Quality Assurance on Un-Doped CsI Crystals for the Mu2e Experiment

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on behalf of the Mu2e calorimeter group

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Introduction

The Mu2e experiment at Fermilab will search for the **neutrinoless conversion of a muon to an electron in the field of a nucleus**

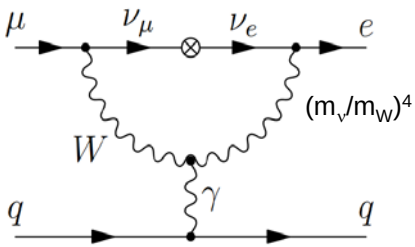
$$\mu N \rightarrow eN$$

This reaction violates charged lepton flavor conservation (CLFV) and is extremely suppressed in the Standard Model: $R_{\mu e} \sim 10^{-52}$.

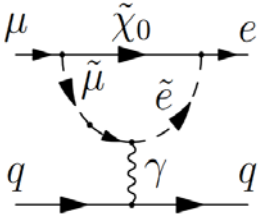
Many New Physics scenarios can enhance CLFV rates to observable values. **Observation of CLFV is an unambiguous sign of New Physics.**

Mu2e aims to improve the current sensitivity by 10000, probing New Physics effective mass scales up to $O(10^3\text{-}10^4)$ TeV

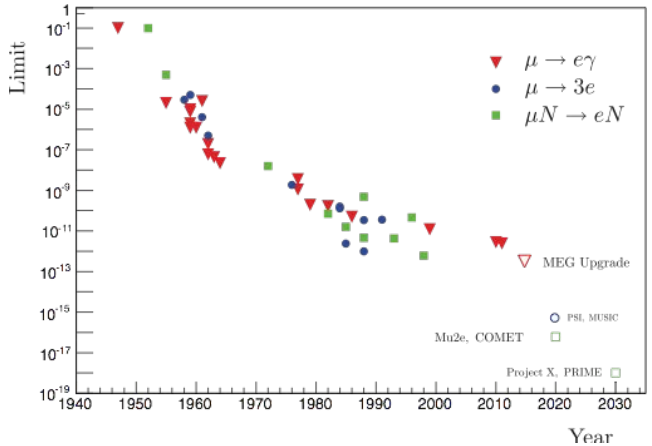
$\mu N \rightarrow eN$

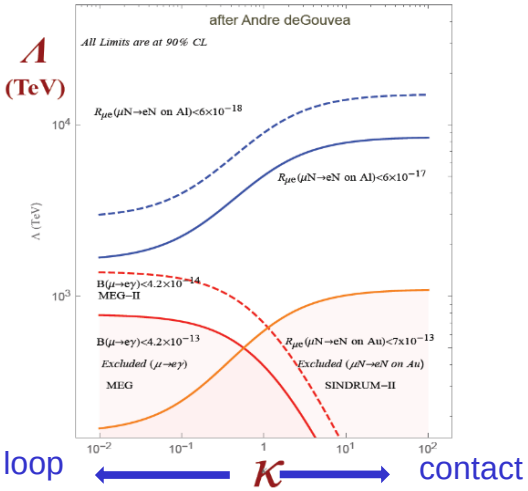


$R_{\mu e} \sim 10^{-52}$ in the νSM

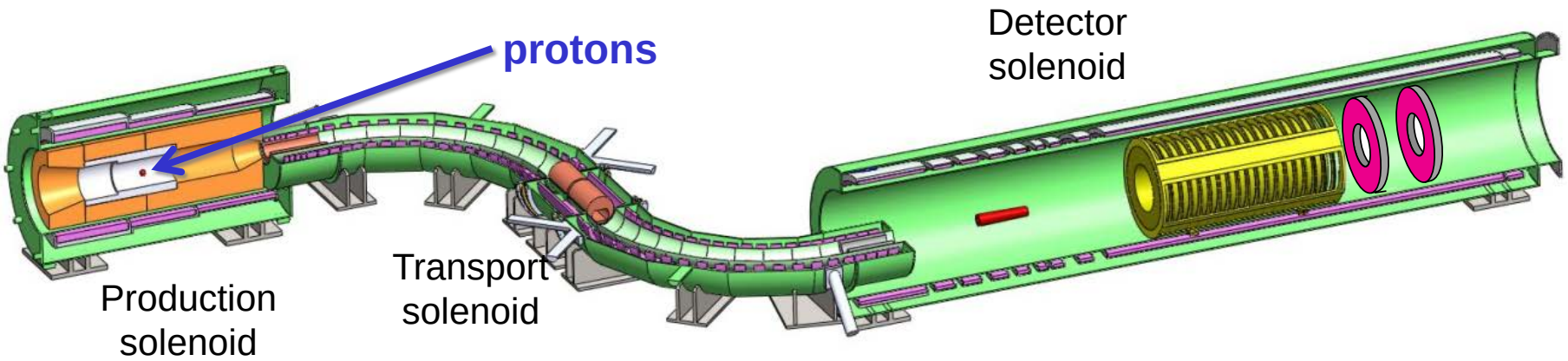


After A. de Gouvêa, P. Vogel, arXiv:1303.4097

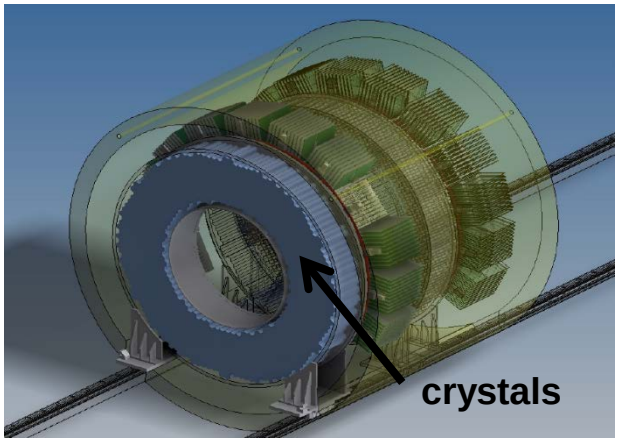




The Mu2e apparatus



Crystal calorimeter composed of two annuli separated by half a wavelength. Each disk is made of 674 pure CsI crystals read by SiPM.



Calorimeter:

Provide independent measurement of energy / time / position with O(5%) / O(0.5 ns) / O(1cm)

Particle identification and independent trigger from tracker

CsI crystal:

Fast scintillating visible light (τ = 30 ns @ 310 nm)

Radiation hard up to 100 krad

Relatively inexpensive

Crystal performance requirements

The following requirements on the crystal have been established:

- **Dimensions:** transverse: ±100 μm, length: ±100 μm. Flatness, perpendicularity and parallelism of faces.

- **Scintillation characteristics**:
  - measured using a bi-alkali PMT with an air gap
  - crystal is wrapped with two layers of 150 mm Tyvek
    - Light output (LO): > 100 p.e./MeV (200 ns gate), defined as percentage of a standard crystal provided to each supplier
    - Energy resolution: FWHM < 45% for 0.511 MeV peak of ^{22}Na
    - Fast (200 ns)/Total (3000 ns) ratio: > 75%
    - Light response uniformity (LRU) < 5%
    - Radiation induced noise (RIN) @1.8 rad/h < 0.6 MeV

- **Radiation Hardness**: Normalized light output after 10/100 krad > 85/60%

Pre-production crystals

A total of 72 crystals from Amcrys, Saint-Gobain and Siccas has been measured at Caltech and LNF, validating the relevance of the specifications and the capability of each supplier to meet them.

Half of the pre-production crystals

Crystal dimension specifications

On the basis of experience gained with the order for prototype crystals, we have arrived at set of mechanical requirements that are

- realistically achievable
- compatible with stacking requirements

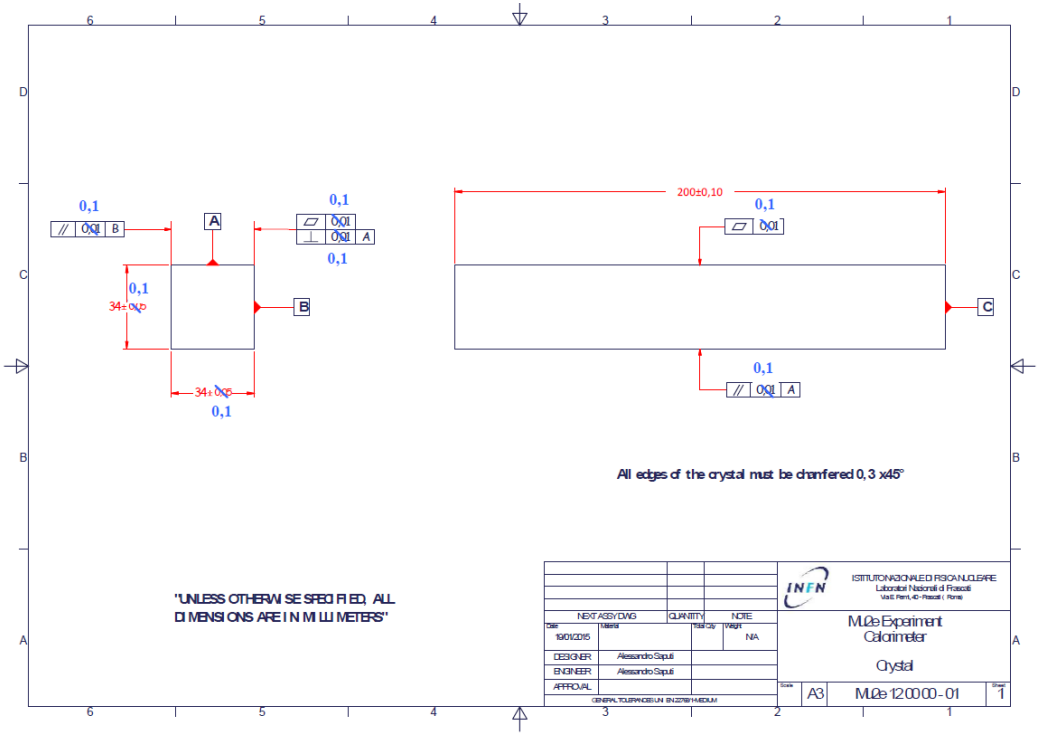
These encompass dimensional and shape requirements:

Dimensionsal requirements

- Cross-section: ±100 μm
- Length: ±100 μm

Shape requirements:

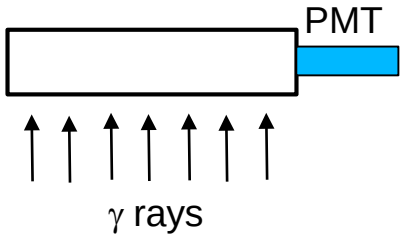
- Flatness of A and B faces
- Perpendicularity of B to A
- Parallelism of A' to A
- Parallelism of B' to B



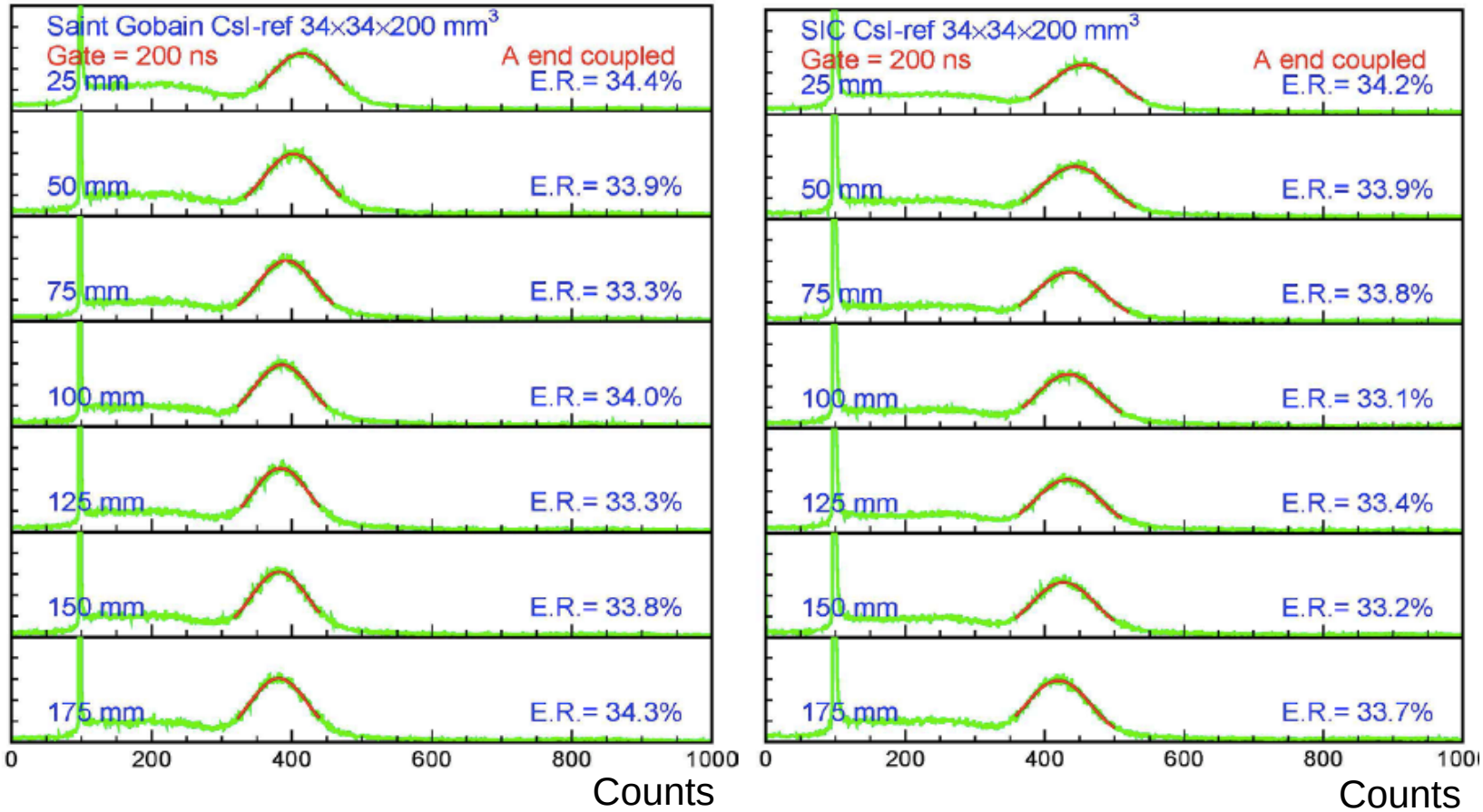
Measurement performed at Fermilab with (high-precision) measuring table

Energy resolution

Measure crystal spectrum with bi-alkali PMT (with air gap) with a ^{22}Na source placed at different position along the crystal with a 200 ns integration gate.



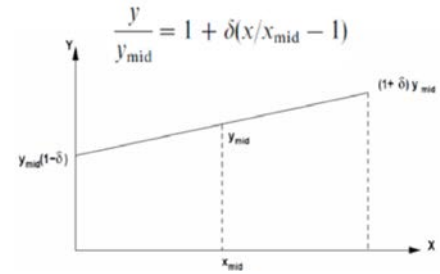
Derive energy resolution and longitudinal response uniformity

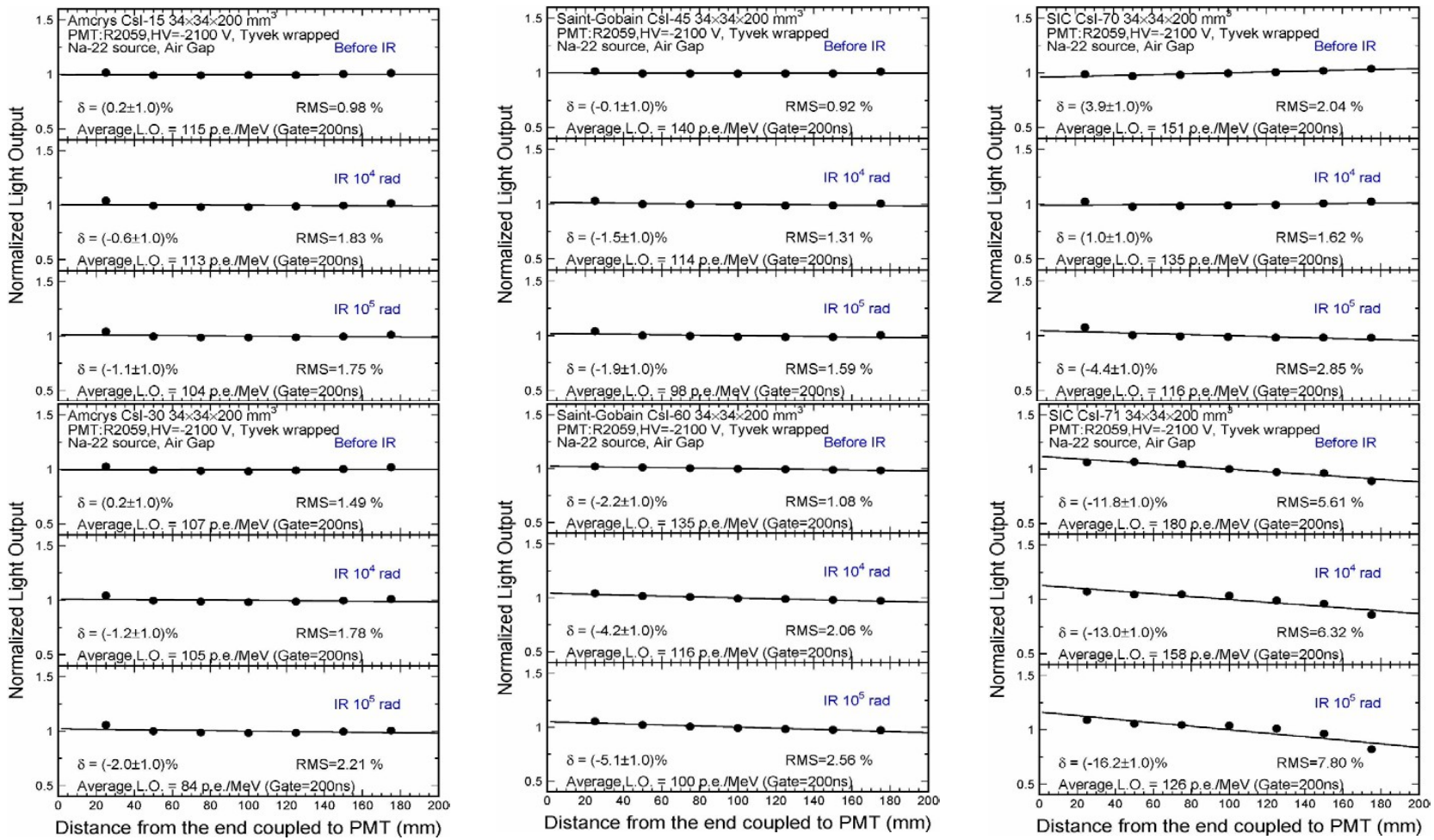


Light output and response uniformity

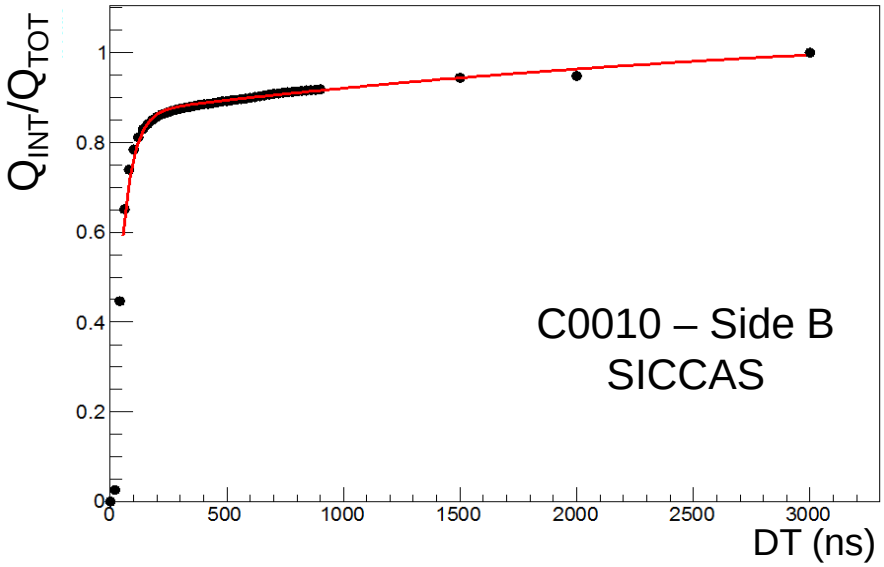
The light output is defined as the average of the values measured at seven points with rms spread as longitudinal response uniformity.

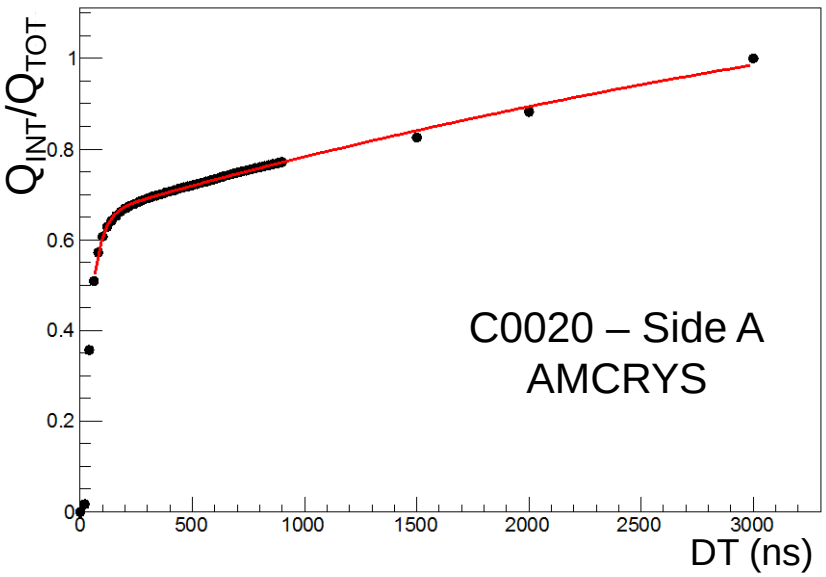
$$\frac{y}{y_{mid}} = 1 + \delta(x/x_{mid} - 1)$$

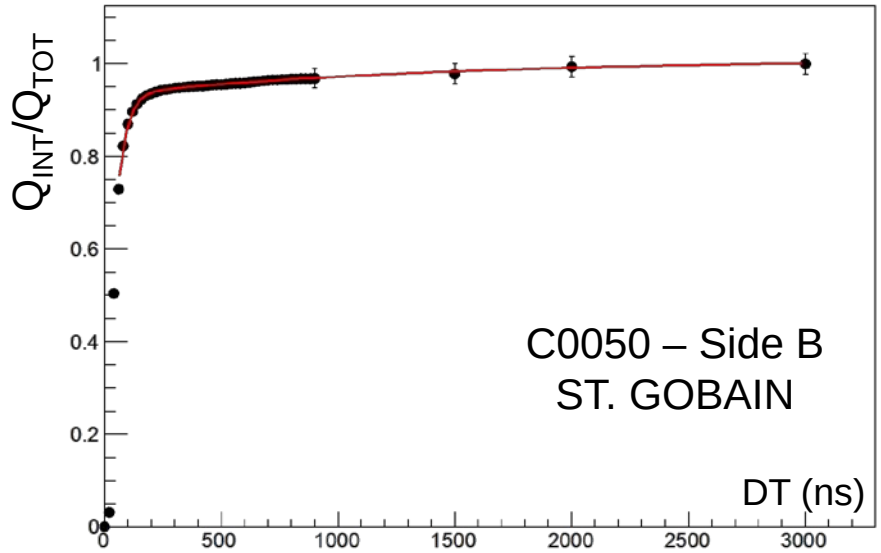




Fast and slow components

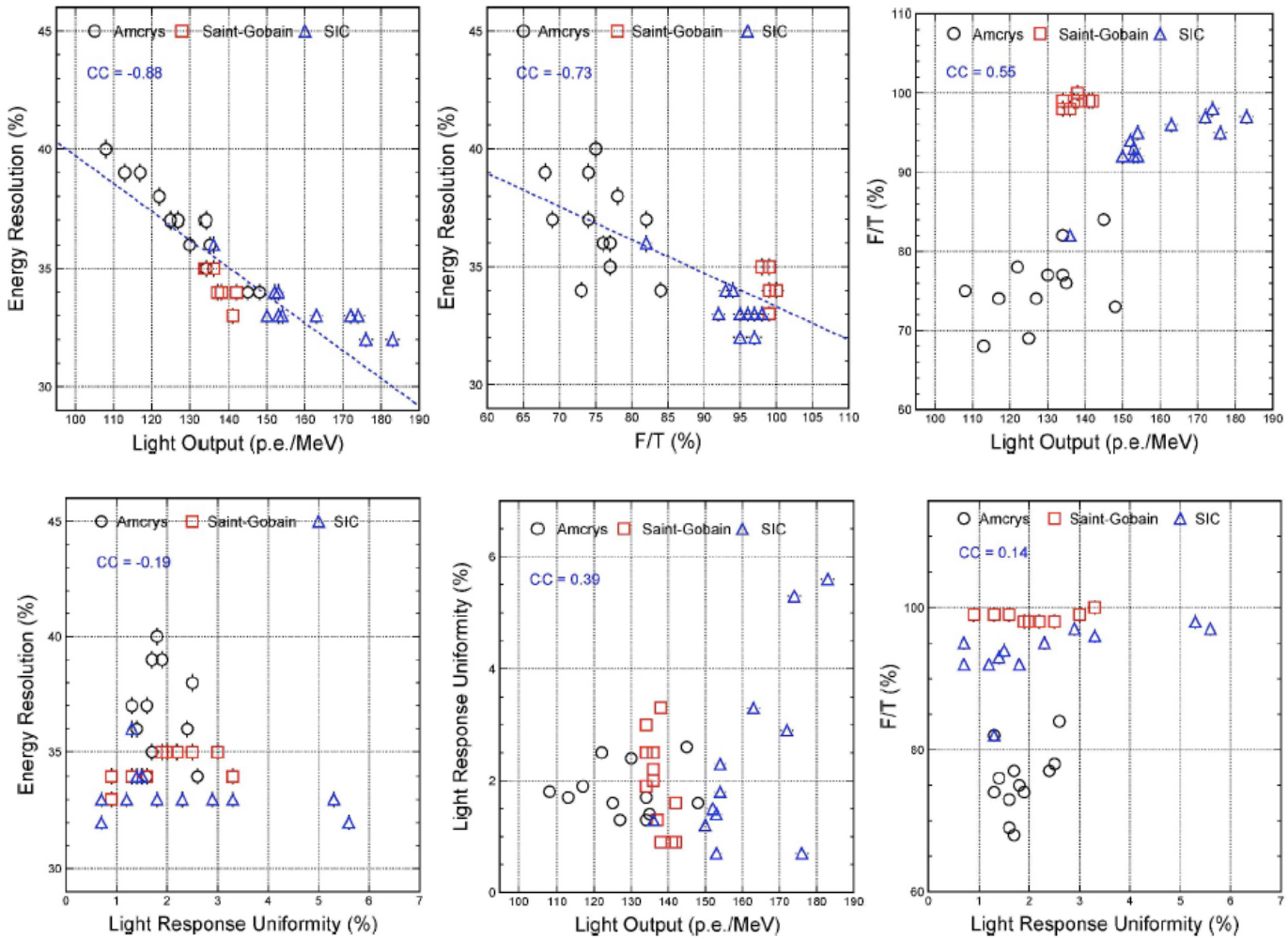






The integrated charge over time is fit with two components to extract the fast and slow contributions and derive the Fast/Total (F/T) ratio.

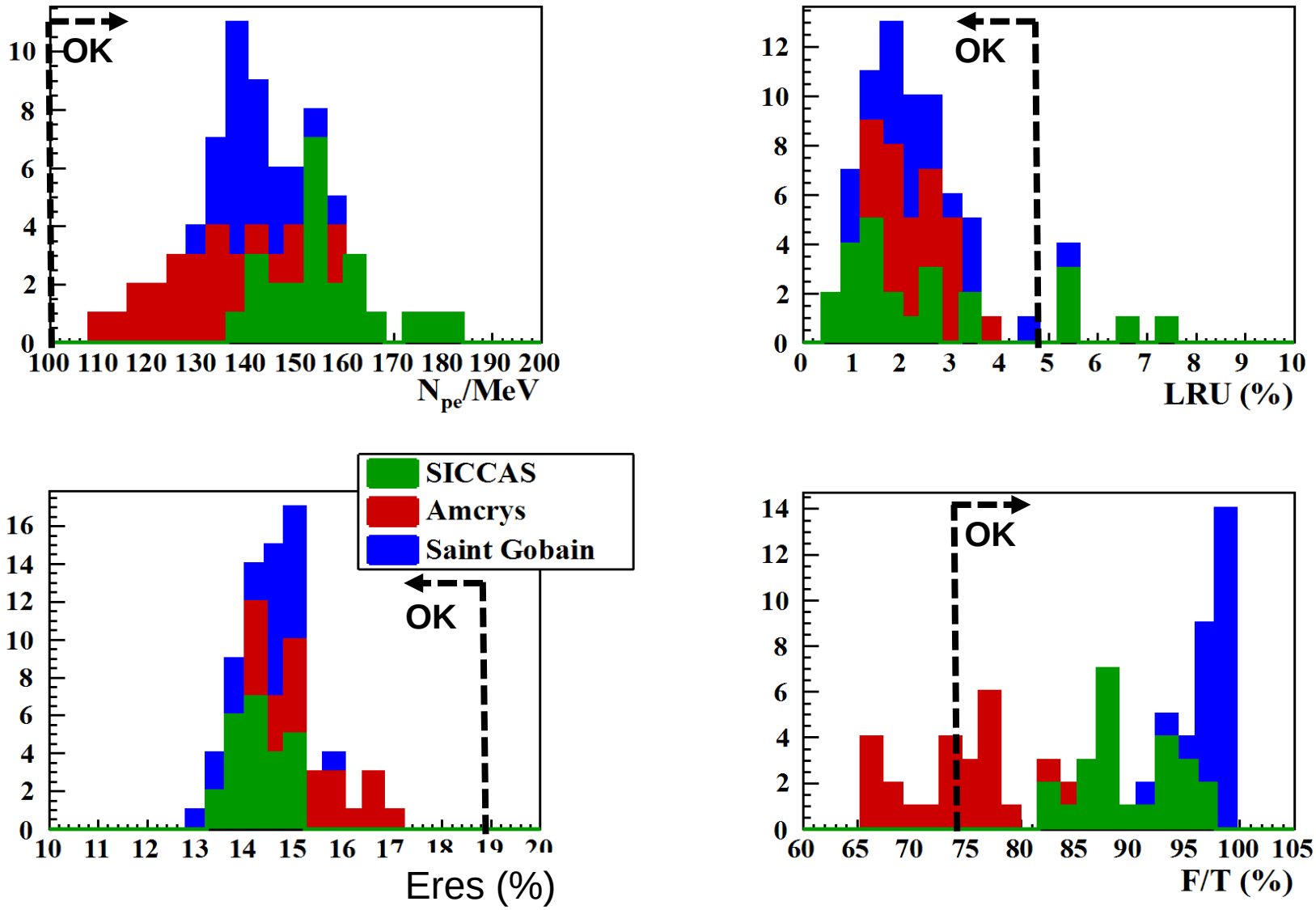
Correlations: energy resolution, LO, LRU and F/T ratio



Correlation between energy resolution, LO and F/T ratio → keep F/T ratio small

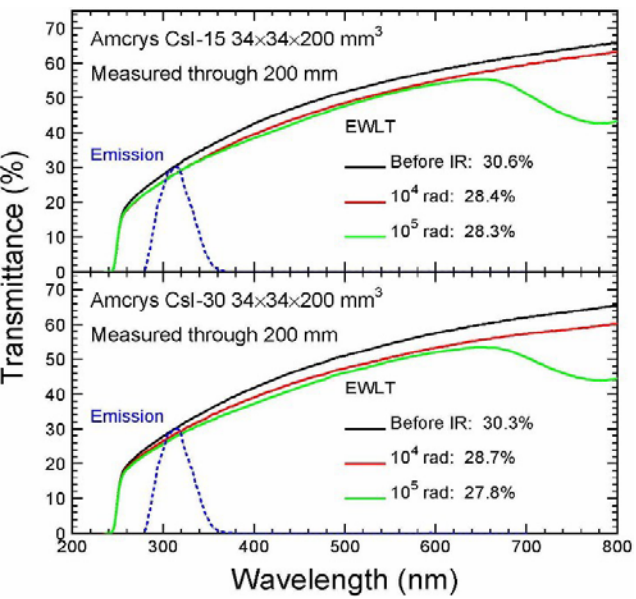
No correlations between LRU and other variables.

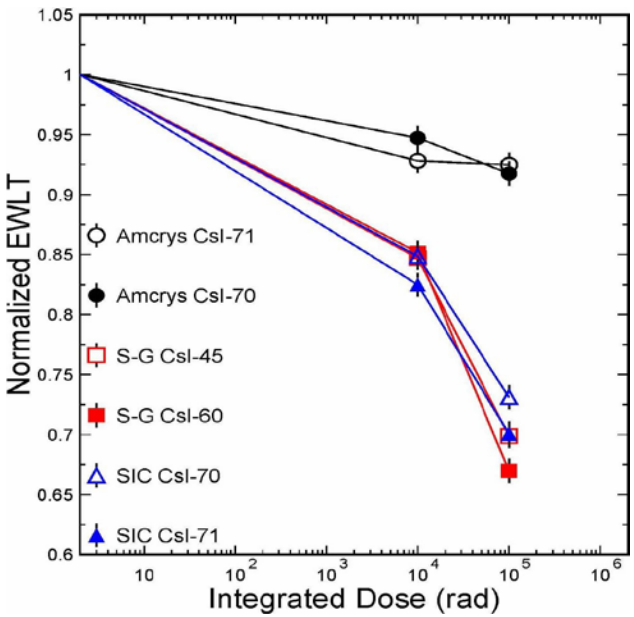
Summary of optical measurements

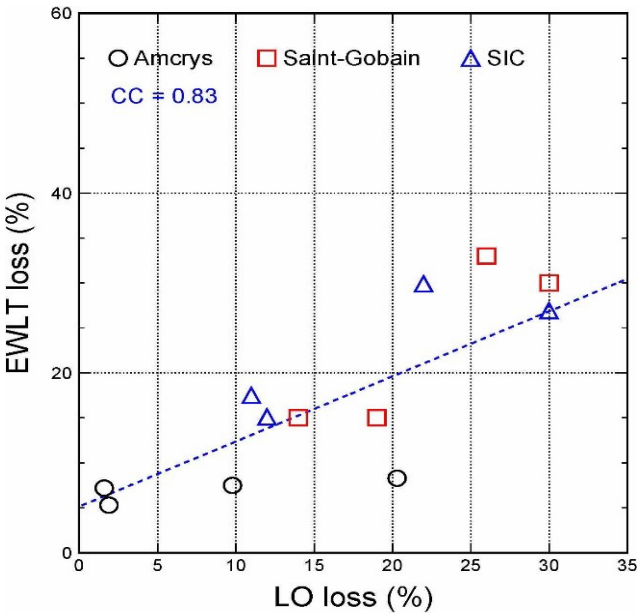


Radiation damage

While the initial light transmittance curve depends on the crystal surface, subsequent variations of the LT spectrum and emission weighted LT are a representation of the effect of radiation damage on light collection inside the crystal.







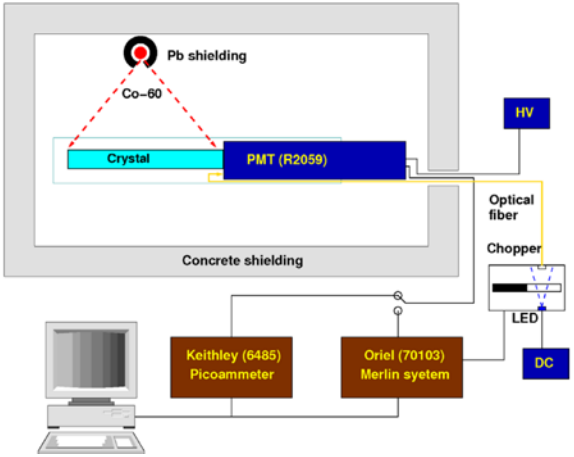
Observe a correlation between EWLT and light output

EWLT = $\int EM(\lambda)LT(\lambda)d\lambda$ represents transparency of entire emission spectrum

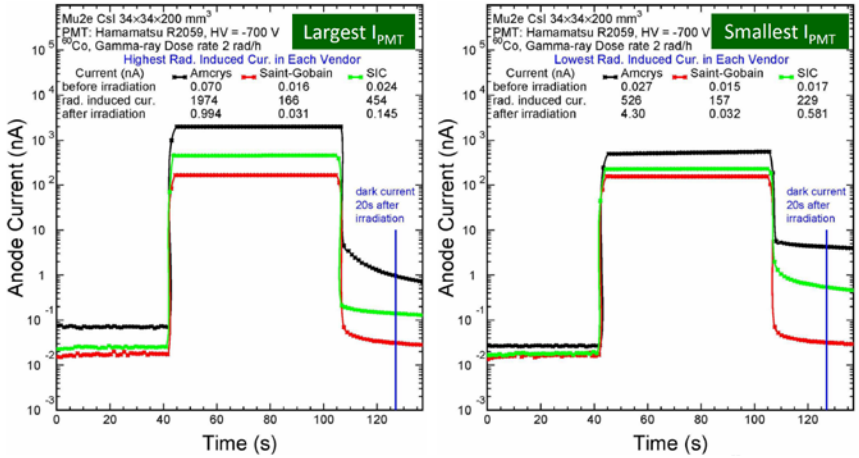
Radiation induced noise

Radiation induced noise (RIN) due to phosphorescence (or "afterglow") after gamma and neutron irradiation

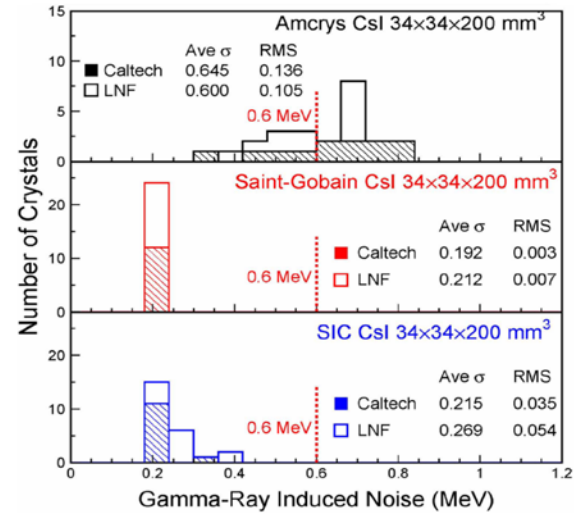
Dose rate from a Co-60 source is 2 rad/hr at the sample

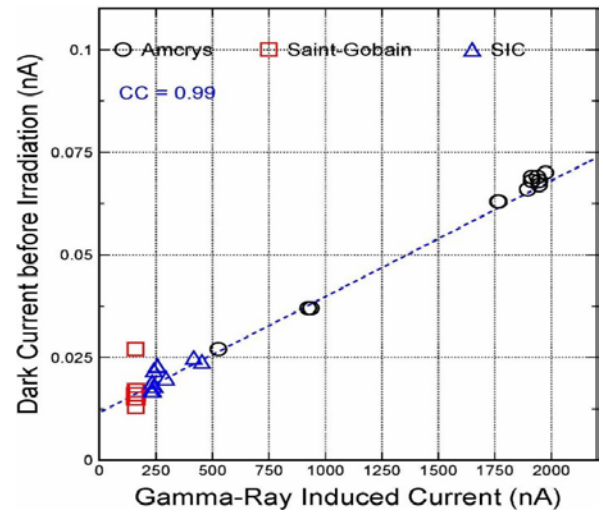


Gamma ray @ 2 rad/h



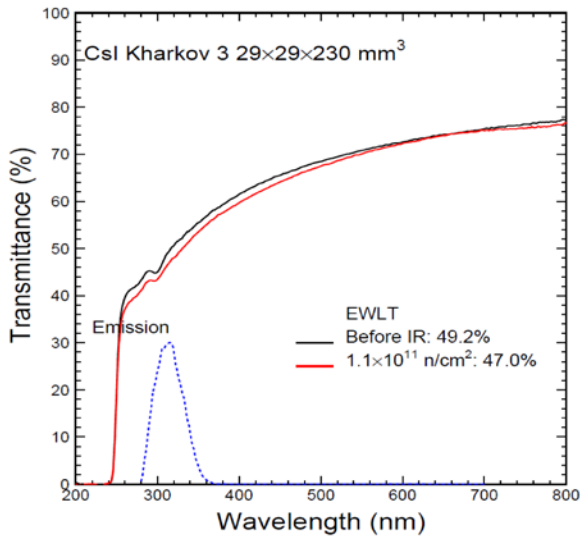
Gamma

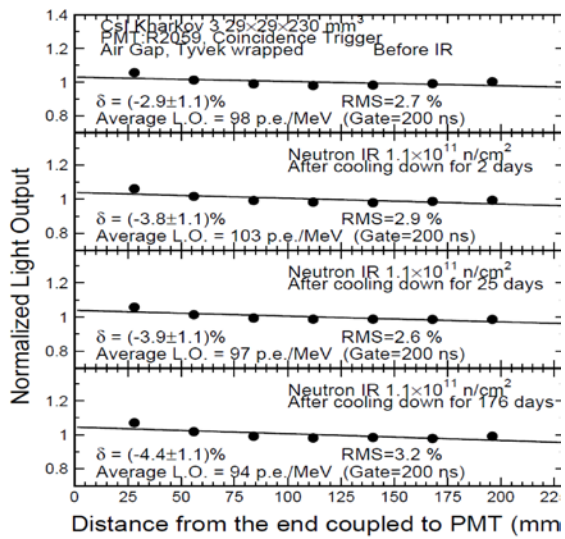


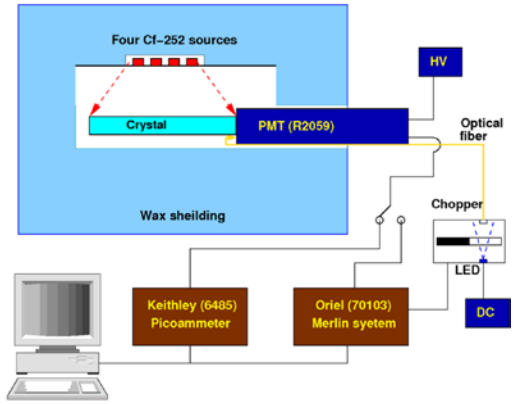


Correlation between dark current and RIN

Light yield loss less than 5% after 10^{11} neutrons

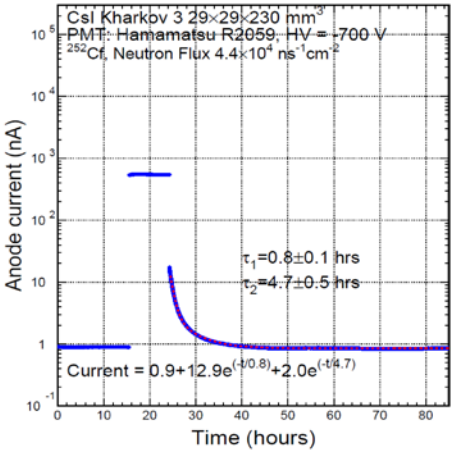




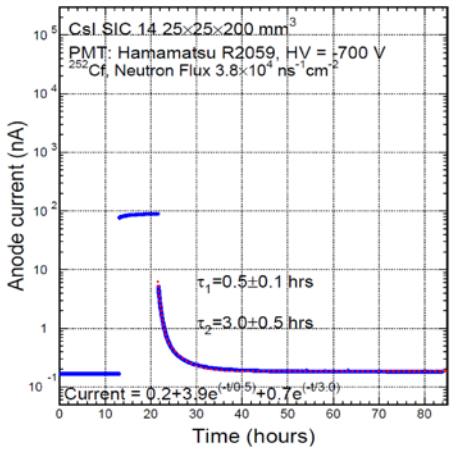


Note: Cf-252 also emits gamma rays, so results are upper bond on neutron induced damage

4.4×10^4 n/cm²/s on sample



3.8×10^4 n/cm²/s on sample



RIN thermal neutrons

Crystal	LY (N_{pe}/MeV)	I (μA)	Mu2e flux (n/cm²/s)	F (N_{pe}/s/dose)	N_{pe} noise (200 ns)	RIN (keV)
ISMA 02	103	7,16	1×10^4	$3{,}02 \times 10^4$	60,3	75,4
ISMA 12	103	4,61	1×10^4	$1{,}94 \times 10^4$	38,9	60,5
ISMA 20	103	5,35	1×10^4	$2{,}25 \times 10^4$	45,1	65,2
ISMA 21	103	7,28	1×10^4	$3{,}07 \times 10^4$	61,4	76,0
SICCAS 1	129	6,83	1×10^4	$2{,}88 \times 10^4$	57,5	58,6
SICCAS 2	126	7,58	1×10^4	$3{,}19 \times 10^4$	63,8	63,4
SICCAS 4	136	10,1	1×10^4	$4{,}27 \times 10^4$	85,5	67,8
OPTOM 2	93	7,65	1×10^4	$3{,}22 \times 10^4$	64,4	86,3

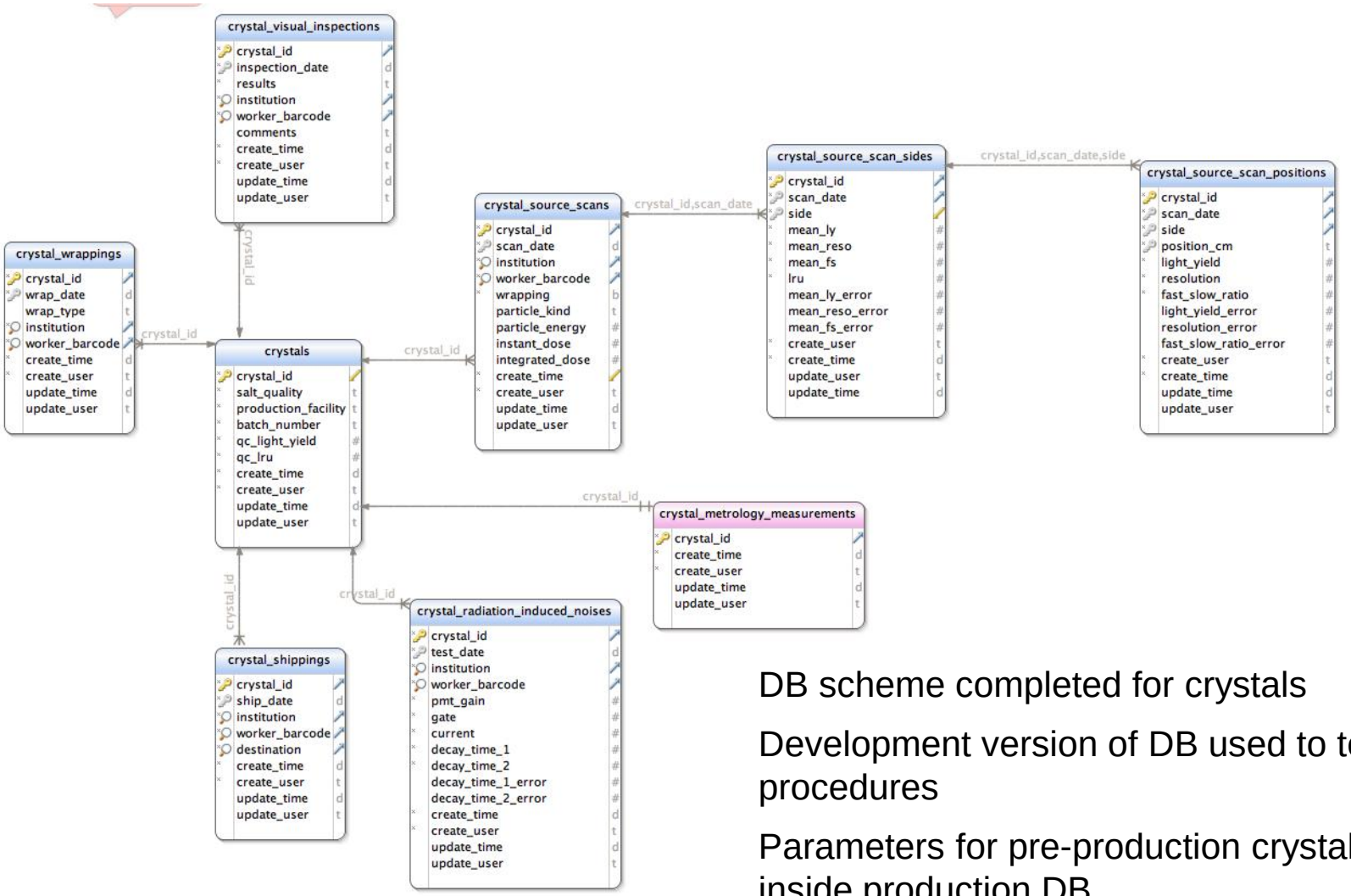
RIN neutron << RIN gamma

Radiation damage results for some crystals

Crystal ID	Batch Number	Dose (krad)	EWLT (%)	Normalized EWLT (%)	L.O. (p.e./MeV)	Normalized L.O. (%)	E.R. (%)	F/T (%)	LRU (%)	δ (%)
C0015	Amcrys-007	0	30.6	100	115	100	38	**69.0**	0.98	0.2
		10	28.4	92.8	113	98.1	38	**70.6**	1.83	-0.6
		100	28.3	92.5	104	90.2	39	**73.2**	1.75	-1.1
C0030	Amcrys-001	0	30.3	100	107	100	40	77.0	1.49	0.2
		10	28.7	94.7	105	98.4	39	78.4	1.78	-1.2
		100	27.8	91.7	84	79.7	41	80.5	2.21	-2.0
C0045	SG-A11827	0	22.9	100	140	100	34	98.7	0.92	-0.1
		10	19.4	84.7	**114**	**81.2**	38	98.2	1.31	-1.5
		100	16.0	69.9	98	69.6	41	100.0	1.59	-1.9
C0060	SG-A11804	0	20.9	100	135	100	34	97.3	1.08	-2.2
		10	17.8	85.2	116	85.7	38	97.8	2.06	-4.2
		100	14.0	67.0	100	73.8	41	99.9	2.56	-5.1
C0070	SIC-2016 A20	0	41.1	100	151	100	35	92.6	2.04	3.9
		10	33.9	82.5	135	89.3	37	90.0	1.62	1.0
		100	28.8	70.1	116	77.1	40	91.4	2.85	-4.4
C0071	SIC-2016 A23	0	23.8	100	180	100	33	95.8	**5.61**	-11.8
		10	20.2	84.9	158	87.5	37	98.4	**6.32**	-13.0
		100	17.4	73.1	126	69.9	42	98.3	**7.80**	-16.2

Mu2e crystal database

Crystal production database (postgresql) developed with the help of Fermilab Scientific Computing Division to store crystal measurements.

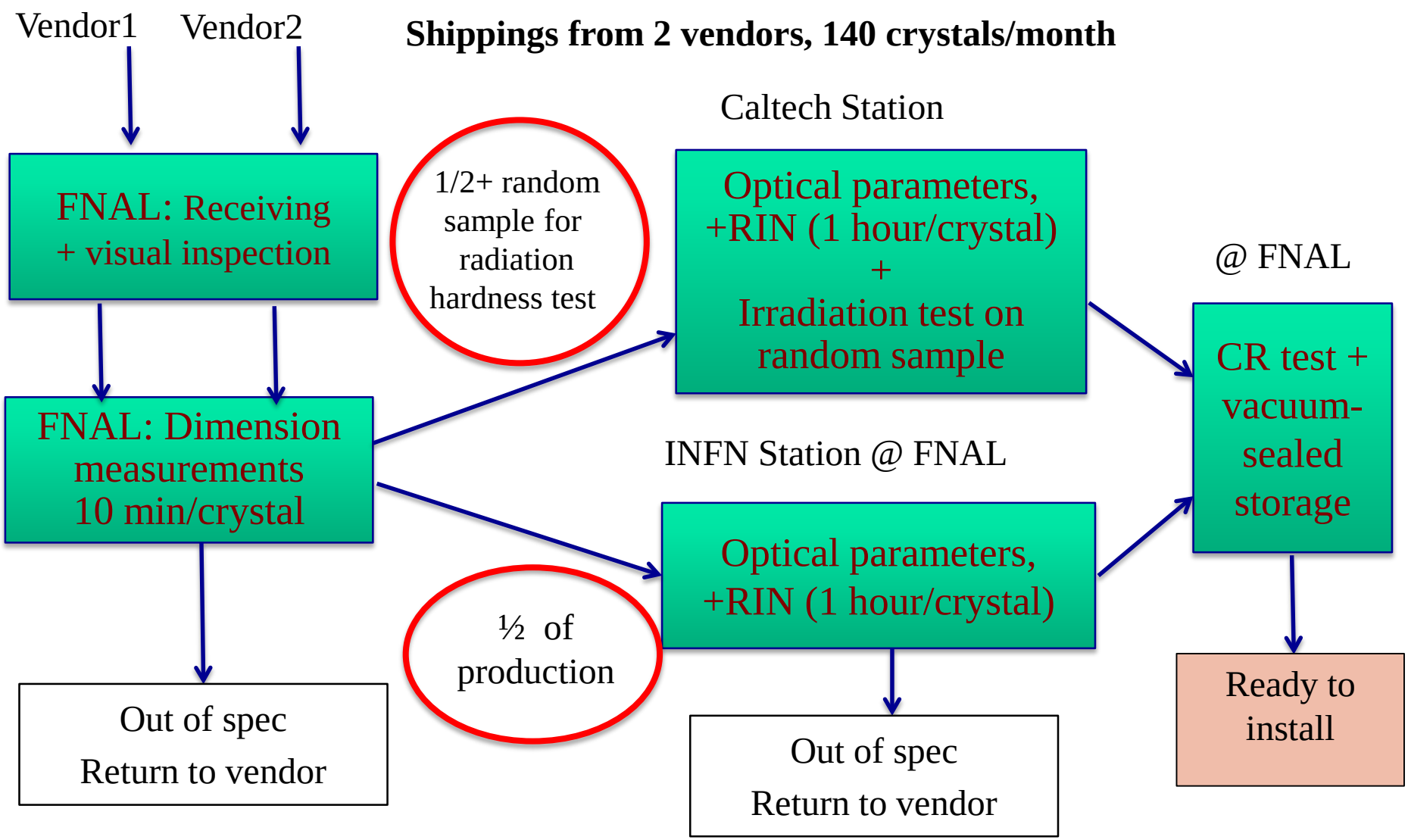


DB scheme completed for crystals

Development version of DB used to test procedures

Parameters for pre-production crystals inside production DB

Production and testing scheme



Summary

CsI crystal specifications for the Mu2e calorimeter have been set on crystal dimensions, scintillation properties and radiation hardness

Measurements on a small sample have been performed to validate these requirements and the capability of suppliers to meet them

Correlations between the energy resolution, light output and the F/T ratio have been observed, indicating the need to keep the F/T ratio as low as possible.

A production database (postgresql) has been developed to store all production information

A comprehensive production and testing plan has been specified. The first crystals should be delivered in the near future.

Extra Material

Caltech – LNF comparison

QA parameter	Producer	Mean LNF	RMS/Mean LNF	Mean CALTECH	RMS/Mean CALTECH
LY (N_{pe}/MeV)	SICCAS	153.0	6.2%	158.2	8.2%
	AMCRYS	137.4	9.2%	128.1	9.0%
	ST GOBAIN	144.8	5.5%	137.3	2.1%
LRU (%)	SICCAS	2.79	76%	2.71	74%
	AMCRYS	2.65	21%	1.82	24%
	ST GOBAIN	2.75	43%	1.92	41%
Eres (%)	SICCAS	14.4	3.2%	14.1	3.4%
	AMCRYS	15.0	5.6%	15.6	5.1%
	ST GOBAIN	14.2	5.0%	14.6	1.9%
F/T ratio (%)	SICCAS	87.6	3.4%	92.4	4.6%
	AMCRYS	71.8	6.2%	75.6	5.7%
	ST GOBAIN	96.3	2.1%	98.7	0.6%