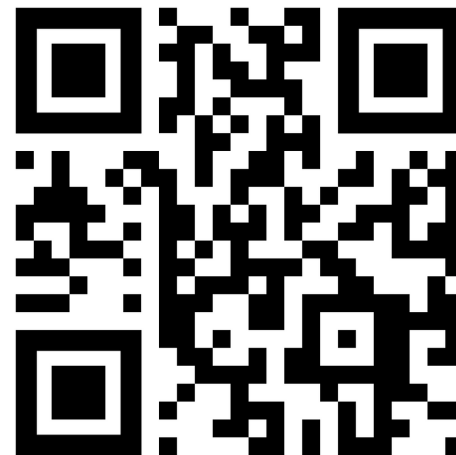


ECal Options for SoLID-Lite

Xiaochao Zheng

University of Virginia



SoLID Ecal Original Design

Ecal:

- 2cm thick scintillator with WLS fibers embedding
- 0.5mmPb/1.5mmSci shashlyk design
- 100cm² hexagon shape, 97 WLS fibers
- 20 X0 (about 40cm)
- 3-module (preshower+shower) prototype tested at FTBF and 2022-23 beam test

SPD:

- LASPD: 2cm scintillator readout on the outer edge, FMPMT tested in field (gain, timing resolution)
- FASPD: 6mm scintillator with WLS fiber embedding, light yield tested
- LASPD (with regular PMT readout): tested in 2022-23 beam test

sPHENIX ECal Overview

TDR: <https://indico.bnl.gov/event/7081/>

- One block is 4cm x 4cm x ~14.4cm W/epoxy+ 2668 dia 0.47mm Scintillating fiber
- backend of block: polished, ESR reflector attached, and glued to support structure
- frontend of block, 4 light guides are attached → one module. One light guide = one “tower”. Each lightguide/tower is readout by 4 3mmx3mm SiPMs. Each 4 SiPMs are passively summed, shaped, amplified, and then readout. So 1 tower = 1 readout
- One sector contains 48*8 towers or 24*4 modules → 1 sector size = ~96cm * (16-22)cm * 14.4 cm (L)
- Full Ecal has 64 sectors = 6144 modules = 24576 towers = 24576 readout channels = 98,304 SiPMs

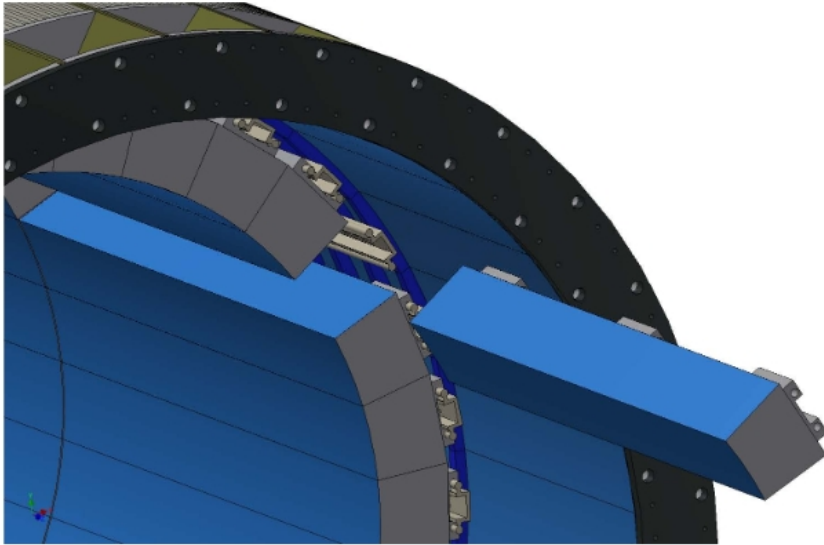
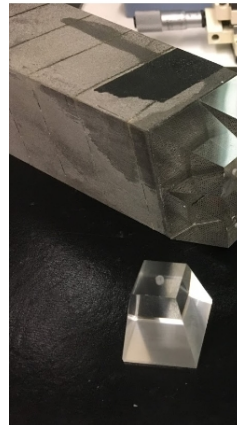
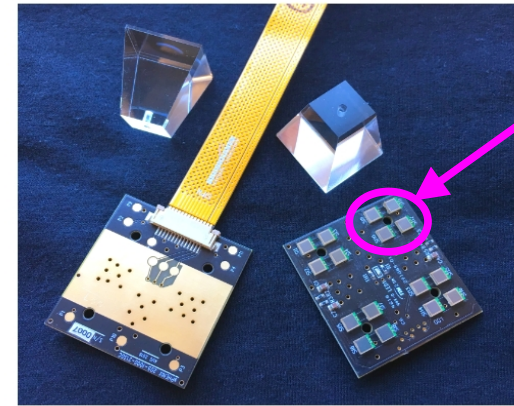


Figure 3.8: EMCAL sector showing installation on the Inner HCal.



Light guides produced by injection molding and finally glued



couple to
one
lightguide
(one
tower)

Figure 3.15: Four-tower SiPM PCB and lightguides. Each tower is read out with four SiPMs. The SiPMs will be optically coupled to the narrow end of the light guide using a clear silicone adhesive.

Comparison

sPHENIX ECal:

block: 4cm x 4cm (trapezoid/tapered)
length: $20X_0 \sim 14.4$ cm

density: 9-10 g/cm³
sampling ratio: 2.3%
 X_0 : 7mm
Moliere radius: 2.3cm

sector weight: 326 kg (estimated)
total weight: 20,890 kg (estimated)

Readout: 24576 channels, each reading the
passive sum of 4 SiPMs

energy resolution: $3 + (13-15)\%/\sqrt{E}$ (FTBF)

Note that since the Sci fibers are along the particle trajectory, separating each block into towers does provide additional granularity.

SoLID ECal:

module: 100cm² (hexagon)
length: $18X_0 \sim 45$ cm (not including fibers)

density: ~ 3.6 g/cm³ (estimate)
sampling ratio: $\sim 20\%$
 X_0 : 2.4cm
Mollier radius: 5cm

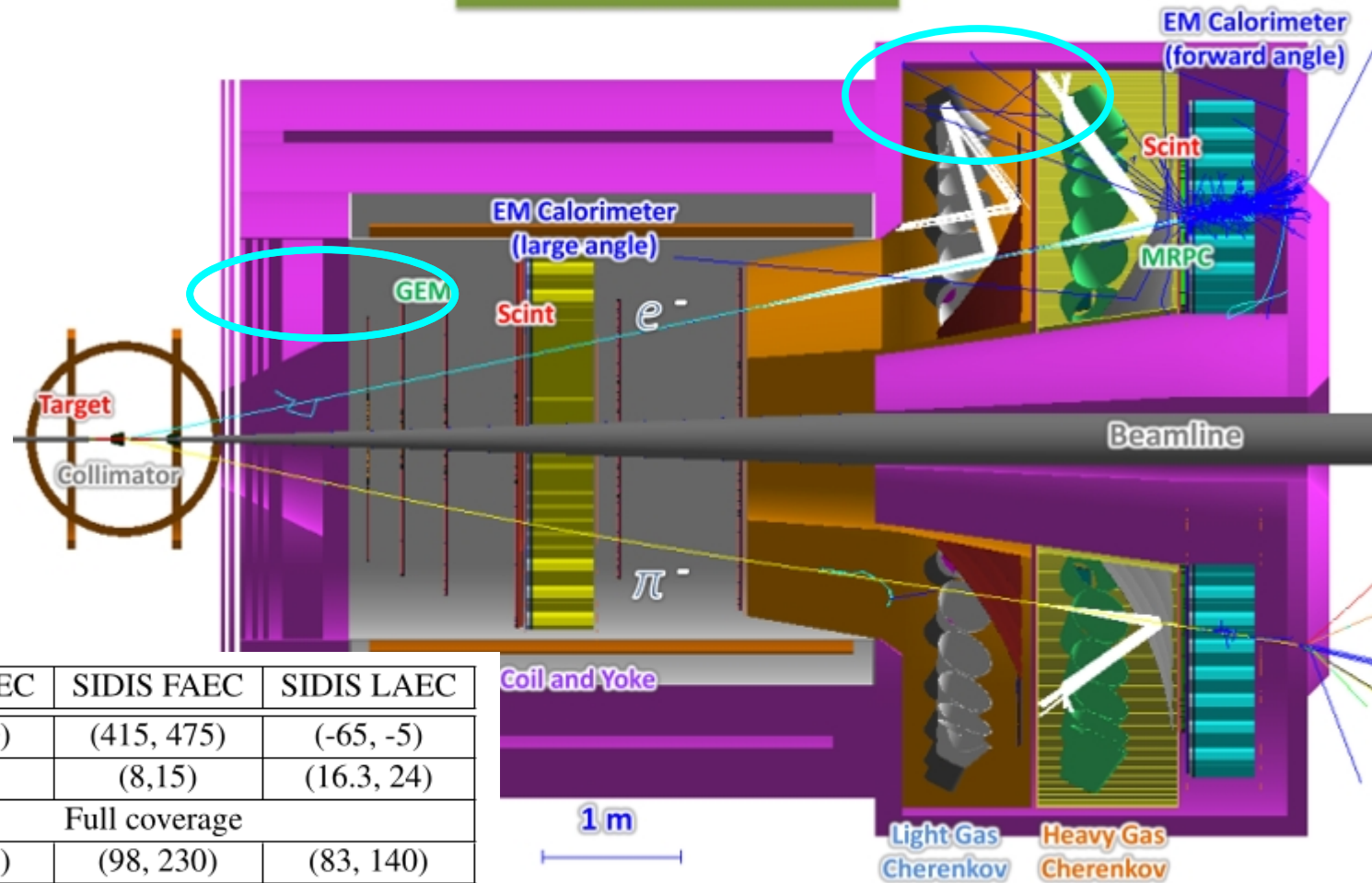
module weight: ~ 14 kg
total weight: 25,200 kg

Readout: WLS $\rightarrow$ clear fiber $\rightarrow$ PMT, 1/module

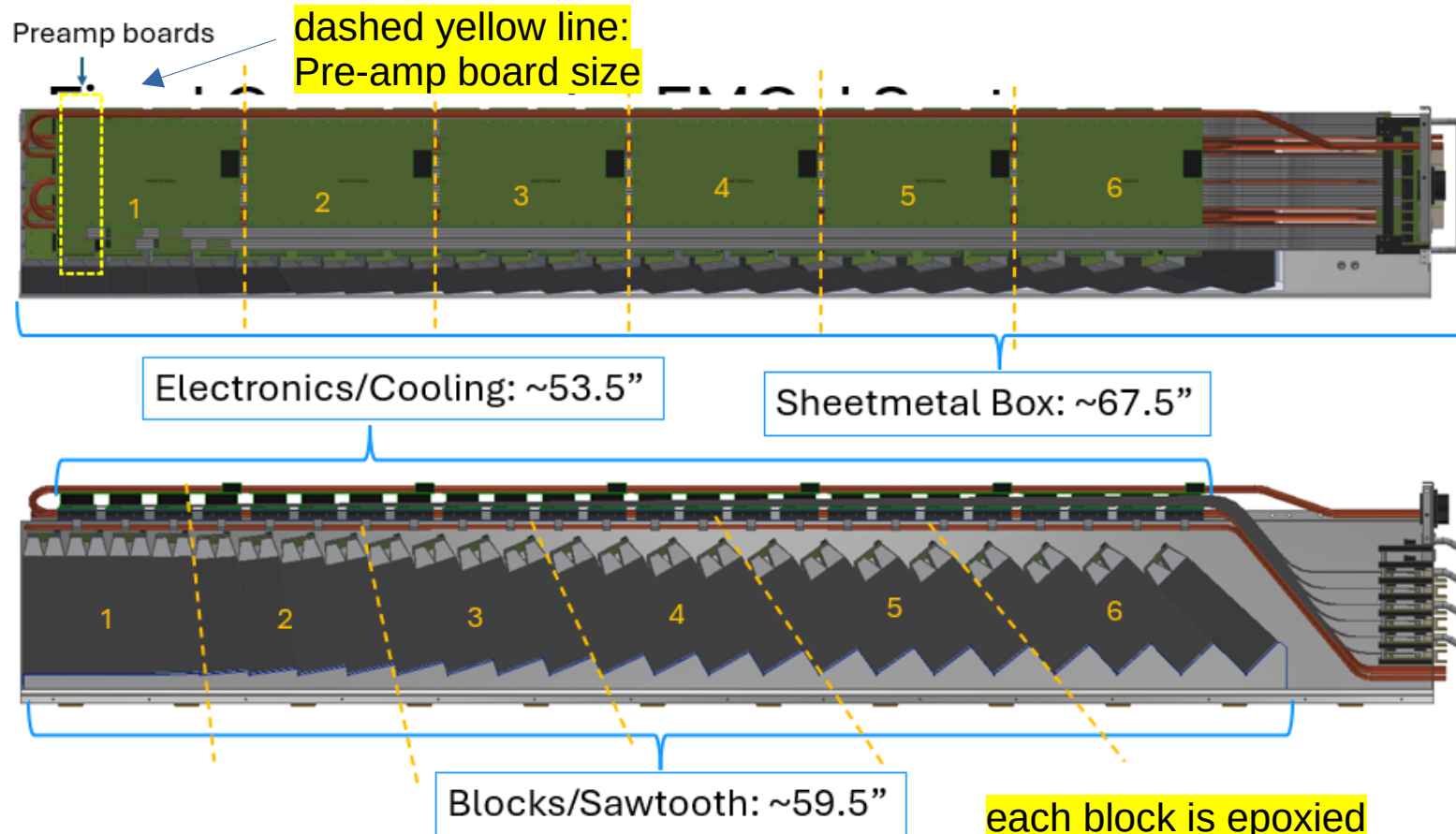
energy resolution: $4.6+10.4\%/\sqrt{E}$ (FTBF)

We can consider summing 16 SiPM to one reach, each reading 4x4 cm² of detection area, roughly “corresponding to” the 100 cm² shashlyk module size.

SoLID (SIDIS He3)



	PVDIS FAEC	SIDIS FAEC	SIDIS LAEC
z (cm)	(320, 380)	(415, 475)	(-65, -5)
Polar angle (degrees)	(22,35)	(8,15)	(16.3, 24)
Azimuthal angle	Full coverage		
Radius (cm)	(110, 265)	(98, 230)	(83, 140)
Coverage area (m ²)	18.3	13.6	4.0
Total number of channels	≈1830	≈1360	≈400



sector weight: 326 kg

1) type of epoxy and approximate thickness: DP460 ~0.5mm

2) Can Pre-amp boards be reused if cutting by yellow lines?
→ it's best we design our own readout (not the most expensive part, about \$25k)

3) possibly cutting lightguides? (making new LGs for the other side?) → NO

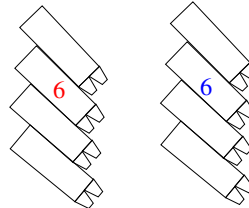
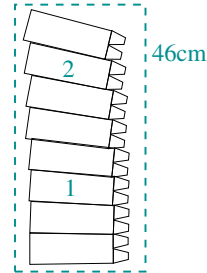
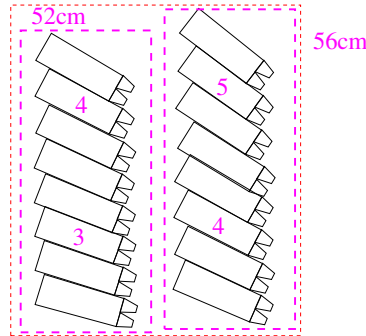
4) same goes with cutting the modules from the support

Geometry & Reconfiguration

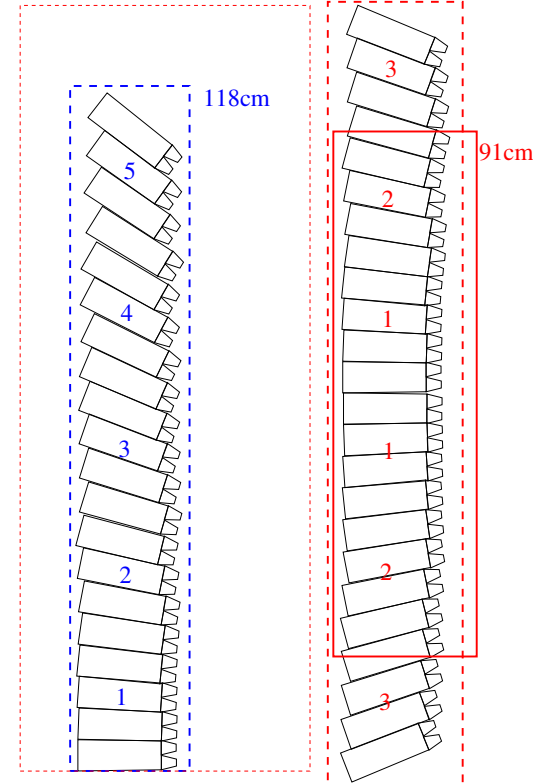
not to scale but particles
would incident like this, so
the lightguides are behind
the blocks

- The goal is to cut as little as possible
- Reuse all blocks and lightguides but must flip side so LG is behind the block
- Right now, all reconfigured sectors are aligned perpendicular to the beamline (solenoid axis), i.e. not “barrel style”

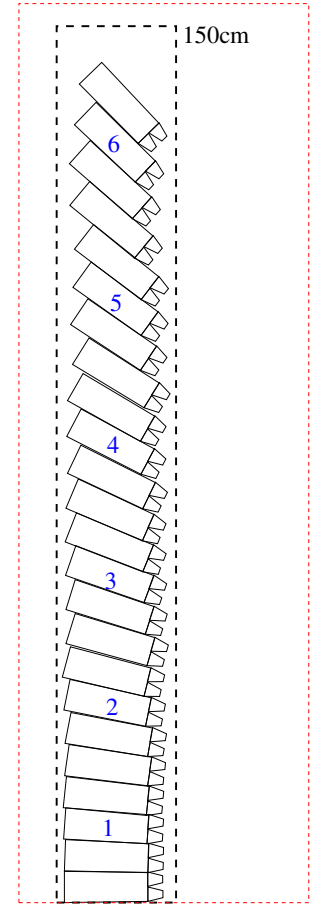
LAEC space



FAEC space



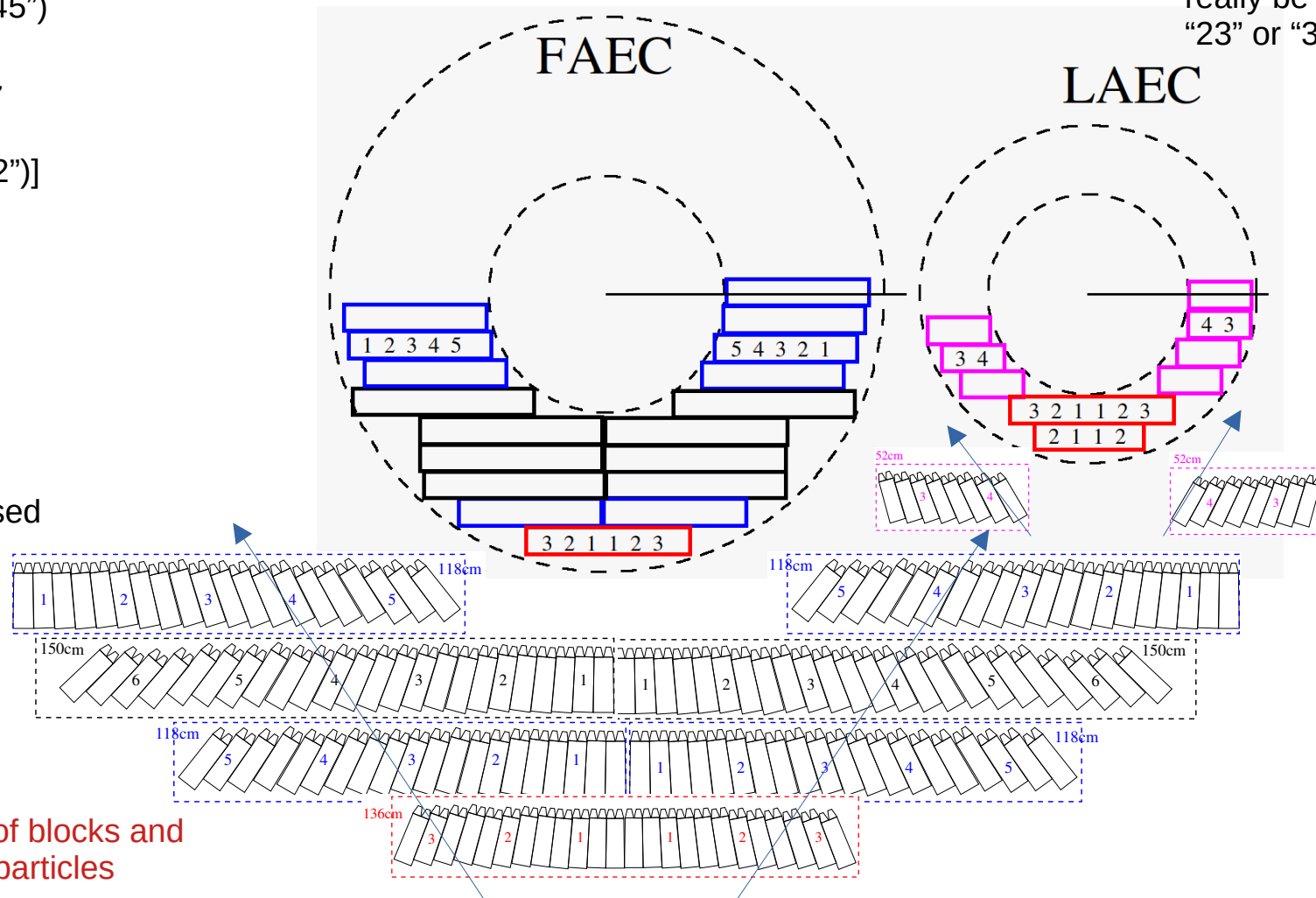
PVDIS EC space



Geometry & Reconfiguration (SIDIS)

note: purple can really be “12” or “23” or “34”

- FAEC would use: 2x [8 original + 9 blue (“12345”) + 1 R (“321123”)]
- LAEC would use: 2x [7 purple (“34”) + 1 R (“321123”) + 1R’ (“2112”)]
- Total sectors used:
 - 16 original
 - + 18 blue (cut into blue/long blue)
 - + 14 (cut into red/purple)
 - leave 16 uncut/unused



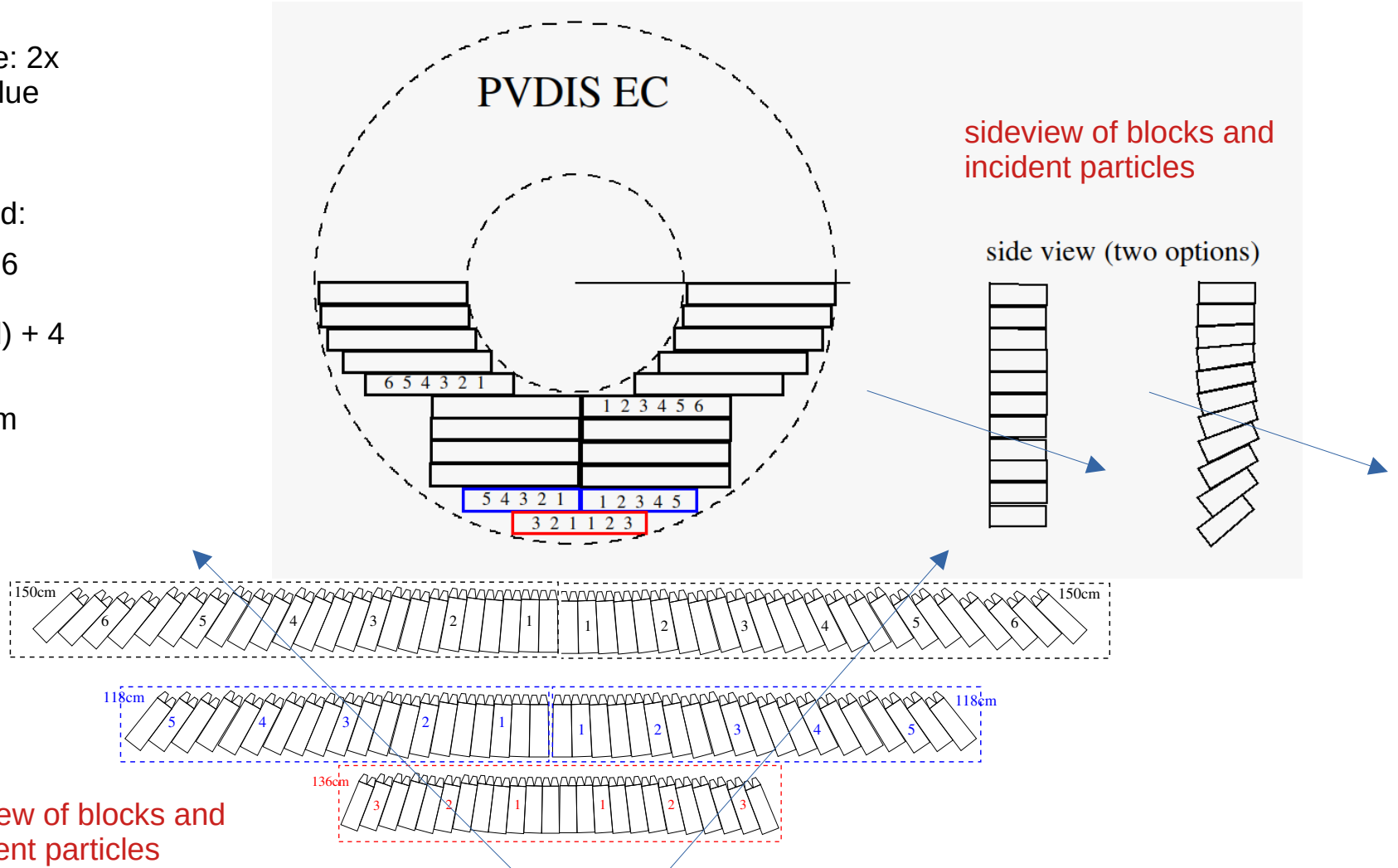
Total #:
 3,936 blocks
 = 3168 (FA) + 768 (LA)
 = 15,744 towers
 = 62,976 SiPMs

topview of blocks and
 incident particles

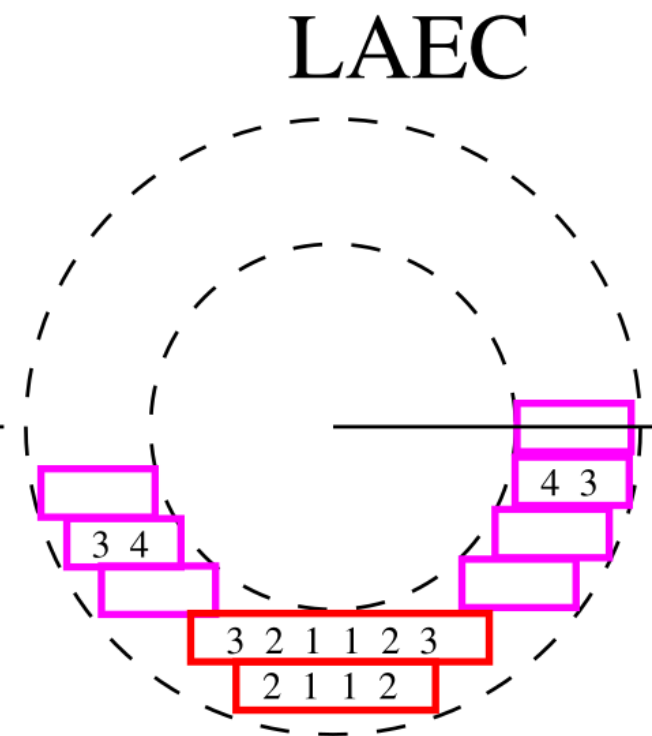
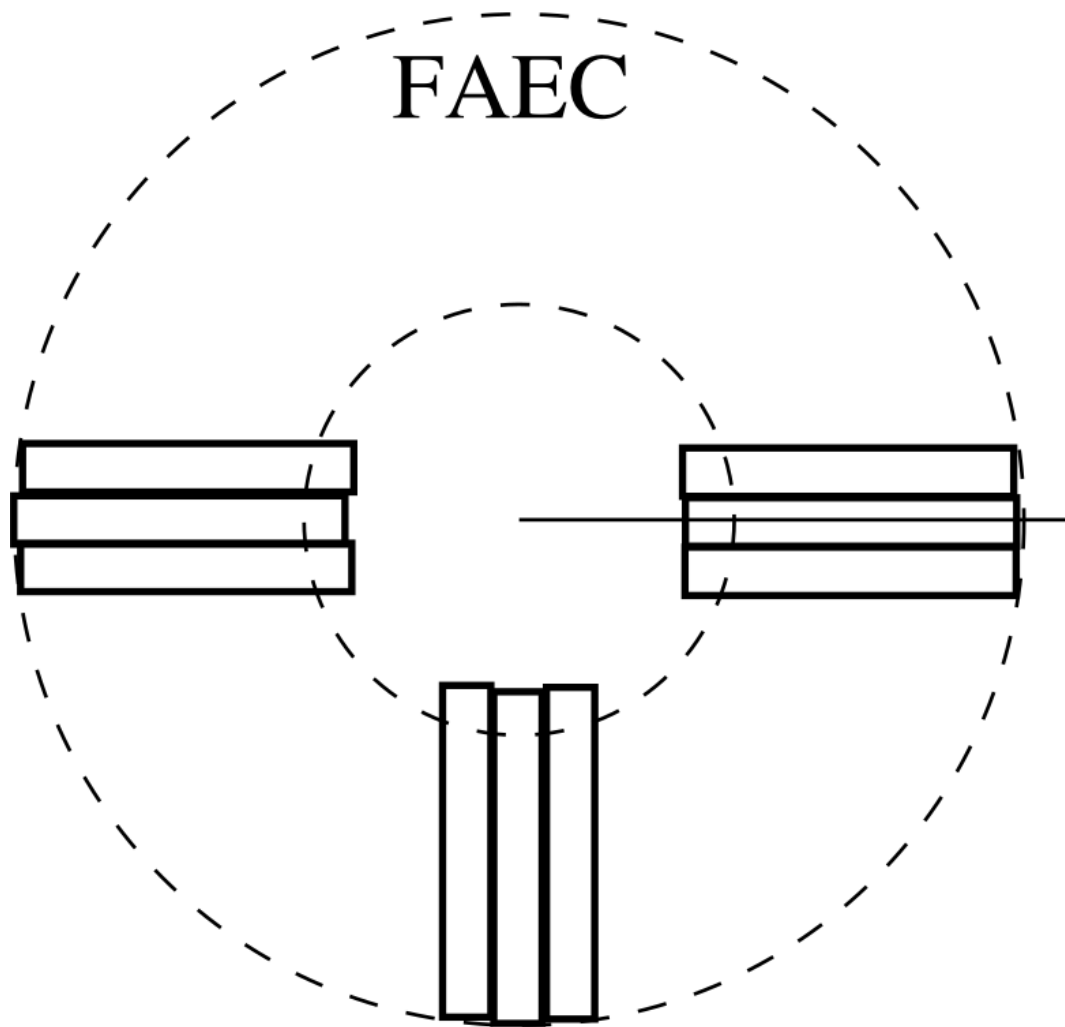
Geometry & Reconfiguration (PVDIS)

- PVDIS would use: 2x
[18 original + 2 blue
("12345") + 1 R
("321123")]
- Total sectors used:
 - 36 original = 16
(SIDIS) + 16
(uncut/unused) + 4
Long-Blue
 - +4B + 2R (from
SIDIS)

Total #:
3968 blocks
= 15,872 towers
= 63,488 SiPMs



4 seg 24 deg FA?



C.A. Aidala et al., <https://inspirehep.net/literature/1789108>, “Design and Beam Test Results for the 2D Projective sPHENIX Electromagnetic Calorimeter Prototype” (2018 prototype)

Light yield calculation:

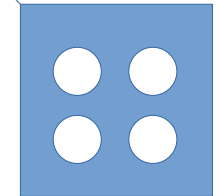
	For 8 GeV electrons:	For MIP particle (assuming 10cm path):
Edep	8 GeV * 2.3% sampling = 184 MeV	2 MeV/cm * 10cm * (20-29)% fill factor = 5.8 MeV
Evis (Birk's effect)	~ Edep/2 = 92 MeV	~ Edep = 5.8 MeV
Nphoton: * 8000/MeV BCF12 efficiency	= 736,000	= 46,400
Nphoton-in-fiber: * 3.4% trapping	= 25,024	= 1578
N photon incident on SiPM: * 15% lightguide	= 3,754	= 237
N pixel fired in SiPM: * 25% PDE	= 938	= 60
N SiPM output electron: * 2.3E5 SiPM gain	= 2.16E8	= 1.36E7
pulse height (assuming 40ns full width)	= 0.0017A	= 0.109 mA
pulse height (in FADC): * 50 Ohm	= 0.086 V	= 5.4 mV

(2 GeV: 0.85mA or ~ 43mV +/- a few mV)

We may want to use a pre-amp of x10

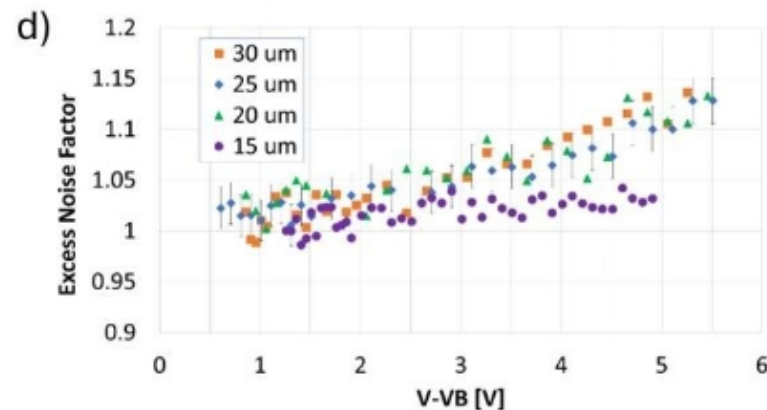
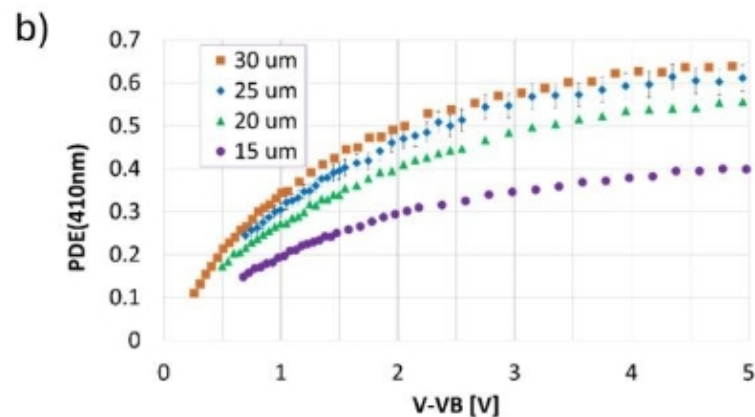
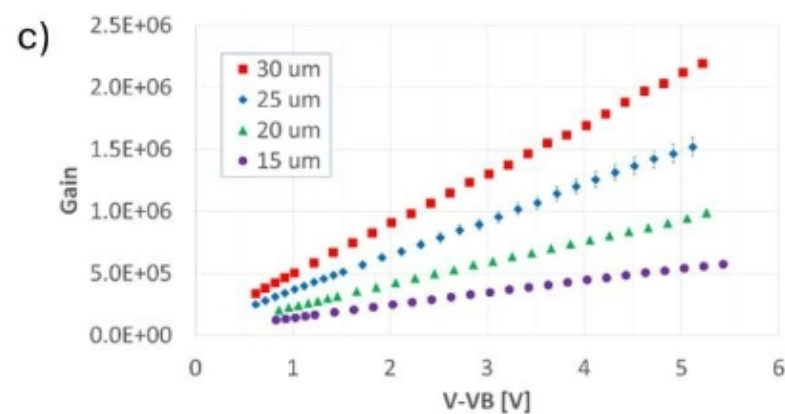
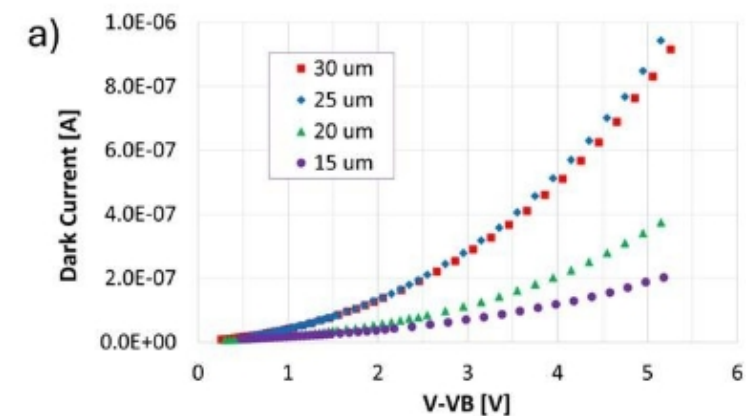
The electron signal will be divided into 16SiPMs so $I_{\text{peak}} = 0.1\text{mA}$ per SiPM
 The MIP signal will be divided into 1-4 towers so $I_{\text{peak}} = 0.008\text{mA}$ per SiPM

each block: 2668 fibers,
 dia 0.47mm, spaced
 1mm center to center.
 The block tapers from
 4x4 to 5.5x5.5cm.



Y. Misienko et al., "Radiation damage studies of silicon photomultipliers for the CMS MIP Timing Detector",
<http://arxiv.org/pdf/2606.10121>

(lower radiation:
<https://inspirehep.net/literature/3177120>



The SiPMs (5 of each cell size) were passively irradiated to a total dose of 2×10^{14} nMeV/cm² (1 MeV equivalent)

All the measurements were performed at $T = -45$ °C inside a commercial freezer [6]

An increase of breakdown voltages was measured after irradiation for all irradiated SiPMs (1.89 V for the 15 μ m SiPM and 0.98 V for the 20 μ m, 25 μ m and 30 μ m SiPMs).

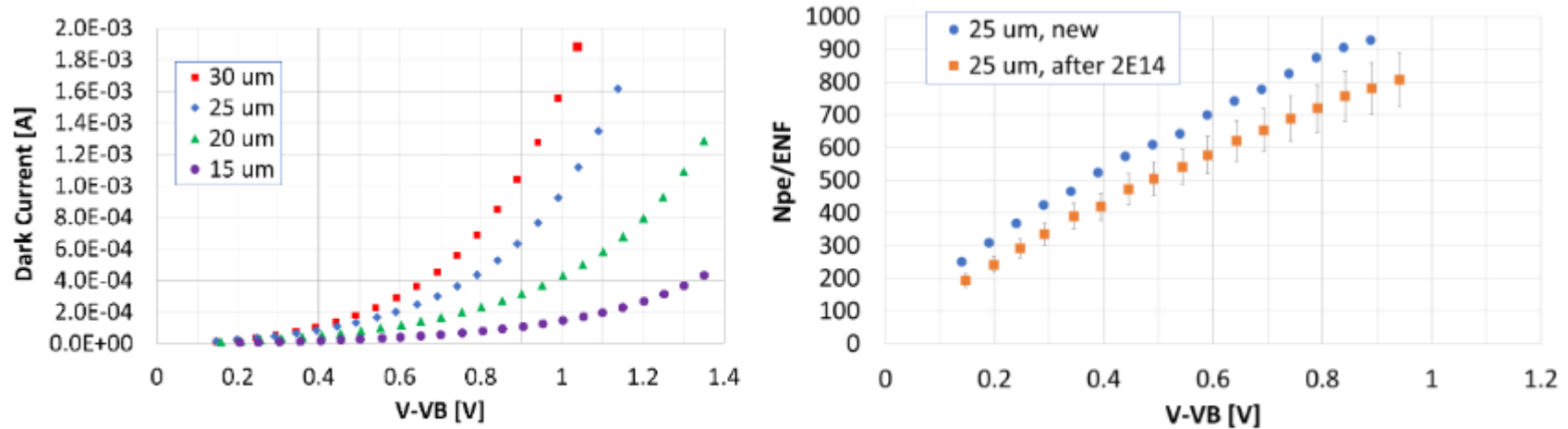


Figure 2. Dark current vs. overvoltage measured for the SiPMs after irradiation and annealing at $T = -45$ °C (left). Dependence of the signal amplitude in photoelectrons on the bias voltage measured for new and irradiated 25 μ m SiPMs at $T = -45$ °C (right).

Thoughts on Readout

1. Lightguide → SiPM area mismatch:

- The lightguide output area is 0.5" sq (1.6cm^2), area matching to 4x (3mm sq) SiPM itself introduces a low efficiency of 22%
- using 4x (6mm sq SiPM) will improve the lightguide efficiency from 15% to 67%
- sensor cost: 64k SiPMs: \$640k for (3mm sq) SiPM (\$10 each) or \$??? for (6mm sq) SiPM (\$? each)
- LV cost:
- FADC (or alternative) cost:

2. Use long clear fiber:

- It doesn't look like we can readout MIP (nor electrons!) under irradiated DCR (see Lorenzo's radiation simulation https://hallaweb.jlab.org/experiment/PVDIS/SoLID/EC/meetings/SoLID_EC_Weekly_minutes.html#20170126)
- Use clear fiber bundle to guide the light out → ~50% efficiency (estimate). The advantage is that (a) we can use PMTs (each block → 4 LG → one 2" PMT); and (b) we can put the blocks in projective direction, reducing cluster spread among blocks.
- sensor cost: 4,000 blocks → 4,000 clear fiber bundles (each going from 4 LG/block to 1 PMT) → 4,000 2" PMTs (\$200 ea) = \$800k
- HV cost:
- FADC (or alternative) cost:

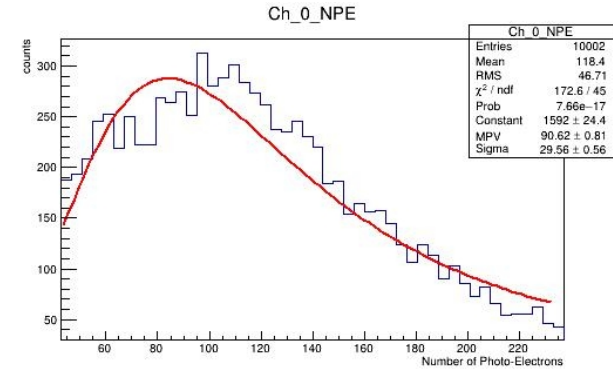
Effect of radiation on the attenuation length of clear fiber, Mengjiao Li and Dong Liu 2024, JINST 19 P11009

<https://iopscience.iop.org/article/10.1088/1748-0221/19/11/P11009>

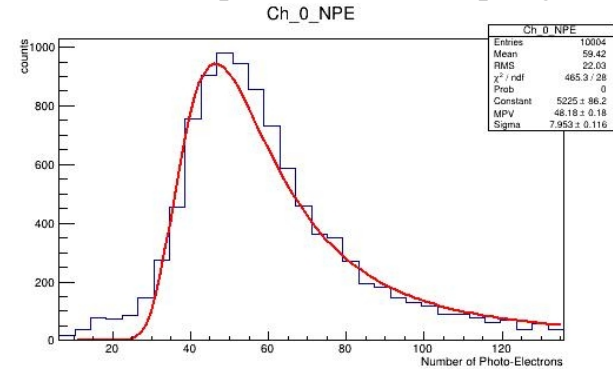
Reported by Mengjiao Li (SDU), 06/17/2021



Number of photons before coupling is 91



Number of photons after coupling is 48



The light loss of green fiber to clear fiber is about **47%** $[(91-48)/91=0.47]$, the attenuation length of the clear fiber is about 17.5m, considering the 3m clear fiber lead to **16%** $[1-\exp(-3/17.5)]$ light loss in transport, we get final light loss from connector of this test is **37%** $[1-(1-47%)/(1-16\%)] \rightarrow$ Xiaochao note: I think 47% is the total loss? my calculation using area matching and cladding thickness gives $0.73 * 0.84$ (attenuation) $* 0.98$ (cladding) = 0.60

Reported by Mengjiao Li (SDU), 06/17/2021

New fiber connector of Chunhui company



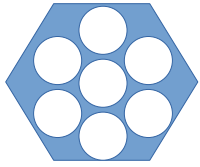
The clear fiber bundle is 3m long

Here are a bundle of 500 clear thin fibers (0.5 mm diameter) →

- Easy to install, only one piece for one Ecal (shashlyk) tower
- Soft, could be bend easily
- Radiation resistance: the same as 1mm PMMA clear fiber



Xiaochao note: 11.2 mm or 0.44" across if in square shape, need a slightly bigger connector for each 0.5" square output area of lightguide.



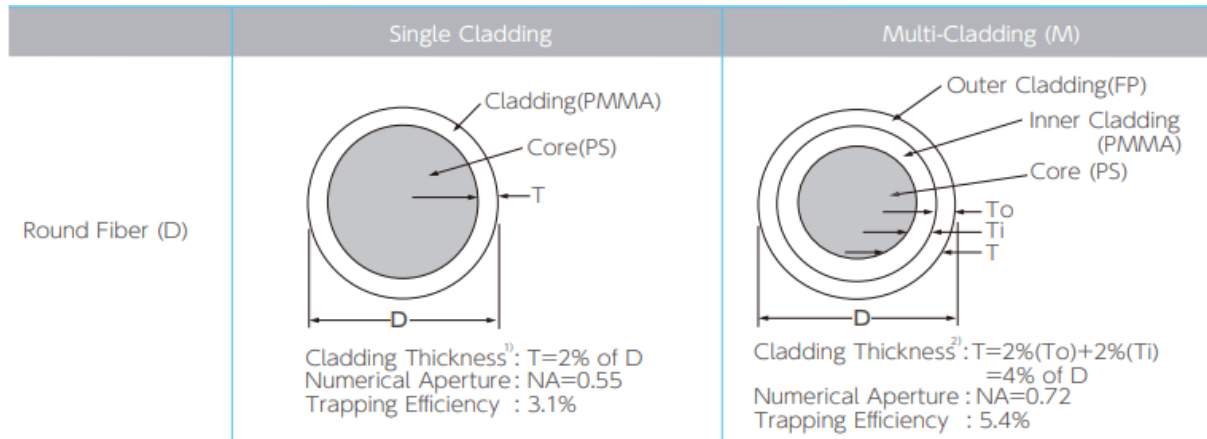
Area matching (resembles a mathcount problem!):

$$R + 2R \times \frac{\sqrt{3}}{2} = a \times \frac{\sqrt{3}}{2}$$

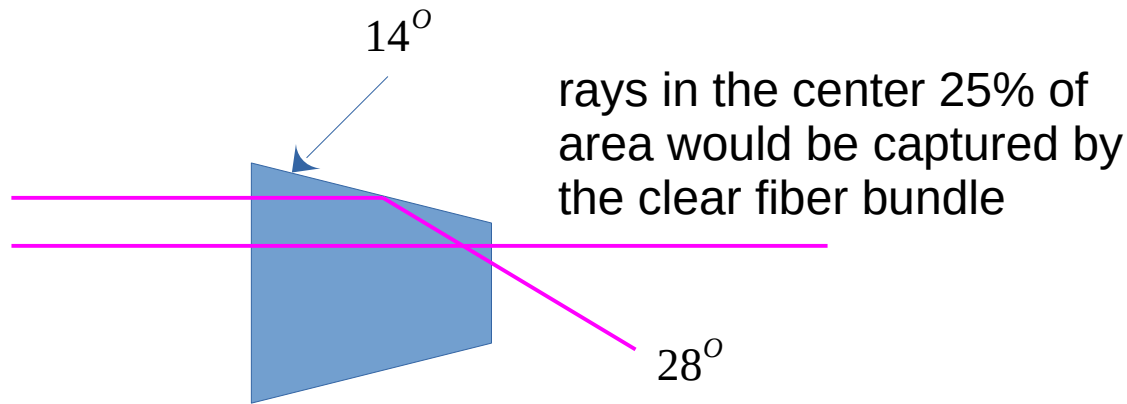
area ratio:

$$\frac{6\pi R^2}{\frac{1}{2}a \times \frac{\sqrt{3}}{2}a} = 0.73$$

Note: matching a fiber bundle to another fiber bundle does **not** square this number, as long as the 2nd fiber bundle covers the full area of the 1st. (The question is: what is the probability for the light to see fiber vs. dead area in the 2nd bundle?)



The same diameter , multi-cladding core is smaller



rays in the outer 75% of area would be lost almost completely



Gemini:

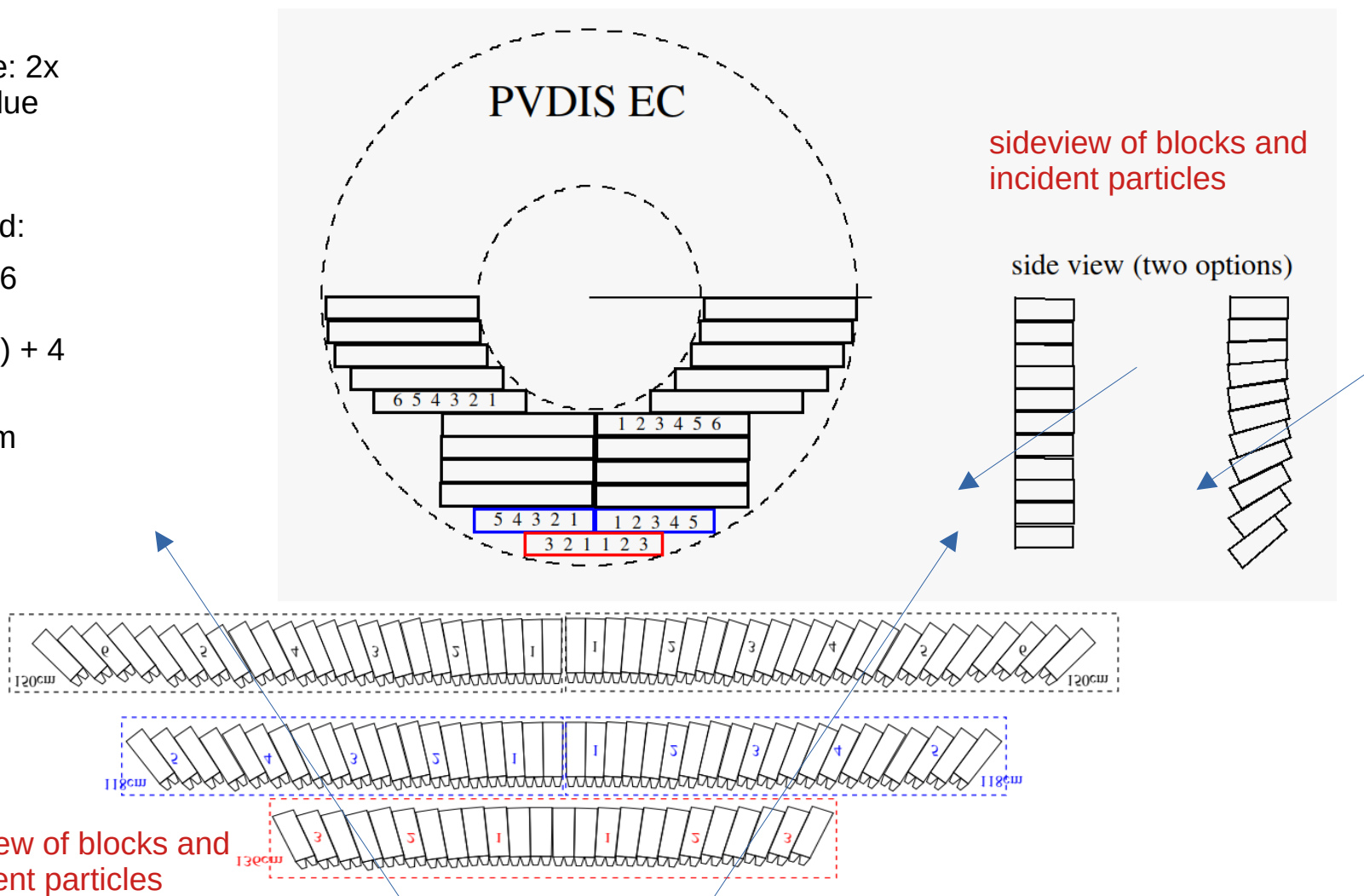
Total System Losses to Consider

The numbers above only account for the *trapping angle* bottleneck. To find your final balance of cost vs. tolerance, you must add the real-world manufacturing constraints of fiber bundles:  Fiberoptics Technology Inc.

Loss Category	Single-Clad Bundle	Double-Clad Bundle
Angular Trapping Loss	75.6%	57.2%
Packing Fraction Loss (<i>gaps between round fibers</i>)	~20% to 30%	~20% to 30%
Fresnel Reflection Loss (<i>air-to-glass interfaces</i>)	~8%	~8%
Estimated Total Light Reaching Cores	~15% to 18%	~28% to 32%

Reversed Orientation

- PVDIS would use: 2x
[18 original + 2 blue
("12345") + 1 R
("321123")]
- Total sectors used:
 - 36 original = 16
(SIDIS) + 16
(uncut/unused) + 4
Long-Blue
 - +4B + 2R (from
SIDIS)



Total #:
3968 blocks
= 15,872 towers
= 63,488 SiPMs

Light yield calculation for fiber bundle design

	For 8 GeV electrons:	For MIP particle (assuming 10cm path):
Edep	8 GeV * 2.3% sampling = 184 MeV	2 MeV/cm * 10cm * (20-29)% fill factor = 5.8 MeV
Evis (Birk's effect)	~ Edep/2 = 92 MeV	~ Edep = 5.8 MeV
Nphoton: * 8000/MeV BCF12 efficiency	= 736,000	= 46,400
Nphoton-in-fiber: * 3.4% trapping	= 25,024	= 1578
* 50% lightguide transmission	= 12,512	= 789
* 25% lightguide tapering	= 3,128	= 197
* 70% clear fiber bundle area matching	= 2,190	= 138
Npe output from PMT: * 25% QE	= 547	= 35
PMT output electron: * 2E6 PMT gain	= 1.09E9	= 6.90E7
cluster splitting (assuming 70%)	= 0.766E9	= 4.83E7
pulse height (assuming 40ns full width)	= 61.3mA	= 0.39 mA
pulse height (in FADC): * 50 Ohm	= 0.3 V	= 19.3 mV
	(2 GeV: 0.15 V)	

could
be 85%

We will need to study the radiation dose in the scintillating fibers

We may want to use a pre-amp of x10

More Thoughts on SPDs

1. FASPD:

- our original design has 240 pieces of 6mm-thick scintillators with WLS fiber embedded on the surface, fragile and low light yield. WLS fibers are connected to clear fibers for readout by MAPMTs.
- what about long scintillator with clear fiber bundle matching the outer end, to PMTs?

2. LASPD:

- current design has 60 long scintillators, lightguide on the outer end.
- FMPMTs discontinued and we hope to use MCP-PMTs, or could use SiPM(??)

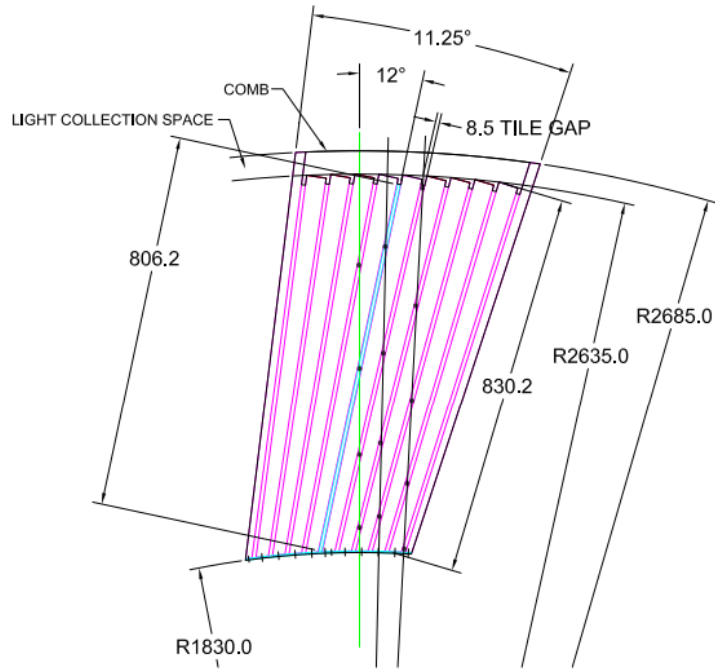


Figure 4.2: Scintillator tiles in a layer of the HCal.

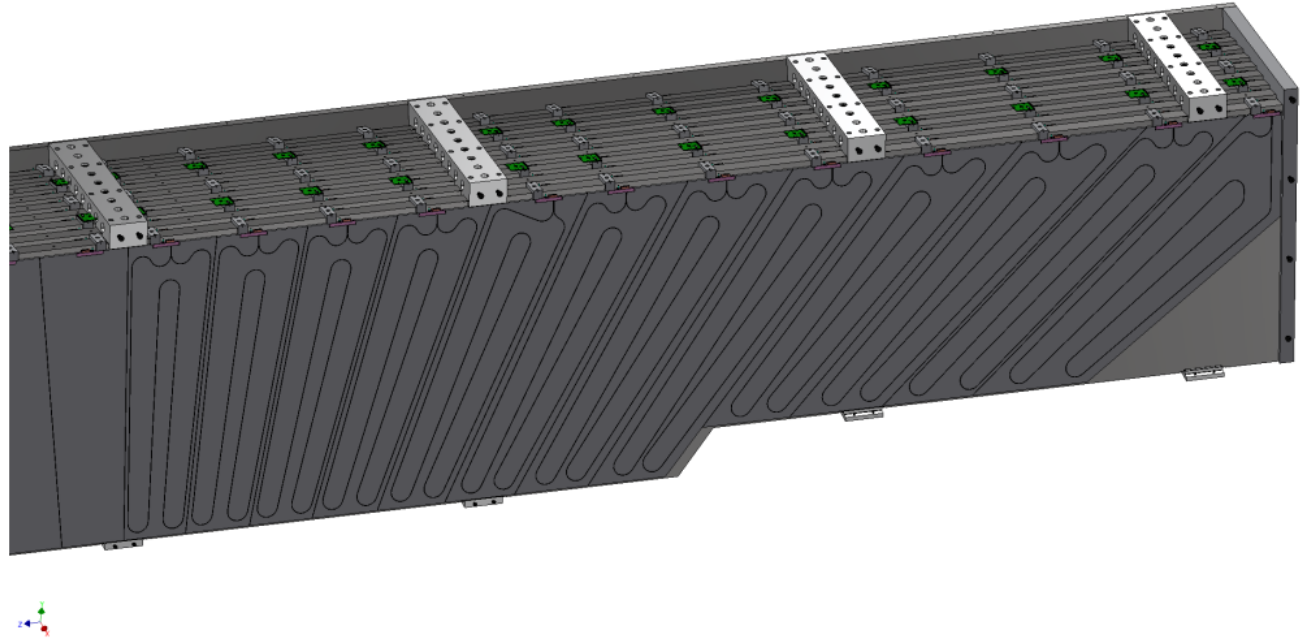


Figure 4.2: Scintillator tiles in a layer of the HCal.

PHENIX → STAR Forward ECal

ECal:

<https://www.osti.gov/servlets/purl/658371>

- Reuse PHENIX Pb-Scintillator calorimeter
 - 1496 channels: $5.52 \times 5.52 \times 33 \text{ cm}^3$
 - $18 X_0$; 0.85 nuclear interaction lengths
- SiPM readout

Table 1: Lead-Scintillator Calorimeter Parameters

Item	Parameters
Lateral segmentation	$5.535 \times 5.535 \text{ cm}^2$
Active cells	66
Scintillator	4 mm, Polystyrene (1.5% PT / 0.01% POPOP)
Absorber	Pb, 1.5 mm
Cell thickness	5.6 mm ($0.277 X_0$)
Active depth	375 mm
WLS fibers per tower	36
Fiber	BCF-99-29a, 1 mm
PMT type	FEU115M, 30 mm, MELS, Russia
Photocathode	Sb-K-Na-Cs
Luminous sensitivity	$\geq 80 \mu\text{a/lm}$
Rise time (20%–80%)	$\leq 5 \text{ ns}$

Backup slides – info from
sPHENIX TDR

sPHENIX used:

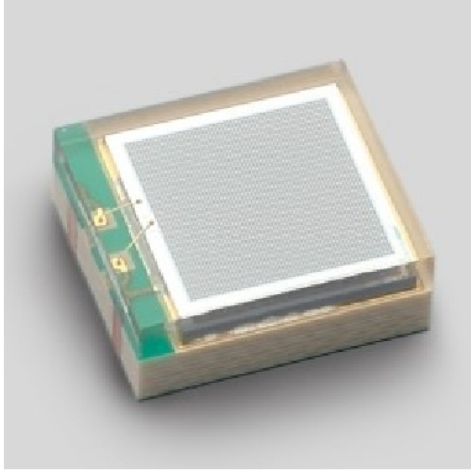


Figure 5.3: Hamamatsu S12572 MPPC (SiPM). The device is $3 \times 3 \text{ mm}^2$ with 40,000 pixels $15 \mu\text{m}^2$.

Hamamatsu recommends:

S14160-3010PS/3015PS

https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/ssd/s14160-1310ps_etc_kapd1070e.pdf

($3 \times 3 \text{ mm}^2$ costs about \$5 each)

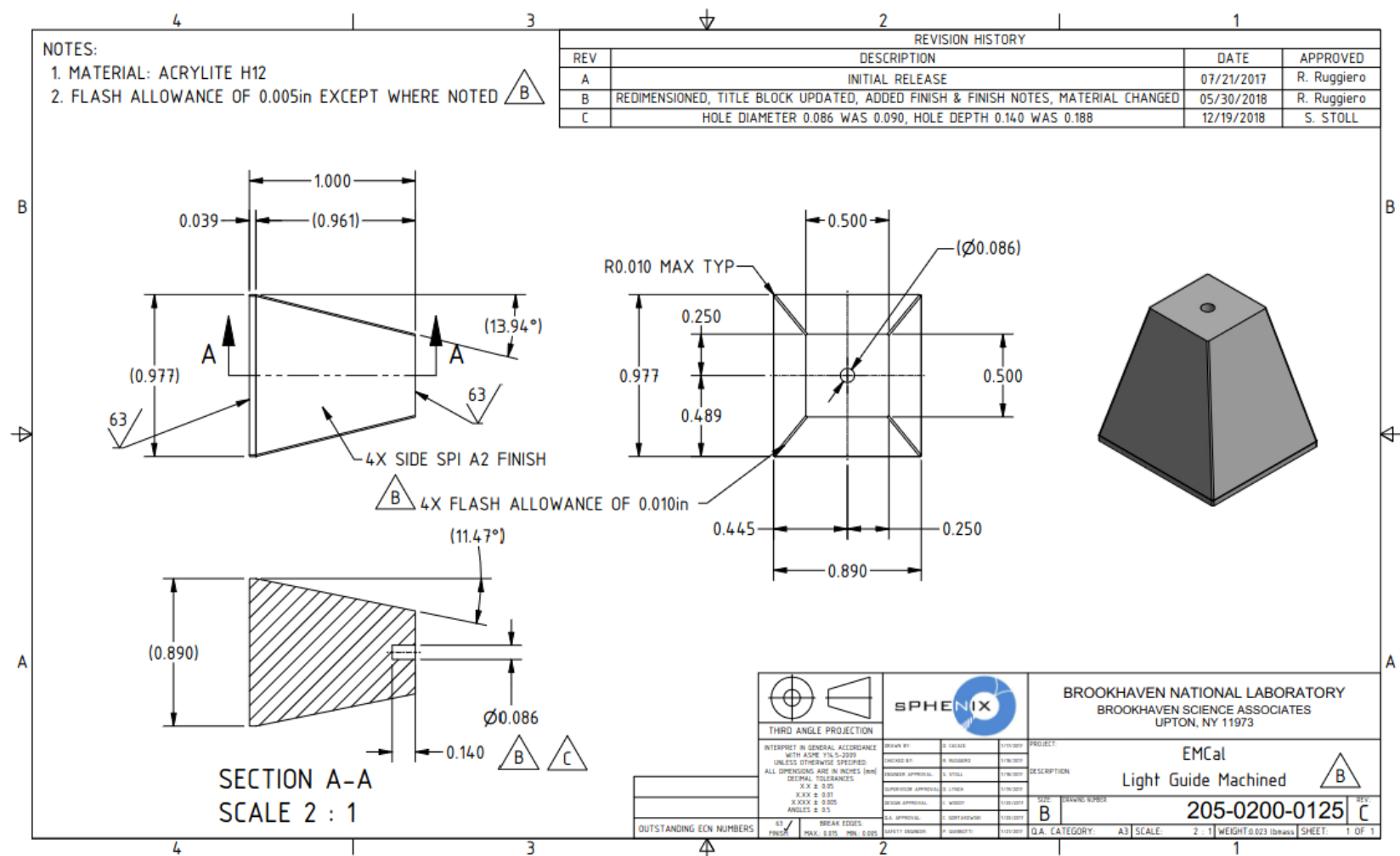


Figure 3.13: Final design for the EMCAL light guides.

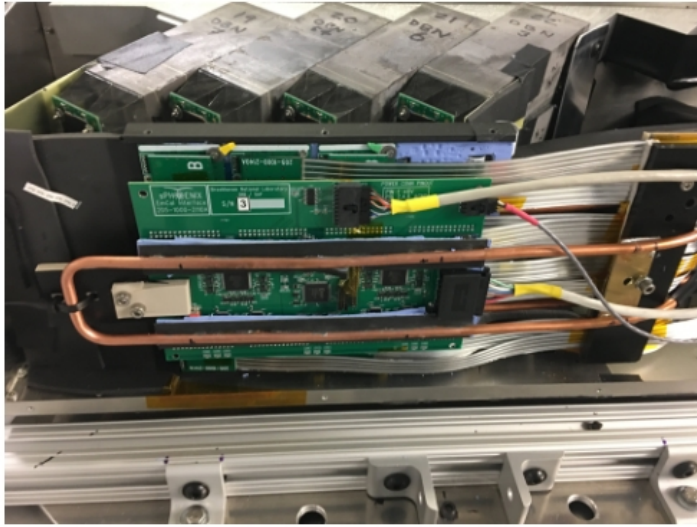


Fig. 4. EMCAL prototype showing the EMCAL blocks, light guides, SiPMs, electronics and part of the cooling system.

More Q&A with Sean S.

- 1) Edep of MIP particles and 8 GeV electrons? N_{pe} (with gain)?
- 2) Typical radiation background?
- 3) SiPM typical dark current rate? biasing current: 30nA (increased to) $\rightarrow$ 1E2 microA
- 4) readout $\rightarrow$ BNL pre-amp/electronics + 25k FADC (Columbia) channels
- 5) CAD ?
- 6) 4x4 block prototype; maybe 3-4 but different designs; with readout/cooling (3 loops) 0C for SiPM noise, others for preamp