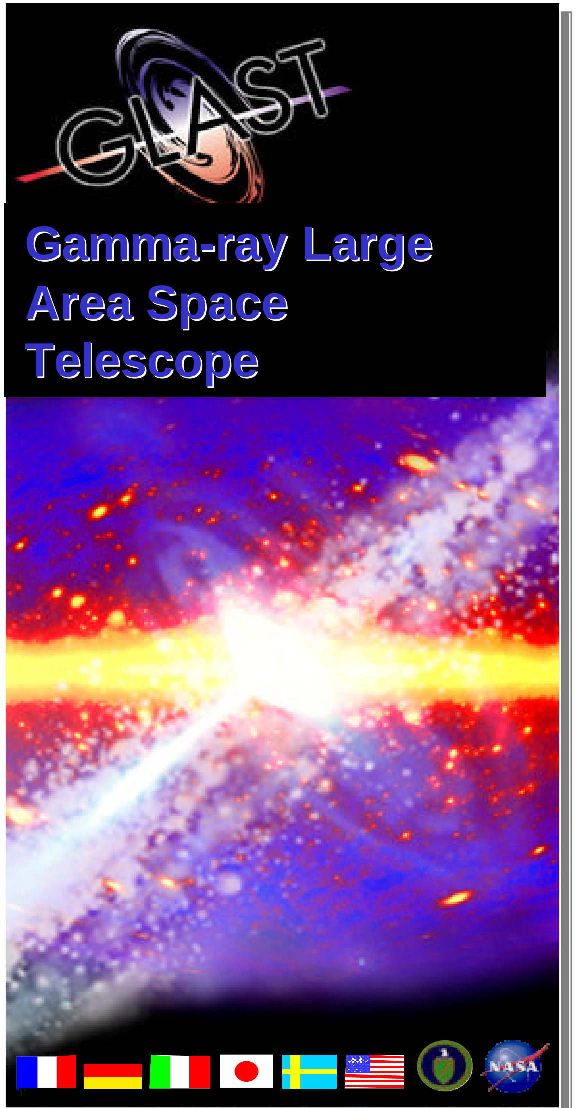


GLAST Large Area Telescope
Calorimeter Subsystem

4.0 Calorimeter Design and Development

J. Eric Grove
Naval Research Lab, Washington DC
Calorimeter Instrument Scientist

eric.grove@nrl.navy.mil
(202)–767–3112

Outline

- Design and Development
  - Science Requirements and Performance
  - Calorimeter Concept
  - Design Evolution
  - LAT Calorimeter Design
  - EM Calorimeter
    - Status and Performance
  - FM Testing and Calibration

Level III Science Requirements

- Requirements that bear on science performance of CAL

Parameter	Requirement
Design	Modular, hodoscopic, CsI > 8.4 RL of CsI on axis
Active area	>1050 cm^2 per module < 16% of total mass is passive material
Energy range	20 MeV – 300 GeV 5 MeV – 100 GeV (single crystal)
Energy resolution (1 sigma)	< 20% (20 MeV < E < 100 MeV) < 10% (100 MeV < E < 10 GeV) < 6% (10 GeV < E < 300 GeV, incidence angle > 60 deg)
Energy resolution (1 sigma) Single crystal	< 2% for Carbon ions of energy > 100 MeV/n, at a point
Position resolution	< 3 cm in 3 dims, minimum-ionizing particles, Incident angle < 45 deg
Angular resolution	15° x cosq, for muons in 8 layers

Level III Requirements

- How do we know Level III requirements are met?
  - Proof by design
  - Proof by simulation
  - Proof by demonstration
    - Prototype calorimeters
    - Engineering Model CAL

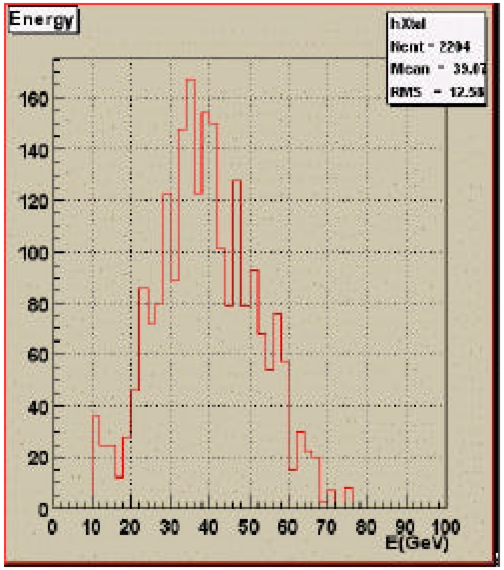
- Geometry requirements
  - Proof by design

Parameter	Requirement
Design	Modular, hodoscopic, CsI > 8.4 RL of CsI on axis
Active area	>1050 cm^2 per module < 16% of total mass is passive material

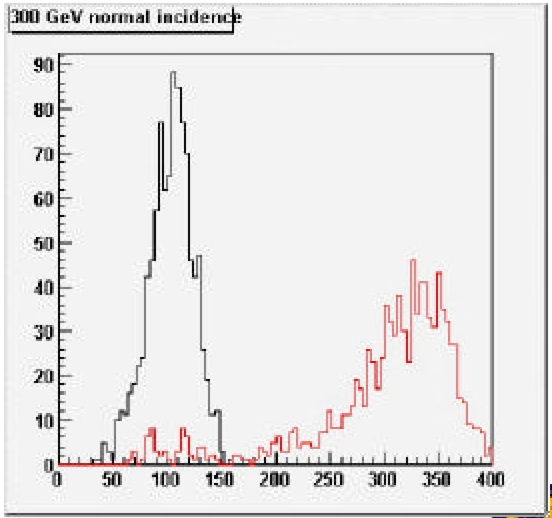
Performance
Modular, hodoscopic, CsI 8.6 RL of CsI on axis
1080 cm^2 per module <14% passive material

Level III: Energy Range

Parameter	Requirement
Energy range	20 MeV – 300 GeV (full CAL) 5 MeV – 100 GeV (single xtal)



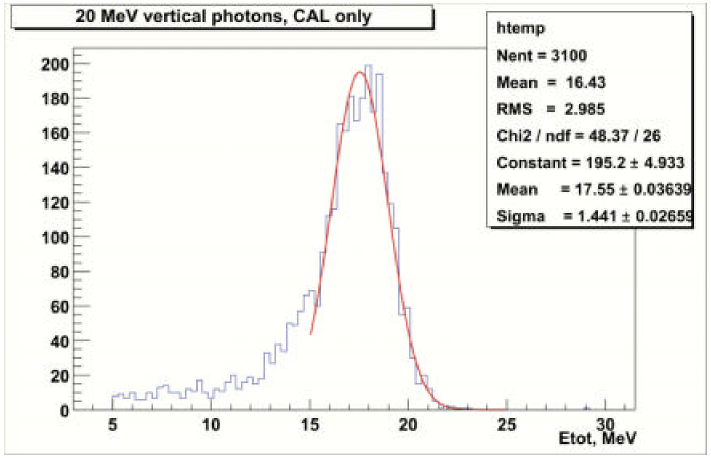
- Proof by analysis/simulation and demonstration
  - Lower limit determined by electronic noise
    - Need to set zero-suppress threshold at 5 x noise
      - EM noise < 0.3 MeV ➔ threshold < 2 MeV
  - Upper limit determined by
    - Saturation of electronics
      - EM saturates at ~100 GeV (single xtal)
    - Shower containment in CAL
      - CAL Monte Carlo simulation



Expected Performance
20 MeV – 300 GeV (full CAL) ~2 MeV – 100 GeV (single xtal)

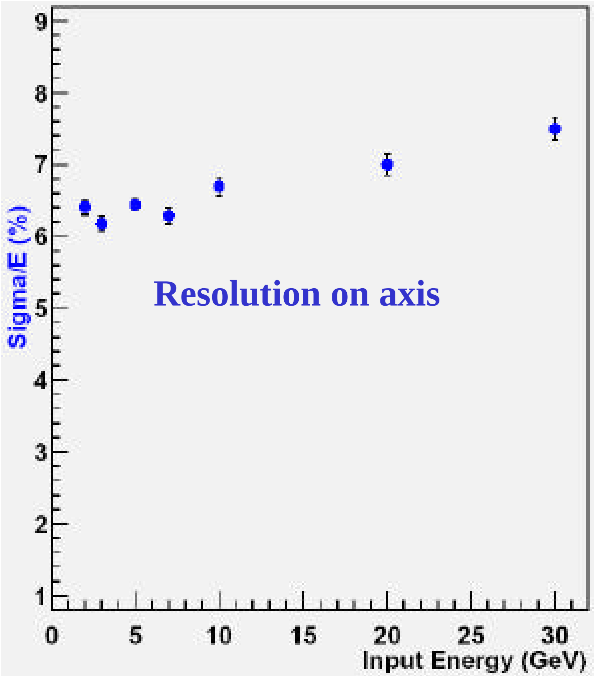
Level III: Energy resolution

Parameter	Requirement
Energy resolution (1 sigma)	< 20% (20 MeV < E < 100 MeV) < 10% (100 MeV < E < 10 GeV) < 6% (10 GeV < E < 300 GeV, >60°)
Energy resolution (1 sigma) Single crystal	< 2% for Carbon ions of energy > 100 MeV/n, at a point



- Proof by simulations, beam tests
  - Below ~ 200 MeV, dominated by Tracker calorimetry
    - Required performance not yet demonstrated at 100 MeV: current best ~15%
  - Above ~ 10 GeV, dominated by leakage

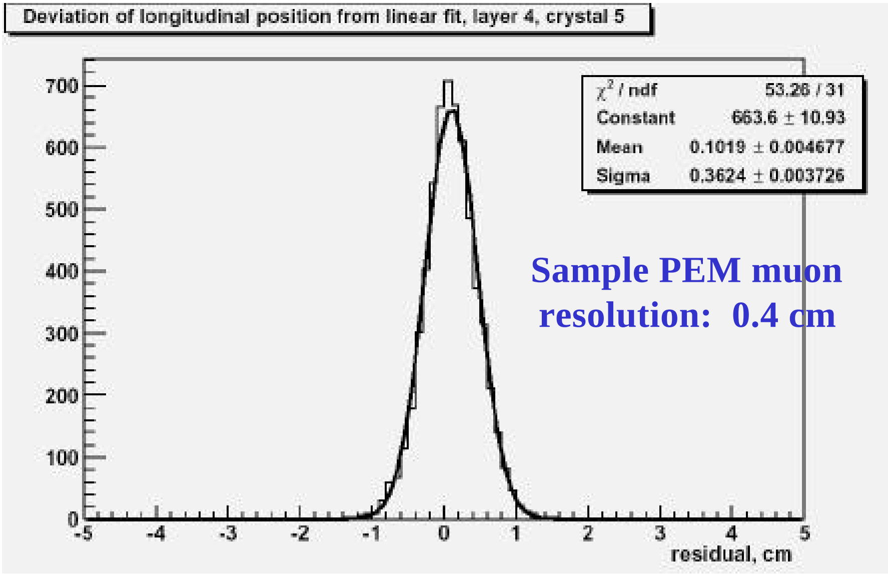
Expected Performance
< 8% (1 GeV < E < 10 GeV) < 6% (10 GeV < E < 300 GeV, >60°)



Level III: Position and Angular Resolution

Parameter	Requirement
Position res	< 3 cm in 3D, min-ionizing, < 45 deg
Angular res	15° x cosθ, for muons in 8 layers

- Proof by demonstration, simulation
  - Cross section of xtal
    - 1.99 cm x 2.67 cm
  - Longitudinal positioning
    - Defined by electronic noise
    - BTEM performance
      - ~3 cm
    - EM performance
      - Typical PEM rms < 0.5 cm
      - EM Module not yet demonstrated
    - Expect FM performance
      - 1.5 cm at 30 deg
  - Angular resolution
    - Calculated from positioning
    - EM performance not yet demonstrated
    - Expect FM performance
      - 8° x cosθ



Naval Research Lab
Washington DC

Calorimeter Concept

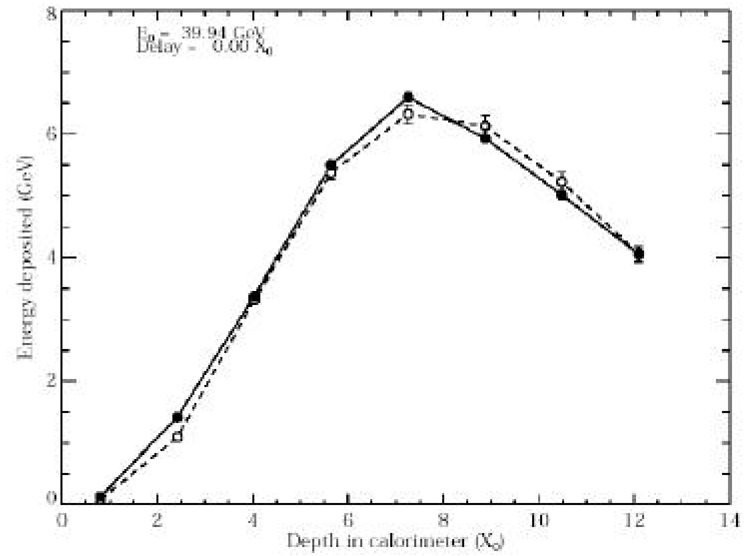
- Calorimeter Concept, or, How we got there from here….
- LAT is modular
  - So CAL is modular
- Active CAL or Sampling CAL?
  - Low E performance rules out sampling
  - Maintain high stopping power for EM showers within the mass budget
- Imaging CAL
  - Energy-profile fitting improves energy resolution
  - Background rejection
  - CAL-only events
- Segmentation
  - Moliere radius is 38 mm
  - Radiation length is 19 mm
  - Bkg rejection requires positioning on same order
    - Xtals have cross section with dimension on this order
    - Xtals give longitudinal positions better than this order

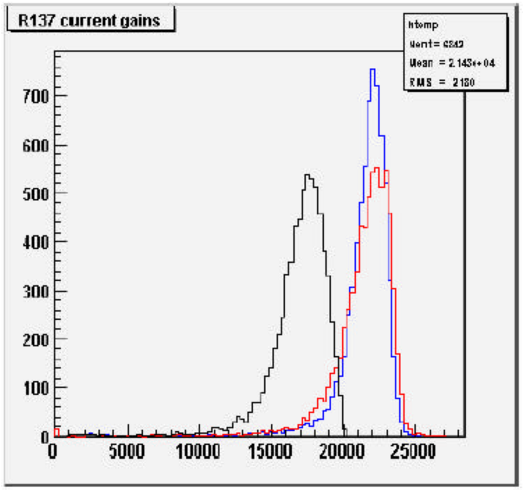
Energy Reconstruction

- **Shower profiling**
  - **Corrects for energy escaping out the back of the CAL**
    - **Mean longitudinal profile of EM shower energy deposition is well-described by gamma distribution:**

$$\frac{dE}{d(bt)} = E_0 \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}$$

  - **Process:**
    - **Measure energies deposited in slices through CAL**
    - **Integrate profile model**
    - **Find best fit for starting point and incident energy**

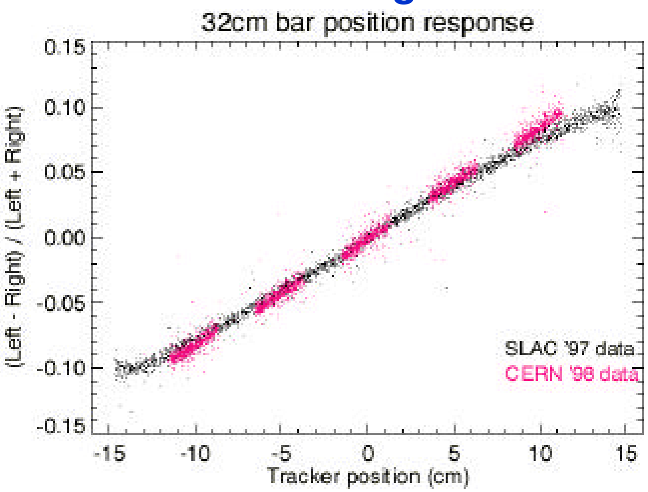


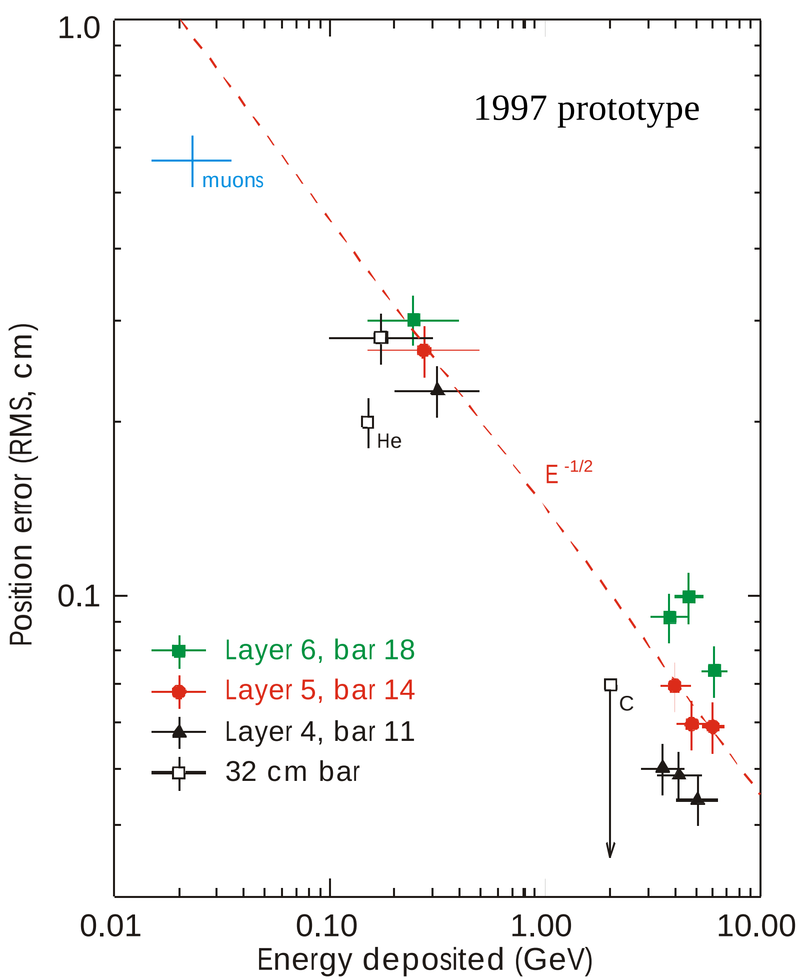


sum 7%
profile fitting 5.3%

Shower Imaging in CsI

- Position reconstruction in xtal
  - Relies on position-dependence of CsI light output ("tapering")
    - Achieved by roughening surface of CsI and reading out both ends
  - Position µ difference in signal
    - Difference = "light asymmetry"
  - Resolution is intrinsically precise
    - In practice, dominated by mapping uncertainty and electronic noise
    - 1997: Demonstrated position error of 10^{-3} of xtal length

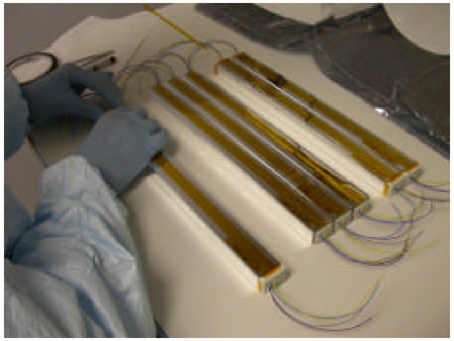


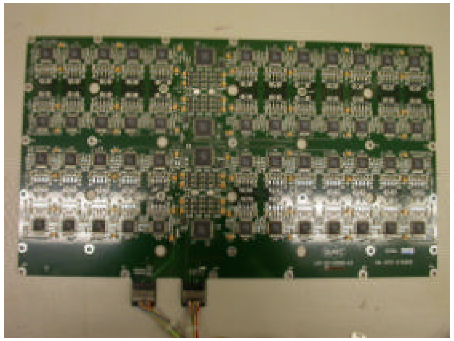


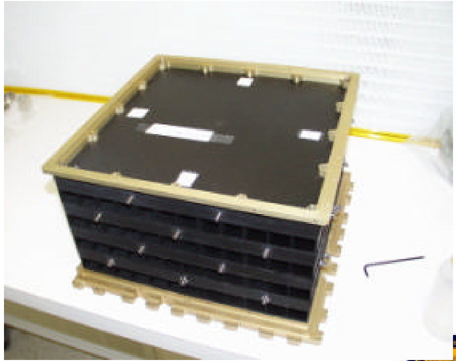
Naval Research Lab
Washington DC

Concept Implementation

- **Detectors**
  - Highly segmented
    - No individual packaging: reject NaI(Tl), use CsI(Tl)
    - CsI(Tl) read with photodiodes gives ~ same light yield as NaI(Tl)
  - Photodiode readout
    - Small, lightweight, low power, rugged
    - Redundant readout gives fault protection and positions within each CsI xtal
- **Electronics**
  - Large channel count requires low power per channel, ASICs
  - Large dynamic range (~10^5) is demanding
  - Need to minimize space, passive/empty volumes
- **Mechanical**
  - Carbon structure gives stable dimensions and fixture of detectors over thermal range and against launch loads
  - Supports detector readout on each side face of CAL

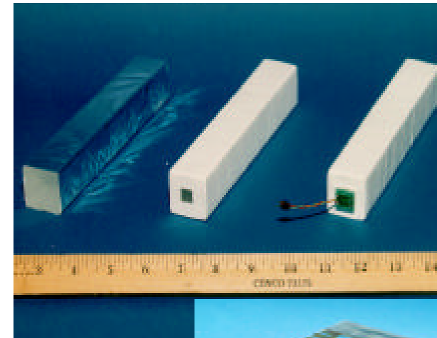




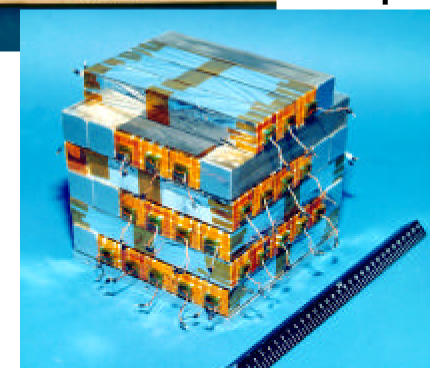


Design Evolution

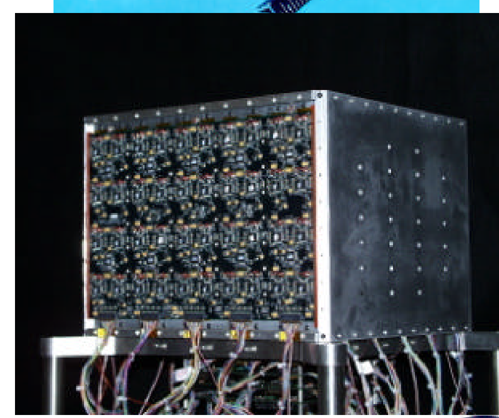
- Sampling calorimeter rejected
- Active CsI calorimeter
  - Initial concept
    - Vertical CsI bars, one PD per xtal
  - 1996 beam test prototype
    - Transverse CsI bars, two PDs per xtal
    - Demonstrated shower energy profiling
  - 1997 beam test prototype
    - Transverse CsI bars, hodoscopic layout
    - Demonstrated good longitudinal position resolution
  - Beam Test Engineering Model (BTEM)
    - Essentially full-size tower (10 xtals x 8 layers)
    - ASIC readout
    - SLAC beam test, GSI beam test, Balloon flight



’96 bars



’97 proto



BTEM

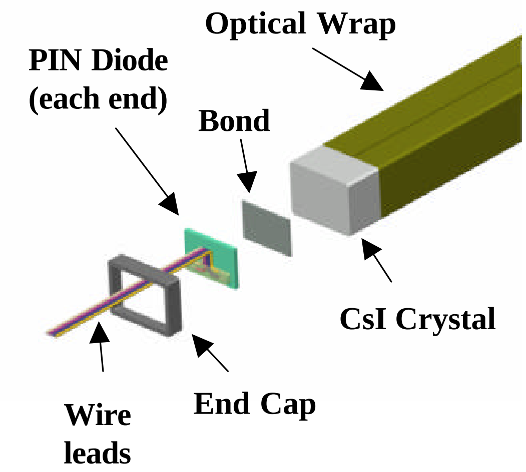
Testing History

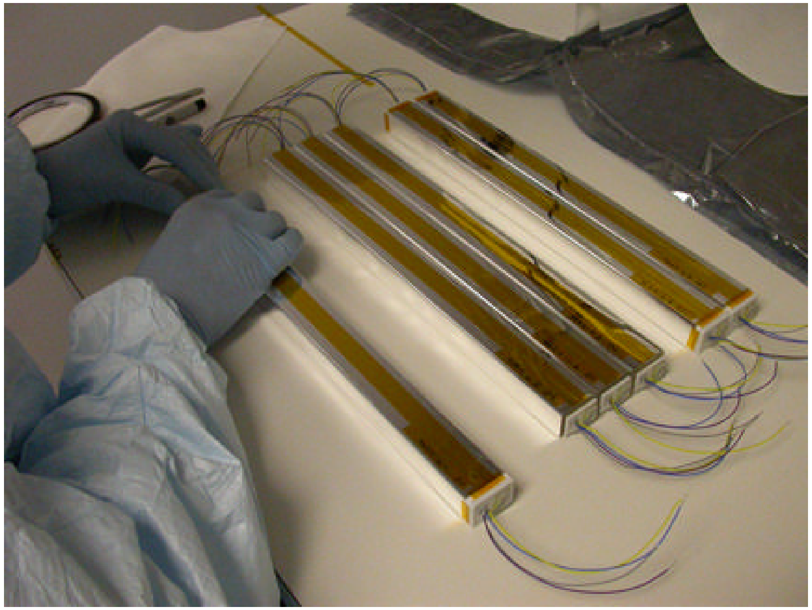
- Calorimeter Beam Tests

Test	Beams	Instrument	Proof of Concept
SLAC 1996	Photon and e	19-cm xtals on axis	CsI(Tl) with PD readout
SLAC 1997	Photon and e	Hodoscopic 19-cm xtals	Shower profiling Position reconstruction
MSU 1998	H, He, and C at 160 MeV/u	1997 CAL and 31-cm xtals	Crystal mapping with particles
CERN 1998	Photon and e	31-cm xtals	Crystal mapping
SLAC 1999	Photon, e, and p	BTEM calorimeter	Full-size Tower concept, DPD, ASICs
CERN 1999	Photon and e	31-cm xtals	High energy shower profiling
GSI 2000	C and Ni at 400-700 MeV/u	BTEM and 37-cm xtals	Charged-particle identification

Crystal Detector Element

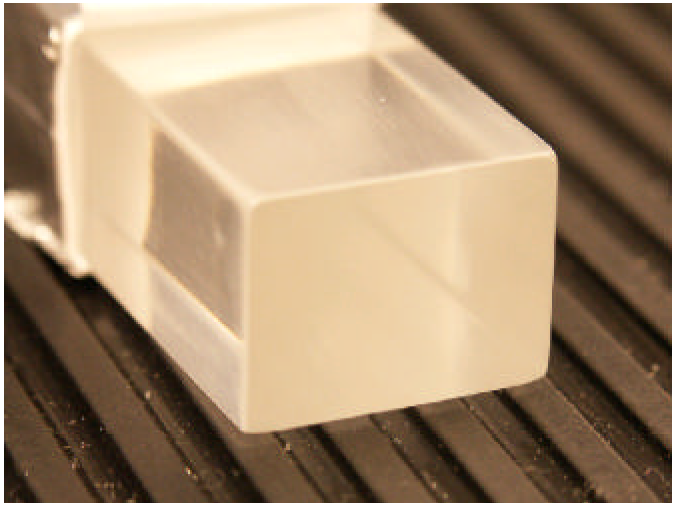
- Principle: CDE is a testable detector
- CDE has four components
  1. Active detector: CsI(Tl) crystal
  2. Readout: two photodiodes
  3. Optical seal: reflective wrapper
  4. Mechanical interface: two end caps





EM CDEs during wrapping and attachment of end caps

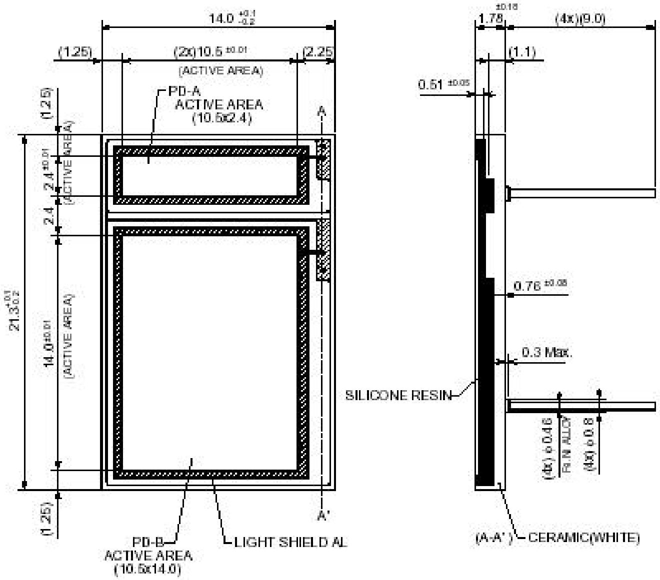
Crystals



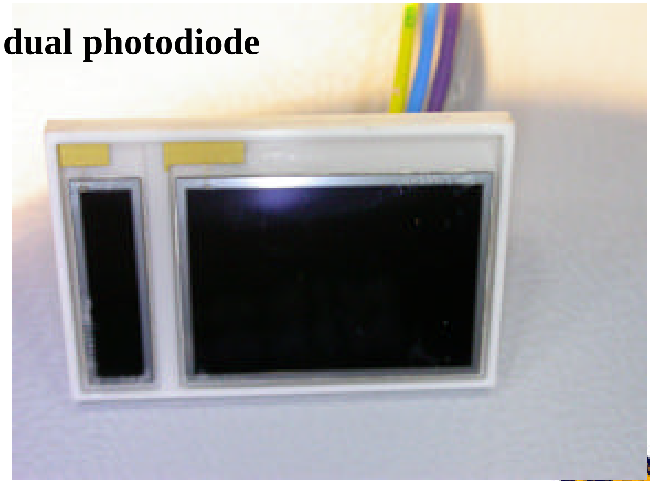
- Principle
  - High light output
  - High stopping power
  - Energy and position sensitive
  - Low cost
  - Compatible with mechanical concept
- Implementation
  - CsI(Tl) crystals
    - Choice of vendors
      - Crismatec (France)
      - Amcrys H (Ukraine)
        - » Identical performance from Amcrys at much lower cost
  - Light tapering
    - Xtal surfaces treated to attenuate light

Photodiodes

- Principle
  - Good spectral response match to CsI(Tl) scintillation
  - Very small mass, volume, and power
  - Rugged
  - Commercial product with space heritage
- Implementation
  - PIN photodiodes
  - Two diodes to help cover dynamic range
    - Both diodes large enough for ground testing (muons)
  - Single carrier for easier mounting
  - Need flexible interconnect to AFEE

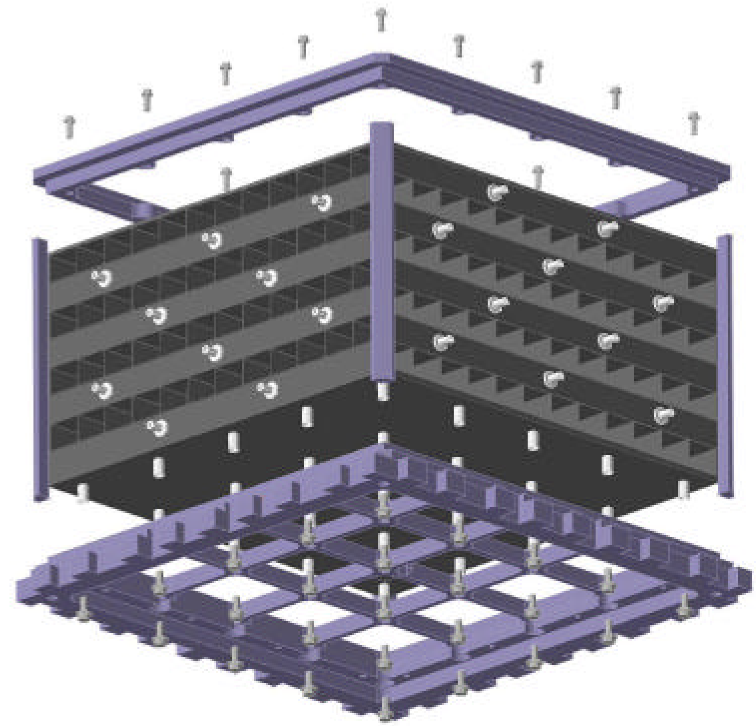


EM dual photodiode

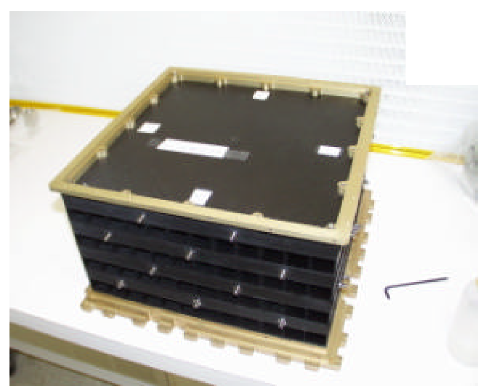


Mechanical Structure

- **Principle: Stable mechanical structure to define CDE locations and secure them against launch loads**
  - **Must hold ~80 kg against ~6 g with ~10 kg**
  - **Must account for thermal expansion of CsI**
- **Implementation:**
  - **Carbon composite structure**
    - **96 individual cells**
  - **Al top, bottom and side plate**
    - **Bottom plate provides attachment to Grid, and support for TEM and Power Supply**
  - **Sides provide support for AFEE boards**

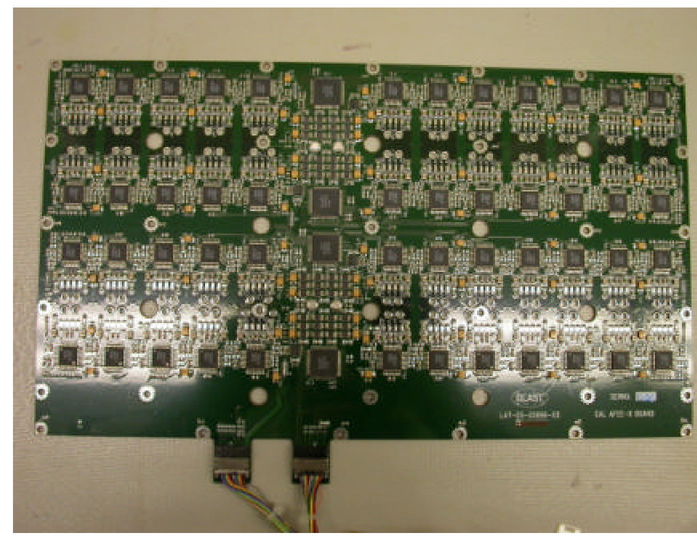


EM Structure



Electronics

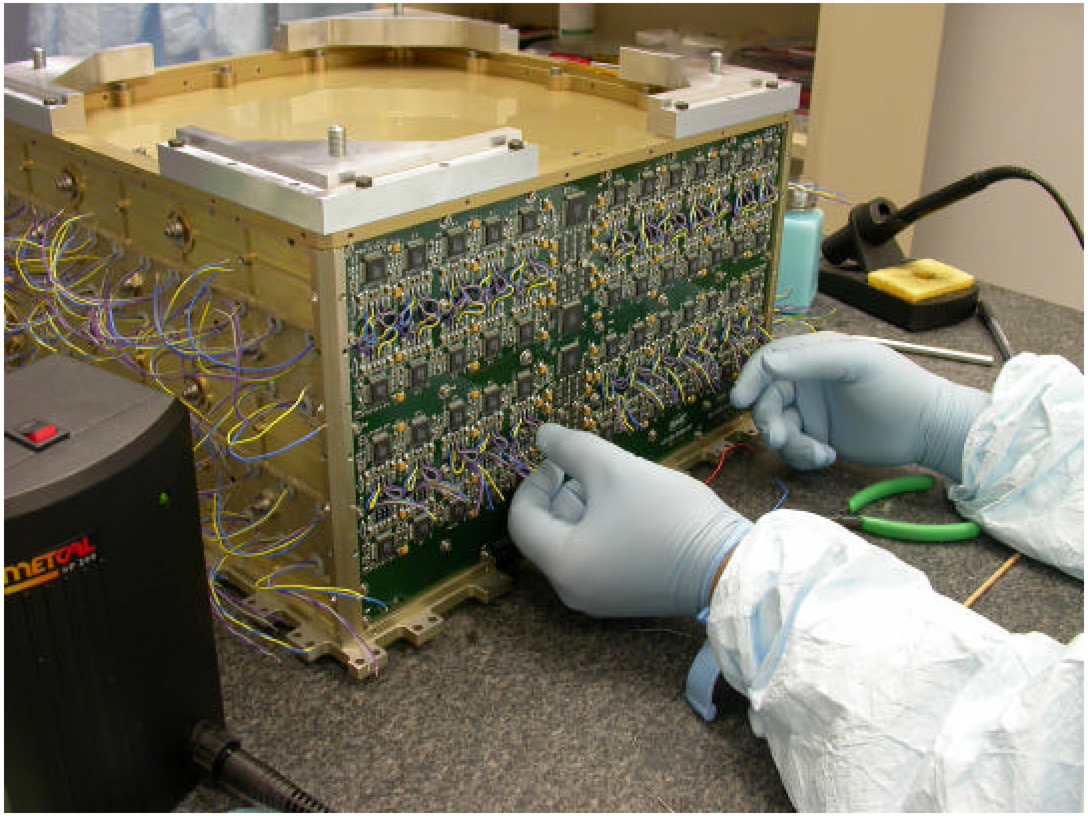
- **Principle**
  - Need to cover a very large dynamic range (few x 10^5)
  - Low noise (~2000 electrons noise)
  - Low power (~20 mW per crystal end)
  - Limited space (8 mm thickness), match pitch of CsI crystals (28x40 mm)
  - Interface to TEM
- **Implementation**
  - Use 1 custom analog and 1 custom digital ASIC to minimize power
  - Use 2 input signals to reduce dynamic range requirement on electronics
    - Each input signal goes into 2 gain ranges
    - Have ranges to 200 MeV, 1.6 GeV, 12.5 GeV and 100 GeV
  - Use commercial 12-bit ADCs
  - Separate analog from digital on front-end (“AFEE”) board
  - Low dead time (20 μs)
  - Sparsify data (zero suppress)



EM AFEE board

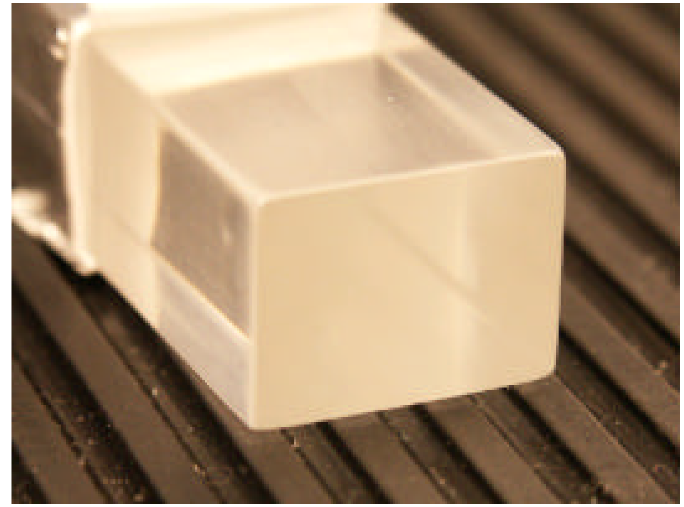
Engineering Model

- EM Calorimeter
  - Full-size calorimeter
  - Fully populated with CDEs and AFEEs



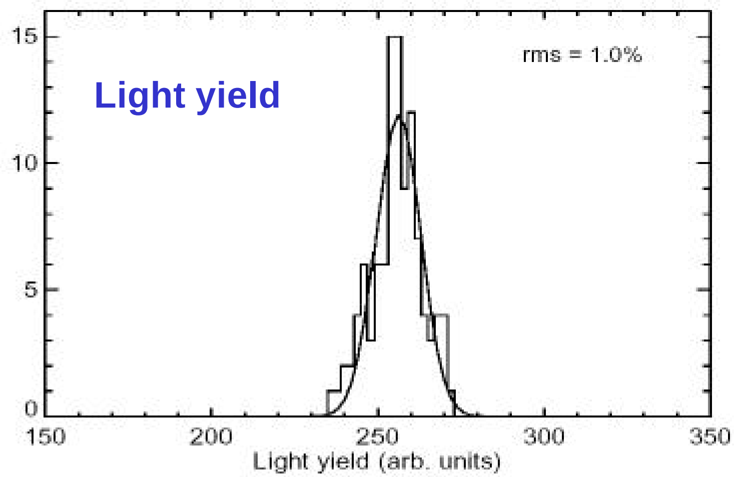
EM Crystal Performance

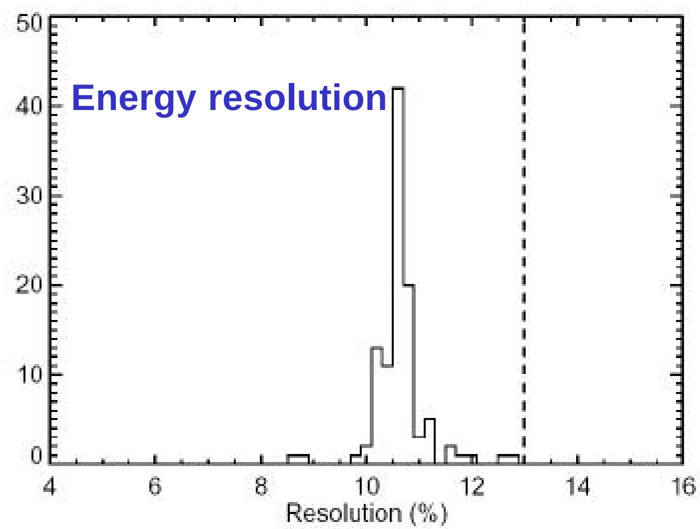
- **CsI(Tl) crystals**
  - Vendor: Amcrys H
  - Procured 244 crystals
  - Dimensional specs changed after purchase, so we committed two sins
    1. Remachined length
    2. Remachined chamfers
  - Amcrys would not guarantee optical performance after this extensive handling, so we waived light taper requirement for EM
- **Testing**
  - Visual inspections performed at NRL
  - Xtal dimensions were verified at Kalmar
  - Optical performance was tested at Kalmar and NRL
    - Xtal Optical Testing Station (XOTS)

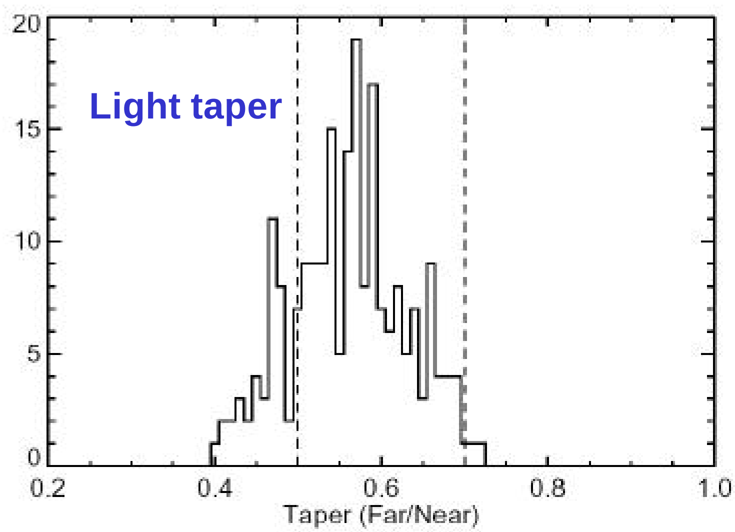


EM Crystal Optical Performance

- Results of EM performance testing with Xtal Optical Test Station
  - Light yield constancy is within spec
  - Light taper is (mostly) within spec
    - One batch was below spec, likely caused by remachining of xtals
    - We waived EM taper requirement
  - Energy resolution is within spec

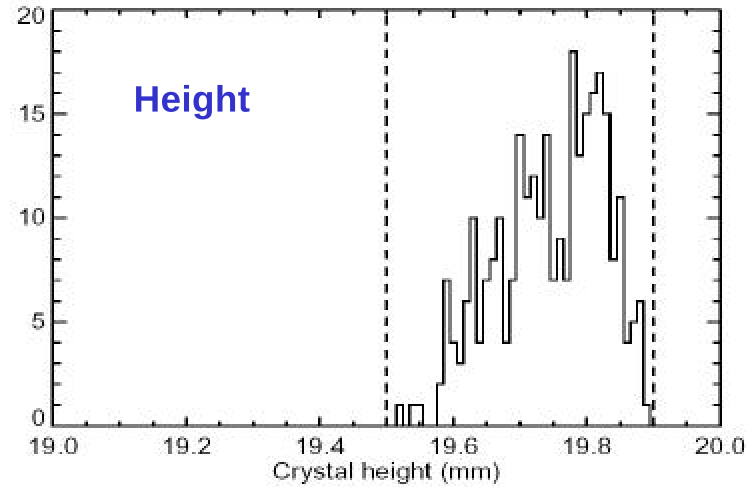


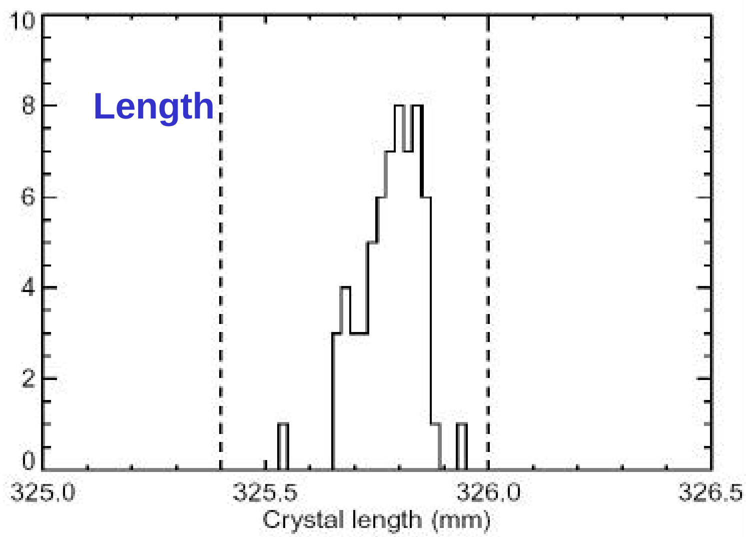


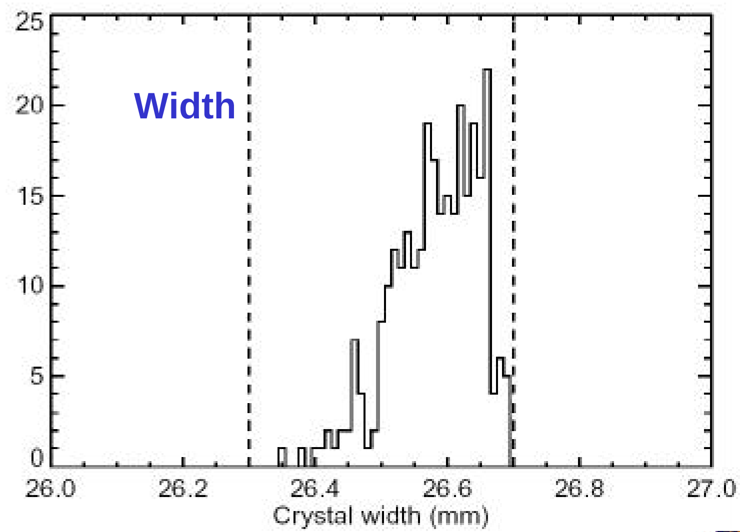


EM Crystal Dimensions

- **Dimensions of EM crystals**
  - **Length, width, and height are within spec**
  - **Note obvious truncating of width distribution**
    - **Optical surface treatment is applied to width**
    - **Xtals needed less surface treatment than Amcrys expected**

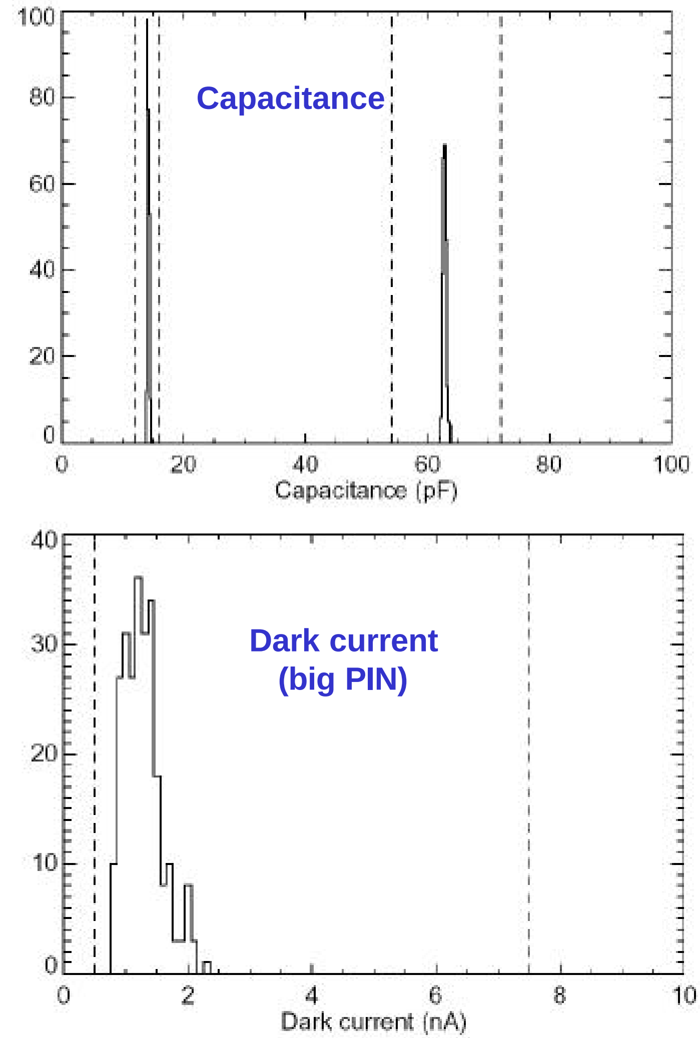






EM Photodiode Performance

- EM photodiode
  - Vendor: Hamamatsu, custom S8576
  - Procured 650 DPDs according to spec LAT-DS-0072-03
- Testing
  - Electrical performance at NRL and in France
    - Within spec
  - Optical performance in France
    - Within spec
  - Radiation hardness in France
    - Within spec
  - Bonding studies at NRL and in France
    - Within spec
  - Thermal stability at NRL and in France
    - Fail (see DPD, section 5.1), so optical window material will change

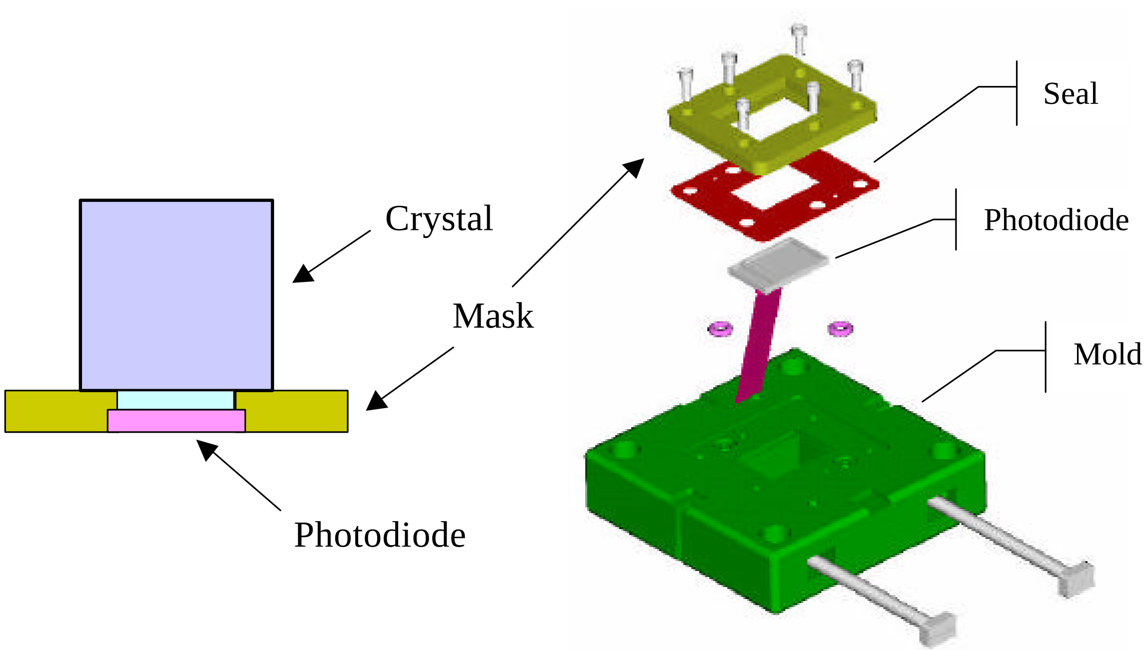


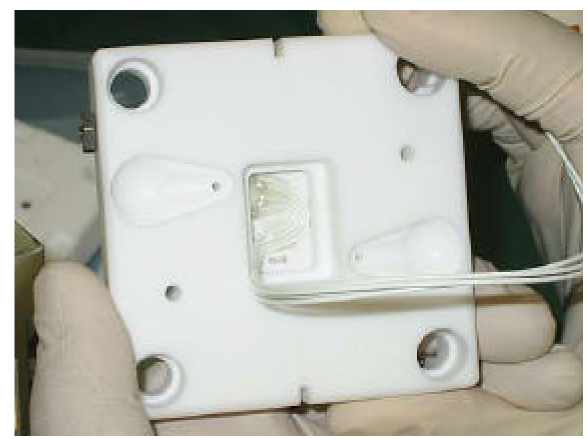
Issue at PDR: Diode Bonding

- Need an optical bond between photodiode and CsI
  1. Must be optically clear
  2. Must adhere to CsI
  3. Must be stable against thermal cycling
  - Items 2 & 3 were a problem
    - CsI behaves like "oiled lead"
      - Not all adhesives adhere to it
    - Mismatch between large coef of thermal expansion (CTE) of CsI and small CTE of PD
      - Hard epoxies used in BTEM failed optically
      - Optical waxes used in earlier prototypes would liquify
  - Extensive research program in US and France
    - Soft epoxies, silicones, bonding surface treatments, …
    - Solution: silicone encapsulant with compatible primer
      - Dow Corning DC93-500 with DC92-023
      - Developed bonding process, implemented on EM CAL

EM Diode Bonding Process

- Bonding process for EM developed together with Swales Aerospace
  - Teflon mask defines bond thickness and area, and locates diode precisely on xtal end face
  - Mold assembly allows diode and xtal faces to be primed prior to bonding
  - Bond material is injected into defined volume and allowed to cure



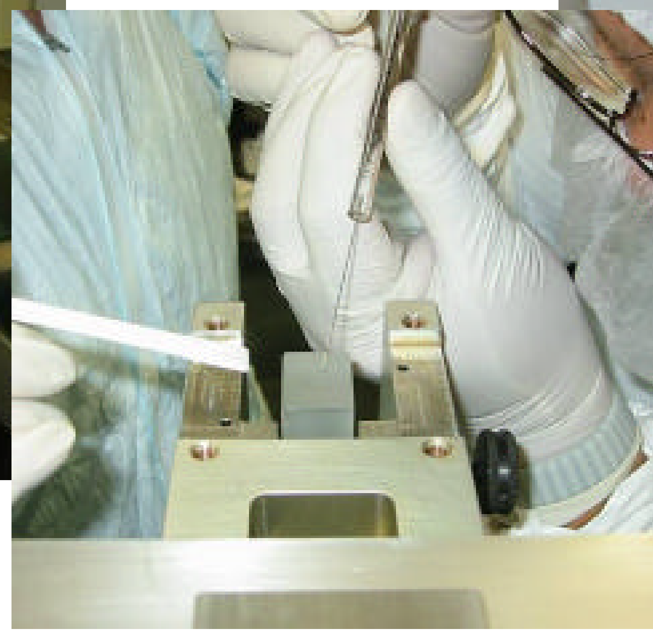


Naval Research Lab
Washington DC

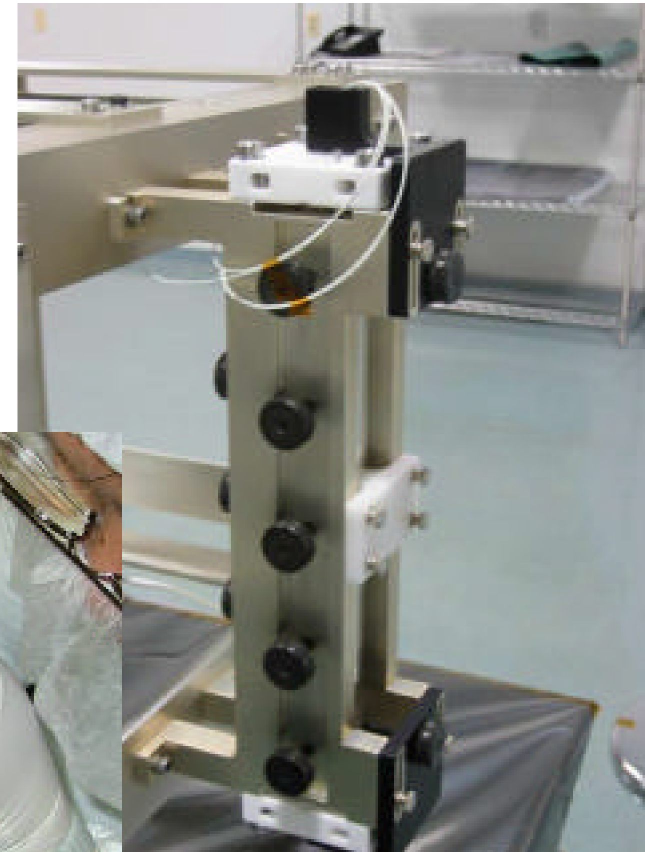
EM Bonding Process

EM build:
110 CDEs at Swales
14 CDEs at Saclay

Hanging xtal in bonding fixture



Priming xtal

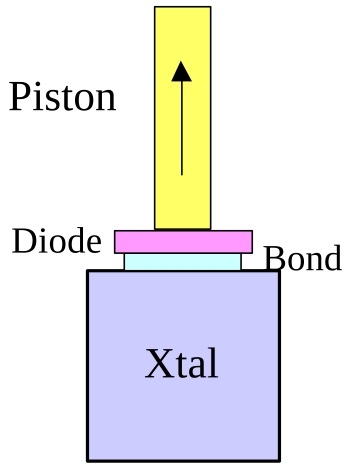


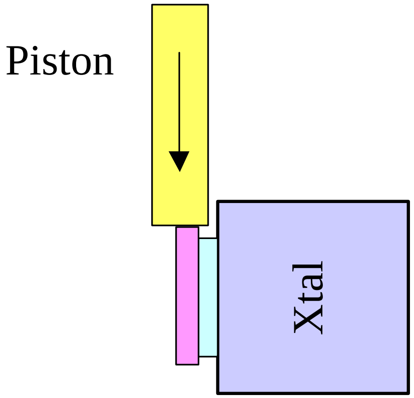
Silicone injected, waiting to cure

EM Bond: Mechanical Strength Tests

- Two types of destructive tests were performed at NRL
  - Tensile strength requirement
    - 10 N (2.2 lbf)
  - Shear strength requirement
    - 0.12 N/mm^2 (8 lbf = 35 N for EM diode)

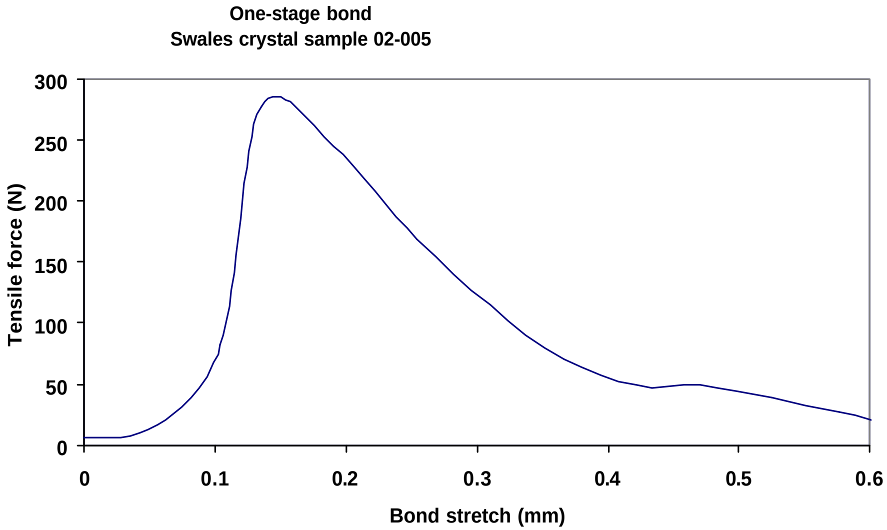
- Samples are pulled or sheared to failure in Dynamic Load Test Stand

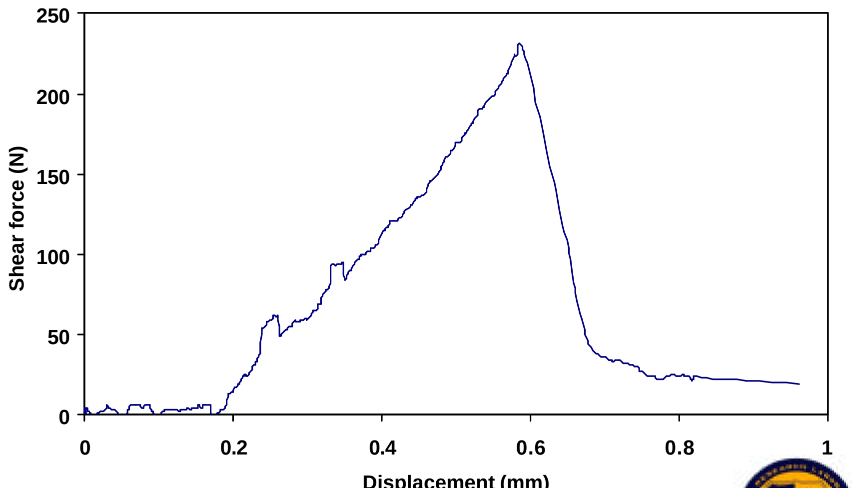




EM Bond: Strength Tests

- More than 65 bonds tested
  - Tensile strength sample
    - Fails at ~280 N
      ➔ 28 x requirement
  - Shear strength sample
    - Fails at ~230 N
      ➔ 7 x requirement
- Typical failures are
  - ~10 x strength requirement
  - At interfaces, rather than in bond material
    - Slightly more likely at diode face
- Adhesion problem with CsI is solved





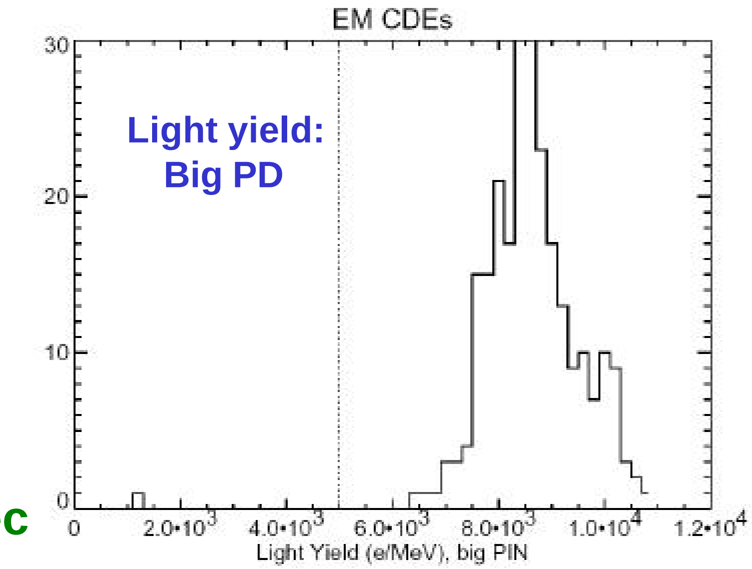
EM CDE Performance

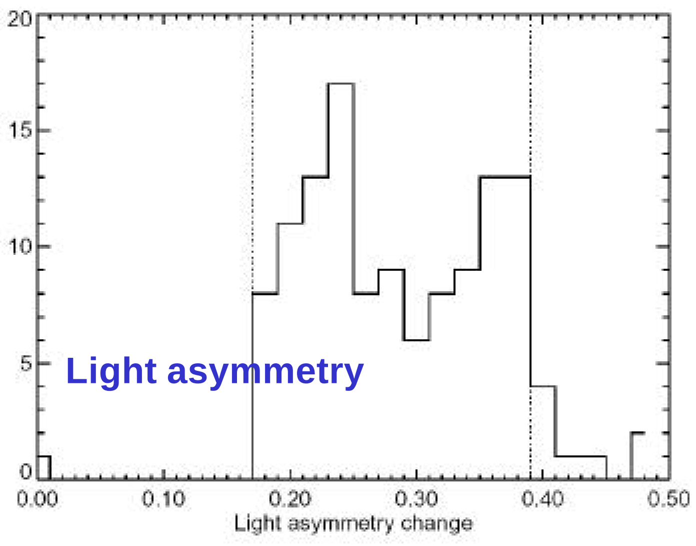
- EM CDE build
  - 110 at Swales Aerospace
  - 14 at Saclay
- Verifying EM CDE performance
  - Mechanical
    - Do they fit in Mech Structure?
  - Optical
    - Muon telescope
      - Two layers of xtals
        - » Top layer is EM CDEs
        - » Bottom layer is prototype 37-cm xtals
      - Lab electronics and DAQ
      - Image muons passing through array
    - Tested all EM CDEs

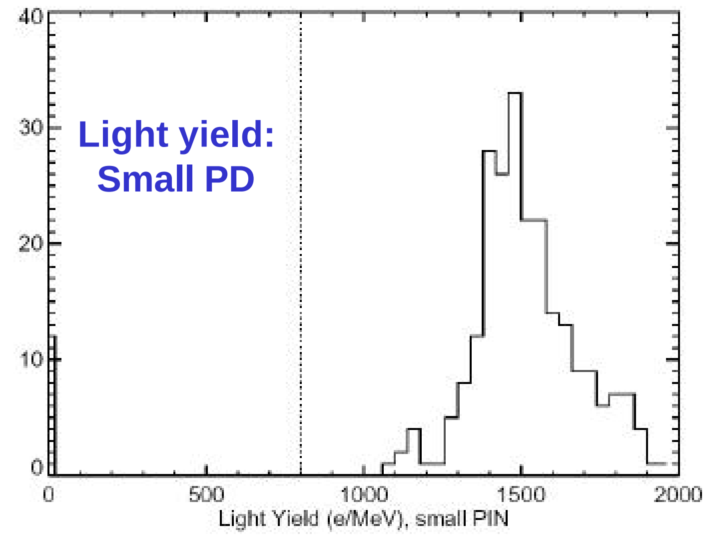
Saclay and Swales CDEs have identical performance

EM CDE Optical Performance

- **Performance of EM CDEs**
  - **Light yield**
    - **Big PD within spec**
      - **Typical: 8000 e/MeV**
      - **EM Spec: >5000 e/MeV**
    - **Small PD within spec**
      - **Typical: 1500 e/MeV**
      - **EM Spec: >800 e/MeV**
  - **Light asymmetry (mostly) within spec**
    - **EM spec: >0.17, <0.39**

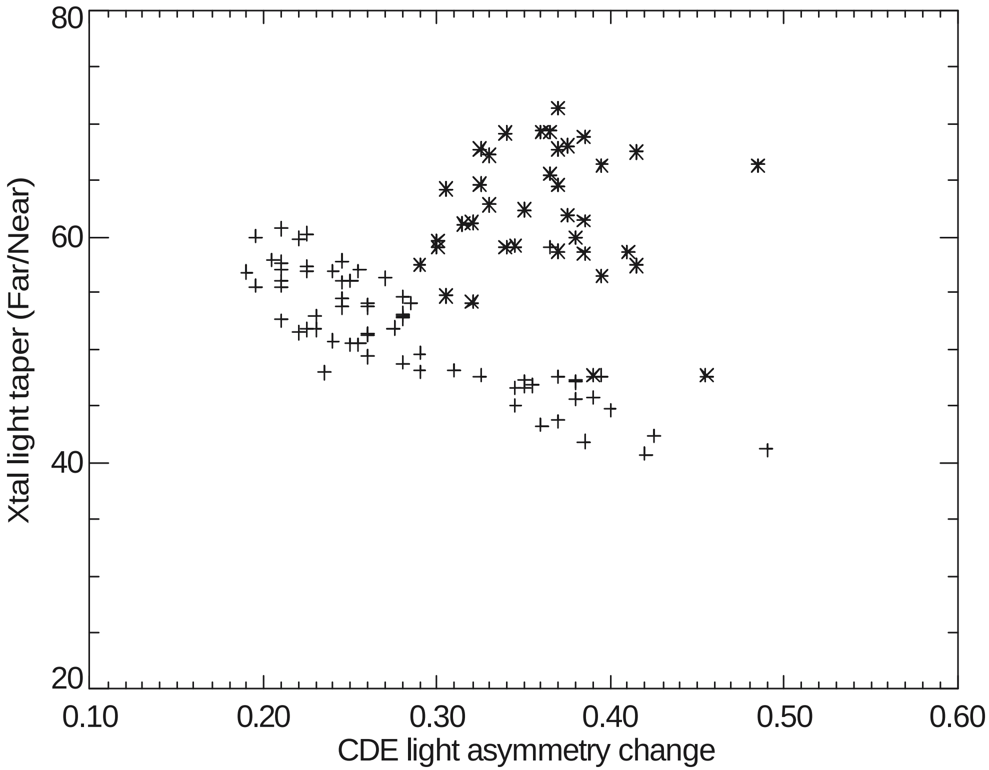






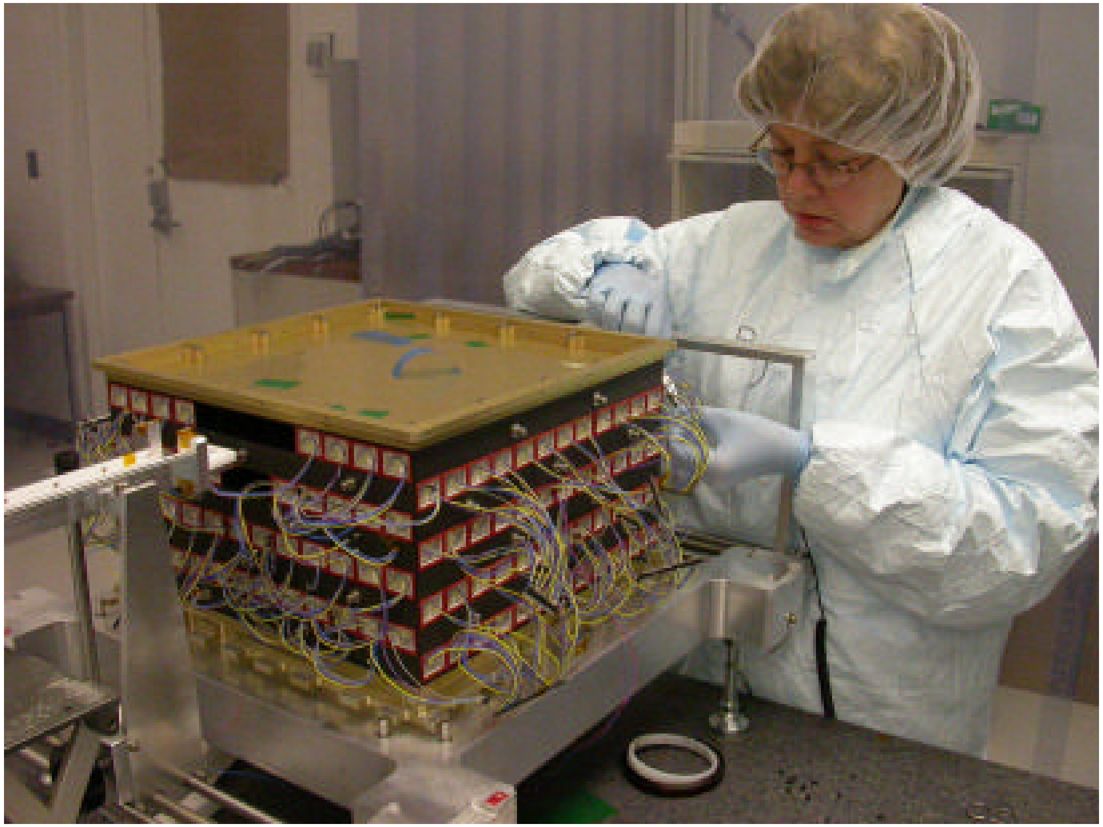
EM CDE Testing

- Comparison of xtal to completed CDE
  - As expected, xtal light taper is strongly correlated with CDE light asymmetry
    - Xtals retapered at NRL (star symbol) are not correlated, also as expected
  - CDE performance is within spec
  - Conclusion: CDE manufacture preserves xtal optical properties



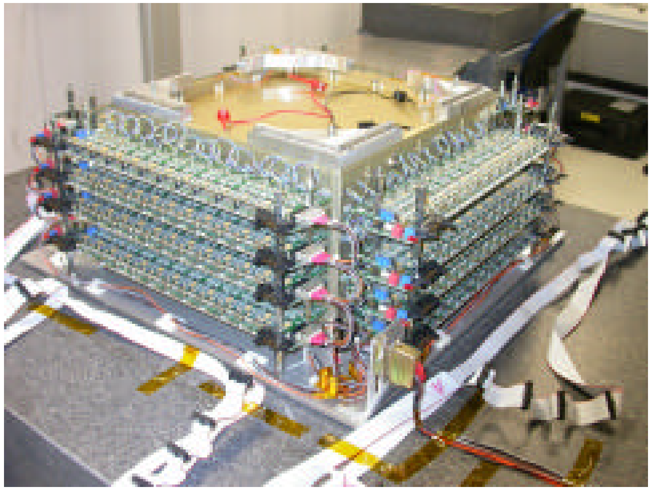
EM PEM Assembly

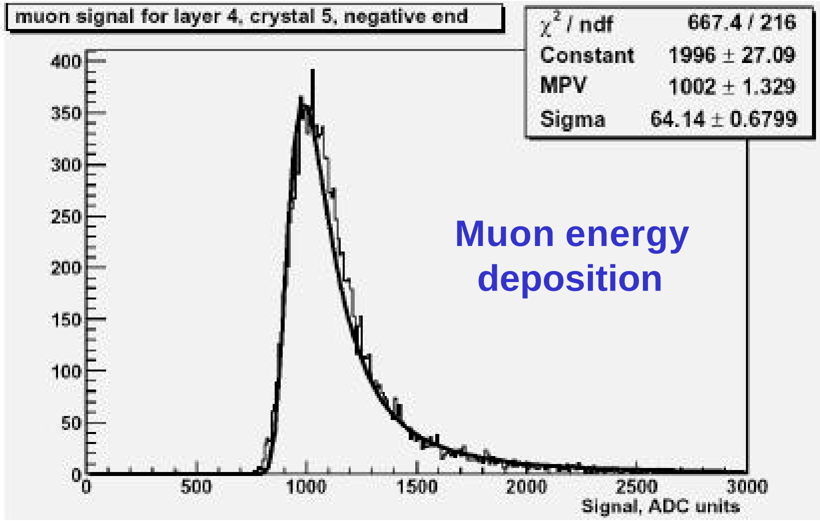
- EM Pre-Electronics Module
  - 82 Swales CDEs and 14 Saclay CDEs successfully inserted into Mechanical Structure

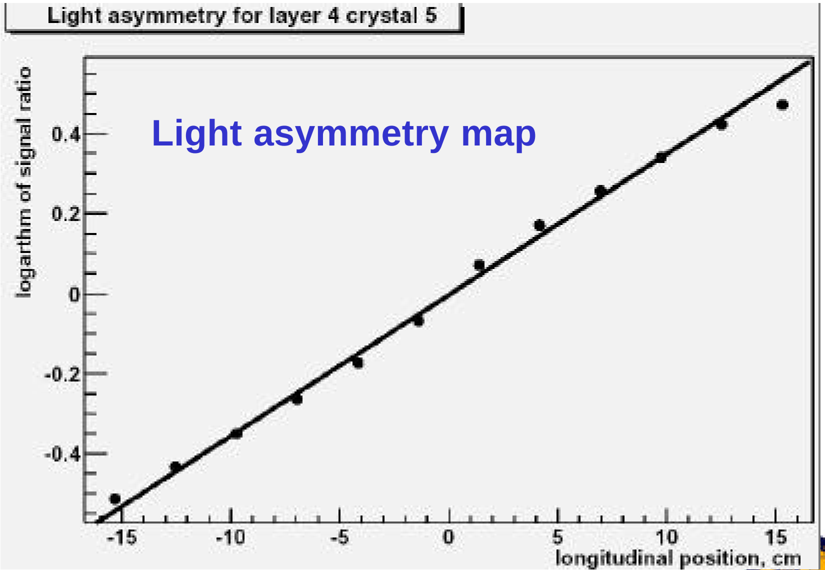


EM Pre-Electronics Module Performance

- Performance of EM PEM
  - Assembled PEM with GSE Checkout electronics
  - >5 million muons collected
  - Data being analyzed with Ground Science Analysis Software system
    - Muon trajectories imaged
    - CDE light tapers mapped



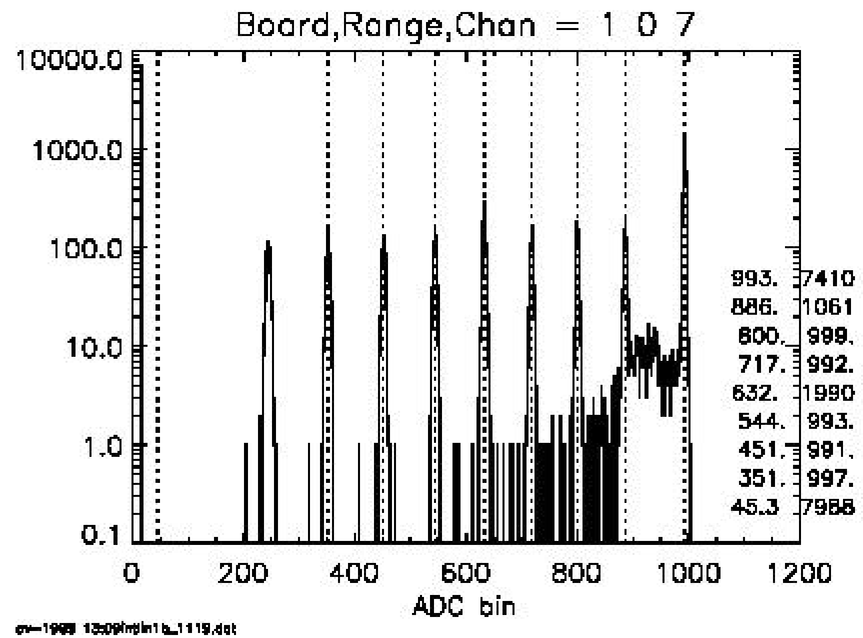




Calibration

- How will we know Flight CAL achieves science requirements?
- How do we calibrate the instrument?
- What needs to be calibrated?
  - Energy measurement
    - Need relative calib among xtals and absolute calib
    - Level III requirements: 3% relative, 10% absolute
  - Position measurement
    - Need calibration of light taper in each xtal
    - Level IV requirement: taper slope uncertainty of 10%
  - Calibration data sources
    - Pre-launch
      - Electronic calibrations
      - Sea-level muons
      - Beam tests of CU (4-module array)
    - On-orbit
      - Electronic calibrations
      - Cosmic rays

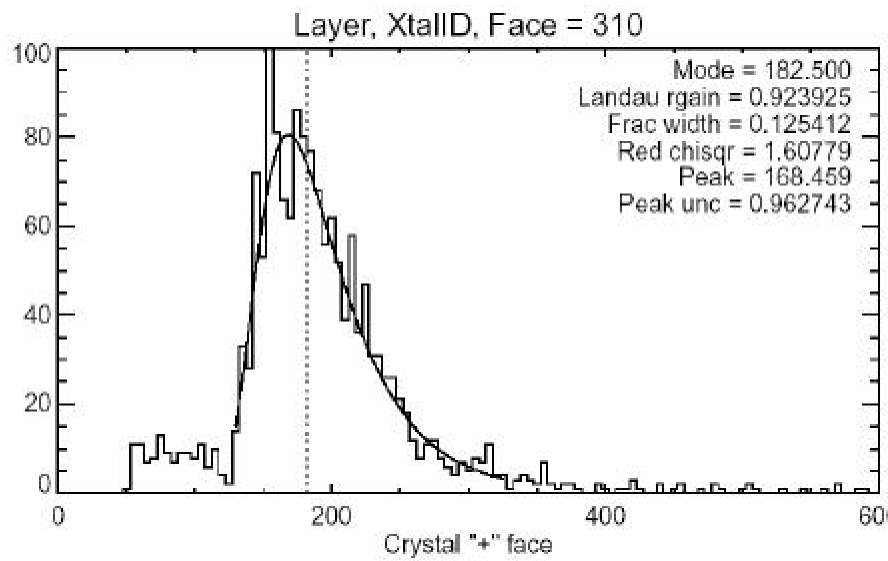
Calibration



- ❑ **Electronic calibration**
  - – **Inject known charge into each Front End**
    - • **Measures**
      - – **Electronic gain (e/bin)**
      - – **Integral non-linearity**
    - • **Does not measure "optical gain"**
      - – **i.e. conversion between energy deposited and electrons at each Front End**
  - – **Automated process can be run on ground or in flight**
    - • **Ramps charge through full dynamic range**
    - • **Returns histogram or centroid of each input**

Calibration

- Sea-level muon calibrations
  - Performed only on ground
    - At CDE level, PEM level, and Module level
  - Image muons passing through detectors
    - Muon DE ~ 11 MeV per xtal, only ~10^{-4} of FE dynamic range
    - Measures
      - Optical gain, i.e. energy per bin
      - Light taper
    - Does not measure full dynamic range
  - Requires hodoscope
    - CDE testing in France
      - External muon telescope
    - PEM and Module testing in US
      - CAL xtal hodoscope
      - TKR, when available

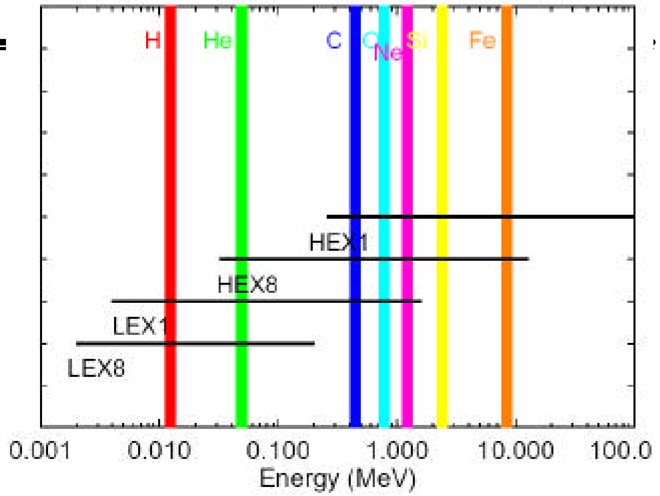


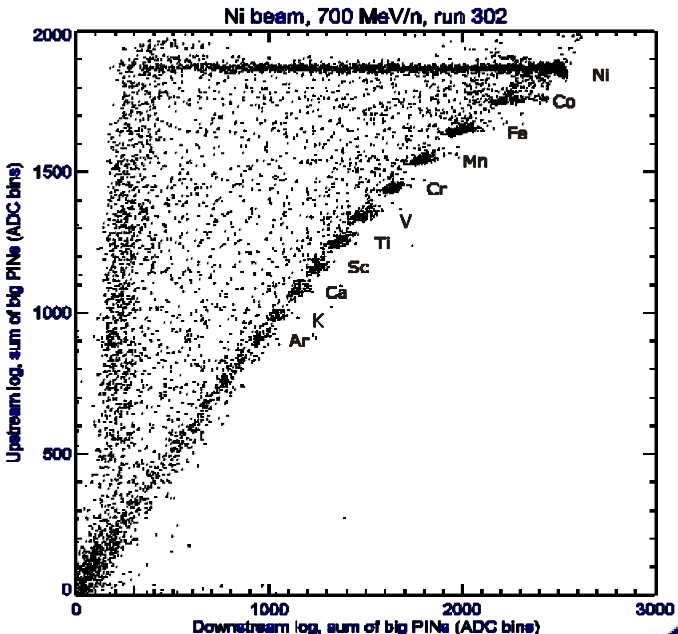
Calibration

- Beam tests
- Engineering Model
  - Scheduled for Nov 03 at GSI (Darmstadt, Germany)
  - Heavy ion beams
    - Measures
      - Energy scale
      - Scintillation efficiency for cosmic rays
- Calibration Unit (CU = first 4 CAL+TKR Modules)
  - To be performed at SLAC, Summer 04
  - Photon, electron, hadron beams
    - Measures
      - Optical gain
      - Light taper
      - Energy scale
    - Does not measure
      - Scintillation efficiency

Calibration

- Cosmic ray calibration
  - Primary energy and position calibration of CAL
  - Performed only on orbit with full LAT instrument
  - High flux of GCRs gives good calibration of most of dynamic range
    - Measures
      - Optical gain
      - Light taper
      - Energy scale
    - Does not measure
      - Scintillation efficiency





Conclusions

- Physical principles of design are well demonstrated
- Expect Flight Model to meet Level III requirements
- Engineering Model tests to date show performance (mostly) within spec
- Methods to determine and calibrate Flight Model performance are understood