Status of R&D on Calorimetry for EIC

The EIC Calorimeter R&D Consortium

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EIC R&D Committee Meeting

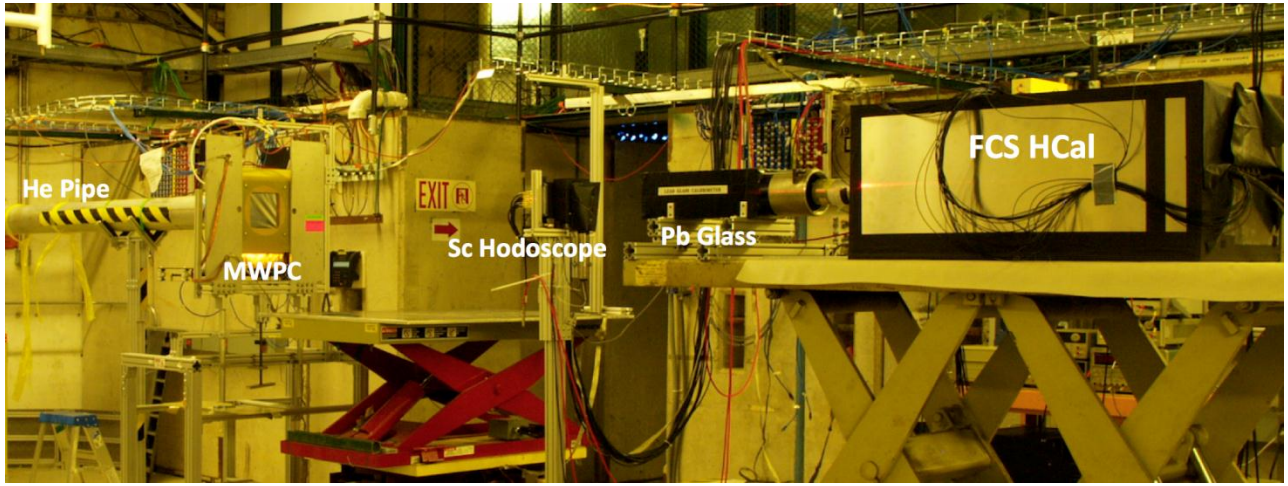
January 22, 2015

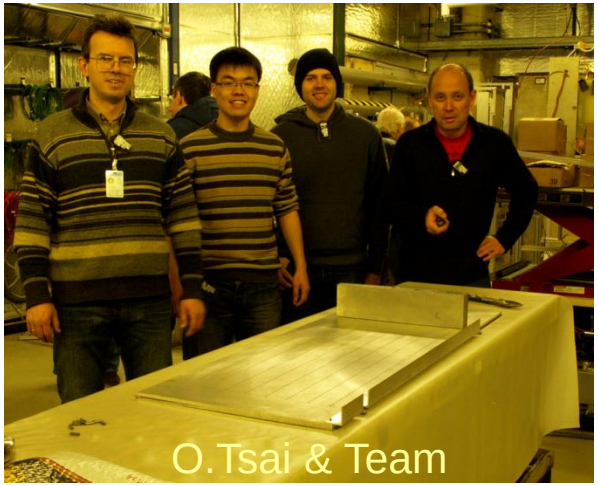
Areas of Investigation

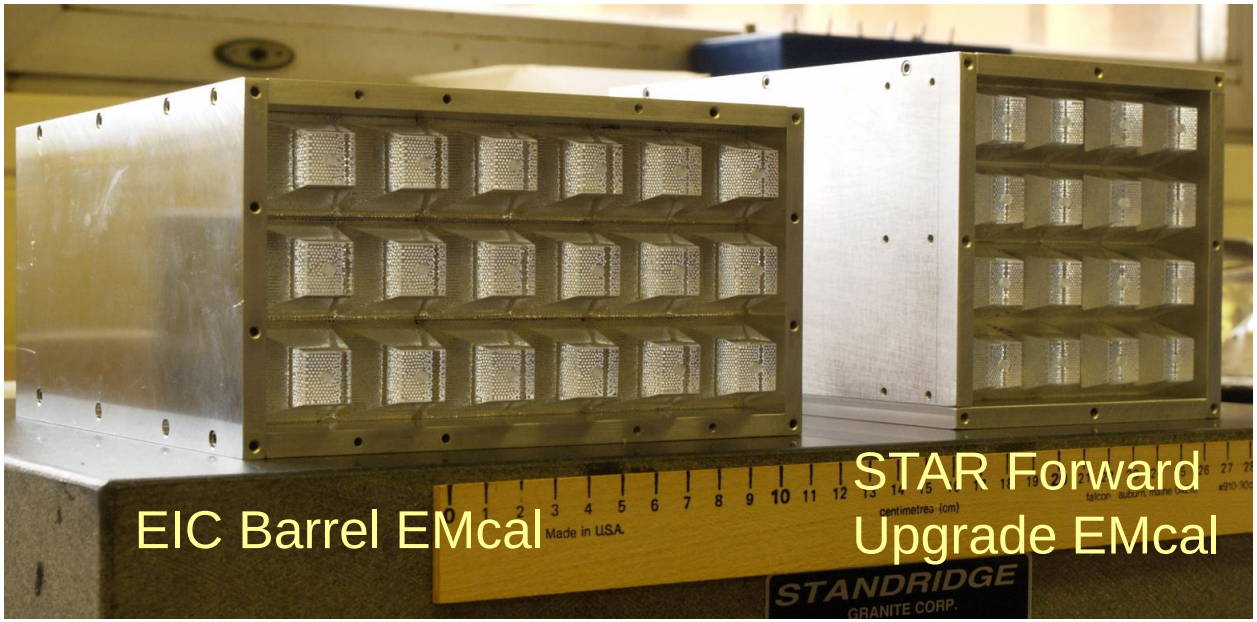
- Development of a tungsten powder epoxy scintillating fiber electromagnetic calorimeter (W/SciFi)
  - UCLA, IU, TAMU, PSU, BNL
- Development of a scintillating tile hadronic calorimeter
  - UCLA, IU, TAMU, PSU, BNL
- Study of radiation damage in SiPMs
  - Mainly BNL
- Development of $PbWO_4$ for a forward EMCAL at EIC
  - CU/JLAB, Orsay, Caltech, BNL, Yerevan
- Development of BSO as an alternative to $PbWO_4$ for a forward EMCAL at EIC
  - USTC, Caltech
- Monte Carlo simulations on calorimetry and related detector systems
  - Mainly BNL

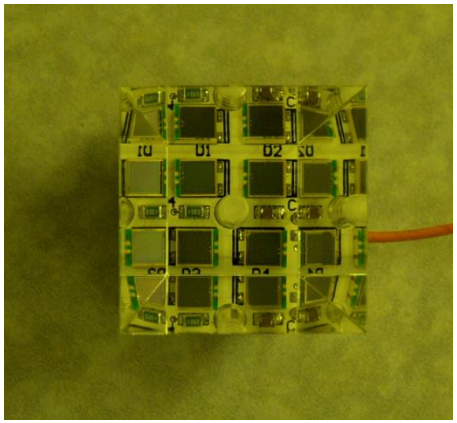
Test of W/SciFi Calorimeter at Fermilab

MT6 Test Beam Area at Fermilab – March 2014



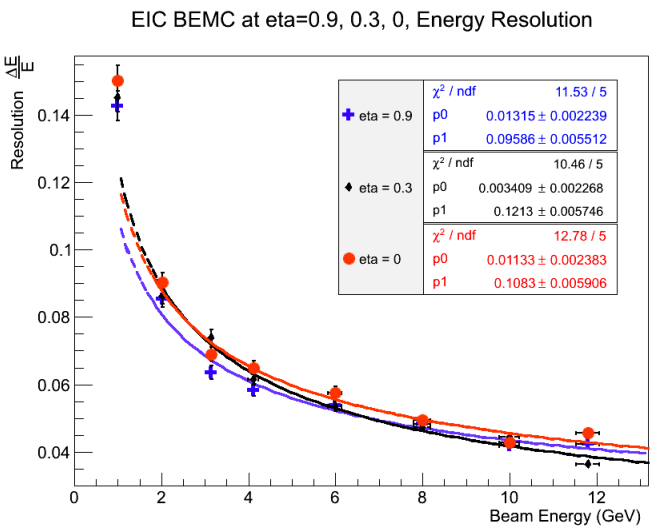


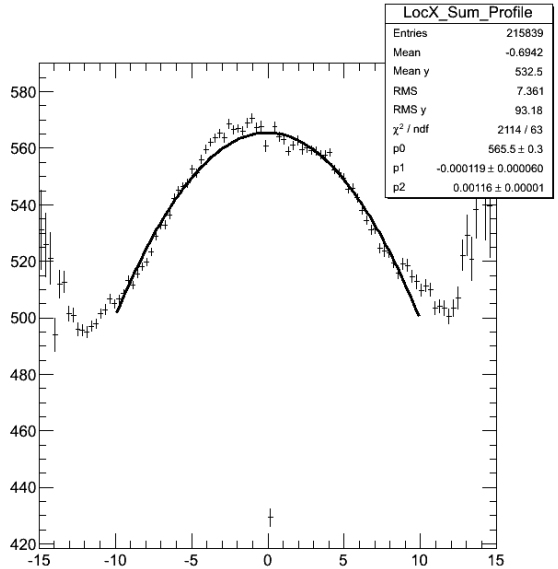


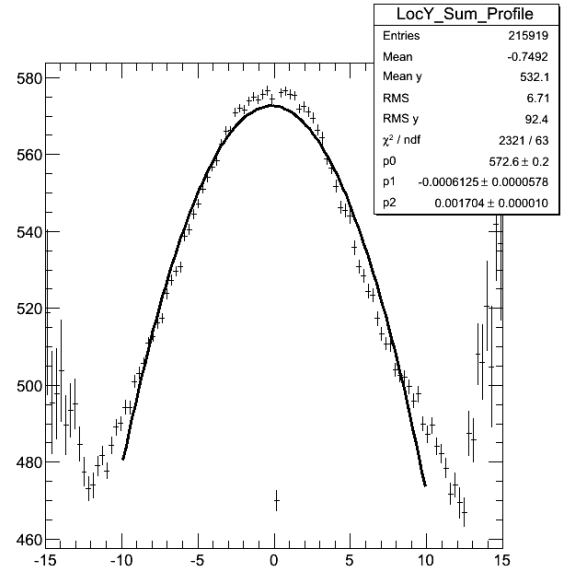


Readout
Four 3x3 mm^2 SiPMs

Improvement of Light Collection Uniformity





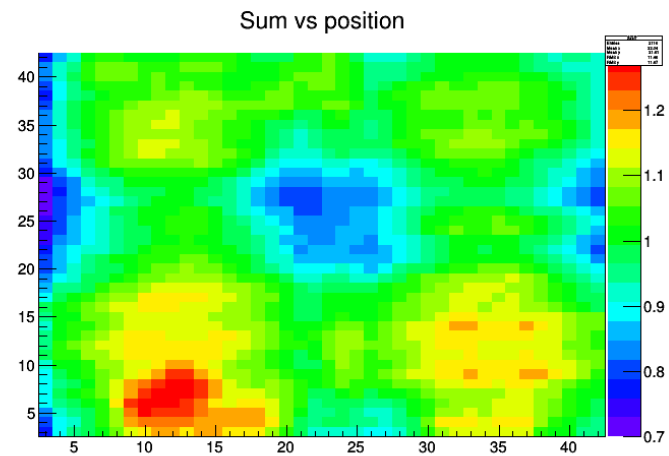


Energy resolution ~ 12%/√E

Light Yield ~ 500 p.e./GeV

Non-uniformities in light collection within a tower leads to variation of response across the module

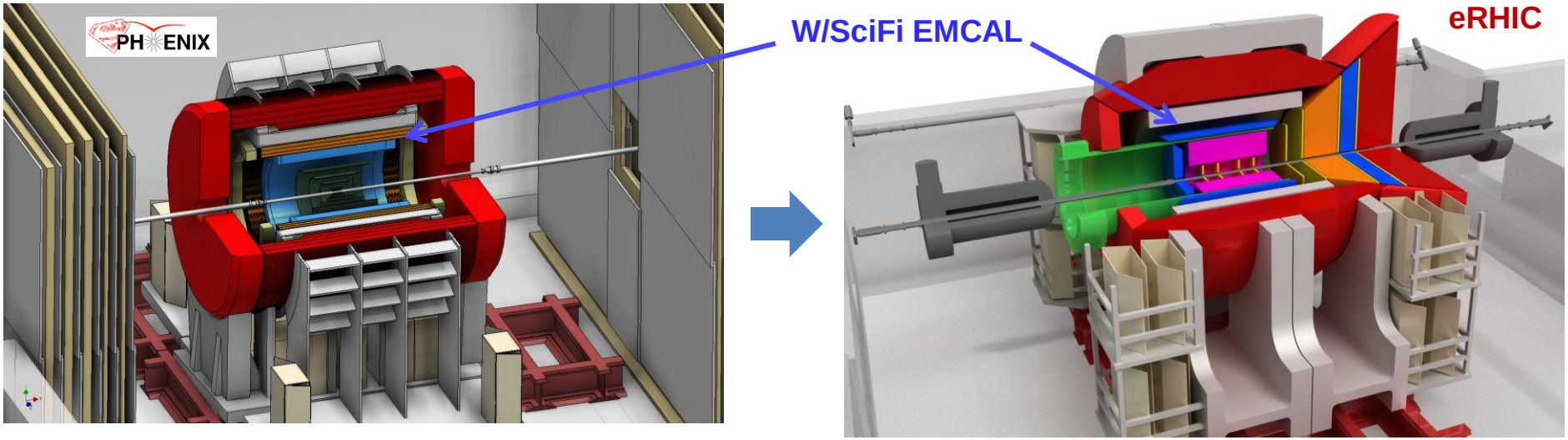
Plan is to use a compensating optical filter between the light guide and the SiPMs to make the response more uniform.



Normalized response of the forward EM prototype when scintillation fibers were excited with UV LED at the front surface of the prototype.

sPHENIX

sPHENIX has adopted the W/SciFi technology for its central barrel EMCAL

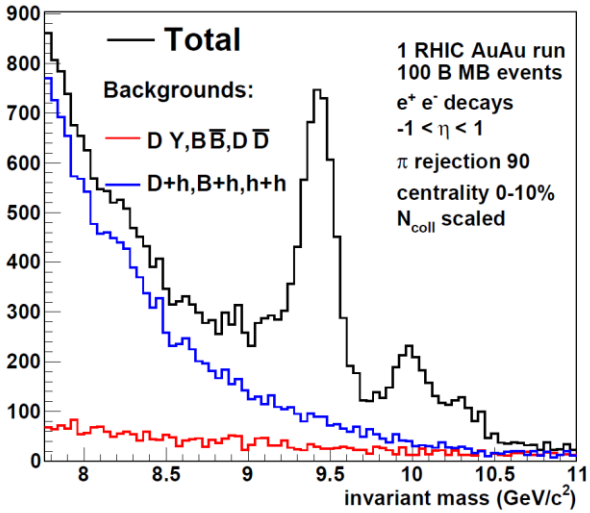


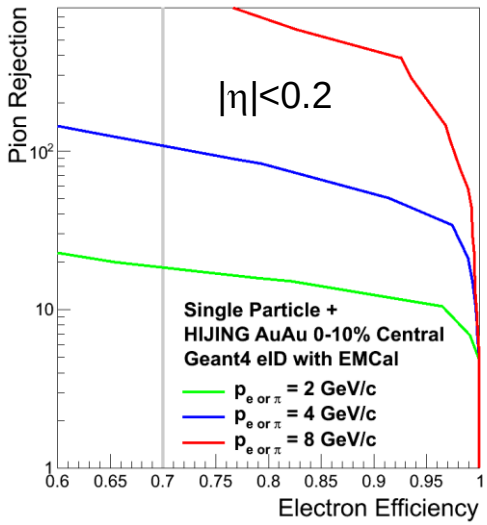
The calorimeter requirements for sPHENIX and eRHIC are different in some ways (e.g., multiplicity and occupancy requirements) but similar in many other ways (e.g., solid angle coverage, energy resolution, etc.)

Since the *same calorimeter* will be used in both heavy ion and eRHIC collisions, we want to be sure that the calorimeter we build will satisfy the requirements of *both experiments*

A Projective Calorimeter

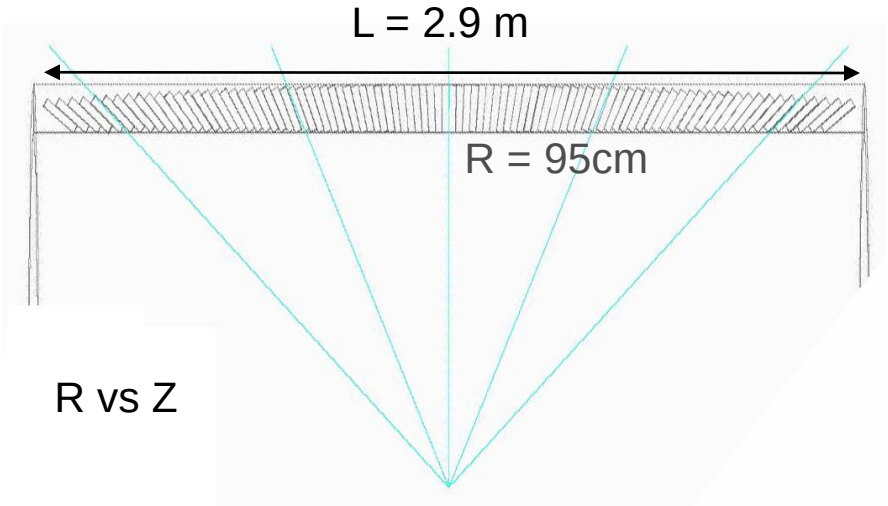
Due to the high multiplicity in central heavy ion collisions, having a fully projective (or at least an *approximately* fully projective) calorimeter has many advantages





Require hadron rejection ~100:1 with electron efficiency ~ 0.7 to identify the Υ with high efficiency

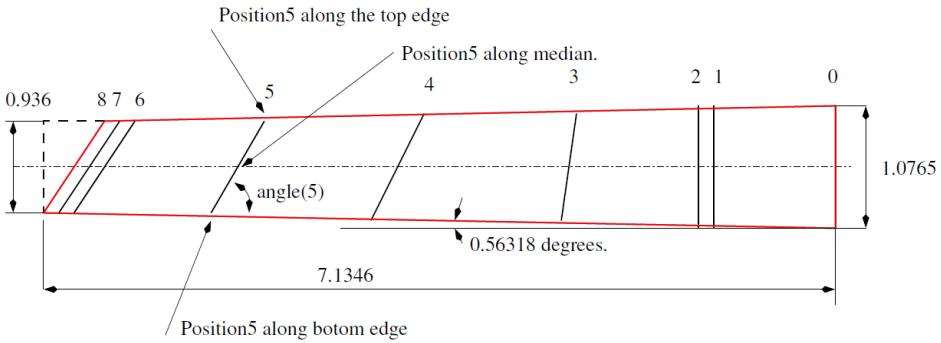
Large background from nearby showers requires projectivity at large η for good electron ID



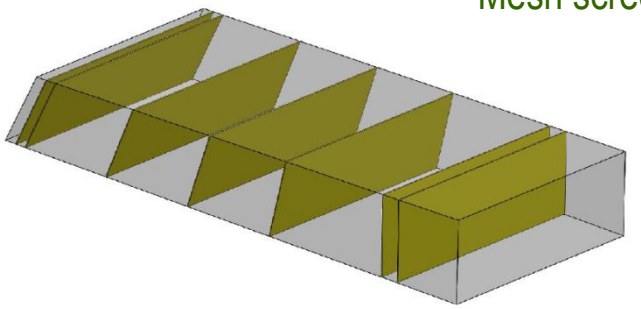
Making Projective Modules

The current technology developed at UCLA can be used to produce 1D tapered modules

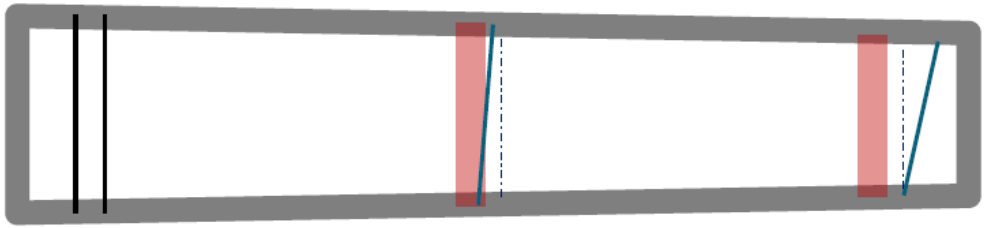
1D tapered module

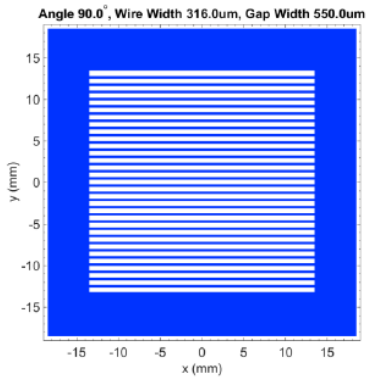


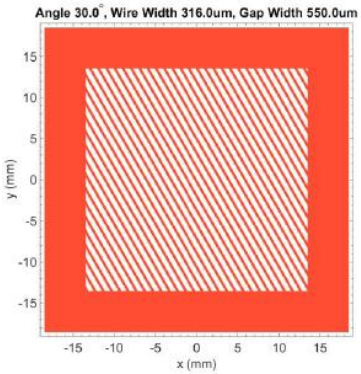
Mesh screens



2D tapered module







J.Huang
BNL

Two slotted wire frames allow two independent rotation angles

This work is being done at BNL and UIUC and supported by PHENIX R&D

Mass Production of W/SciFi Modules

The technique developed for building W/SciFi SPACAL modules at UCLA produces modules with excellent performance but is very labor intensive.

- Many steps
- Must wait for glue to dry at several stages
- Takes overnight to complete one module
- Want good consistency and quality control when producing many modules

Oleg Tsai at work showing us how to build a SPACAL module

A group of 5 people from PHENIX visited UCLA & THP in Dec 2014

Mass Production of W/SciFi Modules

We have asked Tungsten Heavy Powder (the company that supplied the tungsten powder for all the modules that were built at UCLA) to produce a new set of modules using a technique they use to mass produce other tungsten parts.

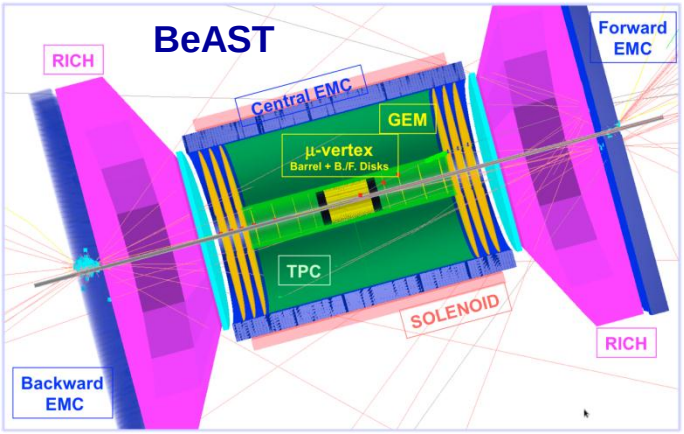
- Fill mold with mixture of W powder and epoxy at the same time (UCLA process requires 2 steps)
- Centrifuge mold to achieve maximum density (can do multiple modules at the same time)
- Possibly avoid clear epoxy step at ends of module using special machining technique
- Develop a process for future mass production

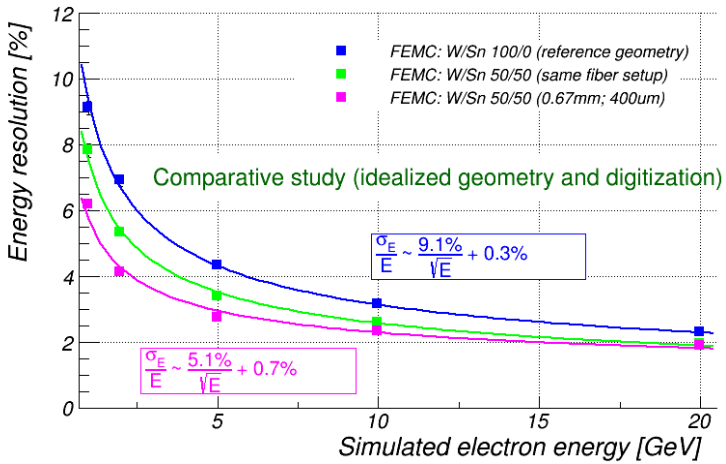
THP group visiting UCLA in September 2014

THP will produce 12 modules (24 2x2 cm^2 towers) using this technique
Expect delivery ~ 2 months ARO
Work will be done under a R&D contract between UCLA and THP
Cost is $40K to THP + UCLA overhead ($10K), funded by PHENIX R&D

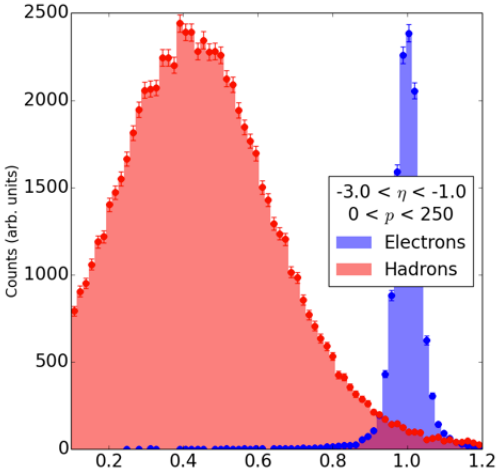
High Resolution SPACAL Modules

With a high magnetic field (3T) and high precision tracking detectors (MAPS) in the forward electron going direction, it is possible to reduce the requirements on the energy resolution of the forward electromagnetic calorimeter to ~ 6%/√E

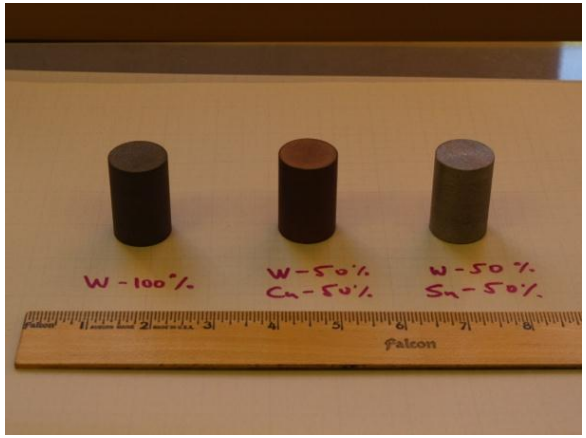




A.Kiselev



e/h separation with a 6%/√E Forward EMCAL



Samples of composite absorbers

- Achieve this by simultaneously increasing the sampling fraction and sampling frequency
- Requires the use of less dense absorbers such as Sn or Cu in the epoxy matrix

HiRes modules are currently being built at UCLA and will be tested in at Fermilab in May/June 2015

Radiation Damage in SiPMs

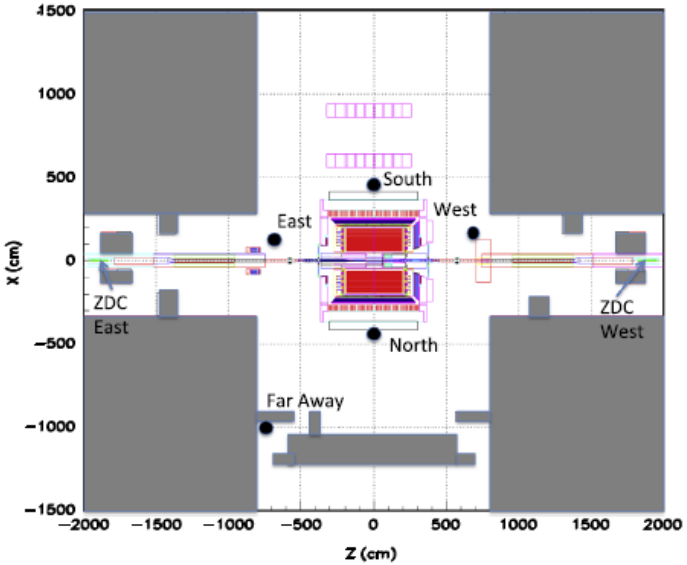
- Radiation damage in SiPMs (particularly from neutrons) has been known for many years (JLAB, CMS,…). However, it has only been recently that we have become aware that this may be a problem at RHIC/eRHIC
- Why did it take so long for us to realize this ?
  - Ionizing radiation levels have always been very low at RHIC

    (~ few krad/year even close to the beam pipe)
  - Activation levels have always been very low

    (no surveys required for equipment going in and out of IRs)
- Thermal neutron levels were first measured by STAR in 2013 (Run 13) and the full neutron spectrum was later simulated for the STAR IR (Y.Fisyak)
- Thermal neutrons were measured in PHENIX in 2014 and several SiPMs were tested in both the PHENIX and STAR IRs in Run 14.
- High levels of thermal neutrons were measured in both IRs and significant effects were seen in all SiPMs ($\Rightarrow$ large increase in noise and dark current)

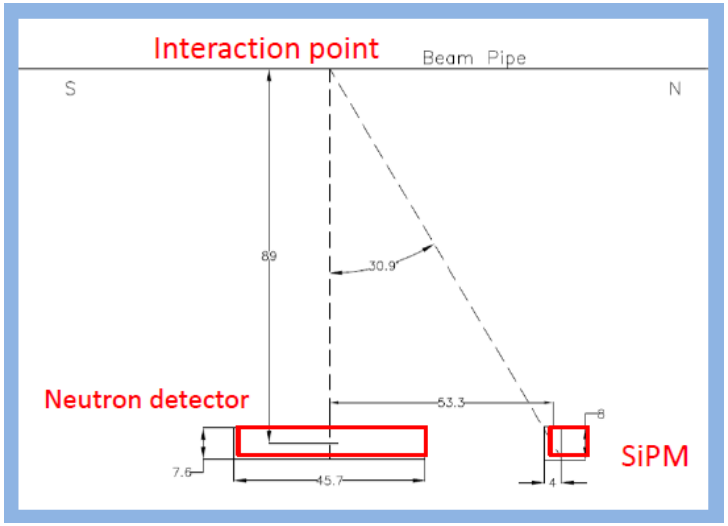
Neutron Fluxes in PHENIX & STAR IRs

STAR (2013)

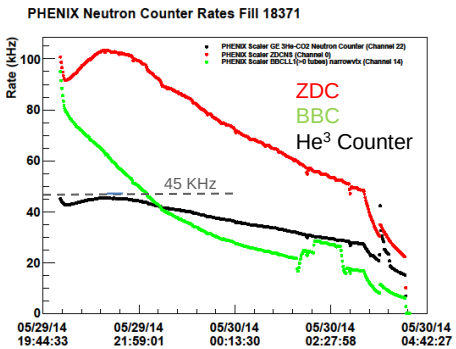


Thermal neutron flux measurements in the STAR experimental Hall
Y.Fisyak et.al., NIM A756 (2014) 68-72.

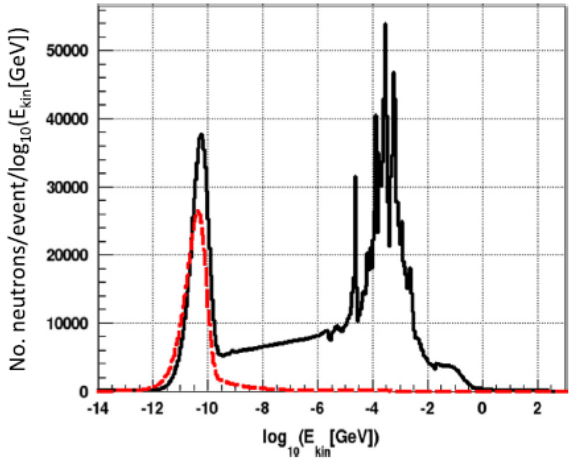
PHENIX (2014)



Raw Counting Rates



Neutron Kinetic Energy Spectrum



Black - full spectrum (GEANT3 Simulation)
Red – Expected spectrum from He^3 detector (convolution with He^3 cross section)

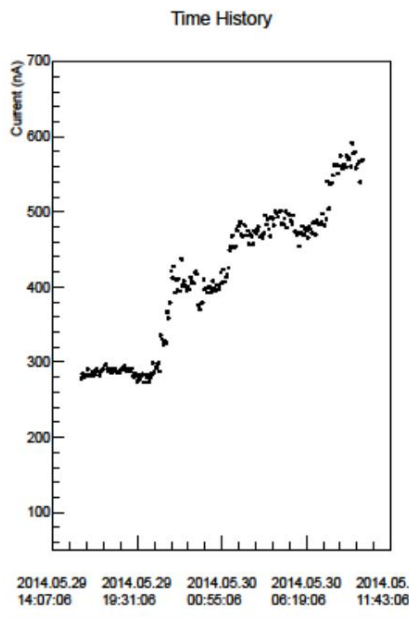
STAR Estimates for 2013 run (L=526 pb^{-1}):

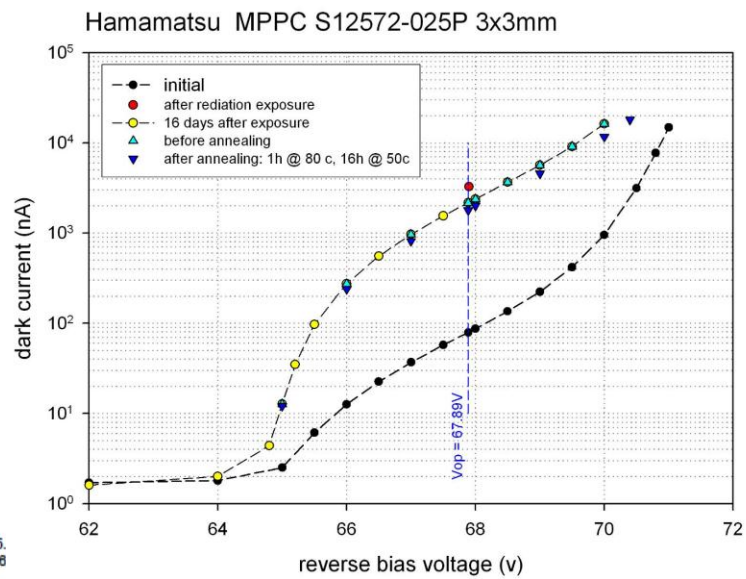
R= 3-8 cm, |Z| < 10 cm : $\Phi_{eq} \sim 8\times10^{10}$ n/cm^2
R= 100 cm, Z = 675 cm : $\Phi_{eq} \sim 2.2\times10^{10}$ n/cm^2

SiPM Measurements in the RHIC IRs

PHENIX

12 days Au+Au running
Total dose ~ 10^9 n/cm^2

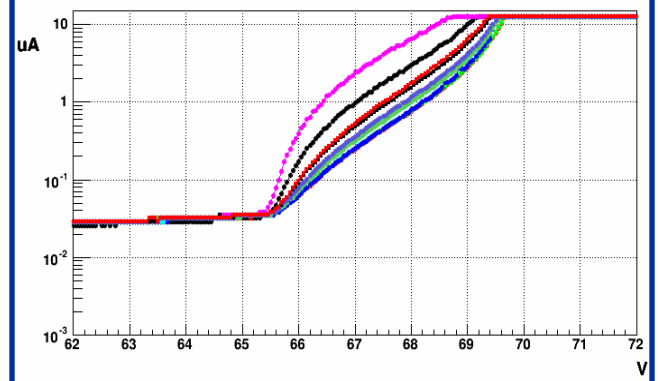


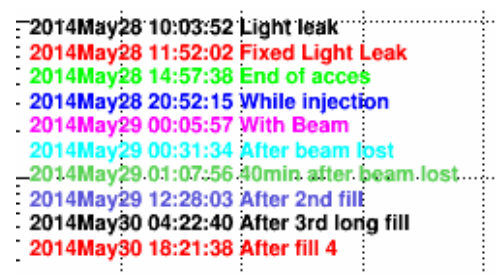


J.Haggerty, S.Stoll

STAR

50 μm Hamamatsu SiPM

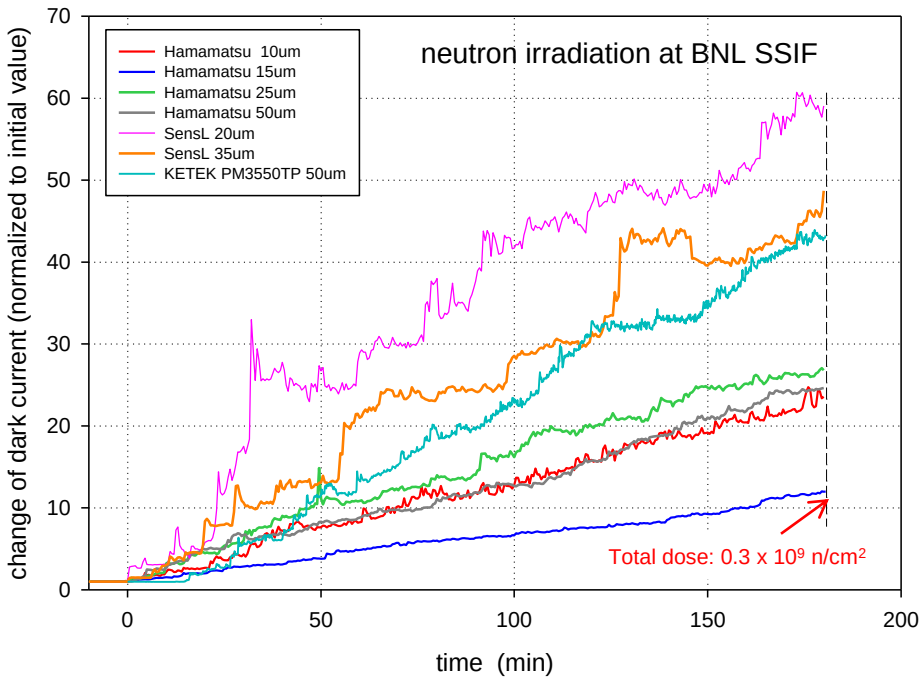




A.Ogawa

Follow Up Measurements with Neutrons

D-T Source at the BNL Solid State Irradiation Facility
Produces high flux of 14 MeV neutrons



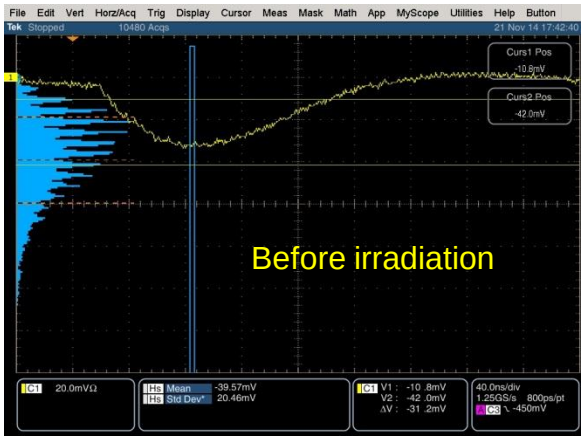
Tested different devices from several manufacturers

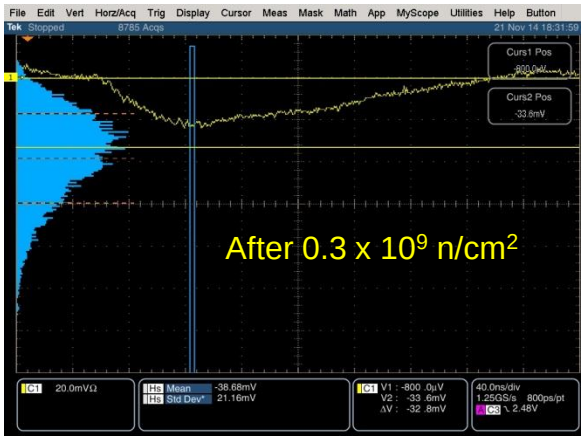
- Effect depends on pixel size (this was also seen by CMS)
- Hamamatsu 15 μm device showed lowest effect
- SensL devices generally performed worse than Hamamatsu (consistent with previous JLAB measurements)
- KETEK devices performed worse than Hamamatsu, but tested more favorably by CMS

Effect of Radiation on Measuring Signals

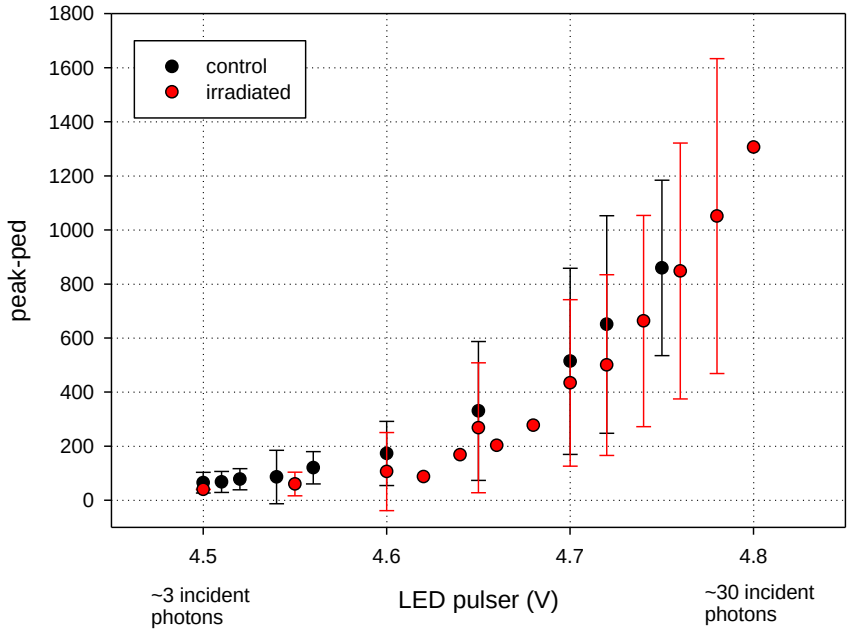
The effect of radiation exposure seems to be mainly an increase in the noise and dark current but does not appear to affect the ability of the SiPM to measure light signals (at least not up to doses ~ 10^9 n/cm^2)

Hamamatsu S12572-025P





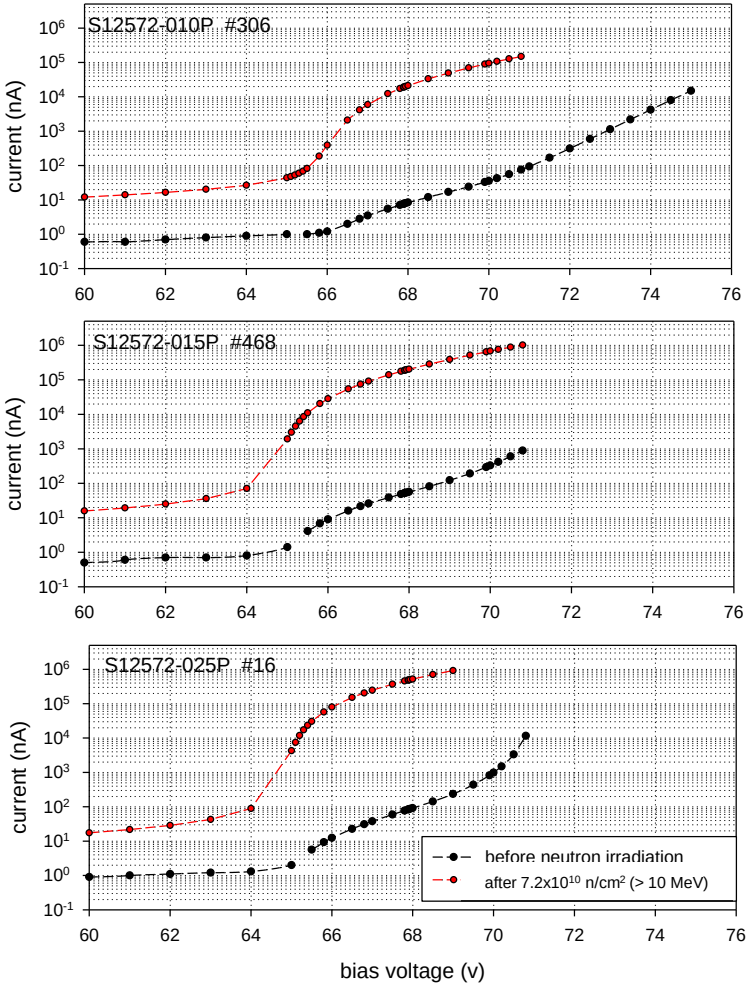
Hamamatsu S12572-025P
Signal integrity at low light levels, irradiated and control device.
(0.3 x10^9 neutrons/cm^2)

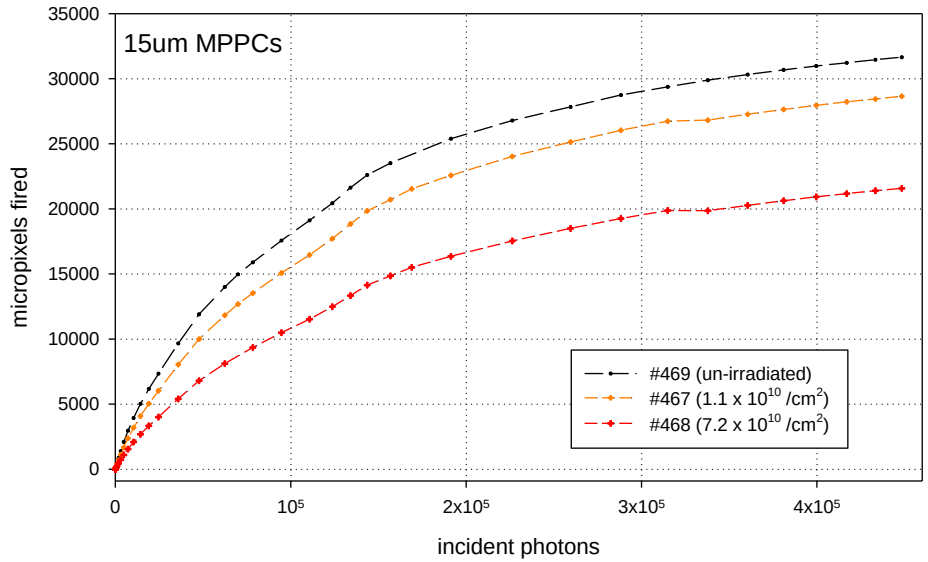


Small amplitude signals measured near the noise level

Effects at Higher Doses

Several Hamamatsu devices were exposed up to 7.2 x 10^{10} n/cm^2
at the LANCE Facility at Los Alamos





- Currents can reach levels ~ mA
- Some loss of pixels (⇒ lower PDE)

The Big Question:
What will the fluences be at EIC ?

R&D on Scintillating Crystals for a Forward EMCAL

Two Approaches:

- Develop a viable source of high quality $PbWO_4$ crystals
- Develop BSO as a low cost alternative to $PbWO_4$

Suppliers of $PbWO_4$ crystals

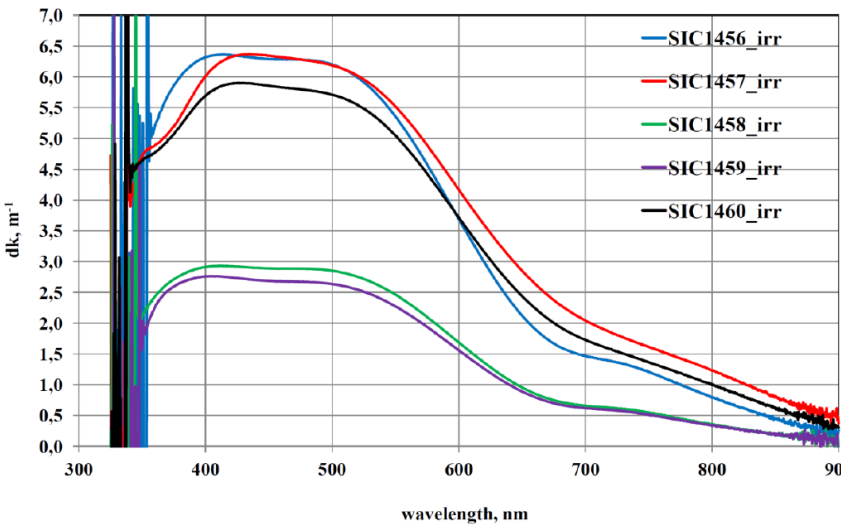
$PbWO_4$ (PWO) was developed for CMS and all crystals used in their barrel and endcap calorimeters were produced by two suppliers:

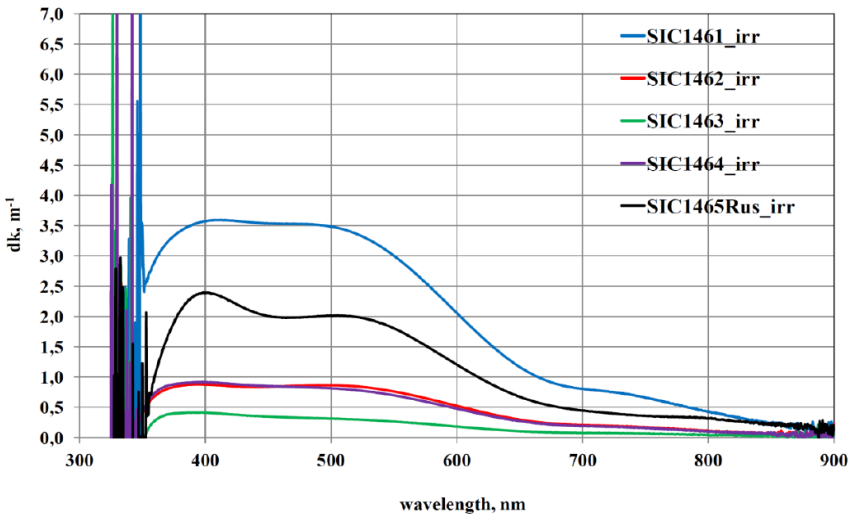
- Bogorodisk Technical Chemical Plant (BTCP)
  - supplied 90% of the CMS crystals
  - used Czochralski growth method
  - currently out of business
- Shanghai Institute of Ceramics (SIC)
  - supplied about 10% of the CMS crystals (used in forward endcap)
  - used Bridgman growth method
  - currently the only supplier of large crystals
  - having quality control issues (as experienced by PANDA)
- ALICE PWO crystals were supplied by North Crystals in Apatity, Russia
  - also currently out of business
- Several companies in the Czech Republic have been involved with PWO production since the beginning. Currently, the company Crytur is producing small crystals and is attempting to scale up to produce large crystals (potential supplier for PANDA)

PWO Crystals Recently Produced at SIC

10 crystals delivered to PANDA in Sept 2014 to study various growth, raw material and doping conditions

Radiation induced absorption coefficient after 30 Gy of ^{60}Co irradiation





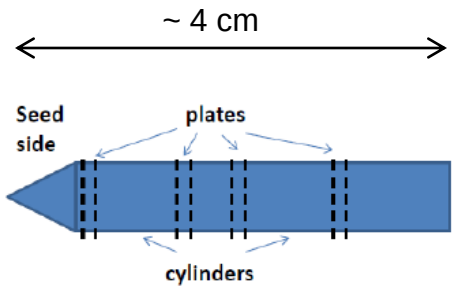
Optimization of growth conditions is still under development

10+5 crystals were received at JLAB in 2014 and are currently being measured

Radiation damage tests with these crystals are planned for early 2015

Progress on Crystal Growth at Crytur

Crystals are produced using the Czochralski method and the *same* raw material as was used by BTCP

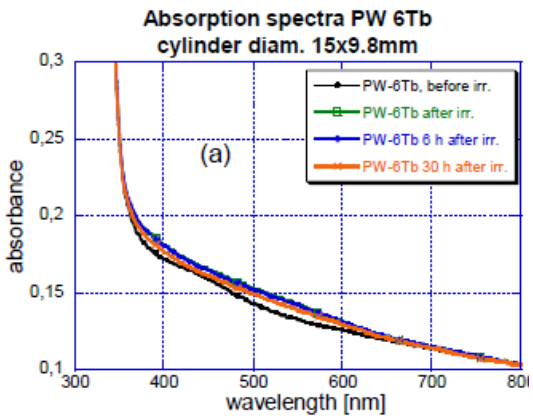


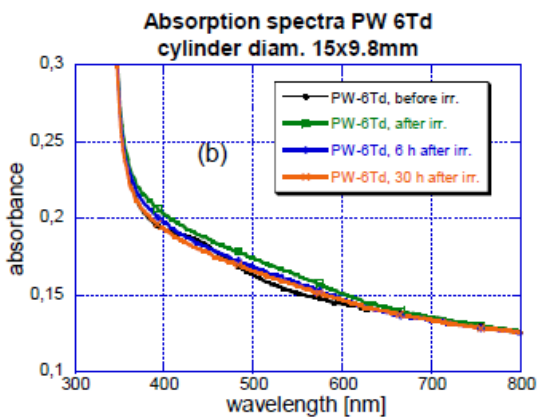
Numerous samples have been grown under different conditions:

- Undoped
- Y-doped
- La+Y doped
- Air atmosphere
- Dry N_2 + small amount of O_2

La+Y doping in N_2+0.1% O_2 seems best so far

Small PWO sample produced at Crytur





- Infrastructure is now being setup at Orsay and JLAB to test future samples
- Radiation damage tests are being planned at JLAB, Idaho, Caltech and BNL

^{60}Co radiation induced absorption for slices of small PWO sample (PANDA)

Specifications for PWO Crystals for EIC

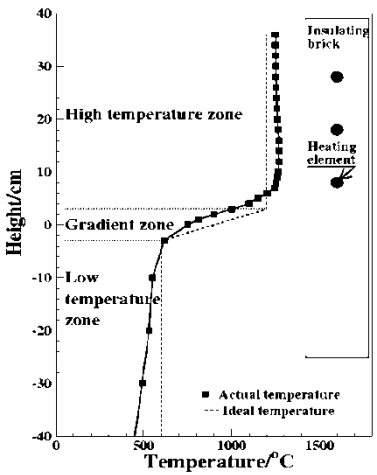
These specifications are still being developed, but one can compare to the CMS and PANDA specifications:

Parameter	**Unit**	**CMS PWO-I**	**PANDA PWO-II**	**EIC**
Luminescence maximum	*nm*	*420*	*420*	*420*
Expected energy range of EMC	*GeV*	*0.15-1000*	*0.01-10*	*0.1-15*
Light Yield at RT	*phe/MeV*	*8.0*	*16.0*	*15?*
EMC operating temperature	*°C*	*+18*	*-25*	
Energy resolution at 1 GeV	*%*	*3.4*	*2.0*	few %/√E
LY(100ns)/LY(1us)		0.9	0.9	
Optical transmission at 360 nm	%	25	35	
Optical transmission at 420 nm	%	55	60	
Optical transmission at 620 nm	%	65	70	
Homogeneity at T=50%	nm	3.0	3.0	
Induced absorption coefficient k at RT, >30 Gy/hr	m^{-1}	1.6	1.1	1.5?
Mean value of k	m^{-1}		<0.75	

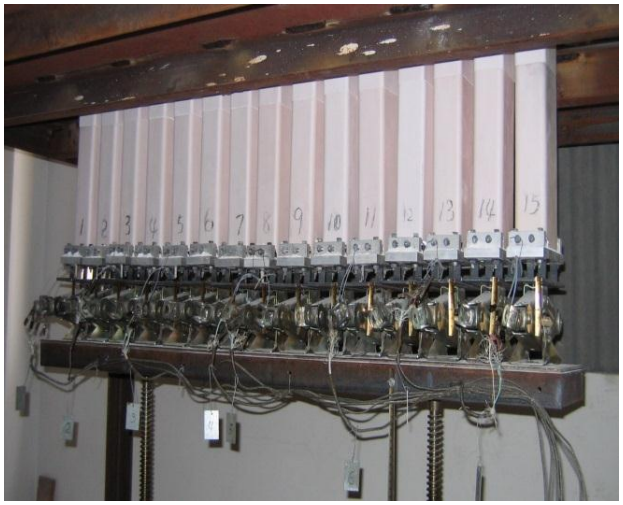
Can probably lower requirement compared to PANDA since energy range is higher

Probably lower requirement than CMS, but requires further investigation

Progress on BSO Development at SIC



Improved temperature uniformity and stability control



Production array with multiple crucibles (allows for 30 crystals per growth run)

Enlarged cross section of crucibles and improved raw material purity

55 mm diameter x 120 mm long ingot

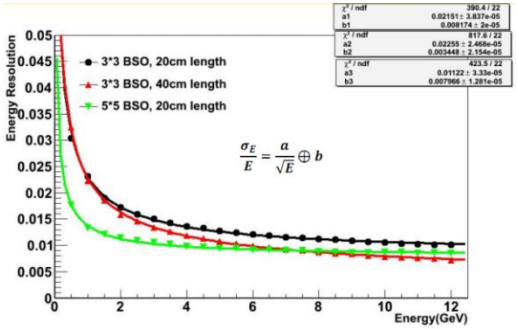
BSO is also being investigated for use as a homogeneous hadronic calorimeter (HHCAL)

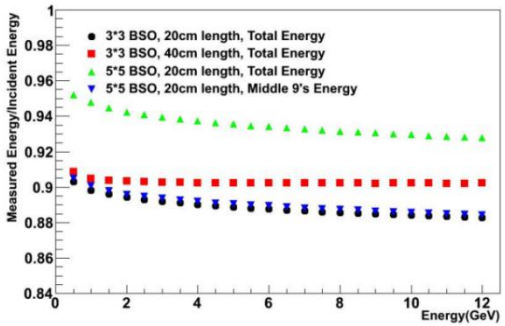
That effort is being supported with a small amount of funding from the HEP community (ANL, Fermilab and Caltech)

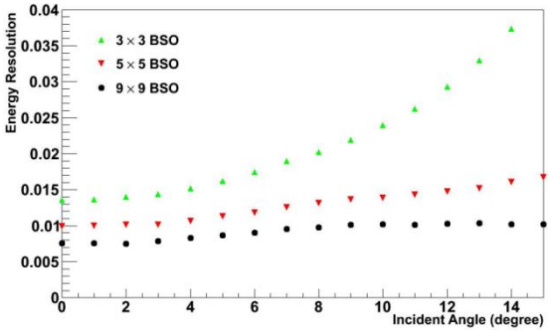
However, the BSO development at SIC is funded primarily out of their own internal funds

Studies with BSO Prototype Module

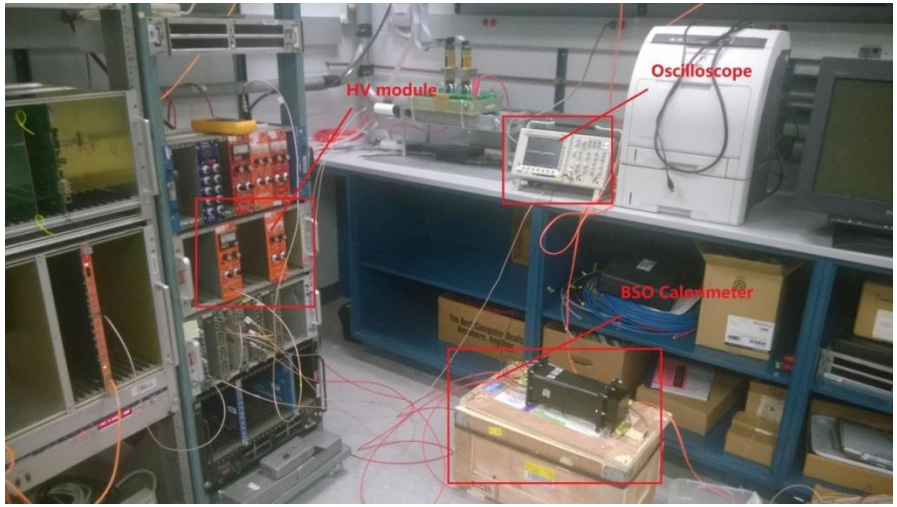
Continued Monte Carlo Simulations



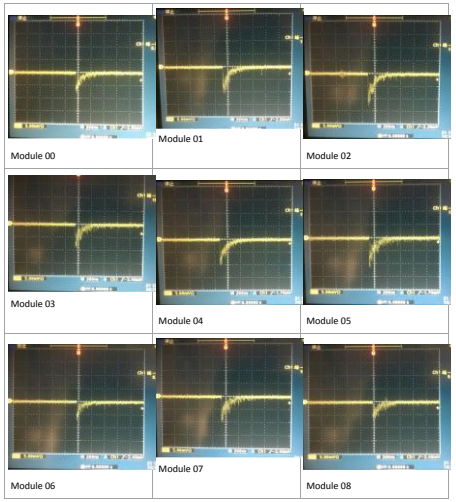




Lab tests with 3x3 prototype module



Test setup at BNL



Cosmic ray signals in each of the 9 modules

Planned beam test in November was delayed due to a change in the SLAC beam schedule
Test is now planned for early 2015

Simulations

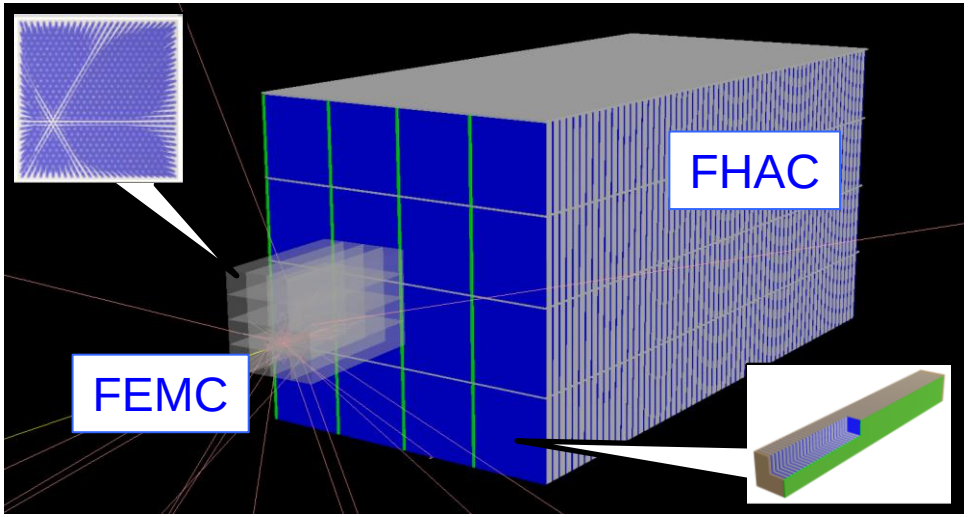
- There has been a *great deal* of effort put into simulations of various detector designs for EIC. These includes both for a dedicated EIC detector, as well as for PHENIX and STAR
  - eRHIC Design Study released in December 2014
  - Revised sPHENIX proposal submitted in November 2014

  The result has been a steady improvement in specifying the design requirements for these detectors and in our understanding of their physics capabilities

- Simulations encompass not just calorimetry but the entire detector design (e.g., calorimetry, tracking and PID are intimately related)

- Simulation effort also supports other R&D studies, such as beam tests, prototype design, etc.

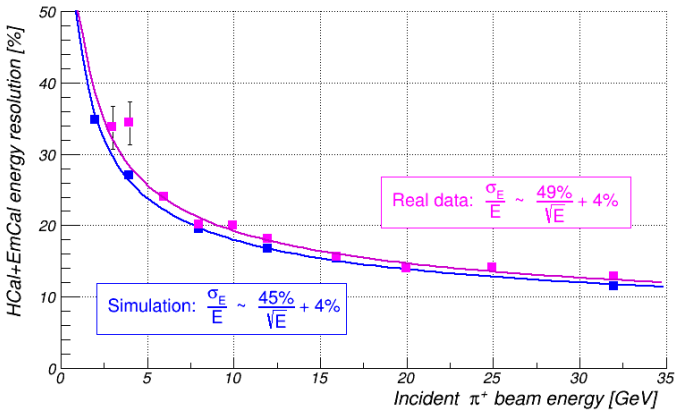
Simulation of Test Beam Detectors

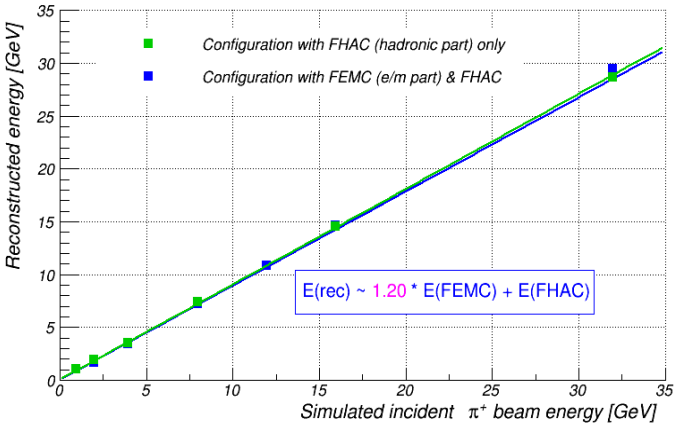


Electromagnetic and hadronic calorimeters of the February 2014 T1018 test beam setup

Simulations include a detailed description of the internal structure of each detector

Energy resolution and linearity of combined EMCAL + HCAL test beam detectors





A. Kiselev

Summary and Future Plans

- W/SciFi calorimeter R&D
  - The W/SciFi SpaCal has now been adopted for the central barrel electromagnetic calorimeter for sPHENIX and the PHENIX group is working with the UCLA group to further develop this technology.
  - We are working with THP to develop a cost effective, mass production procedure for producing SpaCal modules.
  - The PHENIX group is working on developing a fully projective SpaCal module.
  - Techniques are being developed to improve the light collection uniformity which should improve the resolution and uniformity of response.
  - A high resolution W/SciFi SpaCal is being developed that could serve as a forward calorimeter in the electron going direction at EIC. A beam test of a prototype is planned for mid 2015.
- Studies on radiation damage in SiPMs
  - Radiation effects are observed in SiPMs in the RHIC environment.
  - The effects at low dose are mainly an increase in noise, but there appears to be no effect on signal detection capability. At high doses some loss in PDE is seen.
  - We will continue to study radiation damage with neutrons and in the RHIC environment with devices from different of manufacturers over a range of doses.

Summary and Future Plans

- R&D on Scintillating crystals
  - There is currently an issue with quality control and the ability to meet certain detector requirements with the PWO crystals that are being produced at SIC.
  - Crytur is now able to produce small PWO crystals using the same growth method and the same raw material as was used to produce the majority of the CMS crystals. Large crystals should become available in 2015.
  - Infrastructure is being set up at Orsay and JLAB to test new crystals.
  - Radiation damage tests are planned with new samples from Crytur and SIC.
  - When crystals are available, a 5x5 prototype will built and tested in the beam.
  - Development of BSO at SIC is continuing with future plans for mass production.
  - A beam test of the BSO prototype calorimeter is planned for early 2015.
- Simulations on detector design and specifications
  - A significant simulation effort has been put into various detector designs for EIC, both for a dedicated EIC detector, as well as for PHENIX and STAR.
  - Summaries of the current designs are given in the eRHIC Design Study that was released in December 2014 and in the updated sPHENIX proposal submitted in November 2014.

Future Budget Requests (FY16)

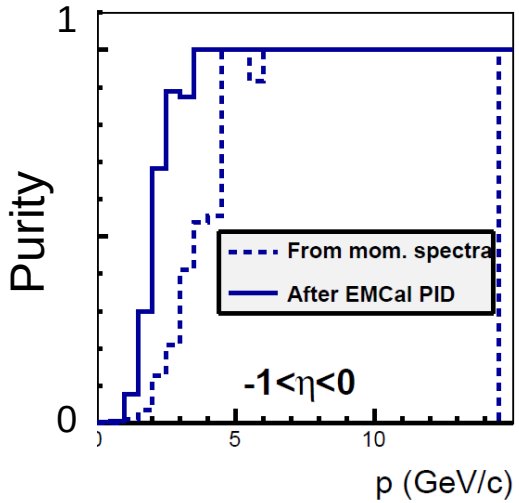
Investigation Area	Amount	Comments
W/SciFi SpaCal	$157K ($130K UCLA $27K BNL)	Includes $50K to THP for mass production development
SiPM Radiation Damage	$23K	Includes some new electronics development
PWO R&D	$120K	Year 2 of original proposal
Total	**$300K**	

Backup Slides

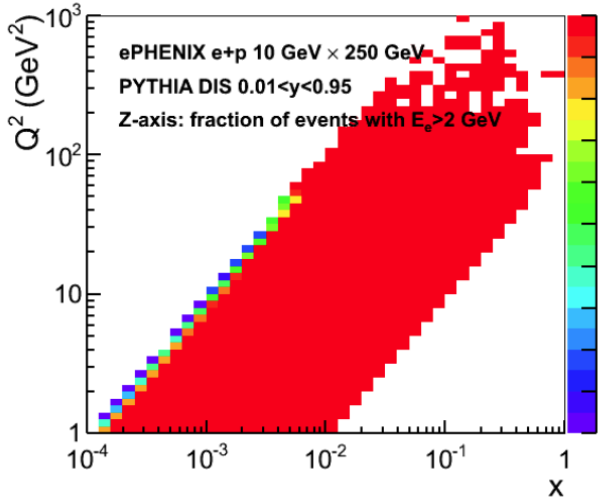
Use of the EMCAL in EIC Physics

- Electron identification (e-EMC, barrel EMC)
- Electron kinematics measurement (e-EMC, barrel EMC)
- DIS kinematics using hadron final states (barrel EMC/HCal, h-EMC/HCal)
- Photon ID for DVCS (All EMC)

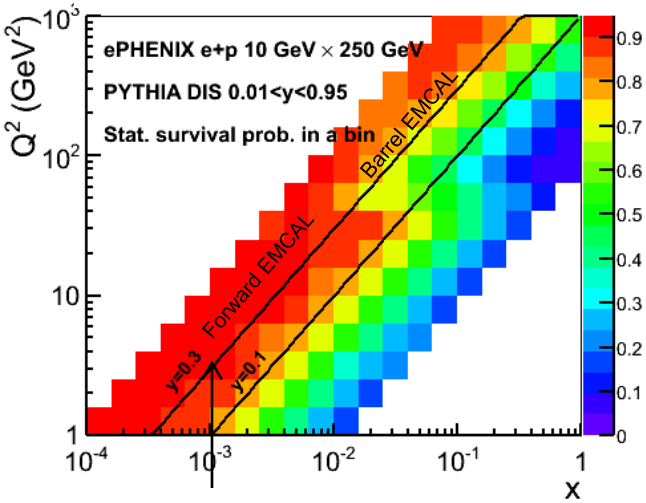
Electron purity after EMCal PID



Fraction of DIS event with good electron ID



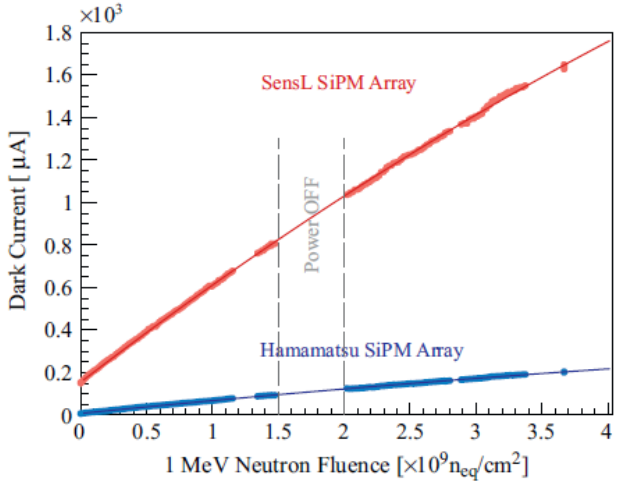
DIS kinematics survivability Electron kinematic method

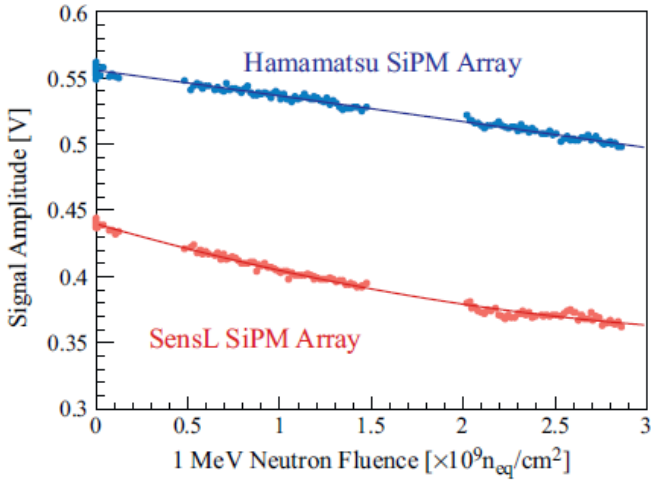


From J.Huang, S. Bazilevsky and K.Boyle

JLAB and CMS SiPM Radiation Damage Tests

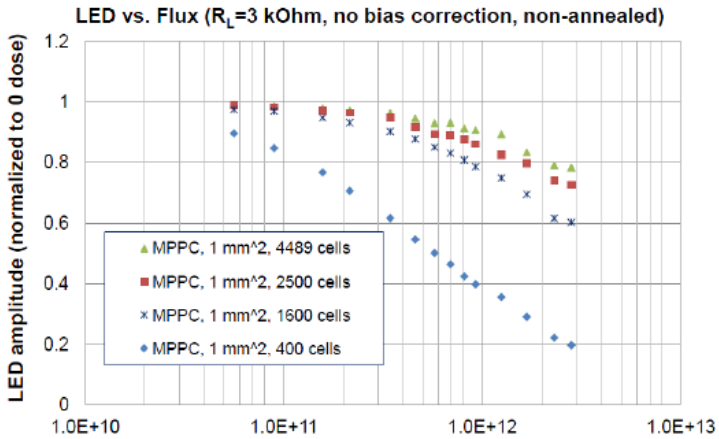
GlueX

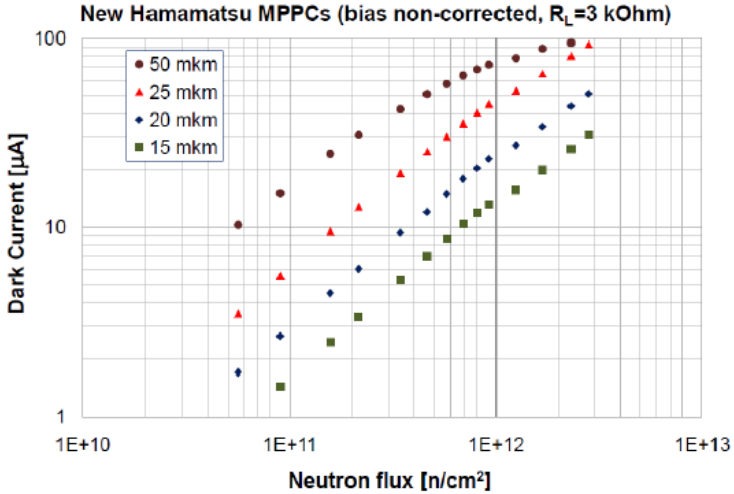




Y.Qiang et.al., NIM A698 (2013) 234-241

CMS





J.Anderson
CALOR 2012