The CMS Shashlik ECAL Project

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Beyond the LHCb Phase-1 Upgrade
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On behalf of

Baylor, Boston U, UC Davis, Caltech, CERN, ETH Zurich, Fairfield, Fermilab, Florida State, INFN (Milano-Bico cca, Roma1, Torino, Trieste), IHEP(Beijing), IHEP(Protvino), INP (Minsk, Moscow, Tashkent), Iowa, JINR Dubna, Kansas State, KIPT Kharkov, ISMA Kharkov, Maryland, MEPHI Moscow, NCPHEP Minsk, Northeastern, Notre Dame, Princeton, Rochester, Saclay, Saha Institute of Nuclear Phys, SINP Kolkata Institute, Texas Tech, TIFR Mumbai Institute, Virginia

Challenges in HL-LHC era in context of CMS

- Pileup: 140-200 interactions per event
- Radiation damage
  - 150 Mrad of ionizing radiation at 9 krad/h
  - Up to 1.5×10^{15} hadrons/cm^2 with E>20 MeV

Solution: Sampling ECAL with target performance

$$\frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E}} \oplus 1\%$$

We considered two configurations for sampling calorimeter

- Shashlik: W/LYSO + Capillaries WLS (as “skewers”)
- Sampling W/CeF3 + Cerium doped quartz fibers along corners

I will discuss Shashlik option only

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Choices for absorber, active layers, sizes

Aim at small effective Moliere radius to mitigate high occupancy from pileup

- Absorber layers = tungsten (R_M=9.3 mm)
- Try not to inflate R_M too much with active layers → scintillator with high light output

Scintillator = LYSO(Ce)

- Hight brightness (30000 photons/MeV)
- Decay time ~40 ns
- Blue / Violet emission

Layers / Cells Dimensions

- Tungsten = 2.5 mm thick
- LYSO = 1.5 mm thick
- Effective R_M = 14 mm, X_0 = 4.8 mm
- Cell transverse dimensions 14×14 mm^2

Sampling fluctuations: $10\%/\sqrt{E}$

Notes for LHCb

Sampling term in resolution can be better than 10%

- LYSO layers can be narrower, up to 1 mm without significant cost increase
- Need to optimize absorber layers (thickness and total number)

Position resolution is $\sim$1 mm

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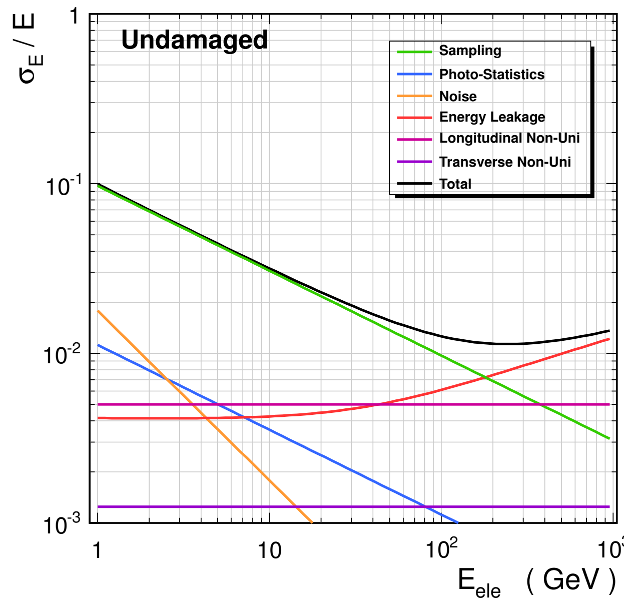
Expected EM energy resolution

Simulations with Geant4 and optical photon transport (SLitrani)
Without radiation damage

Comments

- Energy leakage can be fixed by increasing number of layers
- Transverse non-uniformity assumes “imperfect” corrections. Depends on the angle.



Radiation damage of LYSO

We model radiation damage by estimating index of induced absorption, μ_{ind} as a function of dose, dose rate, hadron fluence.

- Numerous irradiation tests with gammas and protons
- All giving consistent results
- μ_{ind} is slowly increasing, no recovery at room temperature.
- Ionizing damage depends on accumulated dose. Reaching maximum value <4 m^{-1} When? Depends on dose rate.
- Hadron damage depends on fluence, Φ of hadrons with E>20 MeV. $\mu_{ind} = 2 \times 10^{-14} \times \Phi$.

Path length of optical photons in LYSO is very short → minimize effect of radiation damage

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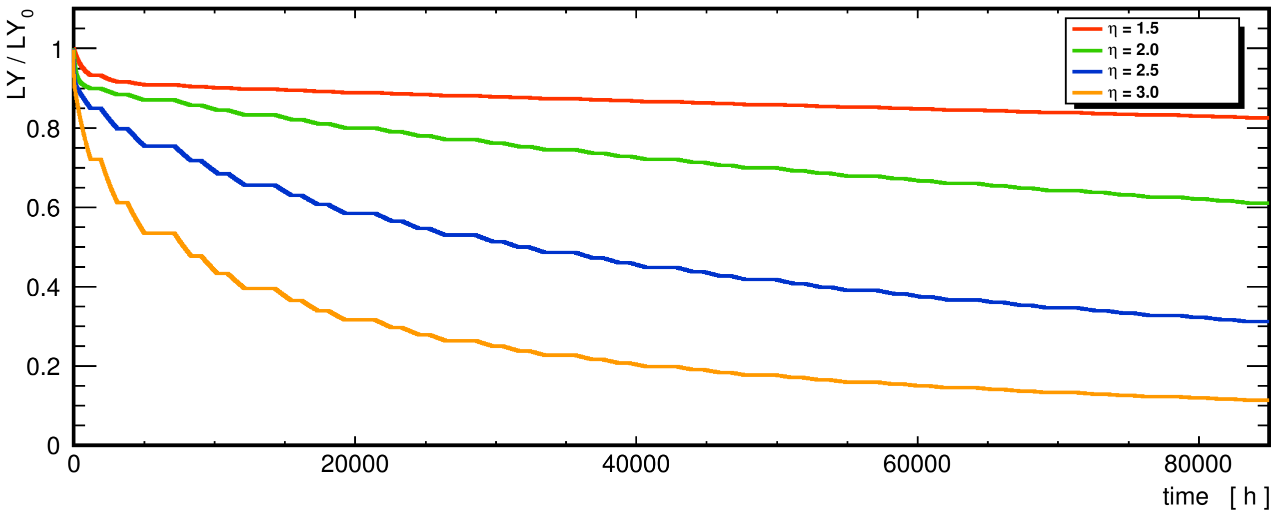
LYSO-W during 12 years of HL-LHC

Degradation of ECAL response to 50 GeV EM shower



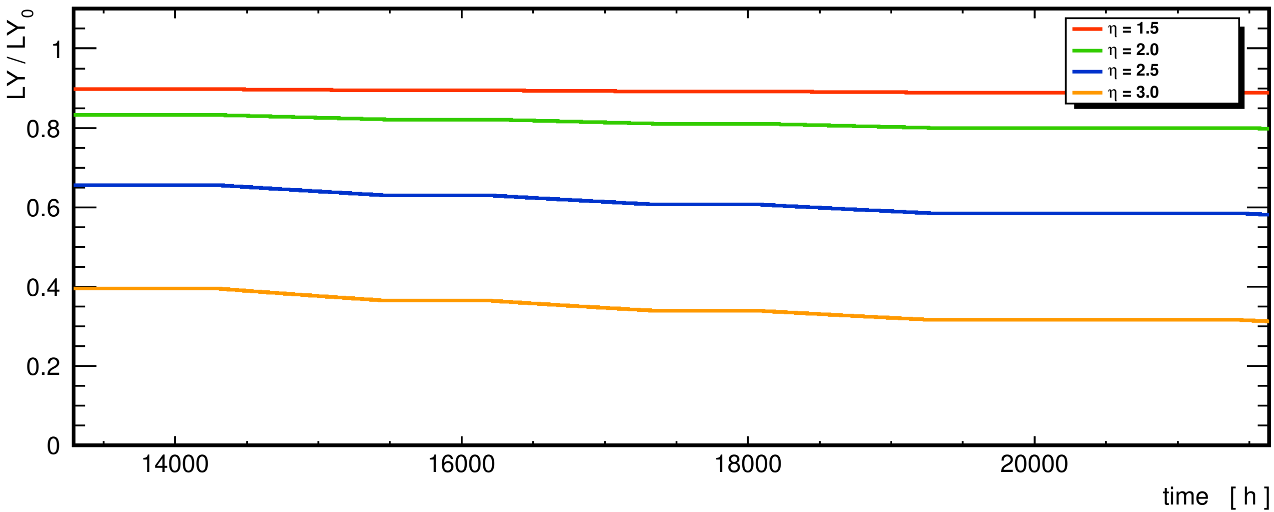
LYSO-W during 3rd year of HL-LHC

Degradation of ECAL response to 50 GeV EM shower

η=3.0 4.7% per month

Very easy to monitor with physics

Laser monitoring also: leaky fiber at the center of the module exites LYSO scintillation

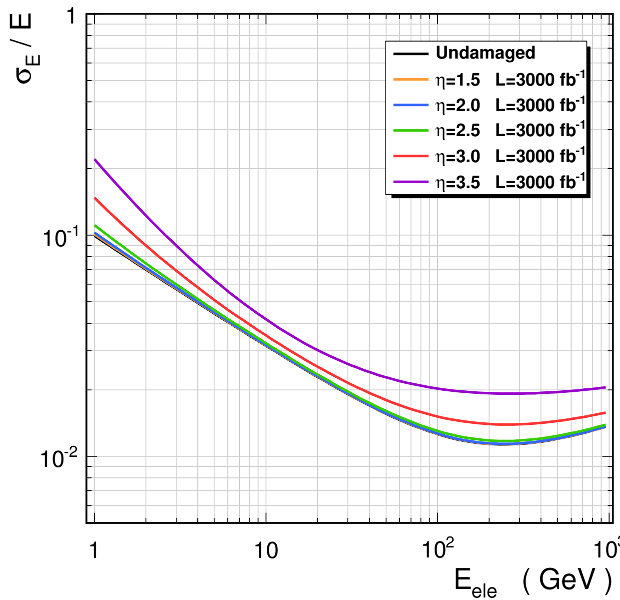


Simulated degradation of EM energy resolution

due to radiation damage

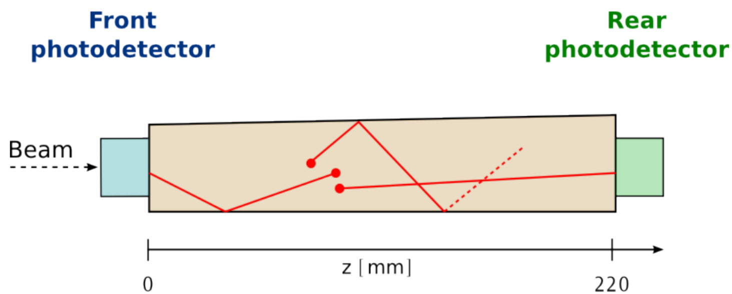
In context of CMS after L=3000 fb^{-1}, radiation environment vs $|\eta|$

η	Dose (Mrad)	Dose Rate (krad/h)	Had>20 MeV (/cm^2)
1.5	1.3	0.1	1.5E+13
2.0	9.0	0.5	1E+14
2.5	40	3.0	4E+14
3.0	150	9.0	1.5E+15



Non-Uniform Light Collection Mitigation: Double-ended Readout

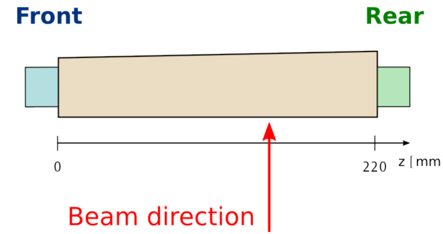
These studies were done for irradiated $PbWO_4$ crystals of 22 cm long.
It is a good illustration of the principle
More details in CALOR2016 presentation by Marco Lucchini.

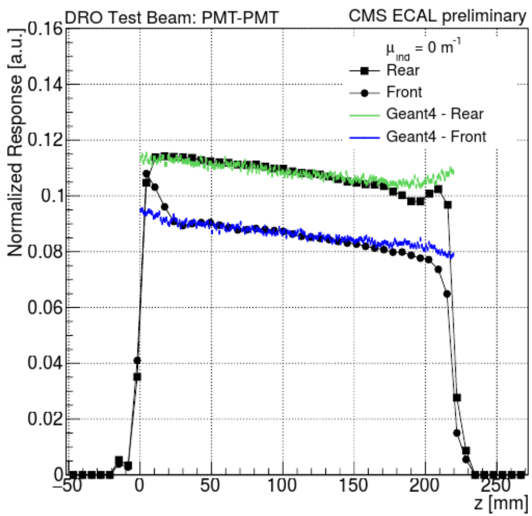


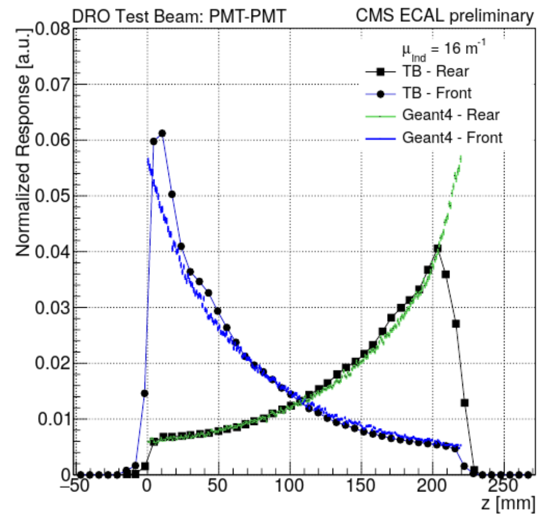
Double-ended read-out

Light Collection

Left: Undamaged crystal
Right: Proton irradiated crystal

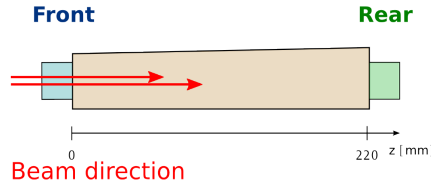


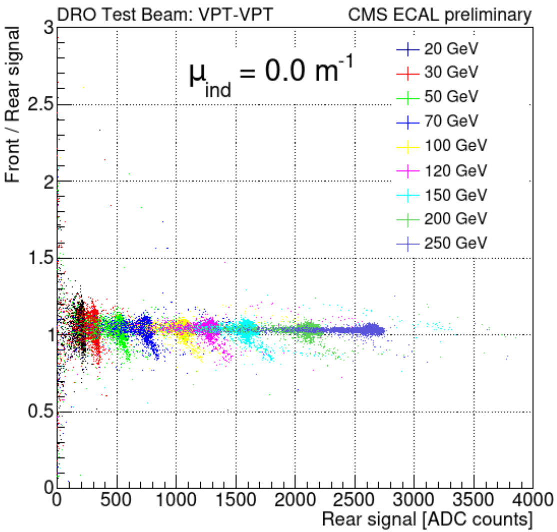


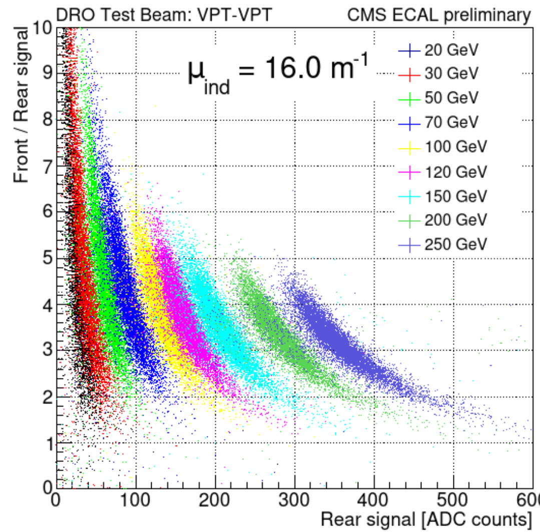


Longitudinal Shower Fluctuations

Left: Undamaged crystal
Right: Proton irradiated crystal

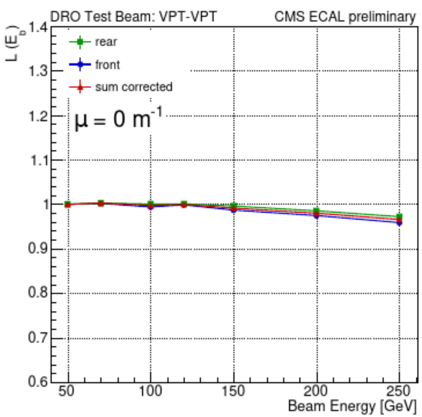


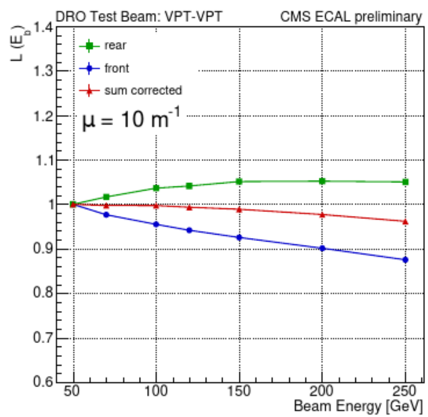


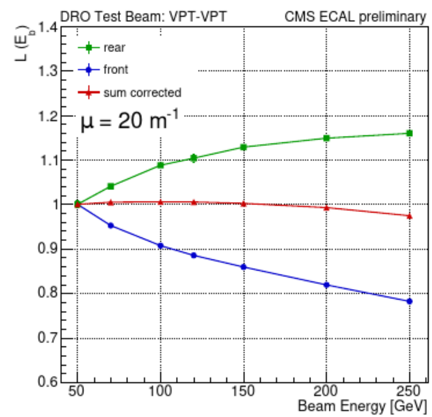


Energy Linearity E_{rec}/E_{beam} normalized to E_{beam}=50 GeV

Left: Undamaged crystal
Middle: Proton irradiated crystal. μ_{ind}=10 m^{-1}
Right: Proton irradiated crystal. μ_{ind}=20 m^{-1}





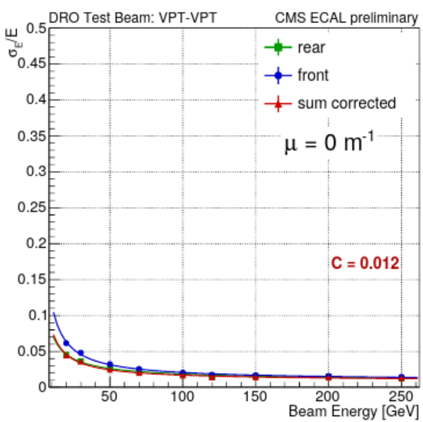


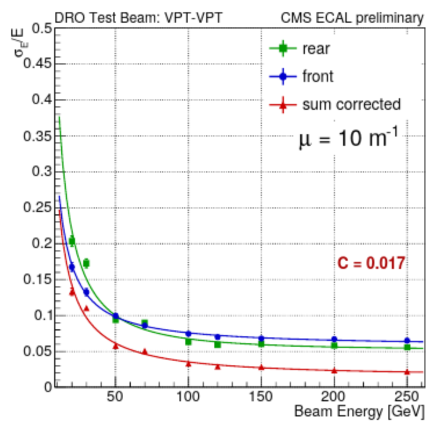
Energy Resolution

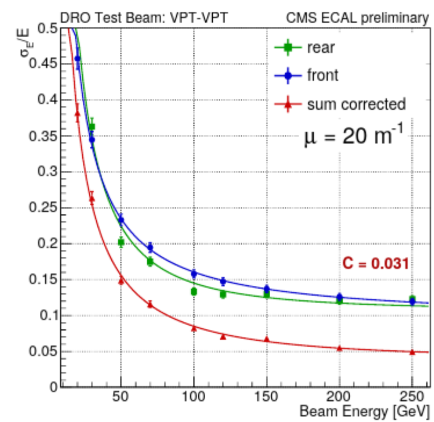
Left: Undamaged crystal

Middle: Proton irradiated crystal. μ_{ind}=10 m^{-1}

Right: Proton irradiated crystal. μ_{ind}=20 m^{-1}







Non-Uniform Light Collection Mitigation: WLS Capillaries

Double-ended readout was not realistic in CMS

Schematic of light collection, WLS and light transfer

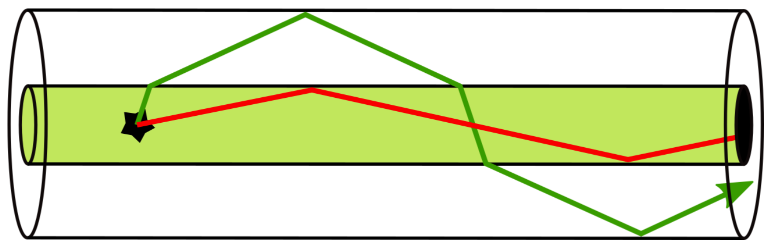
WLS in capillary core

Thick wall, rad hard quartz

$n_{core} > n_{quartz}$

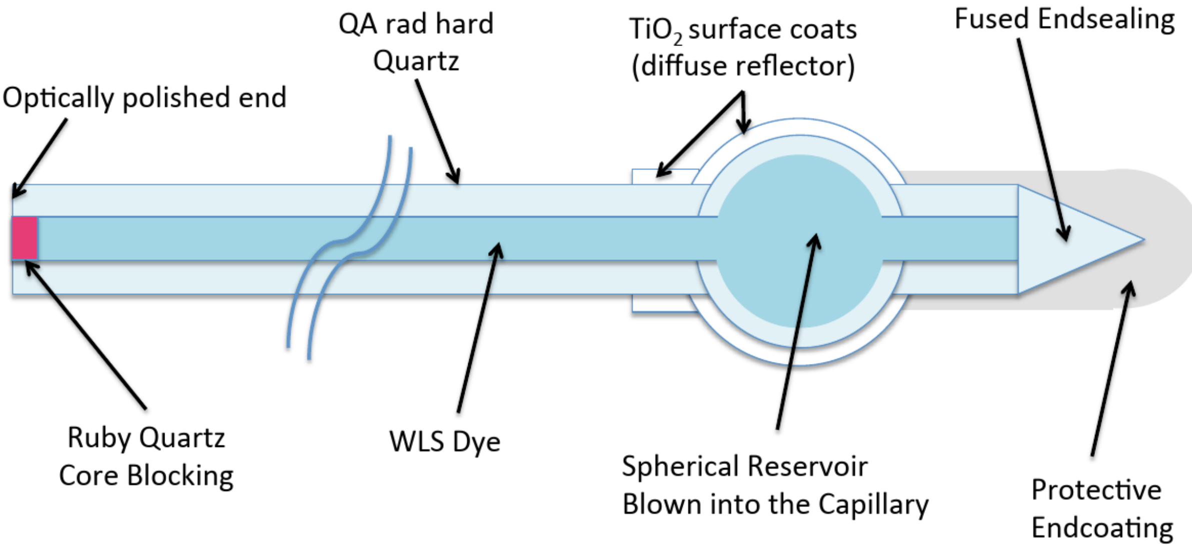
Core is blocked at the readout end

Detected photons to travel most of its trajectory in rad. hard quartz



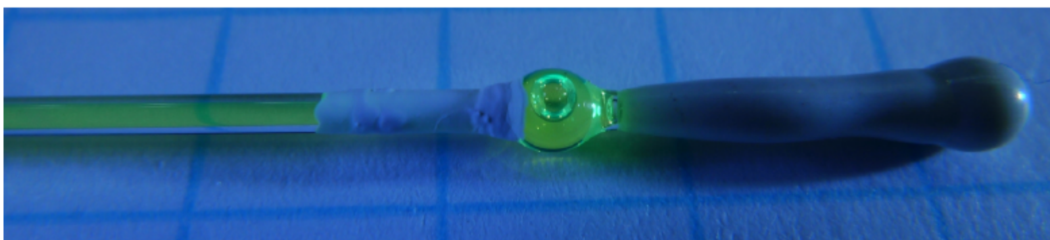
Schematic of “thick wall” capillary

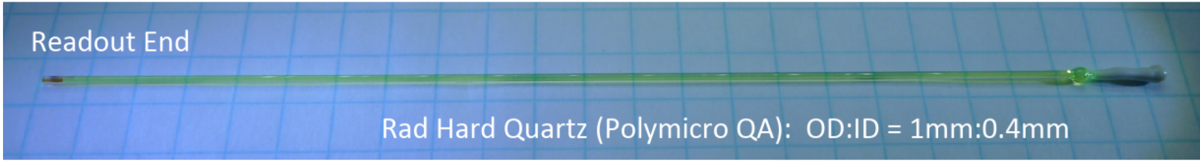
Current form: OD:ID = 1mm:0.4mm



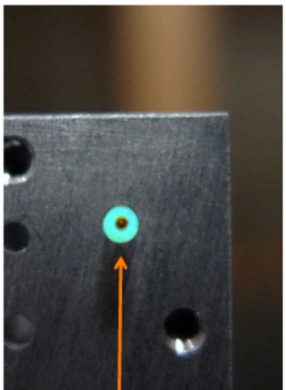
Diffusive Reflector Surface Coating

- Traditional end mirroring is not possible with a capillary of the current structure with a reservoir at the upstream (non-readout) end.
- Instead we have used TiO_2 painted on the external surface of the capillary just downstream of the reservoir (typically a band of 4mm length) and also applying the TiO_2 paint to the reservoir itself.
  - Initial results indicate that the TiO_2 paint improves the light collection from the upstream end of the capillary as well as overall.
  - The TiO_2 coating appears to be robust to 200Mrad of gamma irradiation (highest dose level tested so far).

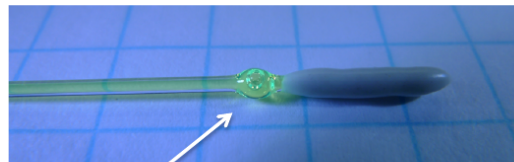




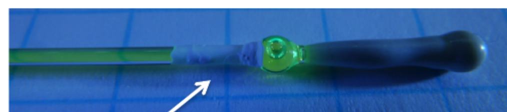
150 mm



Core Blocking



Thermal Expansion Reservoir



Diffusive Reflector (DR) Surface Coating just before the Reservoir

Initial studies has been conducted with WLS liquids

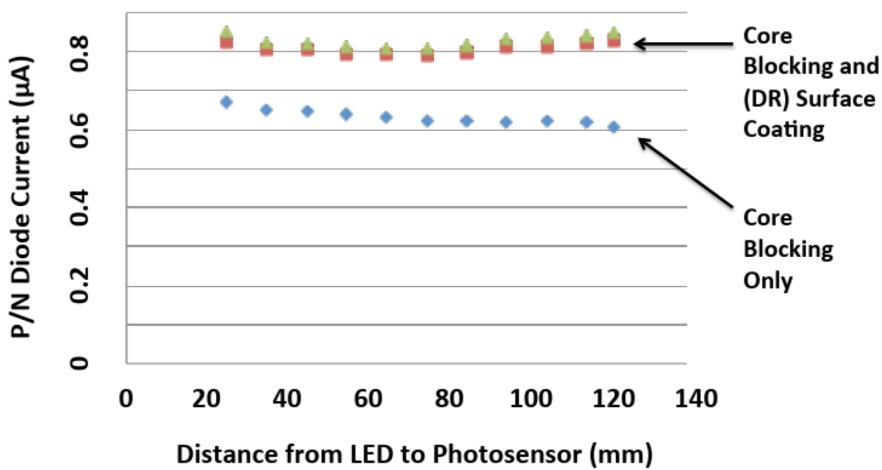
- Motivation is that liquids tend to be relatively radiation tolerant.
- Liquid solvents could be selected for various WLS dyes that would otherwise be insoluble.

- Our preliminary choice of solvent has been a quenched EJ309-based medium
  - High flashpoint
  - Safe handling

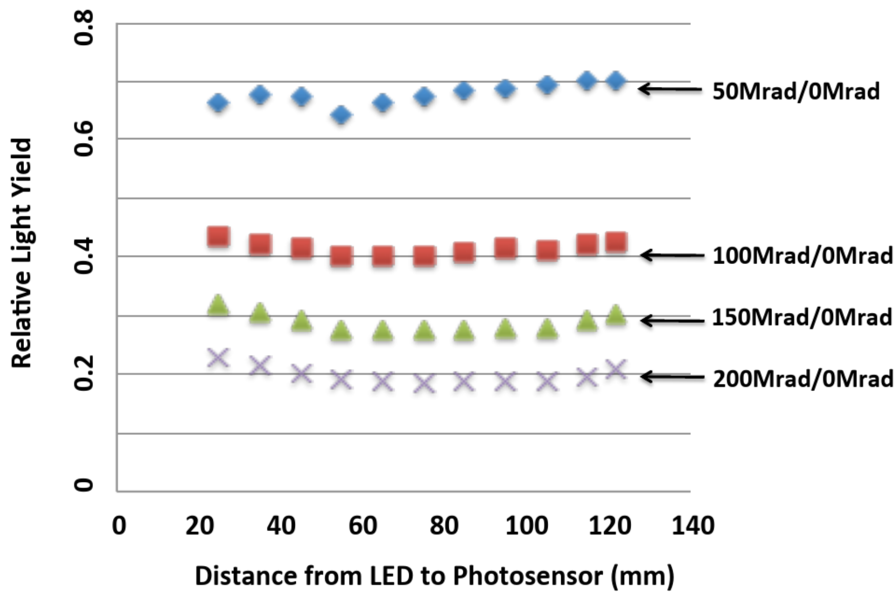
- Our WLS dyes must be tuned for the Scintillation Plates being used.
  - LYSO(Ce) emits at ~425nm.
  - Hence WLS must absorb ~ 425nm.
  - Emission near ~ 500nm provides good spectral matching to solid state photosensors.
  - Examples J2 (similar/identical to Y11) and DSB1
  - DSB1, spectrally similar to J2/Y11 but ~ 2.5x faster.

LED measurements of capillary

Illumination of capillary through side wall at 425 nm
Measure light output of capillary as a function of distance from readout end



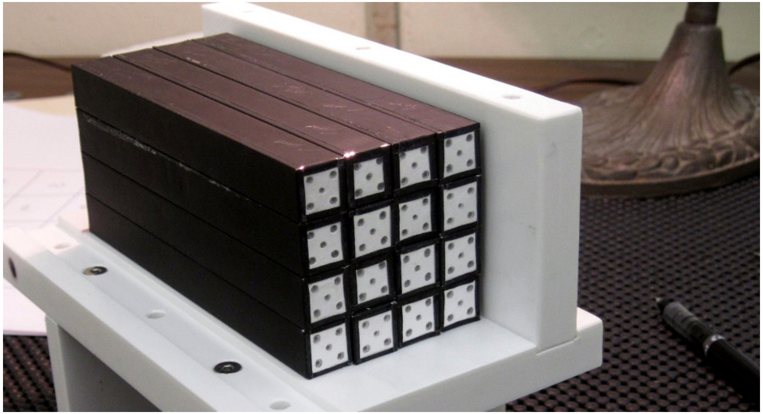
LED measurements of an irradiated capillary



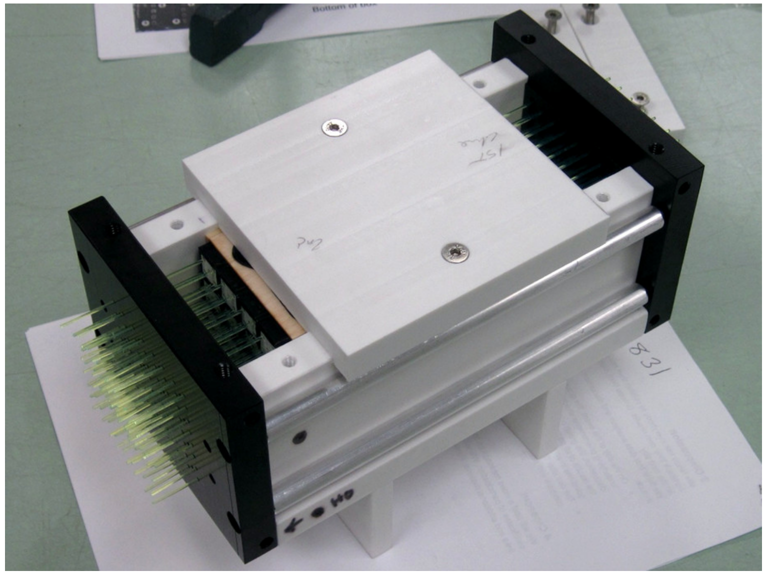
Prototype for Test Beam in CERN

4x4 Array of Shashlik modules. Module is $14\times14\times114$ mm^3

28 W plates 2.5mm thick
29 LYSO plates 1.5mm thick
Holes for WLS 1.6mm/1.7mm diameter in LYSO/W (overkill)
Holes for monitoring fiber 1.2mm



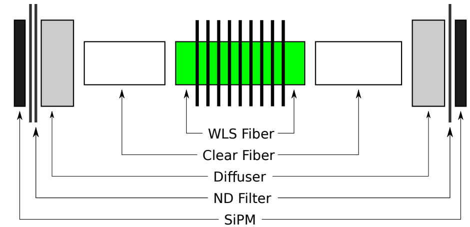
WLS Option One: Y11 Kuraray 1.2 mm diameter

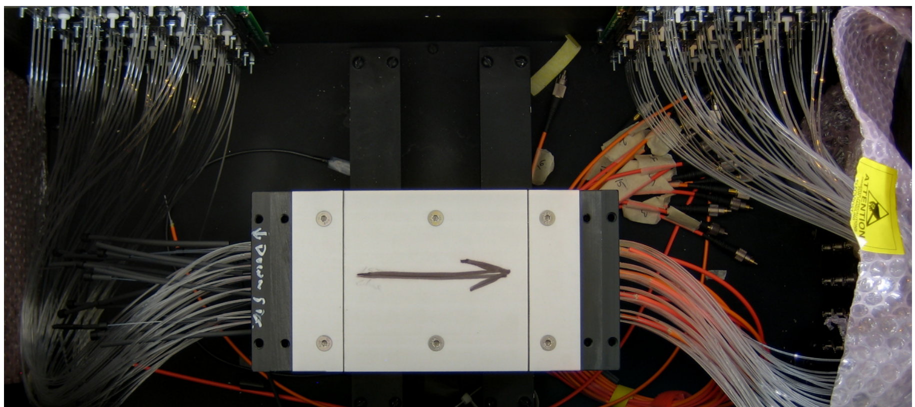


WLS Option One: Double-ended readout

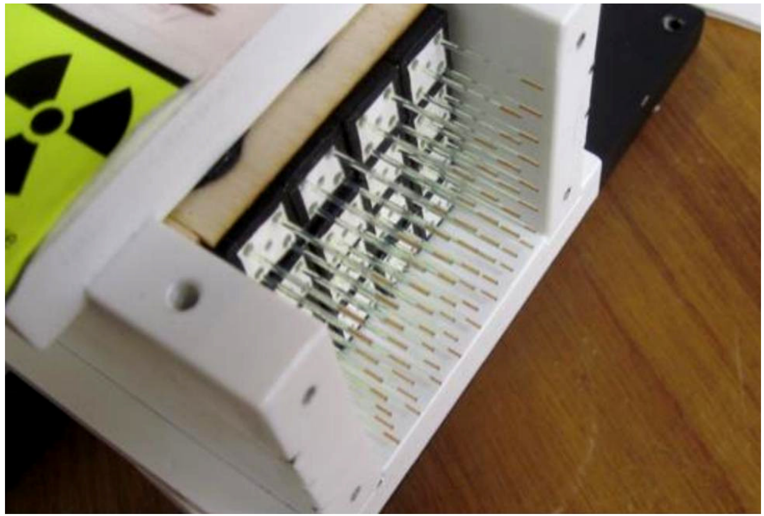
Clear fibers between Y11 and SiPMs

ND filters x32 and x8 to attenuate light



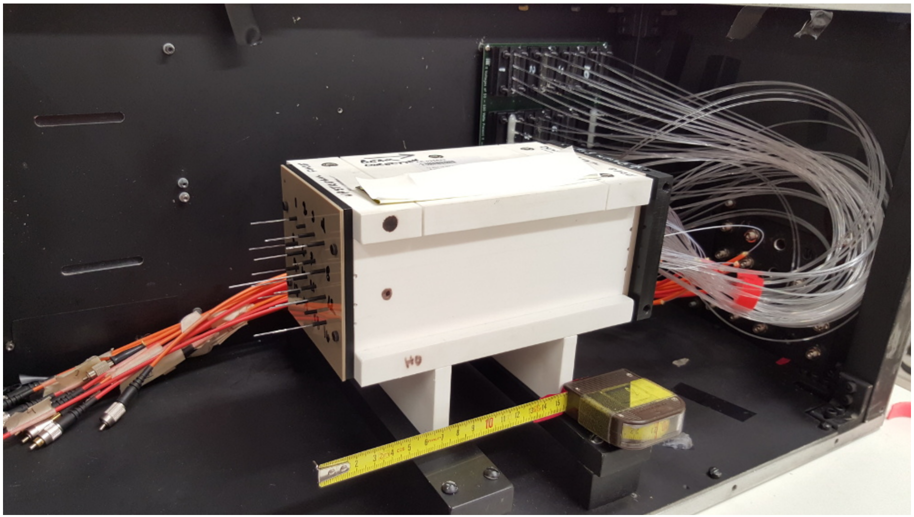


WLS Option Two: Capillaries 1.0 mm : 0.4 mm for OD : ID



WLS Option Two: Single-ended readout

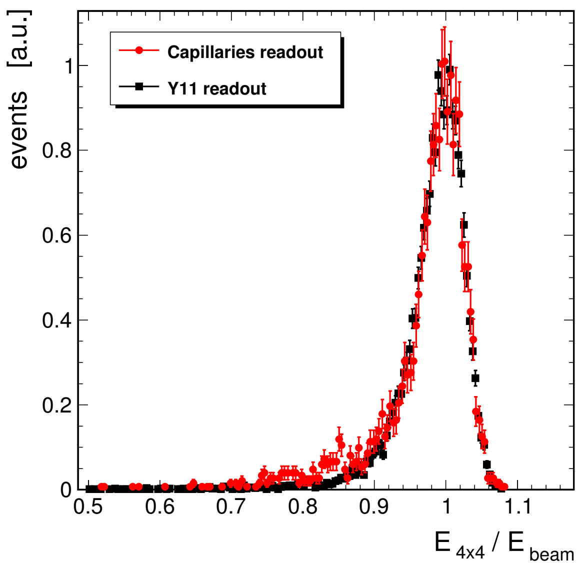
Clear fibers between capillaries and SiPMs

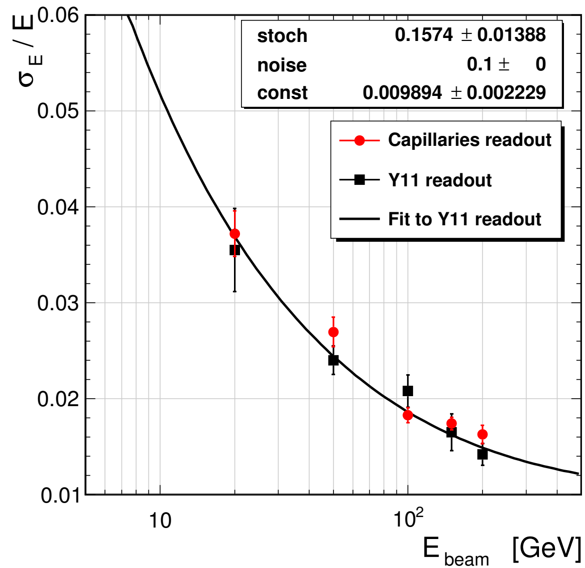


Energy reconstruction. Beam angle 5°⊕ 2.4°

Left: Measured energy by the 4×4 array divided by the beam energy at 100 GeV electrons
Right: Energy resolution (CrystalBall σ) as a function of beam energy

Rad-hard capillaries provide the same energy resolution as that of the much less radiation hard Y11 fibers.





Summary

- Radiation hard Shashlik calorimeter that sustains performance up to 150 Mrad accumulated dose and 1.5×10^{15} hadrons/cm^2 with E$>$20 MeV
- Energy resolution below 2% without corrections has been reached
- Position resolution is $\sim$1 mm
- R&D on capillaries, radiation hardness of crystals, test beam analysis are in progress