Result of Uniformization by Roughening 25 LYSO Crystals

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Caltech

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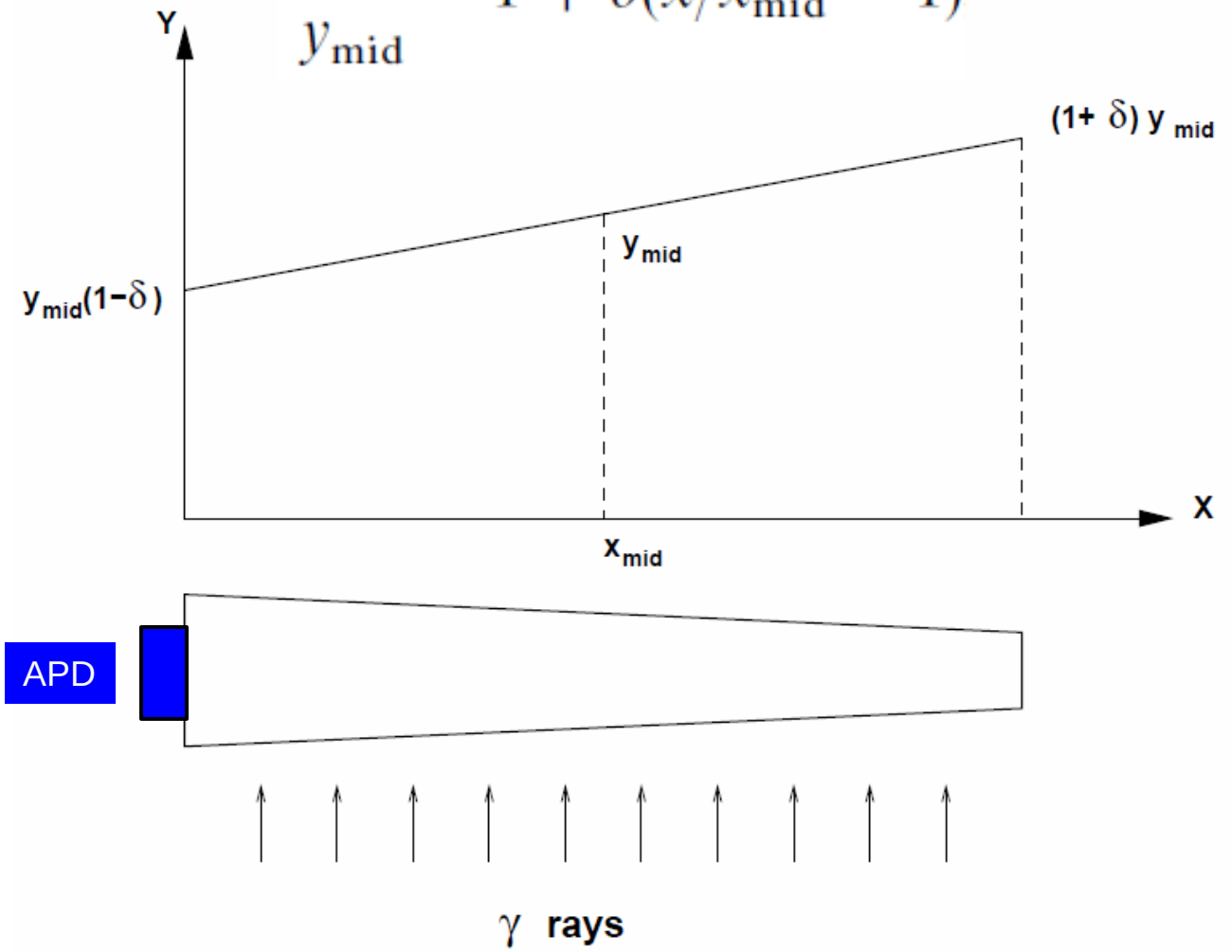
Talk Given in SuperB EMC R&D Meeting

Introduction

- Following CMS experience the light response uniformity is required to be $|\delta| < 3\%$.
- Uniformization with 15 mm wide black paint at the small end of the smallest side surface is not sufficient.
- A ray-tracing simulation shows that $|\delta| < 3\%$ may be achieved with appropriate roughening for one of the side surfaces.
- Following 1st test at SIC for sample SIC-L3 all other 24 LYSO crystals were roughened at Mindrum Precision, Inc., California.

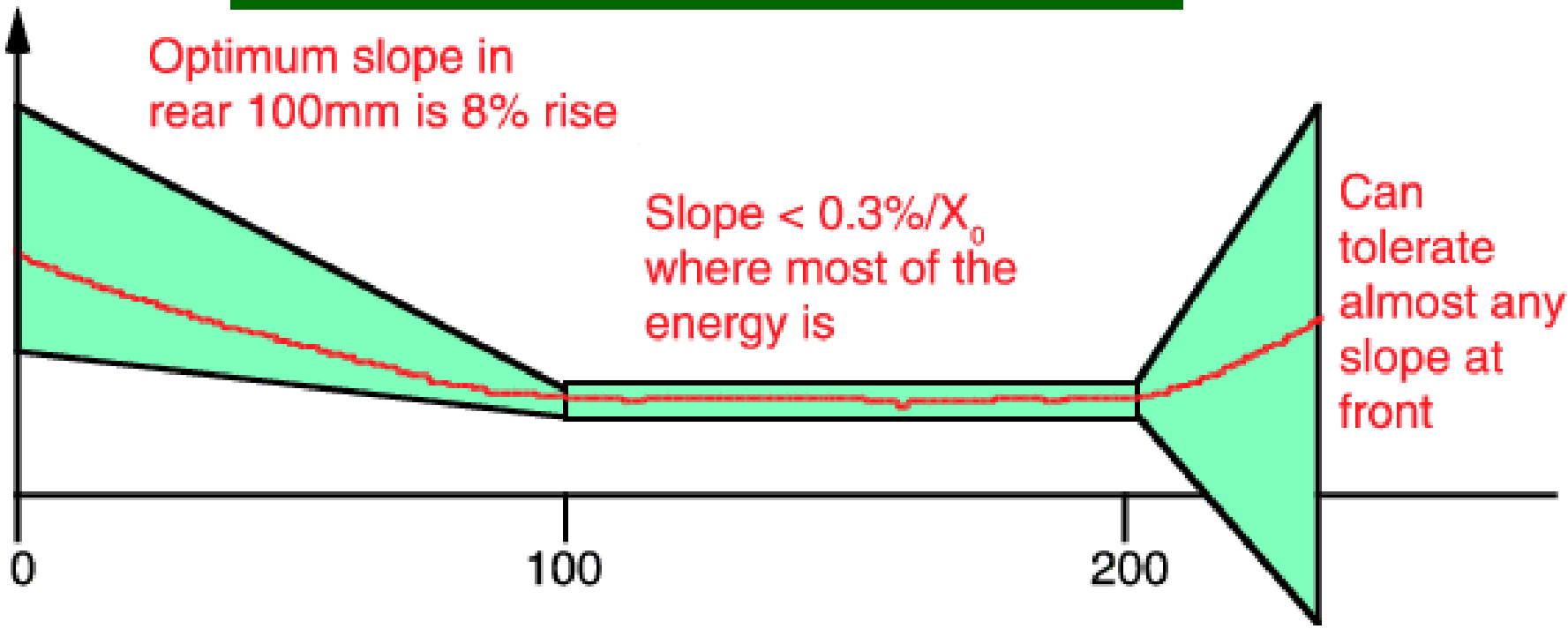
Light Response Non-Uniformity: δ

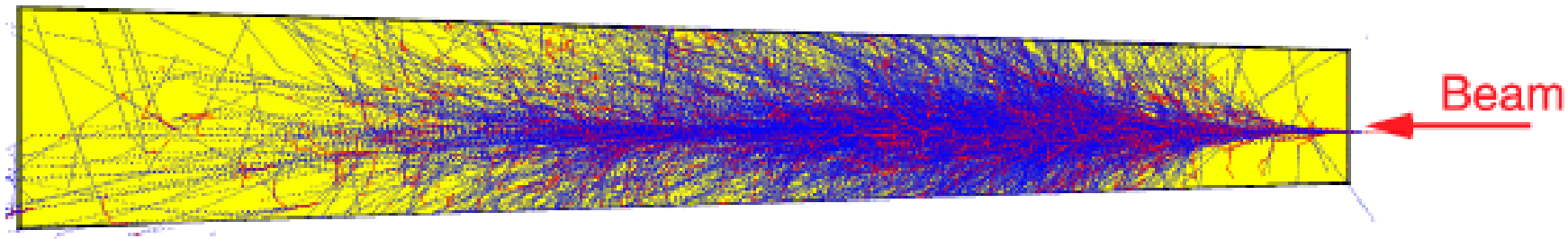
$$\frac{y}{y_{\mathrm{mid}}} = 1 + \delta(x/x_{\mathrm{mid}} - 1)$$



CMS Specification for Uniformity

D. Graham & C. Seez, CMS Note 1996-002

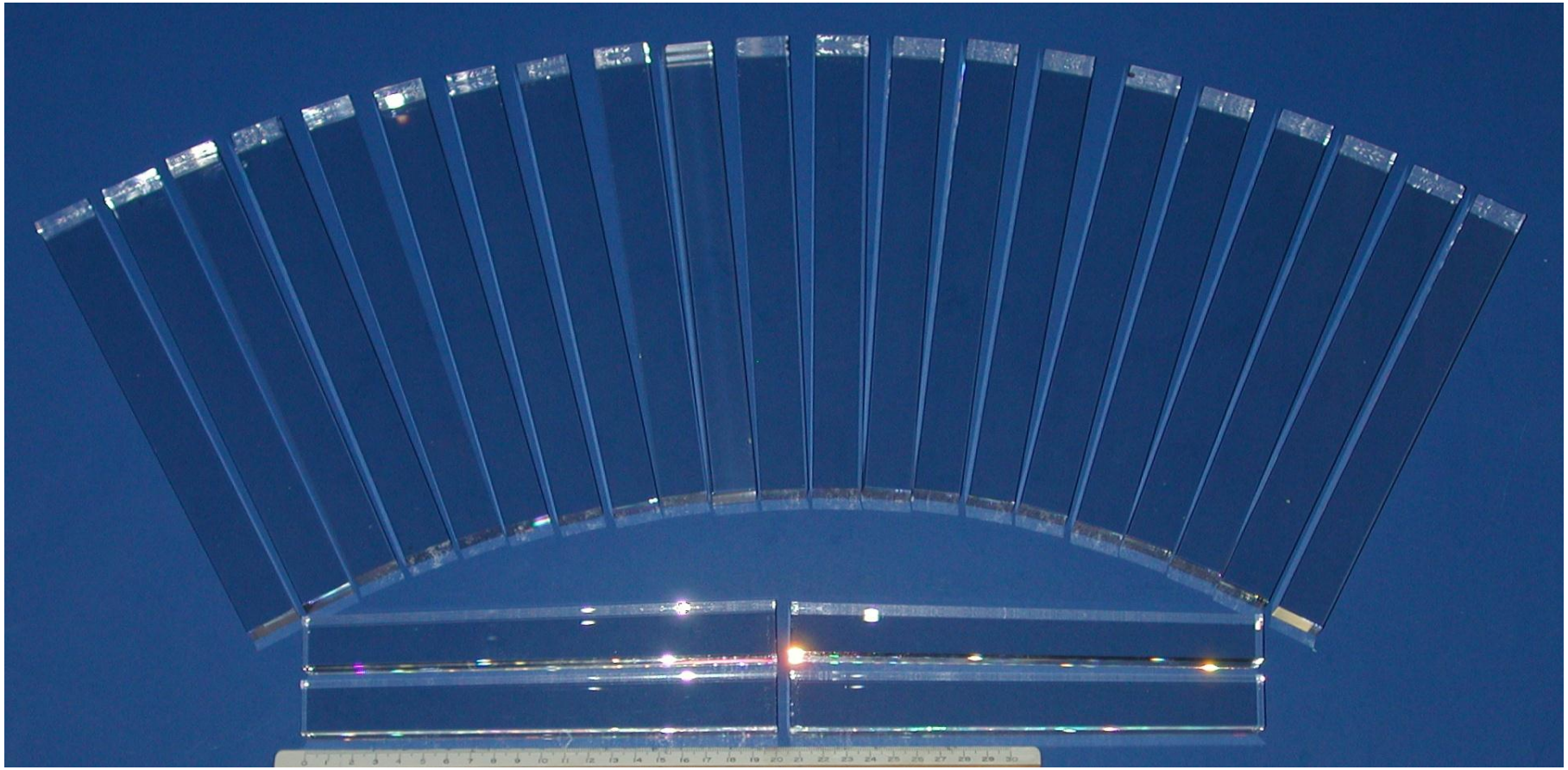




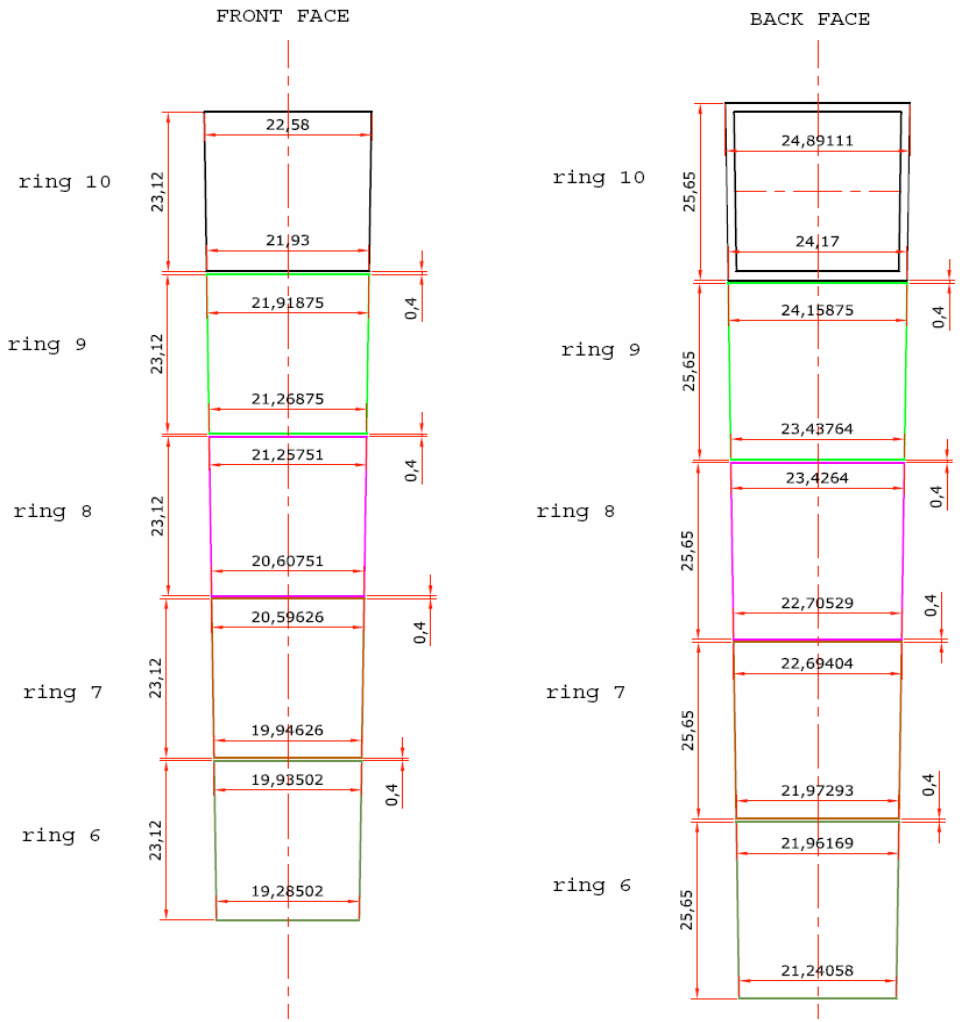
$|\delta| < 3\%$ & 4% for 18 X_0 (SuperB) & 25X_0 (CMS)

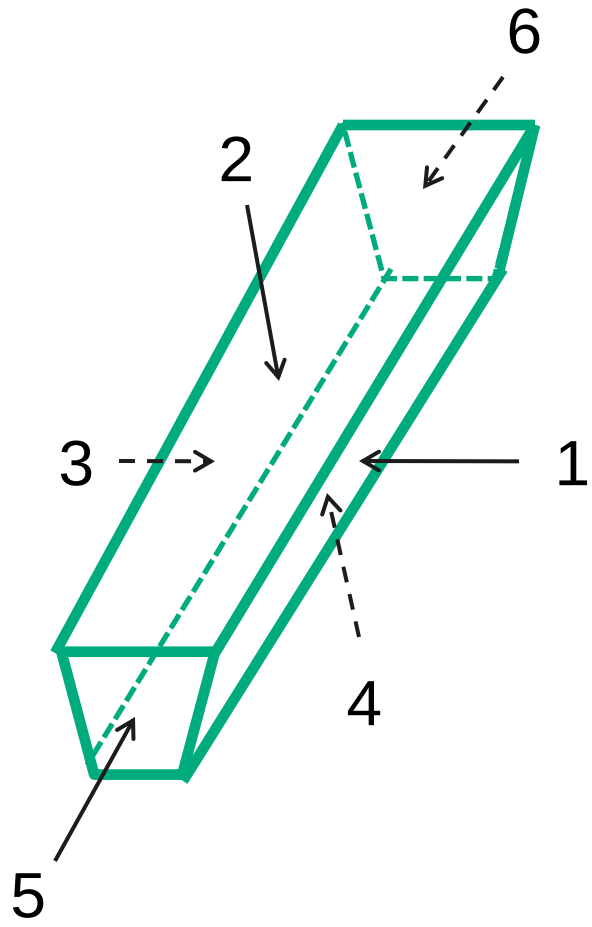
Twenty Five Test Beam Crystals

Crystals are procured from three vendors: Saint-Gobain, SIPAT and SIC, and are characterized and uniformized in Caltech Crystal Laboratory.



Dimensions and Surface Definition





Summary of SuperB Test Beam Crystals

With 15 mm wide black band painted at the small end of the smallest side surface

Caltech-ID	Vendor-ID	Test-Beam-Position	Type	LT @ 420 nm (%)	LY, ER & Uniformity by PMT* (% of candel 1), (FWHM, %), (δ, %)	LY, ER & Uniformity by APD (As)* (p.e./MeV), (σ, %), (δ, %) (rms, %)	LY, ER & Uniformity by APD (Uni)* (p.e./MeV), (σ, %) , (δ, %) (rms, %)	LO Loss %
SIPAT-11	02_08_08	ring 8-3	8	82.3	47.6, 10.7, 5.3	1420, 15.5, 12.9, 6.5	1190, 21.4, 7.2, 3.8	16.2
SIPAT-12	02_08_08	ring 8-1	8	82.2	46.5, 10.4, 3.9	1440, 15.1, 14.2, 7.1	1210, 20.7, 10.0, 5.1	15.9
SIPAT-13		ring 6-1	6	82.6	52.5, 11.5, 2.7	1440, 14.9, 6.8, 3.6	1220, 20.4, 3.4, 2.0	15.3
SIPAT-14		ring 6-2	6	82.7	53.7, 10.9, 3.2	1500, 14.9, 14.4, 7.4	1200, 20.4, 9.0, 4.6	20.0
SIPAT-15		ring 6-4	6	80.7	52.8, 10.5, 3.4	1580, 13.7, 11.9, 6.0	1310, 19.1, 6.1, 3.4	17.1
SIPAT-16		ring 6-5	6	81.1	51.8, 10.1, -0.8	1570, 13.5, 9.7, 5.0	1100, 19.6, 5.3, 2.7	29.9
SIPAT-17		ring 6-3	6	82.1	53.0, 12.2, 3.5	1260, 17.1, 9.8, 4.9	1080, 24.1, 4.9, 2.7	14.3
SIPAT-20	07_10_02	ring 7-2	7	79.8	56.4, 10.0, 5.6	1670, 14.6, 8.7, 4.4	1340, 18.2, 5.1, 2.6	19.8
SIPAT-21	02_10_23	ring 7-5	7	81.6	48.8, 10.9, 3.0	1550, 15.8, 10.7, 5.6	1190, 20.7, 6.1,3.2	23.2
SIPAT-22	07_10_02	ring 7-1	7	81.4	52.6, 11.0, 2.7	1600, 15.2, 9.2, 4.8	1180, 20.3, 5.2, 3.0	26.3
Average				**81.7**	**51.5, 10.8, 3.3**	**1500, 15.0, 10.8, 5.5**	**1200, 20.5, 6.2, 3.3**	**19.8**
SG-S1			8	80.5	52.2, 9.8, 1.0	1370,14.5,9.6,5.0	1040,19.7,5.4,2.8	24.1
SG-S2			8	79.5	54.2, 9.6, 1.4	1400,14.3,9.0,4.7	1040,19.5,6.6,3.4	25.7
SG-S3			9	79.1	56.0, 9.8, 1.0	1370,14.7,8.0,4.2	1000,19.7,6.1,3.2	27.0
SG-S4			9	80.1	56.5, 9.7, 0.1	1310,15.4,9.6,5.0	970,20.5,7.0,3.6	26.0
SG-S5			9	80.9	54.5, 9.9, 3.6	1330,15.0,11.4,5.9	961,20.8,9.8,5.0	27.8
SG-S6			9	79.7	57.6, 9.7, 1.8	1290,15.5,8.3,4.6	980,20.3,5.9,3.1	24.0
SG-S7			9	79.3	55.2, 9.7, 0.5	1350,14.7,5.9,3.5	970,20.7,3.9,2.1	28.1
SG-S8			10	80.7	54.3, 9.8, 1.9	1350,15.2,8.1,4.3	1040,19.6,5.6,2.8	23.0
SG-S9			10	81.4	54.1, 9.8, -1.4	1320,15.0,6.3,3.3	960,20.0,4.9,2.5	27.3
SG-S10			10	79.5	54.3, 9.6, 3.4	1350,14.8,10.8,5.7	990,20.3,5.5,2.8	26.7
SG-S11			10	80.6	51.6, 10.0, 1.4	1330,15.0,6.9,3.7	980,20.4,5.6,2.9	26.3
SG-S12			10	81.2	53.4, 10.0, 0.6	1350,14.7,9.3,4.9	930,20.8,6.0,3.2	31.1
Average				**80.2**	**54.5, 9.8, 1.3**	**1340,14.9,8.6,4.6**	**1000, 20.2,6.0,3.1**	**26.4**
SIC-3			8	80.5	54.8, 10.9, 6.6	1380, 18.0, 15.1, 7.8	1020, 23.8, 10.9, 5.6	26.1
SIC-4			7	77.5	58.7, 11.9, -2.1	1170, 16.8, 9.3, 5.1	880, 23.2, 5.4, 2.9	24.8
SIC-5			7	78.6	59.4, 10.6, -1.8	1290, 15.5, 10.9, 6.1	910, 20.1, 5.4, 2.9	29.5
Average				**78.9**	**57.6, 11.1, 0.9**	**1280, 16.8, 11.8, 6.3**	**940, 22.4, 7.2, 3.8**	**26.8**

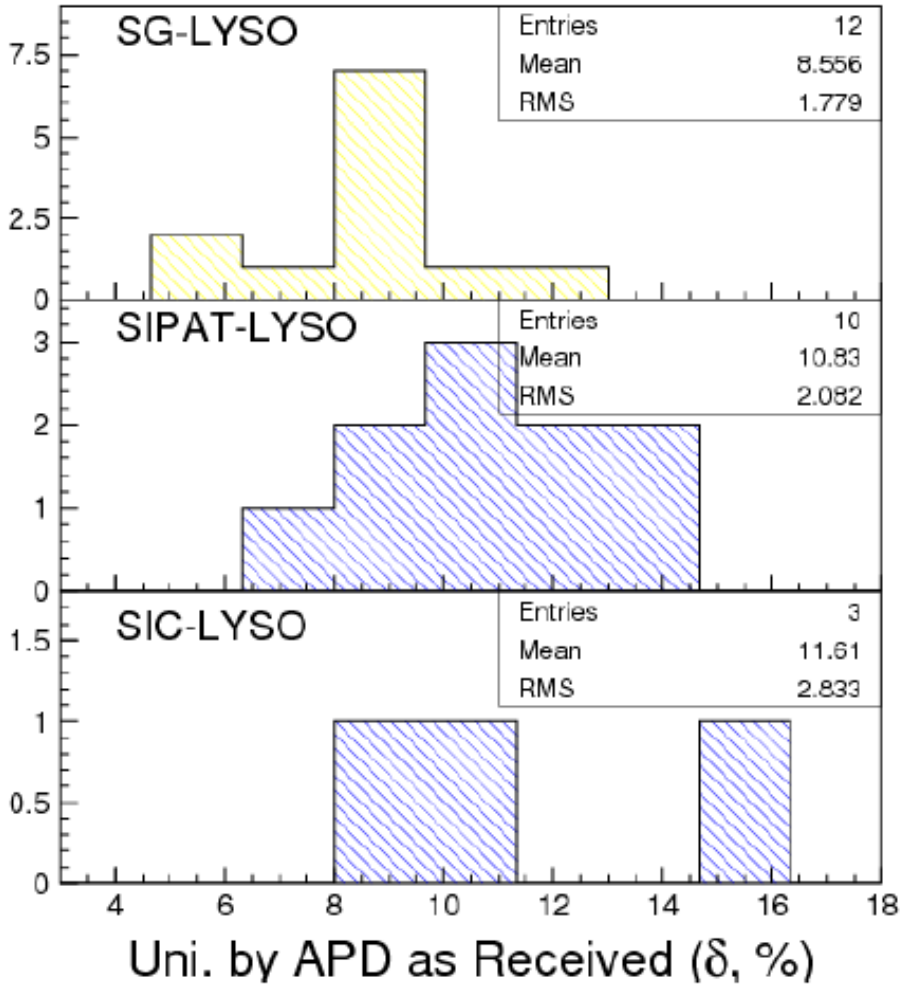
* Light Yield (LY) and Energy Resolution (ER) are the average of the seven points measured along the crysals.

Note 1 Light Yield (LY) for the APD readout is measured with a quartz plate between the crystal and the APDs.

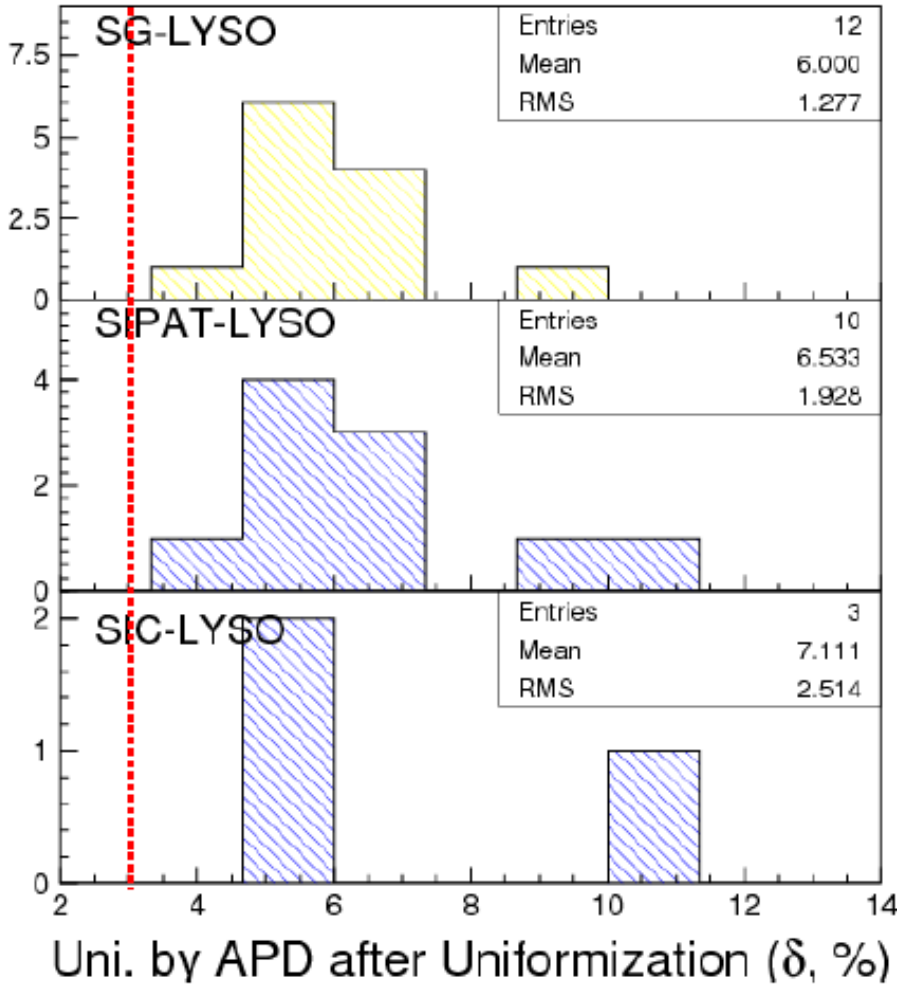
Note 2 Width of the black band at the small end on the smallest side surface: 15 mm

Summary: Uniformity (δ) by APD

Diverse but consistent between vendors
15 mm black paint is not sufficient for |δ| < 3%



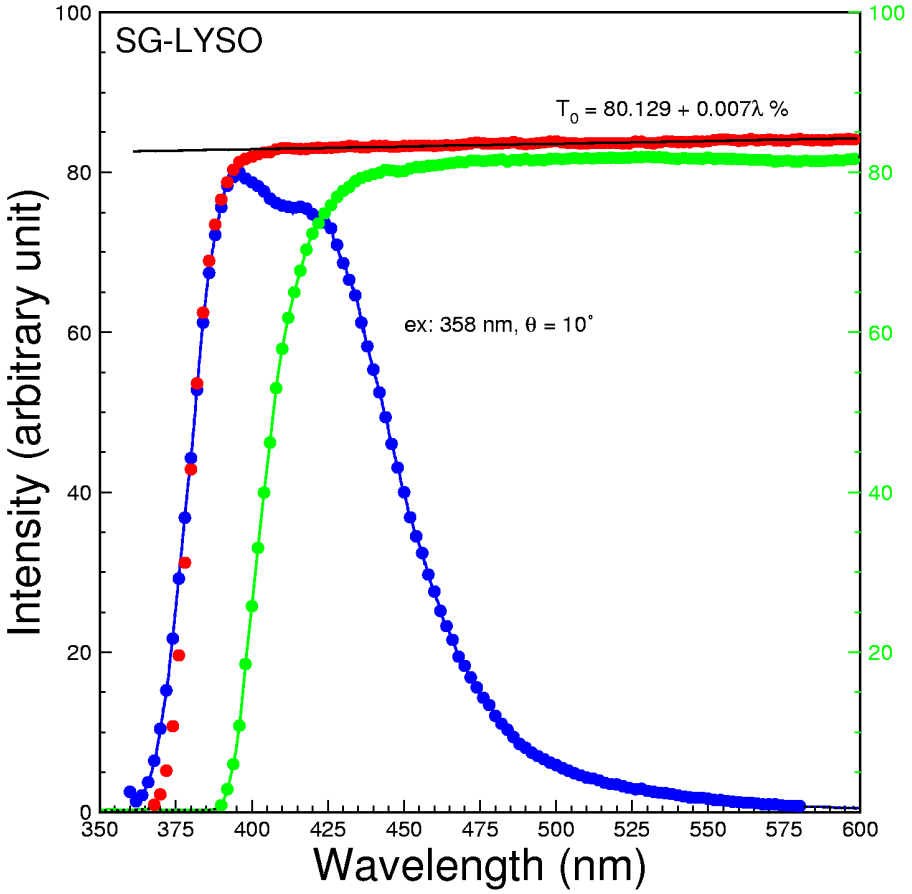
Uni. by APD as Received (δ, %)

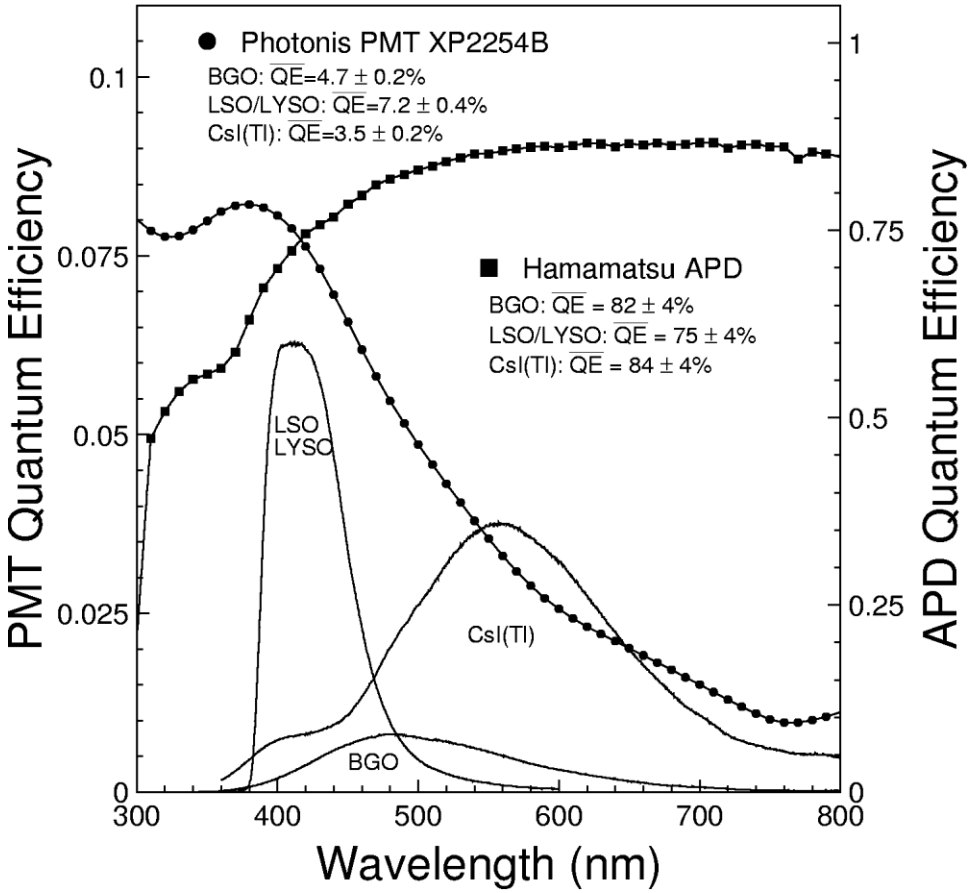


Uni. by APD after Uniformization (δ, %)

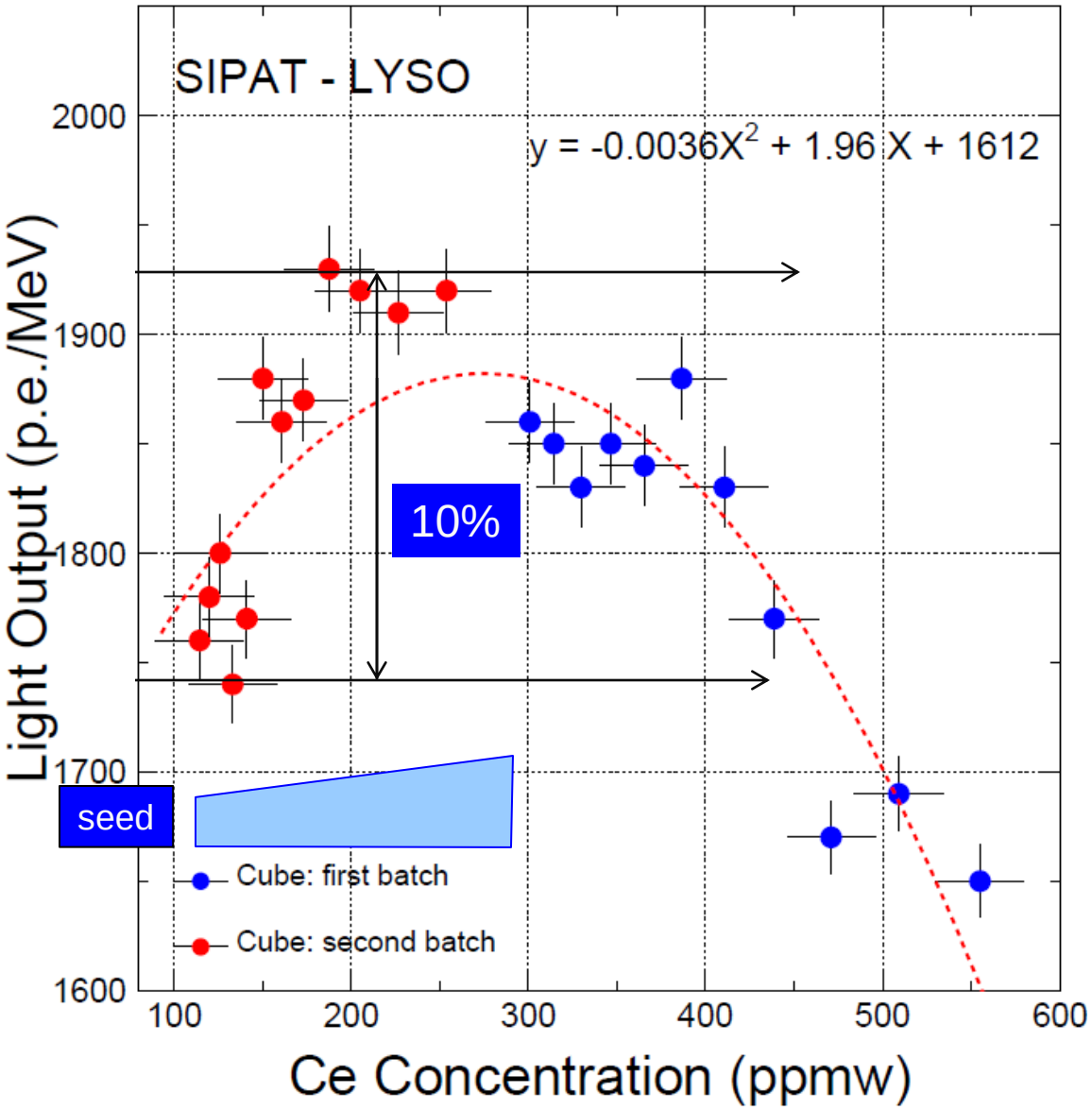
Effect of Self-absorption

It is well known that part of the emission light is absorbed in the crystal: self-absorption.





Effect of Cerium Segregation



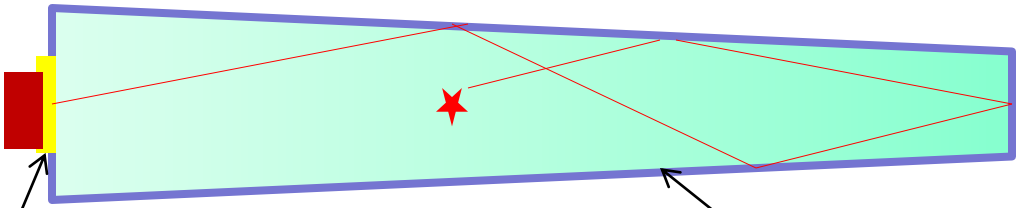
It is also known that cerium concentration along long LYSO crystals is not uniform, causing non-uniformity up to 10% at two ends, indicating up to 5% variation in δ is possible because of cerium segregation.

Ray-Tracing Simulation “set-up”

The simulation package was developed in early eighties, and was used for the L3 BGO and CMS PWO crystals.

SuperB LYSO crystals

2 Hamamatsu
S8664-55
(2×5×5 mm^2)

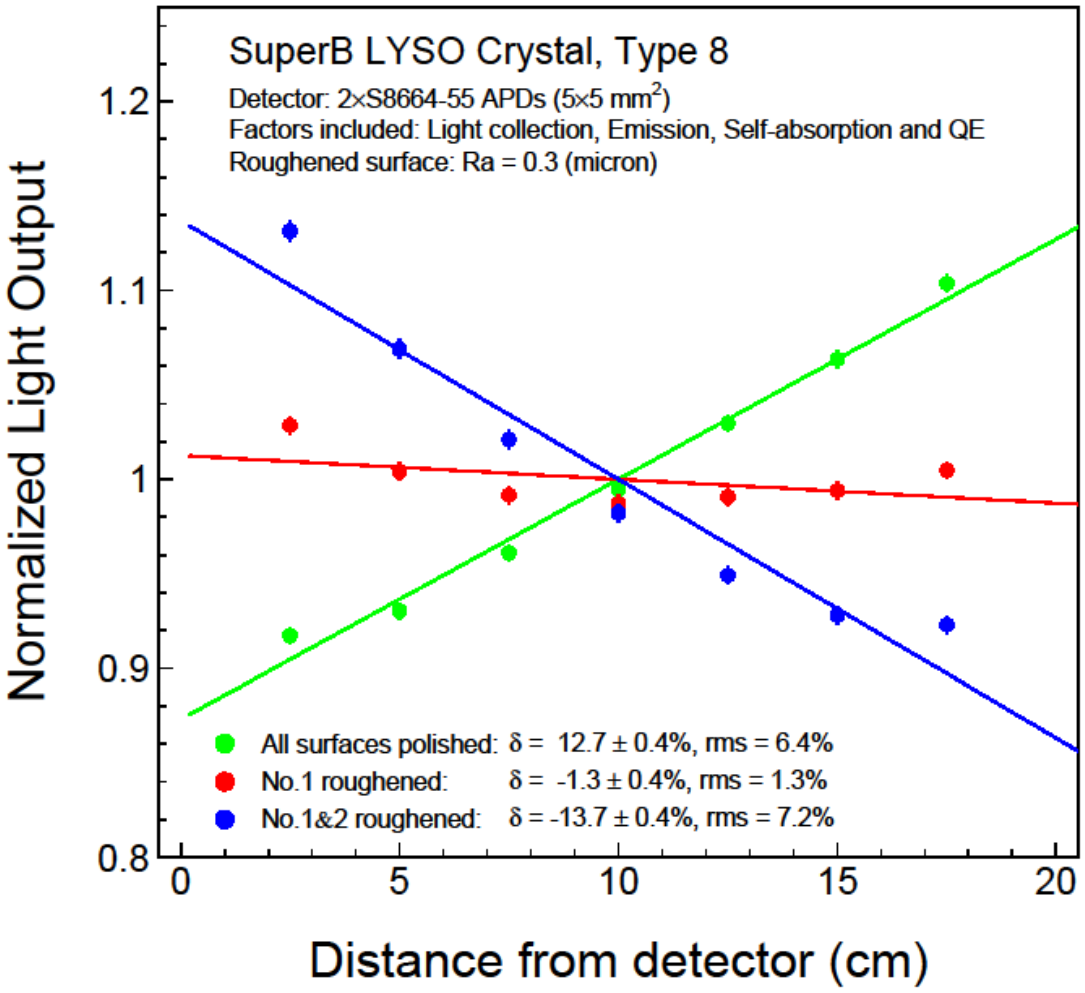


Silicon oil
N=1.52

Tyvek paper

$$LO(z) = LY(z) \int Em(\lambda) LCE(\lambda, z) QE(\lambda) d\lambda$$

Polished and Roughened Surfaces

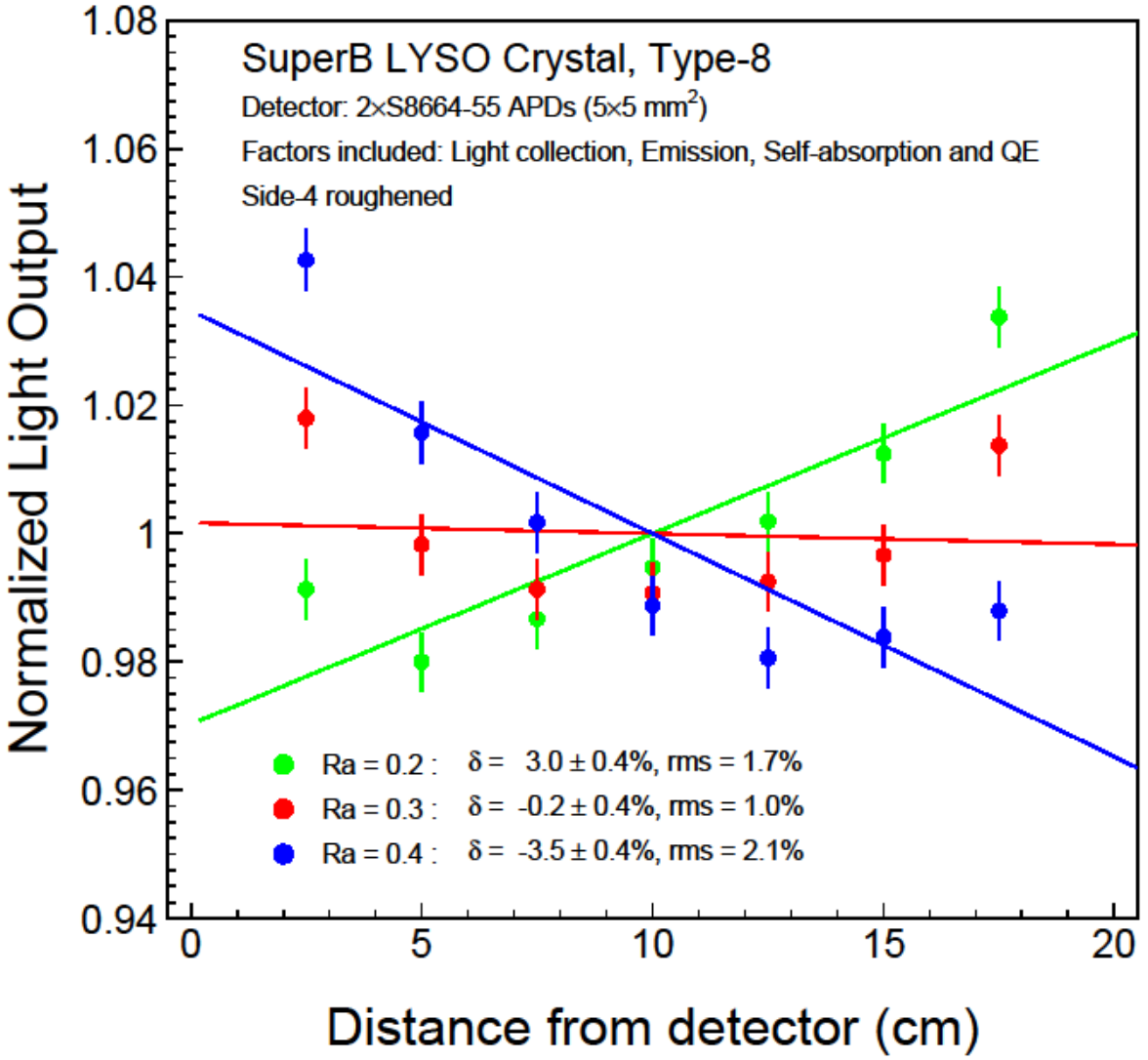


- The optical focusing, effect dominates non-uniformity: δ is about 13% for all polished surfaces.
- Roughened surface(s) can compensate the optical focusing effect.
- The best result is achieved by roughening only one side surface.

How Rough it Should Be?

The R_a matters.

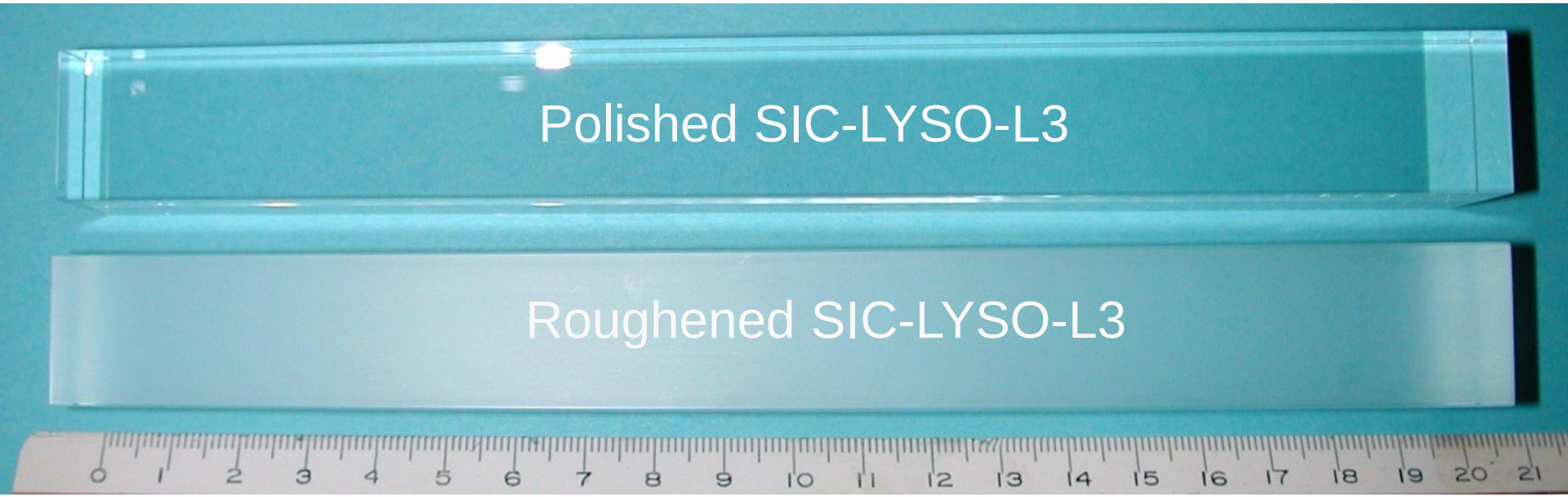
A variation of 0.1 in R_a causes a 3% variation in δ.



Real Exercise: Roughening SIC-LYSO-L3

The smallest side surface of SIC-LYSO-L3 was roughened to Ra = 0.3 at SIC via a two step process

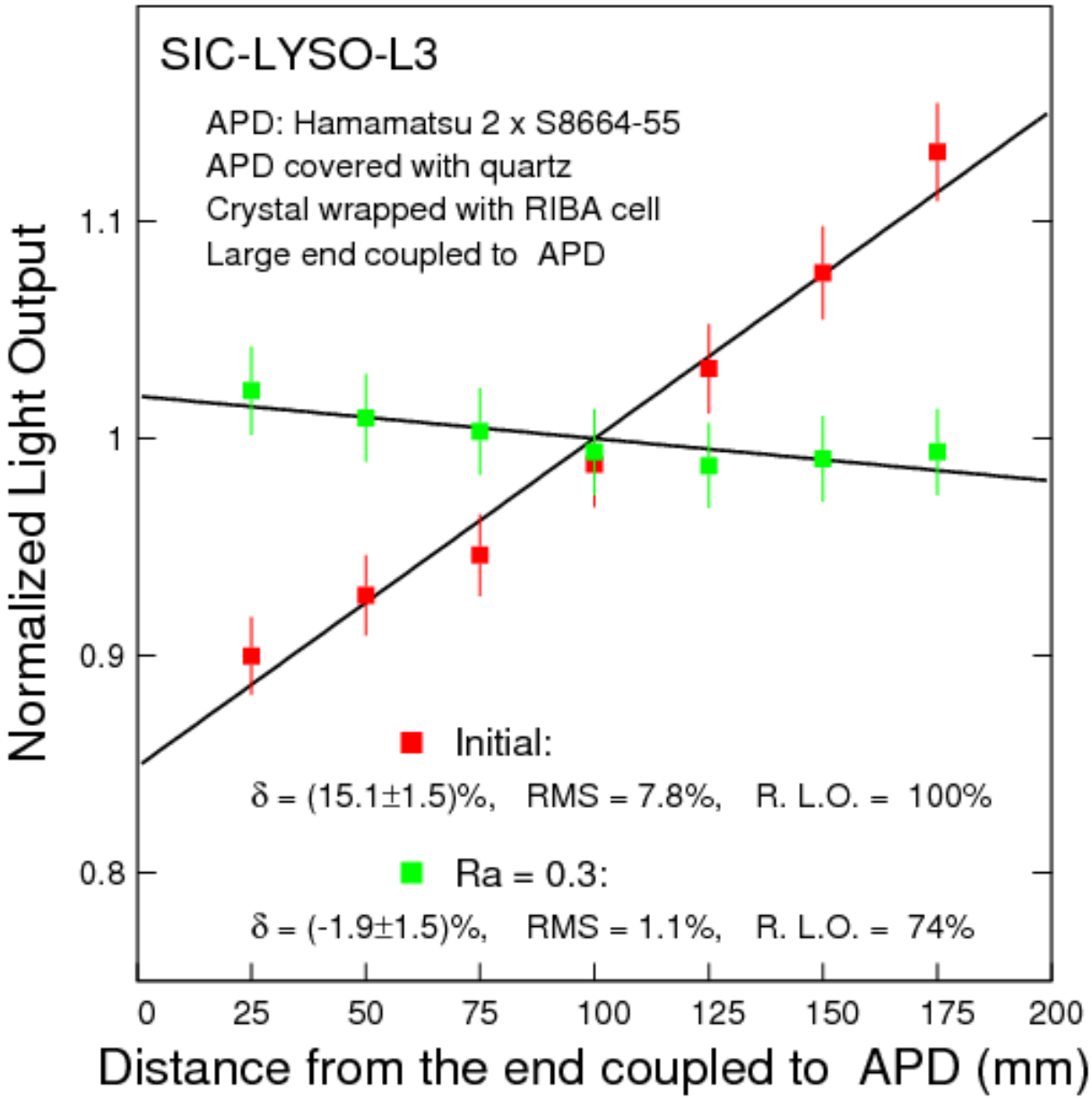
Thanks to SICCAS for roughening this crystal



1st: lapped to Ra = 0.5 by using 11 μm Al_2O_3 powder for 10 min with 2.5 kg weight.
2nd: lapped to Ra = 0.3 by using 6.5 μm SiC powder for 3 min with 1.5 kg weight.

Relative Light Output & Uniformity

Ra = 0.3 uniformize this crystal to < 2%. Ra = 0.25 seems the best for this sample.

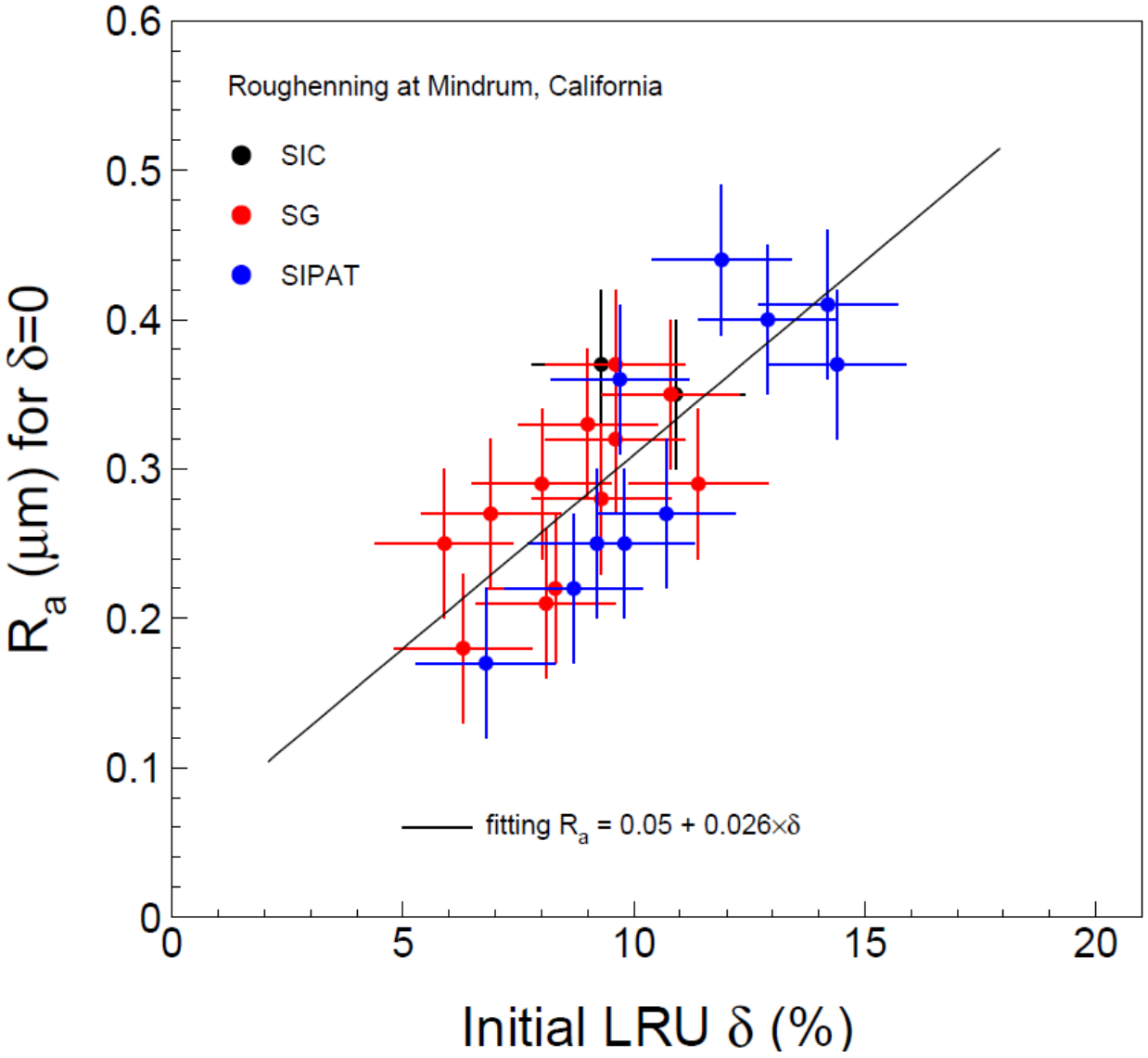


Summary of Ra Used and Uniformity

With the smallest side surface roughened to an optimal value at Mindrum Precision, Inc. California

ID	As received (δ, %)	Opt_1	Opt_2	Opt. Ra LRU, δ=0	Opt. Ra LRU, δ=-0.5%	Ra (vendor)	Final (δ, %)
Samples sent to SILO on June 28, 2011							
SIPAT-13	6.8	0.10	0.21	0.23	0.23	0.22	-2.5
SIPAT-14	14.4	0.29	0.40	0.42	0.44	0.27/0.38	-0.6
SIPAT-15	11.9	0.21	0.34	0.36	0.37	0.35	2.8
SG-S10	10.8	0.18	0.31	0.33	0.34	0.32	1.2
SG-S11	6.9	0.10	0.22	0.23	0.24	0.24	0.9
Samples to be sent to SILO in Future							
SIPAT-11	12.9	0.24	0.36	0.39	0.40	0.38	1.0
SIPAT-12	14.2	0.28	0.39	0.42	0.43	0.35/0.41	0.4
SIPAT-16	9.7	0.16	0.28	0.30	0.31	0.28	2.6
SIPAT-17	9.8	0.16	0.29	0.30	0.31	0.29	-1.7
SIPAT-20	8.7	0.14	0.26	0.28	0.28	0.26	-1.9
SIPAT-21	10.7	0.18	0.31	0.33	0.34	0.32	-2.4
SIPAT-22	9.2	0.15	0.27	0.29	0.30	0.28	-1.5
SG-S1	9.6	0.16	0.28	0.30	0.31	0.27	2.9
SG-S2	9	0.14	0.27	0.28	0.29	0.25	2.6
SG-S3	8	0.12	0.24	0.26	0.27	0.22	2.4
SG-S4	9.6	0.16	0.28	0.30	0.31	0.27	1.8
SG-S5	11.4	0.20	0.32	0.35	0.36	0.30	-0.5
SG-S6	8.3	0.13	0.25	0.27	0.27	0.26	-1.9
SG-S7	5.9	0.09	0.19	0.20	0.21	0.19	1.7
SG-S8	8.1	0.13	0.24	0.26	0.27	0.24	-1.8
SG-S9	6.3	0.10	0.20	0.21	0.22	0.19	-0.5
SG-S12	9.3	0.15	0.27	0.29	0.30	0.29	-0.3
SIC-4	9.3	0.15	0.27	0.29	0.30	0.15/0.28	2.7
SIC-5	10.9	0.19	0.31	0.33	0.34	0.21/0.33	0.6
Samples already roughened							
SIC-3	15.1	0.31	0.41	0.44	0.46	0.30	-1.9

Required Roughness from Mindrum Data



Mindrum data fit a linear function:

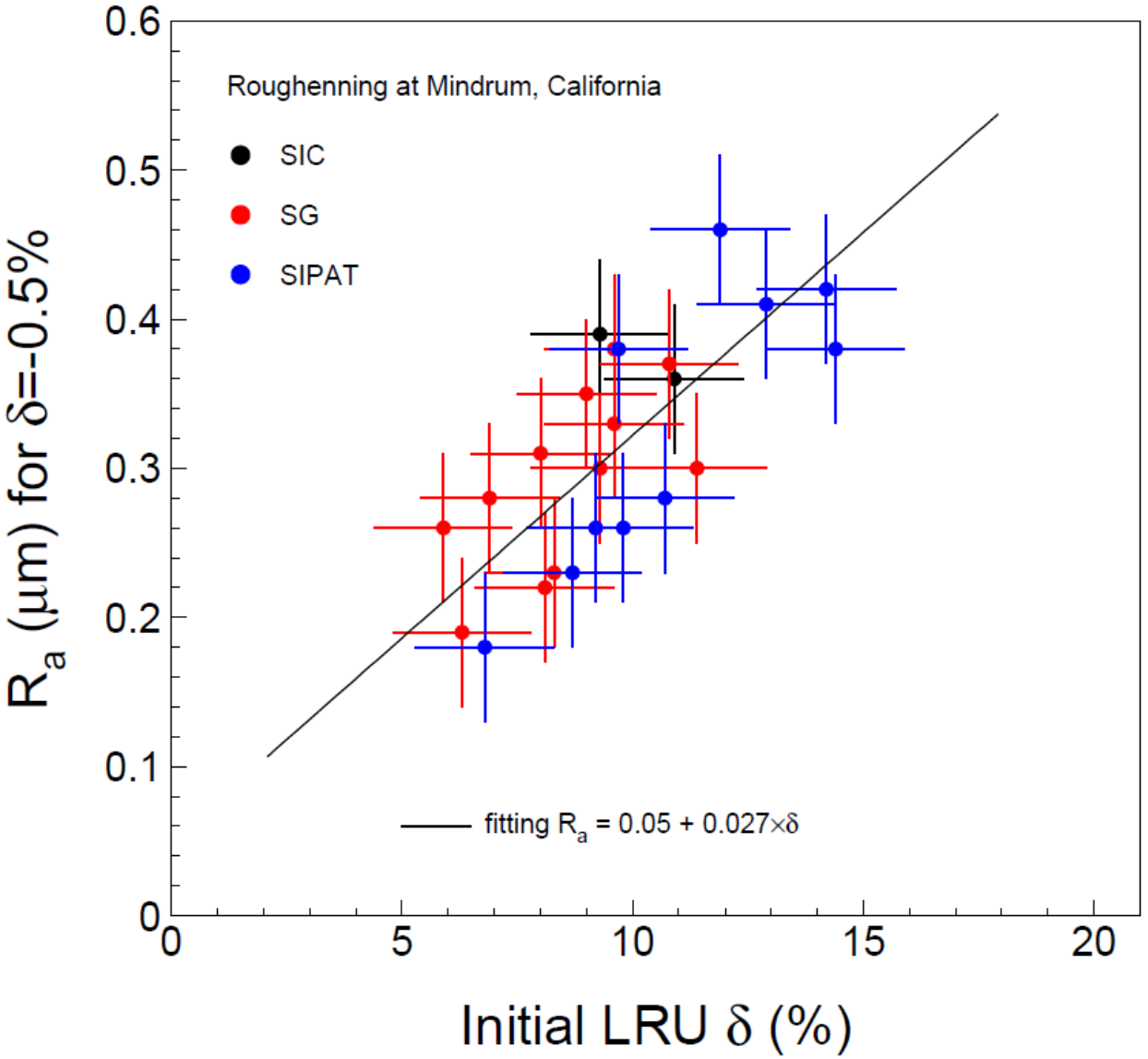
$Ra = 0.05 + 0.026\ \delta$,

which can be used to define the optimal Ra values for the roughening processing at Mindrum.

Required Roughness from Mindrum Data

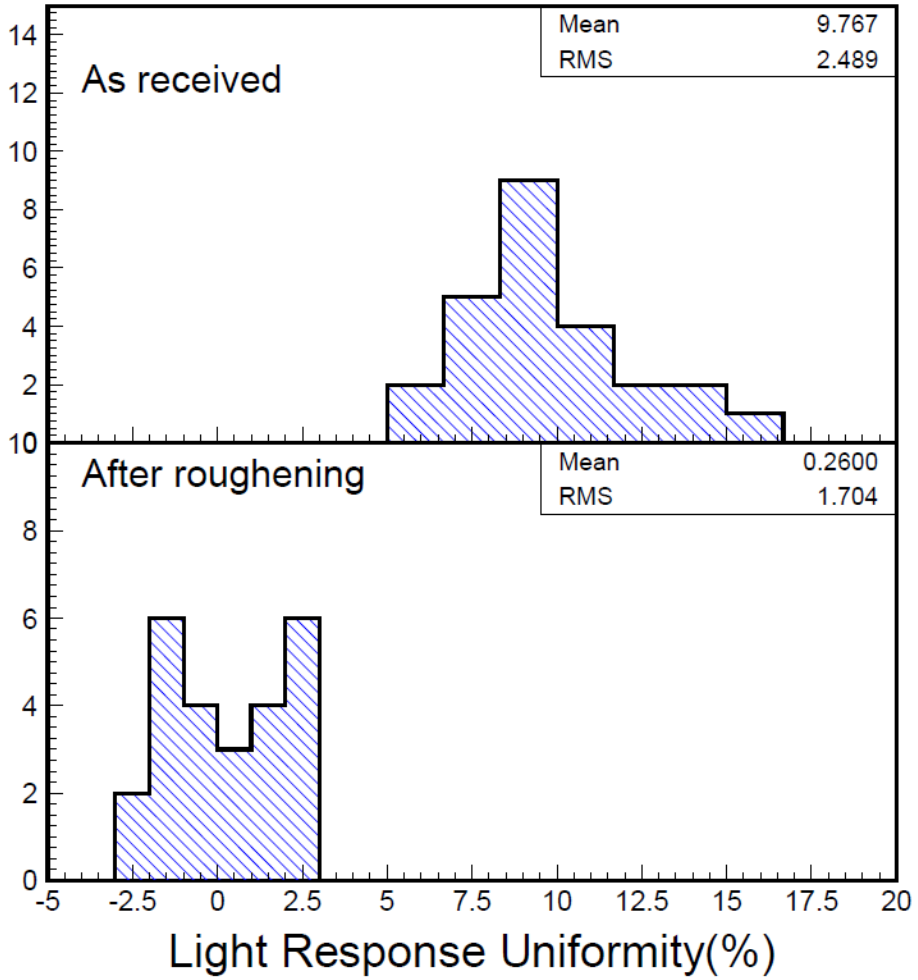
Ra = 0.05 + 0.027 δ

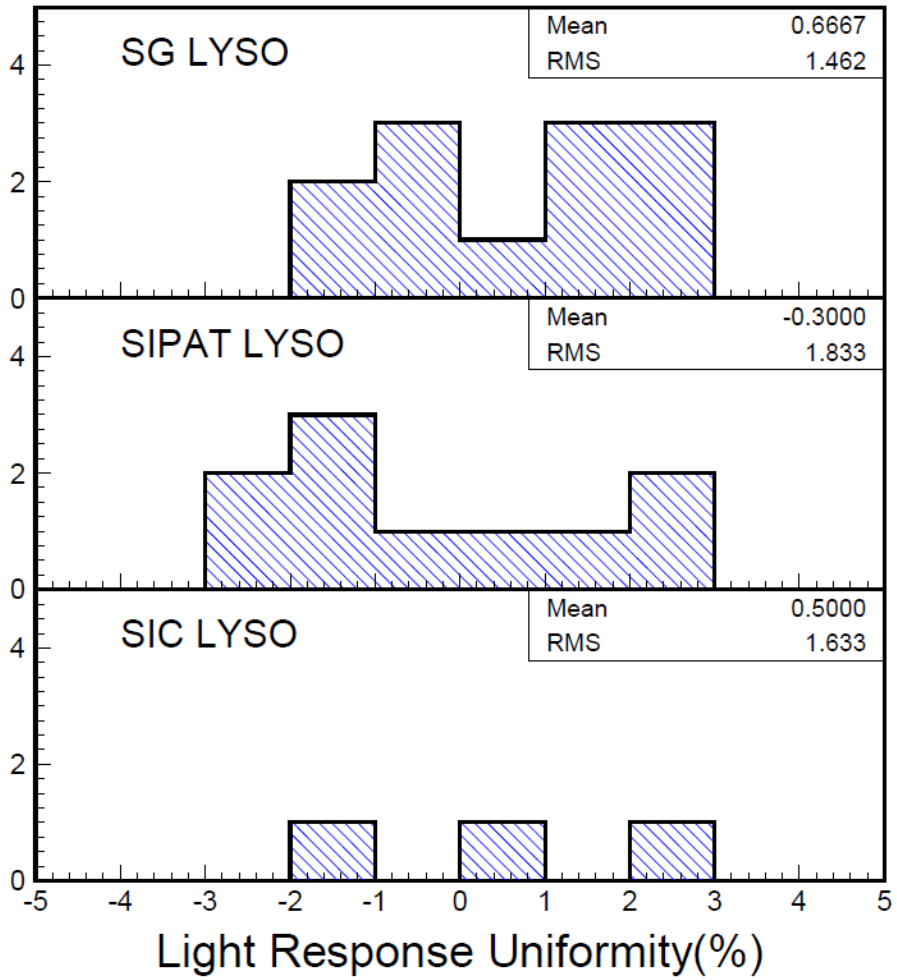
Is the optimal roughness value for δ = -0.5%



L.R.U. before & after Roughening

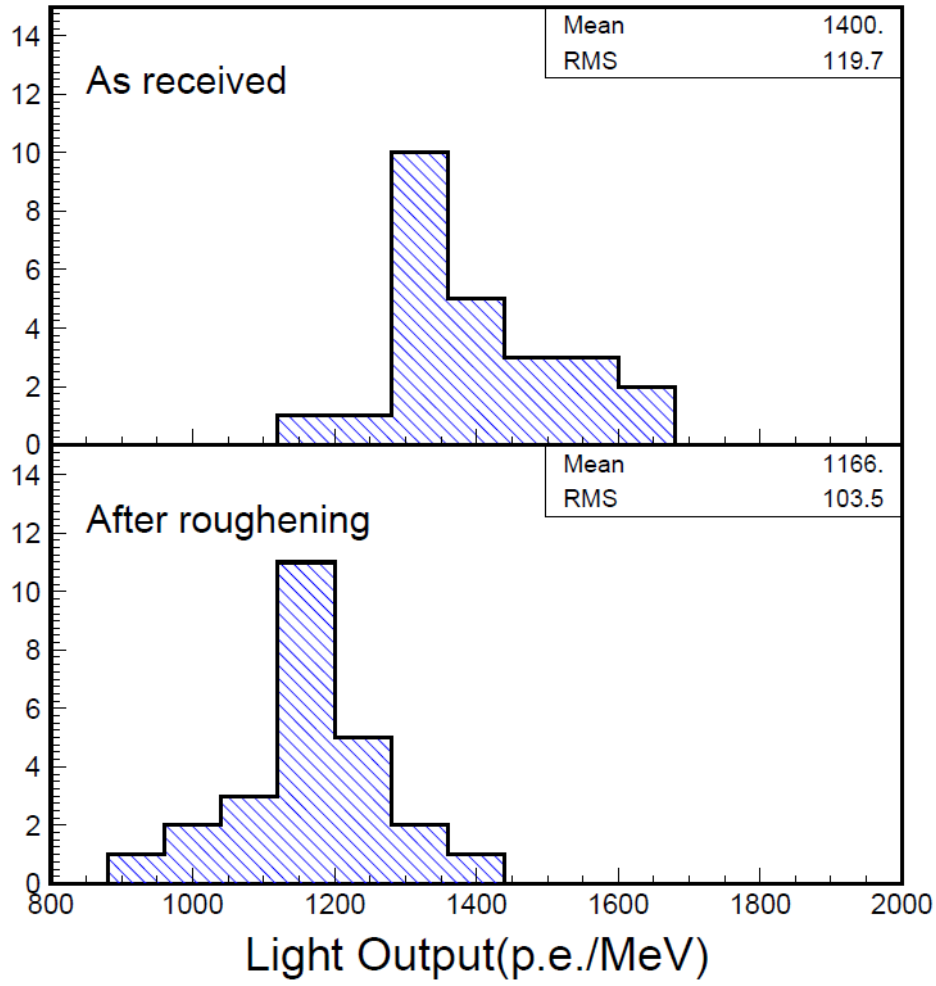
The average of non-uniformity (δ) is reduced from 9.8% to 0.26%. All crystals are within |δ| < 3%.

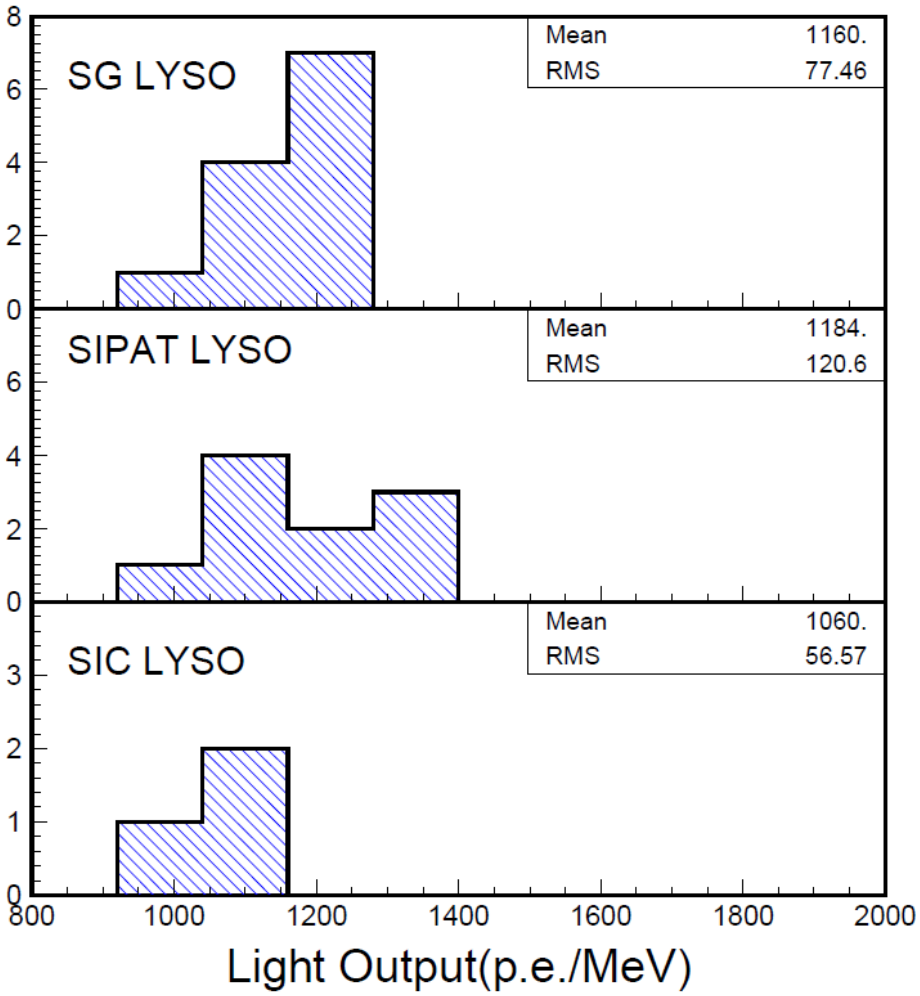




L.O. before & after Roughening

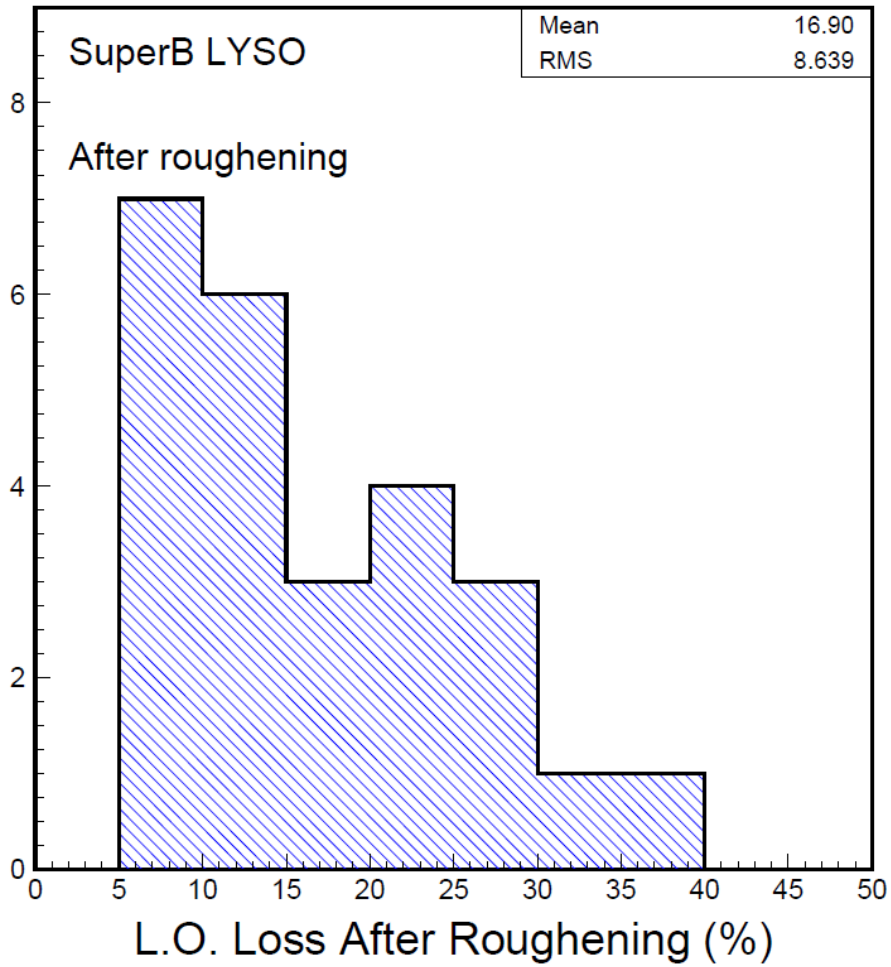
The average light output is reduced from 1,400 to 1,170 p.e./MeV.
Crystals from all three vendors are consist.

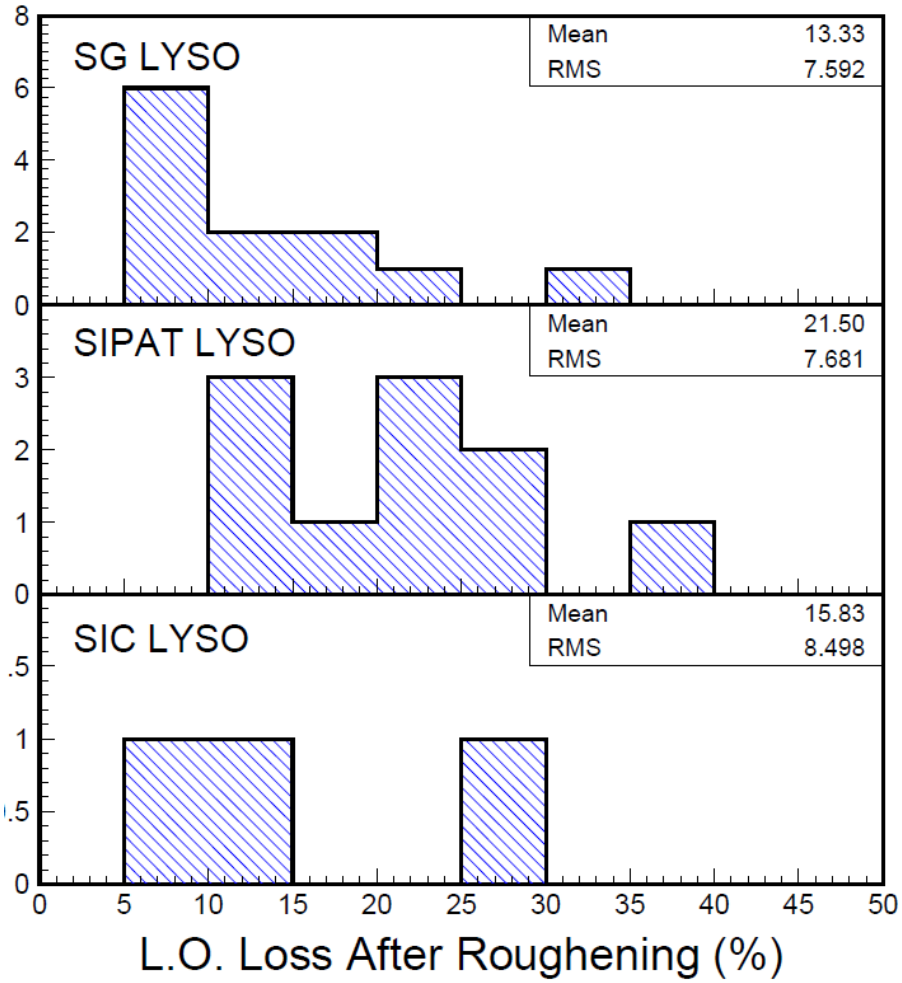




L.O. Loss after Roughening

The roughening caused average LO loss is 17%.
Crystals from SIPAT lose more light.





Summary for All 25 Crystals

With the smallest side surface roughened to an optimal roughness: 0.05 + 0.026 δ

Caltech-ID	Vendor-ID	Test-Beam position	Type	LT @ 420 nm (%)	LO, ER, δ & rms by PMT (As)* (% of candel 1), (FWHM, %), (δ, %)	LO, ER, δ & rms by APD (As)* (p.e./MeV), (σ, %), (δ, %) (rms, %)	LO & δ by APD (Uni)* (p.e./MeV) , (δ, %)	LO Loss (%)
SIPAT-11	02_08_08	ring 8-3	8	82.3	47.6, 10.7, 5.3	1420, 15.5, 12.9, 6.5	1130, 1.0	20.4
SIPAT-12	02_08_08	ring 8-1	8	82.2	46.5, 10.4, 3.9	1440, 15.1, 14.2, 7.1	1120, 0.4	22.2
SIPAT-13		ring 6-1	6	82.6	52.5, 11.5, 2.7	1440, 14.9, 6.8, 3.6	1280, -2.5	11.1
SIPAT-14		ring 6-2	6	82.7	53.7, 10.9, 3.2	1500, 14.9, 14.4, 7.4	1160, -0.6	22.7
SIPAT-15		ring 6-4	6	80.7	52.8, 10.5, 3.4	1580, 13.7, 11.9, 6.0	970, 2.8	38.6
SIPAT-16		ring 6-5	6	81.1	51.8, 10.1, -0.8	1570, 13.5, 9.7, 5.0	1350, 2.6	14.0
SIPAT-17		ring 6-3	6	82.1	53.0, 12.2, 3.5	1260, 17.1, 9.8, 4.9	1120, -1.7	11.1
SIPAT-20	07_10_02	ring 7-2	7	79.8	56.4, 10.0, 5.6	1670, 14.6, 8.7, 4.4	1370, -1.9	18.0
SIPAT-21	02_10_23	ring 7-5	7	81.6	48.8, 10.9, 3.0	1550, 15.8, 10.7, 5.6	1090, -2.4	29.7
SIPAT-22	07_10_02	ring 7-1	7	81.4	52.6, 11.0, 2.7	1600, 15.2, 9.2, 4.8	1170, -1.5	26.7
Average				81.7	51.5, 10.8, 3.3	1500, 15.0, 10.8, 5.5	1176, -0.4	21.5
SG-S1			8	80.5	52.2, 9.8, 1.0	1370,14.5,9.6,5.0	1230, 2.9	10.2
SG-S2			8	79.5	54.2, 9.6, 1.4	1400,14.3,9.0,4.7	1270, 2.6	9.3
SG-S3			9	79.1	56.0, 9.8, 1.0	1370,14.7,8.0,4.2	1270, 2.4	7.3
SG-S4			9	80.1	56.5, 9.7, 0.1	1310,15.4,9.6,5.0	1180, 1.8	9.9
SG-S5			9	80.9	54.5, 9.9, 3.6	1330,15.0,11.4,5.9	920, -0.5	30.8
SG-S6			9	79.7	57.6, 9.7, 1.8	1290,15.5,8.3,4.6	1180, -1.9	8.5
SG-S7			9	79.3	55.2, 9.7, 0.5	1350,14.7,5.9,3.5	1270, 1.7	5.9
SG-S8			10	80.7	54.3, 9.8, 1.9	1350,15.2,8.1,4.3	1140, -1.8	15.6
SG-S9			10	81.4	54.1, 9.8, -1.4	1320,15.0,6.3,3.3	1250, -0.5	5.3
SG-S10			10	79.5	54.3, 9.6, 3.4	1350,14.8,10.8,5.7	1070, 1.2	20.7
SG-S11			10	80.6	51.6, 10.0, 1.4	1330,15.0,6.9,3.7	1140, 0.9	14.3
SG-S12			10	81.2	53.4, 10.0, 0.6	1350,14.7,9.3,4.9	1140, -0.3	15.6
Average				80.2	54.5, 9.8, 1.3	1340,14.9,8.6,4.6	1172, 0.7	12.8
SIC-3			8	80.5	54.8, 10.9, 6.6	1380, 18.0, 15.1, 7.8	1020, -1.9	26.1
SIC-4			7	77.5	58.7, 11.9, -2.1	1170, 16.8, 9.3, 5.1	1090, 2.7	6.8
SIC-5			7	78.6	59.4, 10.6, -1.8	1290, 15.5, 10.9, 6.1	1150, 0.6	10.9
Average				78.9	57.6, 11.1, 0.9	1280, 16.8, 11.8, 6.3	1087, 0.4	14.6

* Light Output (LO) and Energy Resolution (ER) are the average of the seven points measured along the crysals.

Note 1 Light Output (LO) for the APD readout is measured with a quartz plate between the crystal and the APDs.

Note 2 The smallest side surface is roughed to an Optimal Rougheness: 0.05 + 0.026 δ

Summary

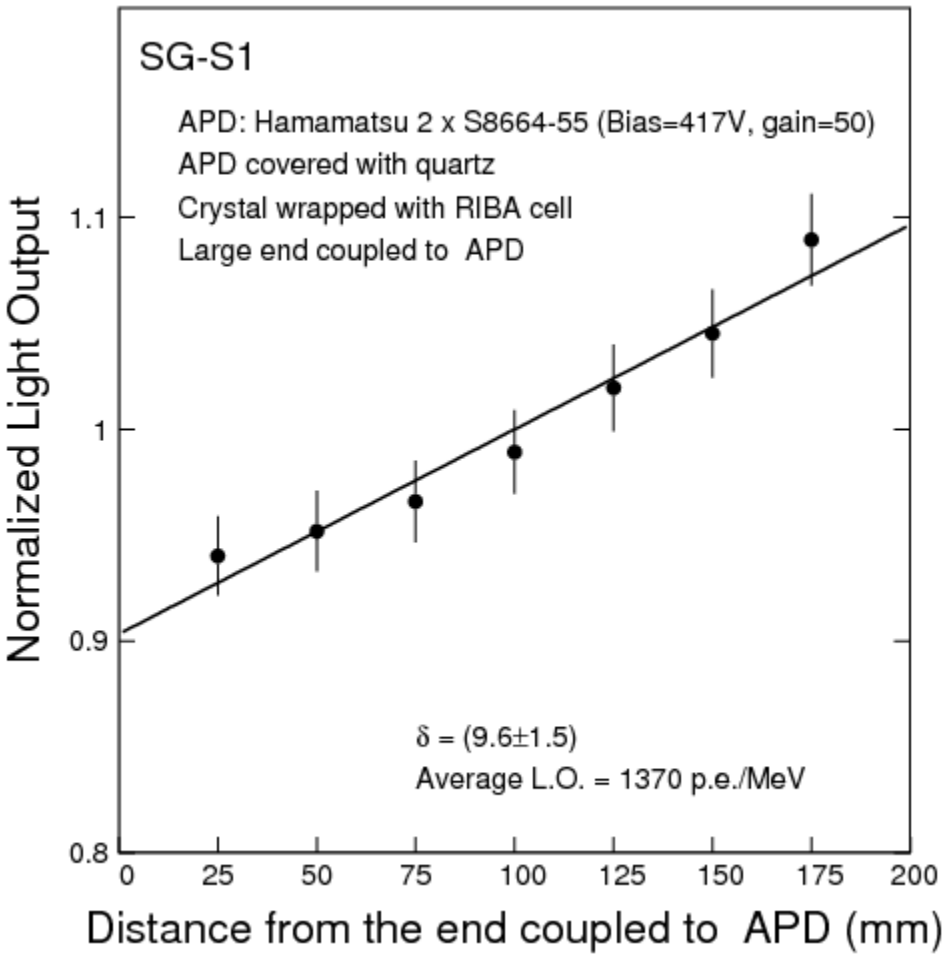
- 24 LYSO crystals show that |δ| < 3% is achieved after roughening at Mindrum Precision, Inc., California, with Ra = 0.05 + 0.026 δ on the smallest side surface.

- The average LO loss after the uniformization is about 17%, which is less than that by 15 mm black paint.

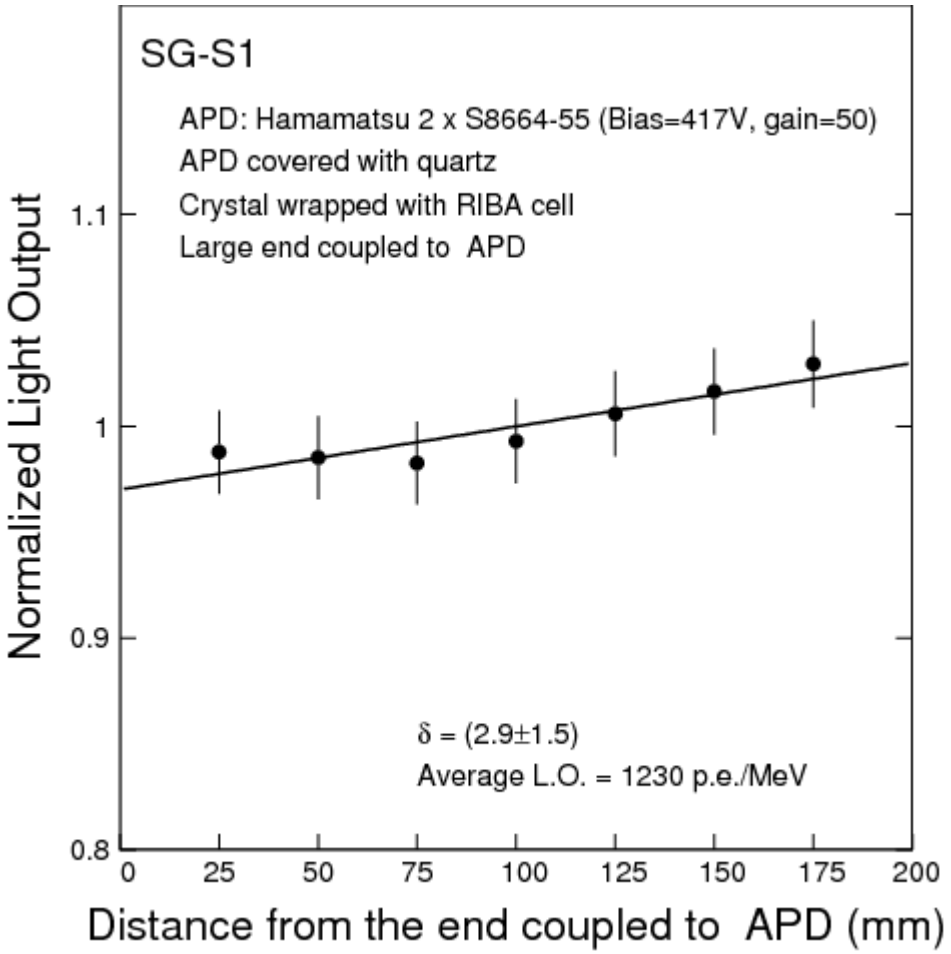
- For mass production, we may live with a universal Ra = 0.3, or a maximum of two Ra values.

L.R.U. before & after Roughness

Before roughening



After roughening.



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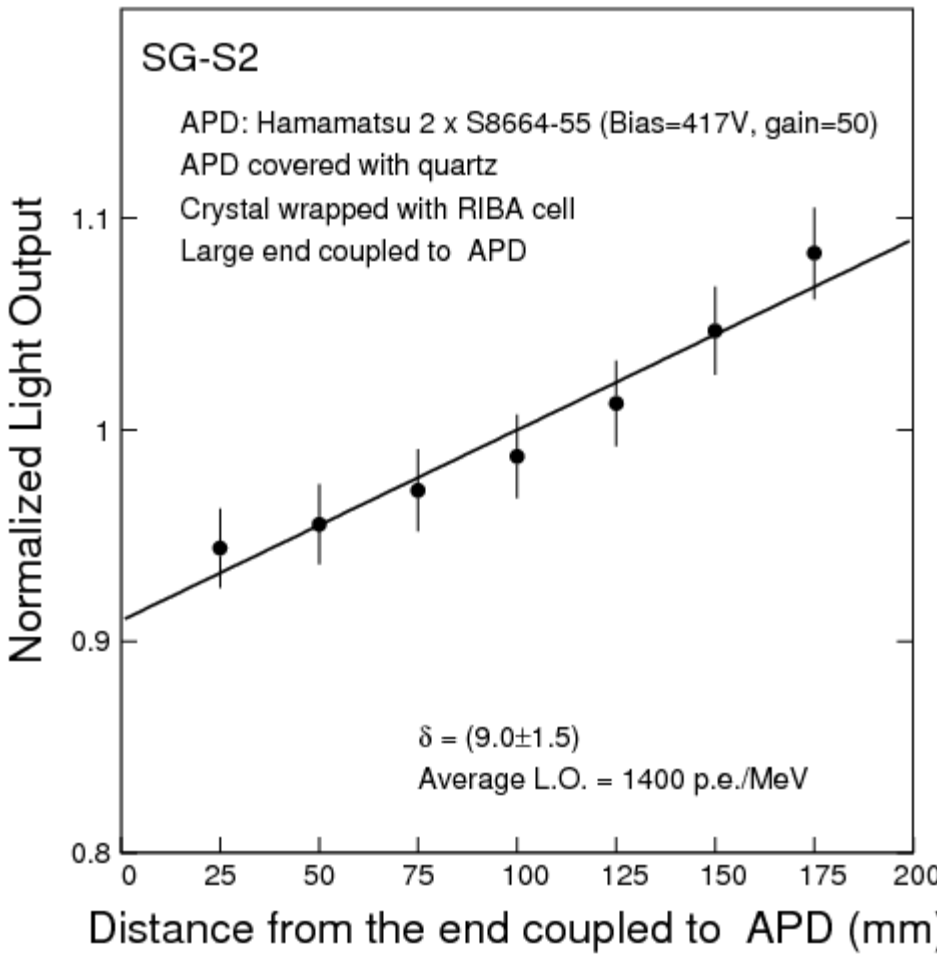
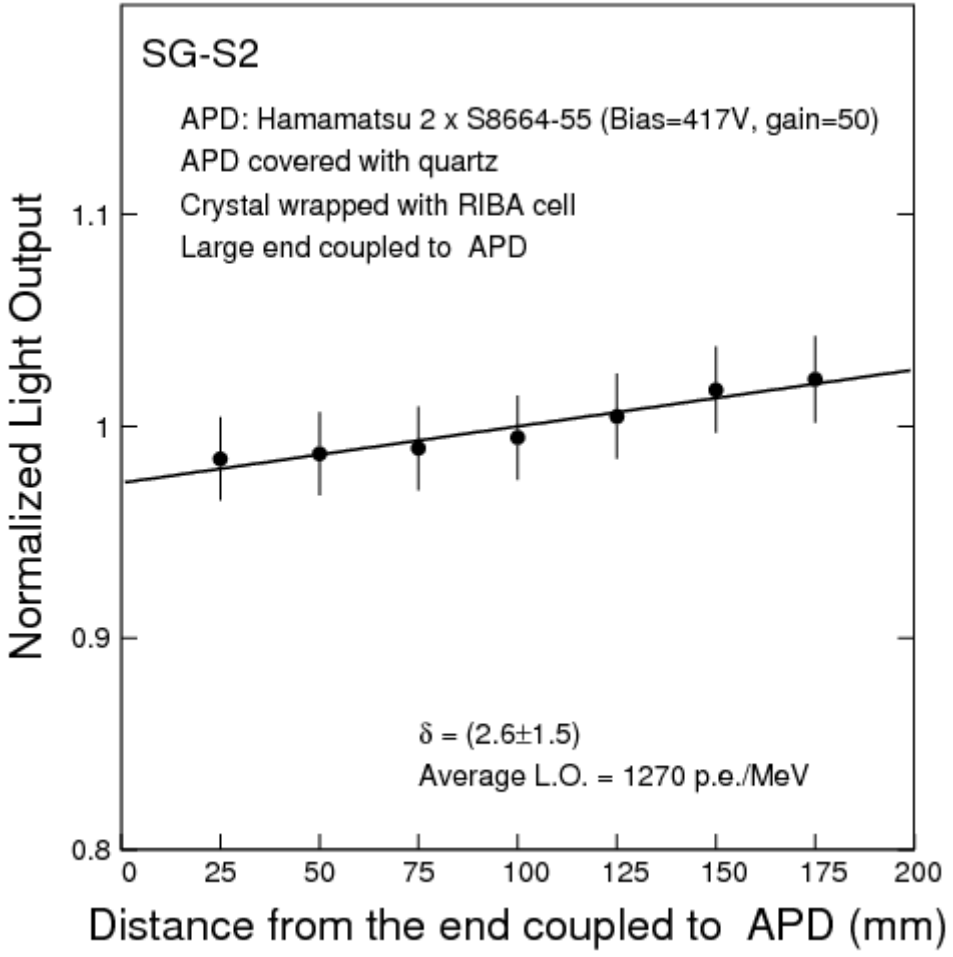


After roughening.



L.R.U. before & after Roughness

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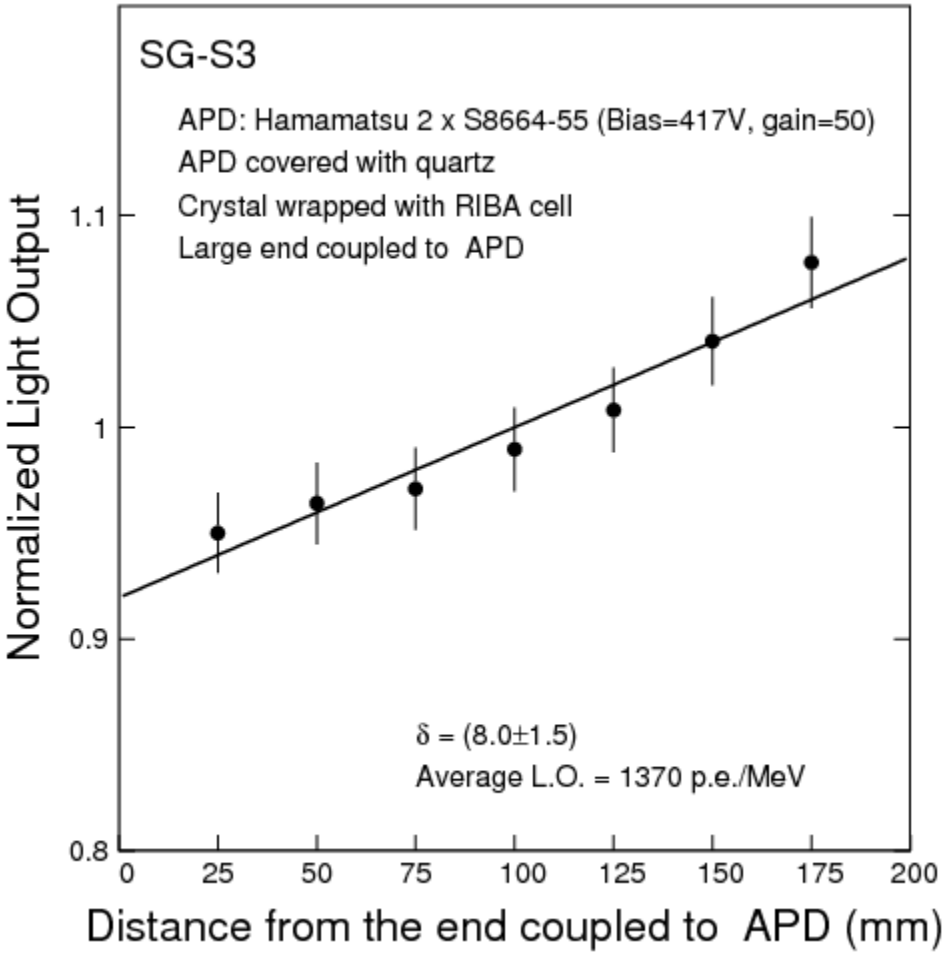

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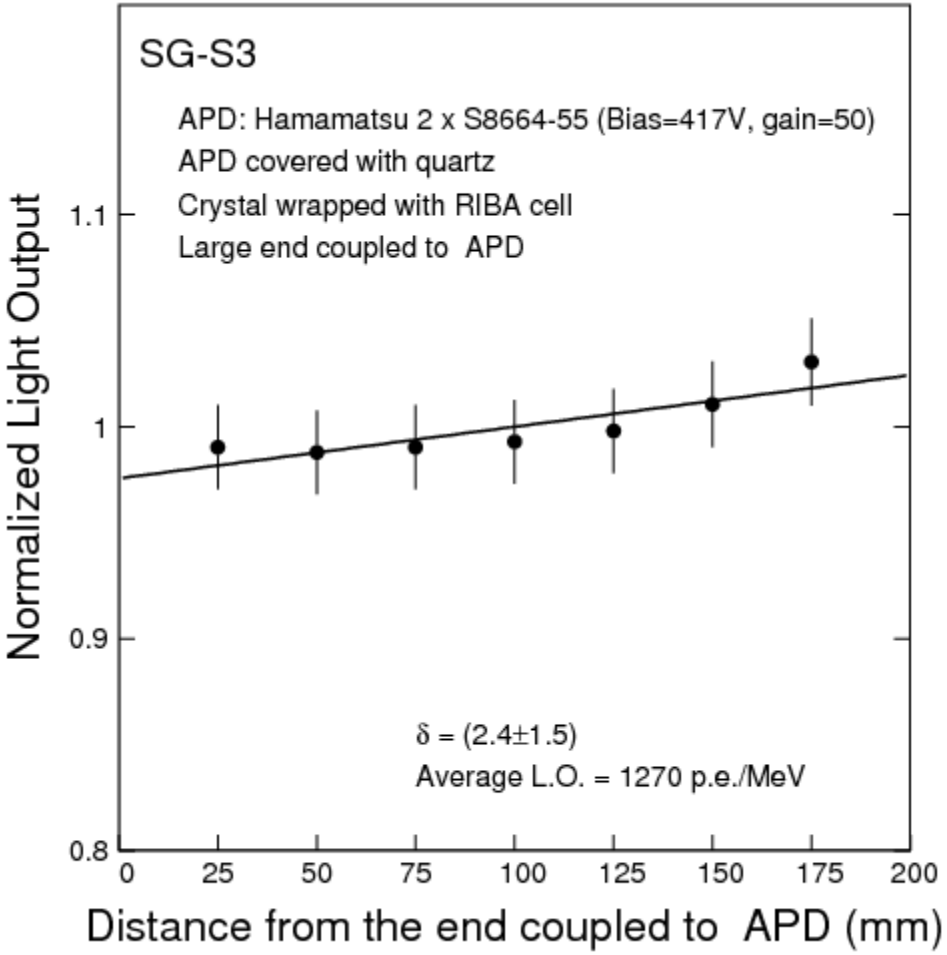

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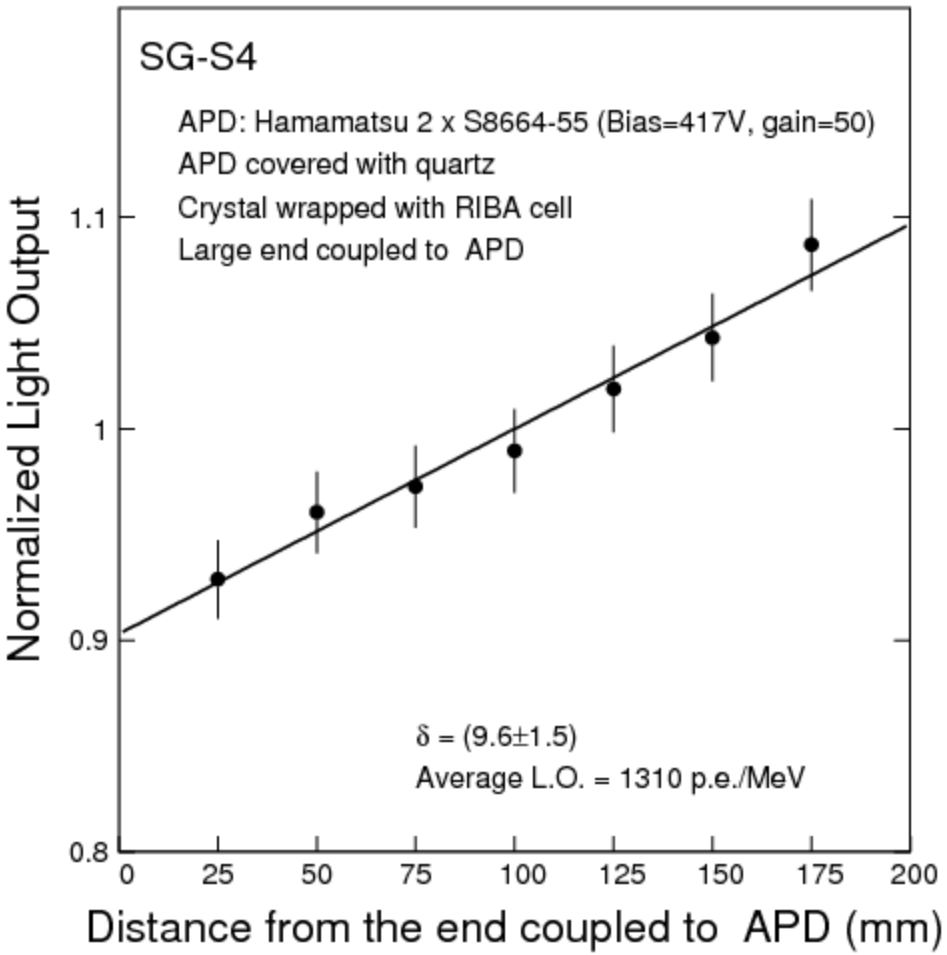

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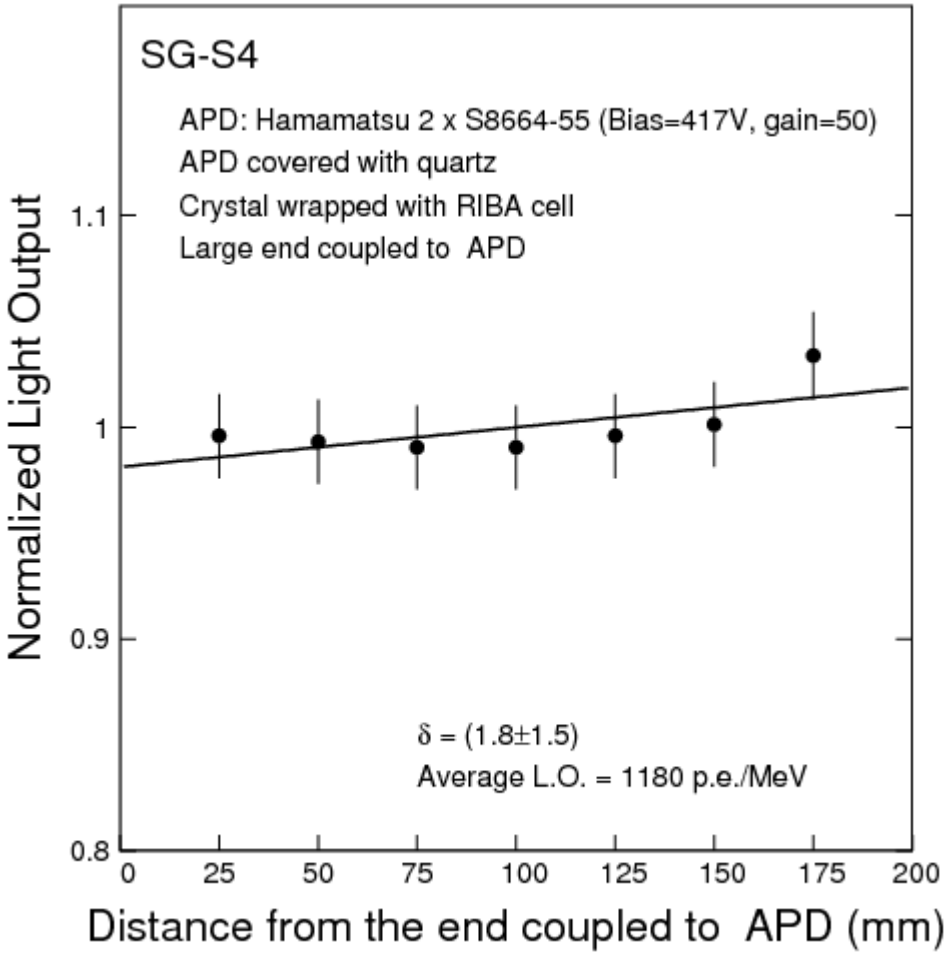

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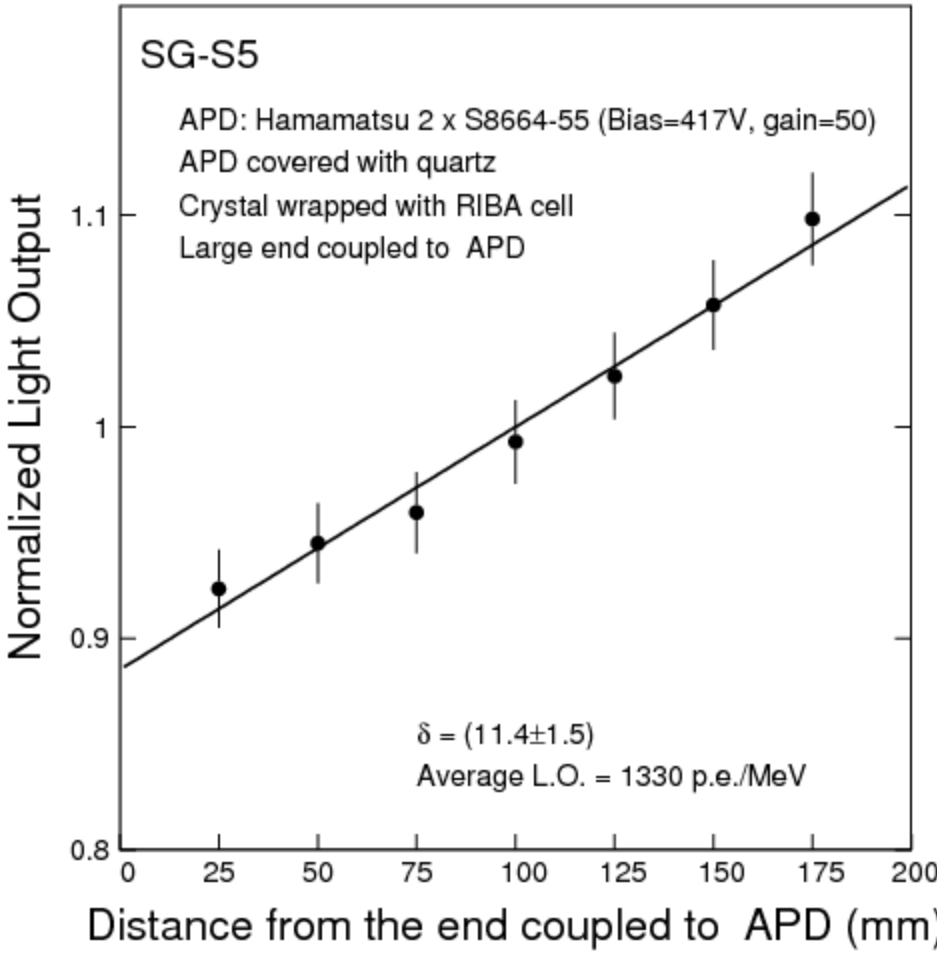

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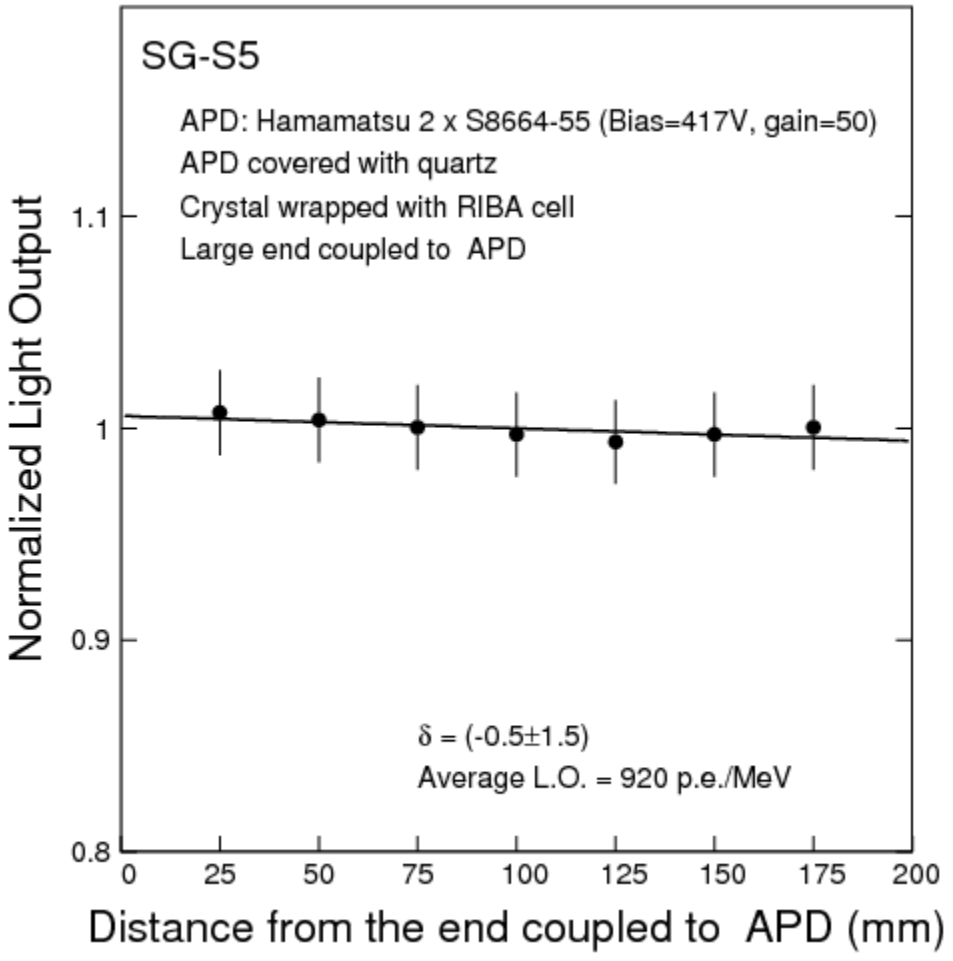

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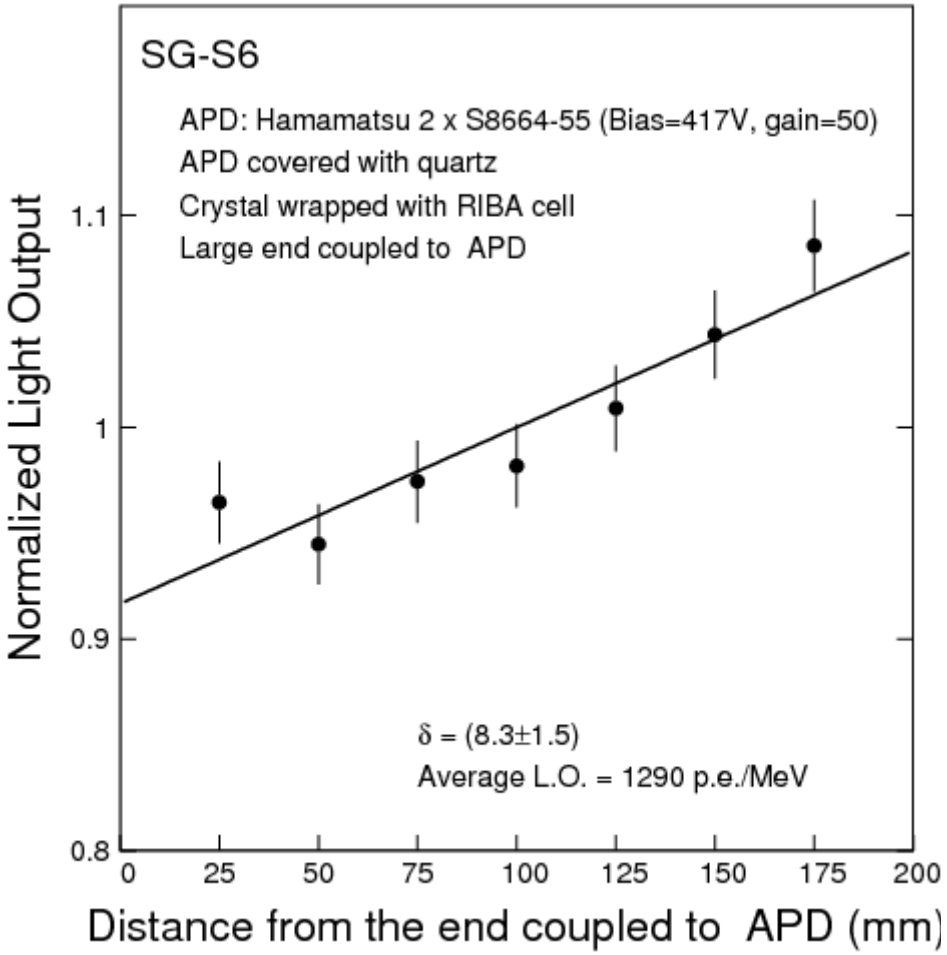

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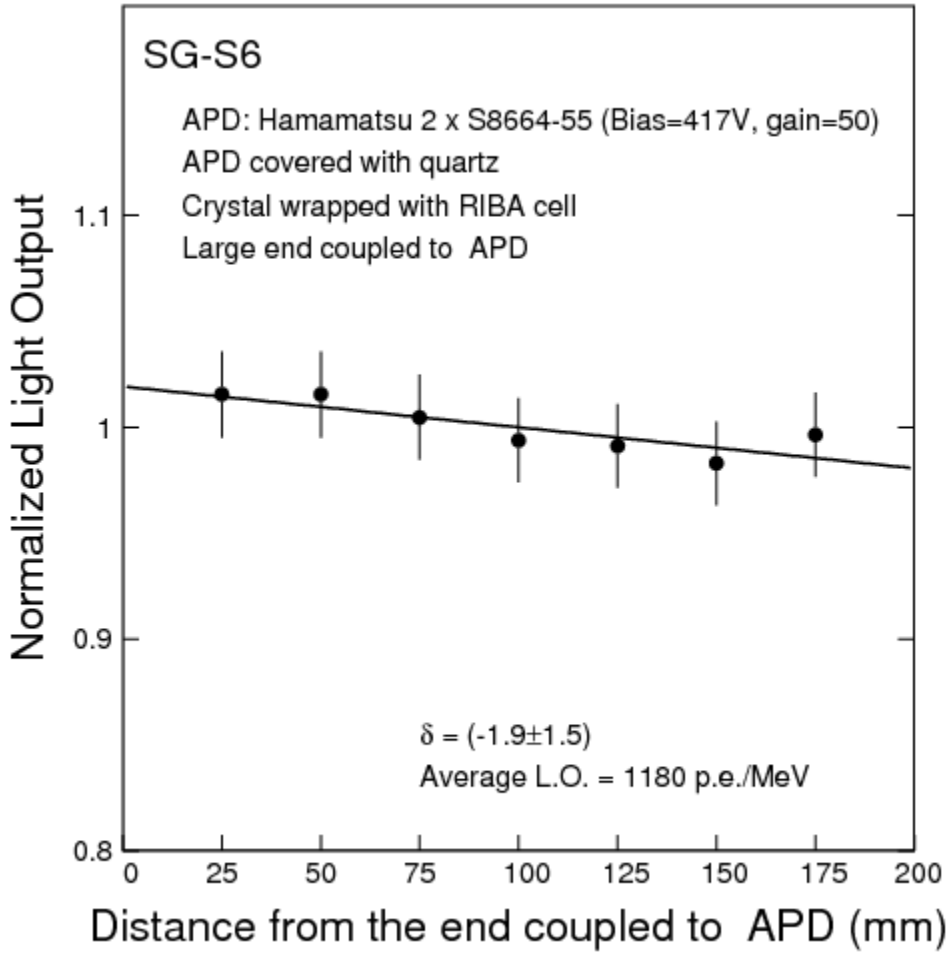

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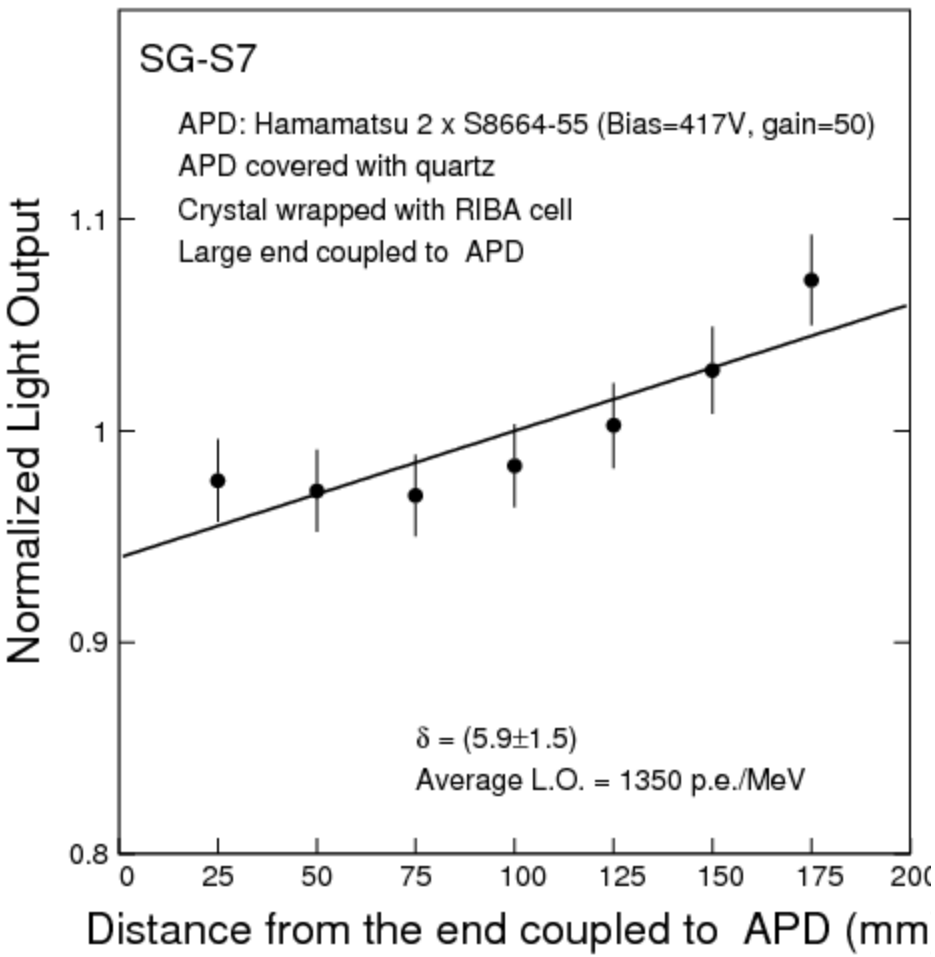

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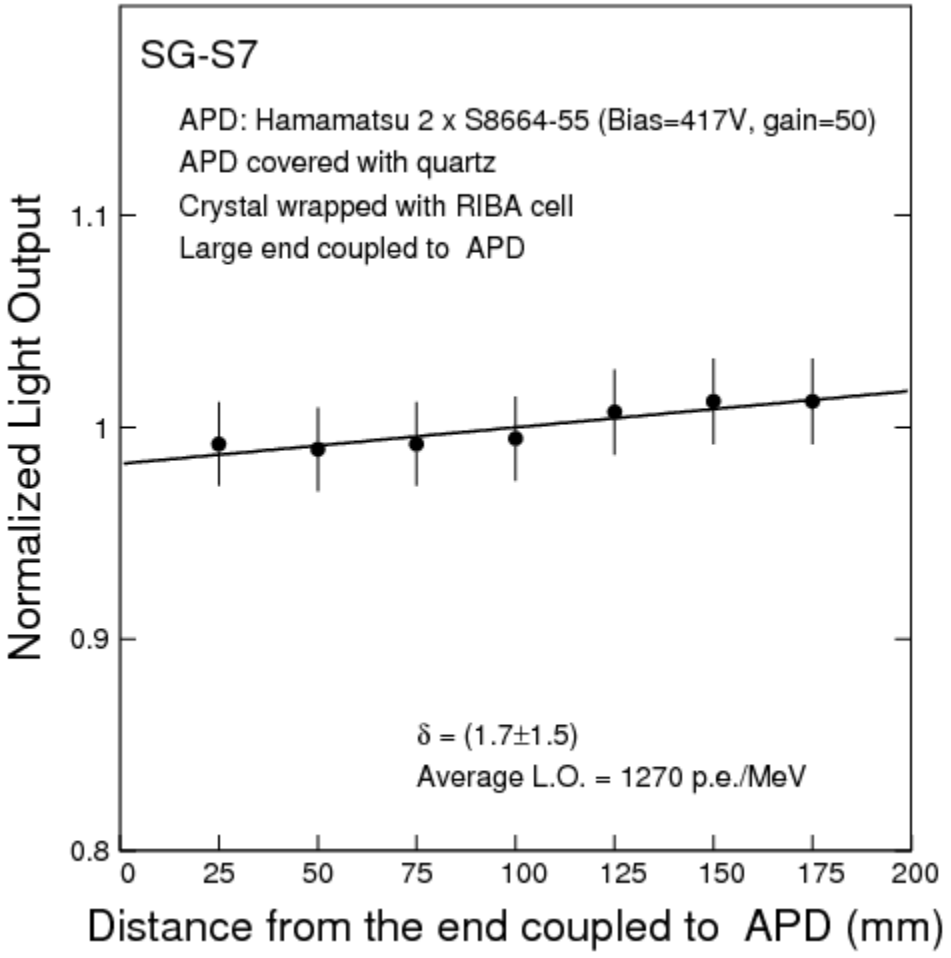

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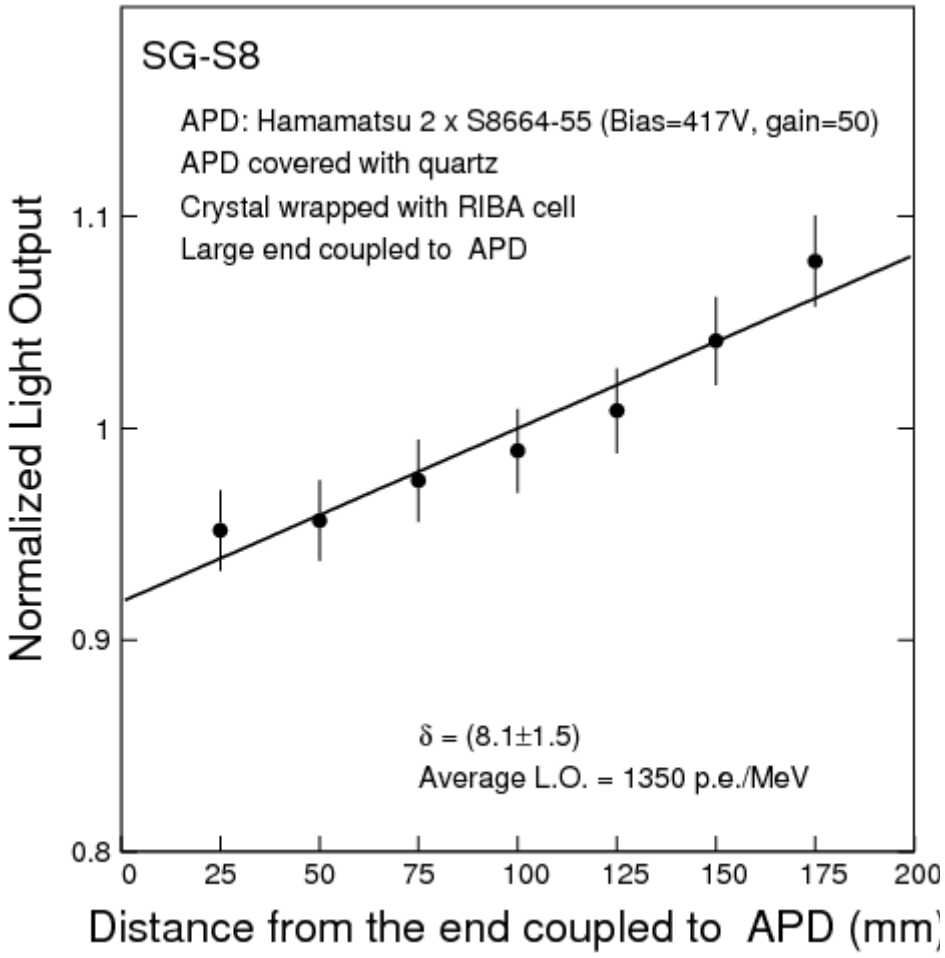

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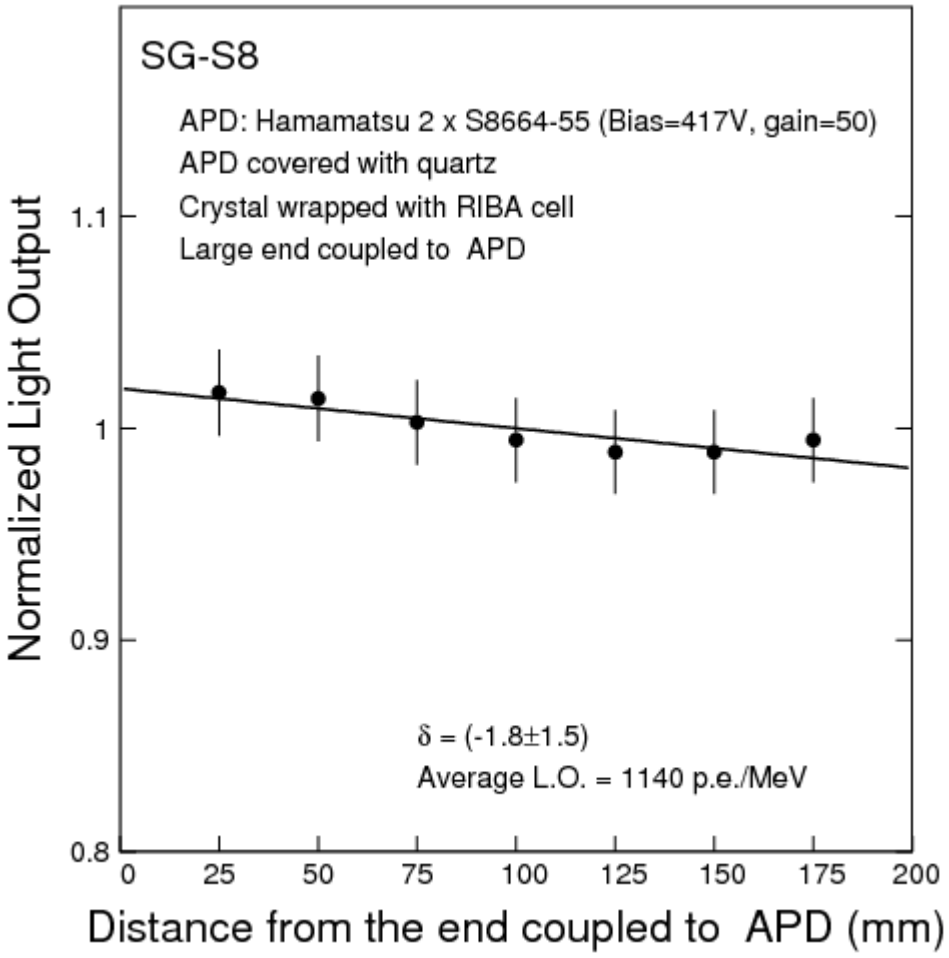

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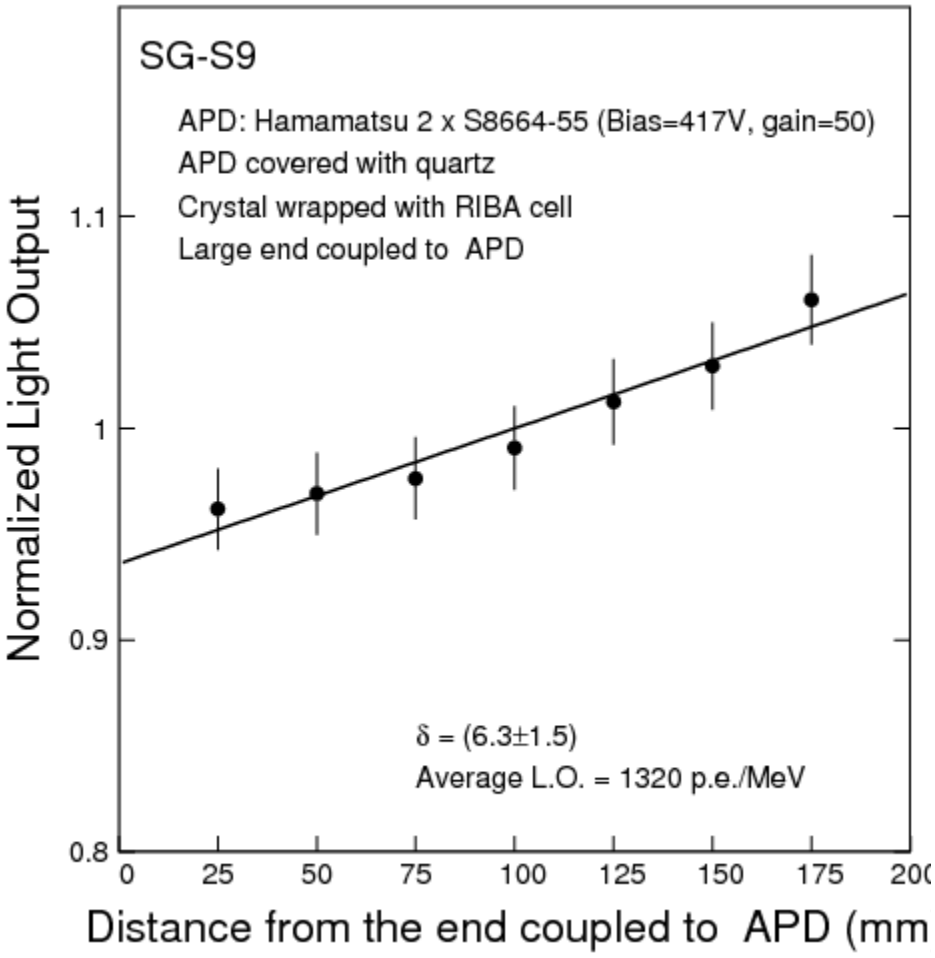

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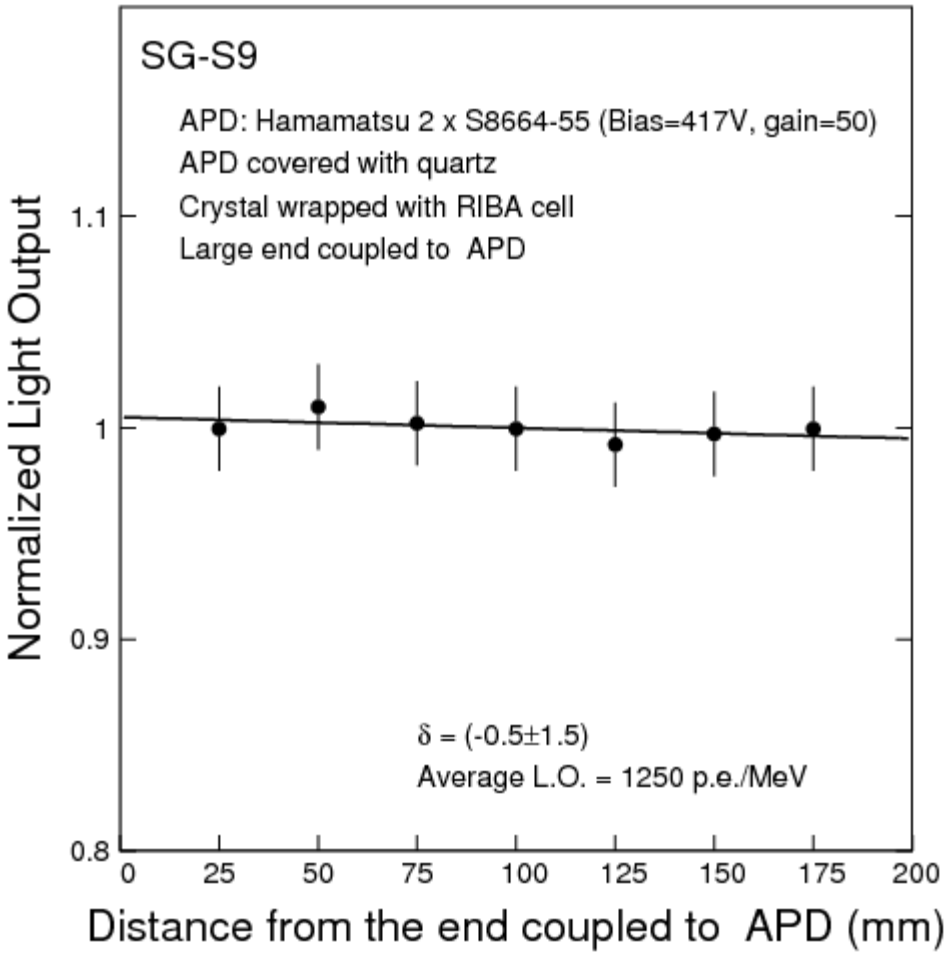

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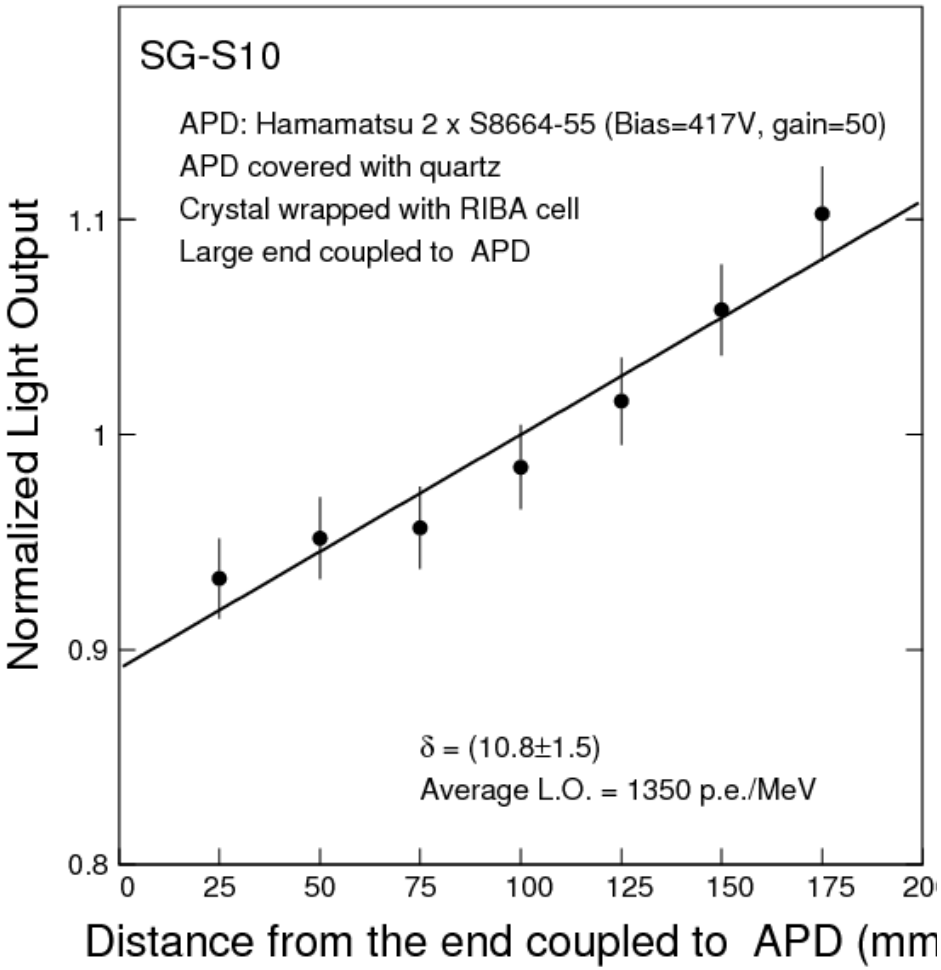

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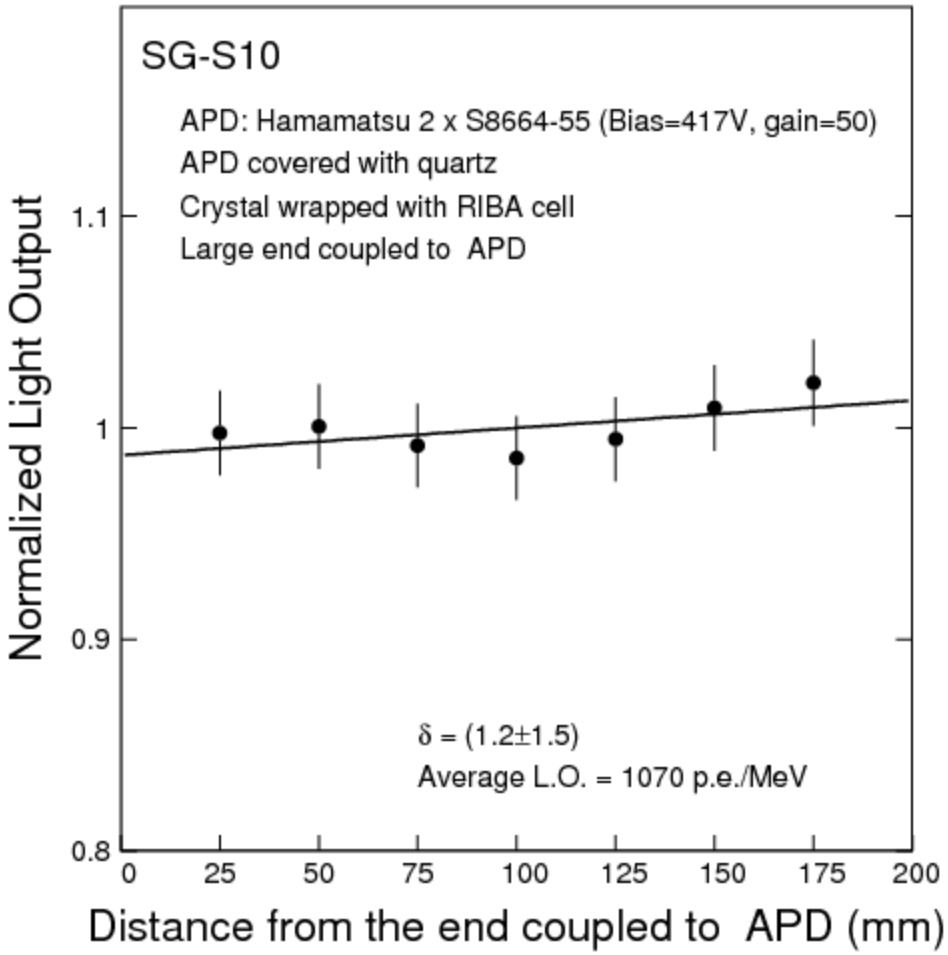

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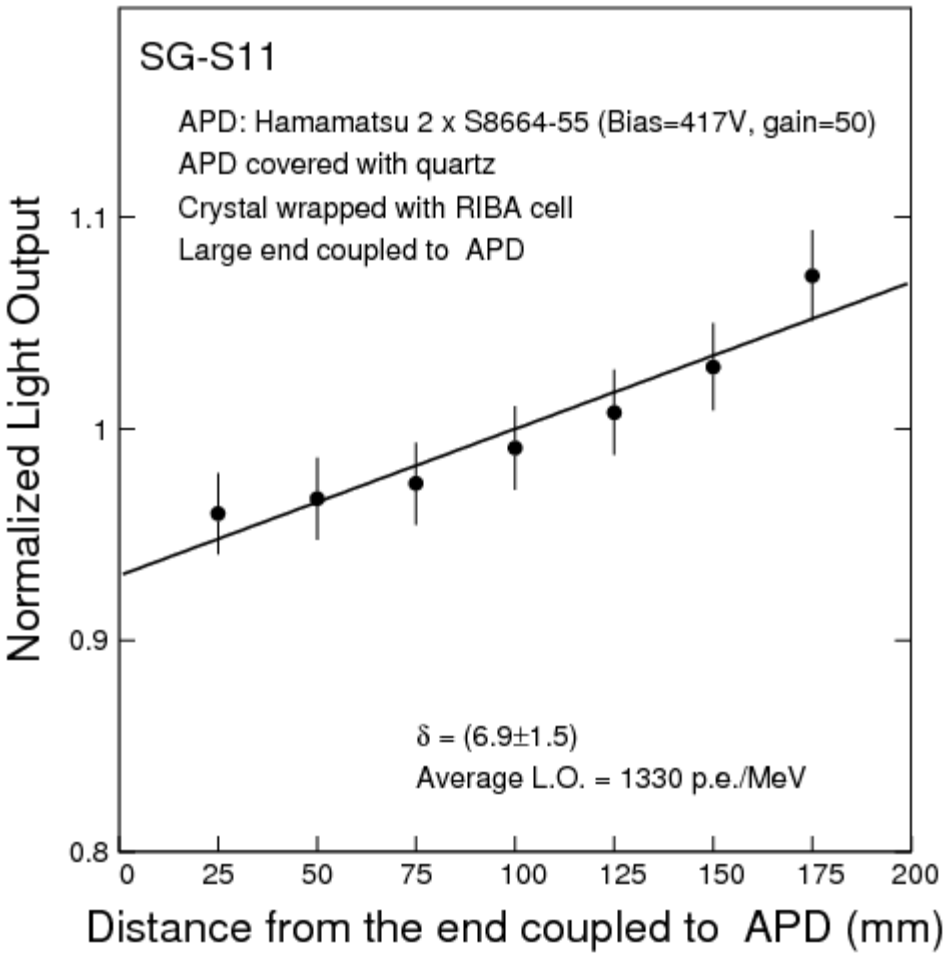

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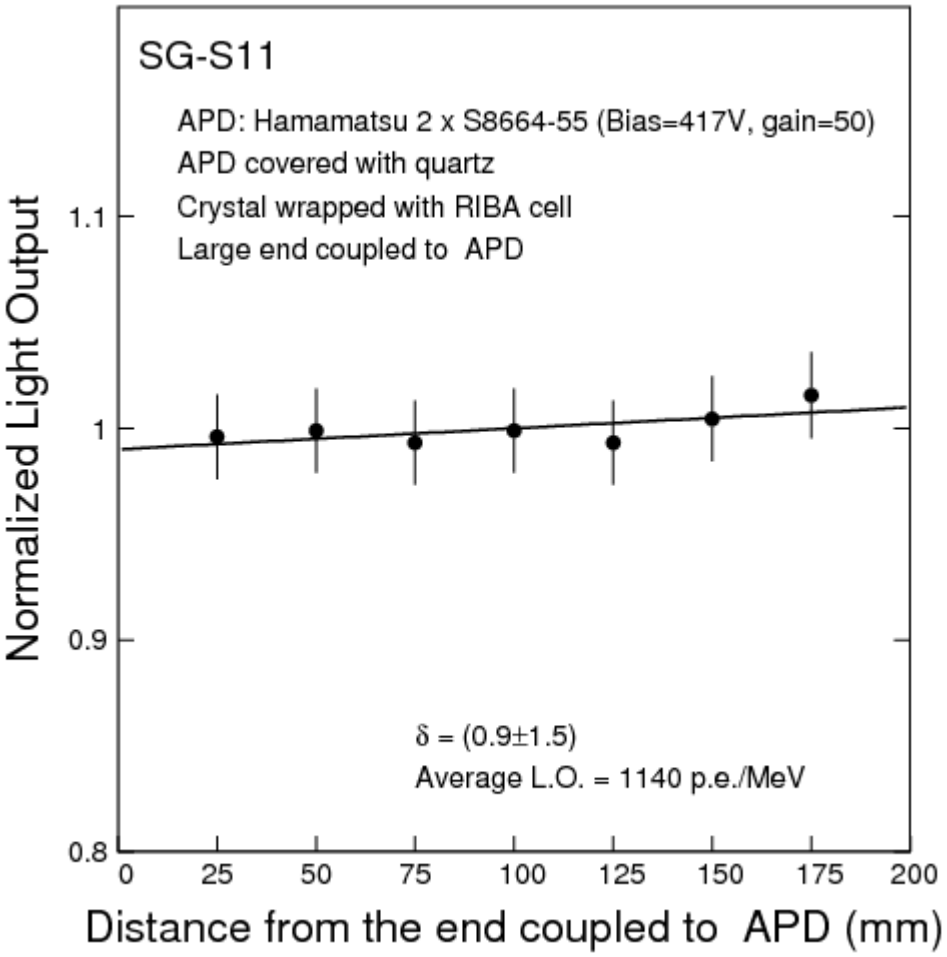

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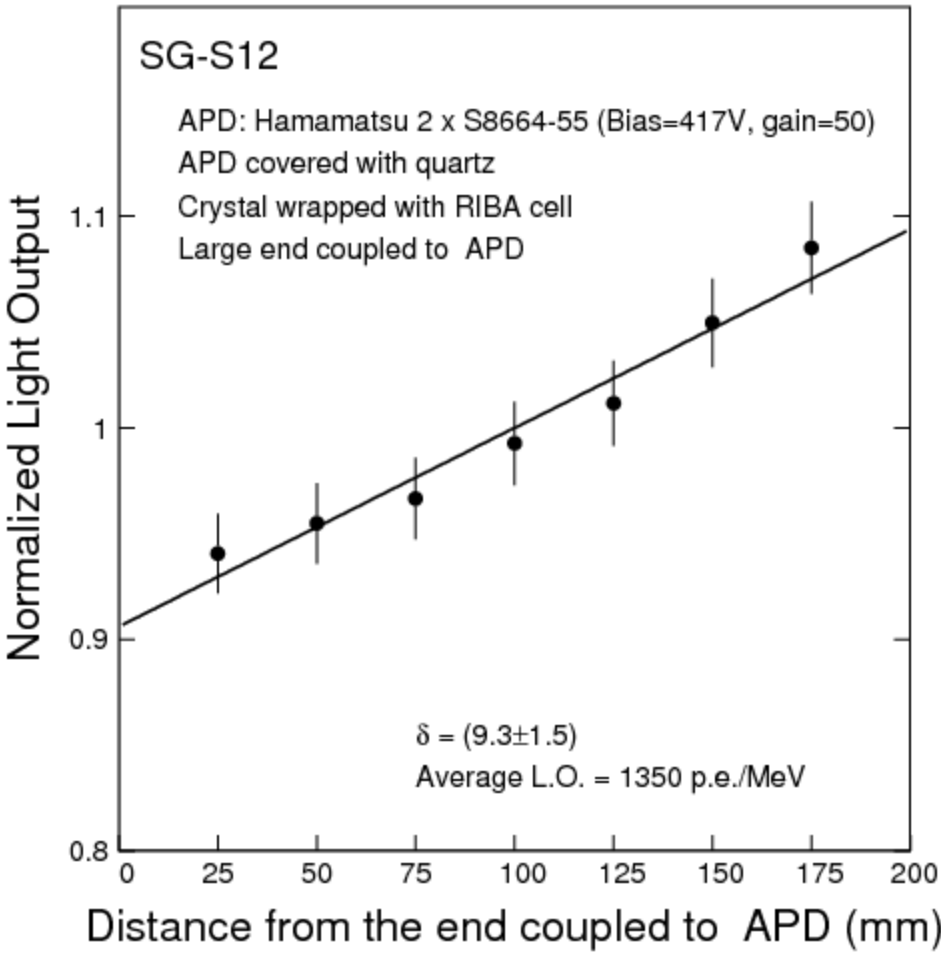

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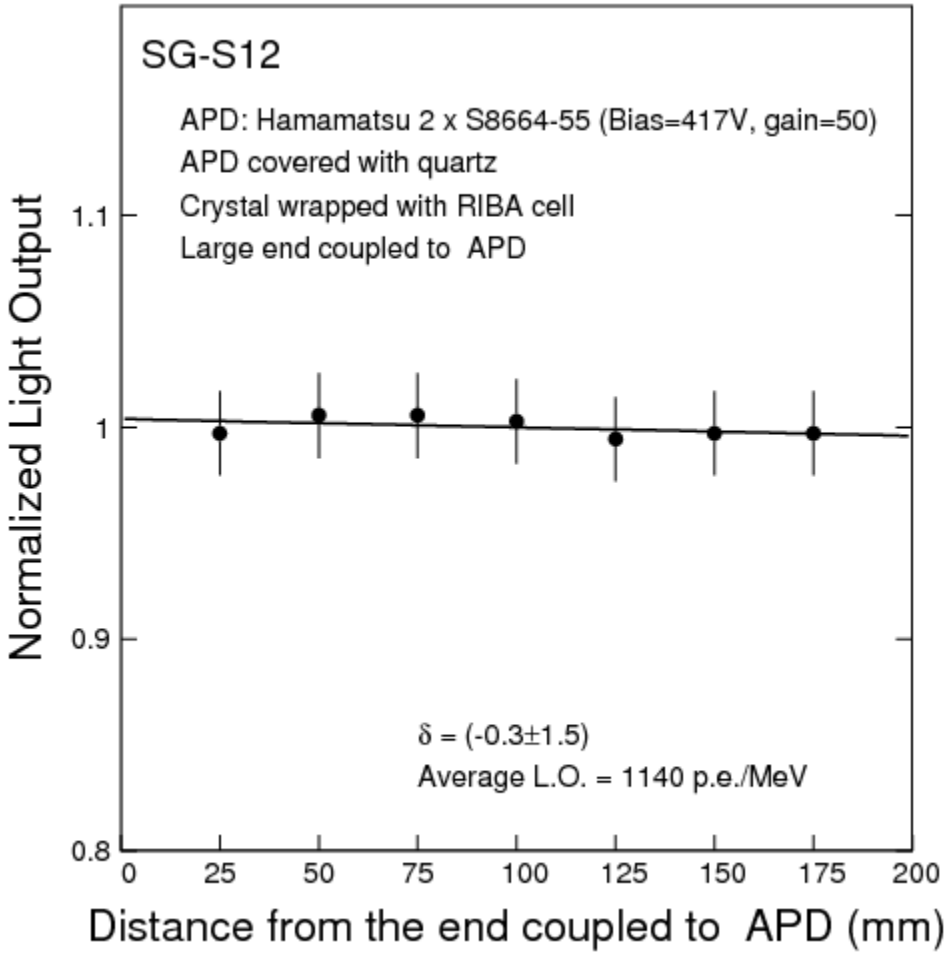

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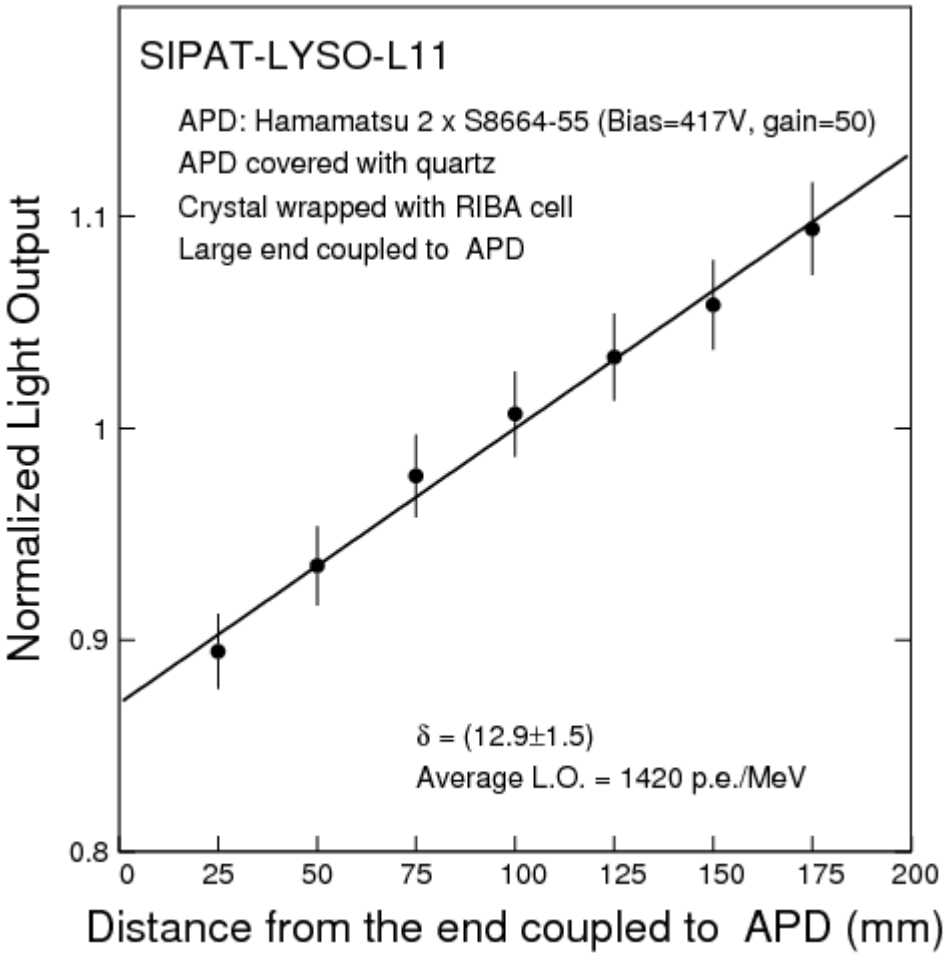

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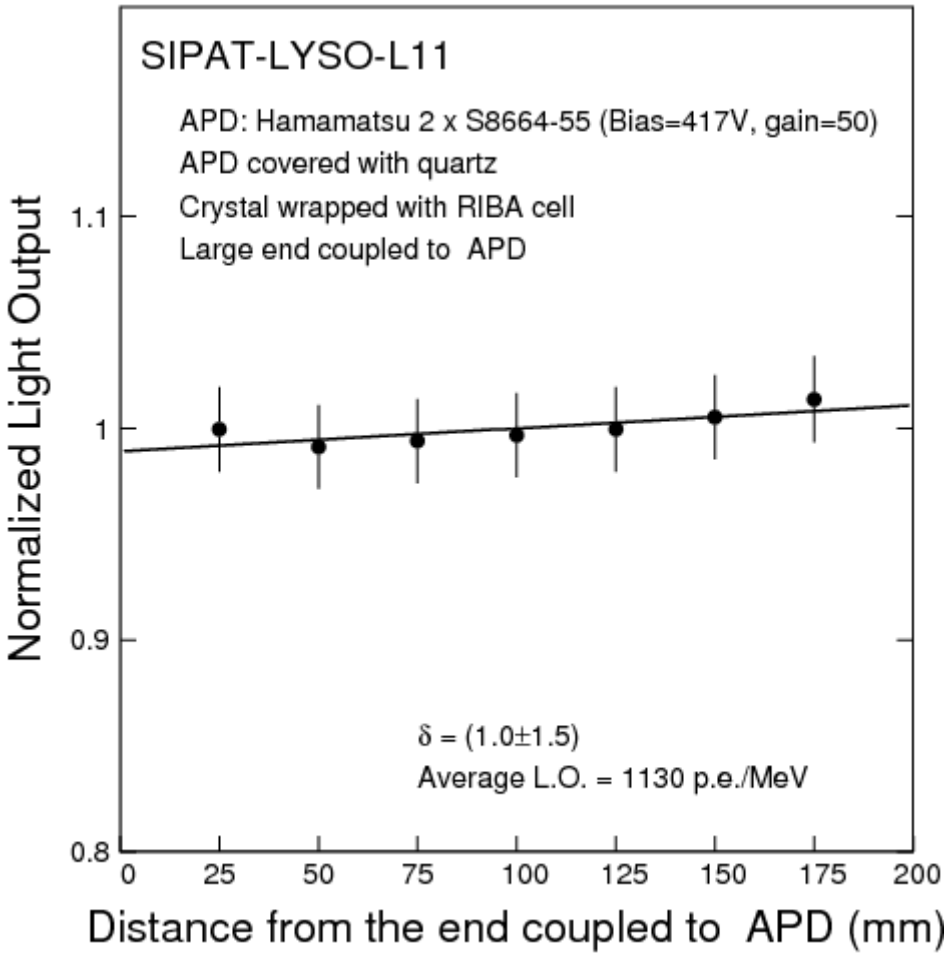

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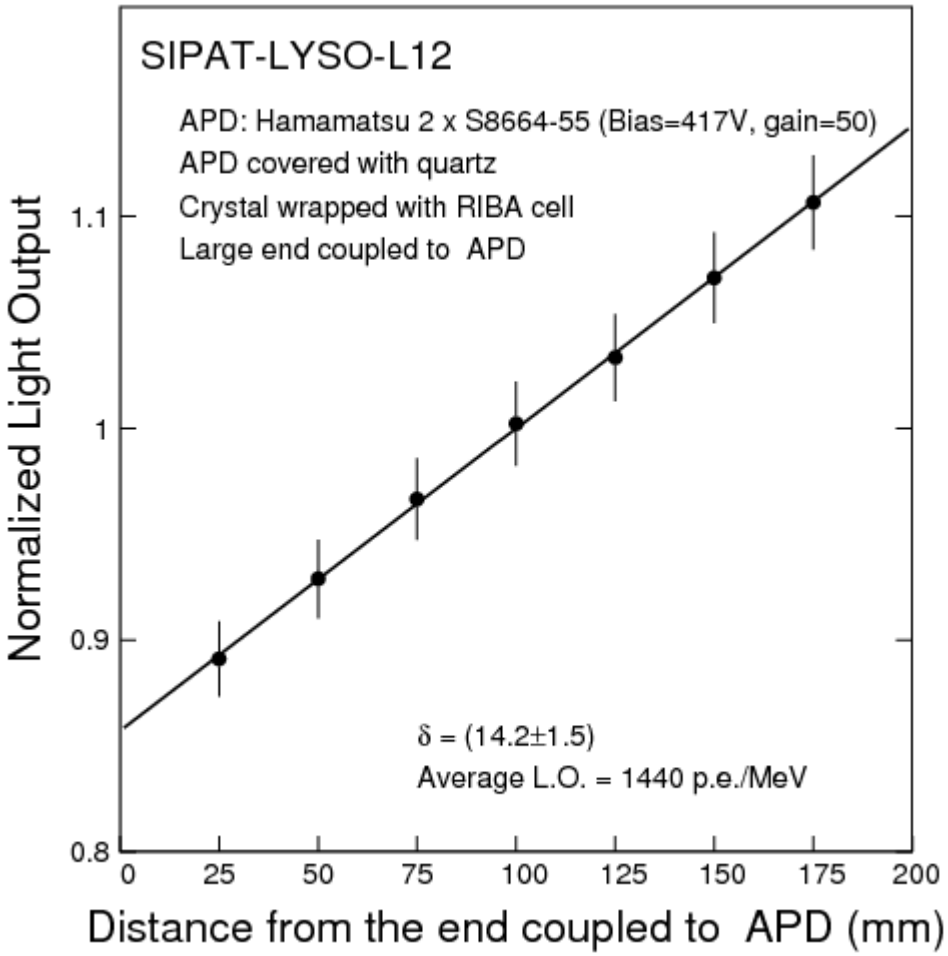

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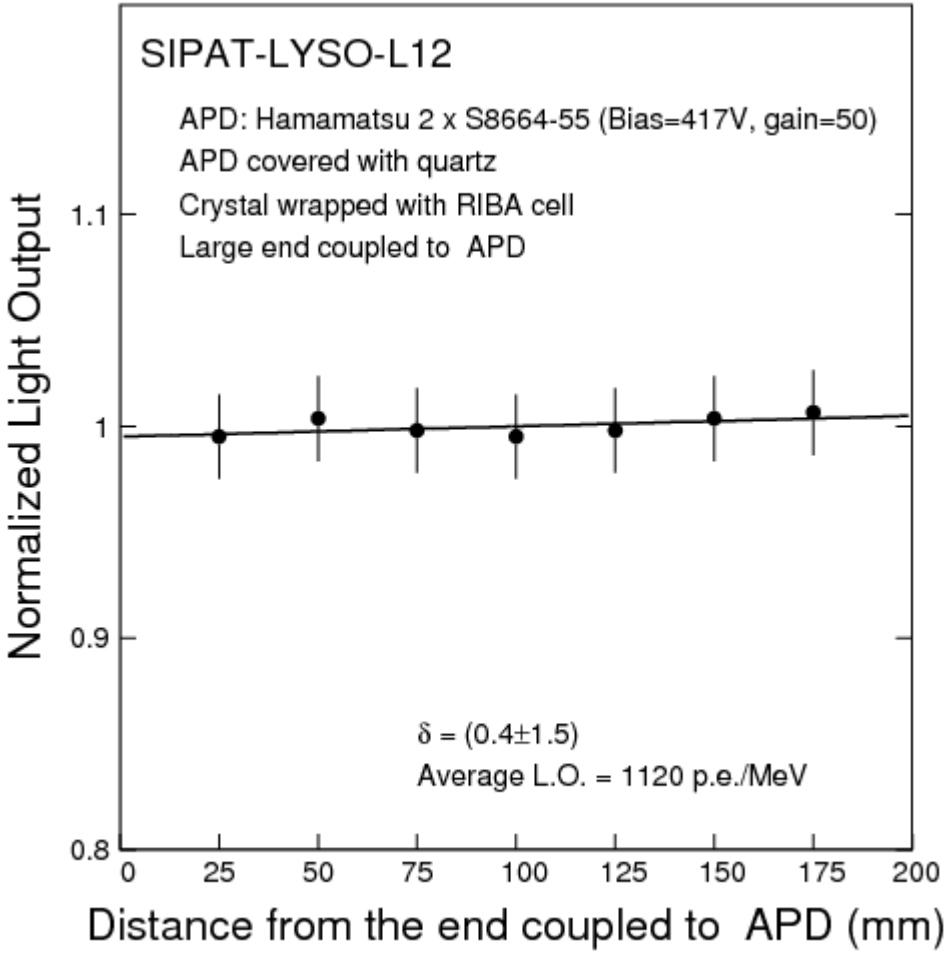

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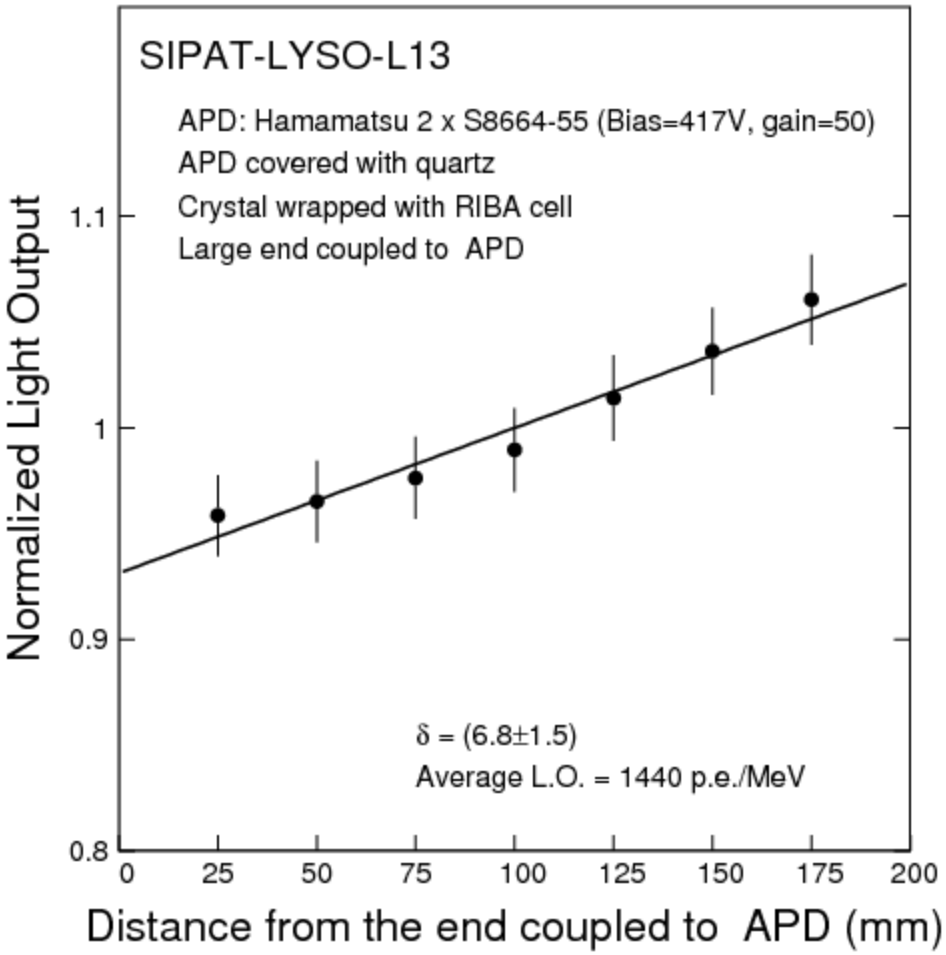
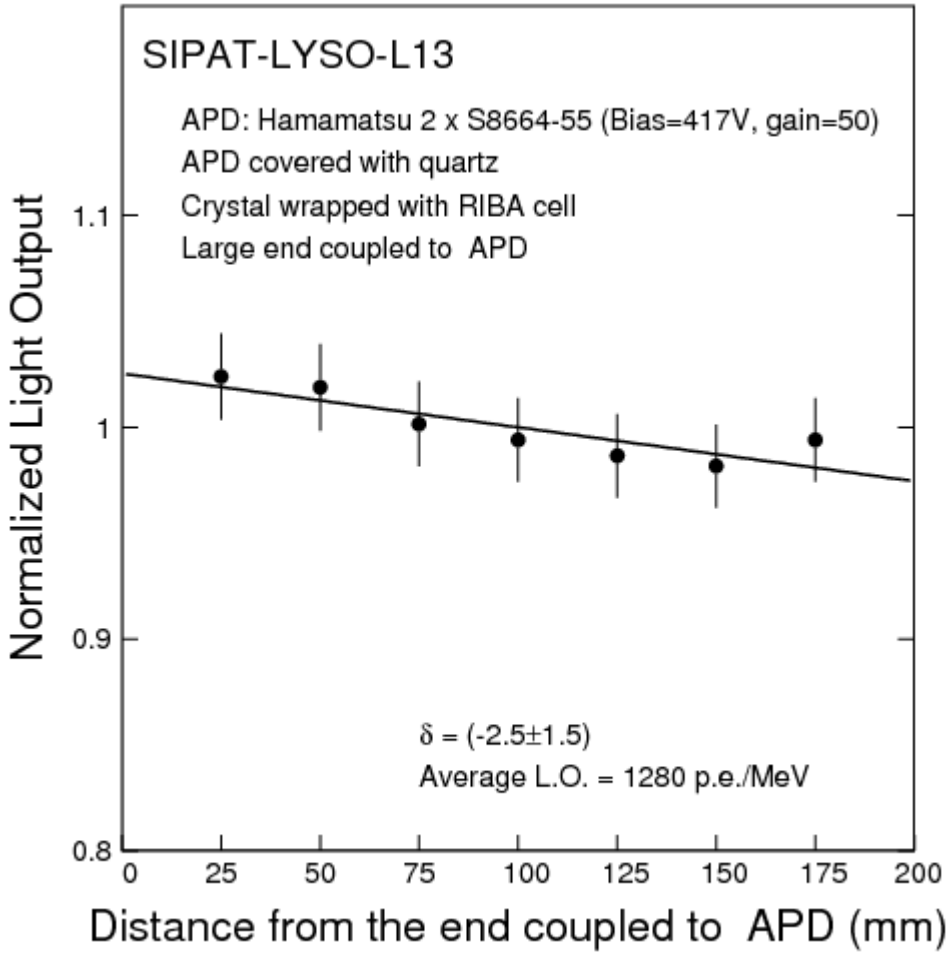


After roughening



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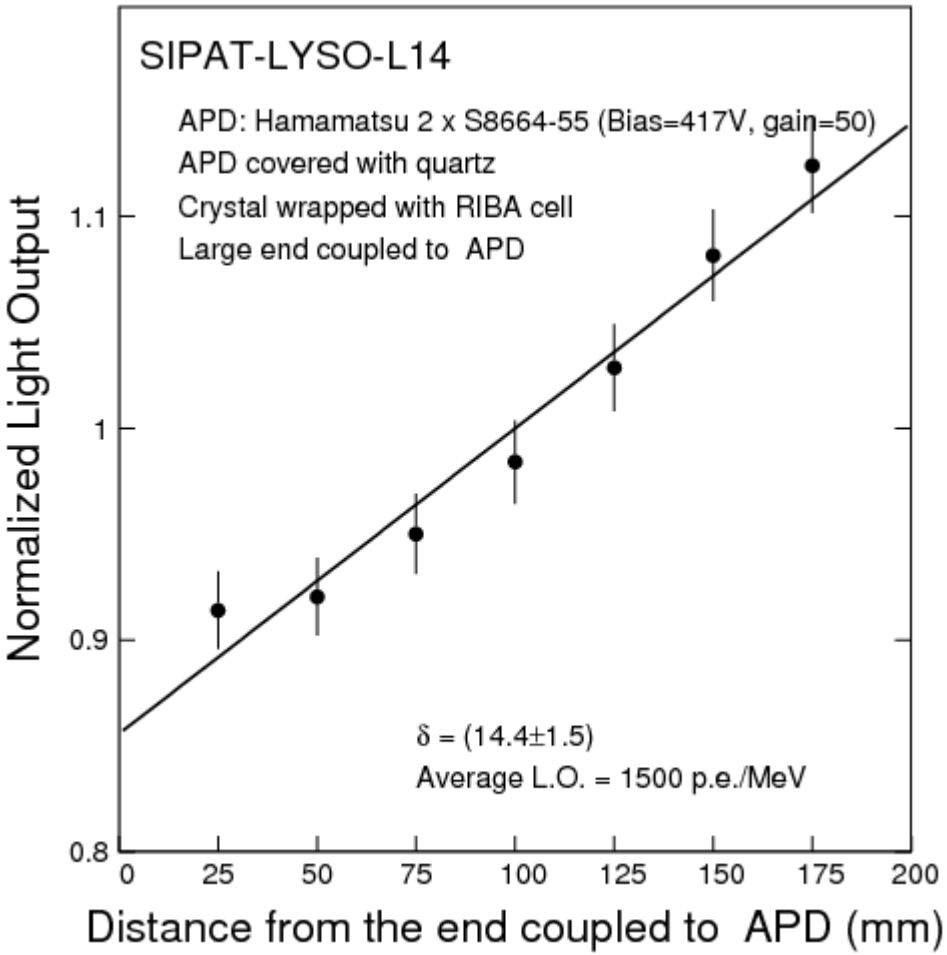

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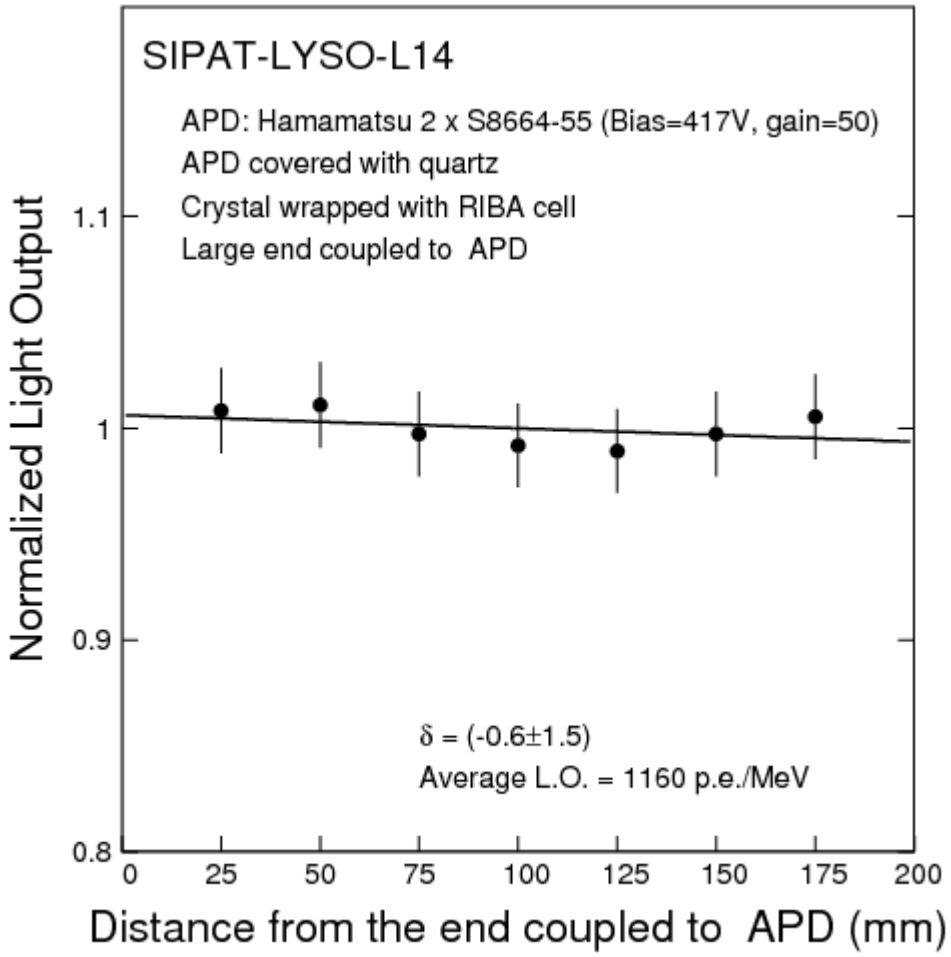

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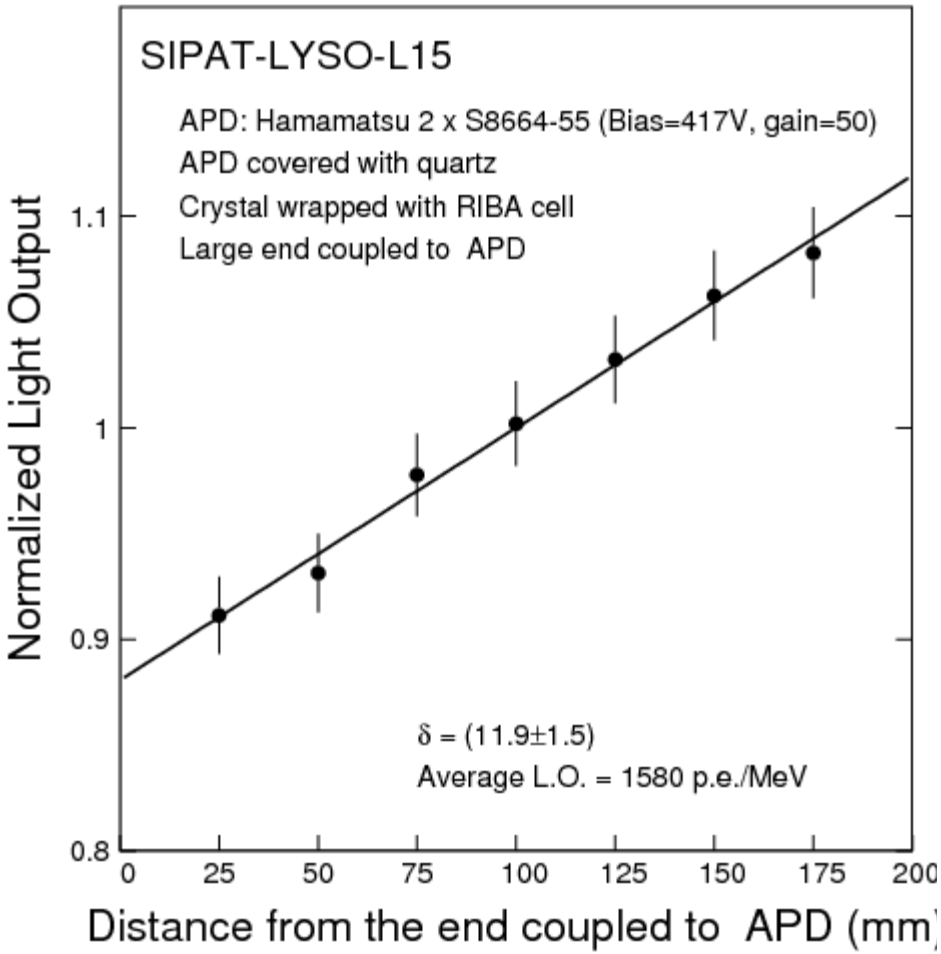

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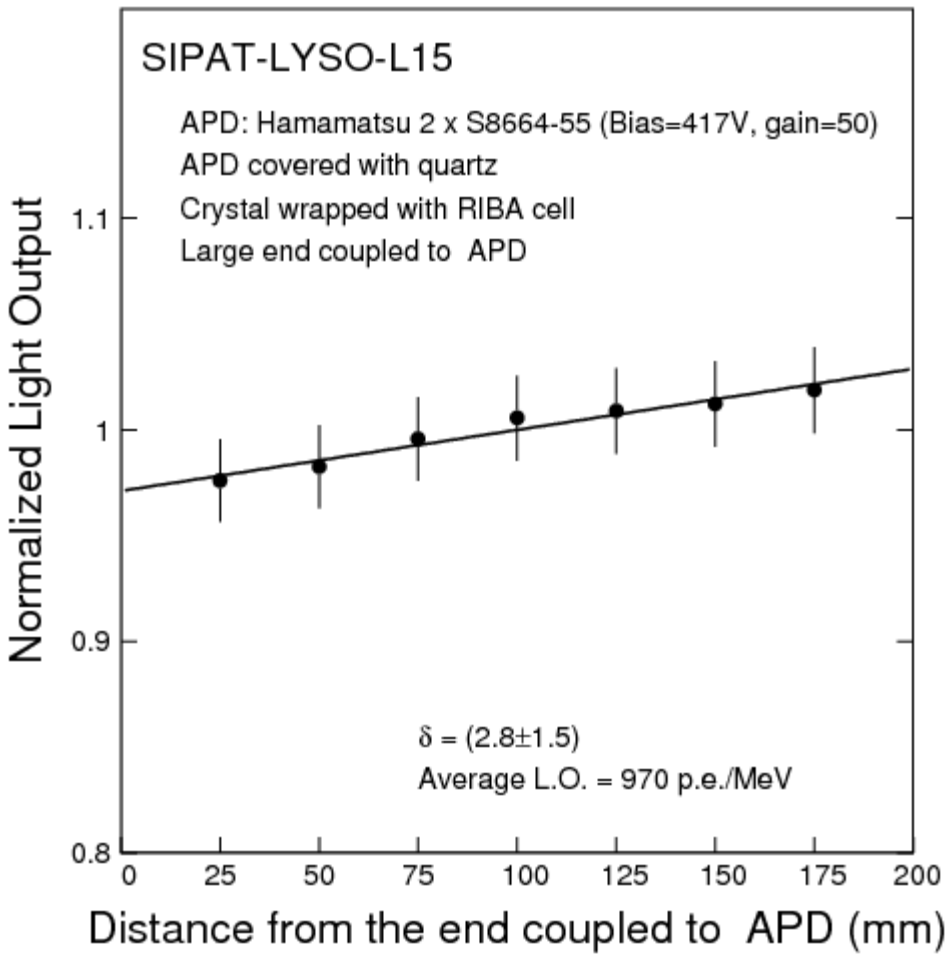

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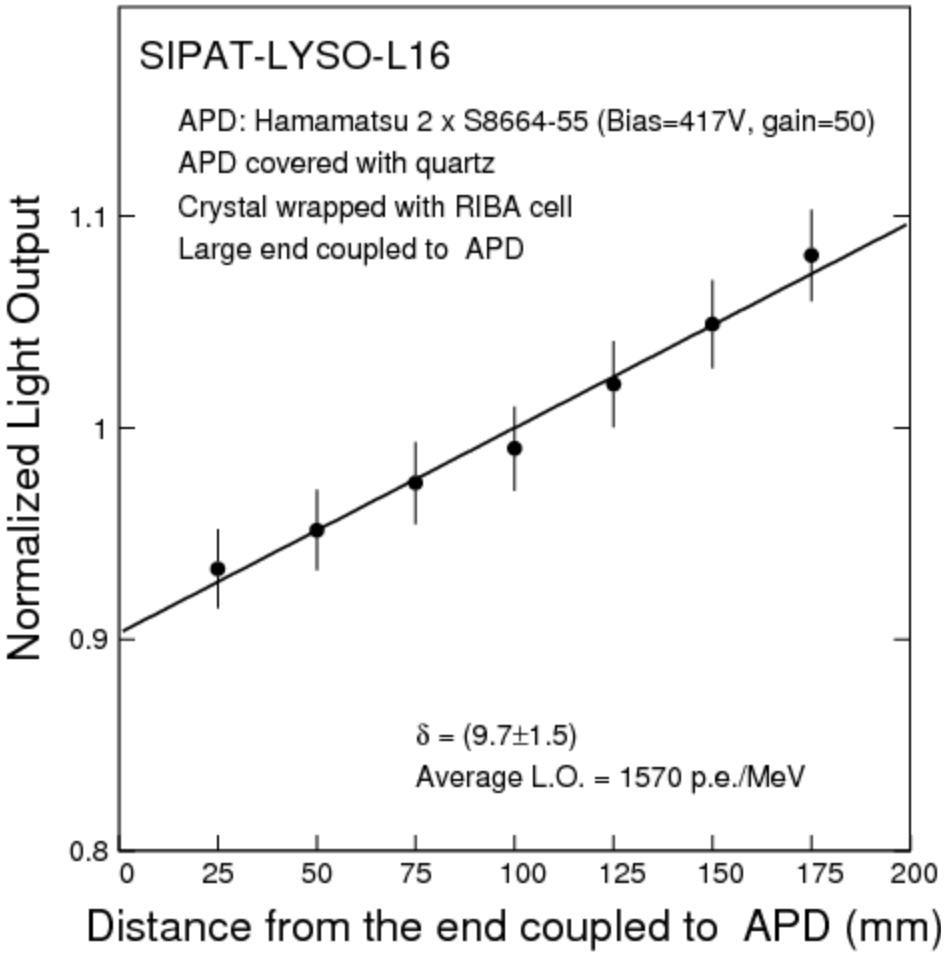

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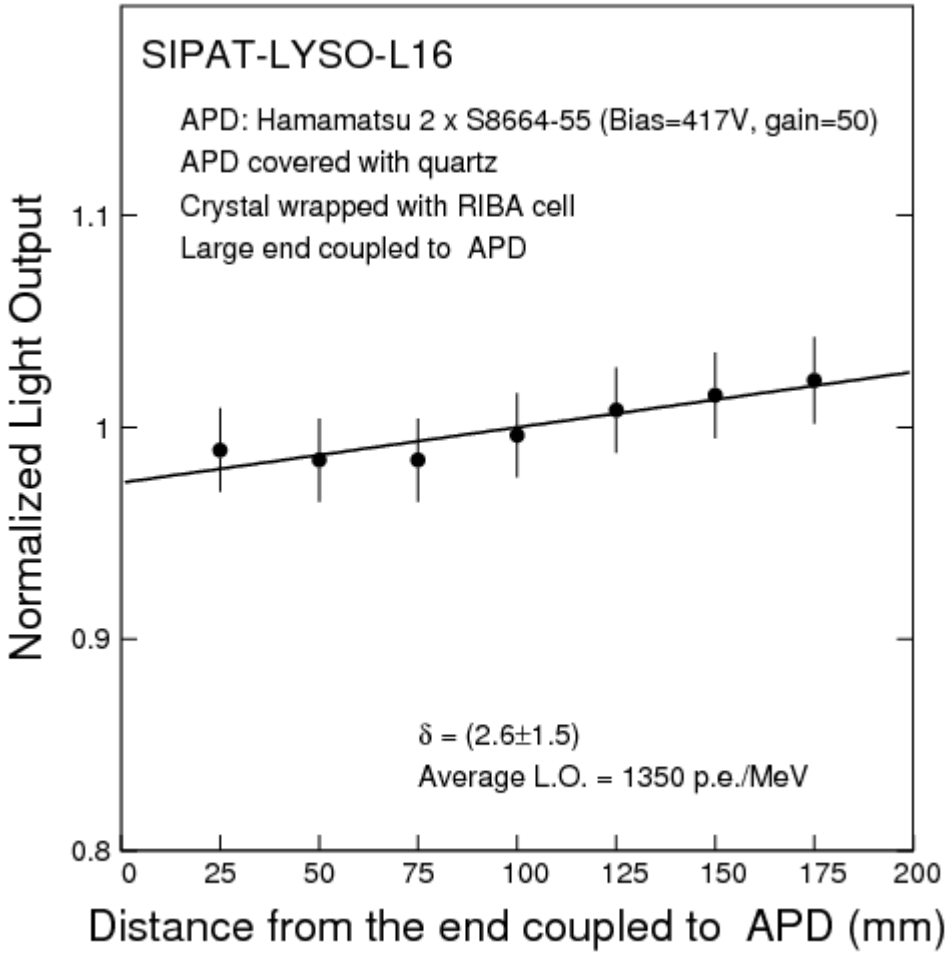

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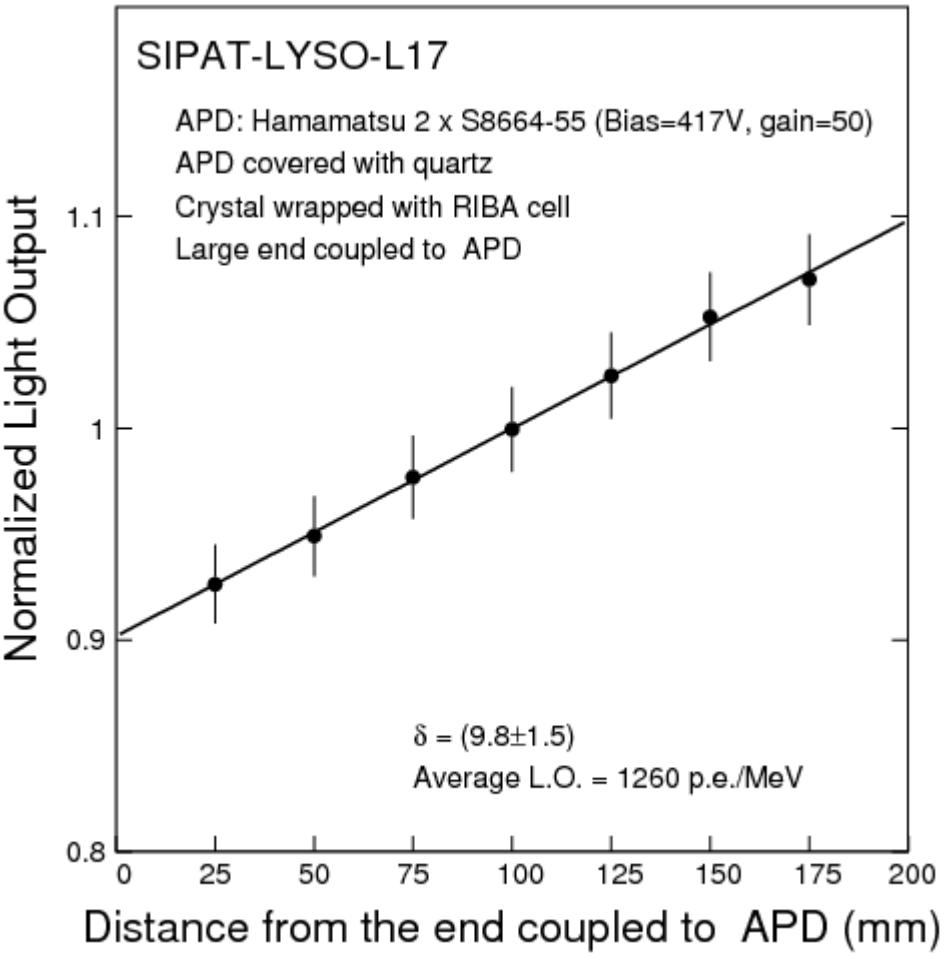

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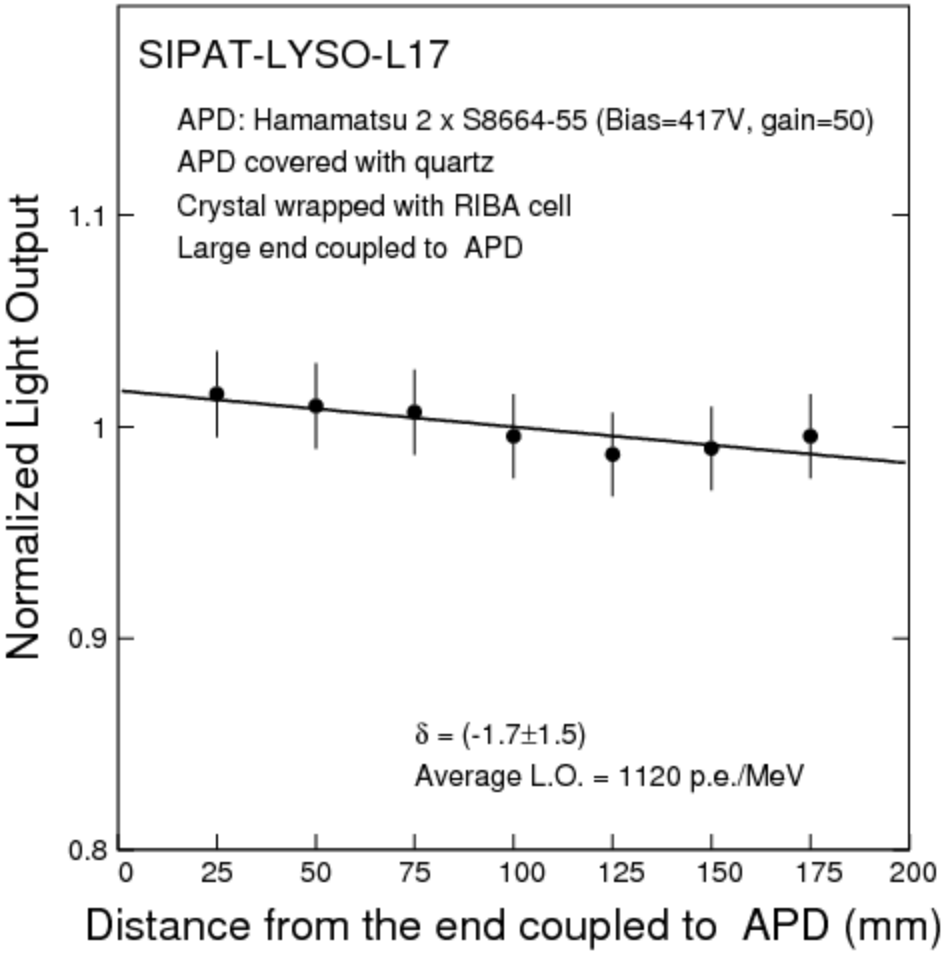

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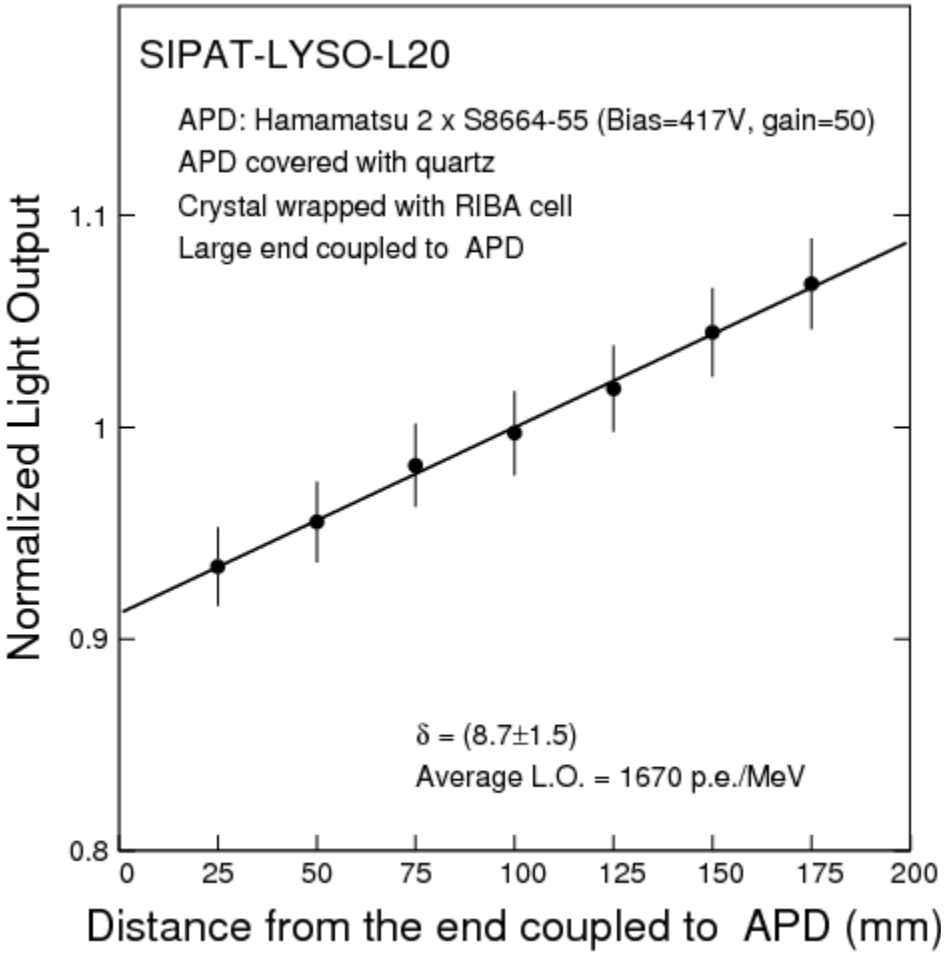
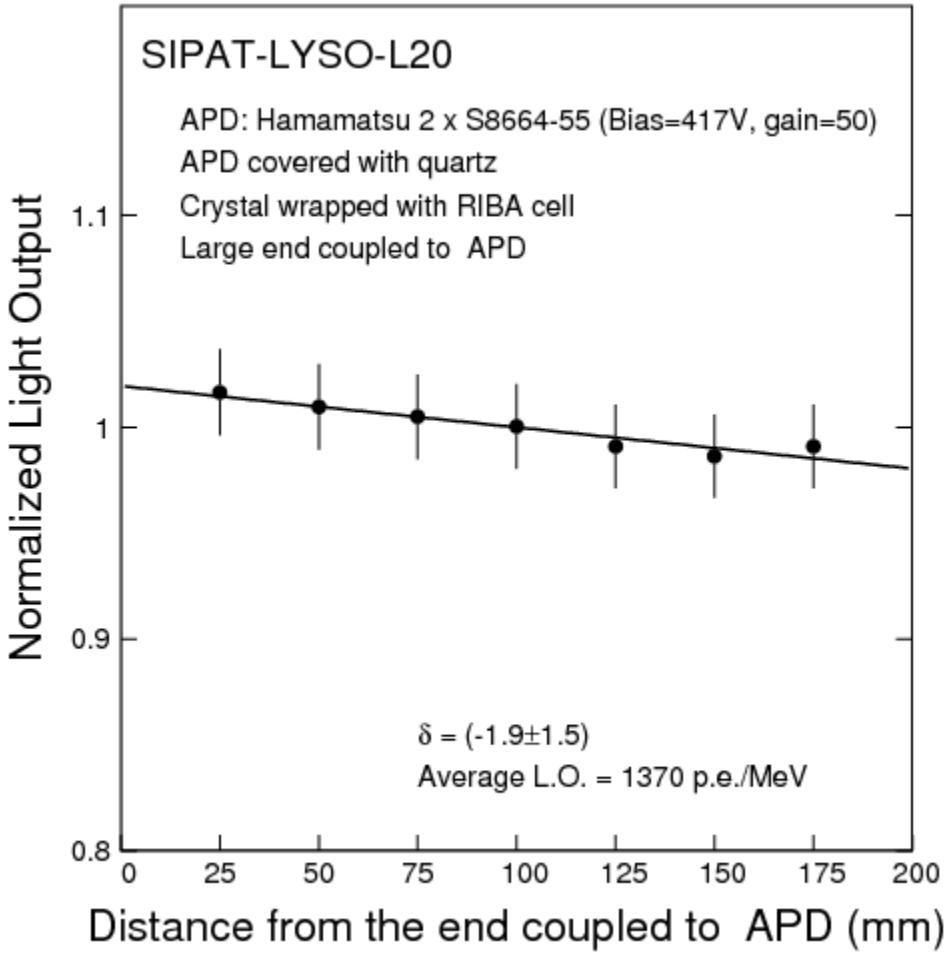


After roughening



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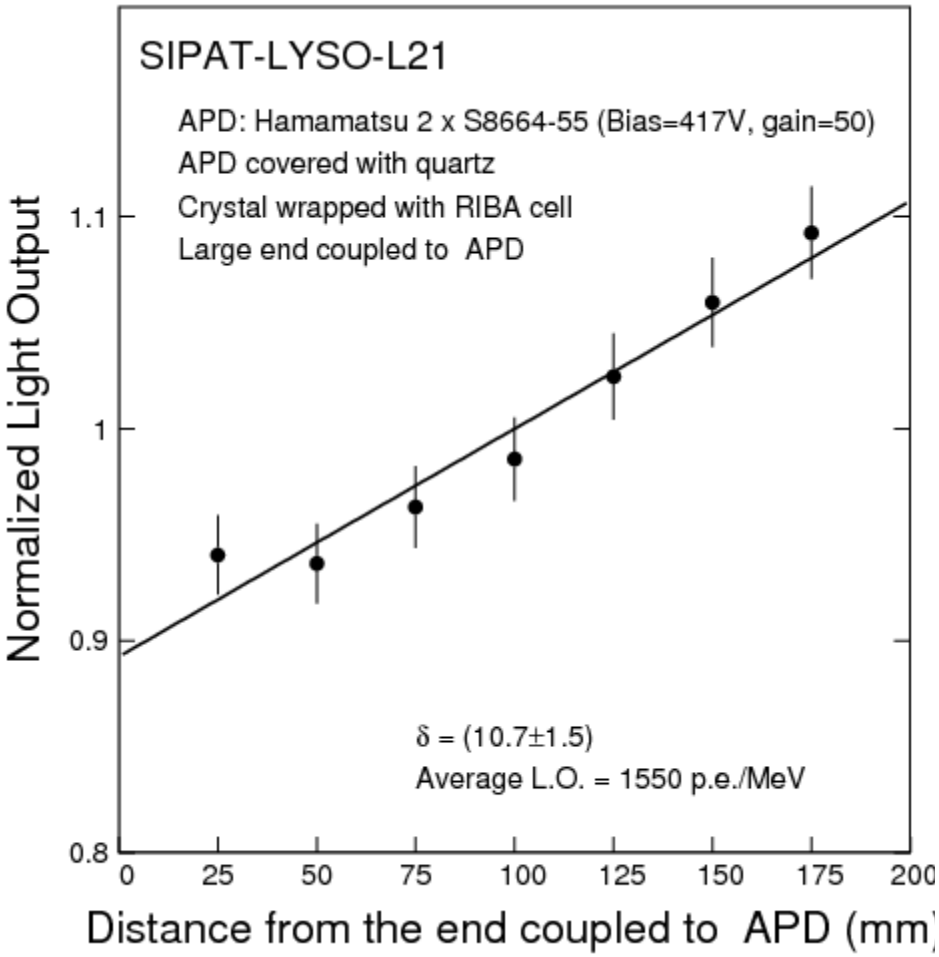

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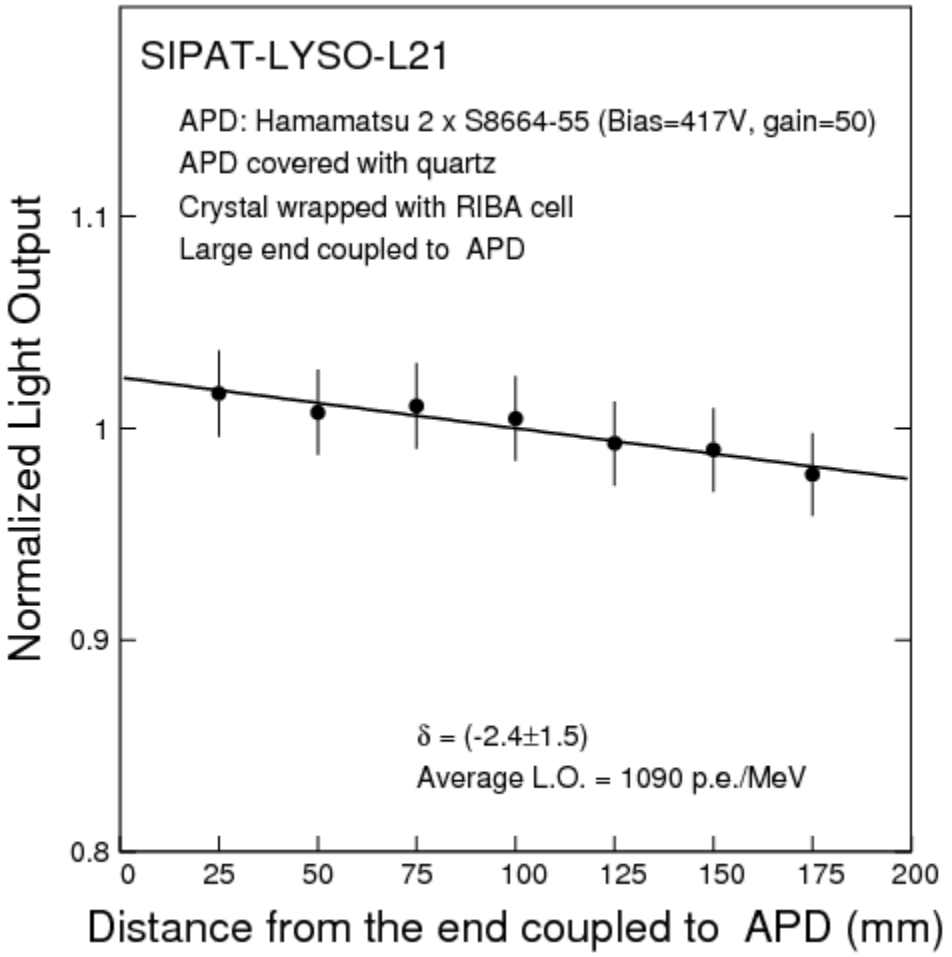

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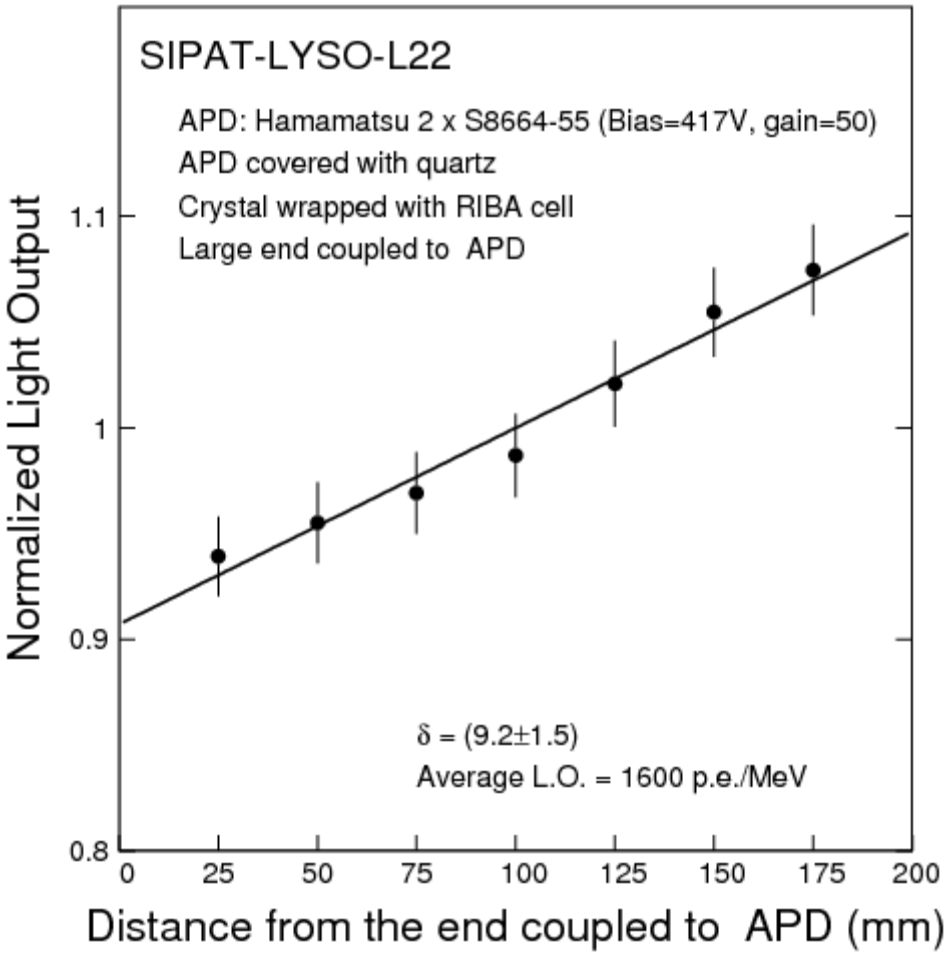

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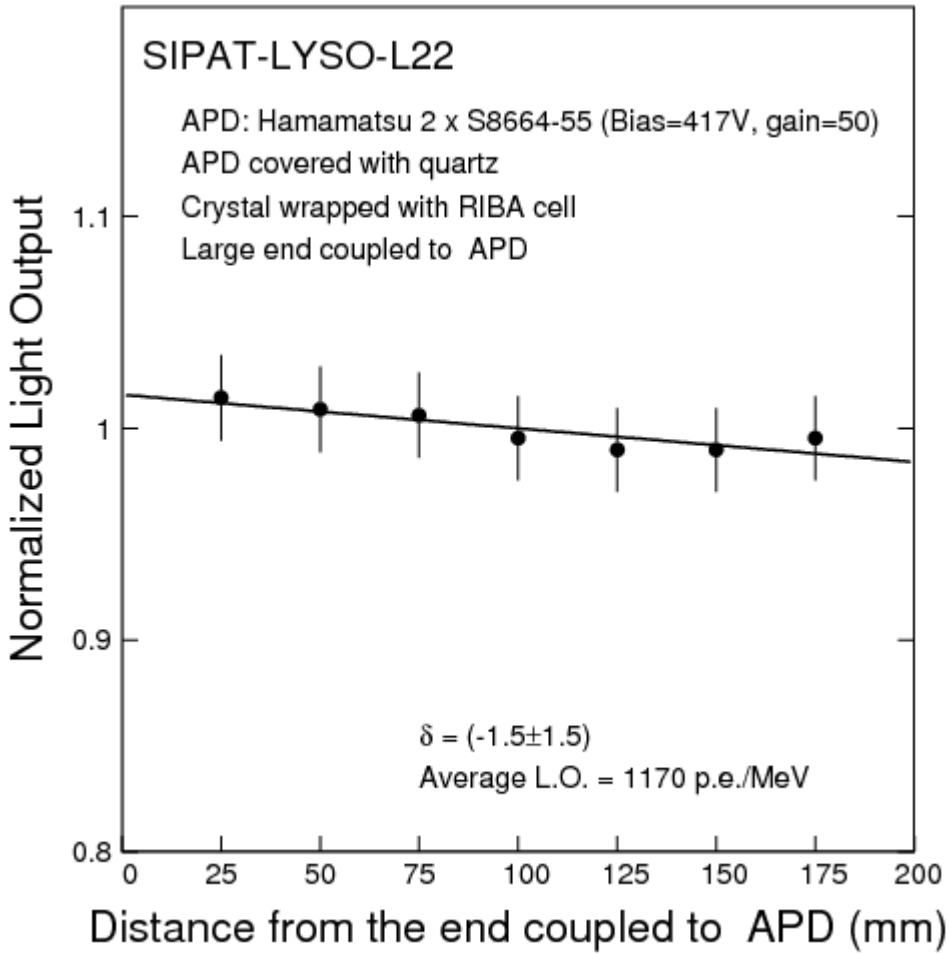
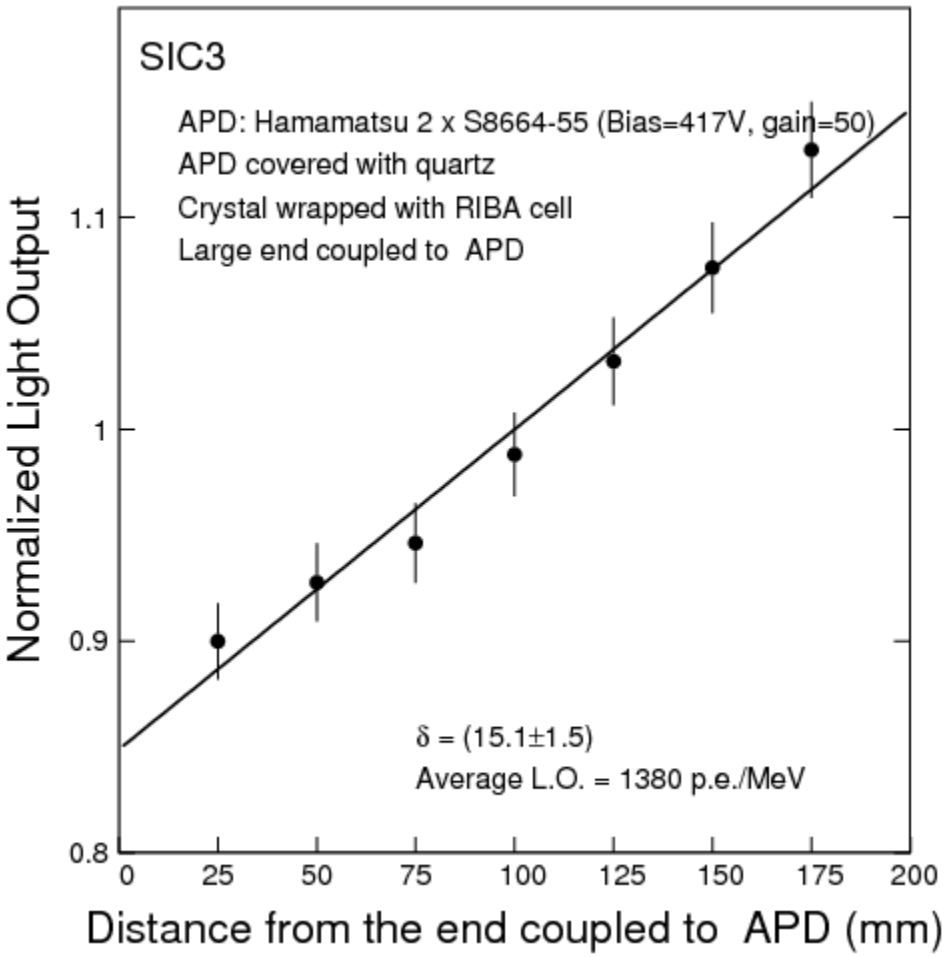
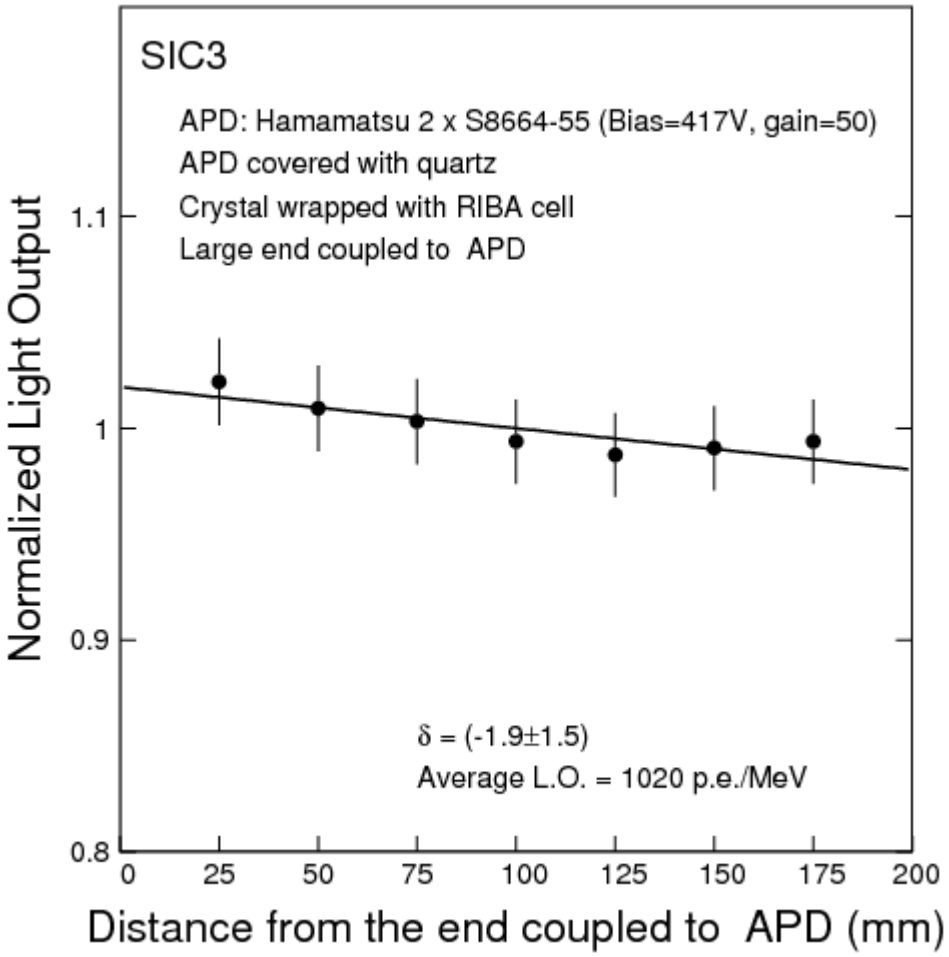


L.R.U. before & after Roughness

Before roughening



After roughening.



L.R.U. before & after Roughness

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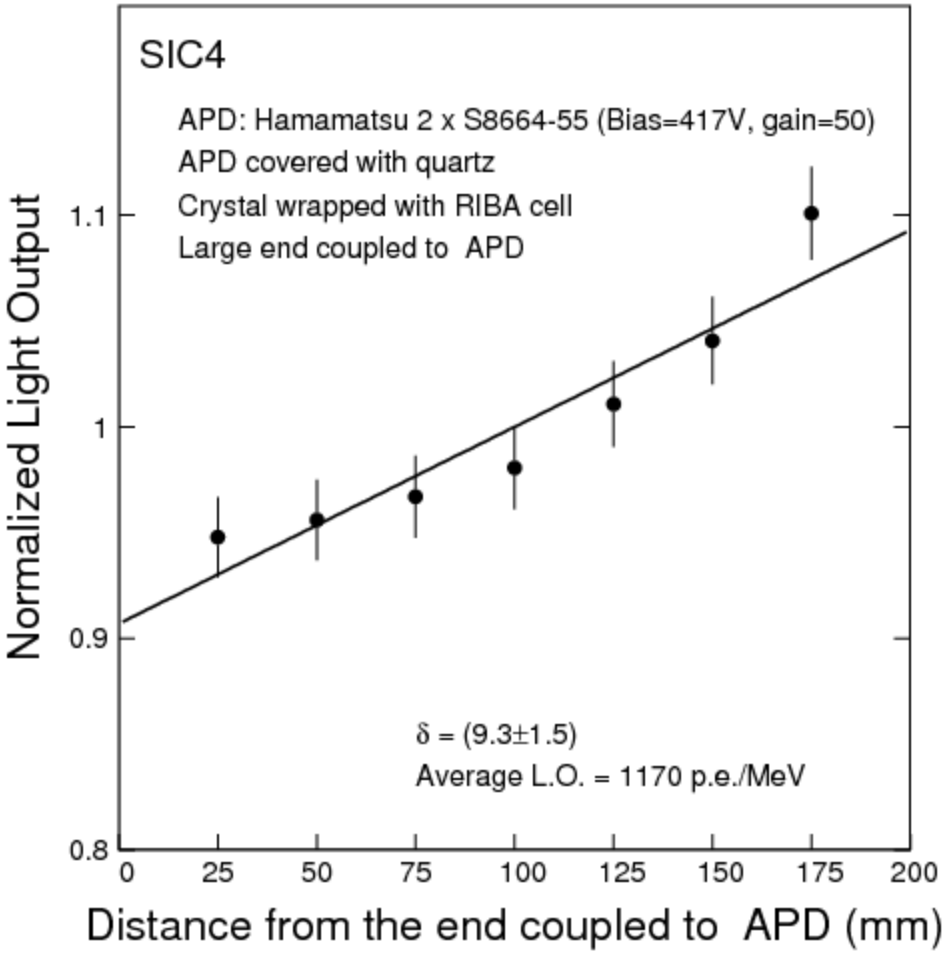
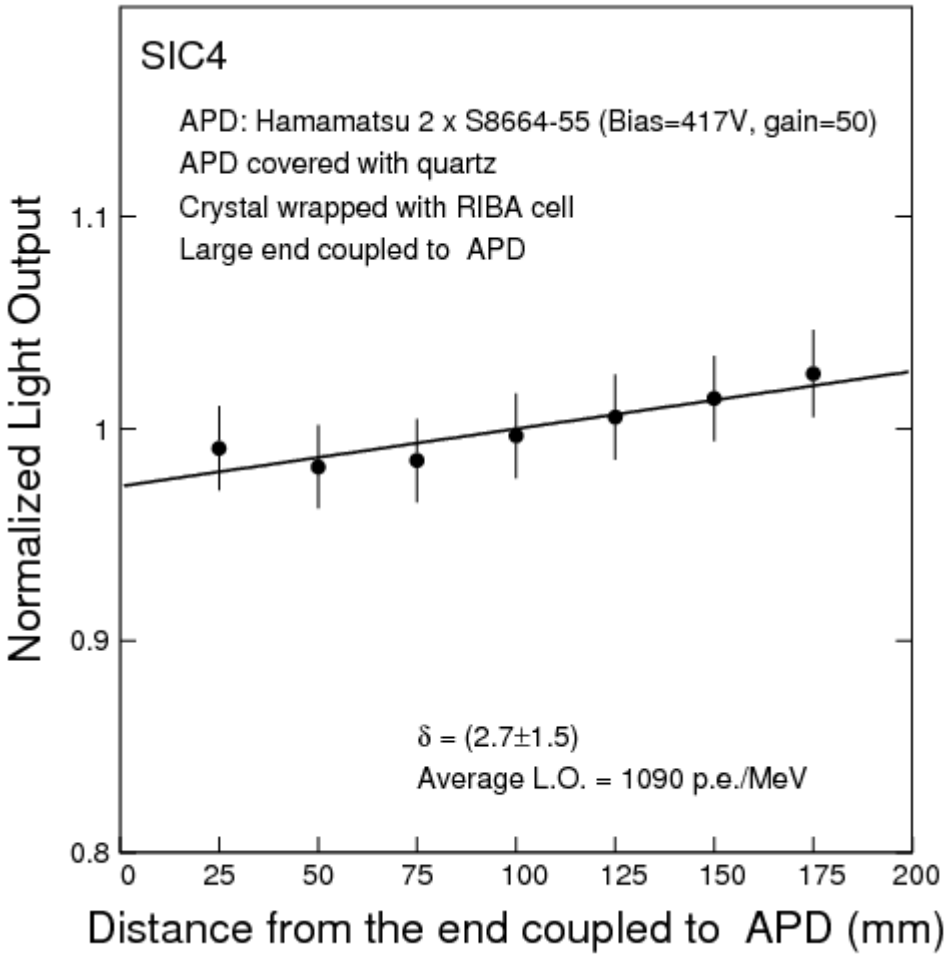
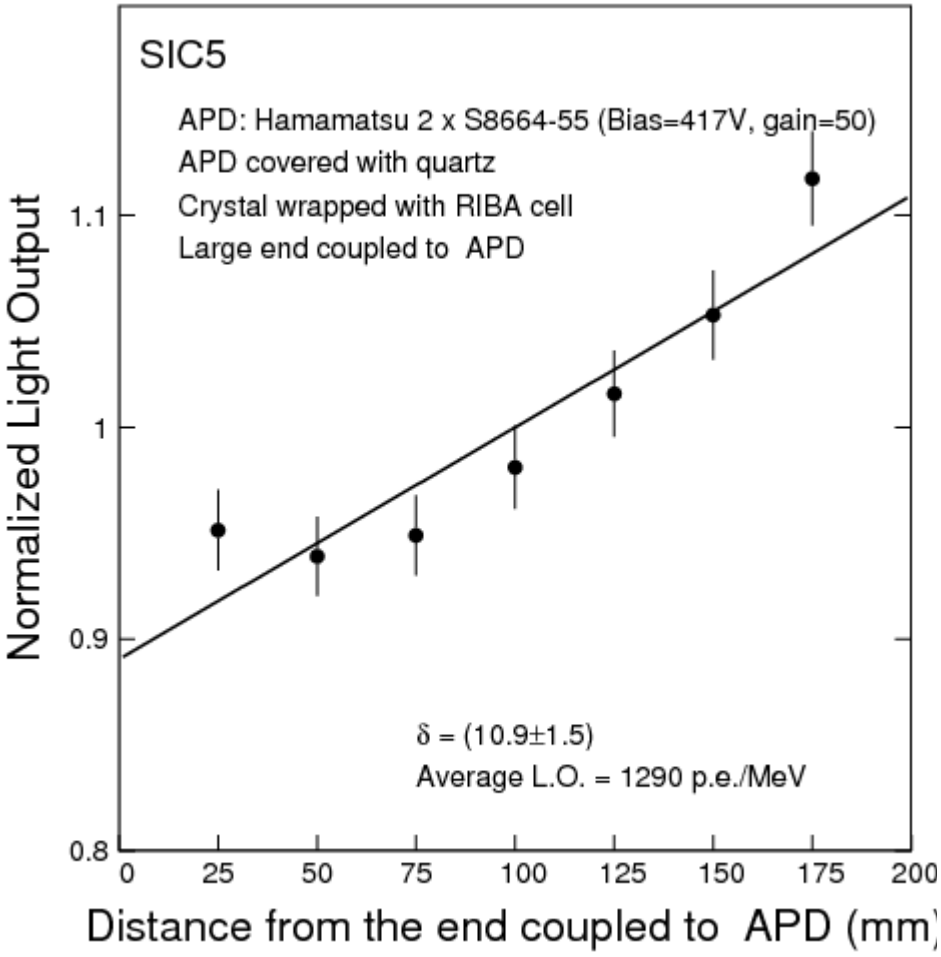
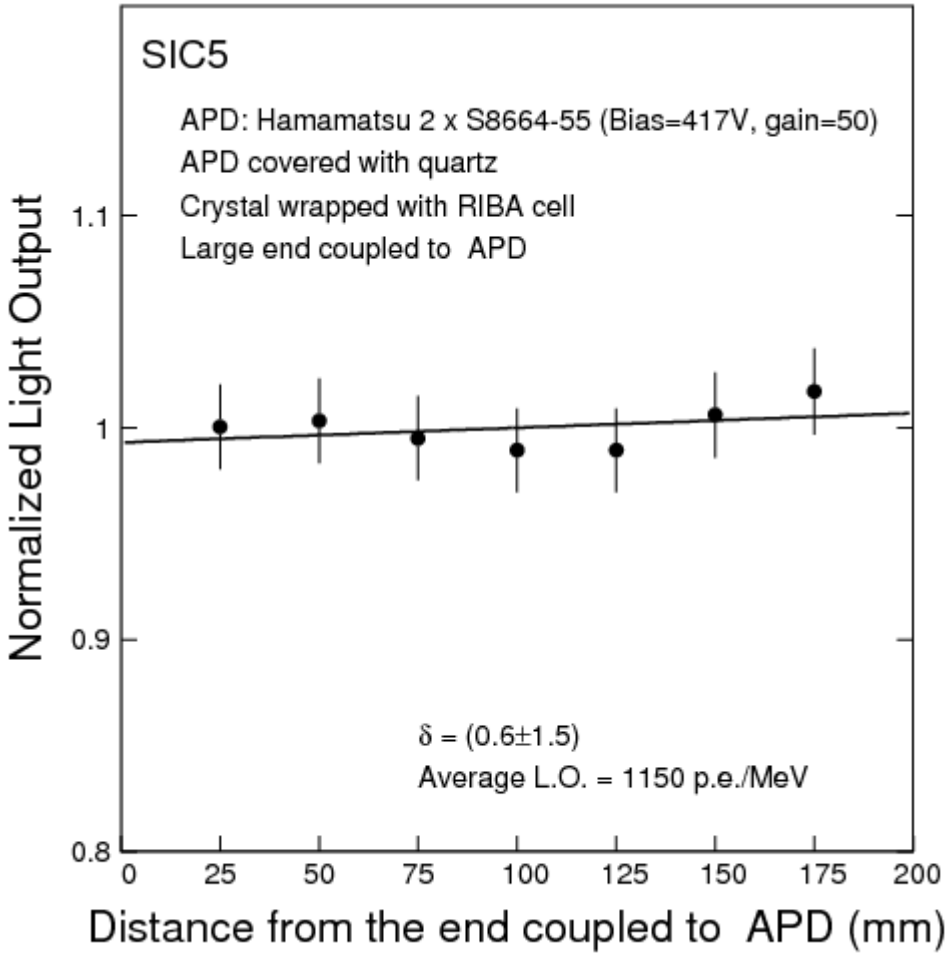


After roughening.



L.R.U. before & after Roughness

Before roughening



After roughening