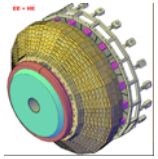

High Performance, Radiation Hard Light-Based EM Calorimetry for Particle Physics Applications

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University of Notre Dame

On behalf of:
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B. Baumbaugh, N. Dev, B. Dolezal, A. Heering, C. Jessop, M. Marinelli, M. McKenna, C. Mohs, Y. Musienko, R. Ruchti, N. Siwietz, J. Taylor, M.Vigneault, M. Wayne
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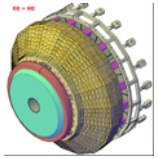
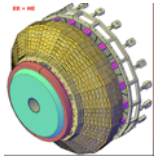


Our Approach…

- **To meet the challenges comparable to CMS in the HL-LHC era:**
  - **High Integrated Luminosity (> 3000 fb-1)**
    - **Near eta ~ 3**
      - **150Mrad of ionizing irradiation**
      - **Up to 3 x 10^{14} protons/cm^2 and up to 5 x 10^{15} n/cm^2**
  - **Significant event pileup (140-200/crossing)**

- **Has both an elemental and holistic perspective…**
  1. **Use dense materials to minimize cross sections and lengths of detector elements**
  2. **Maintain the Molière Radius as small as possible**
  3. **Use radiation-hard materials**
  4. **Keep all optical paths as short as possible**
  5. **Use radiation resistant, high efficiency photosensors**

- **Technique**
  - **Shashlik-style technology is a good match to this approach.**
  - **Proven to be effective in the hadron-collider environment and validated in several major experiments**



Two methodologies

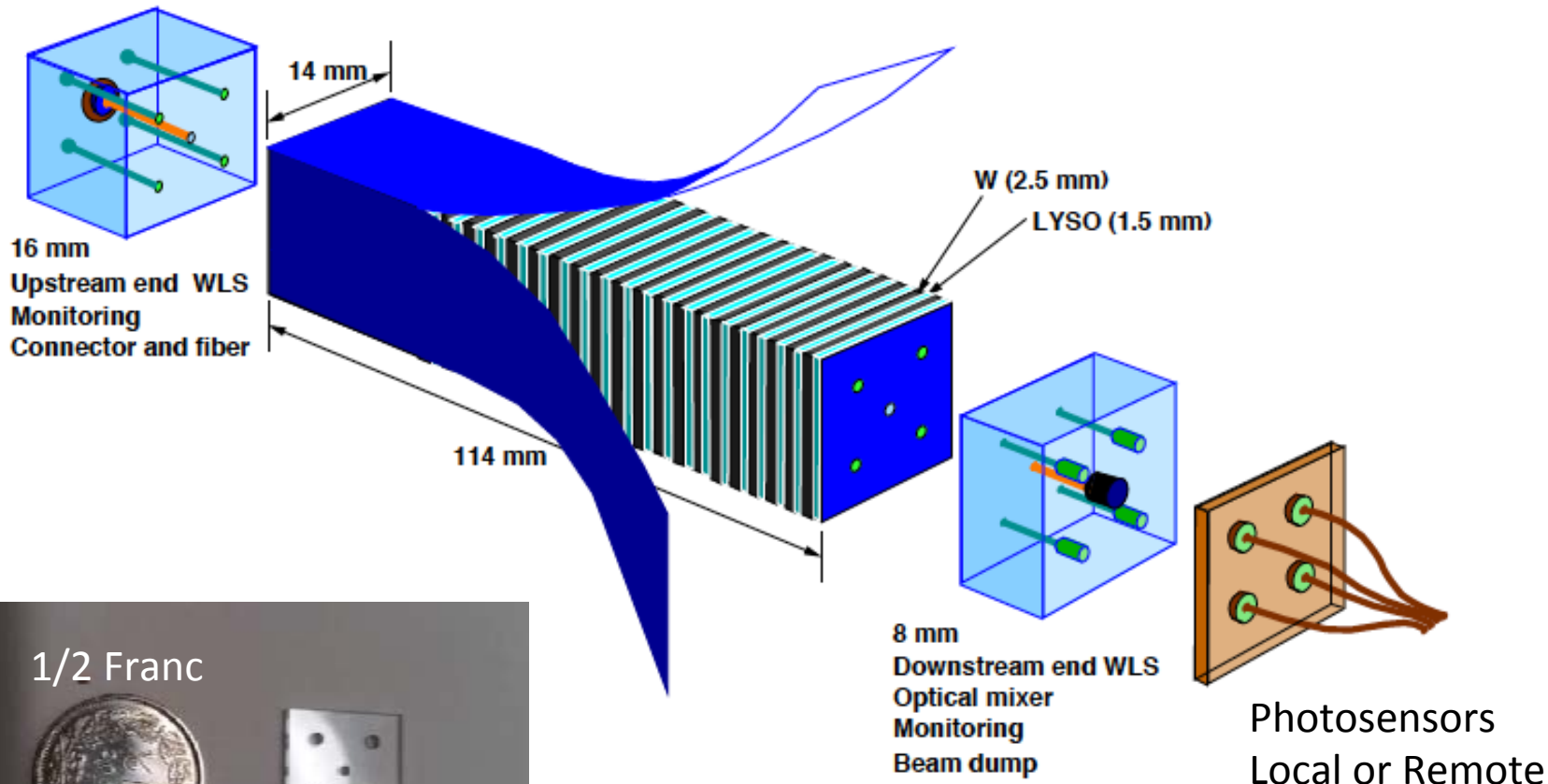
USA: W/LYSO(Ce) + WLS Quartz Capillaries/Structures

- LYSO(Ce)
  - High Brightness
  - Slowly degrades with dose
  - Blue/Violet emission
- WLS Capillaries
  - Liquid cores accommodate various WLS materials
  - Spectral matching straightforward
  - Sealed and Replaceable
- Photosensors
  - GaInP if proximate
  - SiPM, small pix, cooled in a more remote location

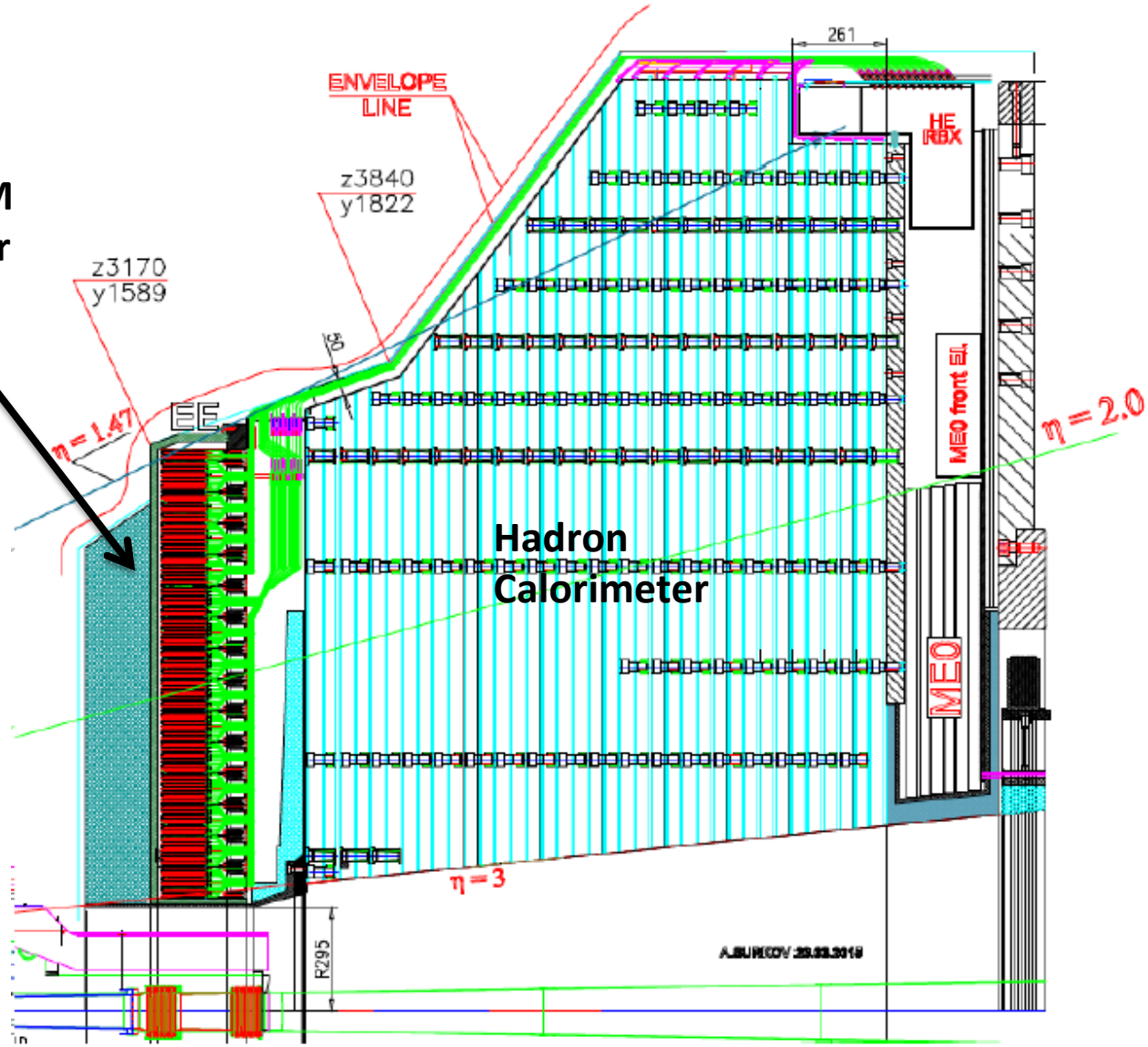
ETH/INFN: W/CeF_3 + Cerium Doped Quartz Fibers

- CeF_3
  - Lower light output
  - Rapid recovery of light loss after dose.
  - UV emission
- WLS Cerium doped Quartz fibers
  - TTU involved in development
  - Spectral match to the CeF_3
  - Solid core material
- Photosensors
  - Similar to W/LYSO method

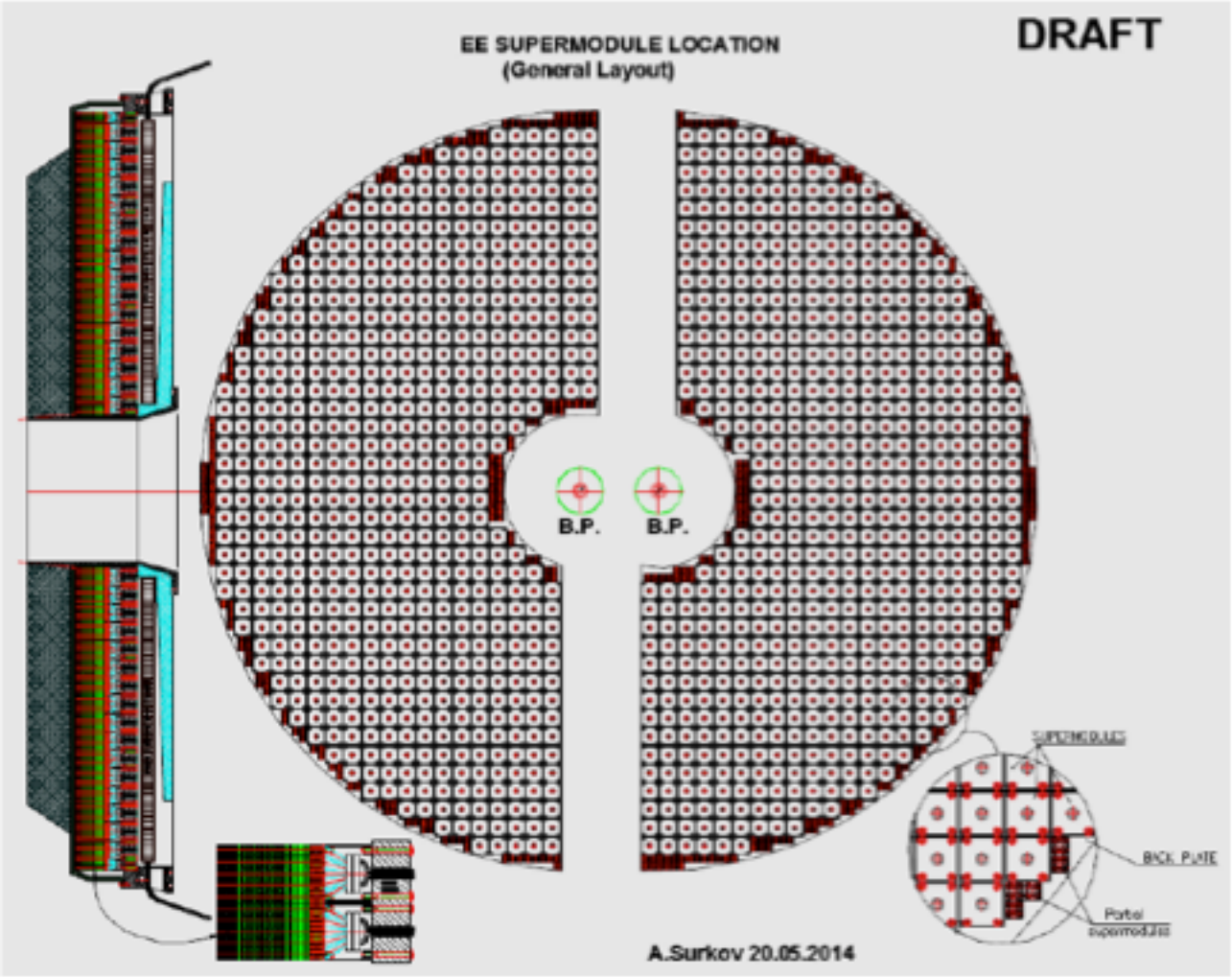
To set the Dimensional Scale of a Shashlik Module…

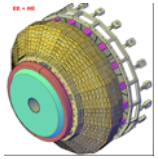


Schematic of a light-based EM calorimeter considered for the CMS Endcap Region



View from the IP of the EM Calorimeter



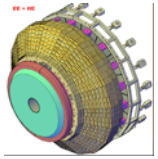


Crystals: LYSO(Ce), CeF_3

Conventional WLS Fibers – [Quartz capillaries and Fibers are being optimized in very recent or upcoming tests]

Photodetection using SiPM or PMTs

PRELIMINARY BEAM STUDIES



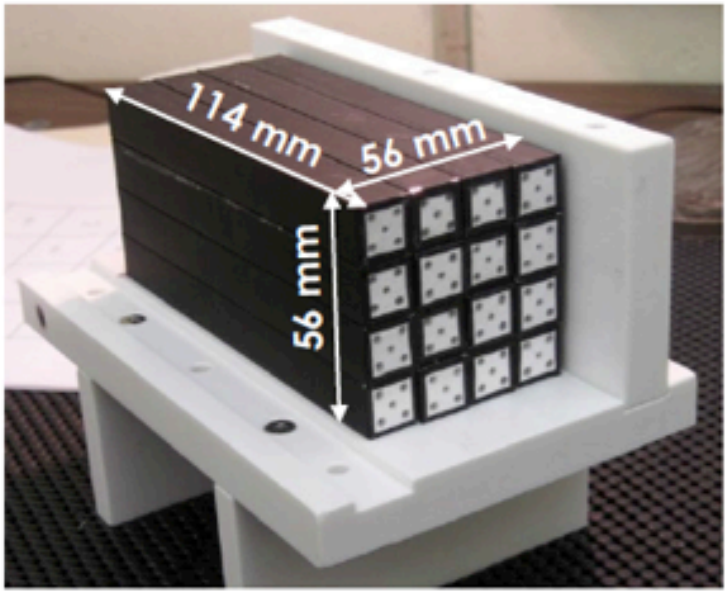
A Shashlik 4x4 Test Array

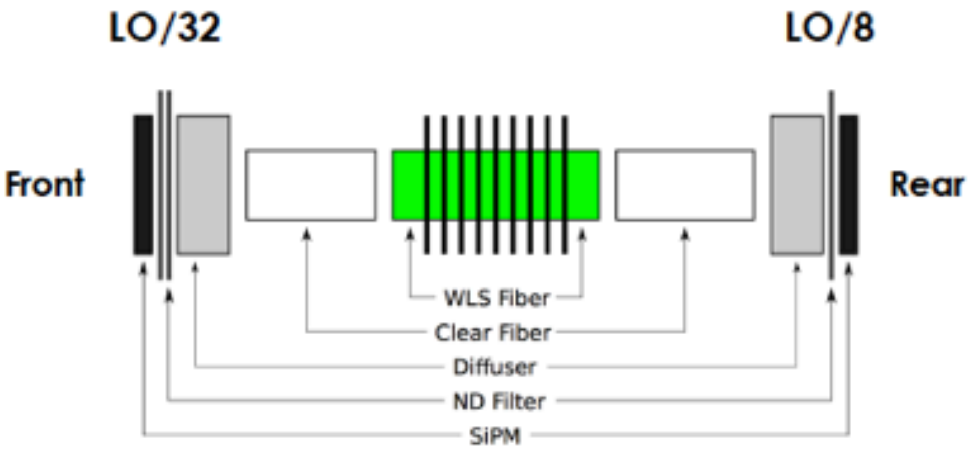
W/LYSO Shashlik Prototype of 16 modules:

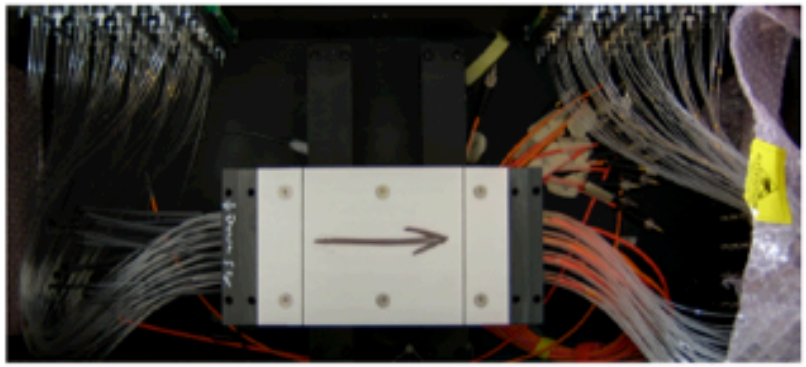
- **28 W plates 2.5mm thick**
- **29 LYSO Plates 1.5mm thick**
- **WLS Fibers: Kuraray 1.2mm dia, Y11**
- **Monitoring Fiber 0.9mm dia**
- **Holes drilled in LYSO Plates/No polishing**

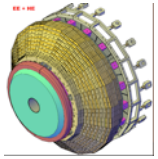
Readout both Upstream and Downstream

- **SiPM (PDE = 20-25%)**
- **Fermilab PADE Boards (Preamp and Digitizer)**
- **Total 128 channels**

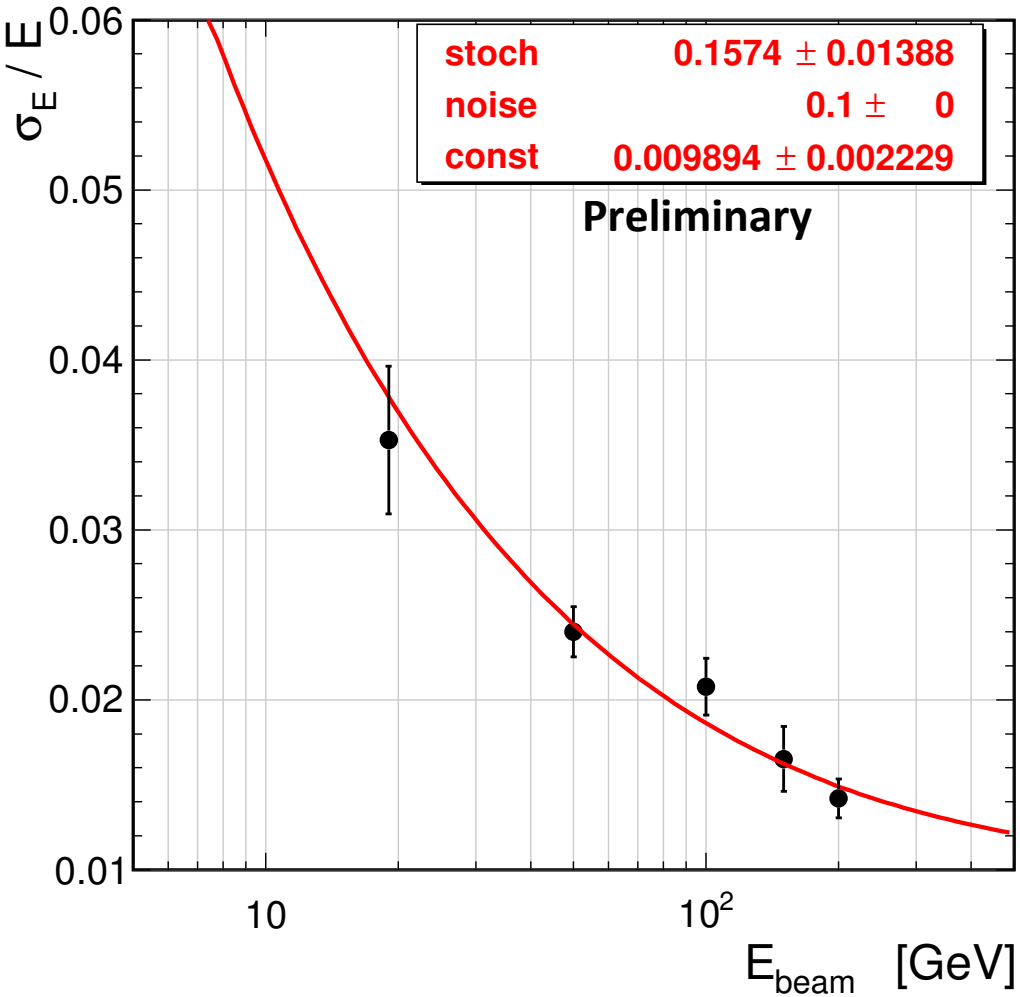


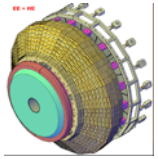




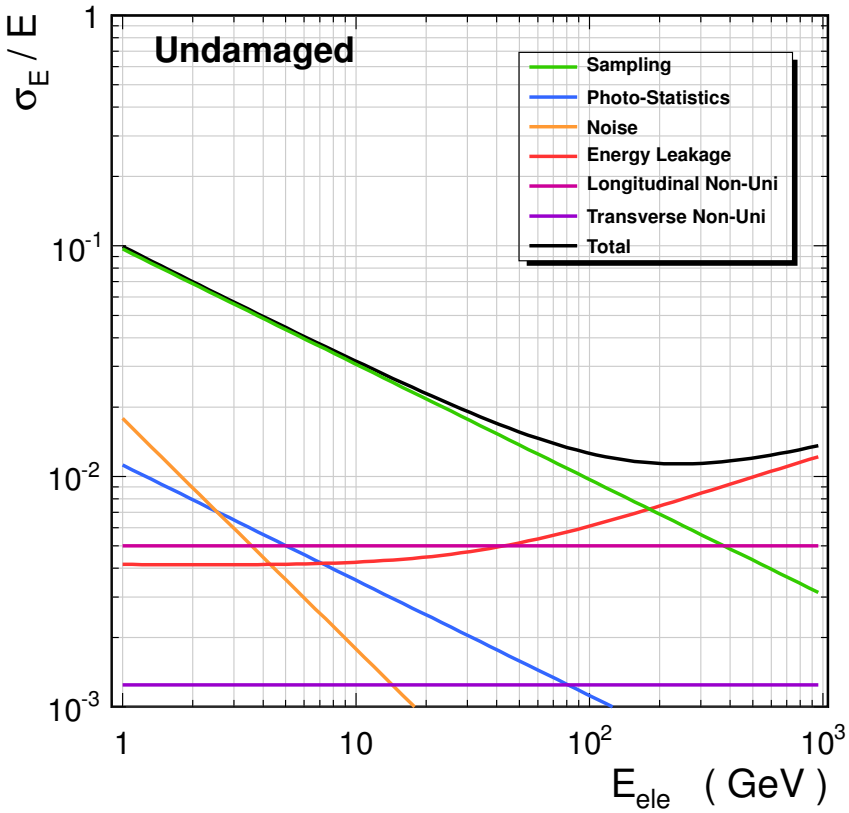


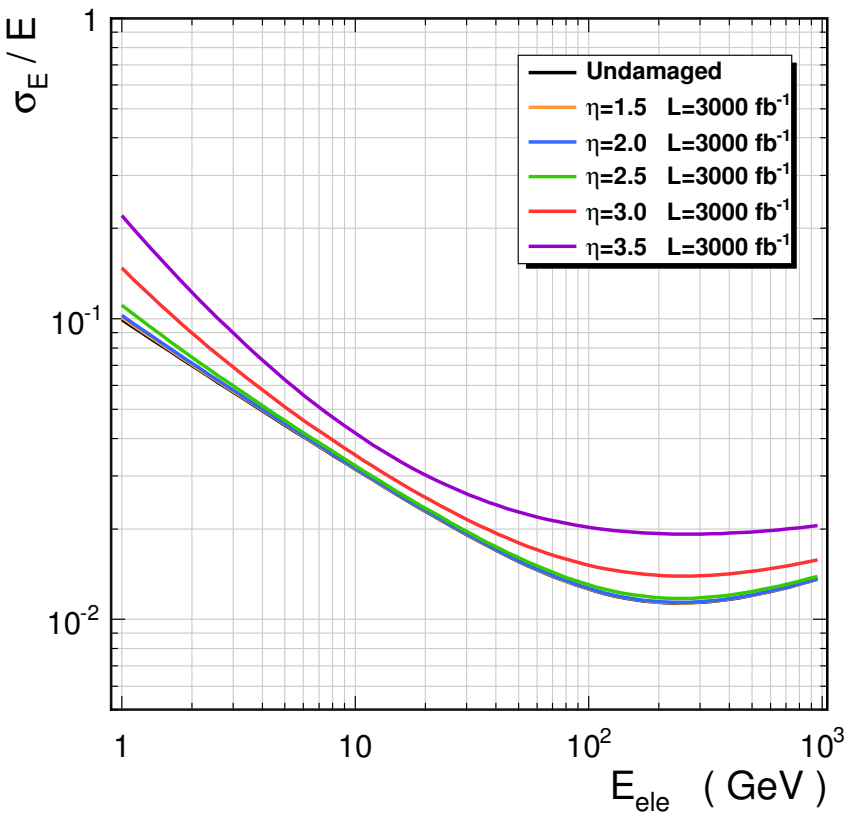
Measurement of Energy Resolution with Electron Beam (CERN H4)



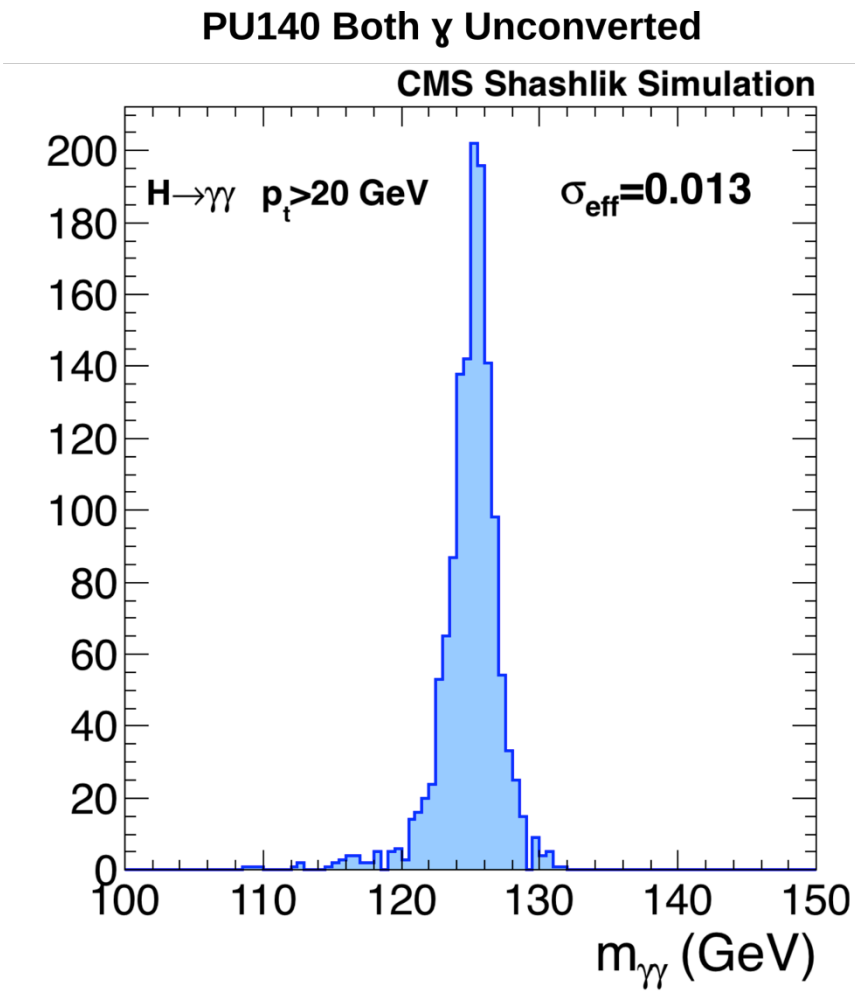


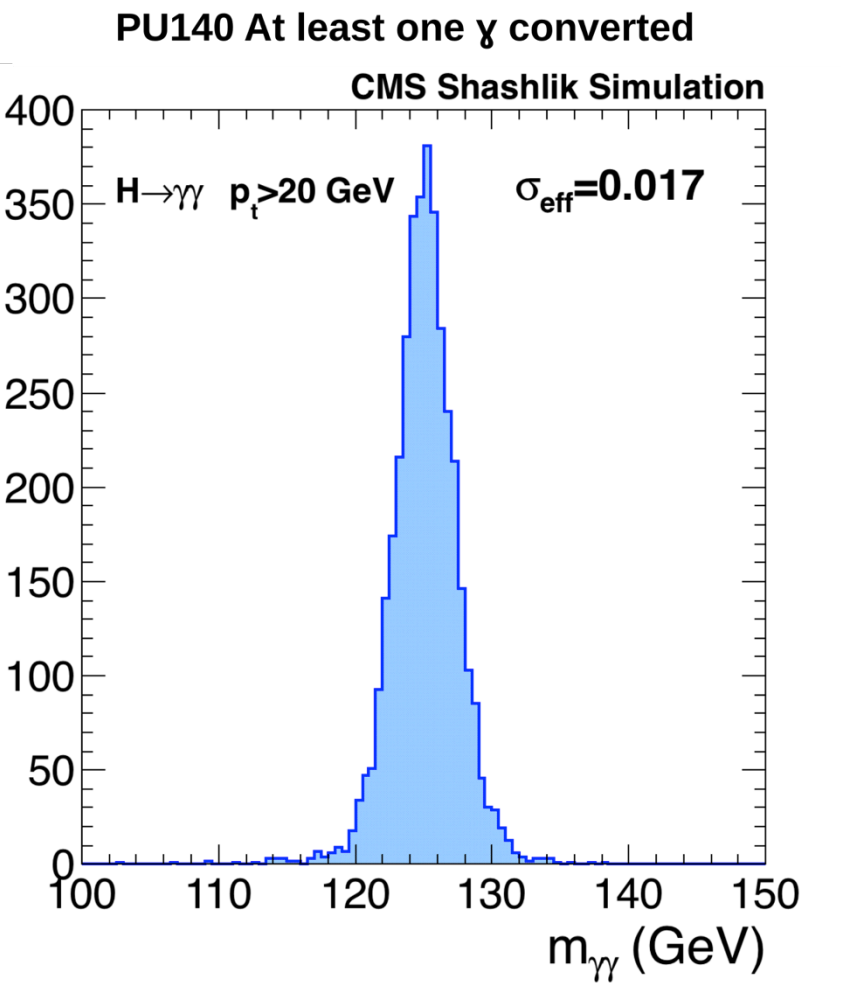
Energy resolution from GEANT4



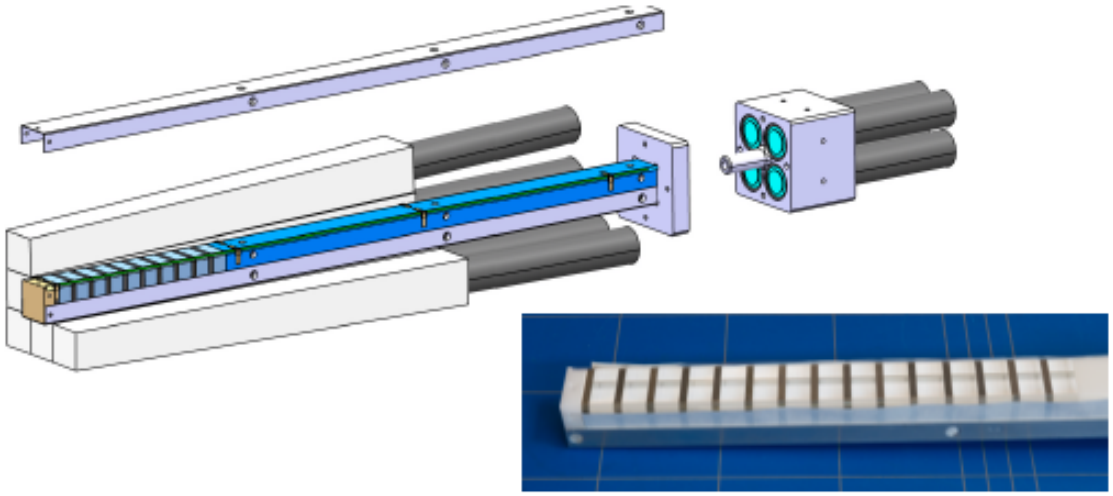


Mass Resolution from CMSSW





Status & Plans For W/CeF$_3$ R&D



2014: Demonstration of W/CeF$_3$ calorimeter concept with WLS readout. W/CeF$_3$ tower + WLS plastic fibres on chamfers + matrix of BGO crystals. PMT readout

May 2014: BTF e- up to 500 MeV

October 2014: H4 e- up to 200 GeV

2015: Test of W/CeF$_3$ with Ce doped quartz fibers

May 2015 H4: 3 chamfers equipped with Ce doped quartz fibres

October 2015 H4: improved Ce doped quartz fibers + test of photodetectors for 2016 prototype

2016: Test matrix of W/CeF$_3$ with "close to final" configuration

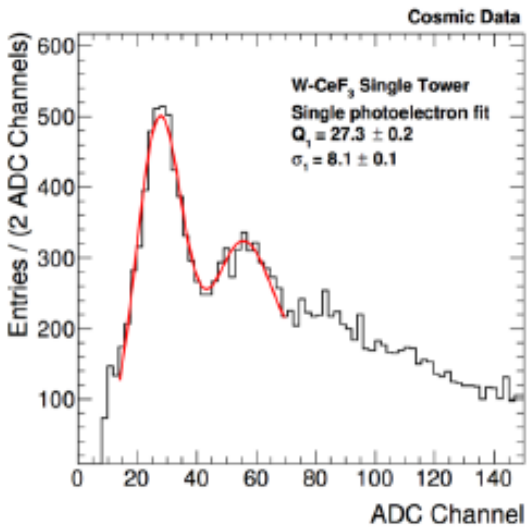
4x3 matrix of W/CeF3

PUBLISHED RESULTS

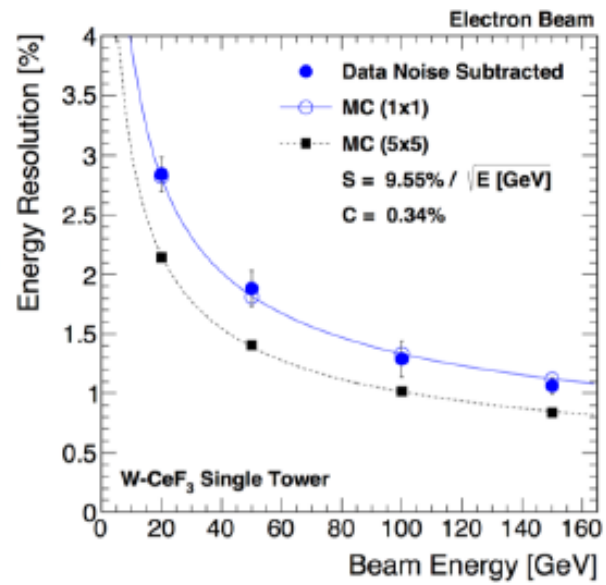
JINST 10 (2015) 07, P07002

NIMA: doi:10.1016/ j.nima.2015.09.055

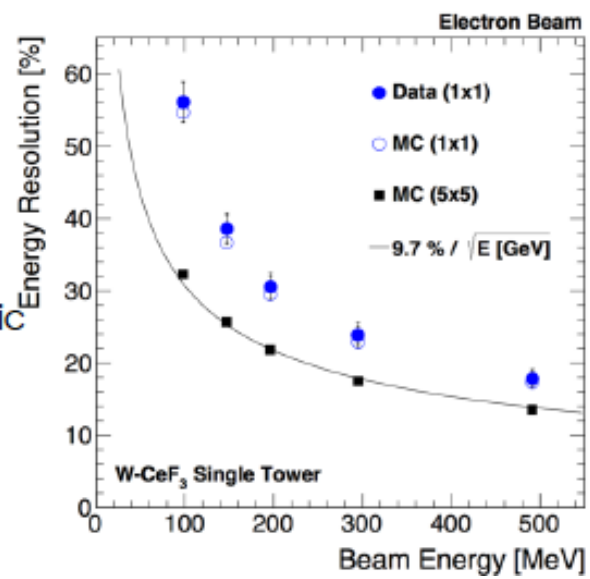
Photoelectron calibration to estimate absolute LY



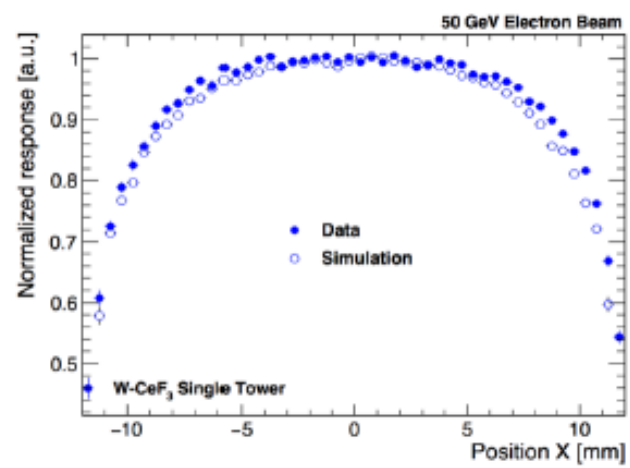
Good data/MC agreement for energy resolution (also constant term)

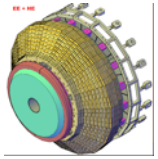


Good data/MC agreement for low electron energy resolution (stochastic term)



Good data/MC agreement for lateral shower development (without modelling yet the light collection uniformity)

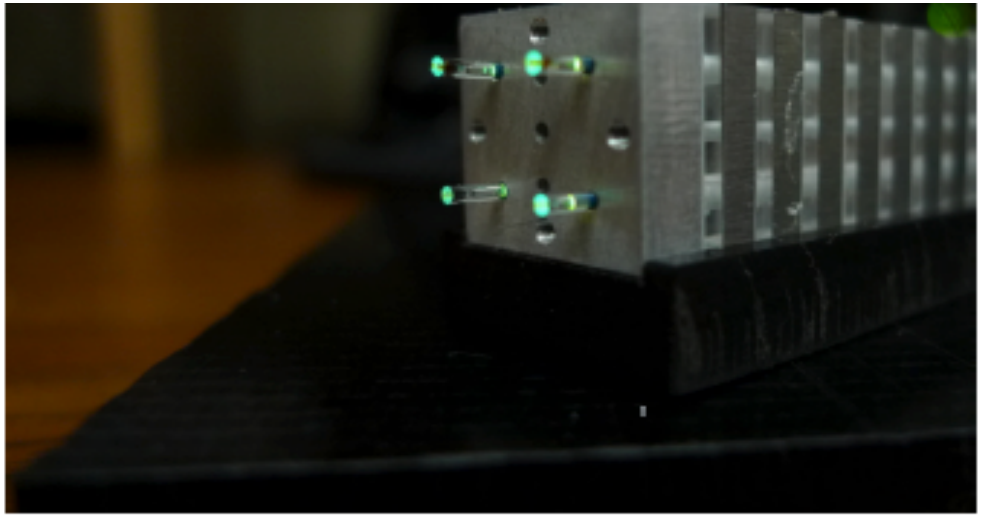


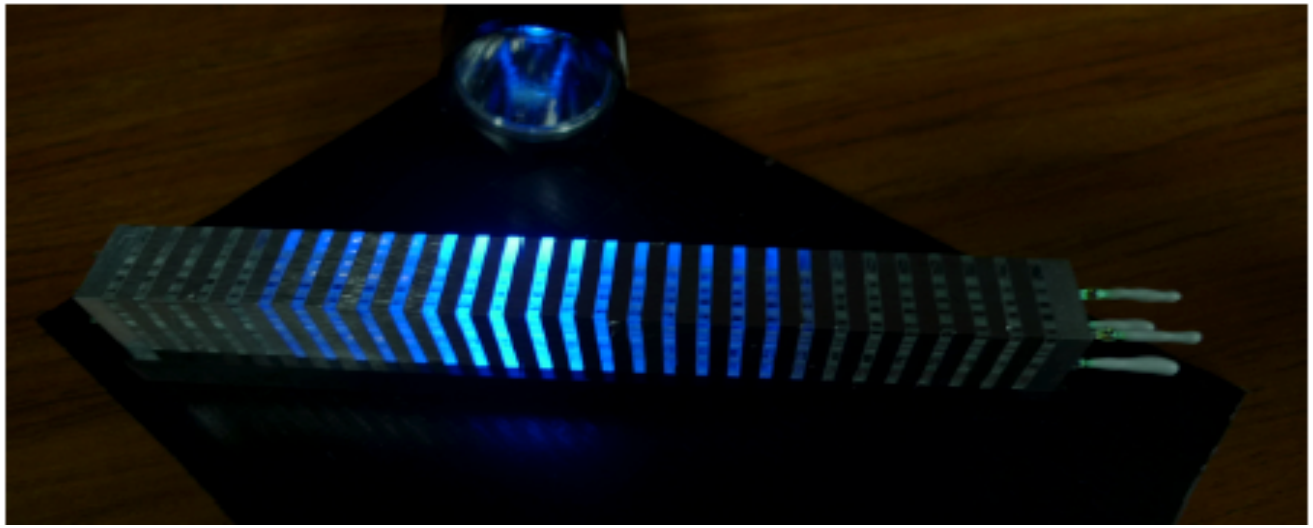


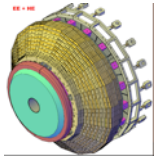
For the US Groups…

R&D ONGOING

A Shashlik Module with W plates, LYSO plates and WLS Capillaries

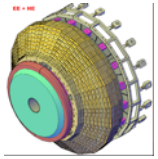






Scintillator Plate Development

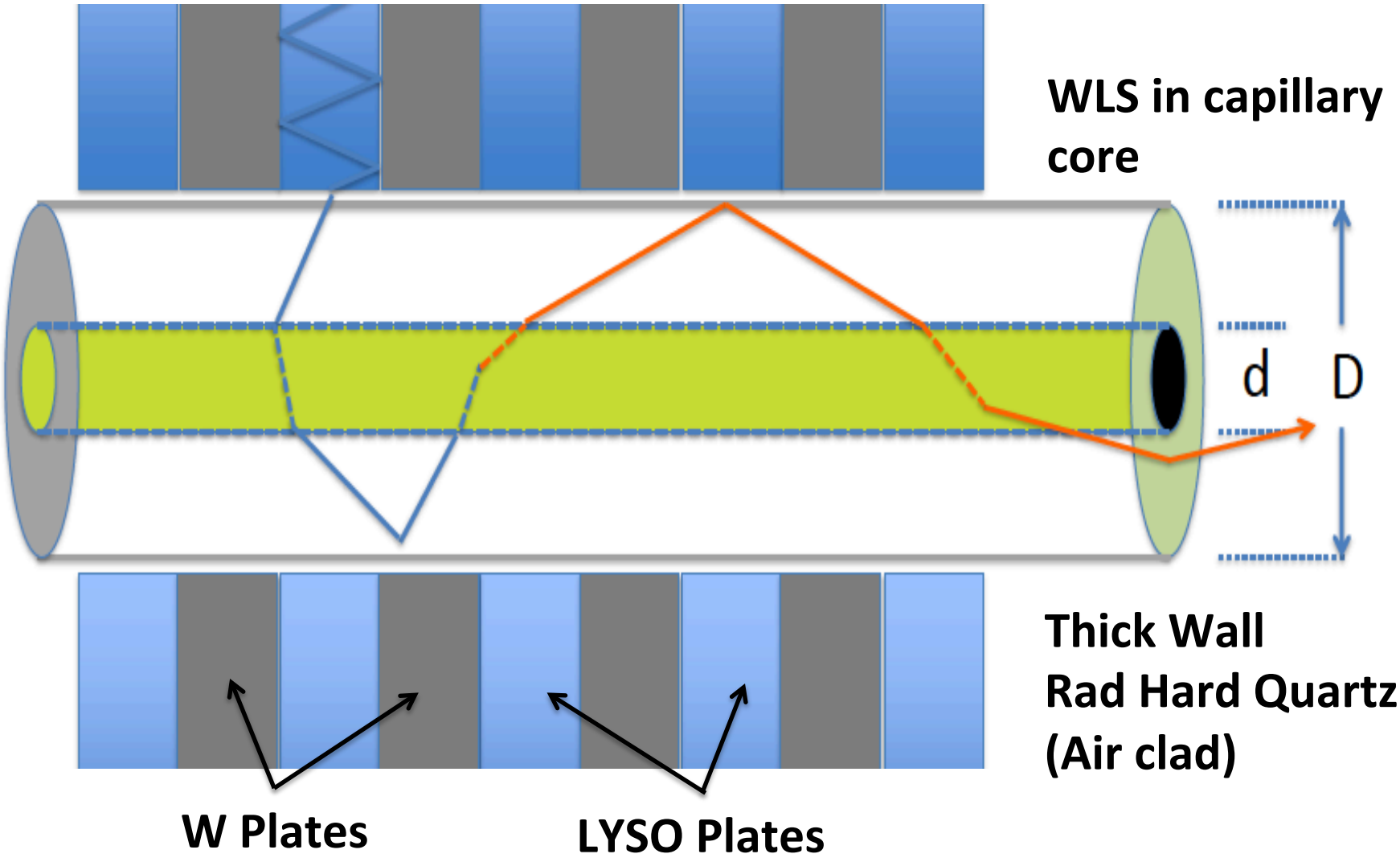
- **LYSO(Ce)**
  - **Plate thickness and dimensions of penetrating holes for WLS Capillaries.**
  - **Scintillator Light Yield and transverse uniformity**
  - **Irradiation studies (proton irradiation) up to 10^{16}/ cm^2**
- **New materials…**
  - **Ceramics for high brightness and potentially lower cost: LuAG(Ce), LuAG(Pr)**
  - **See talk by R-Y Zhu in this session for details.**



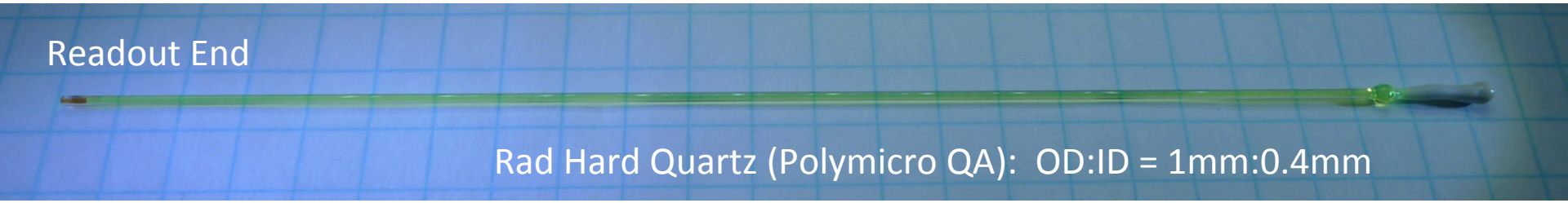
Capillary WLS Structures

- **Objectives:**
  - **1. Good WLS light yield at appropriate wavelengths for absorption and emission.**
  - **2. Uniform response as a function of distance over the length of the capillary where WLS is needed.**
  - **3. Good tolerance to radiation - both EM and hadrons.**

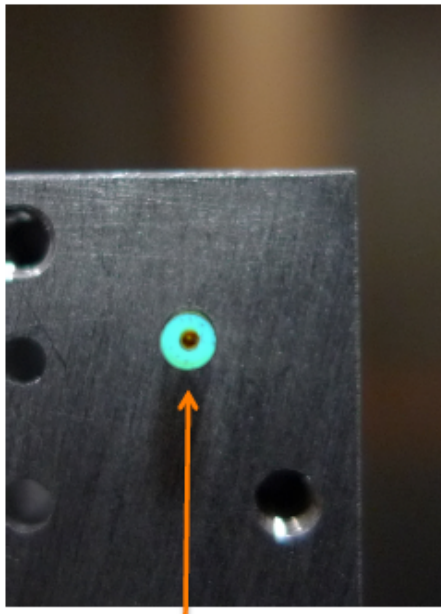
Schematic of light collection, WLS and light transfer



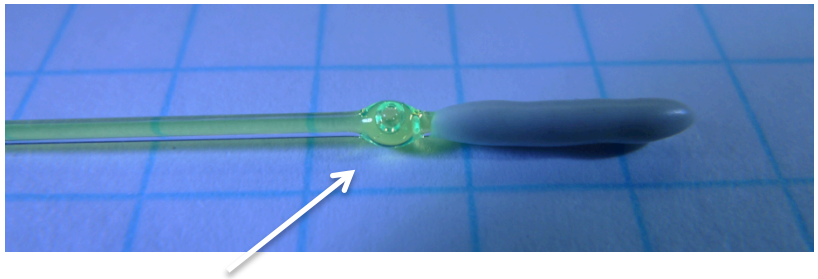
Basic Capillary Structure



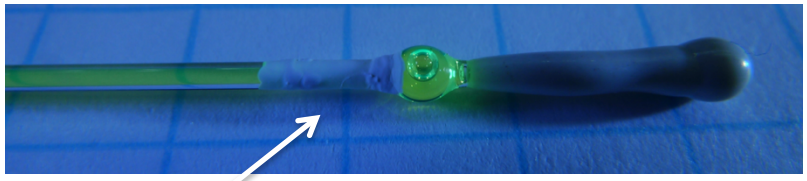
150 mm



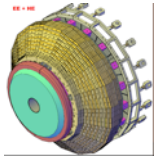
Core Blocking



Thermal Expansion Reservoir

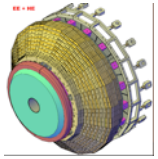


Diffusive Reflector (DR) Surface Coating just before the Reservoir

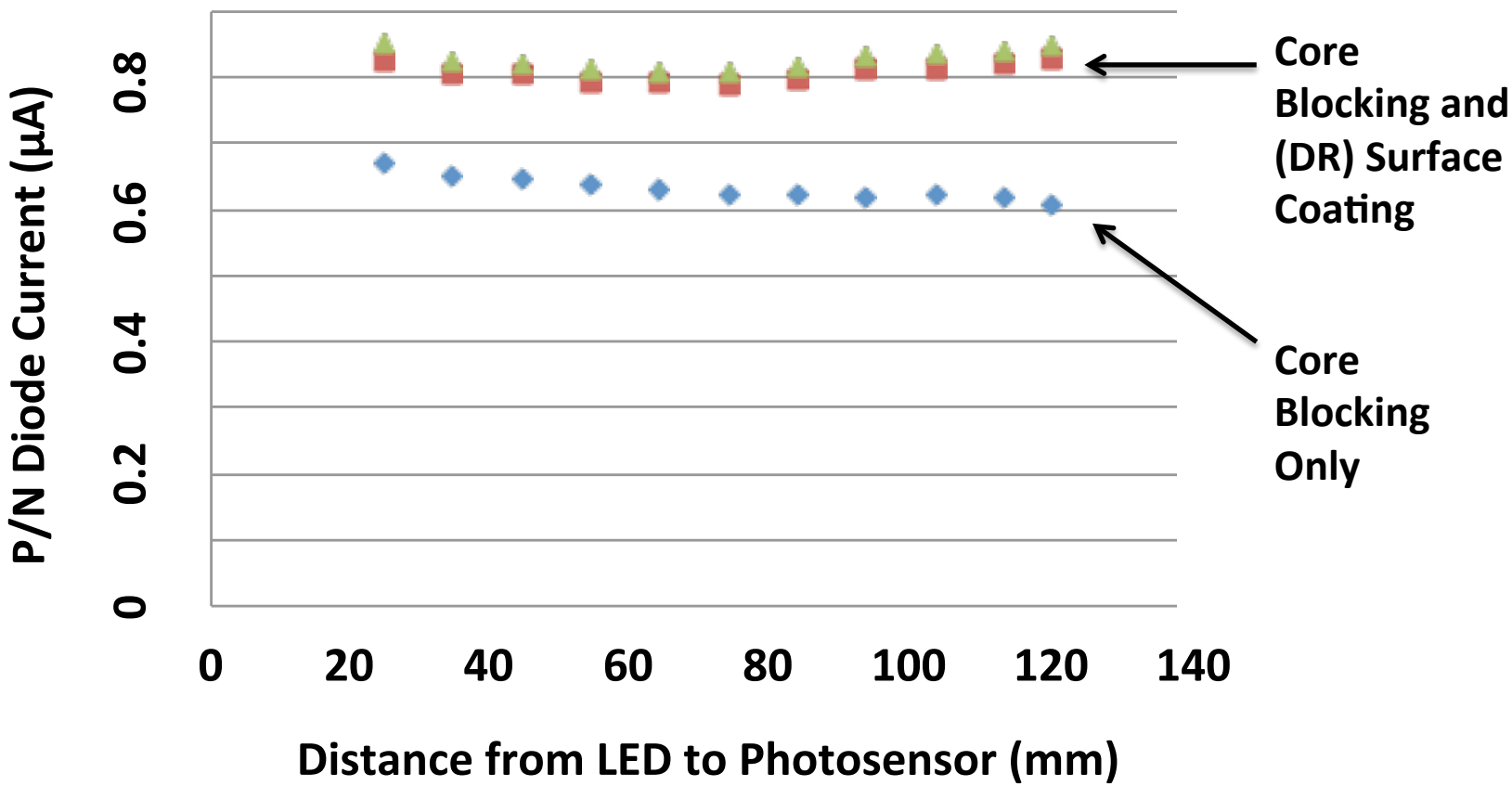


Waveshifters

- **Initial Studies have 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.**

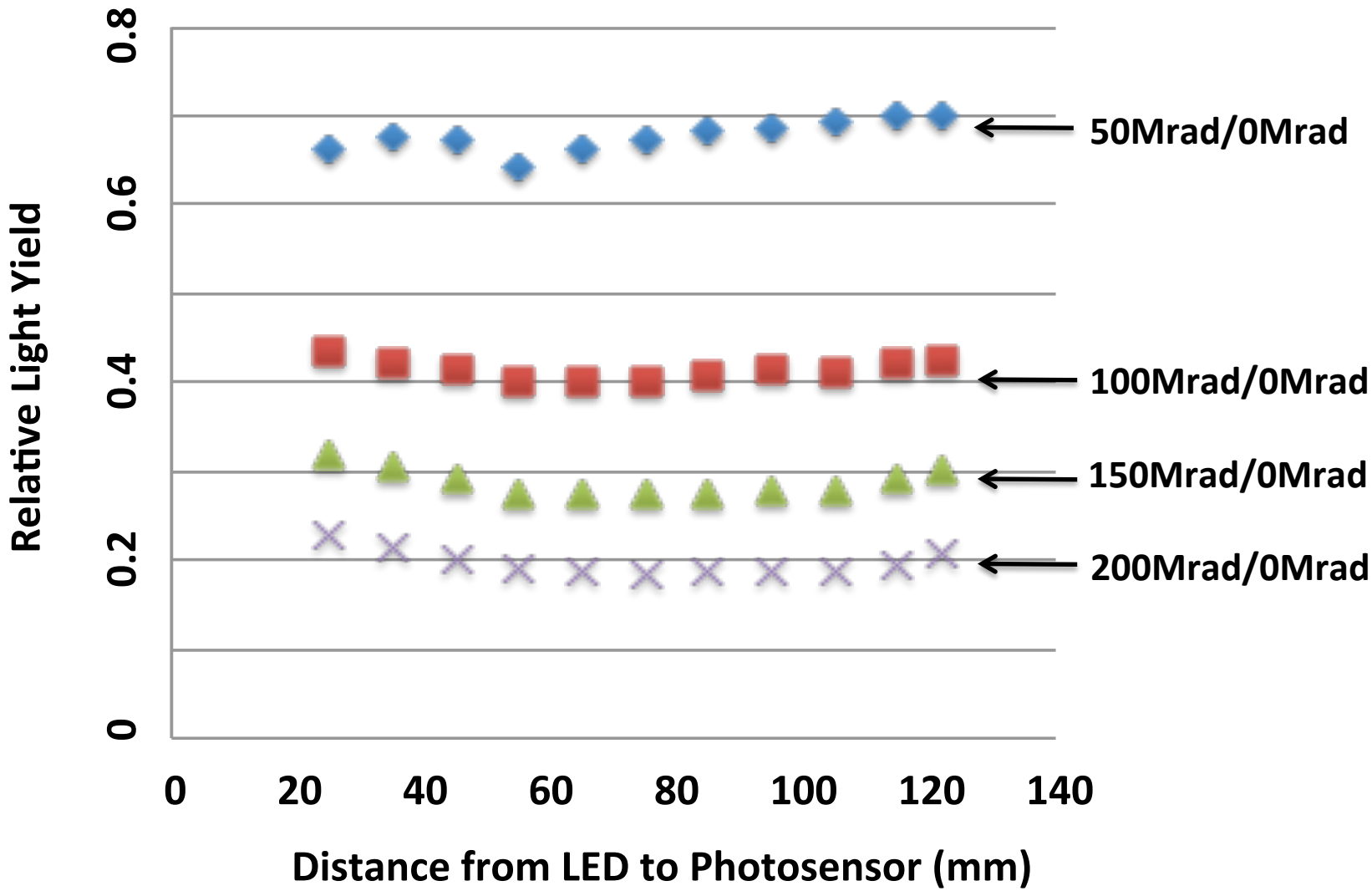


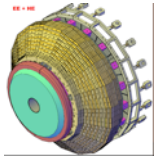
LED Measurements of a Capillary



Illumination of capillary through sidewall at 425nm. Measure light output of capillary as a function of distance from the readout end using a P/N diode and measuring the current from the diode. QuarkNet Students and Teachers involved in these studies.

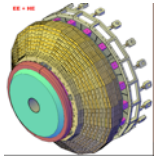
LED Measurements of an Irradiated Capillary





Capillary Structure R&D Effort

- Capillary Fabrication (at ND)
  - WLS Dyes and Dye Concentration Studies
    - DSB1, J2, DSB2, DSF1, Quantum Dots
  - Core blocking
    - Lengths and materials
    - Ruby or other Quartz; Wire stubs
  - Surface Diffusive Coatings
    - TiO_2
- Alternative Structures
  - Specialized Cross Section Capillaries or Optical Fibers
- Characterizations
  - Bench Tests
    - LED excitation (at ND)
  - Radiation Tests
    - Gammas (at ND and Caltech/JPL)
    - Hadrons (at UCDavis, LANL and PS)
  - Laser Tests
    - At CERN (Caltech)



Photosensor R&D

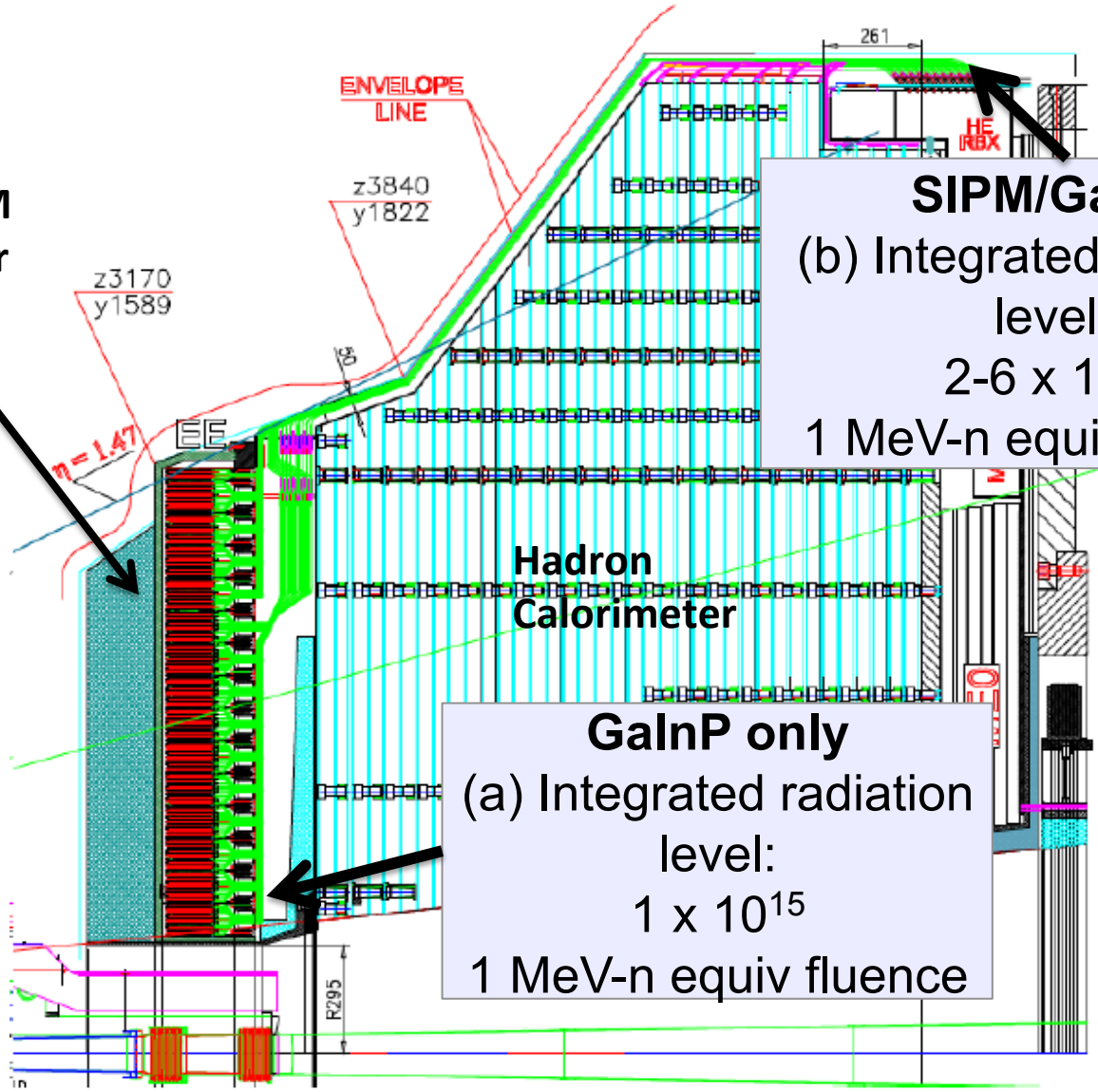
GaInP

- Proximate placement
- Pixels: 5um, 10um
- Large Band Gap affords potential advantages
- Can operate at ambient temperature
- Vendor: LightSpin, Inc

Small Pixel SiPM

- Nearby or remote placement
- Pixels: 5, 7.5, 10, 12um
- Experience with SiPM and multiple vendors
- Operate cooled (down to -30c)
- Vendors: FBK, Hamamatsu…

Radiation Environment for Photosensors

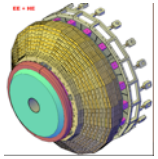


Shashlik EM Calorimeter

Hadron Calorimeter

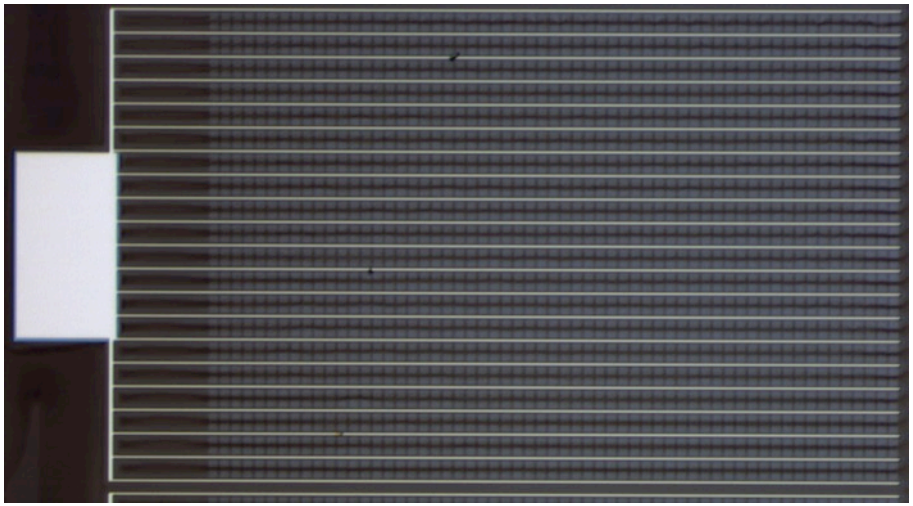
SIPM/GaInP
(b) Integrated radiation level:
2-6 x 10^{11}
1 MeV-n equiv fluence

GaInP only
(a) Integrated radiation level:
1 x 10^{15}
1 MeV-n equiv fluence

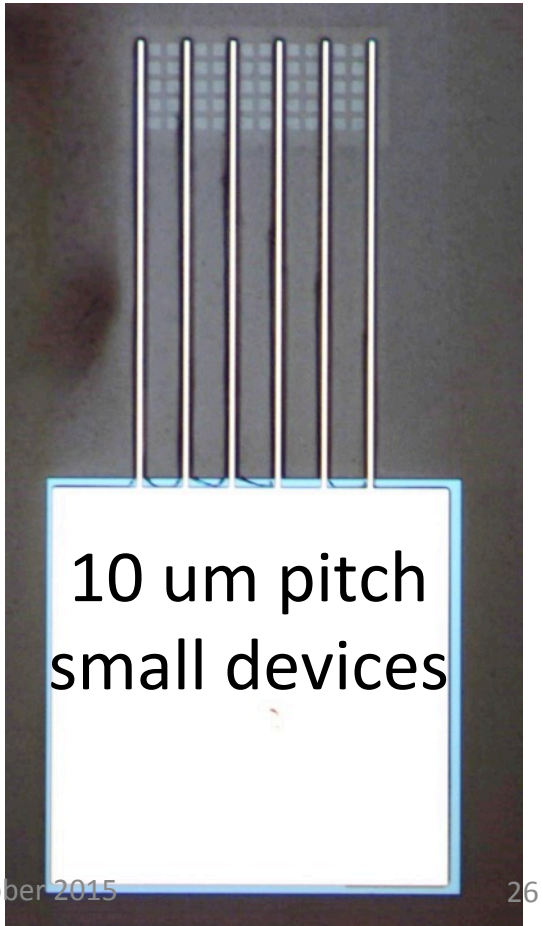


GaInP R&D

- **New round of prototypes just arrived at the end of September ("Generation 5")**
- **Next stage in evolution of device structures:**
  - **Tuning of layer structure**
  - **AlGaAs windows for impedance matching**
- **Alternate lithography patterns to study SPAD isolation/surface effects**

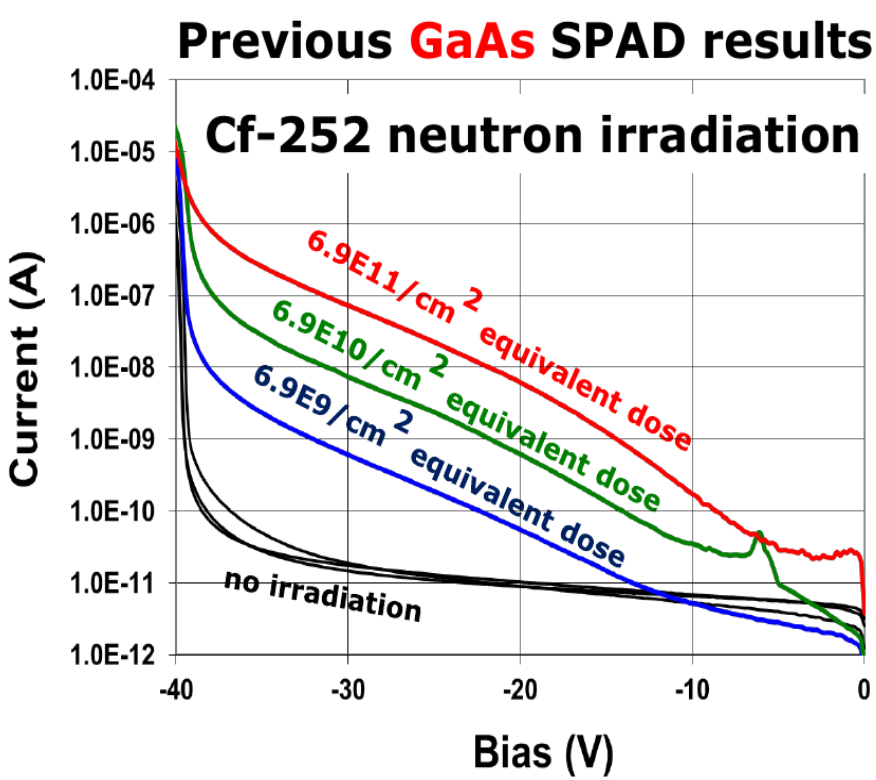


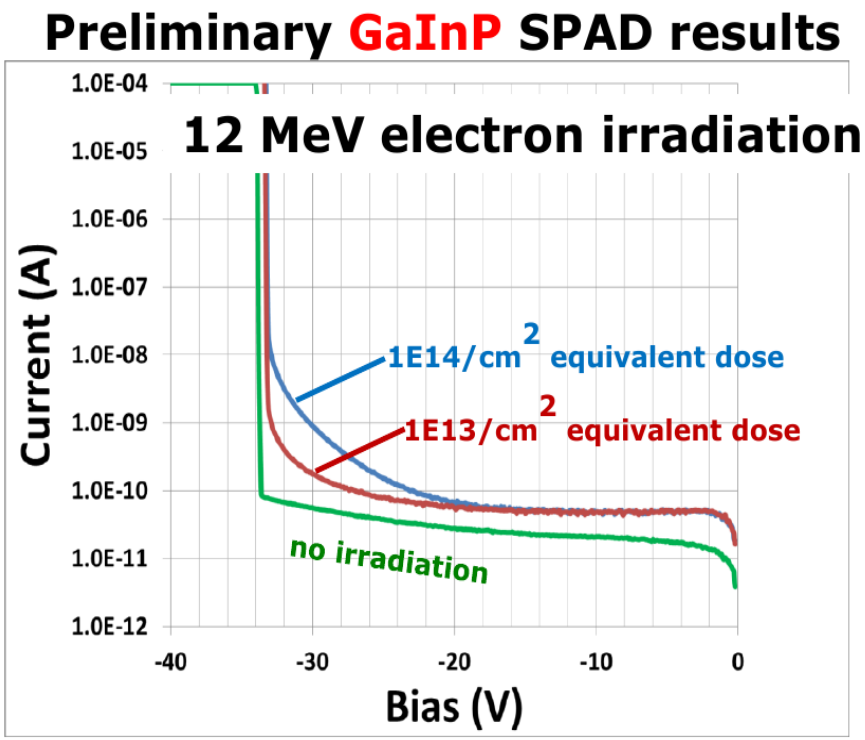
1000 x 1500 um^2 Devices



Radiation hardness from earlier studies on GaInP

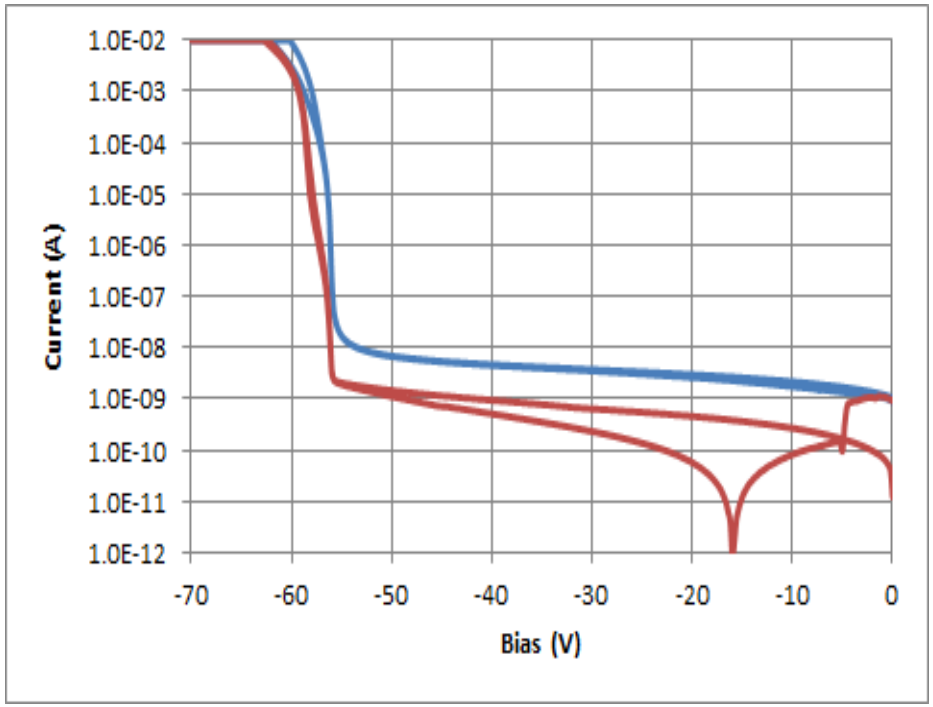
"Generation 3" first GaInP devices compared to GaAs

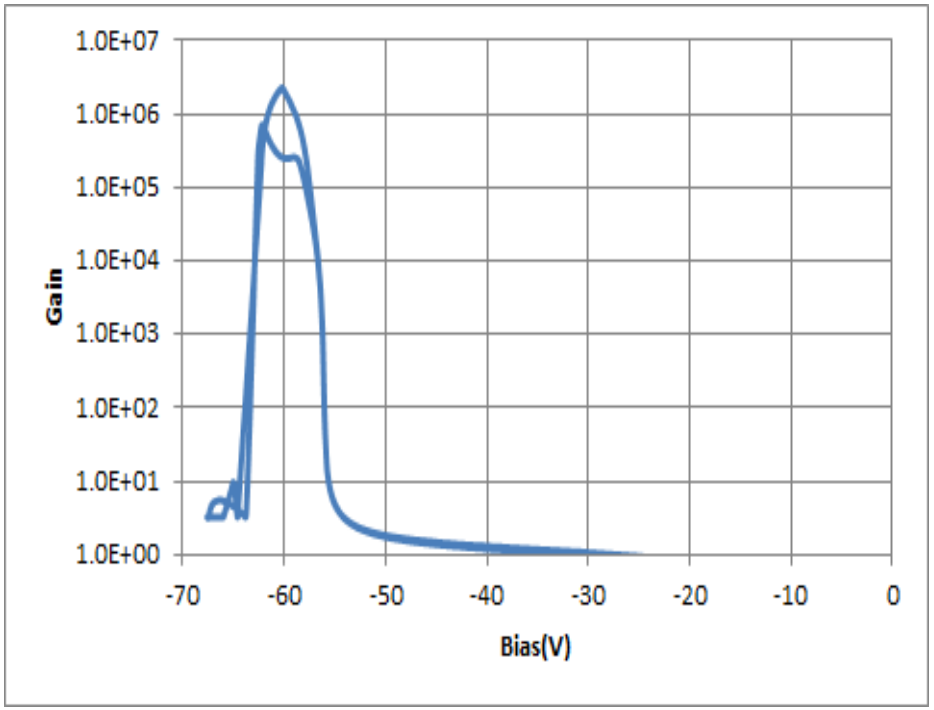




Generation 5 followed these with device structure further optimized for increased radiation tolerance…see next page…

First Look at Gen 5 GaInP Devices
1000 x 1500 um^2

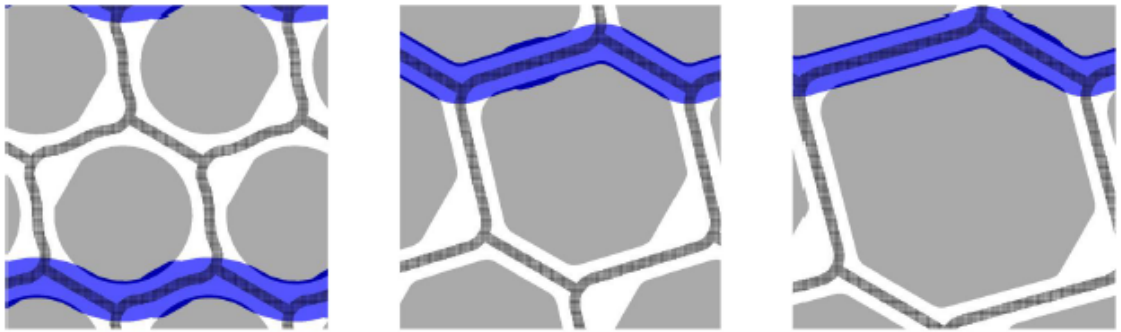




Small Pixel SiPM Development (FBK)

Cell size (um)	Equivalent square cell (um)	Cell density (cells/mm^2)	Fill Factor (L = 0.75 um)	Fill Factor (L = 1.25 um)
7.5	7	20530	57.1%	40.3%
10	9.3	11550	68.1%	54%
12.5	11.6	7400	74.5%	62.1%

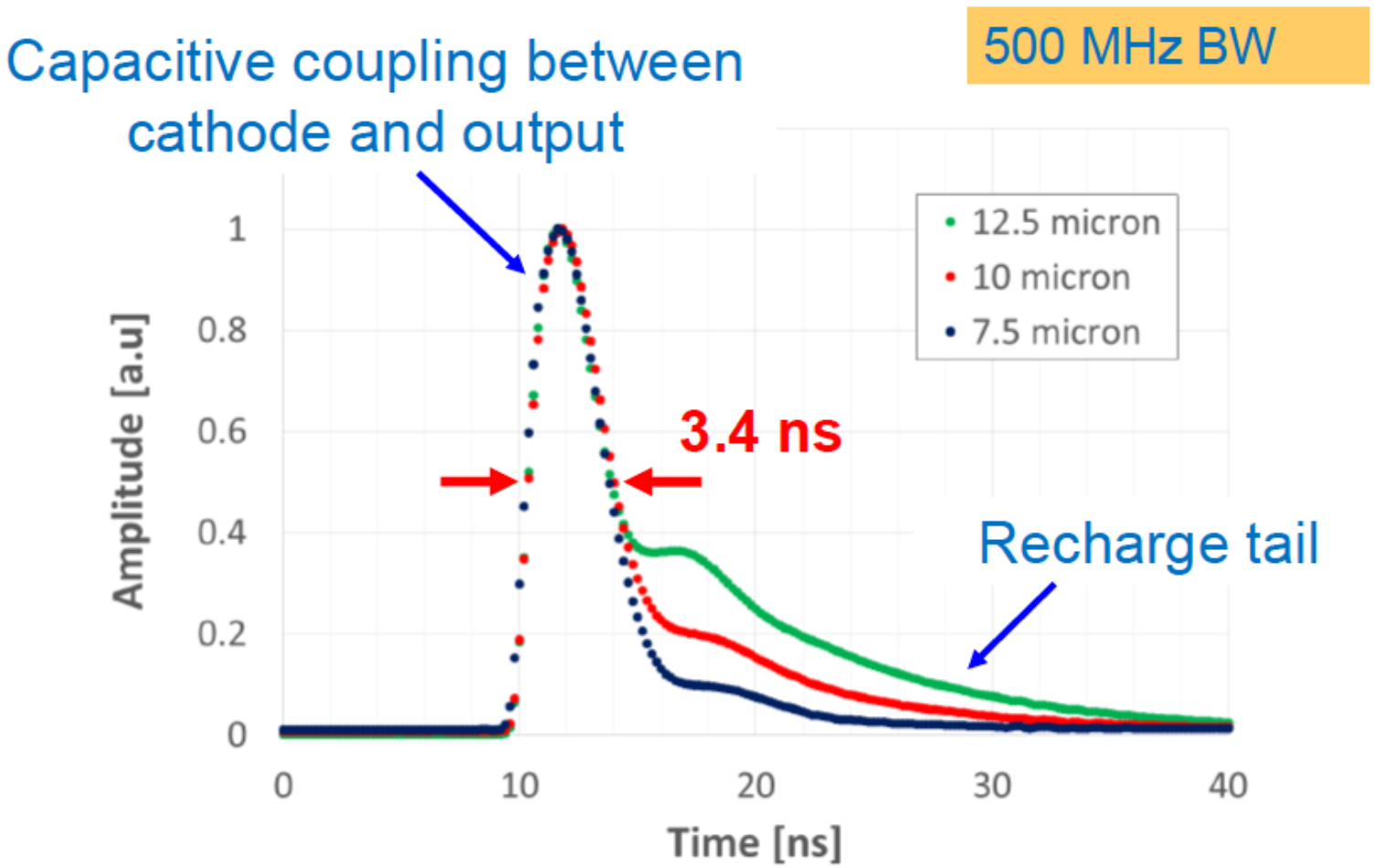
L = 0.75 um

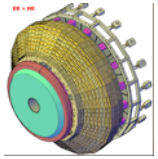


7.5 um 10 um 12.5 um

Layout of different microcells.

Small Pixel FBK SiPM Response to Laser Pulses





SiPM Radiation Damage Test

Irradiation to 1.3 x 10^{14} p/cm^2

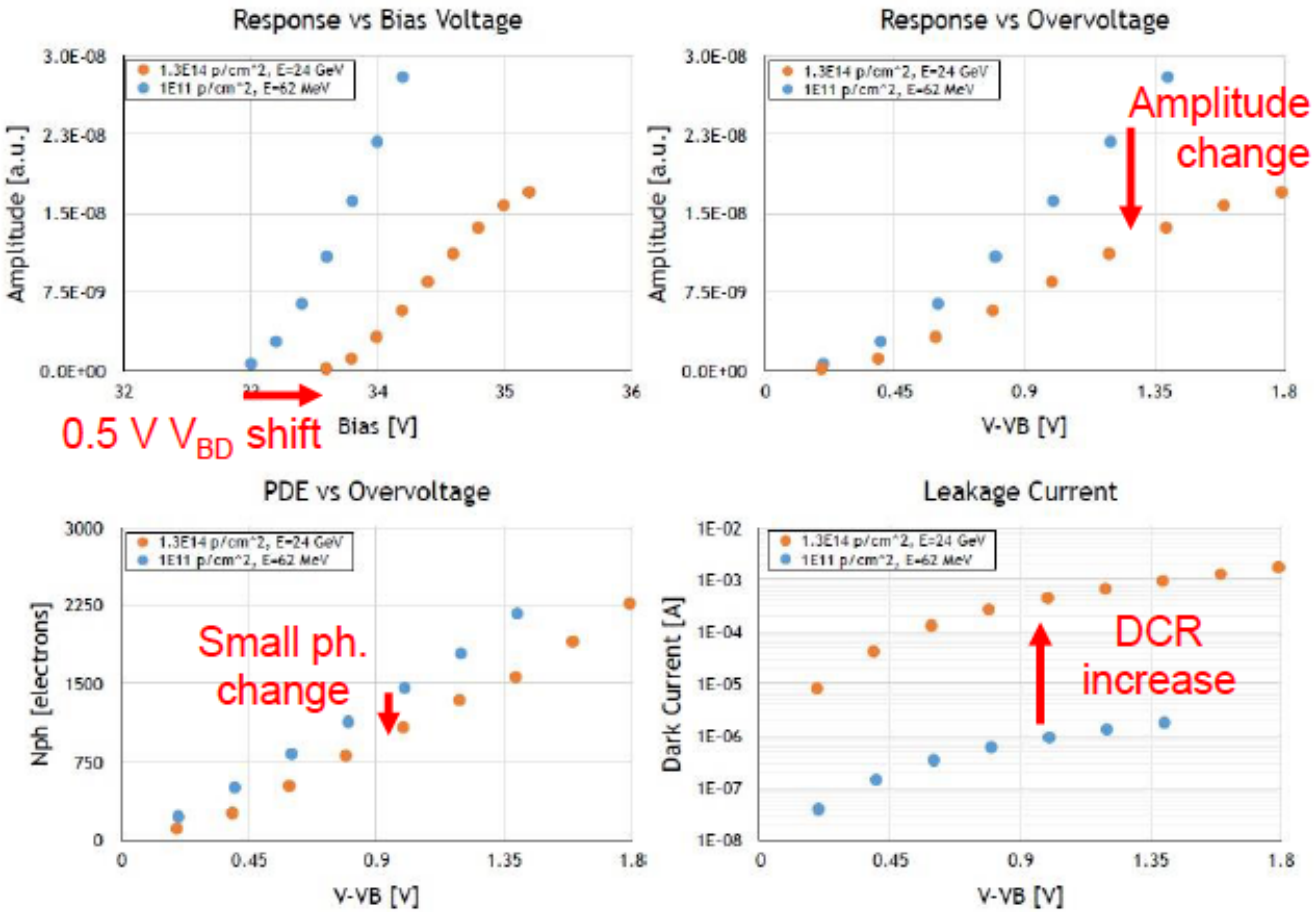
Temp = 23c

Small Bias Shift of 0.5V

Low PDE change

Dark Current 1mA/mm^2

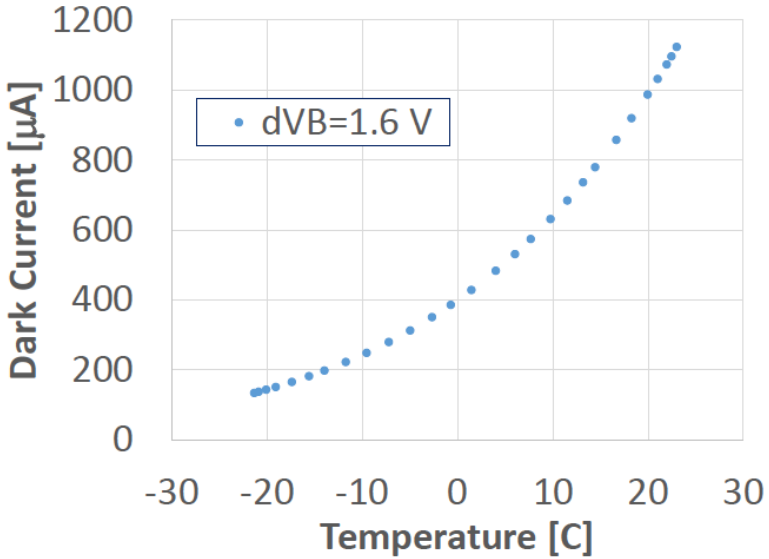
Gain reduction due to heating of the device



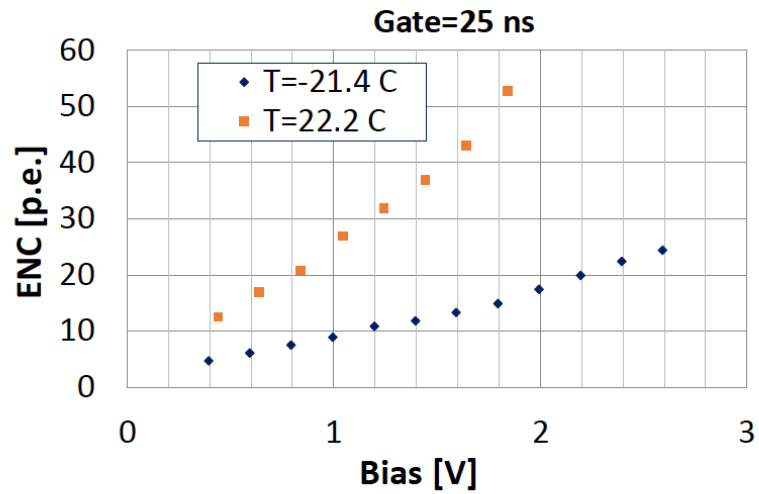
FBK 1mm^2 device with 12 micron pixels

Small Pixel SiPM – Performance vs Temp

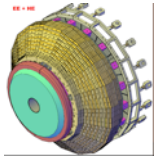
(FBK 1mm^2 device with 12um pixels irradiated to 1.3 x 10^{14} p/cm^2)



Noise (25 ns gate, RMS) vs. dVB (T=22.2 °C and T=-21.4 °C)

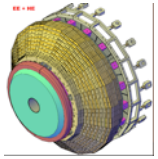


Noise is reduced by a factor of ~3. Optimal operation point: dVB~1.6 V. ENC(1.6 V)~12.5 p.e. RMS (25 ns gate width)



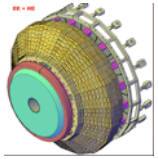
US Groups…

R&D PLANS



R&D Planning

- **Scintillators**
  - Crystal and Ceramic Scintillator development
- **WLS Capillaries and Waveguides**
  - Liquids and solids, Quantum Dots
  - Alternative optical structures
- **Photosensor Development**
  - GaInP Geiger Mode APD Structures
  - Small Pixel SiPM
- **To be tested elementally and in single modules and arrays**
  - Irradiation Testing at UC Davis (Oct 15), LANL (Dec 15), ND (ongoing)
  - Irradiation Testing at PS (Spring 16)
  - Beam Testing at CERN H4/H2 (Nov 15, Spring 16)



R&D Performance Studies…

Beam Tests – resolution, uniformity, timing

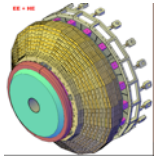
- CERN (H4/H2 as available)

Radiation Tests – up to the highest expected levels

- UC Davis (hadrons)
- LANL (hadrons)
- ND Radlab (gammas)
- Caltech/JPL (gammas)
- CERN PS (hadrons)

Simulations

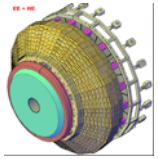
- Standalone GEANT4
- SLitrani for optical photon simulations
- CMSSW – CMS framework for event simulation and reconstruction



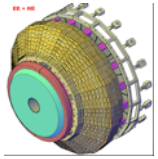
Summary

- **Shashlik technology can provide robust, efficient and high resolution EM Calorimetry under harsh conditions in Particle Physics Experiments.**

- **We are working to further develop, refine and optimize this important technology for applications in future HEP experimentation.**



EXTRAS

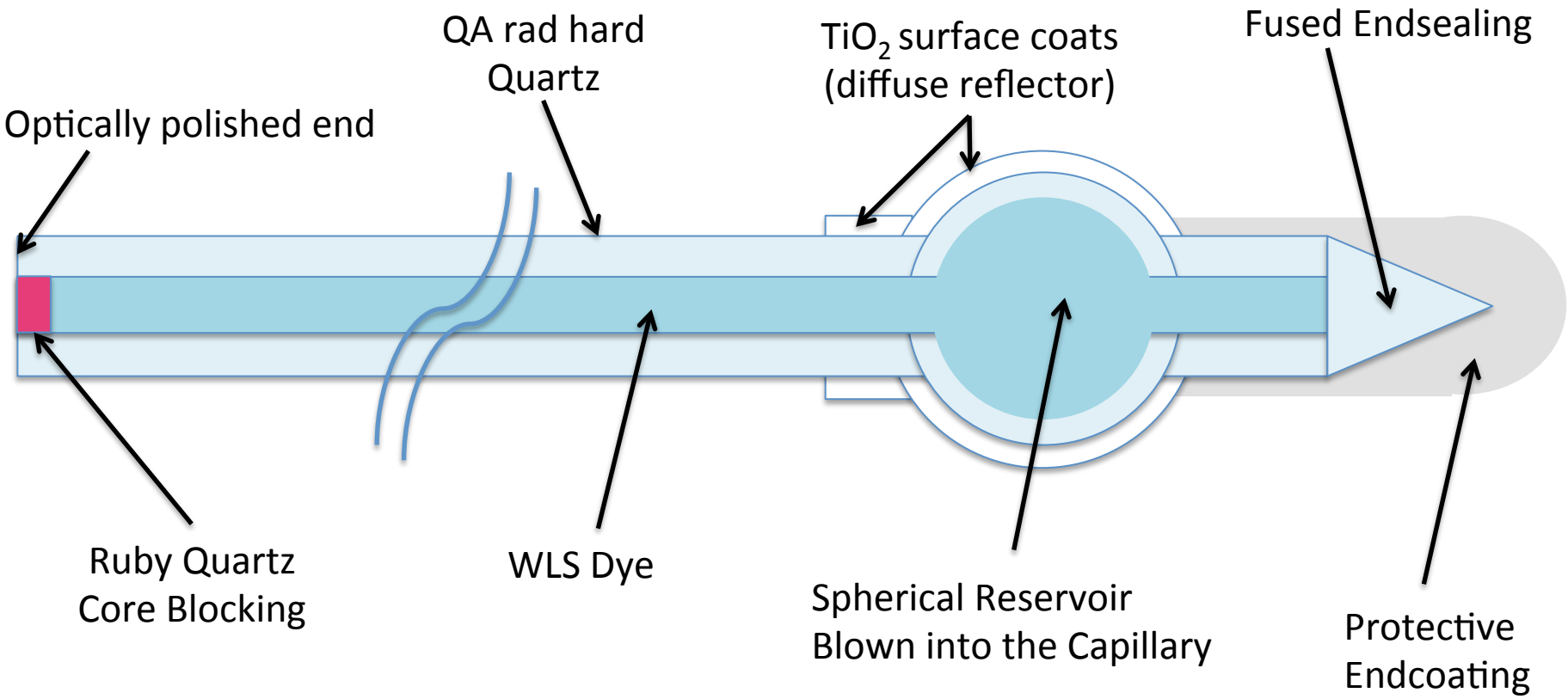


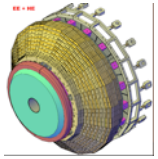
Comparison of W/LYSO Shashlik Modules with $PbWO_4$ crystals currently used in the CMS Endcap (EE) Calorimeter

	W/LYSO(Ce)	$PbWO_4$
Length (mm)	114	220
Transverse size (mm)	14	28.6
Average Molière Radius (mm)	13.7	21
Average Radiation Length X_o(mm)	5.1	8.9
Crystal Light Yield (relative to NaI = 100)	85	0.3
Emission Wavelength	420	425
Decay time (ns)	40	25
Light Output (p.e./MeV)	6-8	2
Temp Dependence (%/C)	-0.2	-2.2

"Thick Wall" Capillary Structure

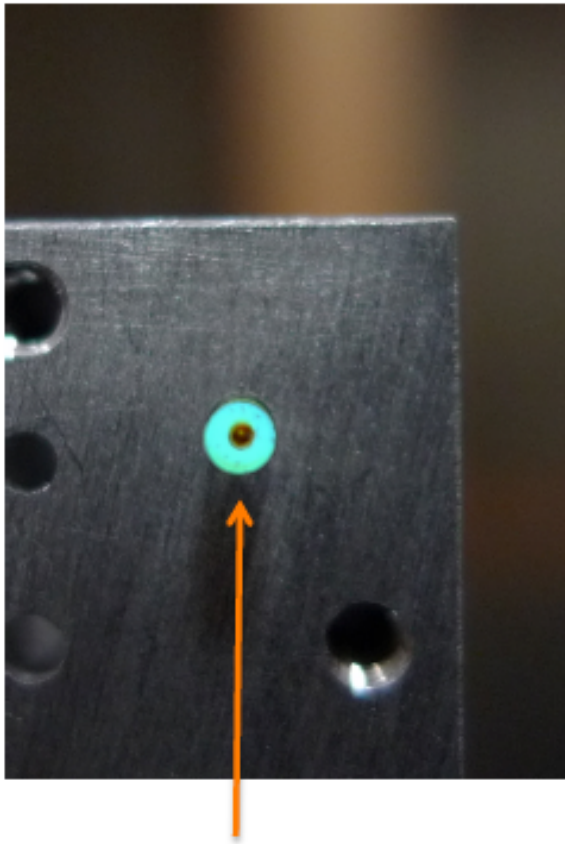
(schematic of current form. OD:ID = 1mm:0.4mm)

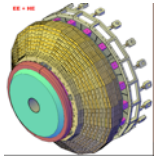




Core Blocking

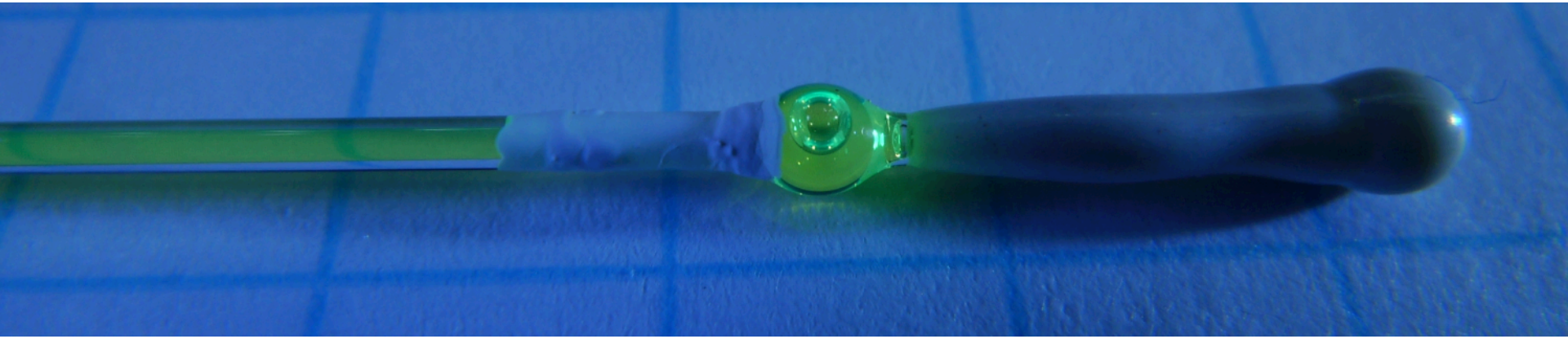
- A light absorbing material is inserted and thermally fused into the core of the capillary at the readout end
  - Ruby Quartz is an example
  - Could be a metallic wire or other material
- This fused end is ground to an optical finish.
- The length of the Ruby Quartz is typically ~3-4 mm, but this length is under study and optimization.

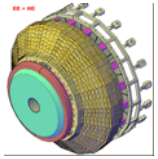




Diffusive Reflector Surface Coating

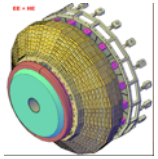
- Traditional end mirroring is not possible with a capillary of the current structure with a reservoir at the upstream (non-readout) end.
- Instead we have used TiO_2 painted on the external surface of the capillary just downstream of the reservoir (typically a band of 4mm length) and also applying the 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).



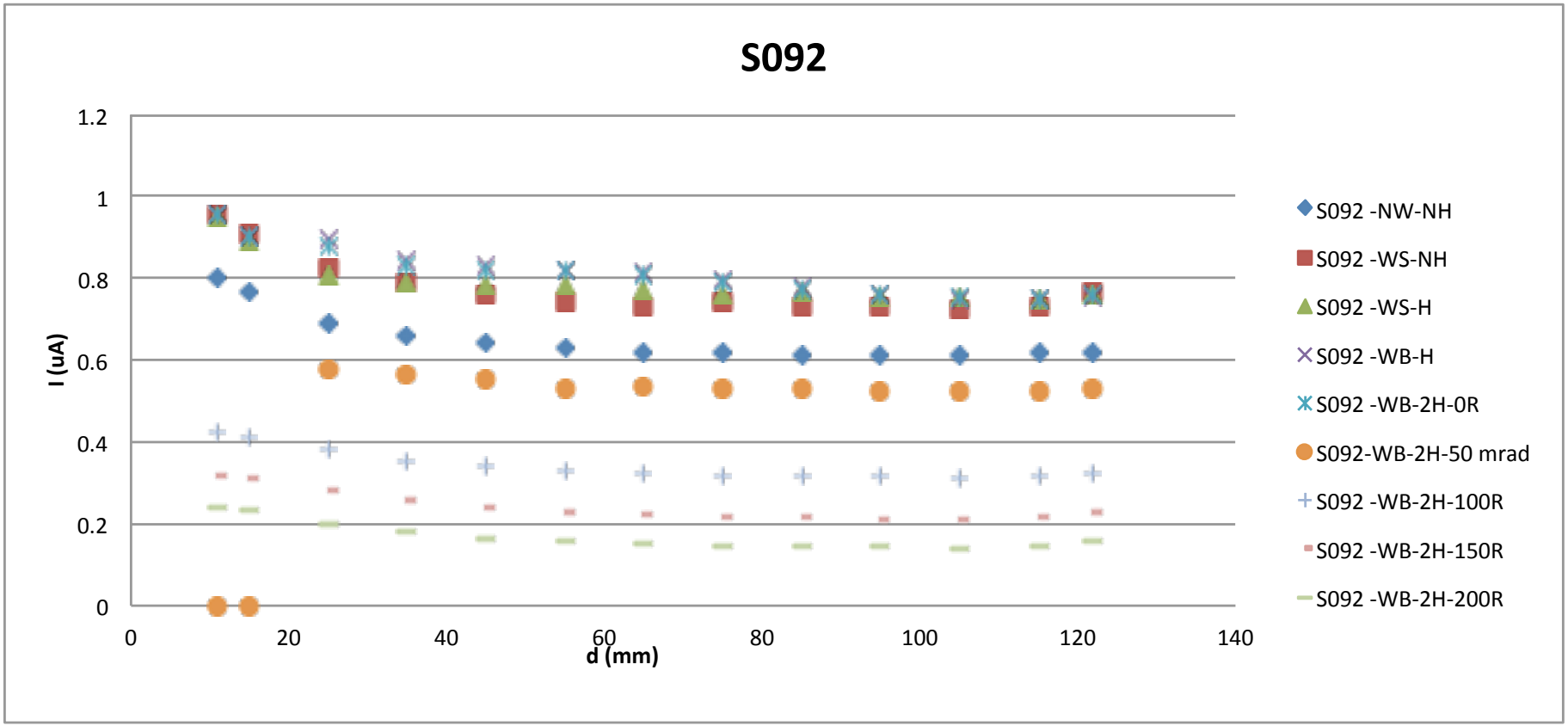


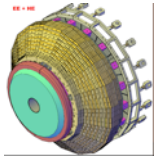
Irradiation Studies with ^{60}Co

- Capillaries were exposed to increasing levels of gamma irradiation in 50 Mrad shots on successive weekends.
- Data was then recorded with LED direct excitation and LED excited LYSO illumination.
- Several dye concentrations have been studied.



LED Direct Measurement
S092 (1/2x)





Observations

- 1/2x DSB1 concentration is current focus since best results (but further study needed)
- TiO_2 diffusive coatings improve light collection overall and help level the upstream end.
- Irradiation effects with gammas:
  - seems to be consistent with the darkening of the Ruby Quartz with gamma dose.
  - The attenuation in the liquid WLS is relatively secondary by comparison but visible.
  - TiO_2 survives up to 200Mrad (highest level tested).