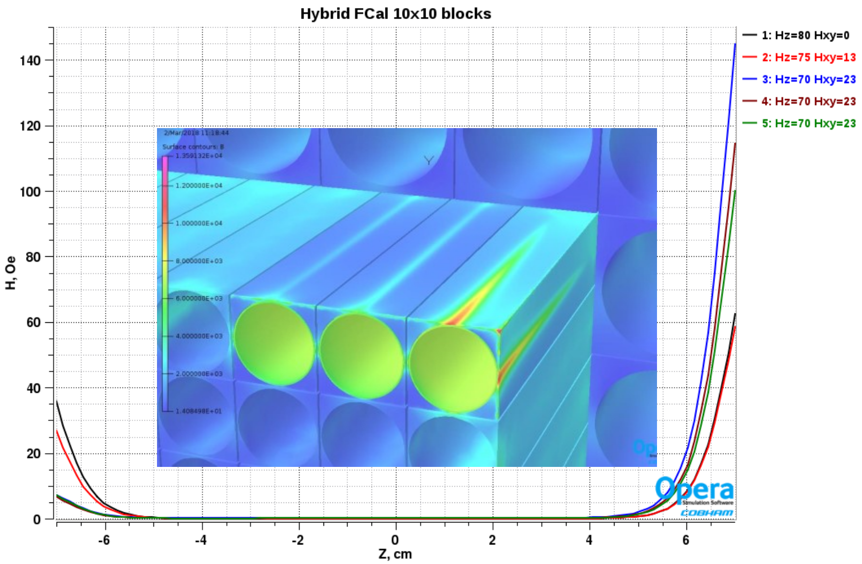
- Fringe field of the GlueX solenoid magnet
  maximum B_z ~ 50 Gauss, B_r < 10 Gauss

  - optimize PMT shielding using TOSCA simulation

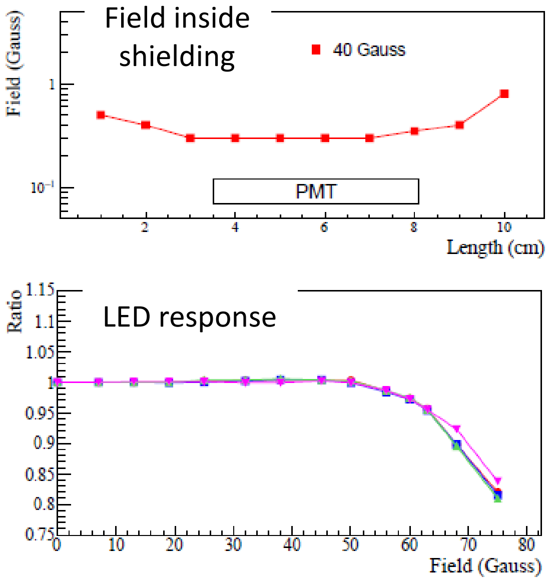
  - study shielding using prototypes positioned into Helmholz coils.
    Check performance in the field using LED



TOSCA Simulation



Prototype positioned inside Helmholz coils



- Extend PMT shielding above the face of the photo cathode
  - 3.5 cm long acrylic light guide with a diameter of 18.5 mm

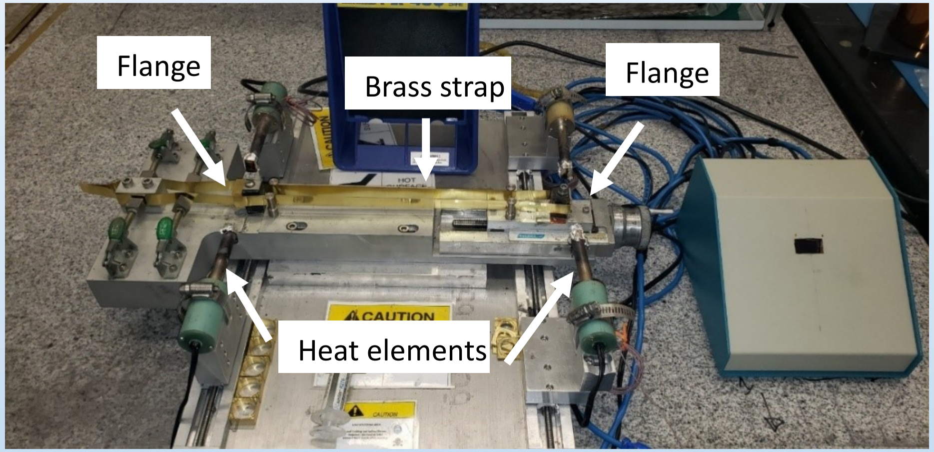
- PMT is placed inside the soft iron housing (AISI 1020 steel)

- Two layers of mu-metal cylinders with the thickness of 350 μm and 50 μm

Preparation Parts for ECAL Modules at Jefferson Lab

- Preparation of parts and fabrication of ECAL modules were performed at JLab, several groups were involved

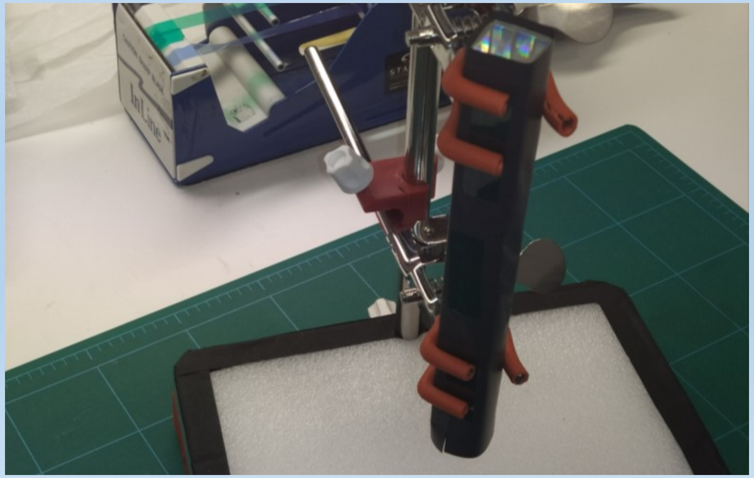
Brazing brass assemblies (holding module assembly)



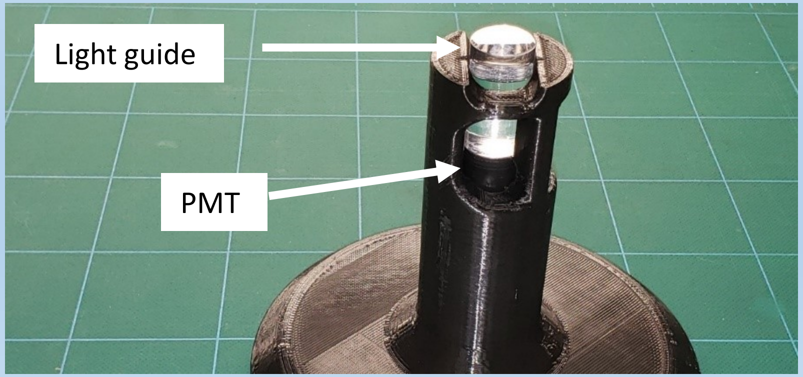
Checking PMTs

Preshaping ESR foils

Wrapping crystals



Gluing Light guides



Students in the ECAL Project

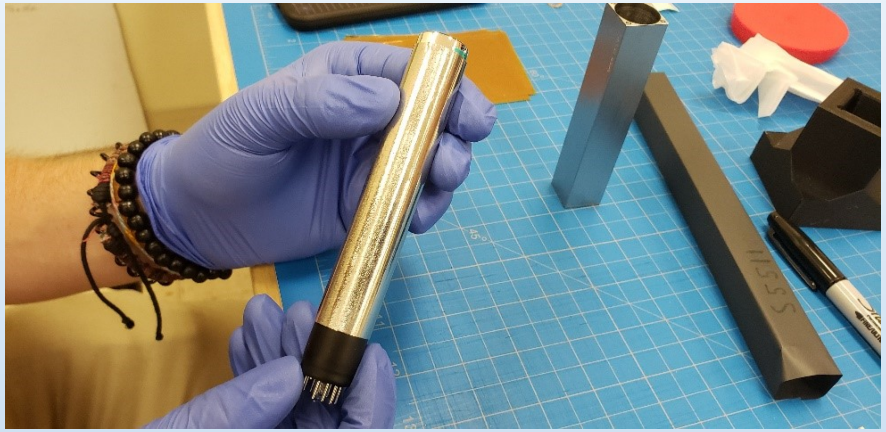
16 students from 10 universities and colleges worked on the project during the summer of 2023

https://halldweb.jlab.org/detectors/fcal2/installation/students_2023/

Fabrication of ECAL Modules at Jefferson Lab

Wrapping modules with the ESR and Tedlar

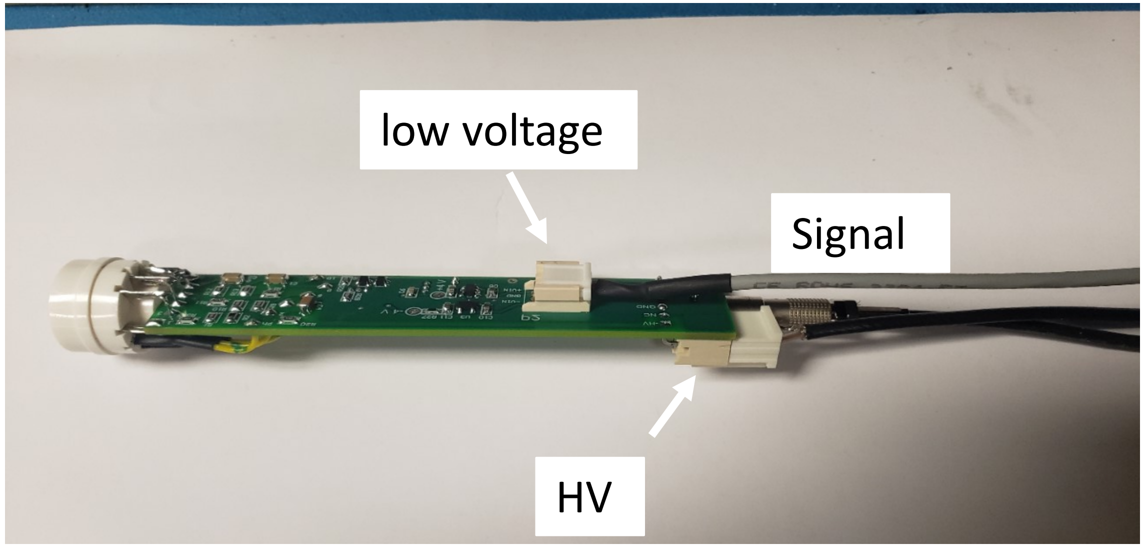
Installation of PMT



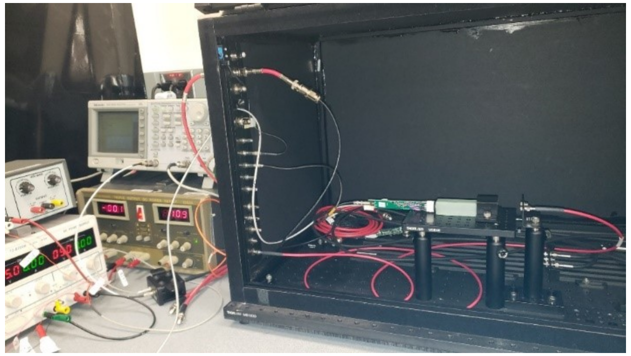
Module fabrication

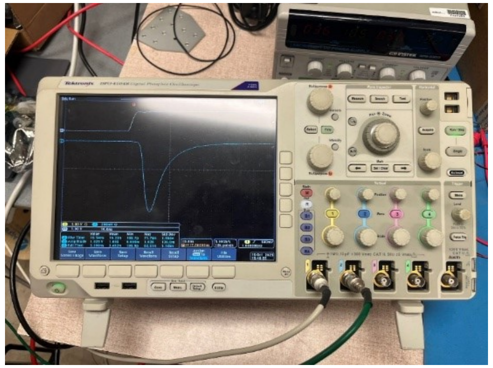
Final quality check

PMT Active Base



Divider test setup



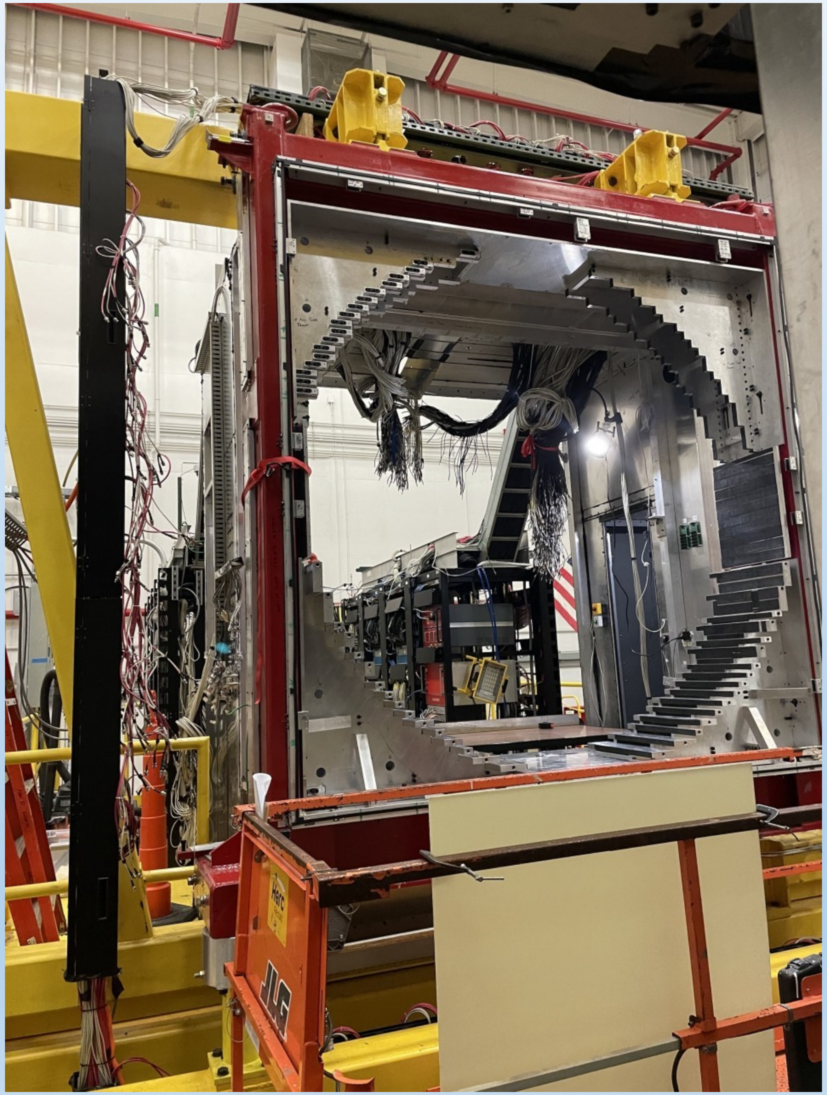


- Designed at JLab
- Modified the original Hamamatsu voltage divider by adding two bipolar transistor to the last two dynodes
  - gain stabilization at high rate
- Added an amplifier positioned on the same PCB with the divider
  - lower the PMT operating voltage and reduce the anode current. Prolongs the PMT's life
  - requires to supply $\pm$ 5 V
- Switches on the PCB allow to by-pass the amplifier
  - enable amplifier on layers around the beam
- Three cables are connected to each divider: signal, LV, and HV
- All dividers were tested using LED
- Studied radiation hardness

Disassembling Lead Glass Calorimeter

Removing lead glass modules

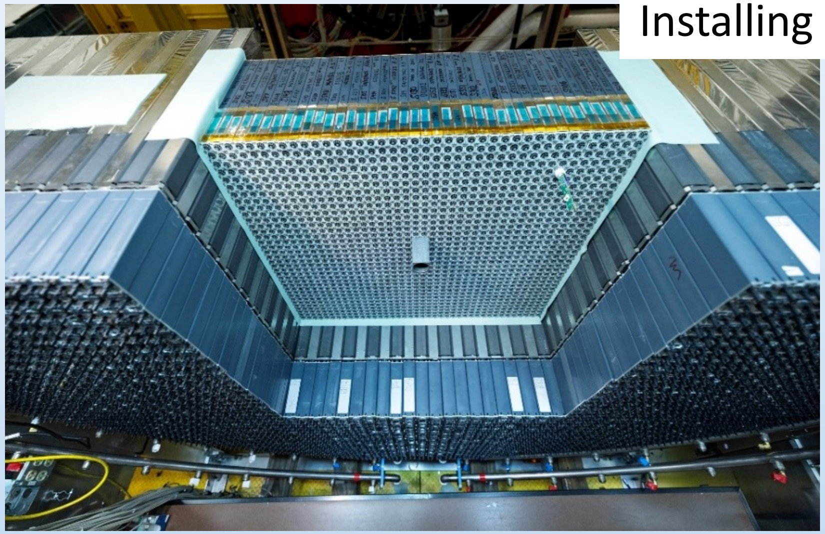
All modules removed



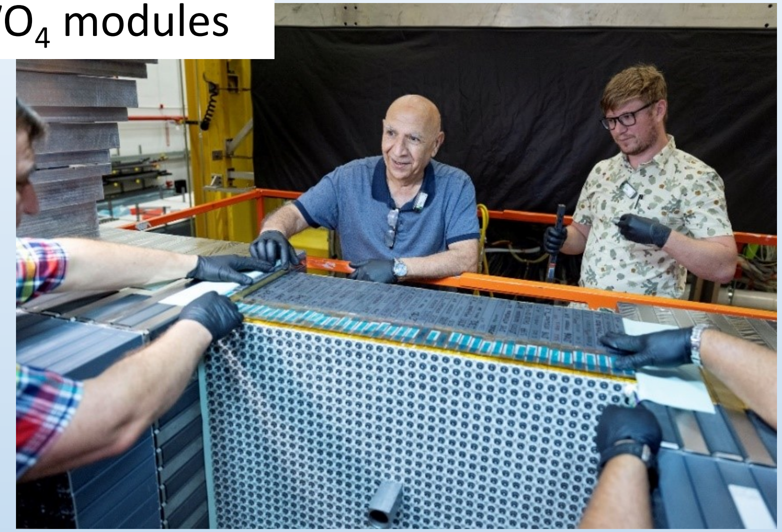
Detector Installation in Hall D

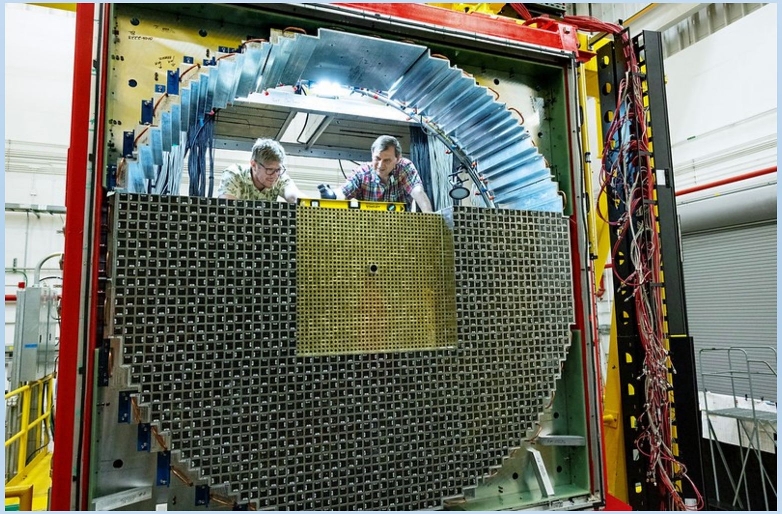
First module installed

Detector installation: July 12 – Oct 6, 2023 (3 months)

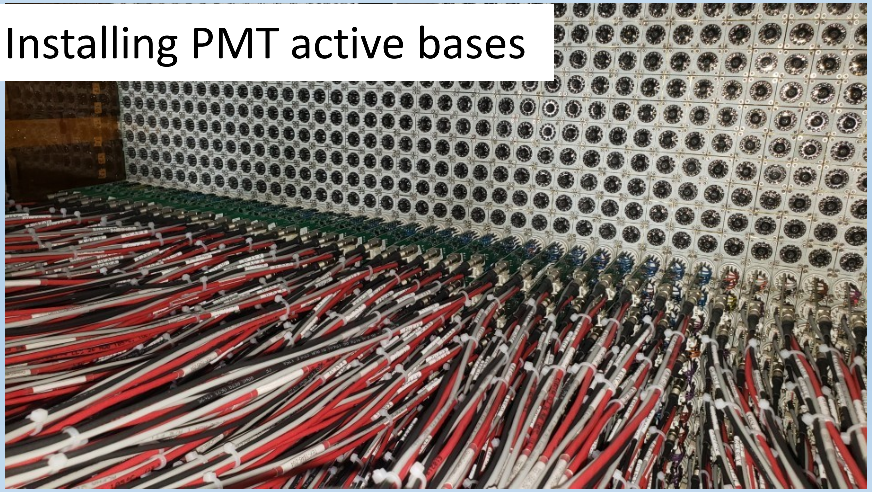


Installing $PbWO_4$ modules



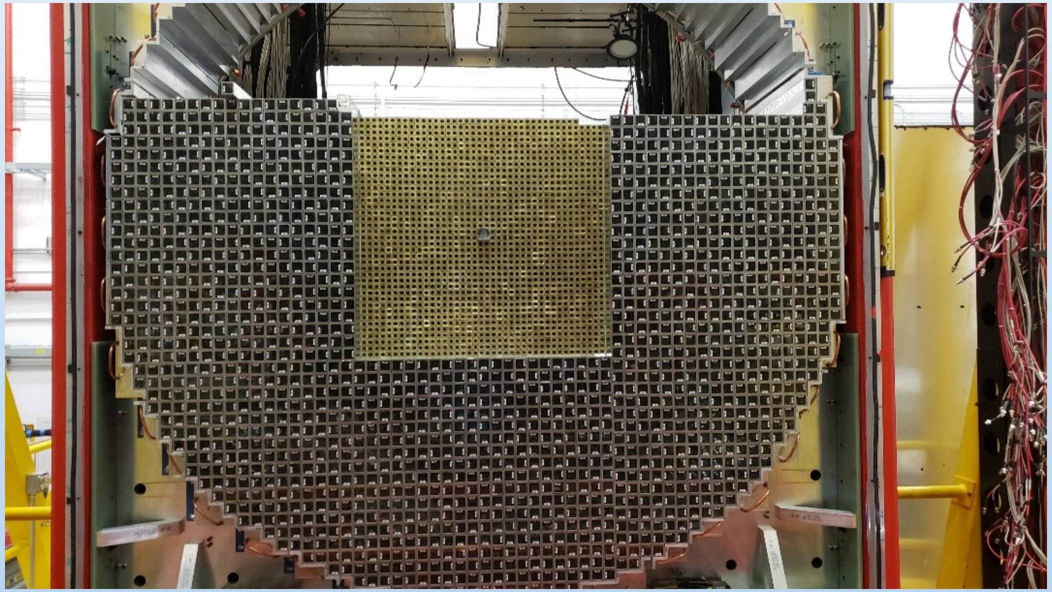


Installing PMT active bases

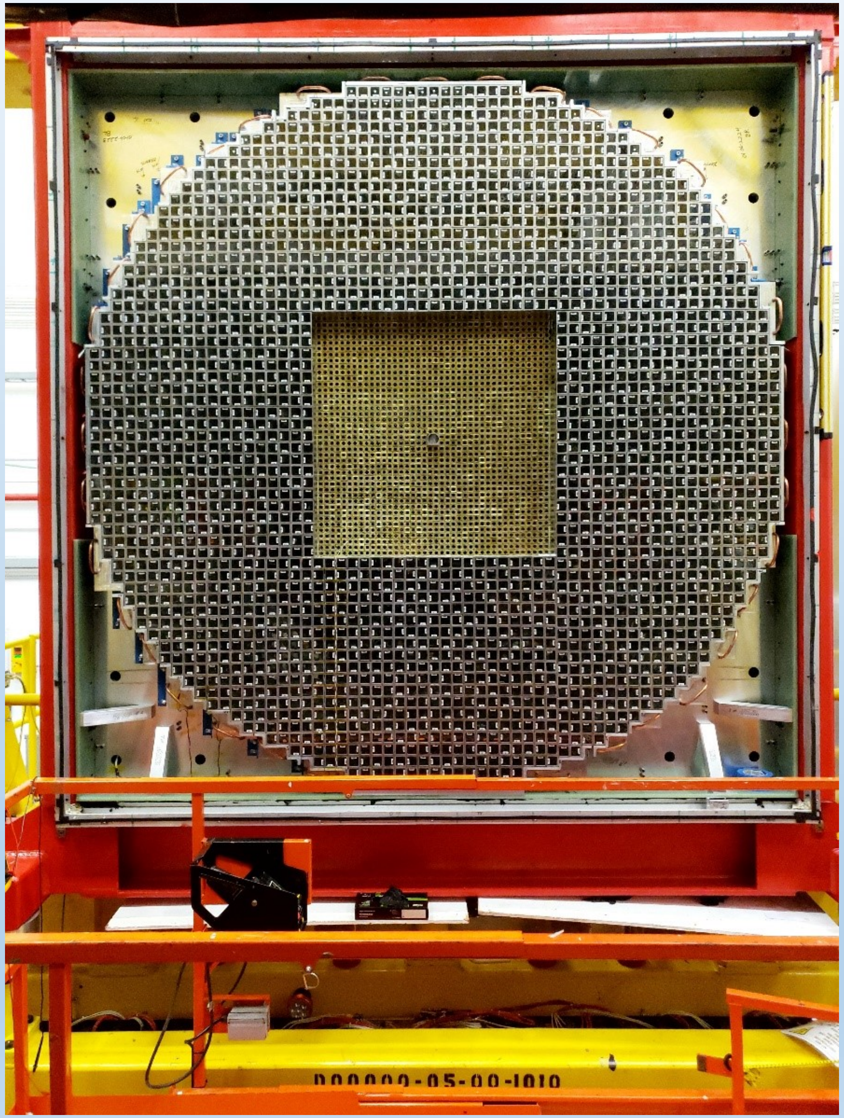


Detector Installation

September 20, 2023



October 6, 2023



- Completed installation of the whole detector by October 6

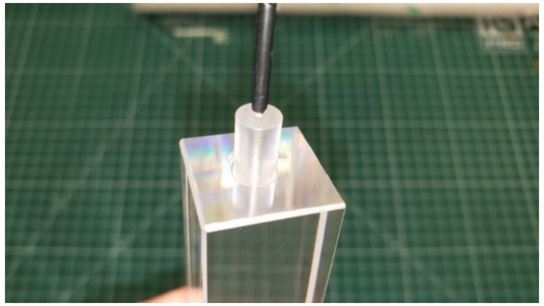
Light Monitoring System (LMS) for the ECAL

- Light source: multiple blue and green LEDs at the input of the integrating sphere (used to mix light)

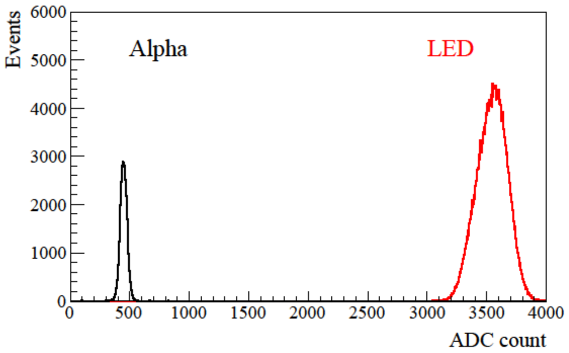
- 500 μm acrylic optical optical fibers (Edmund optics) glued to the face of each module

optical fibers inside the plastic cap

optical cap glued to the crystal



- Light stability is controlled by two reference PMTs, which receive light from two sources:
  - a single fiber from LED and
  - a YAP:Ce scintillating crystal glued to the PMT activated by ^{241}Am α source



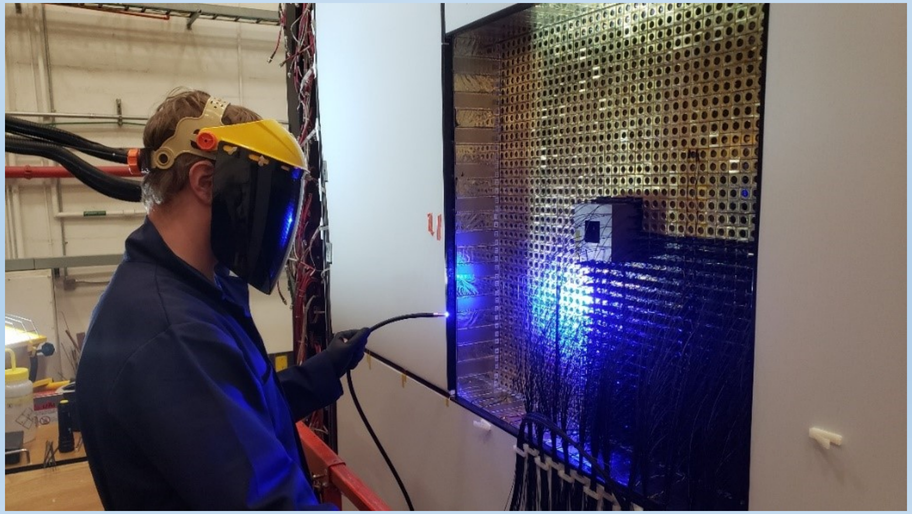
- The LMS is integrated into the detector trigger system and will run during data taking. The typical rate is 10 Hz

- The system was successfully tested a small-scale prototype during the PrimEx η experiment

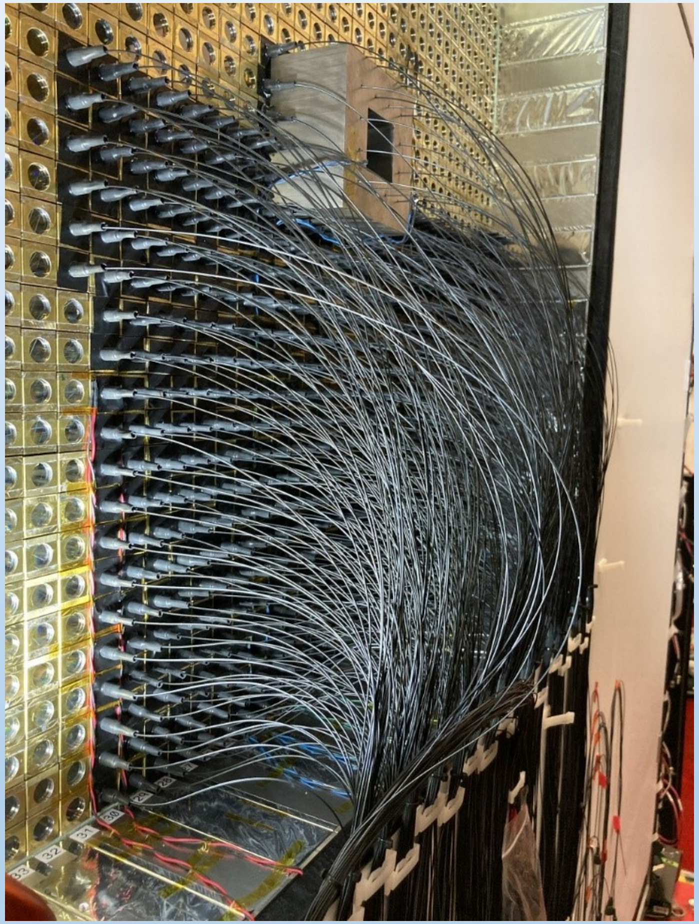
LMS Installation

Optical fibers ready for installation

Gluing optical fibers to crystals (UV curing)



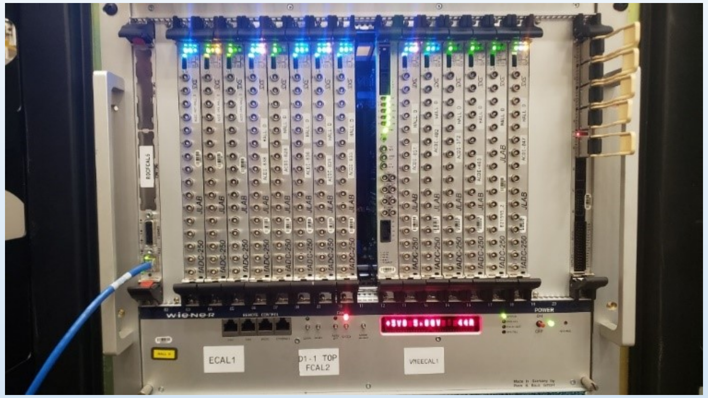
Optical fibers installed



ECAL LMS installed

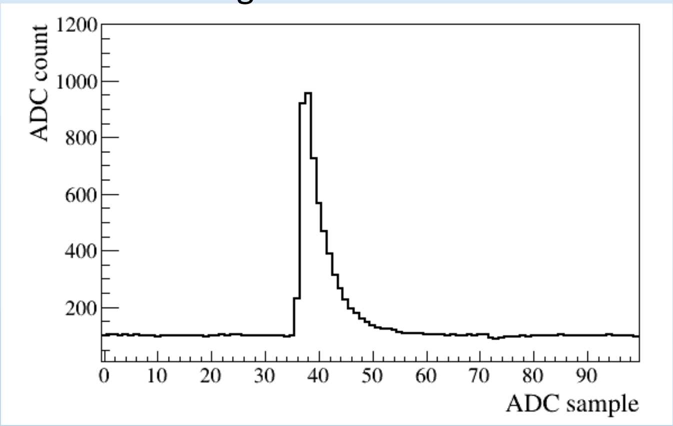
Readout Electronics

VXS crate with flash ADC modules



- Signals from PMTs are digitized using a 12-bit 16-channel flash ADC module operated at a sampling rate of 250 MHz
  - programmable FPGA logic allows pulse processing algorithms for readout and trigger

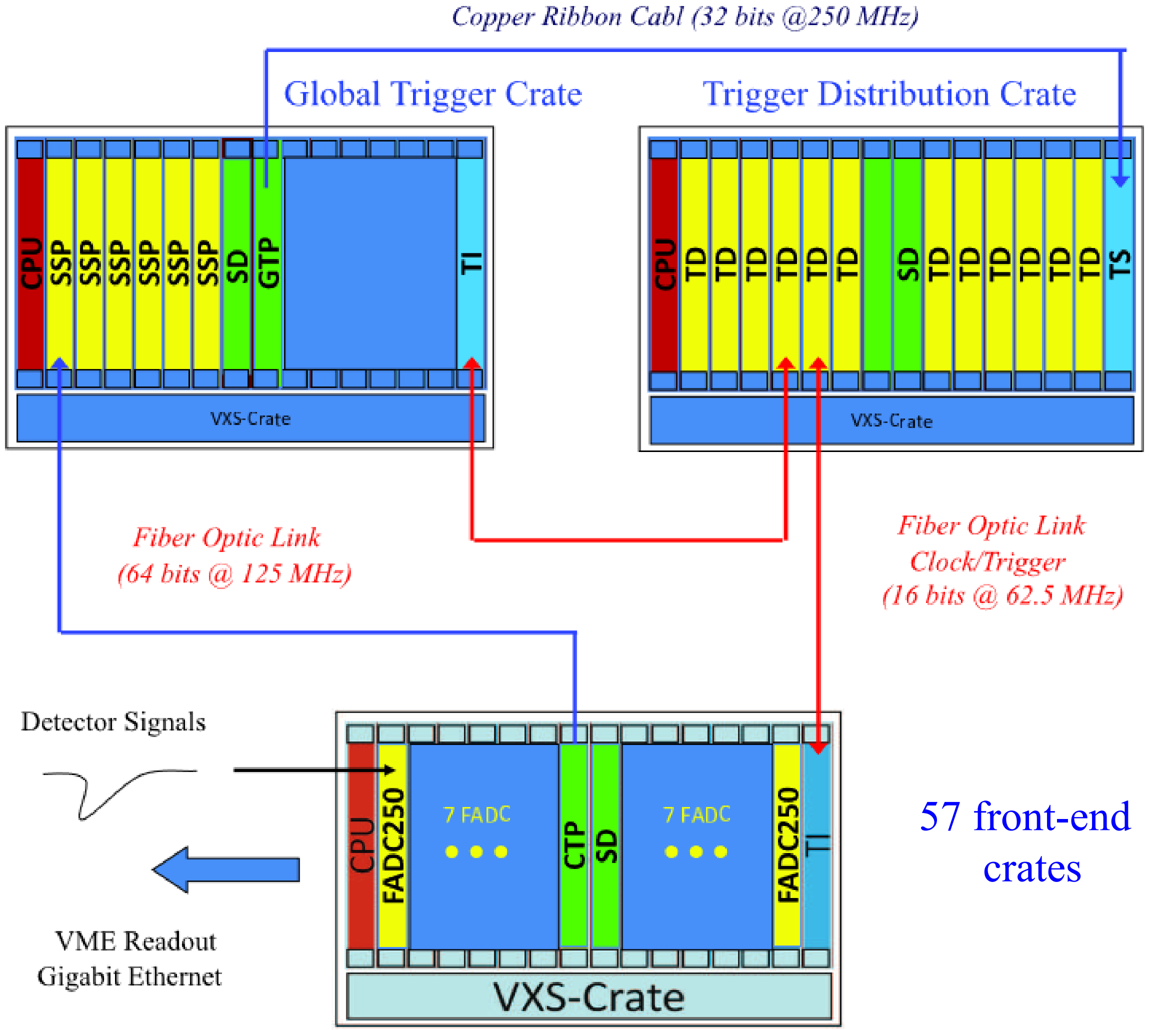
Signal waveform



- Flash ADCs are positioned in a VXS (ANSI/VITA 41.0 standard) crate
  - VME-bus used to readout data
  - high speed serial bus provides network between modules for the trigger

- 100 flash ADCs positioned in 7 VXS crates

Level-1 Trigger & DAQ



- ECAL energy is used in the GlueX trigger
- Custom designed boards at JLab
- Front-end crates are connected to 2 trigger crates using optical links

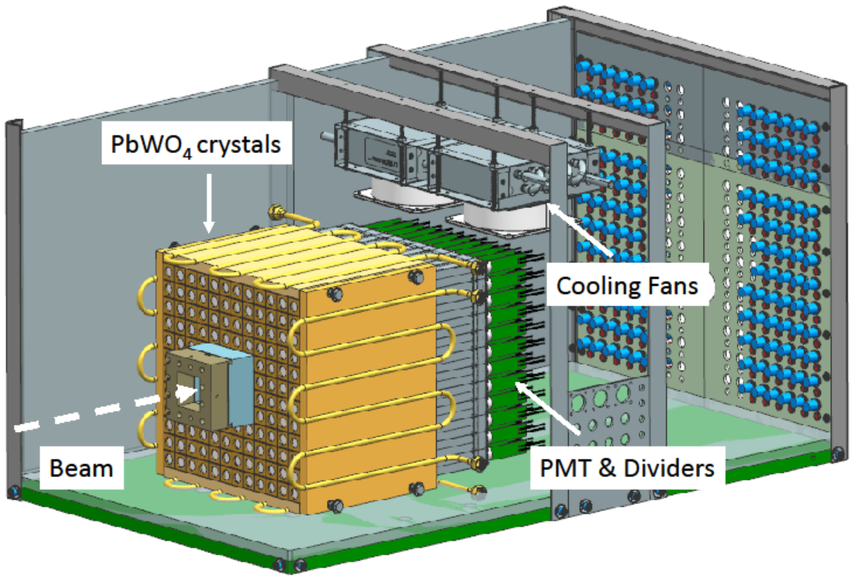
  - energy sums are sent from the calorimeter crates to the trigger crates
  - trigger Supervisor (TS) module distributes triggers to the front-end crates to initiate readout. Also provides 250 MHz clock and crate synchronization

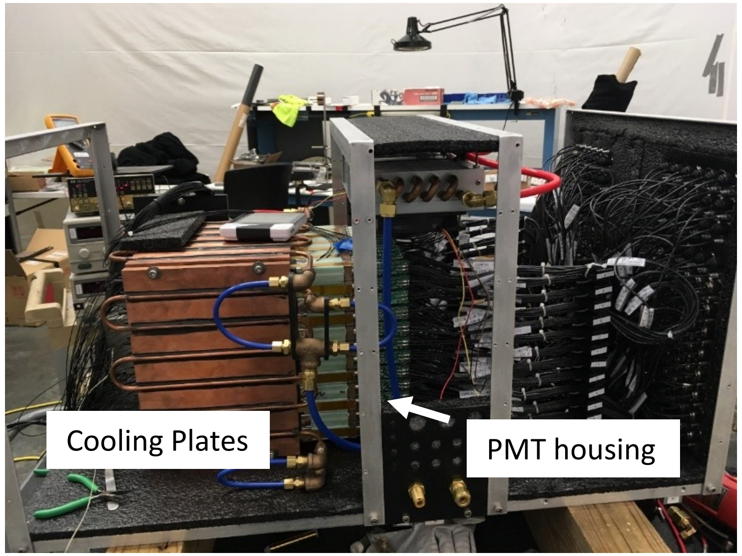
- Fixed trigger latency of about 3 μs
- Pipeline on ADCs and TDCs < 3.9 μs
- Typical trigger rate for high-intensity GlueX experiments is 60 – 70 kHz. The data size from the detector is ~1.3 Gbps

Calorimeter Prototype

Nucl. Inst. Meth. A 1013 (2021) 165683

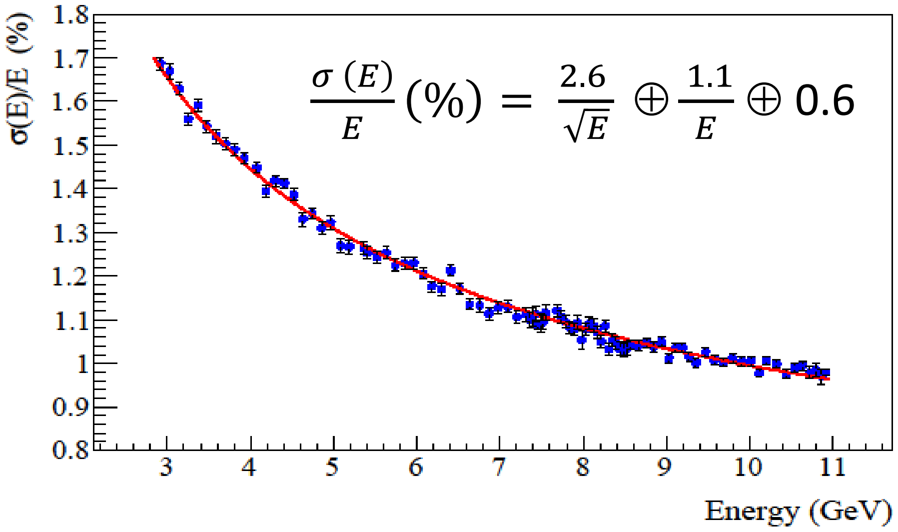
- Consists of an array of 12 x 12 modules made of SICCAS crystals
  - beam hole: 2 x 2 modules
- Used in PrimEx η experiment in Hall D in 2019, 2021, 2022 to reconstruct Compton scattering events
- Positioned on a movable platform
  - each module was inserted into the photon beam for energy calibration
- Temperature stabilization ($17^\circ \pm 0.2^\circ$ during run)
- Beam tests were used to optimize design of the PMT active base
- Instrumented with a light monitoring system, prototype of the ECAL



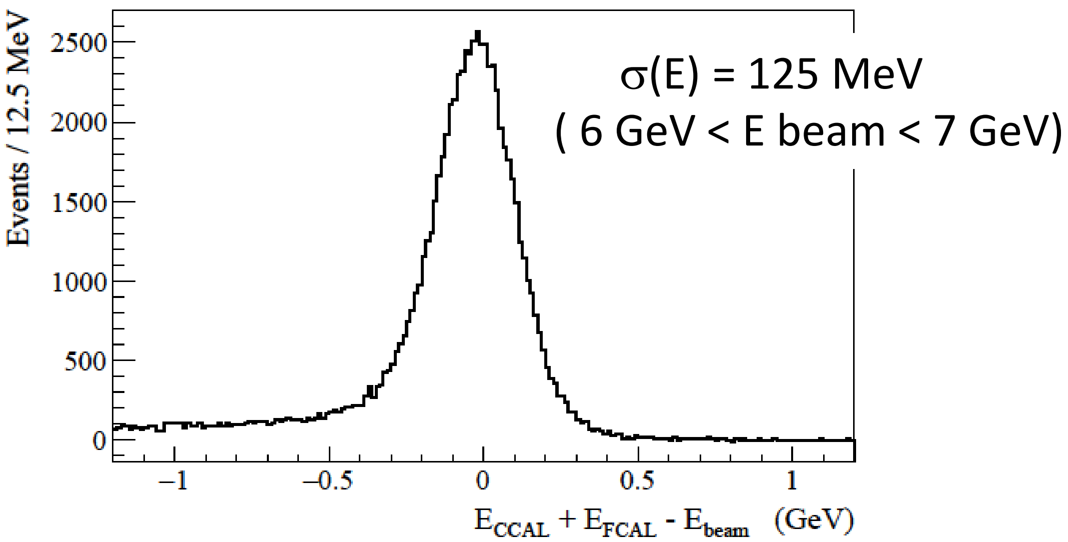


Beam Tests of the Calorimeter Prototype

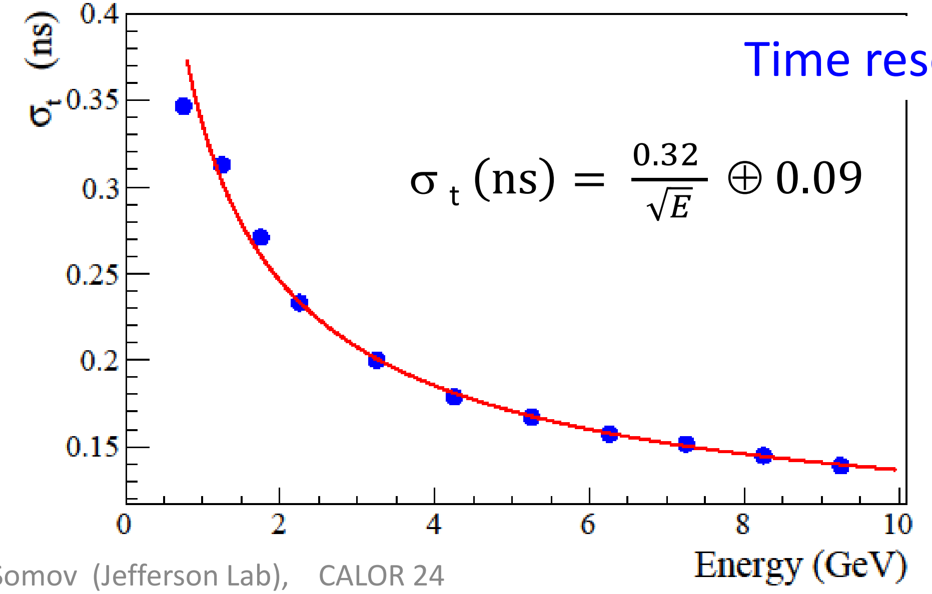
Energy resolution



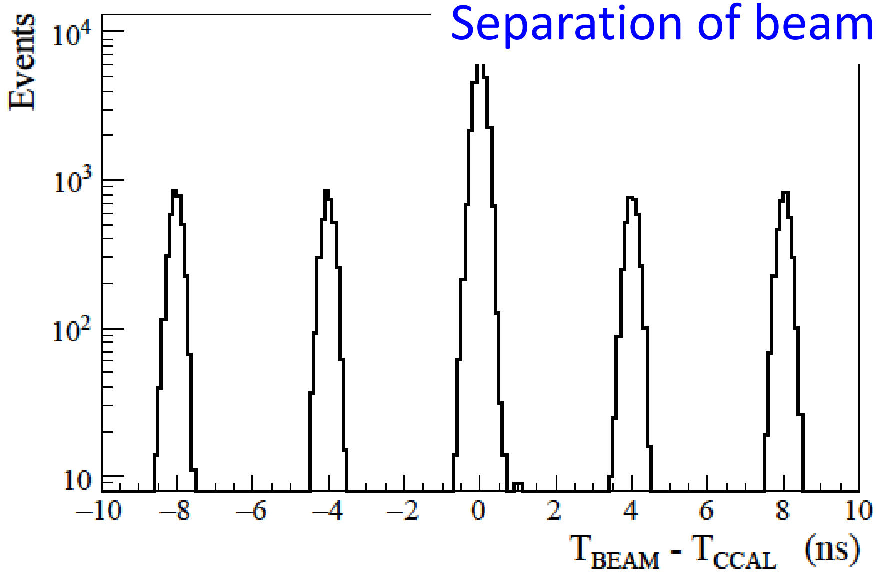
Elasticity distribution (Compton candidates)



Time resolution



Separation of beam bunches



Shower Reconstruction Algorithm

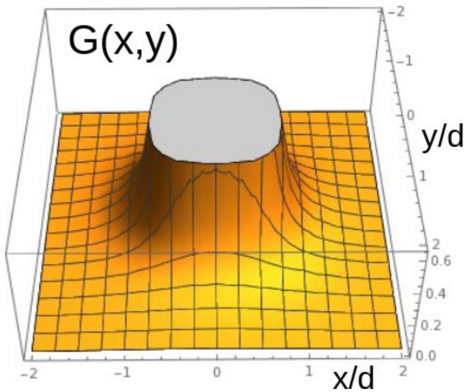
- Island Algorithm has been adopted from the GAMS calorimeter in Protvino (1993)
- The algorithm was successfully used in other JLab's calorimeters such as HyCAL, CCAL.
- The algorithm works with both $PbWO_4$ and Pb-glass modules

  - shower profile was measured and parameterized; using profile libraries

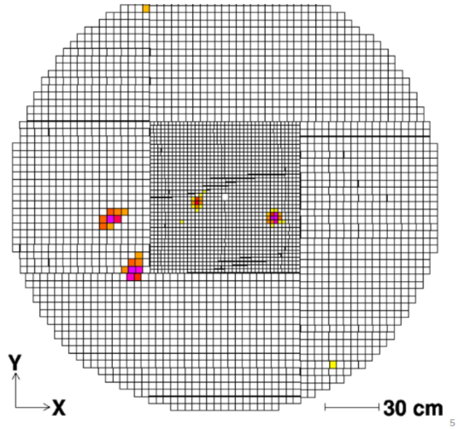
  - fit hits in the detector to the shower profile, can separate showers depending on the fit results

- The new calorimeter geometry has been implemented into the GlueX Geant4 simulation

IHEP 93-153



Geant4 simulation
($\eta \rightarrow \pi^0 \gamma \gamma$ decay)



Summary

- A new electromagnetic calorimeter (ECAL) consisting of 1596 lead tungstate scintillating crystals has been fabricated and installed in the experimental Hall D at Jefferson Lab

- The ECAL replaced the inner part of the forward GlueX lead glass calorimeter of the GlueX detector

- Prior to the ECAL construction, we build a large scale prototype, which was used to study performance of ECAL modules and light monitoring system, and to optimize the front-end electronics. The prototype was successfully used in the PrimEx η experiment

- The ECAL is integrated into the GlueX trigger system, which is based on electronic modules designed at JLab

- The ECAL construction started at JLab in the beginning of 2022. Installation of the detector modules and the LMS have been completed. The detector is currently at the commissioning stage

- The calorimeter should be ready for the physics run in the early fall of the 2024

Thank you