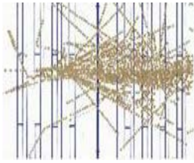

Production and Quality Assurance of Mu2e Calorimeter CsI Crystals

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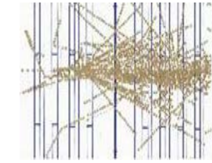
California Institute of Technology

May 22, 2018

Mu2e Calorimeter Collaboration



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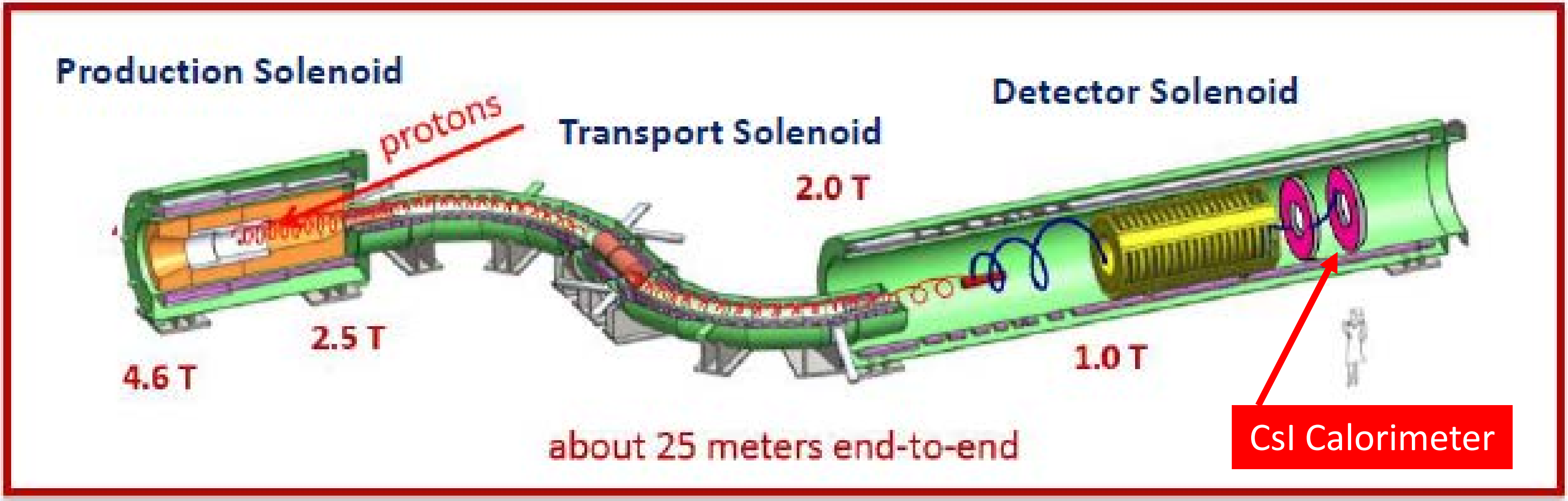
The Mu2e CsI Calorimeter



1,348 undoped cesium iodide (CsI) crystals of 34×34×200 mm^3 readout by a large area silicon photomultipliers (SiPM) array

With a fast decay time of about 30 ns and a light output of more than 100 p.e./MeV measured by a bi-alkali PMT, un-doped CsI crystals provide a cost-effective solution for the Mu2e experiment

Fast and Cost-Effective CsI

Crystal	NaI(Tl)	CsI(Tl)	CsI	BaF_2	BGO	LYSO(Ce)	PWO	PbF_2
Density (g/cm^3)	3.67	4.51	4.51	4.89	7.13	7.40	8.3	7.77
Melting Point (ºC)	651	621	621	1280	1050	2050	1123	824
Radiation Length (cm)	2.59	1.86	1.86	2.03	1.12	1.14	0.89	0.93
Molière Radius (cm)	4.13	3.57	3.57	3.10	2.23	2.07	2.00	2.21
Interaction Length (cm)	42.9	39.3	39.3	30.7	22.8	20.9	20.7	21.0
Refractive Index [a]	1.85	1.79	1.95	1.50	2.15	1.82	2.20	1.82
Hygroscopicity	Yes	Slight	Slight	No	No	No	No	No
Luminescence [b] (nm) (at peak)	410	550	310	300 220	480	402	425 420	?
Decay Time [b] (ns)	245	1220	26	650 0.	300	40	30 10	?
Light Yield [b,c] (%)	100	165	3.7	36 4.1	21	85	0.3 0.1	?
d(LY)/dT [b] (%/ ºC)	-0.2	0.4	-1.4	-1.9 0.1	-0.9	-0.2	-2.5	?
Experiment	Crystal Ball	BaBar BELLE BES III	KTeV BELLE Mu2e	(GEM) TAPS Mu2e-II	L3 BELLE EIC?	Comet {Mu2e,SuperB) CMS MTD	CMS ALICE PANDA	A4 g-2 HHCAL?

a. at peak of emission; b. up/low row: slow/fast component; c. QE of readout device taken out.

Mu2e CsI Technical Specifications

Specifications defined according to physics requirements

- Crystal dimension tolerance: ±100 μm;
- Visual inspection: no cracks, chips, fingerprints, and free from inclusions and bubbles;
- Light output (LO) in 200 ns: > 100 p.e./MeV;
- FWHM Energy resolution for Na-22 peaks: < 45%;
- Light response uniformity (LRU): < 5%;
- Fast (200 ns)/Total (3,000 ns) (F/T) Ratio: > 75%;
- Radiation Induced Noise (RIN) @1.8 rad/h: < 0.6 MeV;
- Normalized LO after 10/100 krad > 85%/60%.

CsI transmittance is affected by its hygroscopic surface quality, so Mu2e specifications do not include a transmittance requirement

36 Preproduction CsI Crystals

CsI Crystal Quality Assurance

A total of 72 preproduction CsI crystals were procured from three vendors: AMCRYS, Saint-Gobain (S-G) Corporation and Shanghai Institute of Ceramics (SIC), and were characterized at Caltech and LNF.

Following preproduction, two vendors were selected: S-G and SIC. Production has started: 52 and 100 crystals received from SIC and S-G as of May, 2018.

While dimension and scintillation properties are measured for all CsI crystals by CMM and automatized stations respectively, radiation hardness is measured for selected samples at Caltech and HZDR.

Measurement Procedure

Crystals were wrapped with two layers of Tyvek paper of 150 μm with a selected end coupled to a bi-alkali PMT Hamamatsu R2059 via an air gap with the coupling end chosen to provide a better LRU.

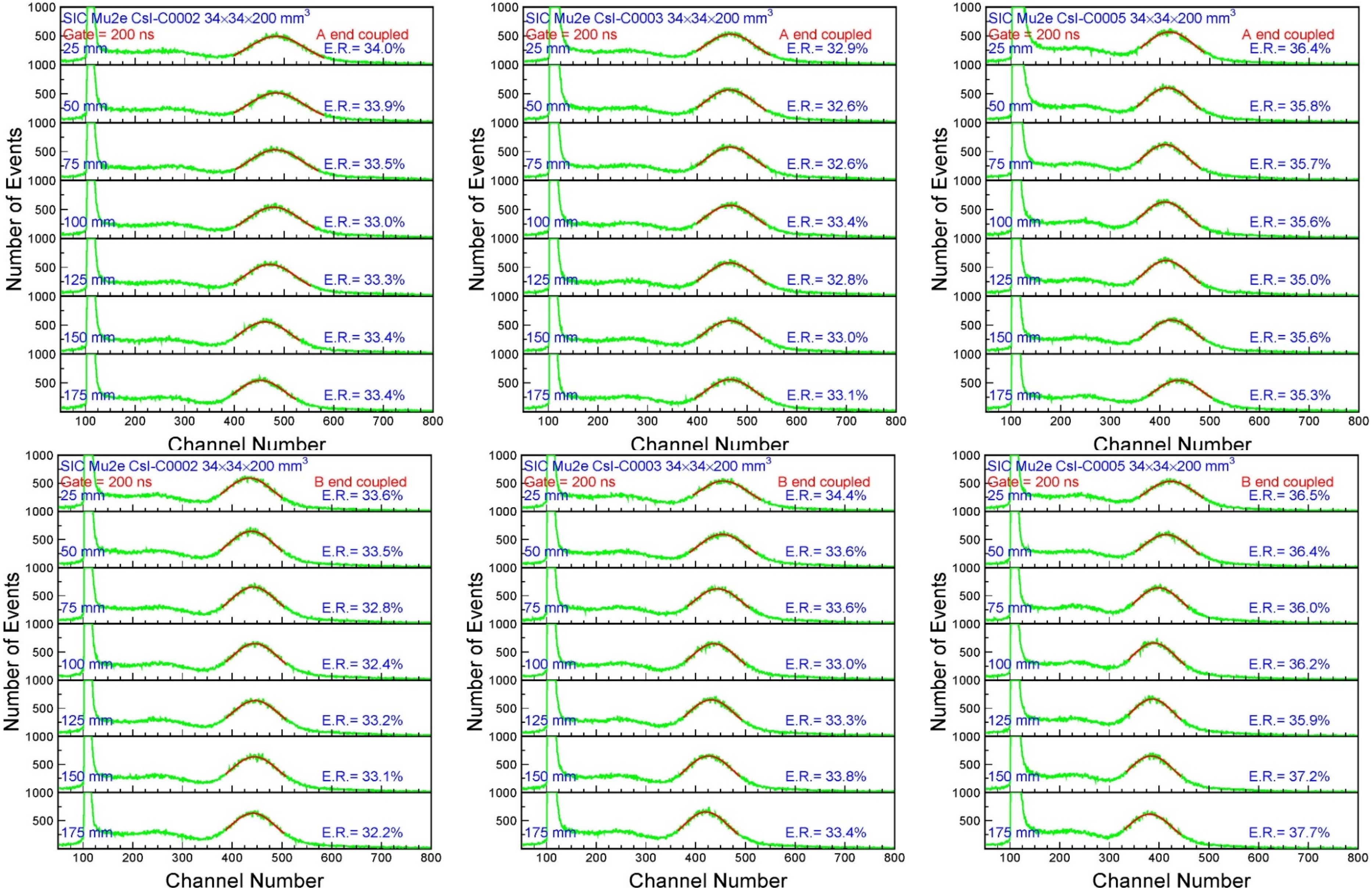
Pulse height spectra were measured by using 0.511 MeV γ-rays from a ^{22}Na source with a systematic uncertainty of about 1% for the peak determination.

The LO and FWHM resolution are defined as the average of seven points measured along the crystal length with 200 ns integration time.

The LRU is defined as the standard deviation (rms) of the seven points. The LO was also measured as a function of the integration time at the point of 2.5 cm from the PMT, from which the F/T ratio is determined.

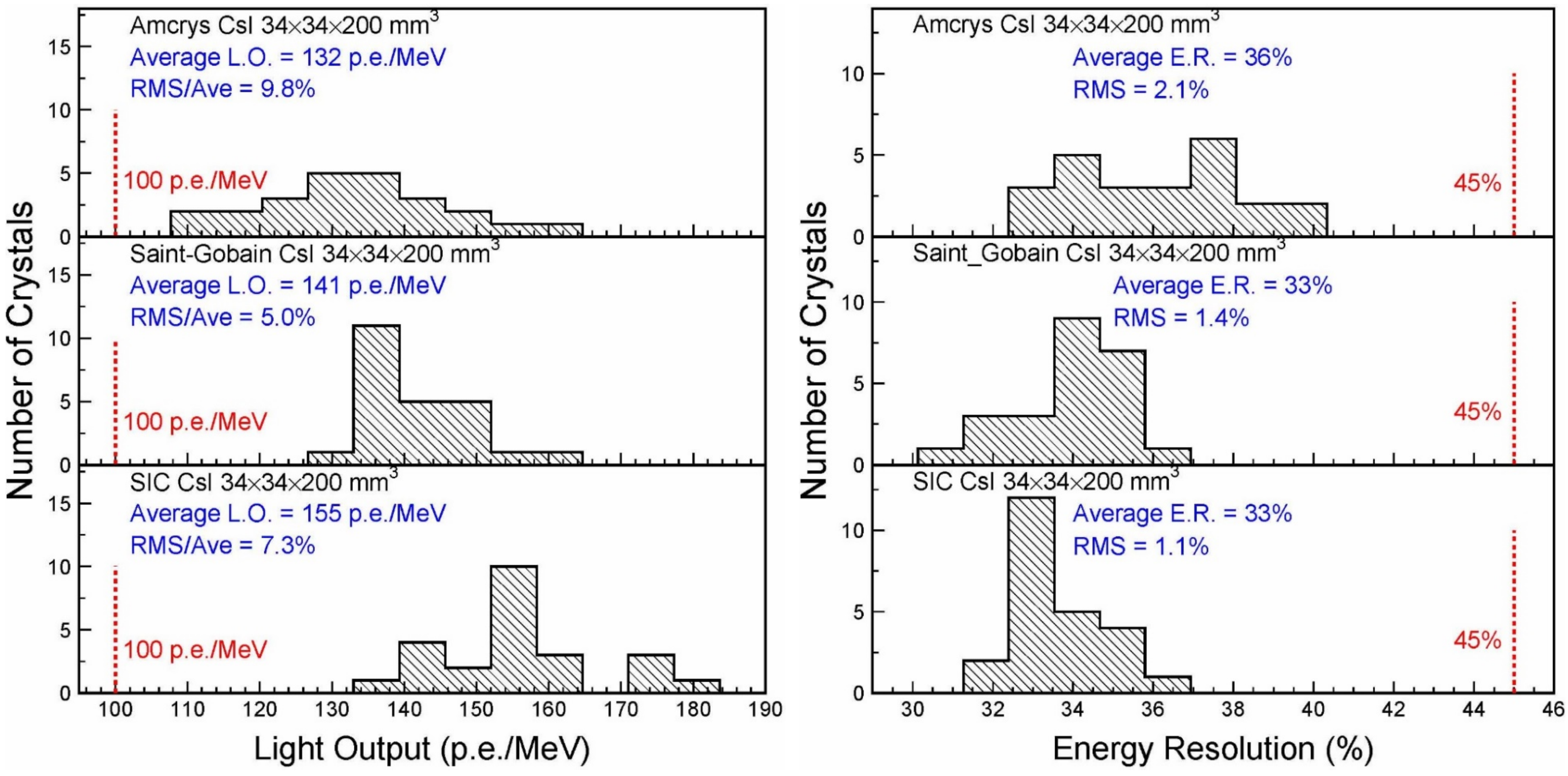
The radiation induced photocurrent was measured as the anode current during irradiation at a dose rate of 2 rad/h, and was used to extract the crystal's RIN at 1.8 rad/h. Radiation damage in both transmittance and LO was measured for two CsI crystals randomly selected from each vendor after 10 and 100 krad. In the photocurrent and LO measurements, crystals were with the same wrapping and air coupled to the same Hamamatsu R2059 PMT.

Typical PHS: Different Coupling End



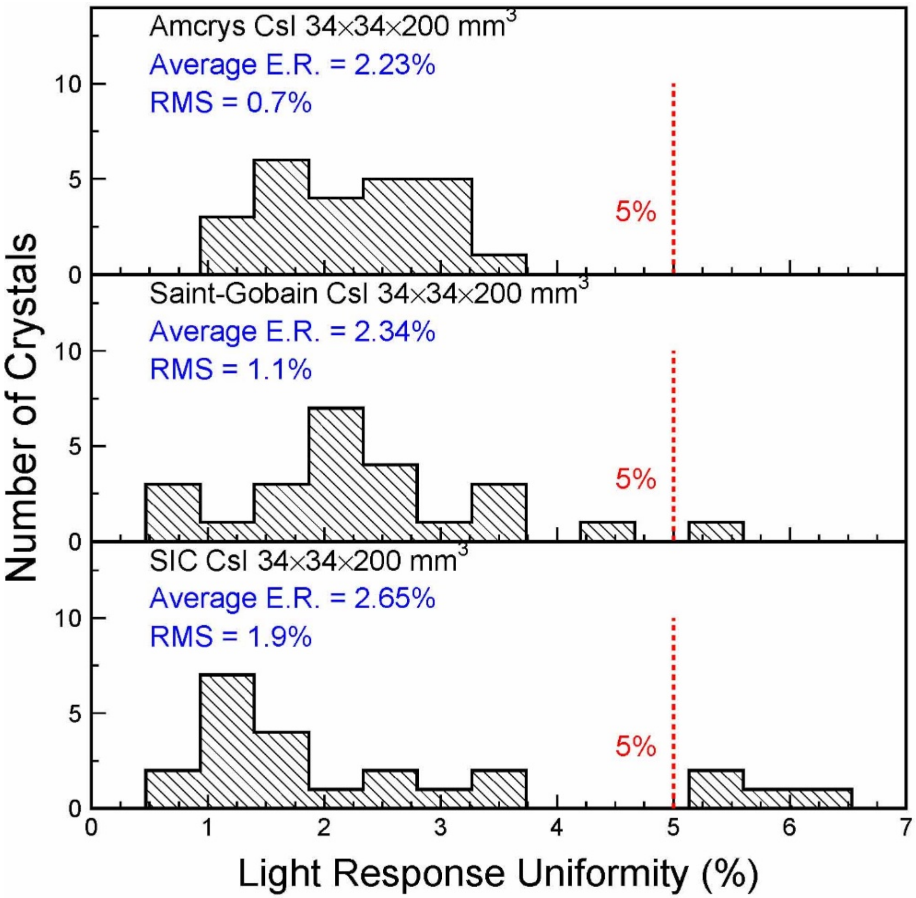
Light Output and Energy Resolution

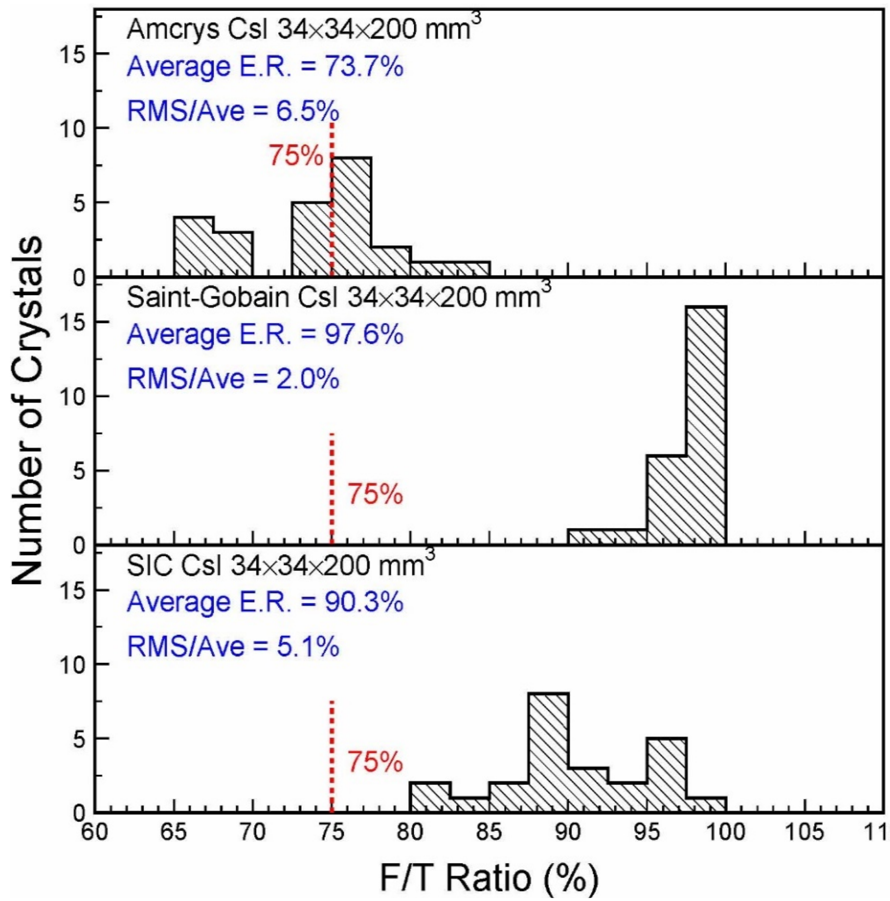
All crystals satisfy these specification



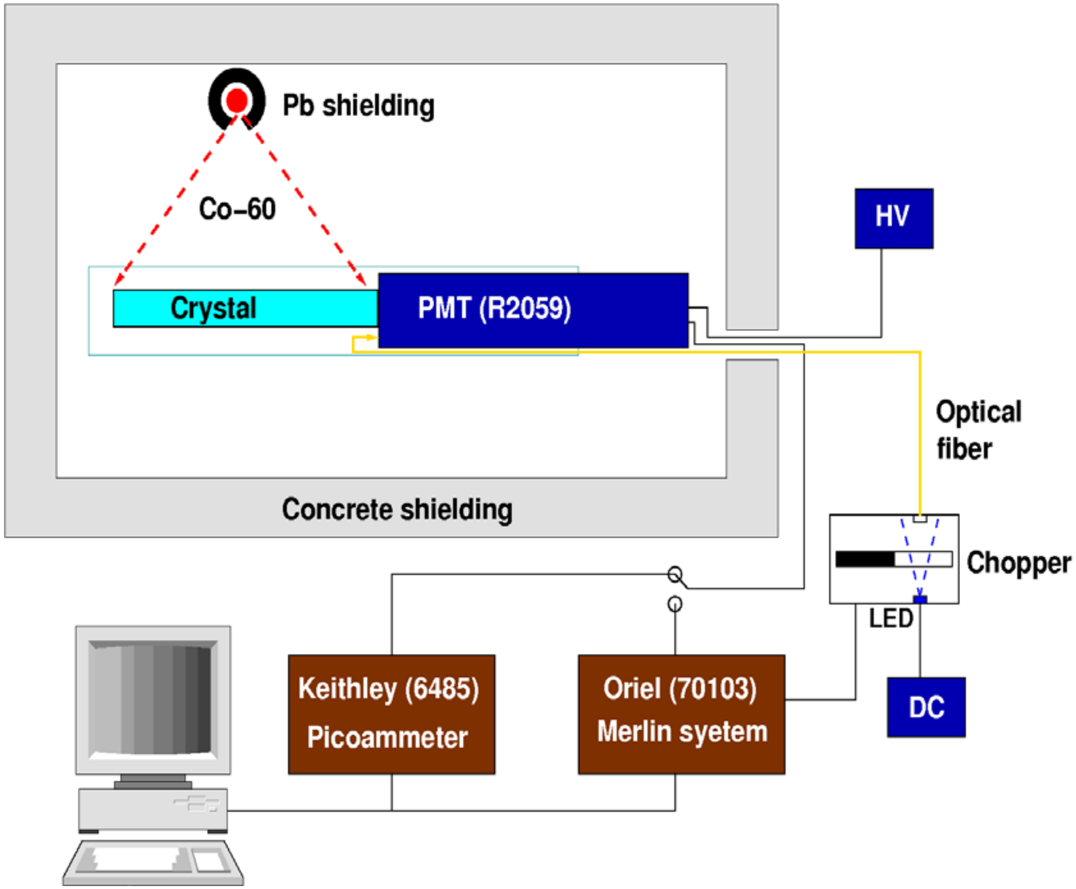
LRU and F/T Ratio

Some crystals fail LRU and F/T specifications





Radiation Induced Photocurrent



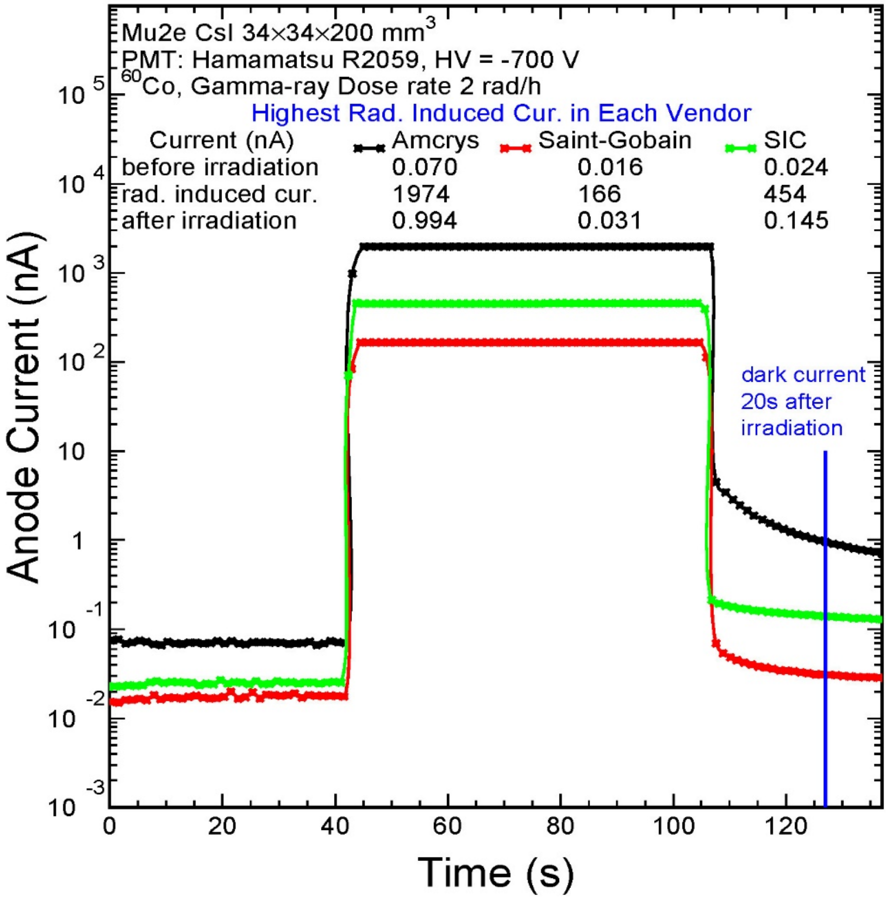
F is radiation induced photoelectron numbers per second, determined by the measured anode current in the PMT @ 2rad/h

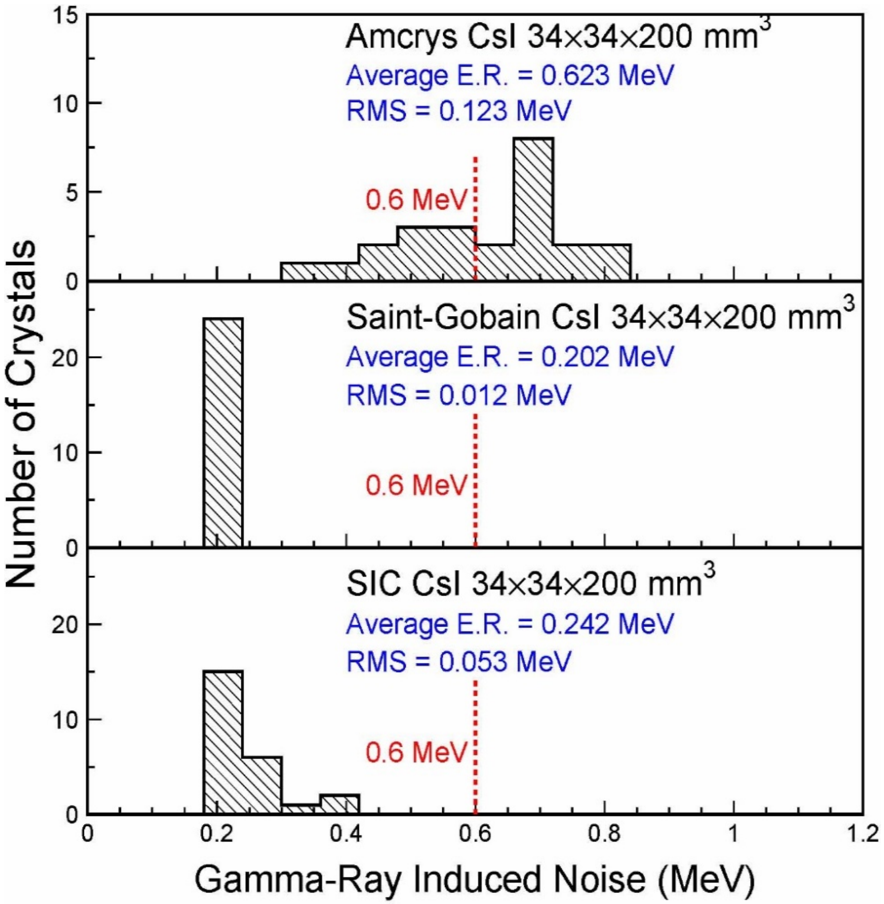
$$F = \frac{\frac{Photocurrent}{Charge_{electron} \times Gain_{PMT}}}{Dose\ rate_{\gamma-ray}\ or\ Flux_{neutron}}$$

$$\sigma = \frac{\sqrt{Q}}{LO}$$ (MeV)

γ-ray Induced Readout Noise

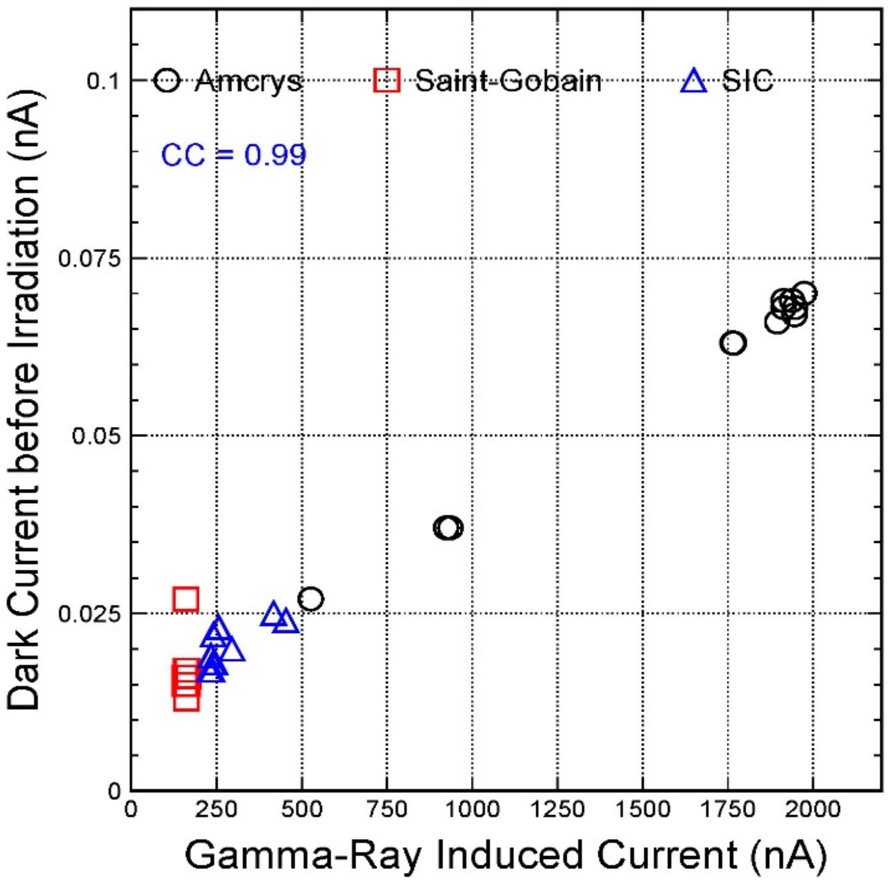
Some Amcrys crystals fail RIN specification

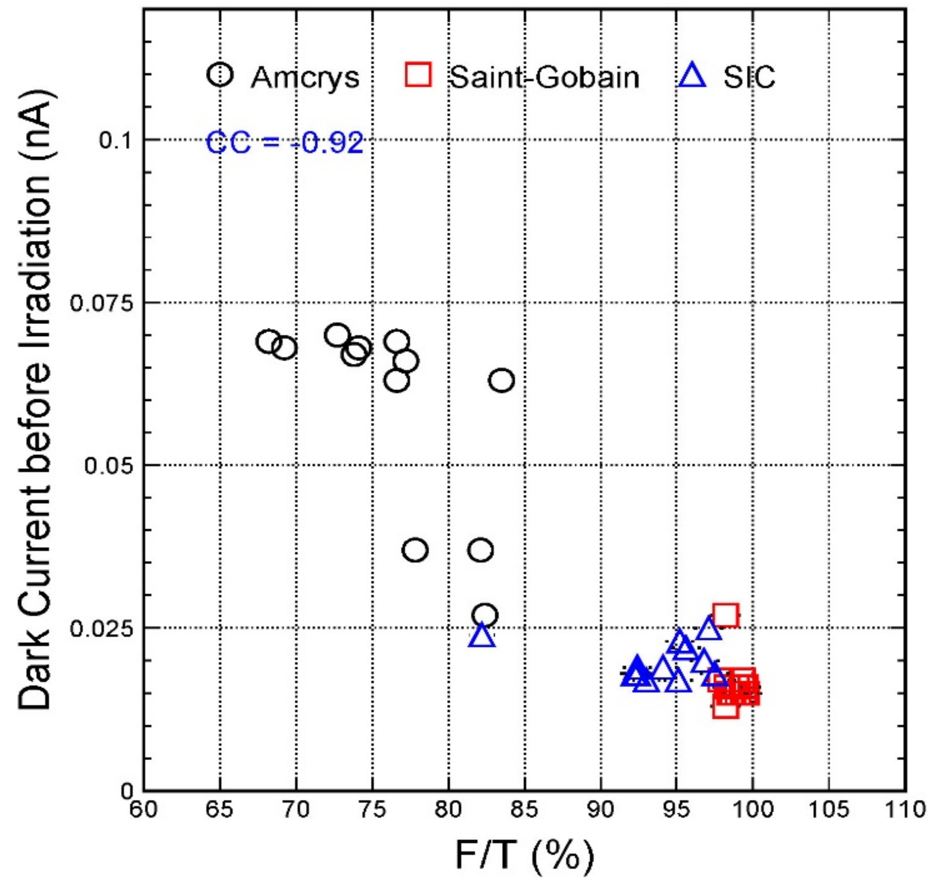




Dark Current vs. γ-ray induced Current and F/T

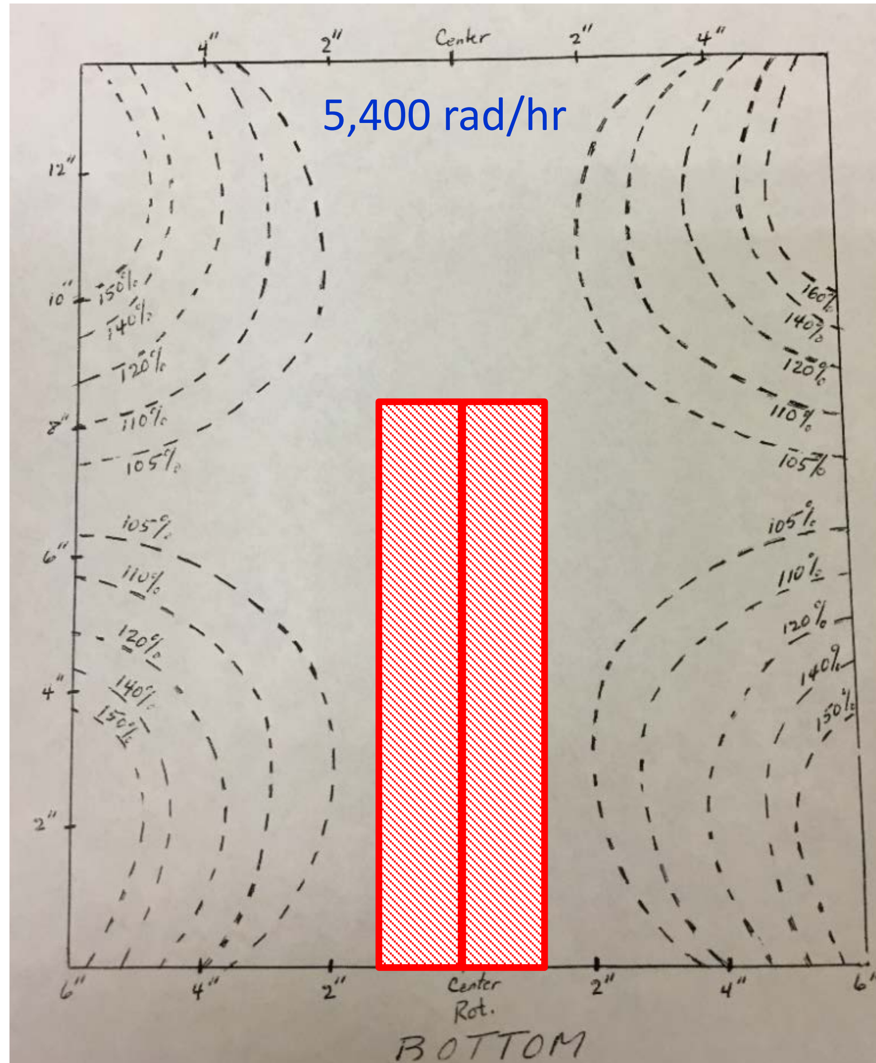
Perfect correlation indicates possibility to measure only one





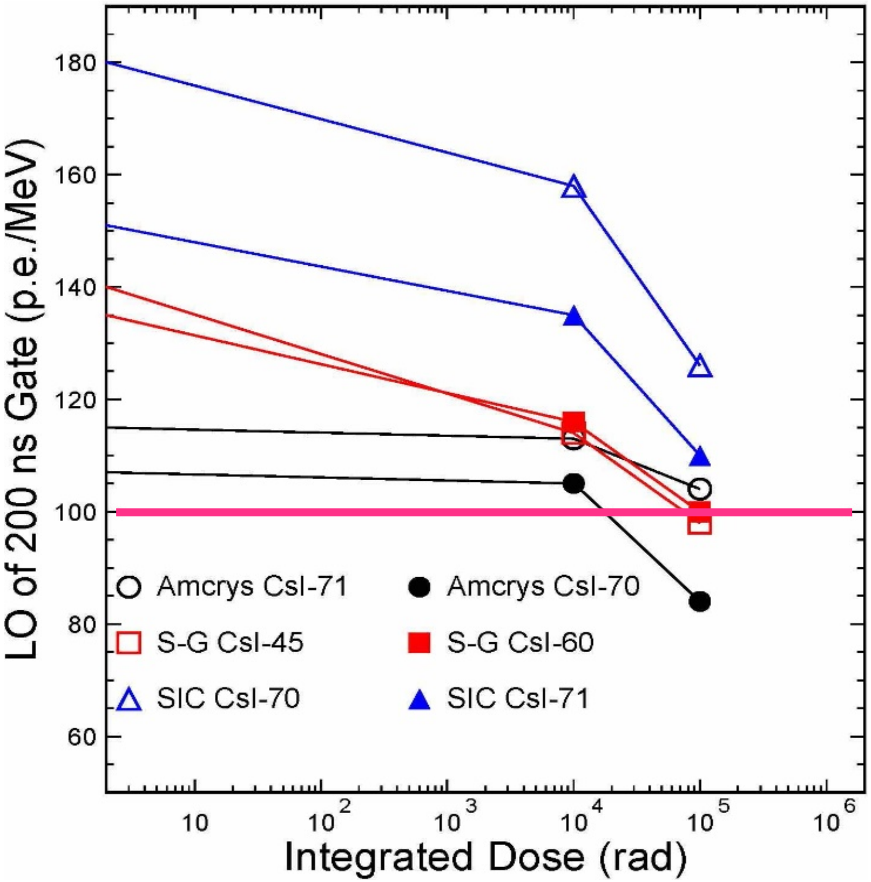
^{137}Cs γ-ray Irradiation Facility

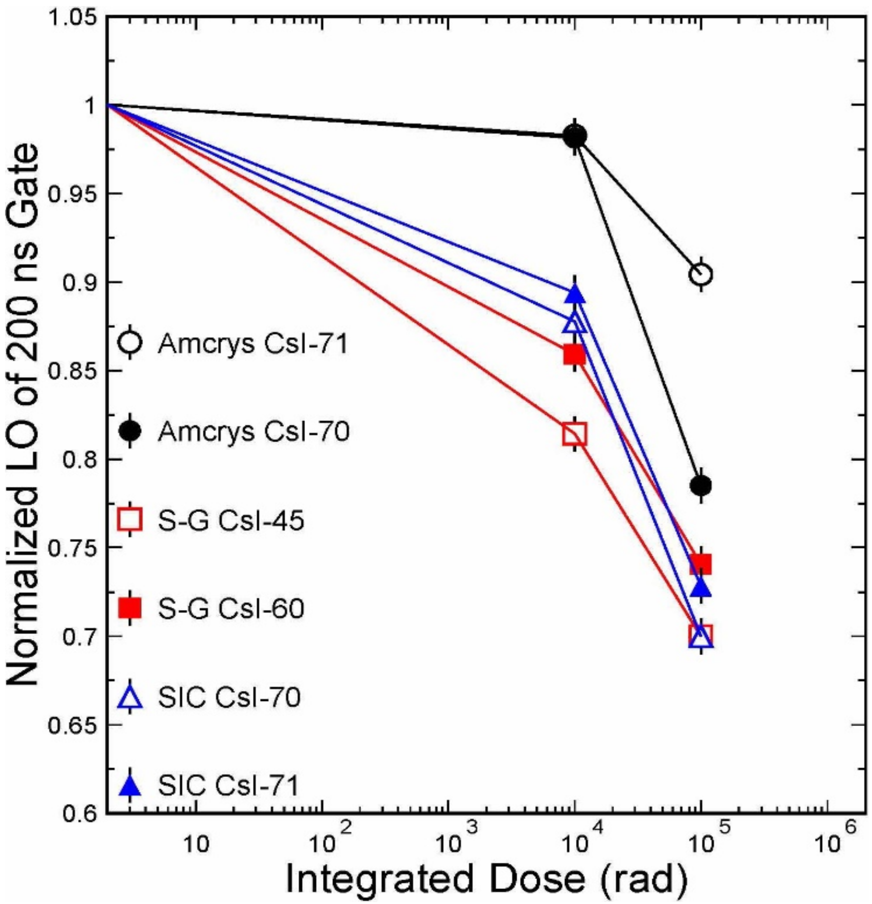
5.4 krad/h at the center with 10% uniformity



Radiation Hardness

Most crystals have LO more than 100 p.e./MeV after 100 krad irradiation promising a robust calorimeter





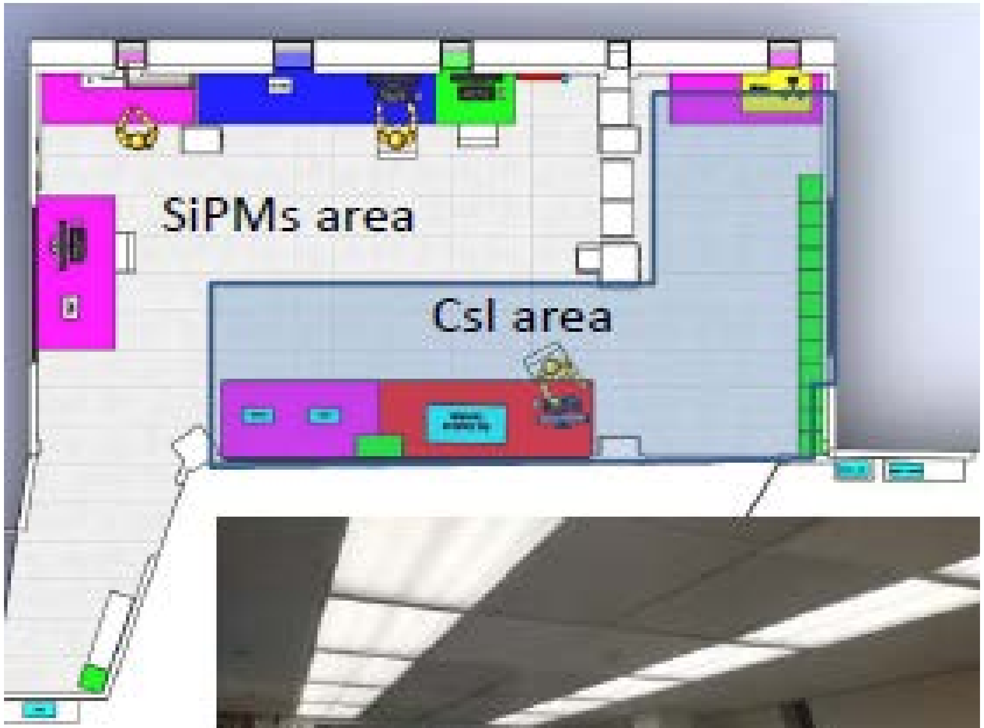
CsI QA in SiDet at Fermilab

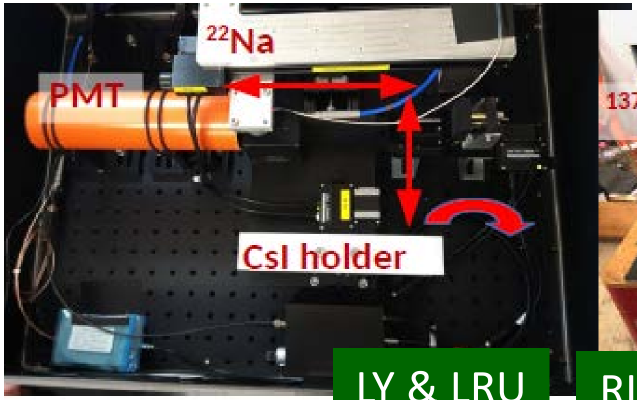
Crystals dimension and shape measured by a CMM.

Scintillation property and RIN measured by automatic stations.

All crystals meet optical spec.

Mechanical property greatly improved after communication with vendors.



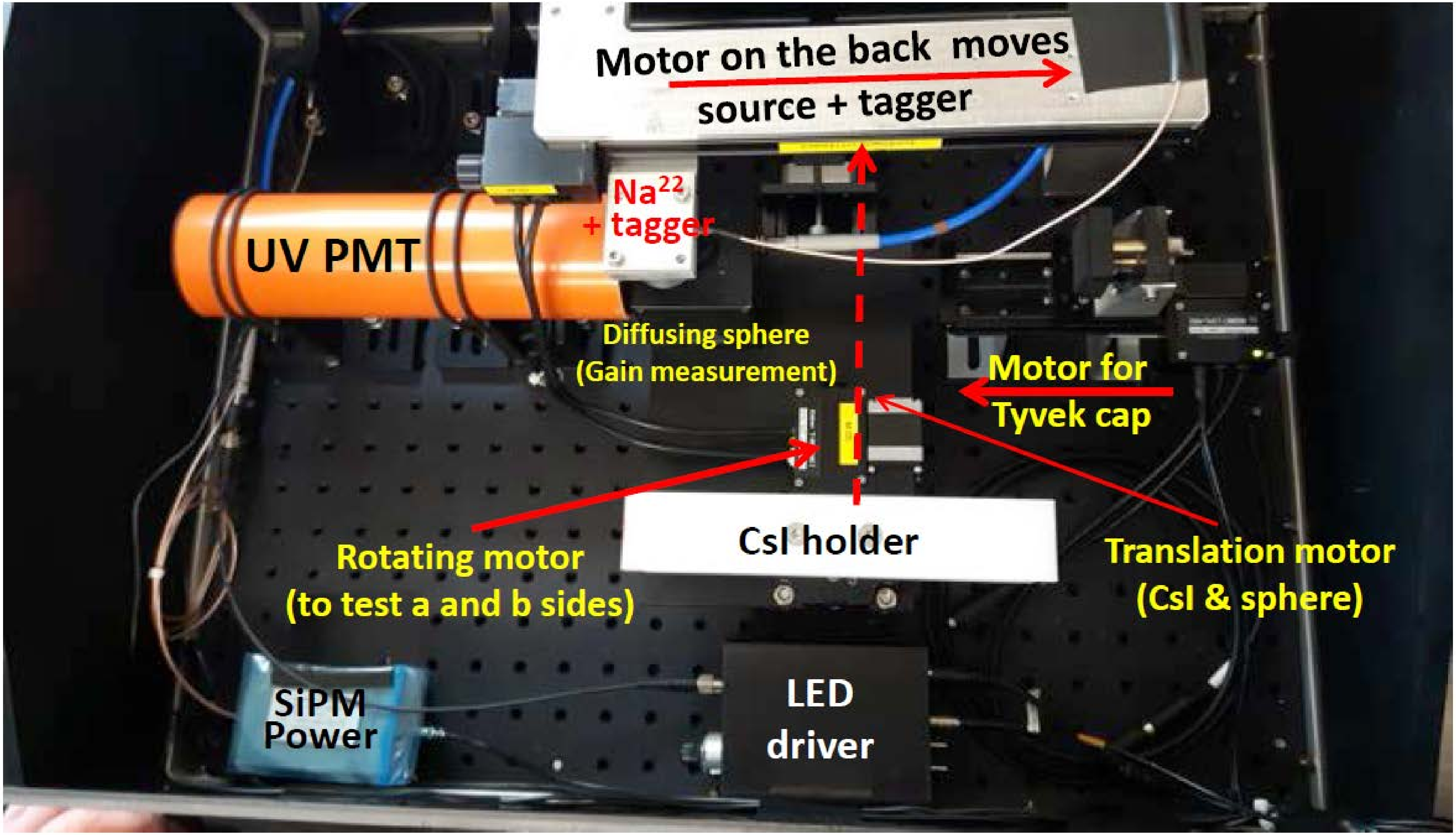


LY & LRU

RIN

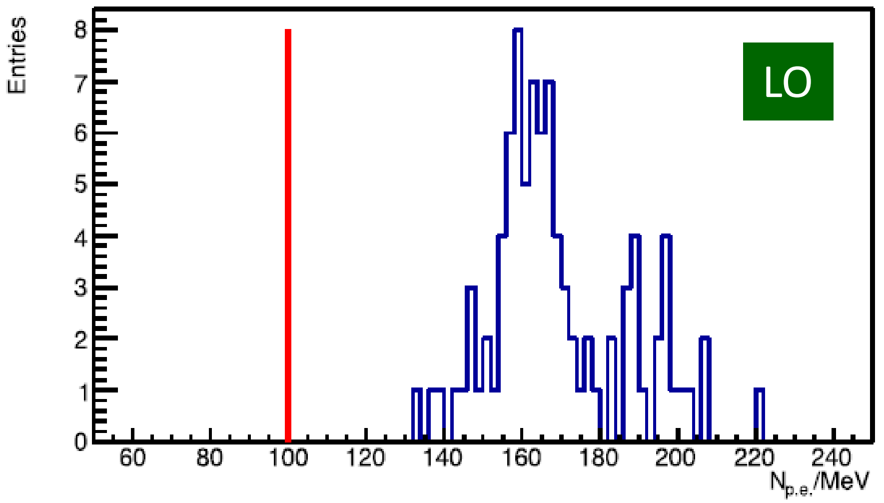
Scintillation Test Station

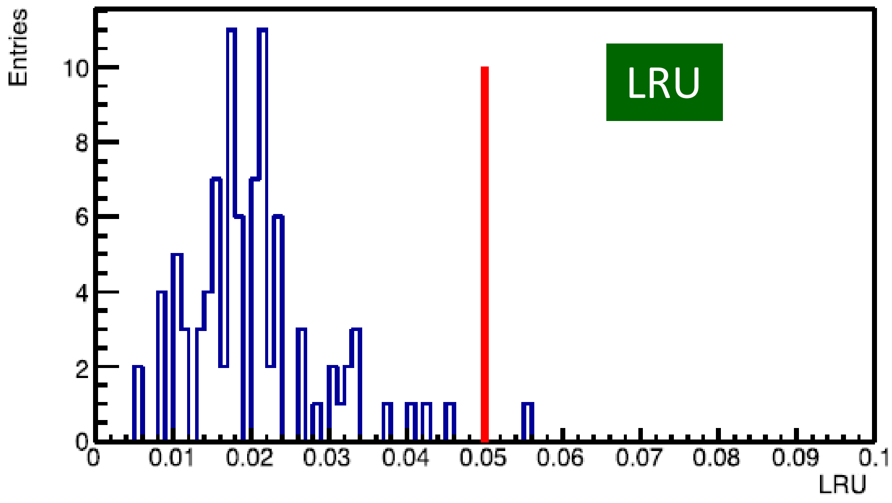
Automatic measurement with four motors to test both a and b side couplings

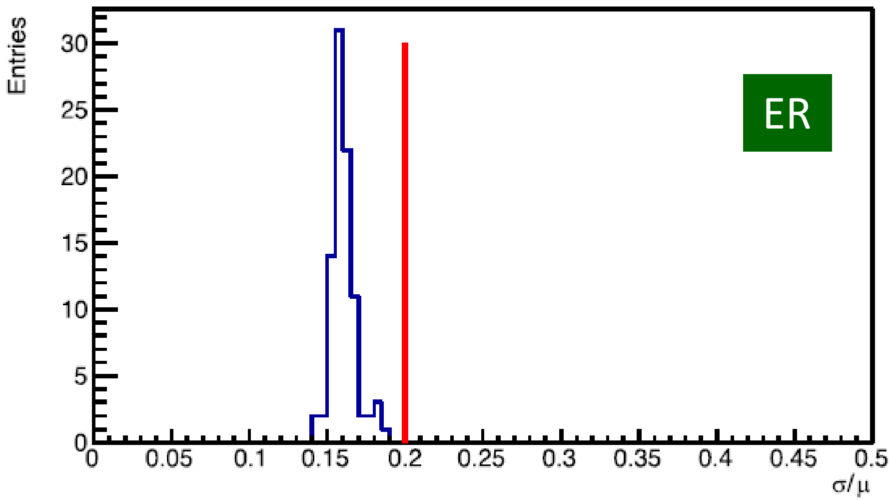


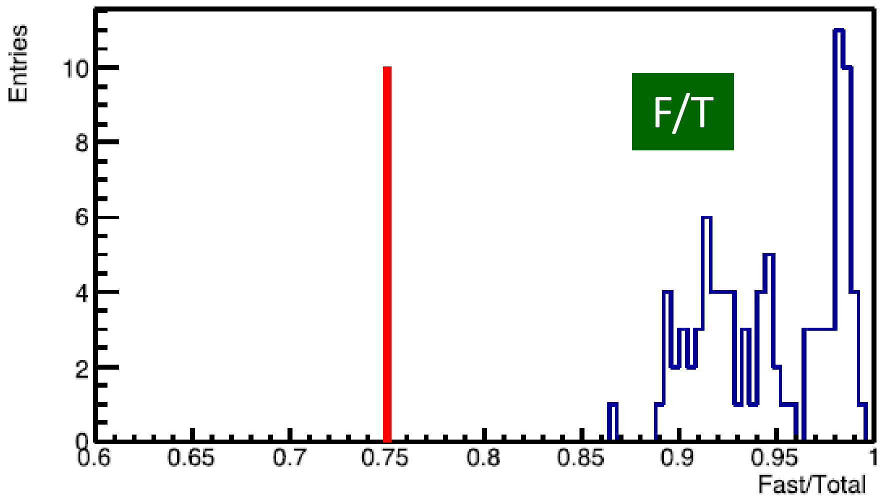
Result of Scintillation Properties

90 crystals tested. One SIC crystal failing LRU. All crystals have F/T ratio > 86%







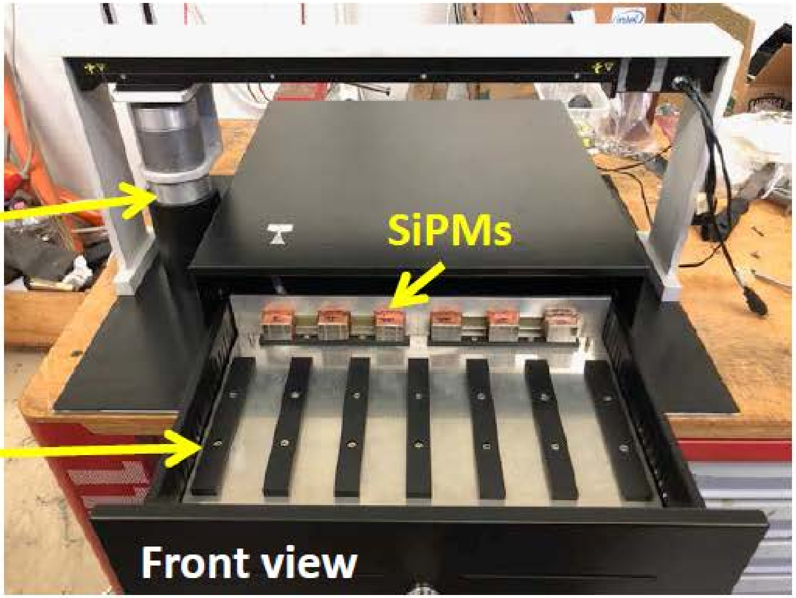


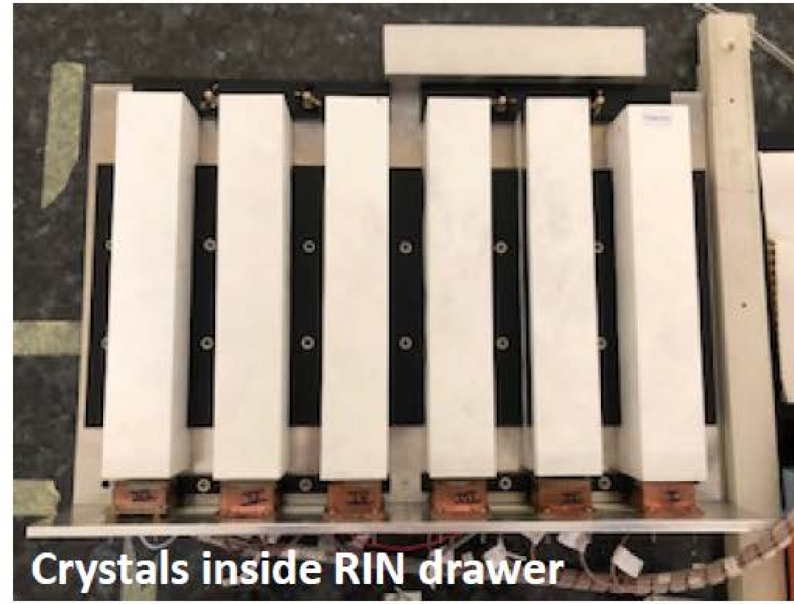
RIN Test Station

Automatized RIN station installed @ FNAL allows to test 6 crystals at the same time

^{137}Cs source
Dose rate:
0.042 rad/h

Crystal
drawer

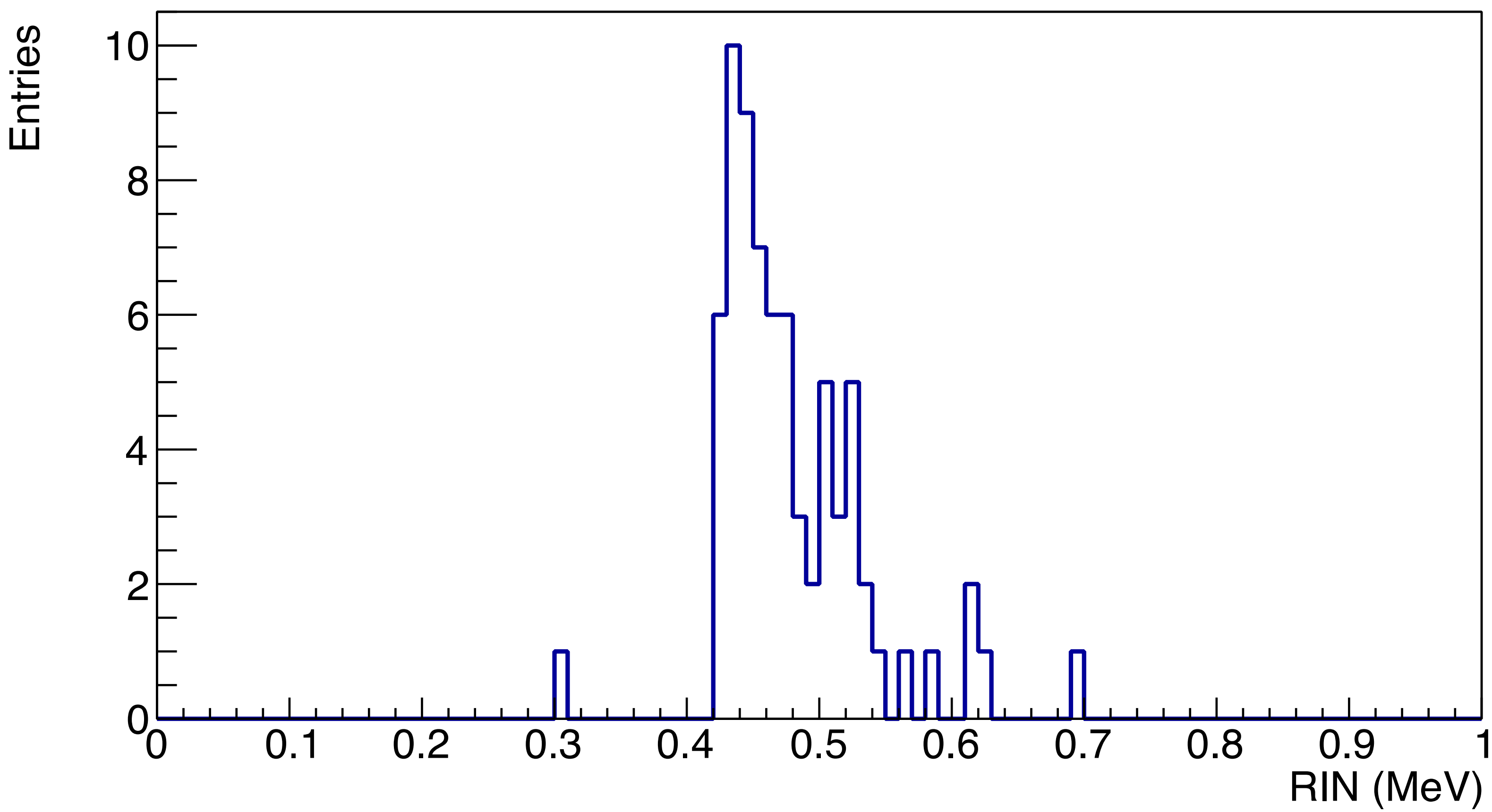




- Crystals with final wrapping, best side coupled to readout
- 2 SiPMs/crystal. Tested also with PMT to compare with specs from producer
- Crystals at a distance of 2 cm from each other; source-crystals distance ~ 12 cm
- The source automatically stops at the center of each crystal while the current is readout

Result of RIN with SiPM Readout

RIN value does not constitute a rejection criteria for crystal, but a parameter of preference. The goal is having a large number of crystals with RIN smaller than 0.6 MeV with PMT readout in a 200 ns gate, which should be scaled according to light collection and QE.

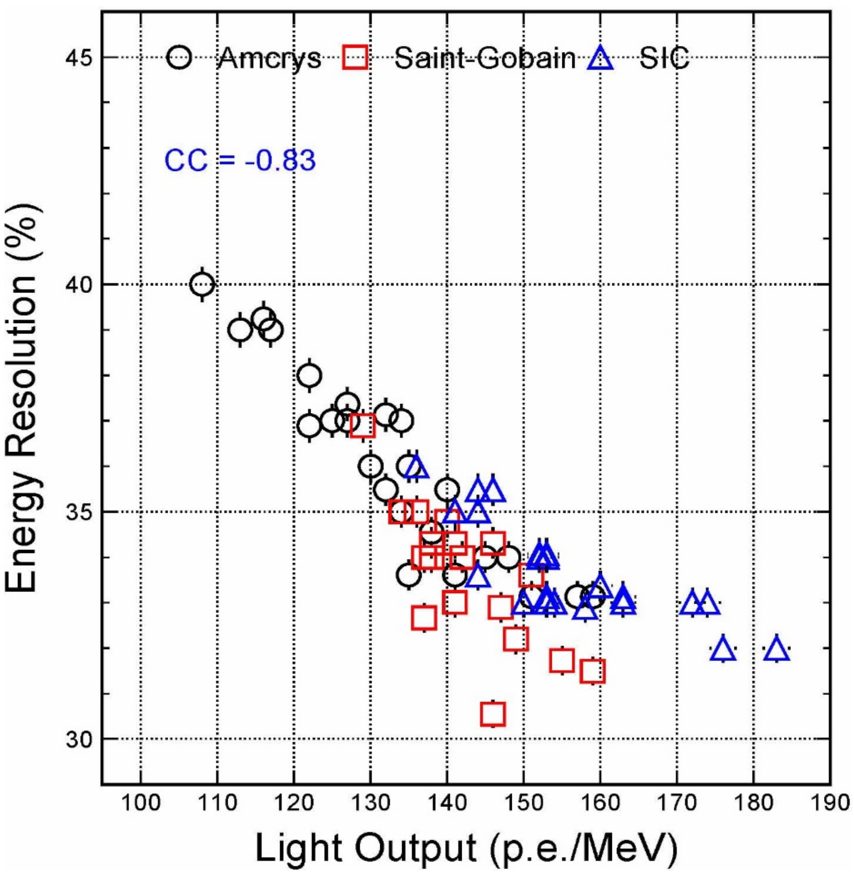


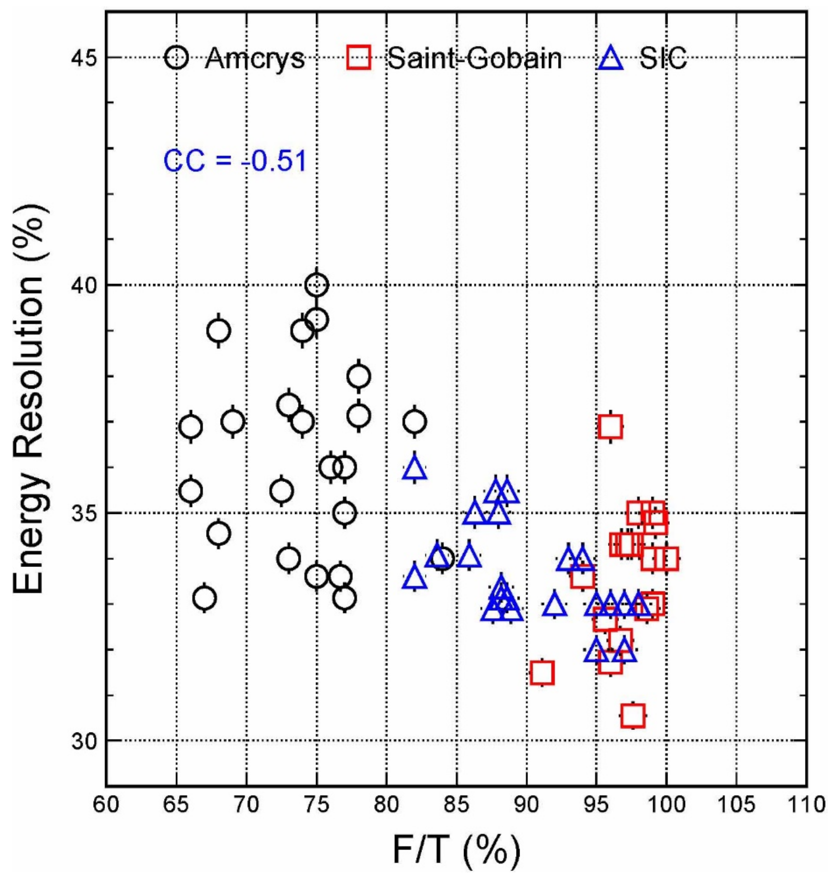
Summary

- Mu2e CsI technical specifications are defined according to physics requirements.
- Three vendors were chosen for preproduction, and S-G and SIC were chosen for production.
- First batch of production crystals has been received. Automatized test stations are fully operational at Fermilab SiDet lab with QA procedure well defined.
- All production crystals have excellent scintillation property.
- Mechanical problem found in S-G crystals, which will be resolved after the visit to S-G last week.

Energy Resolution vs. LO and F/T

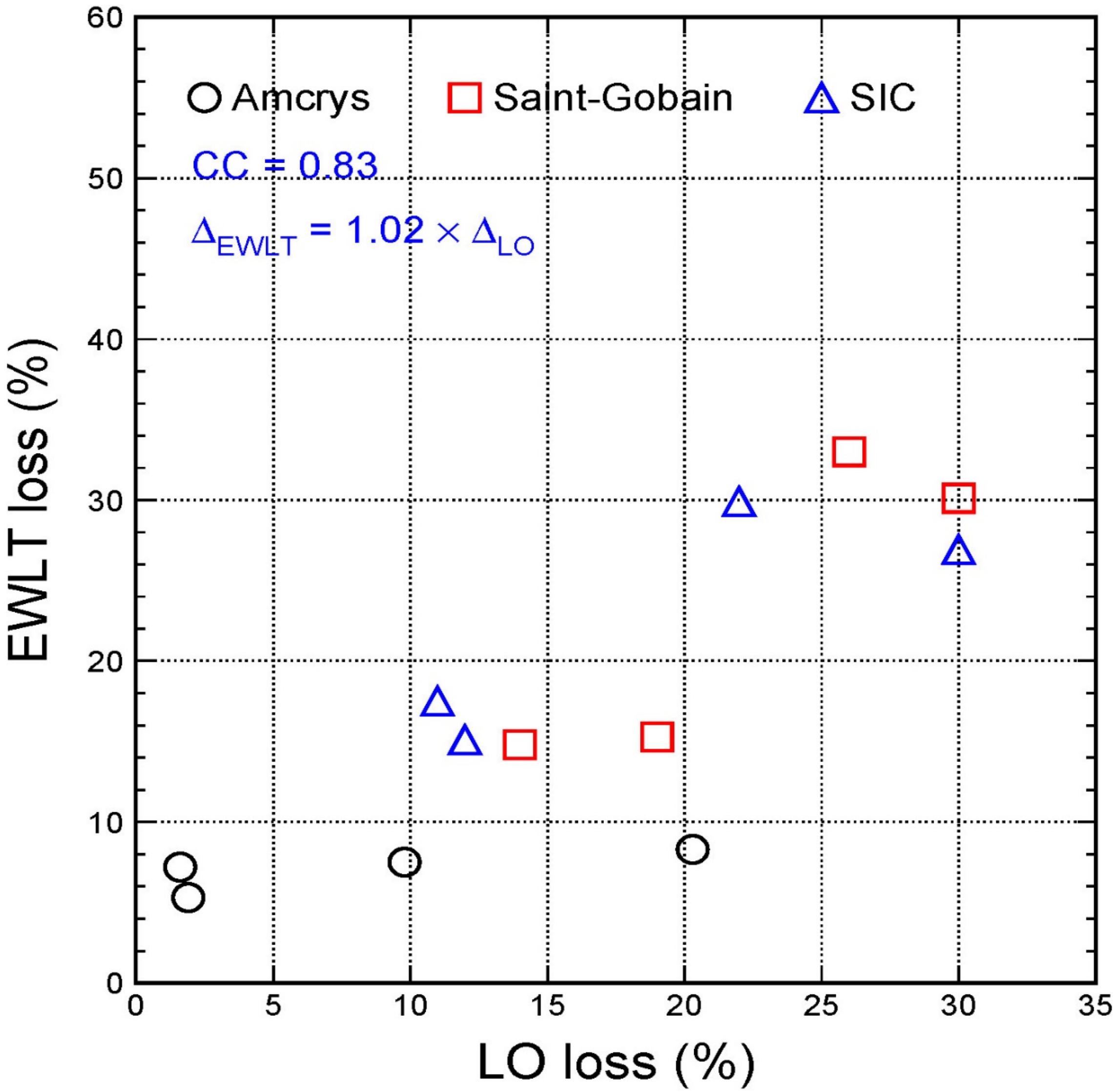
Improving LO and F/T ratio improves energy resolution





LO Loss vs. Transmission Loss

$$EWLT = \int LT(\lambda)Em(\lambda)d\lambda \,/\, \int Em(\lambda)d\lambda.$$



Good correlation indicates that the LO variation can be corrected by measuring crystal's transparency