ECal and SPD Updates

The SoLID ECal Working Group + ECal Beam Test Analysis Team

SoLID Collaboration Meeting

July 7-8, 2025

Outline

1. Hall C ECal Beam Test Overview
2. Beam Test Analysis Progress – since January collaboration meeting
   - PID for charged pions
   - Shower PMT bench testing pictures
   - ML PID (see next talk)
3. Existing radiation hardness data
4. Summary and Outlook

Test Overview

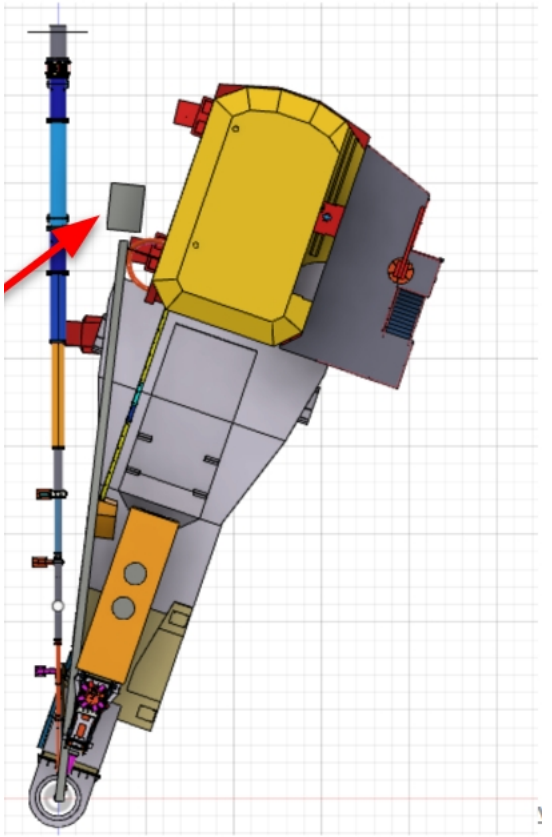
Most/all 18-deg data were taken during E12-10-003 (deuteron electro-disintegration), from Feb. to March 2023

Run	Target	(g/cm^2)	I_{beam} (μA)	$\mathcal{L}$ $(cm^{-2}s^{-1})$
prod.	LH_2	0.71	10	2.7×10^{37}
prod.	LD_2	1.69	10	3.2×10^{37}
$\mathcal{L}$ scan	LD_2	1.69	$15-70$	$(4.8-22) \times 10^{37}$
	carbon	0.574	$15-70$	$(0.3-1.3) \times 10^{37}$
	aluminum	0.476	$15-70$	$(1.0-4.6) \times 10^{36}$

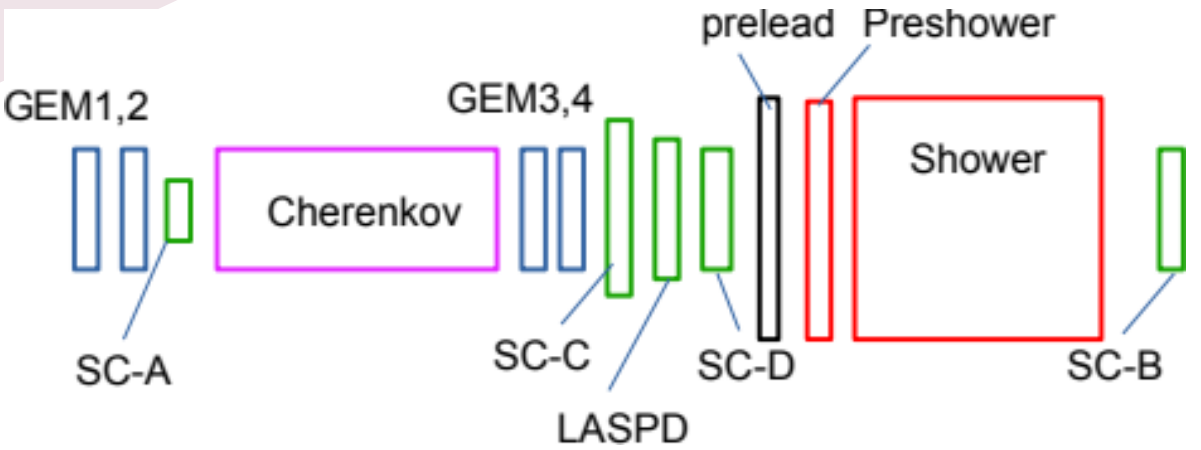
TABLE IV. Target and beam currents used for 18° data taking, including production and luminosity scans. The

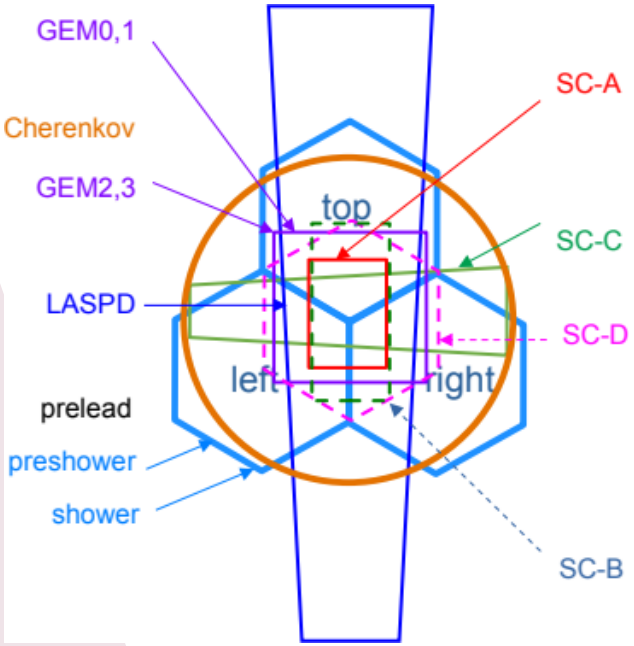
Experiment	Target	I_{beam} (μA)	$\mathcal{L}$ (max) $(cm^{-2}s^{-1})$	Rates (kHz)
SIDIS (n)	40-cm $^3\vec{He}$	15	1.0×10^{36}	100
SIDIS (p)	3-cm $N\vec{H}_3$	0.1	1.0×10^{35}	(10)
J/ψ	15-cm LH_2	3	1.2×10^{37}	30
PVDIS (d)	40-cm LD_2	50	8.0×10^{38}	15×30
PVDIS (p)	40-cm LH_2	50	6.7×10^{38}	(15×13)

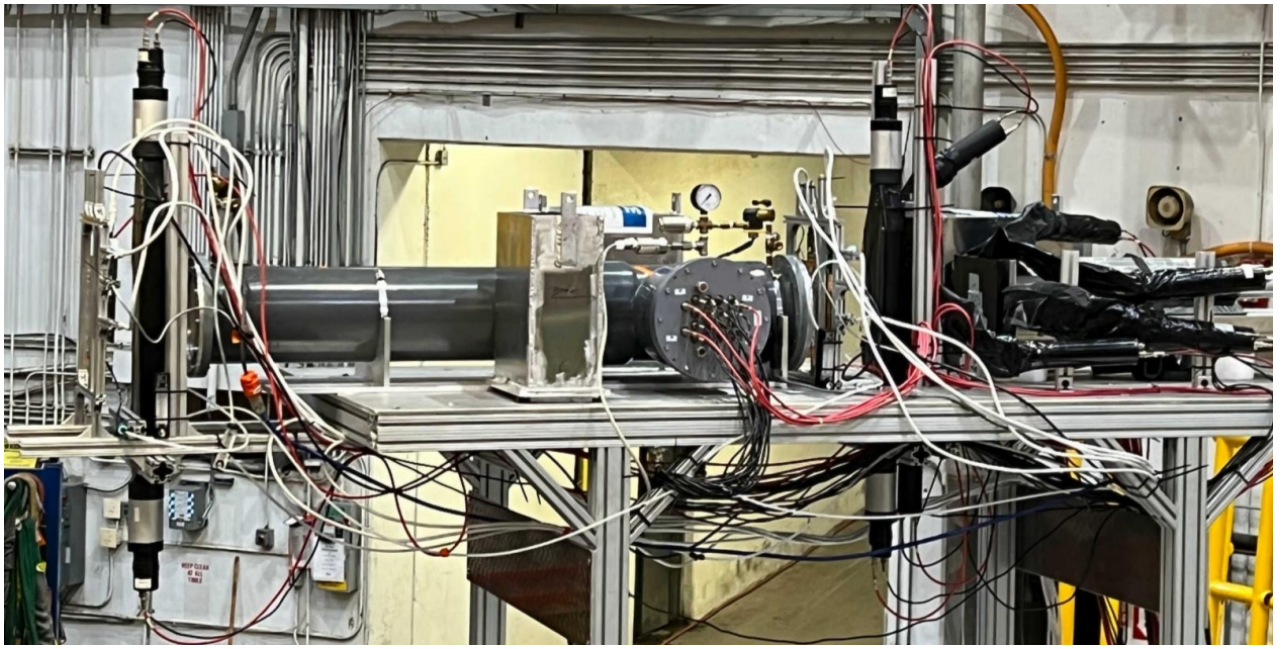
TABLE V. Run conditions for SoLID that include the three main experimental programs. For each program, the maximum luminosity and rates are shown. The

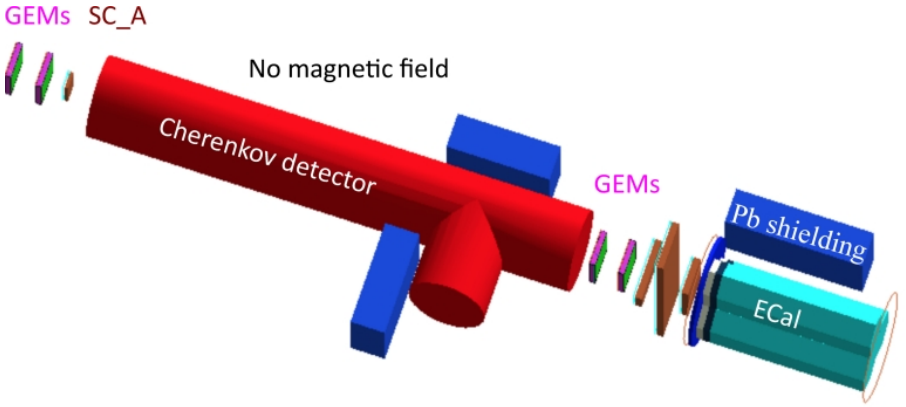


Setup Overview







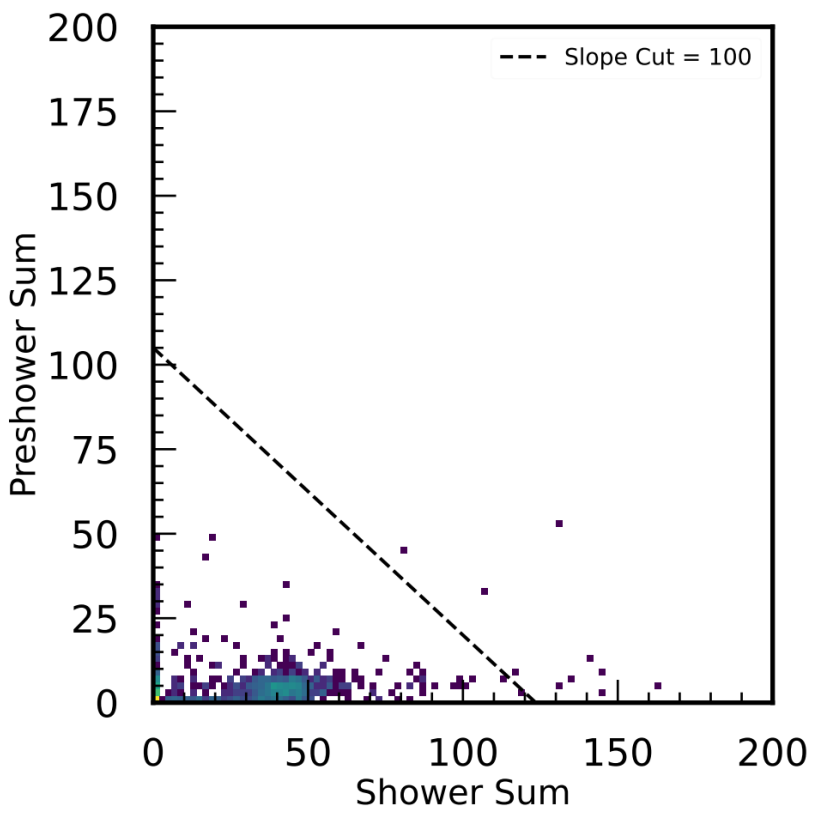


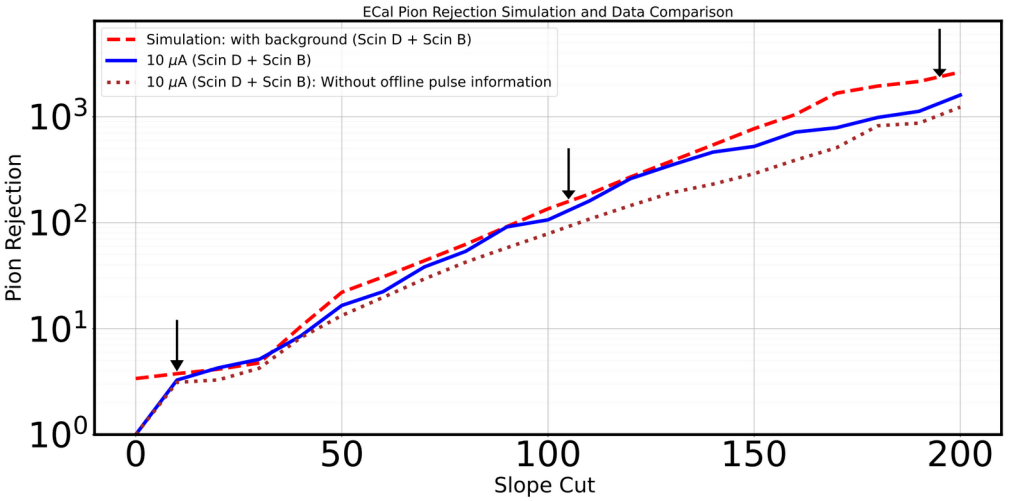
PID Performance

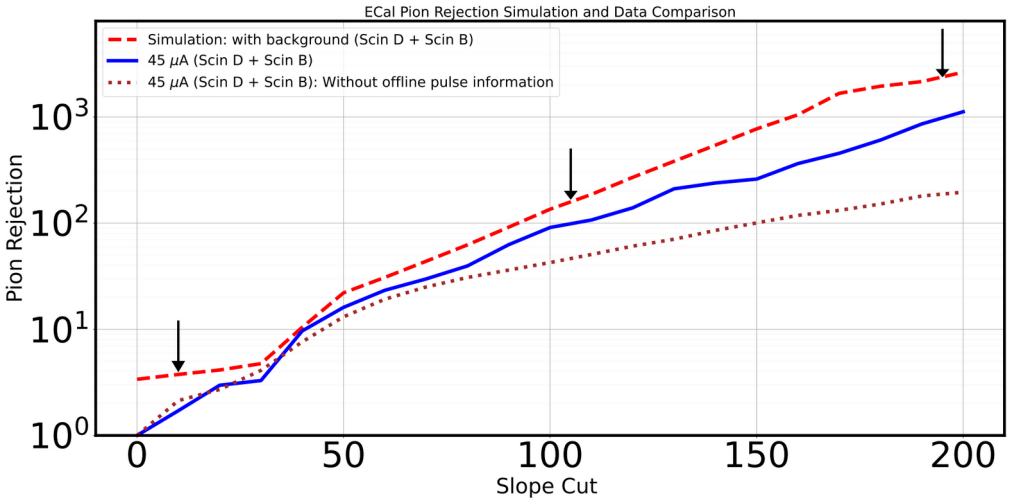
Charged Pion Samples: TS2 events with:

- CerSum<100
- SC-C>500
- LASPD-T(B)>10

A “slope cut” is then applied to study pion rejection of ECal

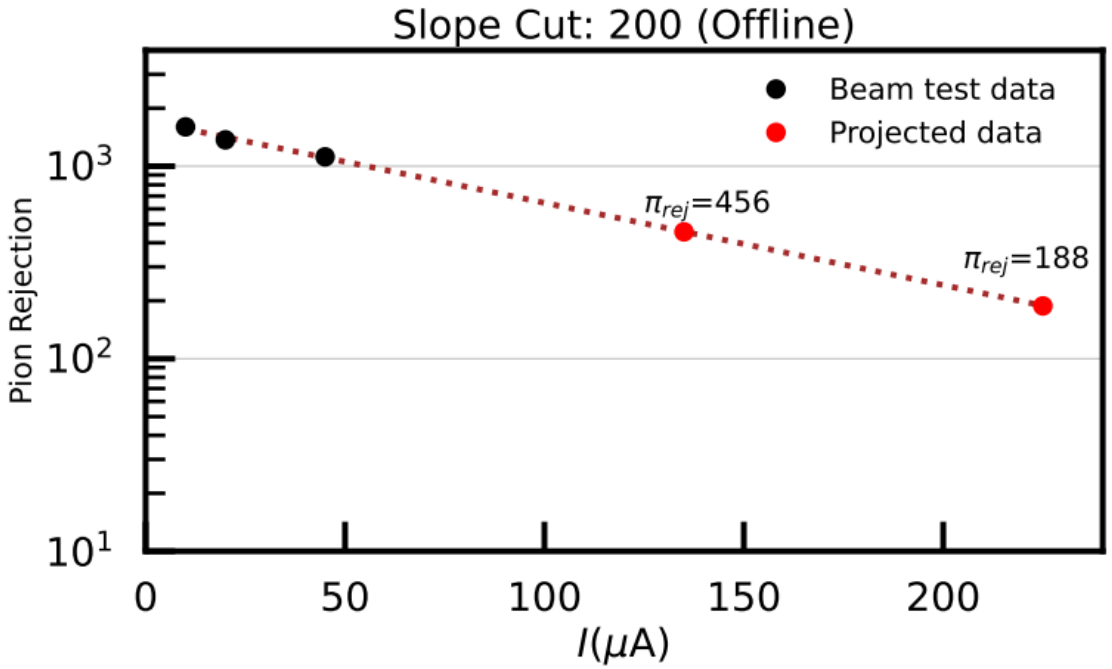


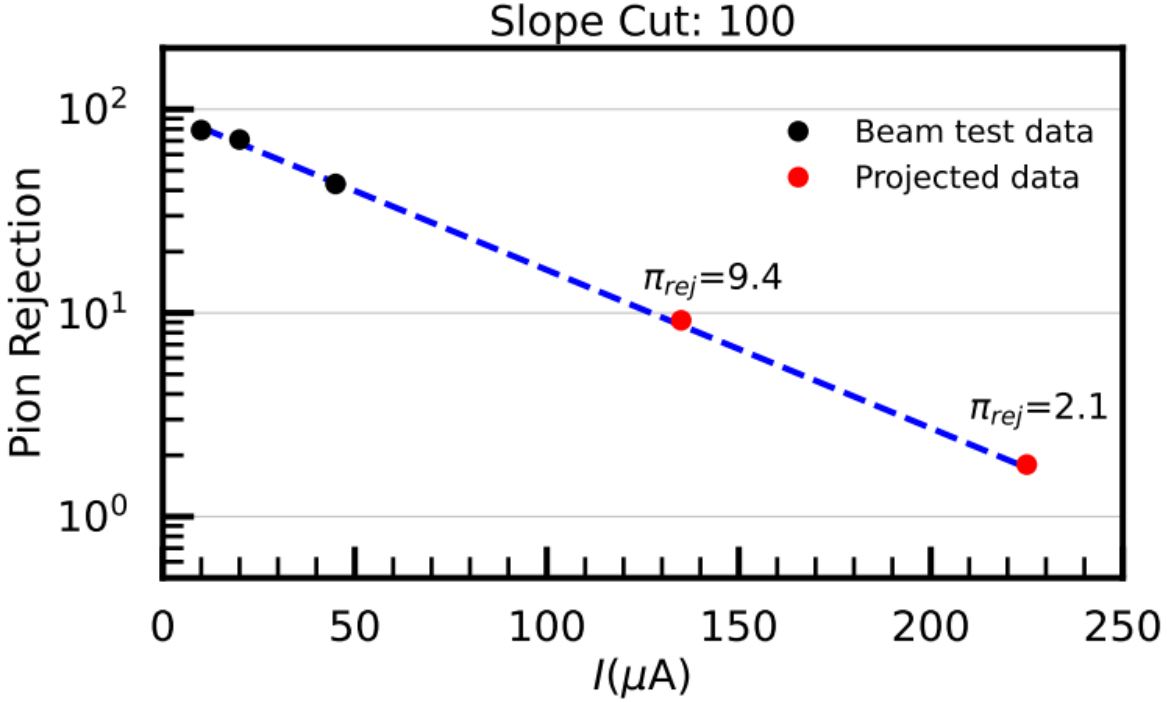




- Arrows in the figure correspond to a 95% electron efficiency for electrons in ranges of (0-1], (1-2], and (2-3] GeV, as determined by simulation
- The three curves are: simulation, data with waveform “cleaning”, and data without waveform “cleaning”

PID Performance – extrapolate to PVDIS running





Offline projection shows that the ECal can provide a factor 100 or better pion rejection for SoLID offline data analysis for all of its physics programs.

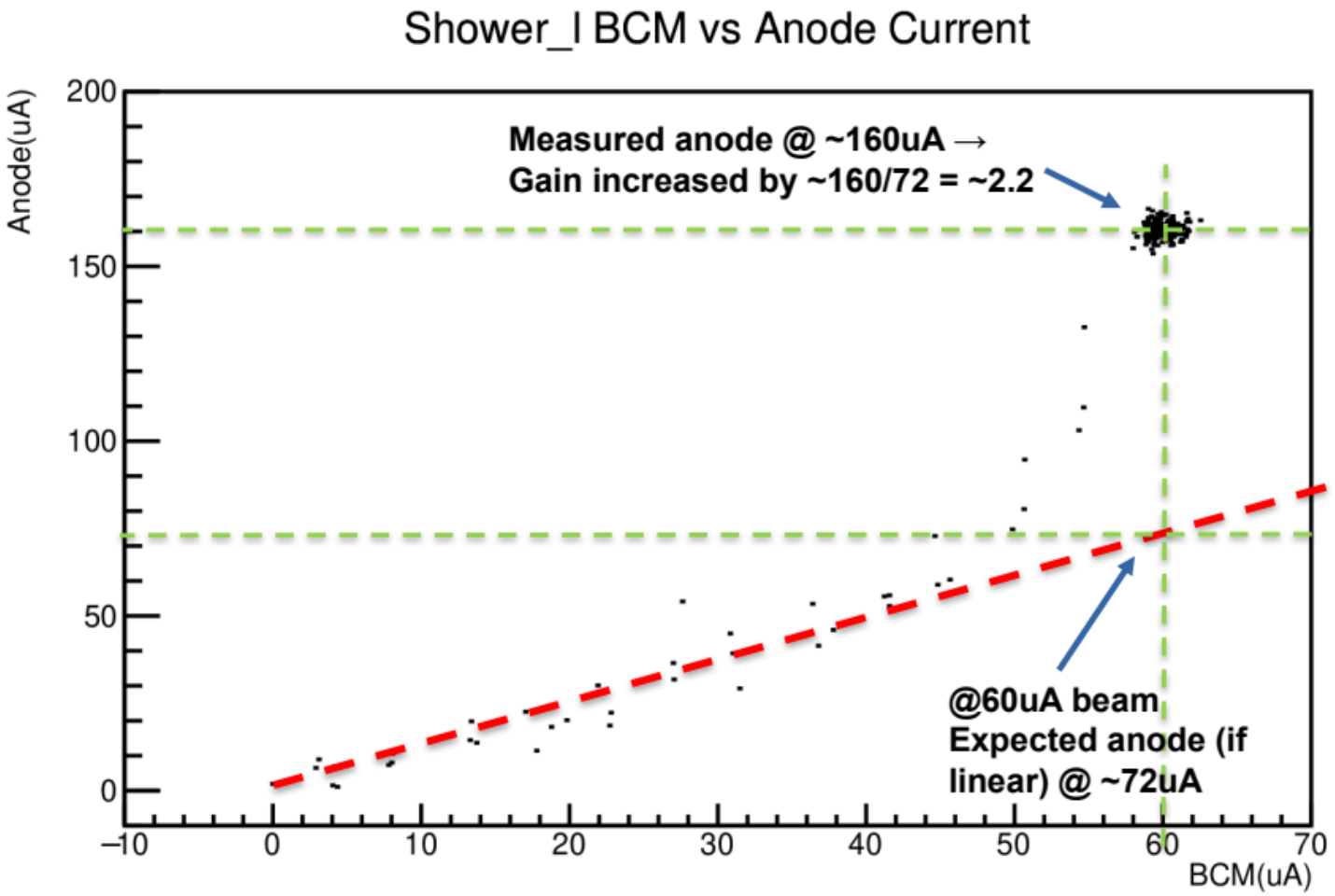
	Desired performance
π^- rejection	$\gtrsim$[50:1]
e^- efficiency	$\gtrsim$90%
Energy resolution	$< 10\%/\sqrt{E}$
Radiation resistance	$\gtrsim$400 kRad
Position resolution	$\lesssim$1 cm

14: Overview of the SoLID calorimeter desired perfo

For **online triggering**:

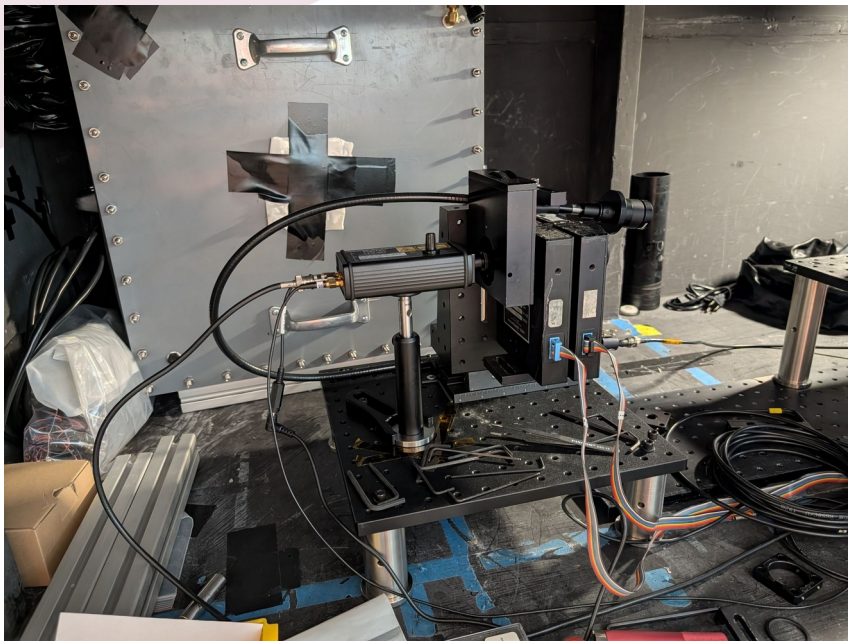
vs. preCDR value/requirement of:
SIDIS FA (2-3):1
SIDIS LA (20-100):1
PVDIS 2:1

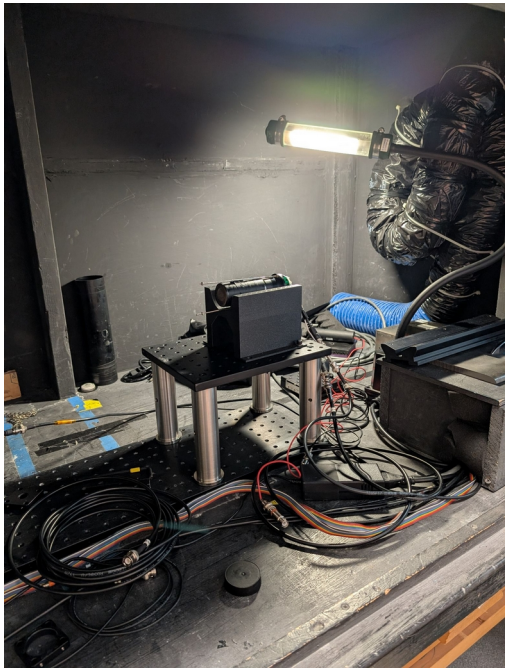
Shower PMT Gain Shift



- Figures made by Ben Raydo (JLab)
- Non-linearity starts at an anode current of 50 uA (Shower Left) or 20-30 uA (Shower Right, Top) – vs. PMT max recommended anode current of 100 uA!

Carl’s darkbox setup is complete
Laser with diffuser and filter wheels, 10-20% increments of intensity
LED is connected to waveguide and a diffuser as well, LED is powered by a function generator
PMT on 3D-printed stand





signal generator for laser

Power supply for LED

Latest simulation gives for the Preshower:

30krad/month for PVDIS. Assuming 6 months of running (180 PAC days), this leads to 180 krad for each calendar year or for the total requested ~180 PAC days.

The following data are from ATLAS, JLab (our data), and SDU (IMP, though incomplete and I have followed up with them)

ATLAS test on WLS fibers:

100krad: Kuraray loss ~ 13% loss; Saint Gobain loss ~17% loss

700krad: Kuraray loss ~ 29% loss; Saint Gobain loss ~ 46% loss

Hall A test on Preshower, up to 180 and 230-286 krad. 15-40% loss (after repositioning fibers)

SDU/IMP test:
121 krad: sample #4
353 krad: sample #5 received only recently, not tested yet

at 121 krad:
- did not observe color change or degradation of mechanical property of fibers for samples 1-4
- PMMA (clear) fiber attenuation length dropped from ~15m to 10m at #4
- WLS fiber (BCRF91A) light output drops to 80% for #4
- scintillator: only slight drop for #4

Beam test summary

- Analysis of the beam test is complete and report 99% ready for review and comments by the collaboration

- Radiation dose study is being looked into
- AI/ML PID analysis is well underway and promising – see Darren's talk
- Some followup study or measurement are needed (ideally):
  - PMT passive base bench testing – ongoing
  - Effect of material non-uniformity in ECal energy resolution (as shown in FTBF report) – ongoing
  - Cherenkov mirror reflectivity (?)
  - radiation hardness of optical grease/glue (existing data?)

- For SoLID ECal, we still need (pre)R&D on:
  - MAPMT readout of Preshower (unless we decide on using regular PMTs – much safer but higher cost)
  - MCP-PMT readout of LASPD
  - PMT active base design and testing → R&D

Backup Slides

ATLAS: NIMA 453 (2000) 255

[Zhiwen's presentation on 02/12/2013]

1Gy=100rad

100krad:
- Kuraray loss ~ 13% loss;
- Saint Gobain loss ~17% loss

700krad:
- Kuraray loss ~ 29%;
- Saint Gobain loss ~ 46%

some recovery after 10 days is observed but not large for BCF91A and Y11

vs. PVDIS 180 PAC days → 180 krad

Table 1
Optical properties of each type of WLS fibers before the irradiation. Average light output at 140 cm and RMS, average attenuation length (L_{att}) and RMS, for ten fibers of each type. The values are normalized to I_{140} of the Y11(200)MSJ fibers

Fiber type	I_{140}	RMS (%)	L_{att} (cm)	RMS (%)
BCF91A MC	0.98	9.6	280	9.5
Y11(200)MSJ	1.00	1.8	280	1.6
S250-100	0.81	5.7	230	5.6

Table 2
Relative light output at $x = 140$ cm, for total doses of 1.16 and 6.93 kGy

Fiber type	$\frac{R(140)}{R(30)}$ for 1.16 kGy			$\frac{R(140)}{R(30)}$ for 6.93 kGy		
	0 days	1 day	10 days	0 days	1 day	10 days
BCF91A MC	0.83	0.86	0.85	0.54	0.56	0.56
Y11(200)MSJ	0.87	0.92	0.91	0.71	0.72	0.74
S250-100	0.60	0.70	0.81	0.52	0.55	0.64

116krad 693krad

Vince's presentation on 01/02/2017

Irradiative Preshower Results

A significant portion (~half) of the light loss seems to be from optical grease degrading

Tile #	Radiation Dose	Before Radiation	With Old Grease	After Replacing Grease	After Replacing Fibers	After Replacing Tyvek Wrapping
Kedi 1	161-164 kRad	87.1	56.6	74.4#	73.3#	N/M
Kedi 2	185-189 kRad	85.4	57.6 (fibers were kinked)	67.3	68.0^	80.3
Kedi 3	31-38 kRad	87.0	66.0	69.7#	77.3	N/M
Kedi 4	9-17 kRad	91.0	55-74*(?) (broken fiber replaced)	86.5#	N/M	N/M
CNCS 1	156-172 kRad	83.4	56.2	49.7^	70.0	N/M
CNCS 2	43-53 kRad	84.7	61.6	71.0	74.5	N/M
CNCS 3	20-24 kRad	81.8	62.5	69.3	N/M	80.2
CNCS 4	230-286 kRad	83.4	41.2	47.2	54.0	58.9

These measurements were taken with PMT S/N 27587 and produced reliable results.
(N/M) no measurement was taken for these configurations. For CNCS 3, both the fibers and Tyvek wrapping were replaced at the same time.

3

SDU fiber and scintillator irradiation test (IMP, Lanzhou)

Dong Liu and Mengjiao Li's presentation on 05/20/2021

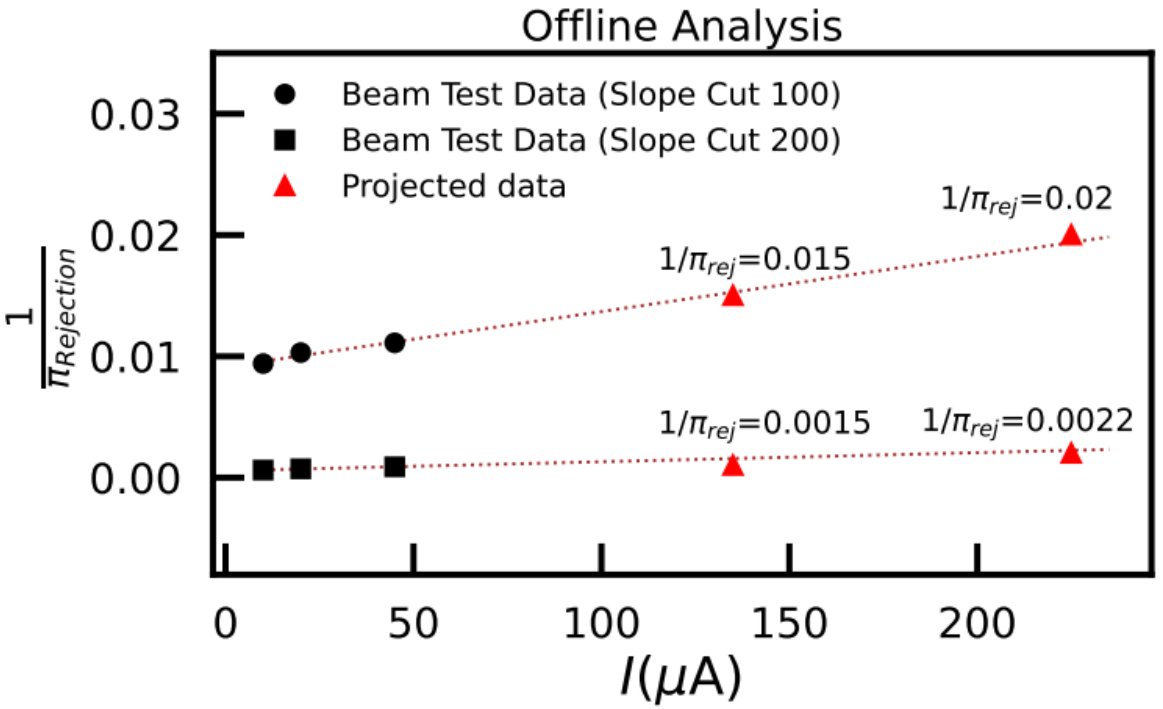
	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
Total Irradiation (MeV/cm^2)	8.569E+11 $10^{11.94}$	1.360E+12 $10^{12.13}$	2.807E+12 $10^{12.45}$	3.665E+13 $10^{13.56}$	1.070E+14 $10^{14.03}$
Test material	BCF98-SC 3m*2 BCF98-SC 6m*1 PMMA 2m*3	BCF98-SC 3m*2 BCF98-SC 6m*1 PMMA 2m*3 BCF91A-MC*3 scintillator*1	BCF98-SC 3m*2 BCF98-SC 6m*1 PMMA 2m*3 BCF91A-MC*3 Scintillator*1	BCF98-SC 3m*2 BCF98-SC 6m*1 PMMA 2m*3 BCF91A-MC*3 Scintillator*1	BCF91A-MC*3 Scintillator*1
	2.83 krad	4.49 krad	9.26 krad	120.9 krad	353 krad

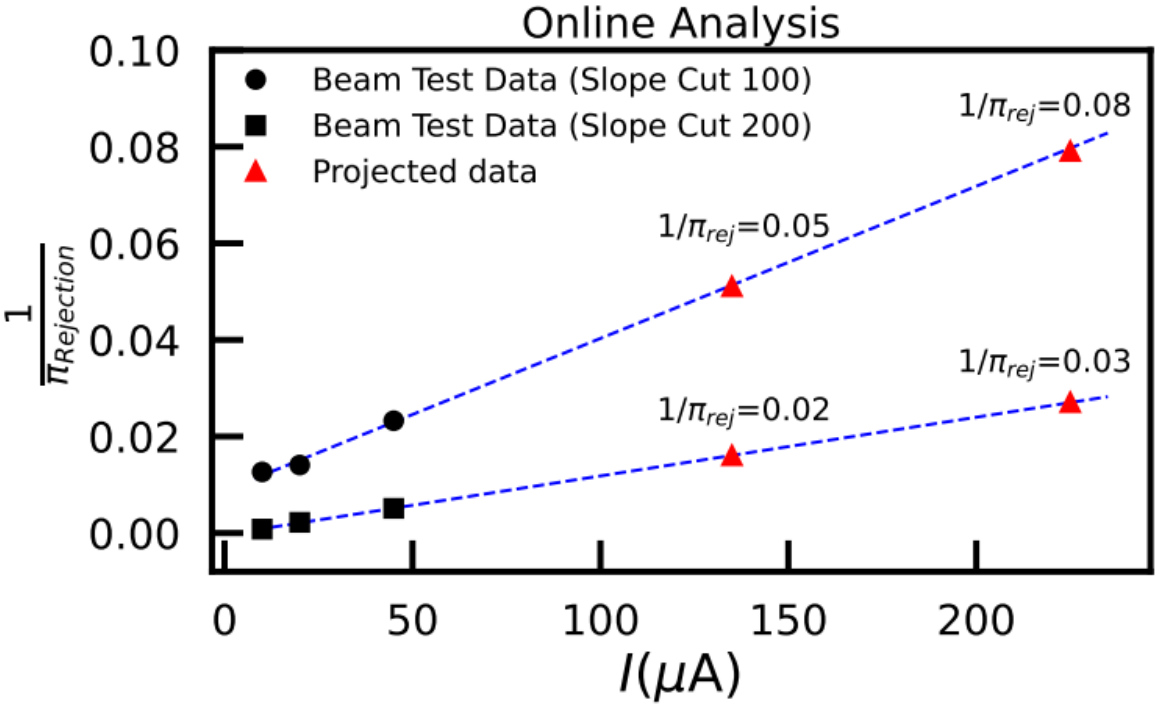
2.12E+14
$10^{14.33}$

700 krad

- Note: 1-n-MeV/cm2 approx= 3.3E-11 Gy and 1Gy=100rad, see Lorenzo's talk at ? …
- Did not observe color change or degradation of mechanical property of fibers for samples 1-4
- PMMA fiber attenuation length dropped from ~15m to 10m at #4
- WLS fiber (BCRF91A) light output drops to 80% for #4
- scintillator: only slight drop for #4

- Sample #5 only recently arrived at SDU, has not had people power to test them.


Offline Analysis
Beam Test Data (Slope Cut 100)
Beam Test Data (Slope Cut 200)
Projected data
$1/\pi_{rej}$=0.02
$1/\pi_{rej}$=0.015
$1/\pi_{rej}$=0.0015
$1/\pi_{rej}$=0.0022
$\frac{1}{\pi_{Rejection}}$
0.03
0.02
0.01
0.00
0
50
100
150
200
$I(\mu A)$


Online Analysis
Beam Test Data (Slope Cut 100)
Beam Test Data (Slope Cut 200)
Projected data
$1/\pi_{rej}$=0.08
$1/\pi_{rej}$=0.05
$1/\pi_{rej}$=0.03
$1/\pi_{rej}$=0.02
$\frac{1}{\pi_{Rejection}}$
0.10
0.08
0.06
0.04
0.02
0.00
0
50
100
150
200
$I(\mu A)$

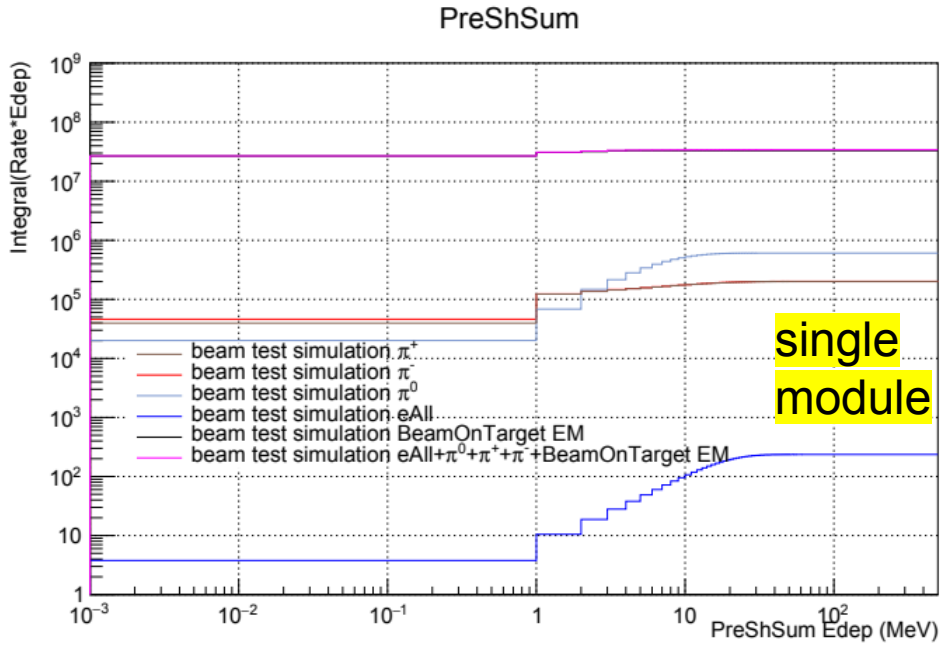
PreShower Radiation Dose

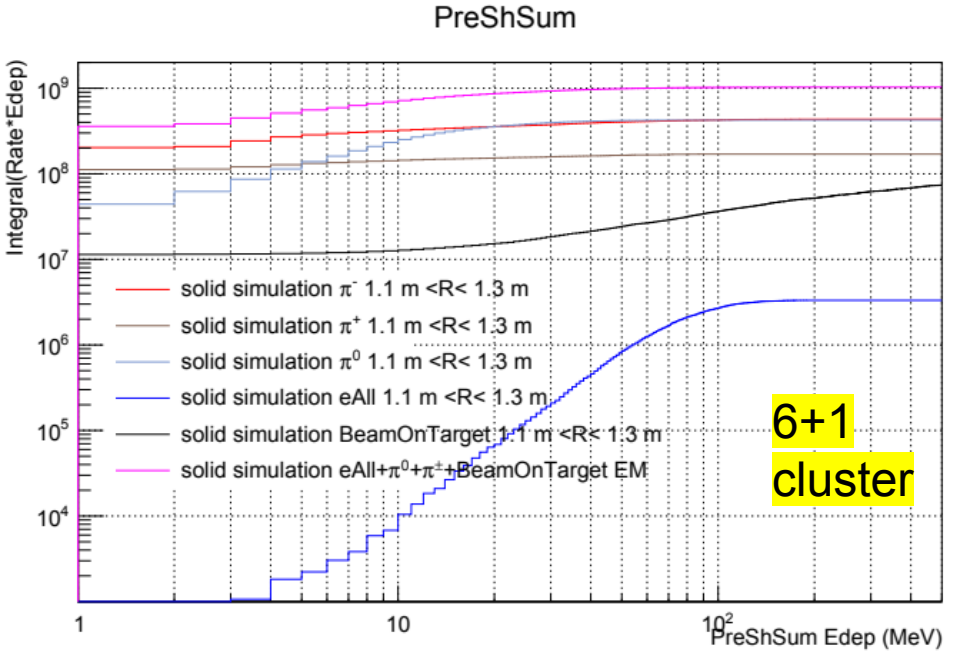
- Radiation dose in Preshower beam test is about factor five lower than SoLID PVDIS running
- radiation dose in the Preshower of SoLID PVDIS is 3 times that of Pre-CDR, due to Pre-CDR only accounted for beam-on-target background:

$$\frac{1.5 \times 10^8 \mathrm{MeV/s} \times 2.59 \times 10^6 \mathrm{sec/month}}{200\ \mathrm{g}} = 311\ \mathrm{J/kg/month} = 31.1\ \mathrm{krad/month}\ . \quad (12)$$

- Significant work (Ye's talk) has been spent on understanding the change from preCDR to present simulation

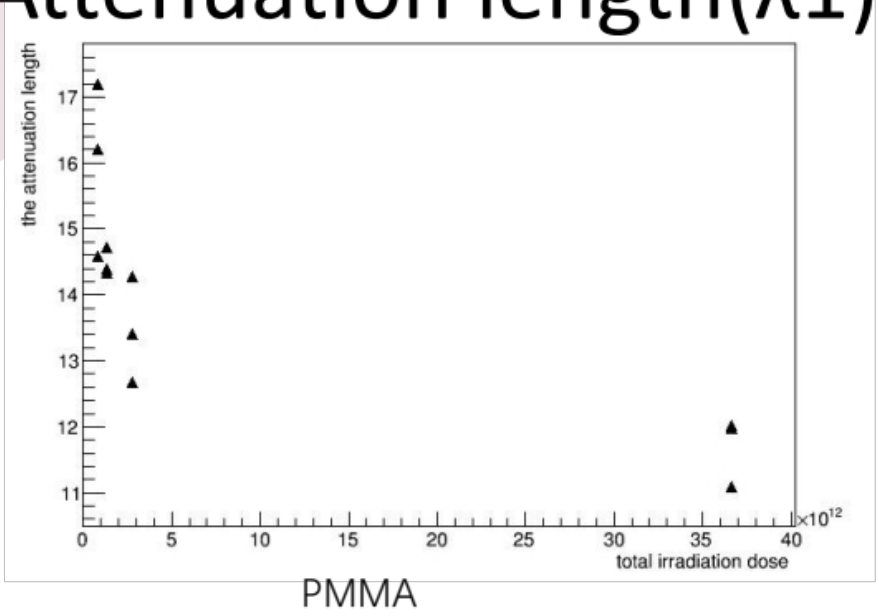
- (Radiation dose in Shower for SoLID PVDIS consistent with the preCDR, factor three higher than beam test)





PMMA

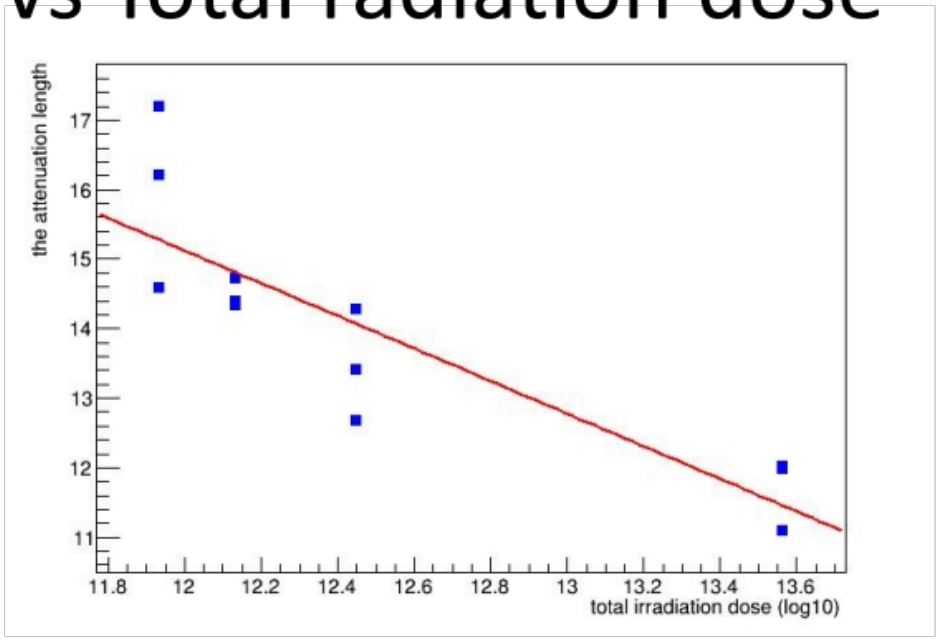
Attenuation length(λ1) vs Total radiation dose



PMMA

2.83 krad 4.49 krad 9.26 krad

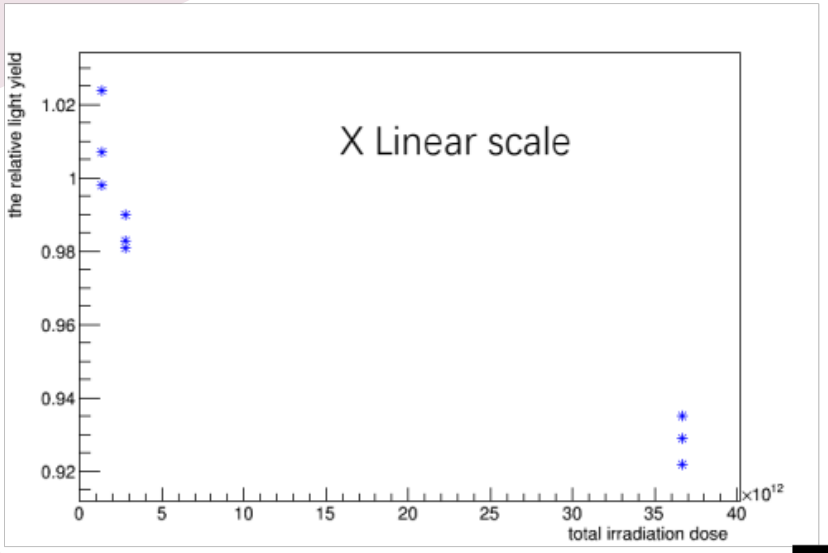
120.9 krad



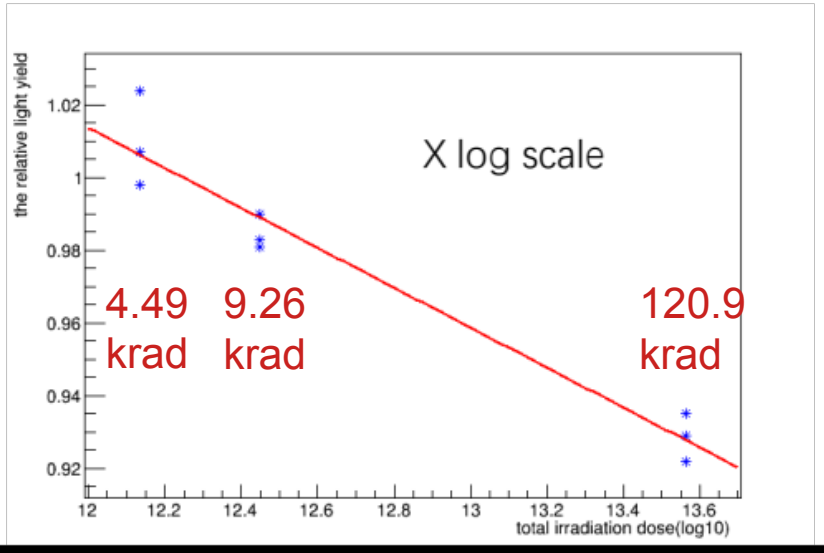

```
Minimizer is Linear
Chi2                      =      8.61186
NDf                       =           10
p0                        =      43.2542   +/-   5.32861
p1                        =     -2.34436   +/-   0.425078
```

for 343 krad, L=43.25-2.344*14.03=10.365 m

WLS fiber （ BCF91A-MC)
Relative light yield vs Total radiation dose



BCF91A-MC




```
Minimizer is Linear
Chi2                      =  0.000572206
NDf                       =              7
p0                        =        1.67286   +/-   0.0625212

p1                        =     -0.0549362   +/-   0.00491128
```

for 343 krad, 1.57-0.0549*14.03 ~ 80%
for 700 krad, 1.57-0.0549*14.33 ~ 78%

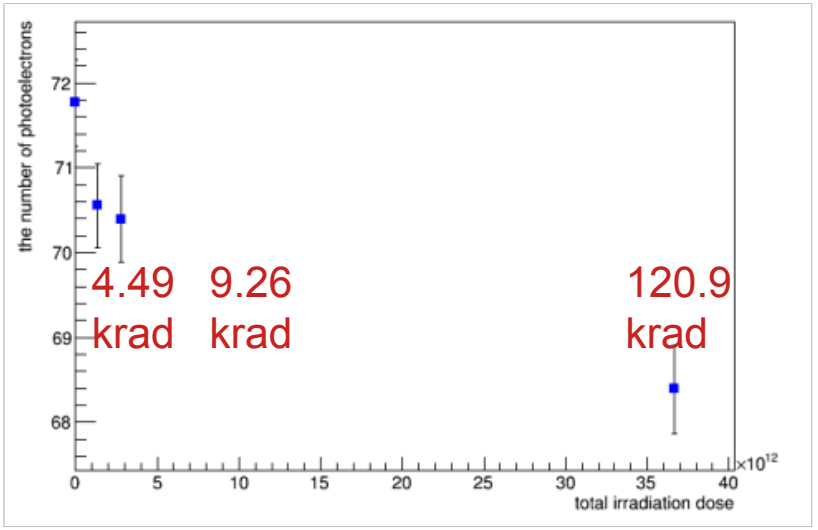
Scintillator test result

scintillator	Total radiation dose (MeV/cm^2)	Number of photoelectrons
Sample 2	1.360E+12	70.55±0.50
Sample 3	2.807E+12	70.39±0.51
Sample 4	3.665E+13	68.39±0.52

landau fitting error

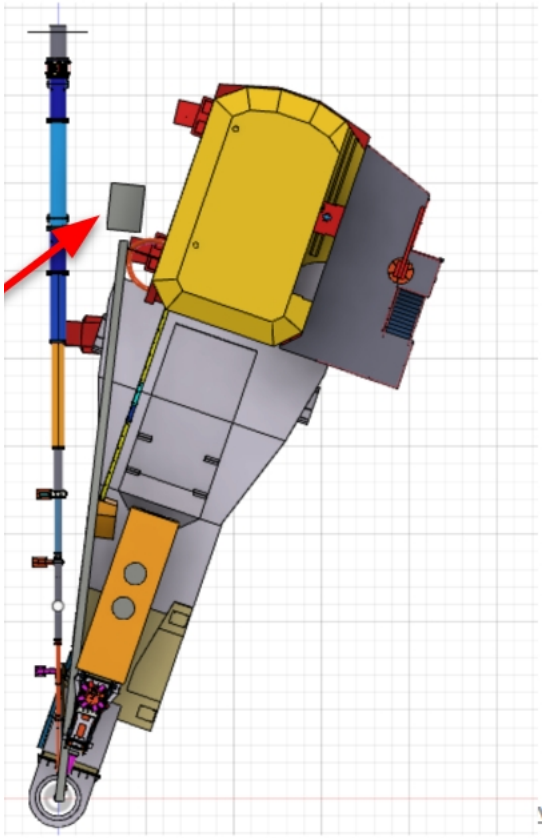
scintillator without irradiation for reference

	Number of photoelectrons
1	71.52±0.51
2	72.77±0.53
3	71.02±0.51
average	71.77



FY22 Hall C Beam Test Overview

1. Goal was to study ECal and SPD performance under high rate, high radiation
2. Installed in Hall C in summer – fall 2022
3. Three stages:
   - 80 deg beam-left in Fall 2022, low rate “commissioning”
   - 7 deg beam-right in Jan 2023, high rate part 1
   - 18 deg beam-right in Feb-March 2023, high rate part 2
   - de-install in March 2023
4. Analysis was focused on:
   - Comparison of data with simulation (see Ye’s talk)
   - detector performance and stability from low to high rate
   - ECal and SPD PID performance
5. Report now ready for review by collaboration, is part of it publishable?



Test Overview

Trigger Signal	Bit	Trig -Type	Trigger Logic (threshold)	Goal
TS1	0001	1	CerSum (35mV) ($\approx$ 2 p.e.)	e
TS2	0010	2	SC-B (35mV) .and. SC-D (35mV) ($\approx$ 0.5 MIP each)	$\pi^{\pm}$
TS3	0100	4	SC-C(31mV).and.SC-D(35mV) .and.ShSum (varies)	$e, \pi^{\pm}$
TS4	1000	8	ShSum (varies)	e or γ

TABLE III. Trigger setup for the majority of the 18° data taking. The threshold for CerSum corresponds to approximately 2 photoelectrons (p.e.), while those of SC-B, SC-C and SC-D correspond approximately to half of the minimal ionization particle (MIP) peak. SC-A was originally used in TS3 in place of SC-C, but was found to saturate and removed from the trigger during the test.

Shower PMT Gain Shift To Do

- Several issues contributed to the PMT gain shift during the beam test:
  - PMT anode current too high (non-negligible to divider current)
  - PMT HV divider redistribution and gain shift – our study shows a Total gain shift of order 20-30%, factor 10 smaller than data
  - Possible change in PMT dynode emission behavior
- Concern: non-linearity appears at only ½ to ¼ of the max anode current

SoLID Readout Considerations

	LASPD	FASPD
PMT	MCP-PMT	R11265-100-M16
transverse size (cm^2)	636	466
thickness (cm)	2.0	0.6
Radiation dose (/mon)	2krad	2krad
Total E_{dep} (MeV/s)	6.1×10^7	1.3×10^7
Total $N_{p.e.}/s$	4.6×10^9	1.4×10^8
PMT gain	3E3	1E5
I_{anode} (μA)	2.0 (average)	1.6 (1/4 max)
Pre-amp gain	20	20
Total gain	6E4	2E6
MIP E_{dep} (MeV)	4.0	1.2
MIP N_{pe}	300	10
MIP height(mV)	10	10
Q_{anode} (C)	38	36

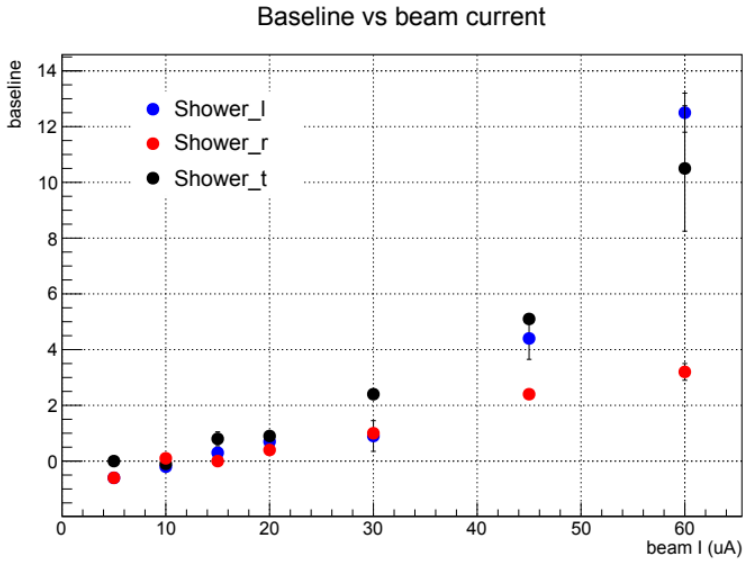
TABLE XII. Calculation of PMT requirements for LASPD and FASPD at SoLID SIDIS running conditions. The radiation dose (in krad/month) is from the pre-CDR. The energy deposit rate (in MeV/s) is calculated from the radiation dose. The signal height is estimated using a 30 ns half-width triangular pulse. Note that the MCP-PMT specification indicates "2.0 μA average anode current" rather than a maximum value. The total PMT anode charge is calculated assuming 200 days of SIDIS running at 100% efficiency. *Xiaochao: someone should check these numbers, see my calc here*

	Preshower	Preshower	Shower
PMT	R11265-100-M16	R11102	R11102
size (cm^2)	100	100	100
thickness (cm)	2.0	2.0	30.0
Radiation dose (/mon)	30 krad	30krad	10krad
Total E_{dep} (MeV/s)	1.5×10^8	1.5×10^8	7.2×10^8
Total $N_{p.e.}/s$	1.5×10^9	1.5×10^9	7.2×10^9
PMT gain	8E3	4E4	1E4
I_{anode} (μA)	2.1 ($\frac{1}{3}$ max)	10 ($\frac{1}{10}$ max)	10 ($\frac{1}{10}$ max)
Pre-amp gain	30	6	10
Total gain	2.4E5	2.4E5	1E5
MIP E_{dep} (MeV)	3.0	3.0	40
MIP N_{pe}	30	30	400
MIP height(mV)	10	10	27
e max E_{dep} (GeV)	–	–	2
e max N_{pe}	–	–	20000
e max height (mV)	–	–	2180
Q_{anode}	96	480	291

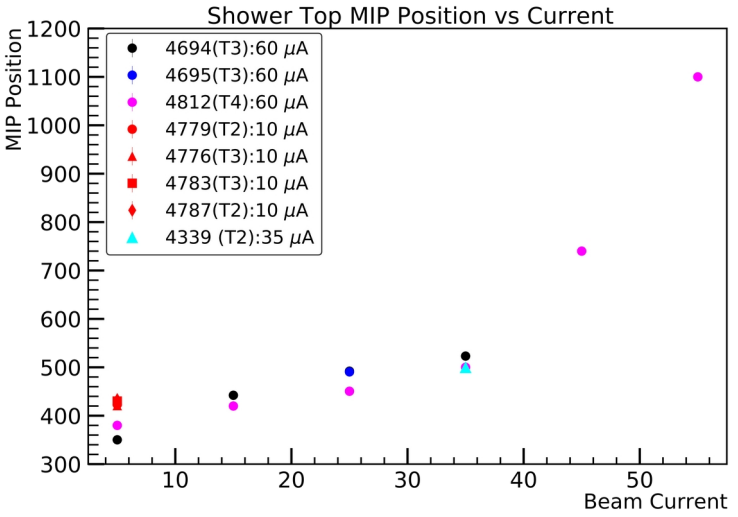
TABLE XIII. Calculation of PMT requirements for Preshower and Shower for SoLID PVDIS conditions. The Shower thickness accounts the scintillators only. The signal height is estimated using a 30 ns half-width triangular pulse. For the Shower, the energy deposit and expected peak height are shown for electrons of maximum momentum of 8 GeV. Note that the Shower pre-amp gain can be higher, or that it can be used to detect electrons above 10 GeV. The total PMT anode charge is calculated assuming 300 days of PVDIS running at 100% efficiency. (The preshower readout can be problematic because the 96 C is per channel!) *Xiaochao: someone should check these numbers, see my calc here*

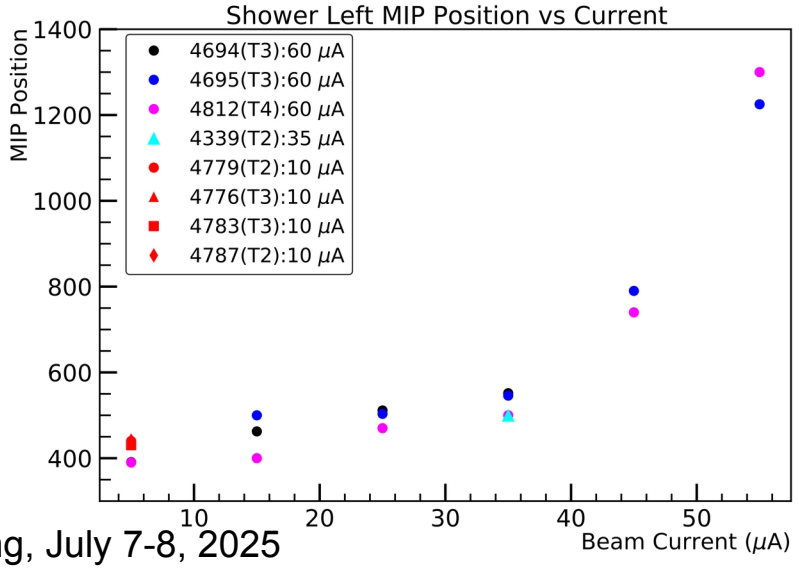
Shower Performance and Stability

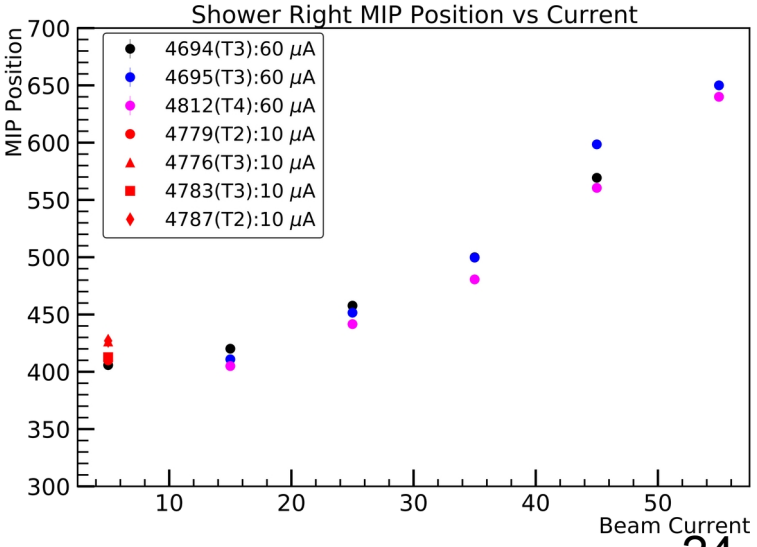
- All three shower modules showed baseline shift (larger anode current than Preshower due to lack of pre-amps)

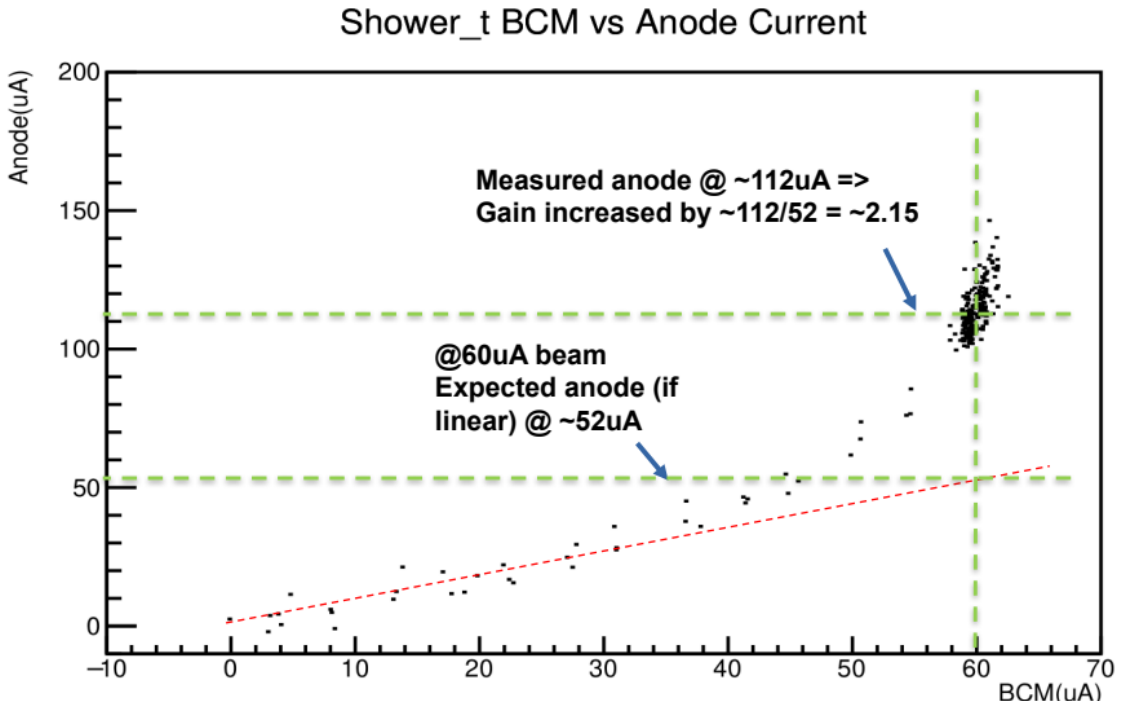


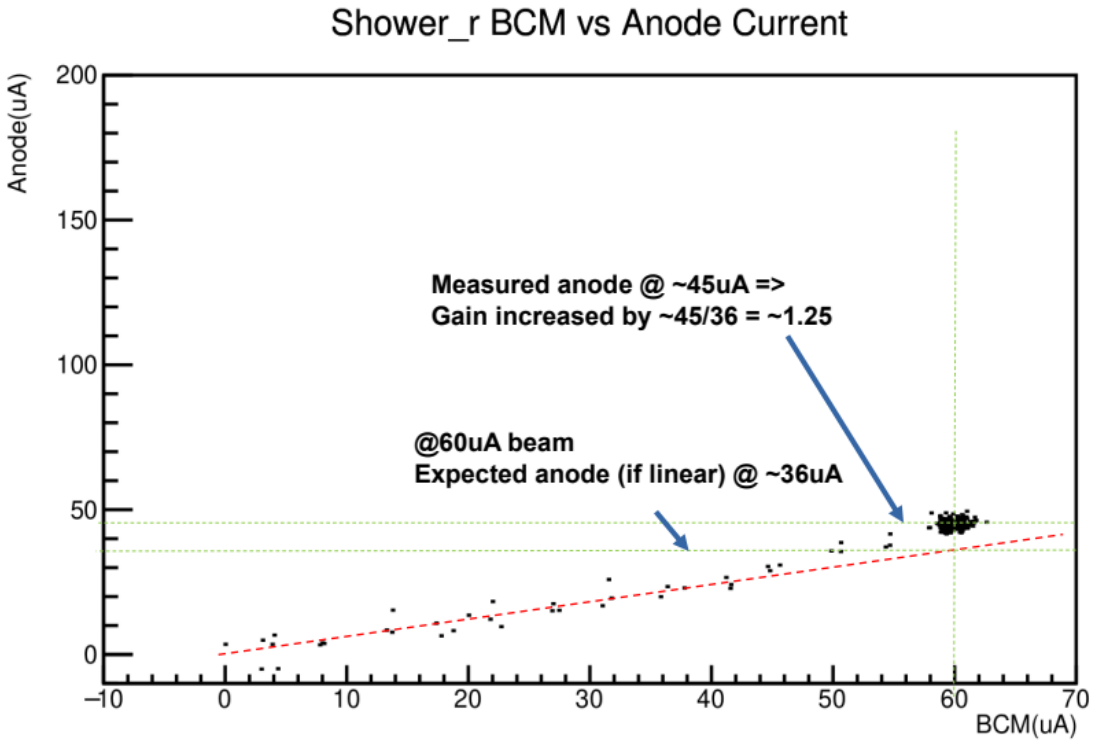
- MIP position shifts nonlinearly with beam current above the baseline shift, indicating PMT gain shifts








Shower_t BCM vs Anode Current
Anode(uA)
BCM(uA)
Measured anode @ ~112uA =>
Gain increased by ~112/52 = ~2.15
@60uA beam
Expected anode (if
linear) @ ~52uA


Shower_r BCM vs Anode Current
Anode(uA)
BCM(uA)
Measured anode @ ~45uA =>
Gain increased by ~45/36 = ~1.25
@60uA beam
Expected anode (if linear) @ ~36uA