Report from the Calorimetry Group

October 7, 2015

B. Bilki, E. Ramberg, R. Rusack

CPAD Instrumentation Frontier Meeting
October 5-7, 2015
University of Texas at Arlington

Introduction

- **Task is to identify the challenges and key elements in possible solutions for the High Energy Physics experiments in the next few decades.**

Parallel Session: Calorimetry - Palo Pinto (10:30-18:30)

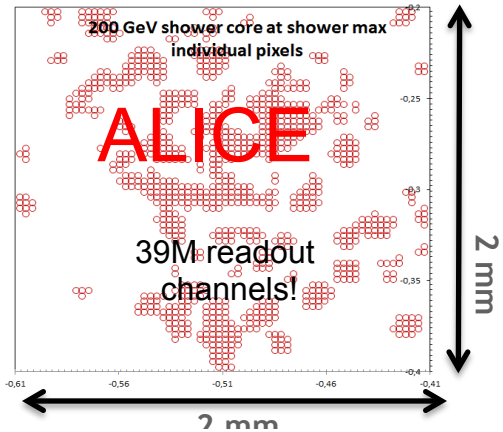
- Conveners: Bilki, Burak (University of Iowa / Argonne National Laboratory); Ramberg, Erik (Fermilab)

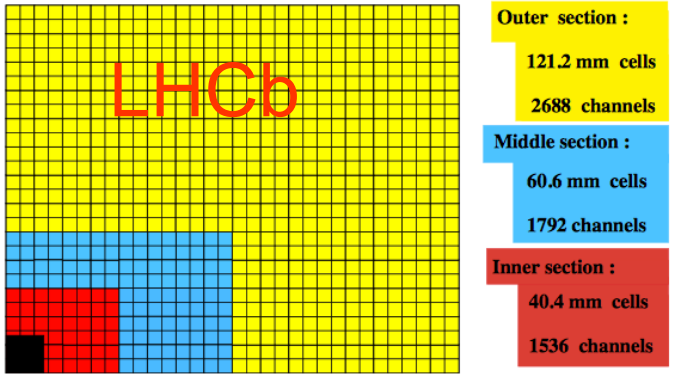
time	title	presenter
10:30	Progress in imaging calorimetry/CALICE results/Event reconstruction	Dr. REPOND, Jose (Argonne National Laboratory)
11:10	The challenges of CMS calorimetry	RUSACK, Roger (University of Minnesota)
11:50	Precision timing in calorimetry	SPIROPULU, Maria (Caltech)
12:30	Lunch	
13:30	Recent advances in crystal calorimetry	MURAT, Pavel (Fermilab) ZHU, Ren-Yuan (Caltech)
14:20	Homogenous calorimetry	PARA, Adam (Fermilab) ZHU, Ren-Yuan (Caltech)
14:50	New radiation-hard materials	FREEMAN, Jim (Fermilab) ONEL, Yasar (University of Iowa)
15:30	Coffee Break	
16:00	Radiation-hard light-based electromagnetic calorimetry	Prof. RUCHTI, Randy (University of Notre Dame)
16:30	Noble liquid element calorimetry (MEG)	Dr. SAWADA, Ryu (ICEPP, the University of Tokyo)
17:10	Secondary Emission calorimetry	BILKI, Burak (University of Iowa / Argonne National Laboratory) XIE, Si (Caltech)
17:50	Large-scale calorimetry for astrophysics	WIENCKE, Lawrence (Colorado School of Mines)

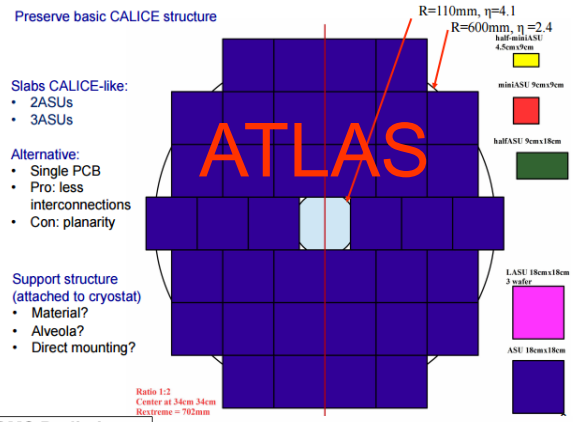
12 talks on
10 topics!

Findings – Imaging Calorimetry

- CALICE demonstrates and leads the clear trend from conventional calorimetry to imaging calorimetry.
- All LHC experiments have adopted or are considering adopting imaging technologies for their calorimeter upgrades.

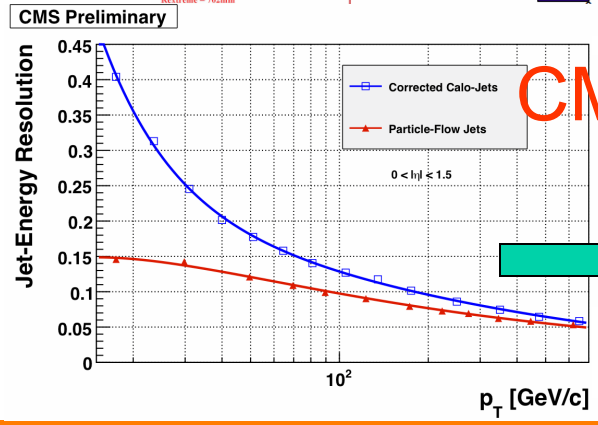


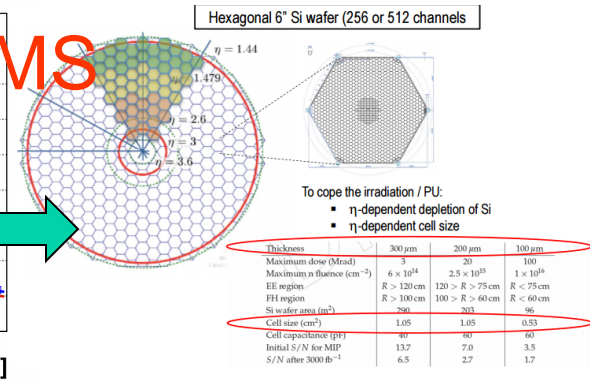




J. Repond for the CALICE Collaboration

Rigorous tests of hadronic interaction models.





Thickness	300 μm	200 μm	100 μm
Maximum dose (Mrad)	3	20	100
Maximum n fluence (cm^{-2})	6×10^{14}	2.5×10^{15}	1×10^{16}
EE region	$R > 120$ cm	$120 > R > 75$ cm	$R < 75$ cm
FH region	$R > 100$ cm	$100 > R > 60$ cm	$R < 60$ cm
Si wafer area (m^2)	290	203	96
Cell size (cm^2)	1.05	1.05	0.53
Cell capacitance (pF)	40	60	60
Initial S/N for MIP	13.7	7.0	3.5
S/N after 3000 fb^{-1}	6.5	2.7	1.7

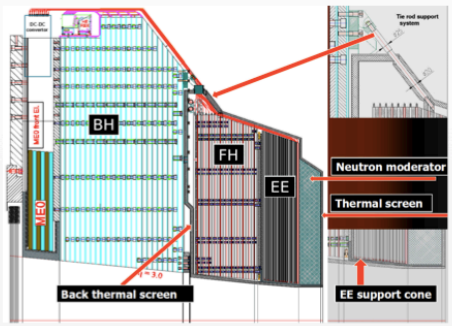
Findings – Challenges of CMS Calorimetry

R. Rusack for the CMS Collaboration

Radiation damage and high pile-up.

- Upgrade readout of barrel electromagnetic calorimeter.
- Refurbish the scintillator of front part of the barrel hadron calorimeter
- Replace endcap calorimeters with a new silicon based high granularity sampling calorimeter. First implementation of imaging calorimetry in a hadron collider experiment!
- Keep the quartz fiber forward calorimeter at the highest η region.

Key Parameters of Endcap Calorimeter



Construction:

- *Hexagonal Si-sensors built into modules.*
- *Modules with a W/Cu backing plate and PCB readout board.*
- *Modules mounted on copper cooling plates to make wedge-shaped cassettes.*
- *Cassettes inserted into absorber structures at integration site (CERN)*

Key parameters:

- *593 m² of silicon*
- *Pixel size 1 cm and 0.5 cm².*
- *21,660 modules*
- *92,000 front-end ASICS.*
- *Power at end of life 115 kW.*

System Divided into three separate parts:

EE – Silicon with tungsten absorber – 28 sampling layers – 25 X_0 + ~1.3 λ

FH – Silicon with brass absorber – 12 sampling layers – 3.5 λ

BH – Scintillator with brass absorber – 11 layers – 5.5 λ

EE and FH are maintained at – 30°C. BH is at room temperature.

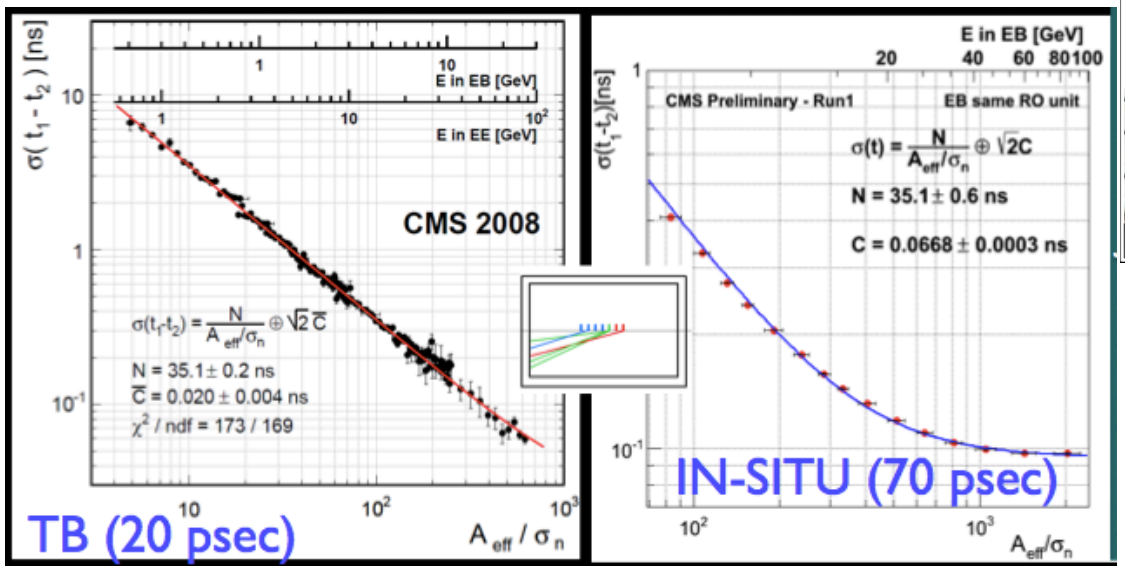
The Detector Challenges

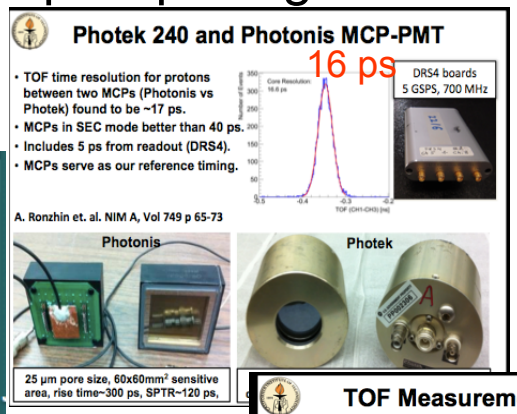
- ***Detector materials.***
  - Silicon & Scintillator.
- ***Radiation hard electronics.***
  - Low power large number of channels.
- ***Module Engineering***
  - Need automated assembly
- ***Low power rad-hard front-end preamp.***
  - Data flow on and off detector.
- ***Precision timing:***
  - Registration.
  - Clock distribution at the system level.
- ***Data Extraction***
  - 6 million channels at 40 MHz 12-bits/channel.
- ***Power distribution.***
  - DC-DC converters.
- ***System cooling.***
  - Operation at -30°C due to irradiation of the silicon.
- ***Event reconstruction and selection.***
  - Real time pattern recognition at level 1 and in HLT.

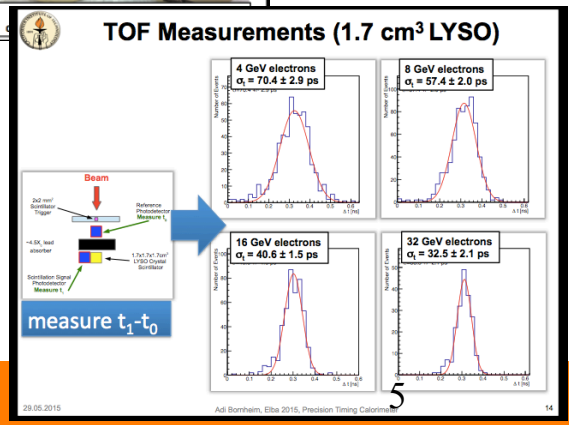
Findings – Precision Timing in Calorimetry

M. Spiropulu

- Test beam results are always better than in-situ measurements.
- Major limitations: clock distribution, slow pulse shaping and poor exploitation of raw signal.
- Fast timing expertise and equipment exist to implement timing for HL-LHC.
- Need to push forward for better precision for pileup mitigation in future hadron colliders e.g. FCC-hh.



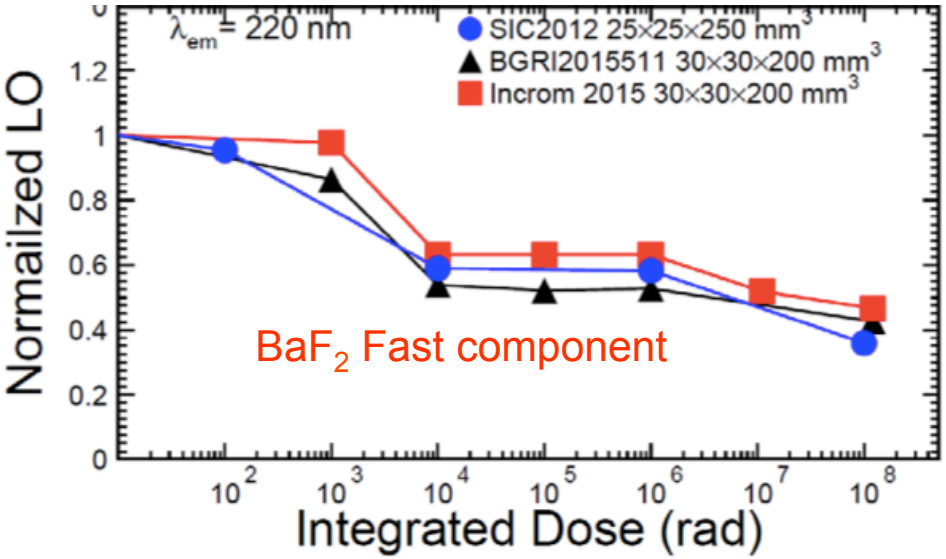


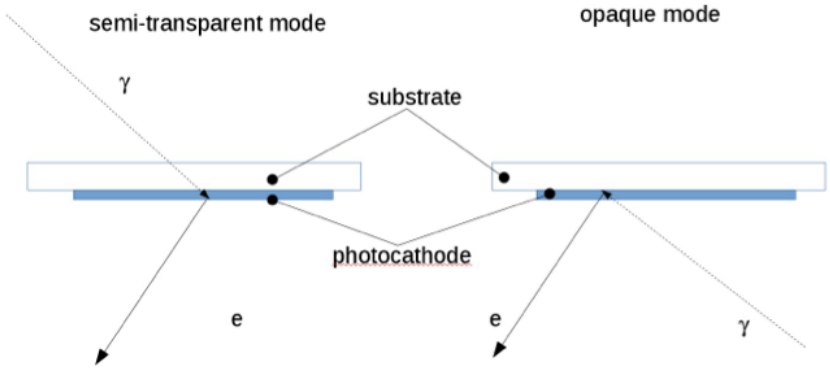


Findings – Advances in Crystal Calorimetry

- Several future crystal calorimeter implementations: LYSO for COMET (Mu2e, Super B and CMS at HL-LHC) BaF_2 and PbF_2 for Mu2e and g-2 respectively at Fermilab PbF_2, PbFCl, BSO and BGO for Homogeneous HCAL for LC.
- Extensive radiation damage studies were performed.
- Various crystals, inorganic scintillators, glasses and ceramics may offer solutions for future HEP experiments.

P. Murat
R.Y. Zhu





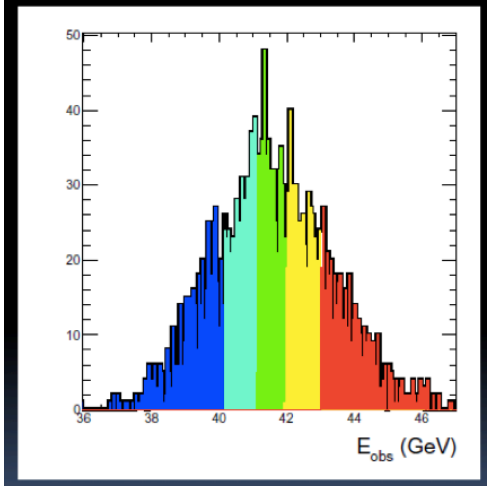
Deposit GaN photocathodes directly on the MCPs!

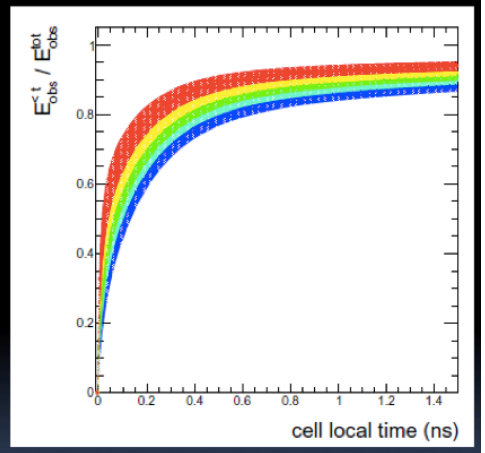
Findings – Homogenous Calorimetry

- The concept of "Dual-Gate Calorimetry" is introduced.
- Hadron calorimetry with high resolution and linear response is possible with this technique.
- Fast, dense, inorganic scintillators need to be explored.

A. Para
R.Y. Zhu

Correlation of the Time Evolution and Total Observed Energy (50 GeV pion)





Late energy depositions are related to neutron component: Use dual time gate to make the energy correction.

About 80% (on average) of the energy of hadronic showers is deposited within 0.5 nses)

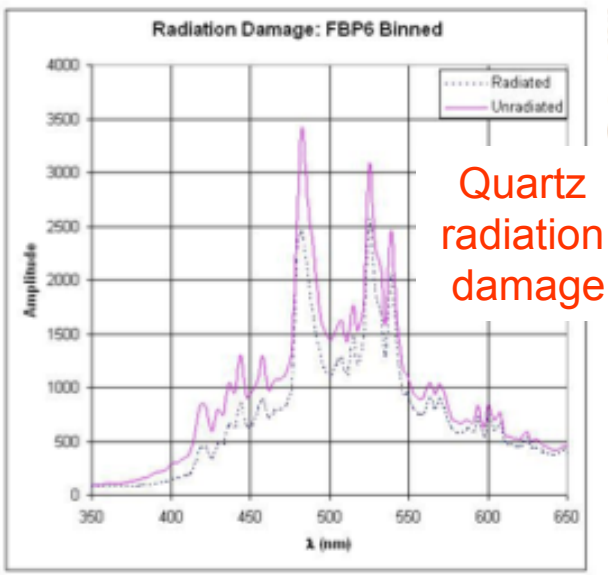
Short gate of 1 ns optimizes both the stochastic and the constant term.

Candidate crystals for Homogenous calorimetry

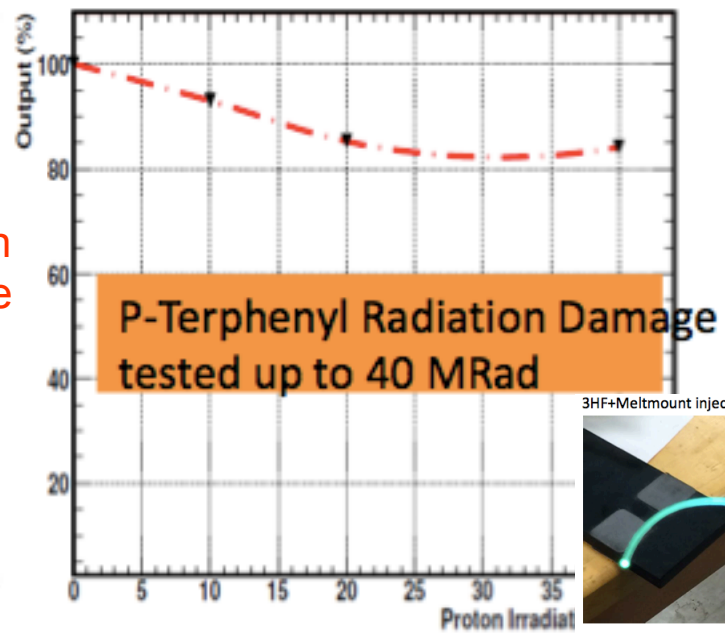
Parameters	$Bi_4Ge_3O_{12}$ (BGO)	$PbWO_4$ (PWO)	PbF_2	PbClF	$Bi_4Si_3O_{12}$ (BSO)
ρ (g/cm³)	7.13	8.29	7.77	7.11	6.8
λ_I (cm)	22.8	20.7	21.0	24.3	23.1
n @ λ_{max}	2.15	2.20	1.82	2.15	2.06
τ_{decay} (ns)	300	30/10	?	30	100
λ_{max} (nm)	480	425/420	?	420	470
Cut-off λ (nm)	310	350	250	280	300
Light Output (%)	100	1.4/0.37	?	17	20
Melting point (°C)	1050	1123	842	608	1030
Raw Material Cost (%)	100	49	29	29	47

Findings – New Radiation-Hard Materials

- Limited options for intrinsically radiation-hard scintillators. Y. Onel
- Coating radiation-hard Cerenkov radiators (e.g. quartz) with inorganic scintillators enable various options.
- Radiation-hard wavelength shifters need further (immediate) attention.

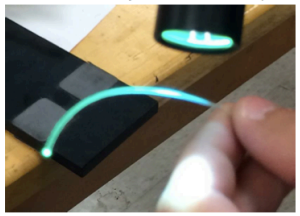


Quartz radiation damage

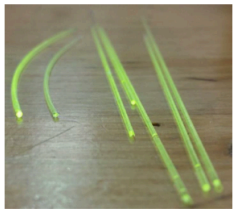


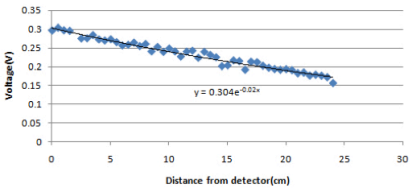
P-Terphenyl Radiation Damage tested up to 40 MRad

3HF+Meltmount injected TeflonAF 800μm ID



CdSeZnO nanodots in Sylgard 184
Injected into Capillaries Teflon; AFQuartz





Attenuation length: 3HF in polyurethane in Quartz Capillary: L= 50 cm 1/e.

CdSeZnO Nanodots in Sylgard 184 for hot injection into Capillaries

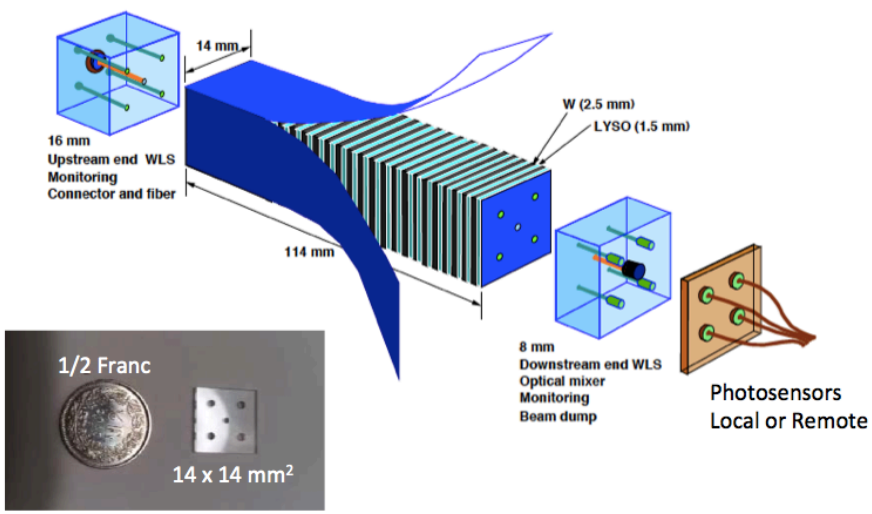
20 Mrad of neutron
75 Mrad of gamma
At ANL

Findings – Radiation-Hard, Light-Based Electromagnetic Calorimetry

- Shashlik technology was demonstrated to provide robust, efficient and high-resolution electromagnetic calorimetry under radiation-harsh conditions.

R. Ruchti

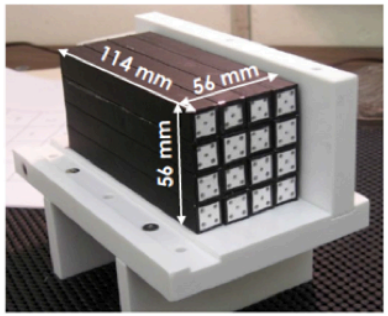
- Compact design with rad-hard crystals, wavelength shifting capillaries and photosensors.

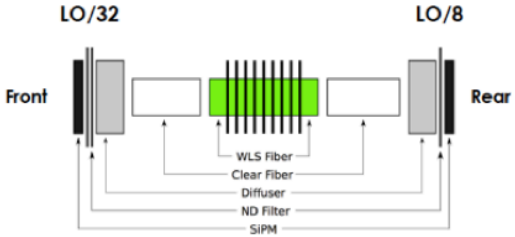


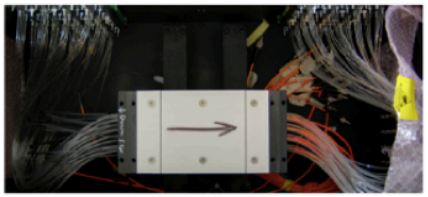
A Shashlik 4x4 Test Array

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**



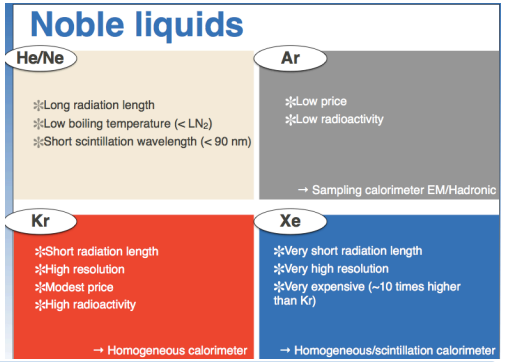


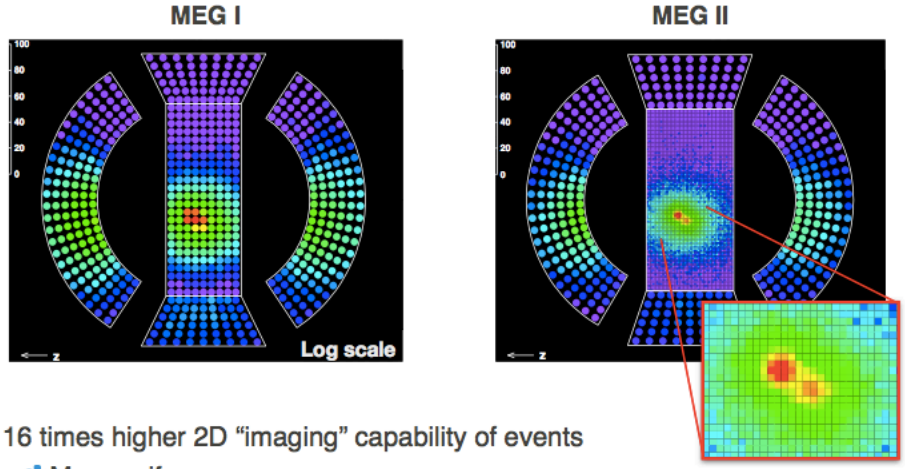


Findings – Noble Liquid Element Calorimetry

- Major impact points are the newly developed VUV-sensitive SiPMs and simultaneous utilization of scintillation and ionization signals in the noble liquids (segmented TPC).

R. Sawada



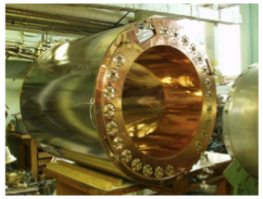


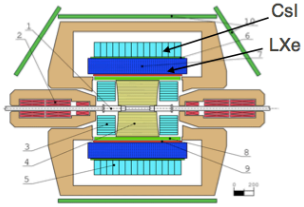
16 times higher 2D "imaging" capability of events
- More uniform energy respose
- Better position resolution with using the shower-shape information
- Pileup identification

Experiment	Type	Material	Signal	Resolution (%)
D0	Sampling	LAr	Ionization	$16/\sqrt{E} \oplus 0.3 \oplus 0.3/E$
H1	Sampling	LAr	Ionization	$12/\sqrt{E} \oplus 1$
ATLAS	Sampling	LAr	Ionization	$10/\sqrt{E} \oplus 0.4 \oplus 0.3/E$
NA48/62	Homogeneous	LKr	Ionization	$3.2/\sqrt{E} \oplus 0.42 \oplus 0.09/E$
KEDR	Homogeneous	LKr	Ionization	3 @ 1.8 GeV
CMD-3	Homogeneous	LXe	Ionization	$1.78/\sqrt{E} \oplus 1.86$ combined resolution with CsI
MEG	Homogeneous	LXe	Scintillation	1.7 @ 50 MeV

CMD-3 LXe calorimeter

VEPP-2000 e^+e^- collider in Novosibirsk





- Combined calorimeter, LXe + CsI
  - 400 l LXe : 5.4 χ_0
  - LXe+CsI : 13.5 χ_0
- Successful operation since 2009
- another 5 — 10 years operation expected.
- Upgrade study of the readout electronics aiming at 1 ns time resolution is ongoing.

Findings – Secondary Emission Calorimetry

- Intrinsically radiation-hard and fast electromagnetic calorimetry option for harsh radiation conditions.
- Unique capabilities of precision shower timing and position measurements.
- Feasible for large-scale applications and fine readout segmentation hence imaging calorimetry.

B. Bilki
S. Xie

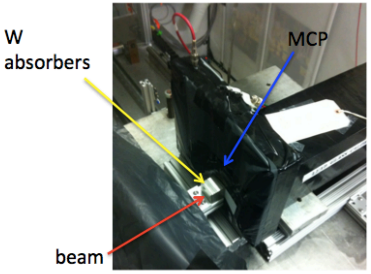
Secondary Emission (SE) Calorimetry with MCPs

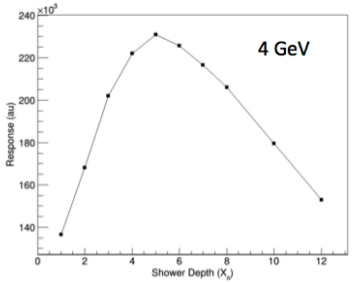
Tested the LAPPD with up to 12 3 cm x 3 cm x 0.35 cm W plates

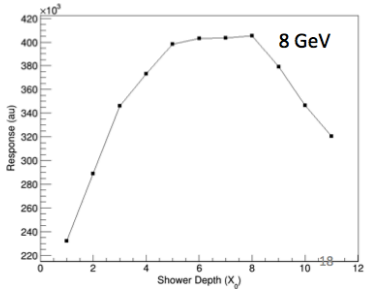
4 GeV and 8 GeV secondary beams were used triggering with positrons (i.e. with the Čerenkov counter signal in the trigger decision)

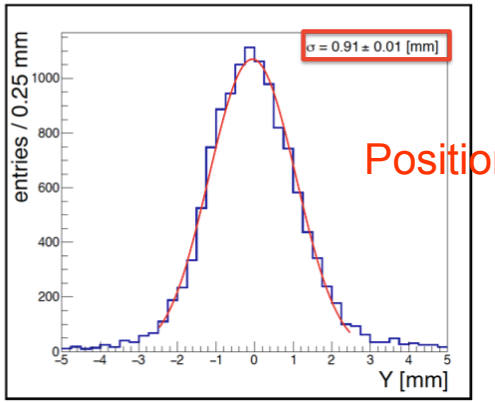
Two strips were read out at one end (smaller than the shower size)

Results quite encouraging!

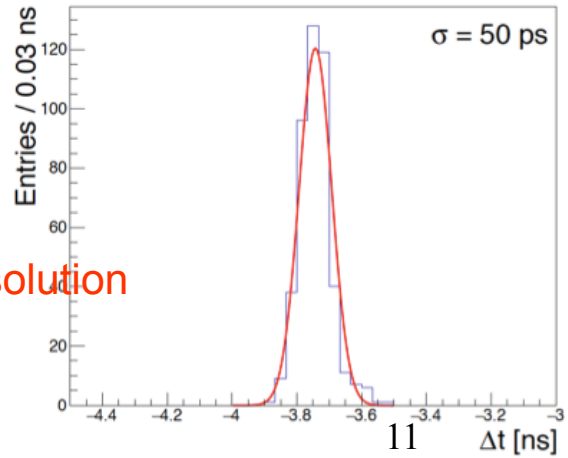








Position resolution

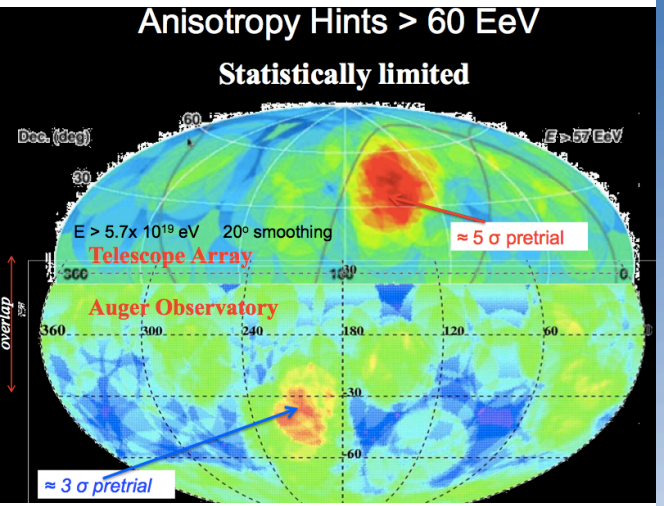


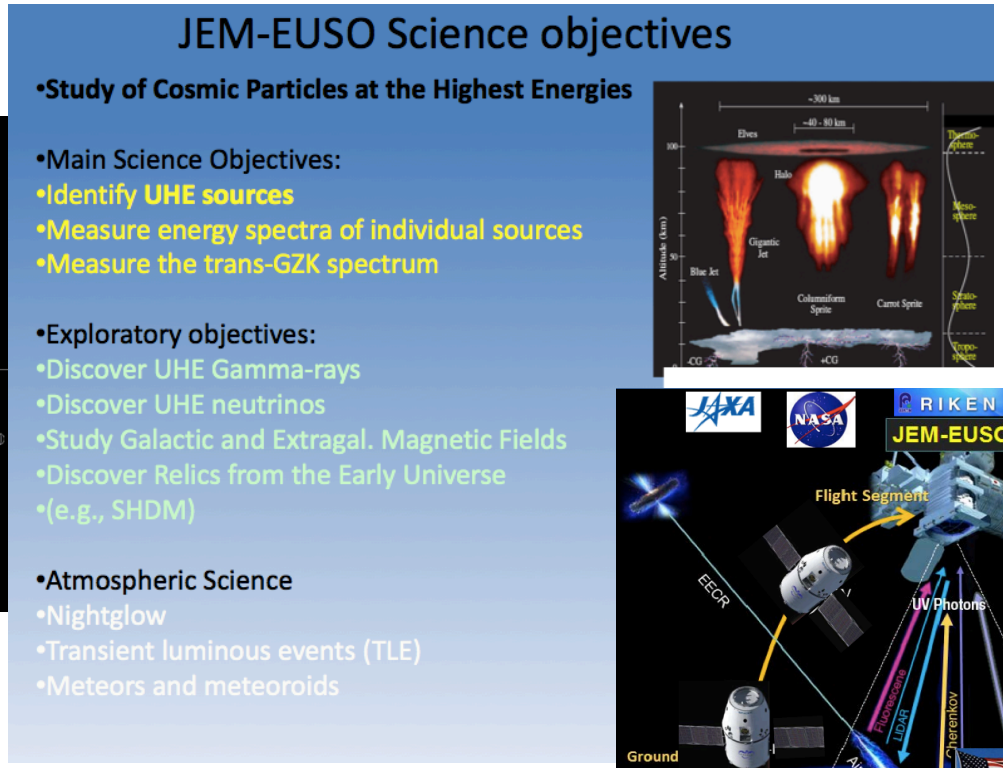
Time resolution

Findings – Large-Scale Calorimetry for Astrophysics

- Large (ground) and really large (space) calorimeters for the detection of Ultra High Energy Cosmic Rays are demonstrated.
- Low-statistics critical data.

L. Wiencke





Comments

- Significant R&D investments in imaging calorimetry (CALICE in particular) have borne fruit in both hardware and Particle Flow Algorithms.
- Precision timing (<100 psec) in calorimetry has been shown at the few channel level, but remains challenging for a full system.
- Many options exist for crystal calorimetry. There is no ‘perfect’ crystal that meets all needs. Progress is being made on all fronts.
- Simulation studies of Dual-Gate (fast vs slow) show that it is a compelling alternative in dual readout hadron calorimetry.
- R&D on new very-radiation-hard materials is necessary for any future/upgrade collider detector. Examples for EM calorimetry include shashlik and secondary emission.
- Noble liquid calorimeters (Kr, Xe, Ar) are a very mature technology that give excellent energy resolution.
- Future very large scale ($>10^{18}$ eV) astrophysics calorimeters require advanced photodetector arrays that can be triggered rapidly.

Identification of Risks and Opportunities

Risks:

- Precision timing
- Radiation-hardness

(The reality deviates from predictions obtained from small-scale demonstrators.)

Opportunities:

- Explore better mating crystals/scintillators and photodetectors. Might result in immediate implementation in other areas including medical and security.

Recommendations

- The success in the collider physics discoveries for the next ~ 20 years will require imaging calorimetry. Expertise in Particle Flow Algorithms and imaging calorimeters must be reinforced.

- R&D for system-wide clock generation and transmission and wave-form digitization should be emphasized to solve the foreseen pile-up problems in future collider machines.

- A systematic plan needs to be generated to search for and fully characterize alternative radiation-hard scintillators, crystals, ceramics, surface coatings, wavelength shifting fibers and capillaries.

- A plan should be formulated to test homogenous, dual readout concepts (including ‘dual-gate’). The design for a test beam module with at least λ^3 size needs to be made.

Possible Grand Challenge Ideas

A long list of challenges; long standing; each item has a different weight for different implementation; each item has been improving continuously:

- large-scale (physical size, channel count),
- low-power,
- high-performance (high-resolution, powerful algorithms),
- high-speed, precision, affordable readout,
- radiation-hard,
- …