Proton Fluence for LYSO Samples Irradiated at ITA: TSW-1830 in 2021

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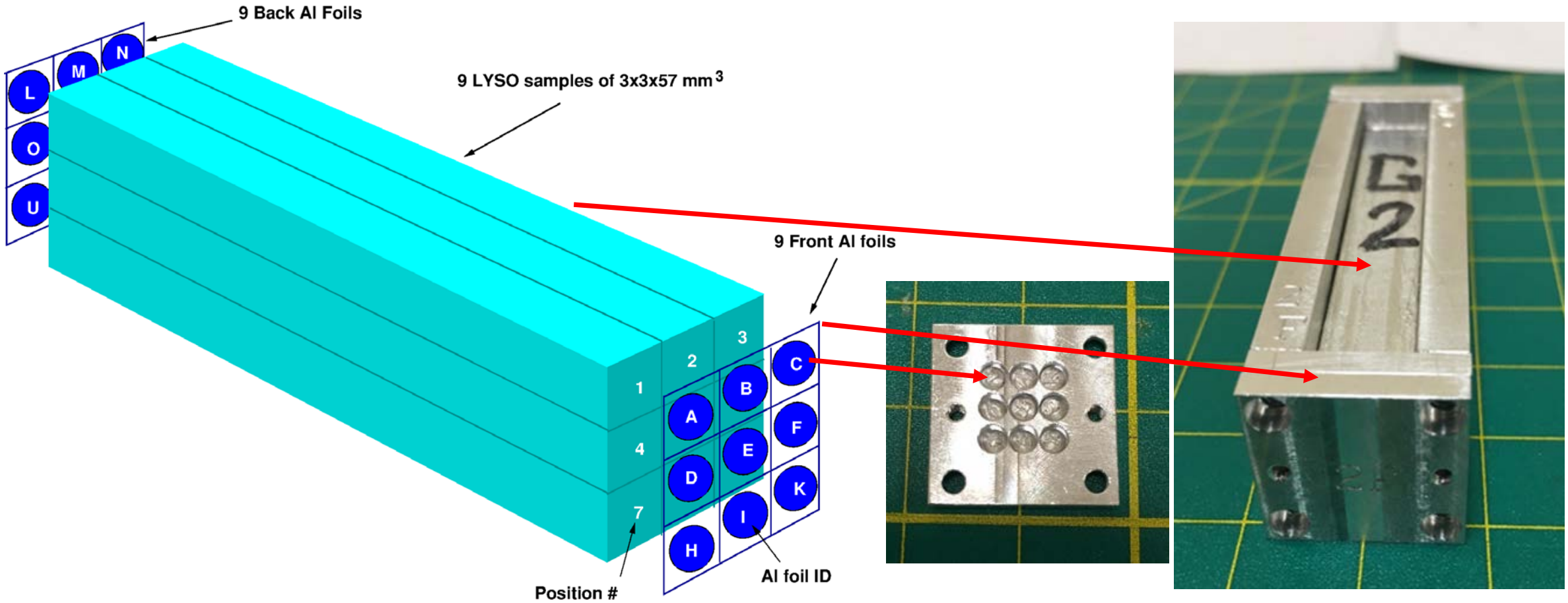
Introduction

- The ITA at the end of the MTA beamline provides 400 MeV protons with a flux of 4.7E+12 p/min and a FWHM spot size adjustable between 10 and 26 mm.
- 27 LYSO bars in three groups of 9 each were irradiated to 2.5E+13 p/cm^2 at ITA in June with 26 mm beam spot, or about 44 min/group, as reported by Ren-Yuan on July 7, 2021, in the CMS BTL general meeting.
- Radioactivity of Na-22 and Be-7 isotopes was measured for Al foils at front and back of each LYSO bars at FNAL Radionuclide Analysis Facility (RAF) in July and August.
- Based on FNAL RAF reports, the proton fluence at front and back of each LYSO bar was calculated, results from the two isotopes are combined by error weighted average.

A Group of Nine LYSO Bars

- Nine (3x3) LYSO bars with 9 each of Al foils mounted on the clamps at the front and back ends
- Total 18 Al foils in each group were measured separately after irradiation at FNAL RAF.



Be-7 and Na-22 Measurement at FNAL ITA

- Each Al foil was counted using an Ortec GEM-70185-S HPGe detector and weighed using a Sartorius Cubis Model MSE524P-100-DU balance.
- Na-22 and Be-7 peaks were fitted and corrected to activity (pCi/g) right after irradiation.

Fermilab
Environment, Safety and Health Section

Radionuclide Analysis Facility
Gamma Analysis Report
Issued by Meka E. Francis

Report Date: July 23, 2021
Work Request #: 21-274
Submitted by: Joel Fulgham on 6/30/21
Workbook: HPGe#2-14, page(s) 50

ITA Cal Tech Dosimeter Chips - 1F

The ESH Section/RPO/RCT Team submitted 9 aluminum dosimeter chip samples on Work Request# 21-274 for activation analysis. Each sample was counted on the date and time listed below at Fermilab Site 39 Annex using an Ortec GEM-70185-S HPGe detector (crystal diameter 71.8 mm) in a model LS-1116 Nuclear Lead Company, Inc. ultra-low background lead shield. Peaks in the sample spectra were fitted using Ortec GammaVision© for Windows Model A66-B32 Version 8.01. Each chip was weighed using a Sartorius Cubis Model MSE524P-100-DU balance. The following table lists the radionuclides detected in the samples along with the corresponding specific activities, which have been corrected to the time of sampling. The portion of the quoted error due to solid angle, mass, efficiency and self-attenuation was 5.9%. A list of the regions of interest (ROIs) used to calculate the results is attached in Appendix A.

SampleID#	Sample Date	Sample Time	Chip ID	Count Information	Chip Mass	Count Date/Time	Radionuclide	Activity (pCi/g)
210615JF12	6/15/2021	14:45	1F-A	7,200sec @ 2cm	0.0130 ± 0.0002 g	7/16/2021 7:50	Be-7 Na-22	5,500 ± 1,300 1,460 ± 210
210615JF13	6/15/2021	14:45	1F-B	7,200sec @ 2cm	0.0121 ± 0.0002 g	7/16/2021 14:37	Be-7 Na-22	5,300 ± 1,500 2,040 ± 180
210615JF14	6/15/2021	14:45	1F-C	7,200sec @ 2cm	0.0130 ± 0.0002 g	7/20/2021 7:54	Be-7 Na-22	4,800 ± 1,300 1,460 ± 180
210615JF15	6/15/2021	14:45	1F-D	7,200sec @ 2cm	0.0119 ± 0.0002 g	7/20/2021 10:02	Be-7 Na-22	7,400 ± 1,600 2,110 ± 220
210615JF16	6/15/2021	14:45	1F-E	7,200sec @ 2cm	0.0136 ± 0.0002 g	7/16/2021 9:58	Be-7 Na-2	6,000 ± 1,200 1,600 ± 160
210615JF17	6/15/2021	14:45	1F-F	7,200sec @ 2cm	0.0131 ± 0.0002 g	7/15/2021 16:34	Be-7 Na-2	,700 ± 1,100 1,400 ± 160
210615JF18	6/15/2021	14:45	1F-H	7,200sec @ 2cm	0.0120 ± 0.0002 g	7/20/2021 12:05	Be-7 Na-22	6,800 ± 1,400 1,800 ± 200
210615JF19	6/15/2021	14:45	1F-I	7,200sec @ 2cm	0.0122 ± 0.0002 g	7/20/2021 15:26	Be-7 Na-22	7,400 ± 1,400 1,440 ± 170

Isotope Atom Number from Activation Data

For a radioactive isotope with a decay time τ,

$$N = N_i e^{-t/\tau}$$

$$\frac{dN}{dt} = -\frac{N_i}{\tau} e^{-t/\tau}$$

Set t=0 at the measurement time,

$$N_i = \frac{dN}{dt} \times \tau = \frac{dN}{dt} \times \frac{t_{1/2}}{ln2}$$

Where, $t_{1/2}$ is half-life time in second.

Initial isotope atom number may be calculated by using activation data:

1 Curie = 3.7×10^{10} decay/second

or

1 pCi = 3.7×10^{-2} decay/second

$t_{1/2}$ (Na-22) = 8.206×10^{7} sec

$t_{1/2}$ (Be-7) = 4.598×10^{6} sec

Proton Fluence from Initial Isotope Atom Number

[1] EPJ Web of Conferences **146**, 11039 (2017) , DOI: 10.1051/epjconf/201714611039

When irradiation time << isotope decay time,

$$N_i = F \times N_a \times \sigma$$

N_i : number of isotope atoms,
N_a : number of Al atoms,
F : proton fluence in cm^{-2},
σ : activation cross-section in cm^2.

So,

$$F = \frac{N_i}{N_a \times \sigma}$$

Al foil data
Dimensions: Φ2.5×1 mm^3
Al density: 2.7 g/cm^3
Al foil weight: 0.01325 g
Al atom mass: 26.982 u
Cross-sections from [1]:

$^{27}Al\ (p,x)^{22}Na$: (15.42±0.56) mb
$^{27}Al\ (p,x)^{7}Be$: (2.96±0.11) mb

Fluences are calculated using Be-7 and Na-22 counting data for each foil, and are combined to a relative error weighted average

Summary of the Group-1 Front

Average fluence is $(2.16 \pm 0.07) \times 10^{13}$ p/cm^2

ID	Proton Fluence Be-7 (cm^{-2})	Fluence ± err Be-7 (cm^{-2})	Proton Fluence Na-22 (cm^{-2})	Fluence ± err Na-22 (cm^{-2})	EW Fluence (cm^{-2})	EW Fluence ± err (cm^{-2})
1F-A	2.04E+13	4.8E+12	1.86E+13	2.7E+12	1.90E+13	2.3E+12
1F-B	1.97E+13	5.6E+12	2.60E+13	2.3E+12	2.45E+13	2.2E+12
1F-C	1.78E+13	4.8E+12	1.86E+13	2.3E+12	1.84E+13	2.1E+12
1F-D	2.75E+13	5.9E+12	2.69E+13	2.8E+12	2.70E+13	2.6E+12
1F-E	2.23E+13	4.5E+12	2.04E+13	2.0E+12	2.08E+13	1.9E+12
1F-F	3.23E+13	4.1E+12	1.78E+13	2.0E+12	2.13E+13	1.8E+12
1F-H	2.53E+13	5.2E+12	2.29E+13	2.5E+12	2.35E+13	2.3E+12
1F-I	2.75E+13	5.2E+12	1.83E+13	2.2E+12	2.05E+13	2.1E+12
1F-K	2.40E+13	3.5E+12	1.74E+13	2.4E+12	1.90E+13	2.0E+12
Avg =	2.41E+13	1.6E+12	2.08E+13	7.9E+11	2.16E+13	7.2E+11
Std =	4.6E+12		3.6E+12		2.9E+12	

Summary of the Group-1 Back

Average fluence is $(1.59 \pm 0.07) \times 10^{13}$ p/cm^2

ID	Proton Fluence Be-7 (cm^{-2})	Fluence ± err Be-7 (cm^{-2})	Proton Fluence Na-22 (cm^{-2})	Fluence ± err Na-22 (cm^{-2})	EW Fluence (cm^{-2})	EW Fluence ± err (cm^{-2})
1B-L	1.63E+13	4.1E+12	1.77E+13	1.9E+12	1.73E+13	1.8E+12
1B-M	1.93E+13	4.5E+12	1.44E+13	2.5E+12	1.57E+13	2.2E+12
1B-N	1.32E+13	3.3E+12	1.72E+13	1.8E+12	1.61E+13	1.6E+12
1B-O	2.42E+13	4.1E+12	1.44E+13	2.7E+12	1.70E+13	2.2E+12
1B-R	2.64E+13	5.2E+12	2.01E+13	2.4E+12	2.18E+13	2.3E+12
1B-S	1.82E+13	4.8E+12	1.30E+13	2.3E+12	1.44E+13	2.1E+12
1B-U	1.26E+13	5.6E+12	1.32E+13	2.4E+12	1.31E+13	2.3E+12
1B-X	1.60E+13	4.5E+12	1.36E+13	2.3E+12	1.43E+13	2.1E+12
1B-Y	1.75E+13	4.5E+12	1.20E+13	2.2E+12	1.35E+13	2.0E+12
Avg =	1.82E+13	1.5E+12	1.51E+13	7.6E+11	1.59E+13	6.9E+11
Std =	4.6E+12		2.7E+12		2.7E+12	

Summary of the Group-2 Front

Average fluence is $(1.46 \pm 0.07) \times 10^{13}$ p/cm^2

ID	Proton Fluence Be-7 (cm^{-2})	Fluence ± err Be-7 (cm^{-2})	Proton Fluence Na-22 (cm^{-2})	Fluence ± err Na-22 (cm^{-2})	EW Fluence (cm^{-2})	EW Fluence ± err (cm^{-2})
2F-A	1.97E+13	4.5E+12	1.78E+13	2.3E+12	1.84E+13	2.1E+12
2F-B	1.67E+13	4.5E+12	1.07E+13	1.9E+12	1.25E+13	1.9E+12
2F-C	1.97E+13	3.4E+12	9.29E+12	2.3E+12	1.24E+13	1.9E+12
2F-D	2.30E+13	5.6E+12	1.57E+13	1.9E+12	1.78E+13	2.1E+12
2F-E	1.93E+13	4.5E+12	1.32E+13	2.0E+12	1.50E+13	1.9E+12
2F-F	1.30E+13	4.8E+12	1.50E+13	2.0E+12	1.44E+13	2.0E+12
2F-H	2.38E+13	4.5E+12	1.55E+13	2.5E+12	1.80E+13	2.2E+12
2F-I	1.26E+13	4.8E+12	1.02E+13	2.5E+12	1.09E+13	2.3E+12
2F-K	1.49E+13	4.5E+12	1.13E+13	1.8E+12	1.24E+13	1.8E+12
Avg =	1.81E+13	1.5E+12	1.32E+13	7.2E+11	1.46E+13	6.8E+11
Std =	4.1E+12		3.0E+12		2.8E+12	

Summary of the Group-2 Back

Average fluence is $(0.95 \pm 0.07) \times 10^{13}$ p/cm^2

ID	Proton Fluence Be-7 (cm^{-2})	Fluence ± err Be-7 (cm^{-2})	Proton Fluence Na-22 (cm^{-2})	Fluence ± err Na-22 (cm^{-2})	EW Fluence (cm^{-2})	EW Fluence ± err (cm^{-2})
2B-L	1.86E+13	3.7E+12	1.03E+13	2.5E+12	1.28E+13	2.1E+12
2B-M	1.26E+13	5.9E+12	7.00E+12	2.4E+12	8.67E+12	2.5E+12
2B-N	8.17E+12	4.5E+12	5.35E+12	2.4E+12	6.19E+12	2.2E+12
2B-O	8.17E+12	5.6E+12	1.27E+13	2.4E+12	1.14E+13	2.4E+12
2B-R	7.80E+12	4.5E+12	7.89E+12	2.2E+12	7.86E+12	2.0E+12
2B-S	1.34E+13	4.8E+12	8.53E+12	2.2E+12	9.97E+12	2.1E+12
2B-U	1.49E+13	4.8E+12	8.65E+12	2.2E+12	1.05E+13	2.1E+12
2B-X	1.23E+13	4.1E+12	1.09E+13	1.8E+12	1.13E+13	1.7E+12
2B-Y	1.00E+13	4.8E+12	5.35E+12	2.2E+12	6.74E+12	2.1E+12
Avg =	1.18E+13	1.6E+12	8.53E+12	7.5E+11	9.49E+12	7.1E+11
Std =	3.6E+12		2.5E+12		2.3E+12	

Summary of the Group-3 Front

Average fluence is $(1.91 \pm 0.08) \times 10^{13}$ p/cm^2

ID	Proton Fluence Be-7 (cm^{-2})	Fluence ± err Be-7 (cm^{-2})	Proton Fluence Na-22 (cm^{-2})	Fluence ± err Na-22 (cm^{-2})	EW Fluence (cm^{-2})	EW Fluence ± err (cm^{-2})
3F-A	3.31E+13	5.2E+12	2.23E+13	2.3E+12	2.52E+13	2.2E+12
3F-B	1.82E+13	5.2E+12	1.40E+13	2.5E+12	1.51E+13	2.3E+12
3F-C	2.04E+13	5.6E+12	1.41E+13	1.8E+12	1.59E+13	2.0E+12
3F-D	3.01E+13	5.9E+12	2.72E+13	2.5E+12	2.80E+13	2.5E+12
3F-E	2.97E+13	4.5E+12	1.78E+13	2.3E+12	2.11E+13	2.1E+12
3F-F	1.86E+13	5.2E+12	1.22E+13	2.5E+12	1.40E+13	2.3E+12
3F-H	2.68E+13	5.9E+12	2.10E+13	2.7E+12	2.26E+13	2.5E+12
3F-I	2.08E+13	5.9E+12	1.49E+13	2.7E+12	1.65E+13	2.5E+12
3F-K	1.71E+13	4.8E+12	1.20E+13	2.0E+12	1.34E+13	2.0E+12
Avg =	2.39E+13	1.8E+12	1.73E+13	8.0E+11	1.91E+13	7.6E+11
Std =	6.1E+12		5.2E+12		5.3E+12	

Summary of the Group-3 Back

Average fluence is $(1.30 \pm 0.08) \times 10^{13}$ p/cm^2

ID	Proton Fluence Be-7 (cm^{-2})	Fluence ± err Be-7 (cm^{-2})	Proton Fluence Na-22 (cm^{-2})	Fluence ± err Na-22 (cm^{-2})	EW Fluence (cm^{-2})	EW Fluence ± err (cm^{-2})
3B-L	1.34E+13	4.5E+12	1.23E+13	2.2E+12	1.27E+13	2.1E+12
3B-M	1.89E+13	4.8E+12	1.37E+13	1.8E+12	1.55E+13	2.0E+12
3B-N	1.52E+13	4.8E+12	9.04E+12	2.3E+12	1.11E+13	2.2E+12
3B-O	1.23E+13	5.2E+12	7.25E+12	3.3E+12	8.93E+12	2.8E+12
3B-R	2.56E+13	4.8E+12	1.55E+13	2.3E+12	1.89E+13	2.2E+12
3B-S	1.26E+13	5.2E+12	1.16E+13	2.3E+12	1.19E+13	2.3E+12
3B-U	1.60E+13	5.6E+12	1.08E+13	2.2E+12	1.25E+13	2.4E+12
3B-X	2.08E+13	4.8E+12	1.09E+13	2.3E+12	1.42E+13	2.2E+12
3B-Y	1.39E+13	3.5E+12	9.55E+12	2.0E+12	1.10E+13	1.8E+12
Avg =	1.65E+13	1.6E+12	1.12E+13	7.7E+11	1.30E+13	7.5E+11
Std =	4.5E+12		2.5E+12		2.9E+12	

Error Weighted Average Fluence

Fluence for G1, G2 and G3 is 1.88, 1.192 and 1.61$\times 10^{13}$ respectively

Group	Front EW Avg Fluence (cm^{-2})	± Error (cm^{-2})	Back EW Avg Fluence (cm^{-2})	± Error (cm^{-2})	Average Fluence (cm^{-2})	± Error (cm^{-2})
1	2.16E+13	7.2E+11	1.59E+13	6.9E+11	1.88E+13	5.0E+11
2	1.46E+13	6.8E+11	9.49E+12	7.1E+11	1.19E+13	4.9E+11
3	1.91E+13	7.6E+11	1.30E+13	7.5E+11	1.61E+13	5.3E+11

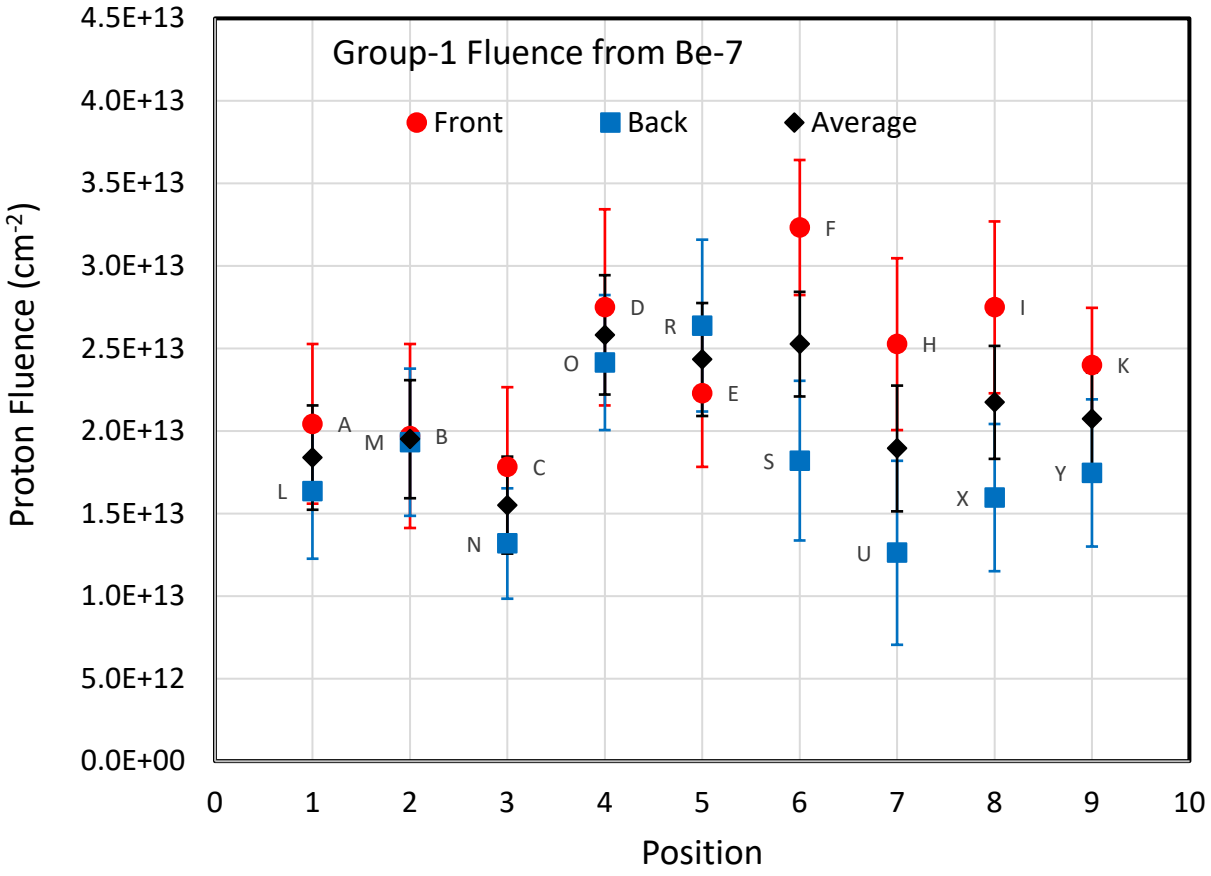
Ratio between the Be-7 and Na-22 Fluence

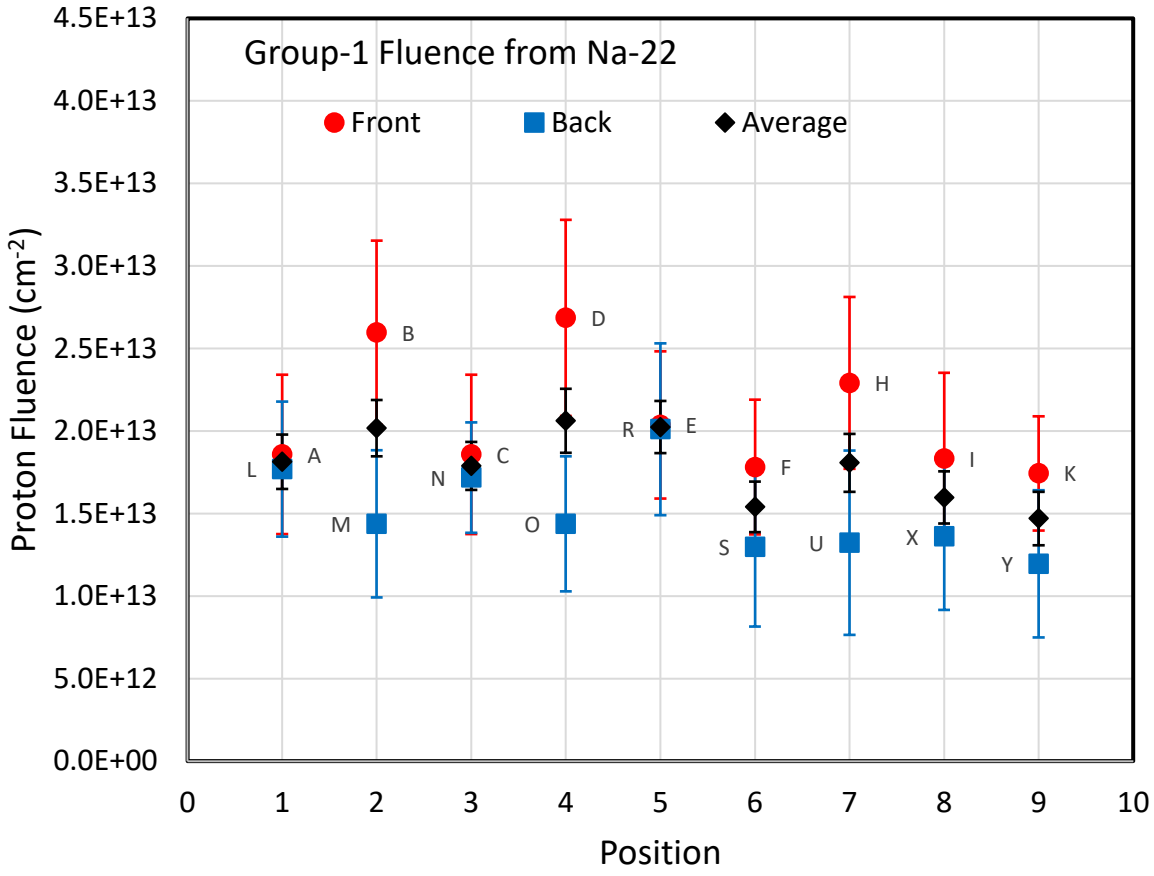
Consistent ratio between Be-7 and Na-22 fluence for both front and back Al foils

Group	Front Avg Fluence$_{Be-7}$ (cm^{-2})	Error (cm^{-2})	Front Avg Fluence$_{Na-22}$ (cm^{-2})	Error (cm^{-2})	Back Avg Fluence$_{Be-7}$ (cm^{-2})	Error (cm^{-2})	Back Avg Fluence$_{Na-22}$ (cm^{-2})	Error (cm^{-2})	Front Be-7/Na-22 Ratio	Error	Back Be-7/Na-22 Ratio	Error
1	2.41E+13	1.6E+12	2.08E+13	7.9E+11	1.82E+13	1.5E+12	1.51E+13	7.6E+11	1.16	0.09	1.21	0.12
2	1.81E+13	1.5E+12	1.32E+13	7.2E+11	1.18E+13	1.6E+12	8.53E+12	7.5E+11	1.37	0.14	1.38	0.22
3	2.39E+13	1.8E+12	1.73E+13	8.0E+11	1.65E+13	1.6E+12	1.12E+13	7.7E+11	1.38	0.12	1.47	0.18
								Avg =	1.30	0.07	1.35	0.10

Summary of Al Foil Data: Group-1

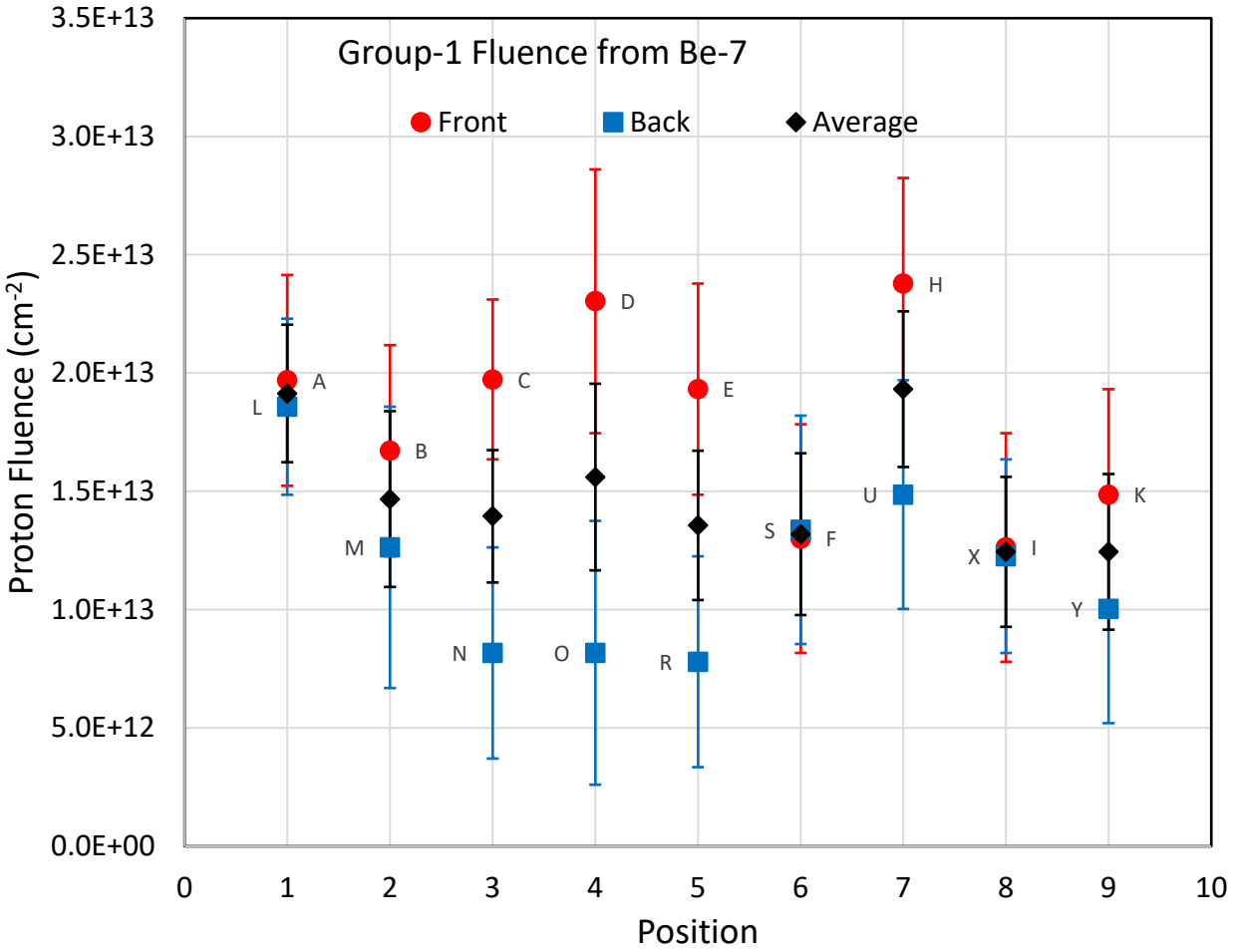
No clear beam shape observed in front and back Al foil data

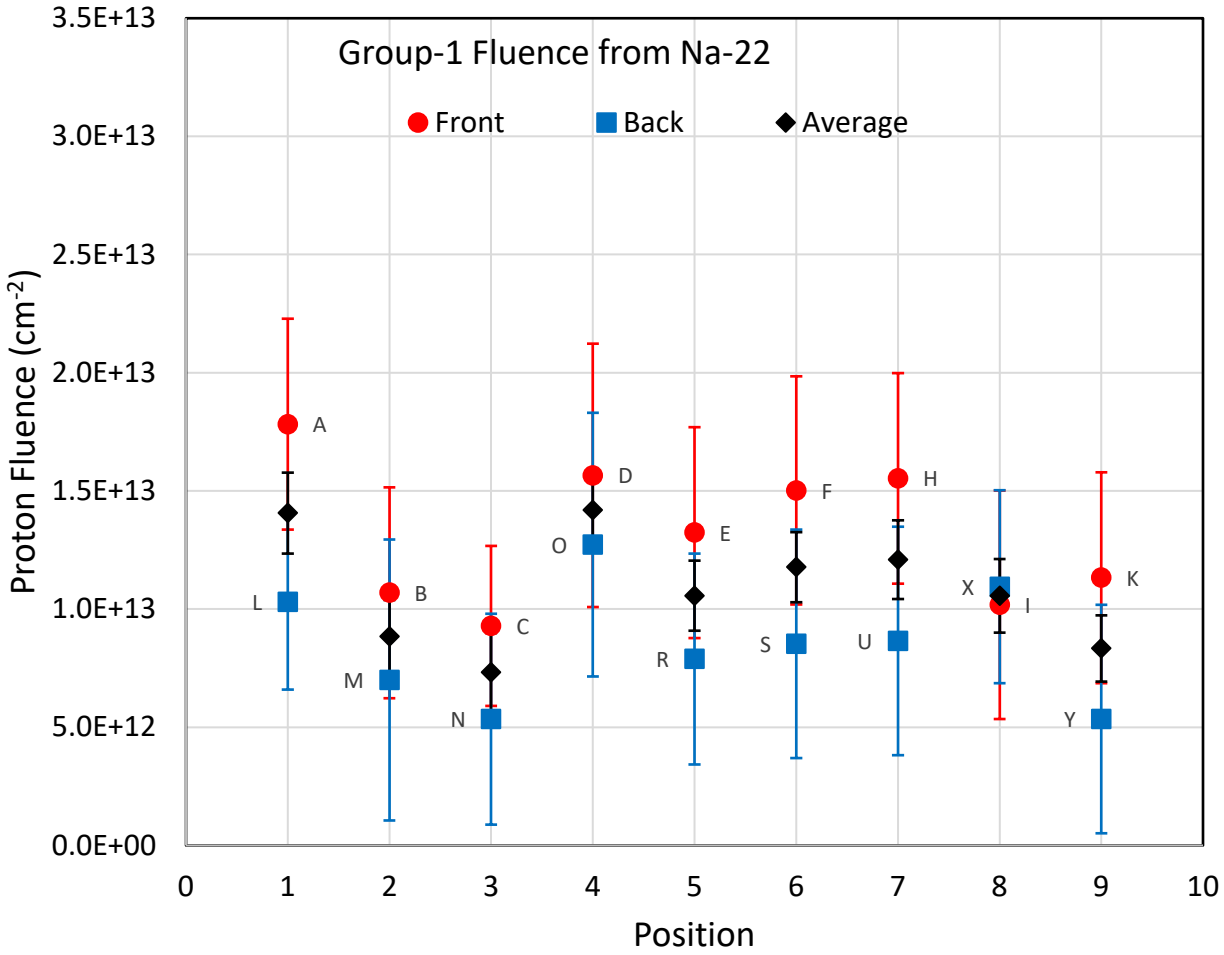




Summary of Al Foil Data: Group-2

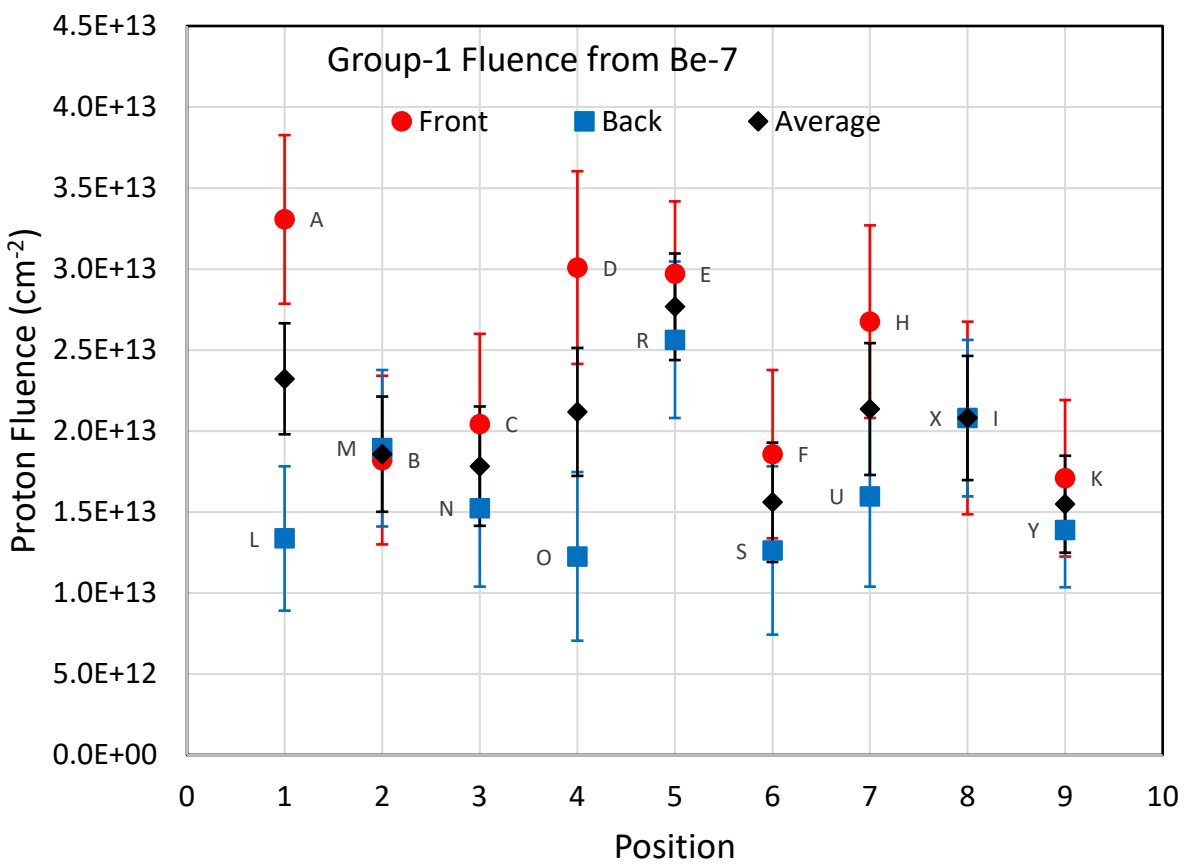
No clear beam shape observed in front and back Al foil data

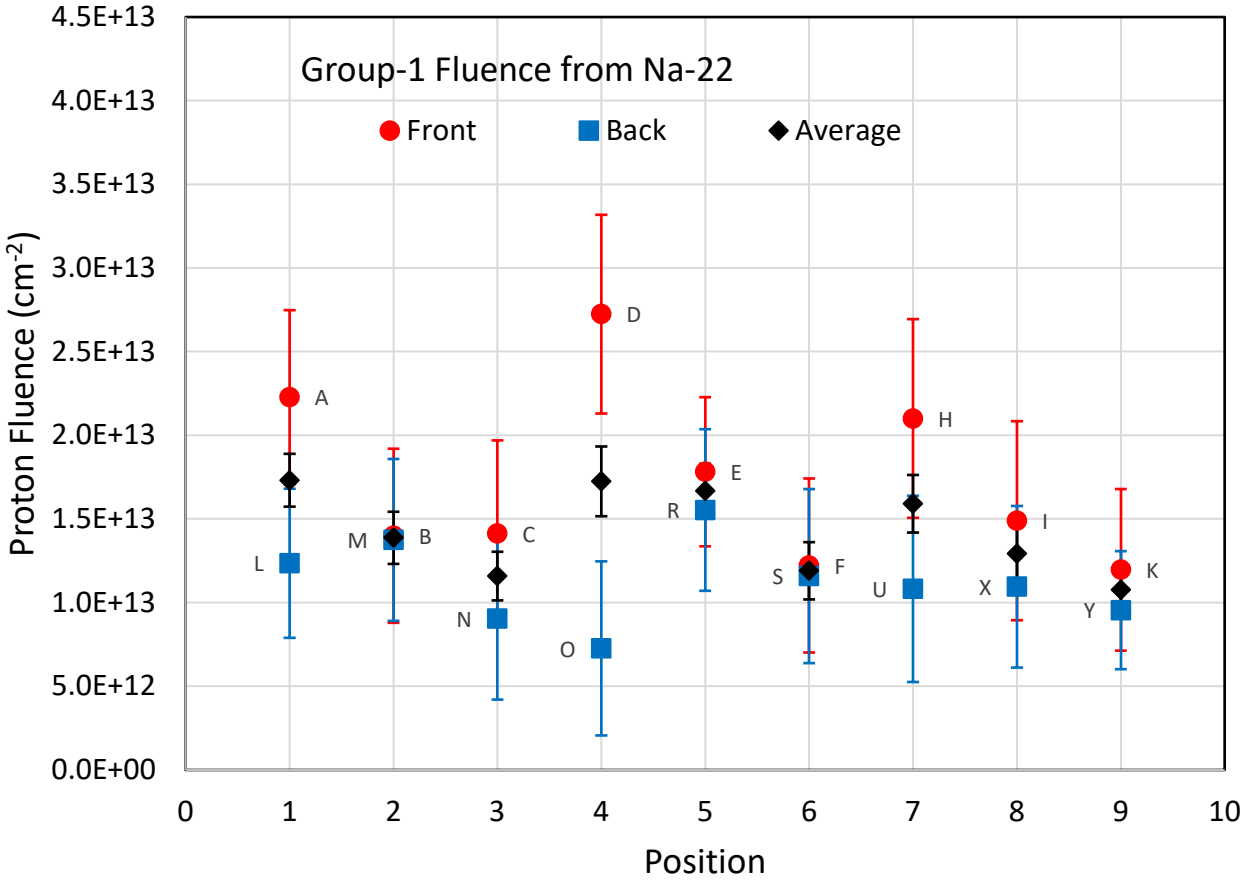




Summary of Al Foil Data: Group-3

No clear beam shape observed in front and back Al foil data





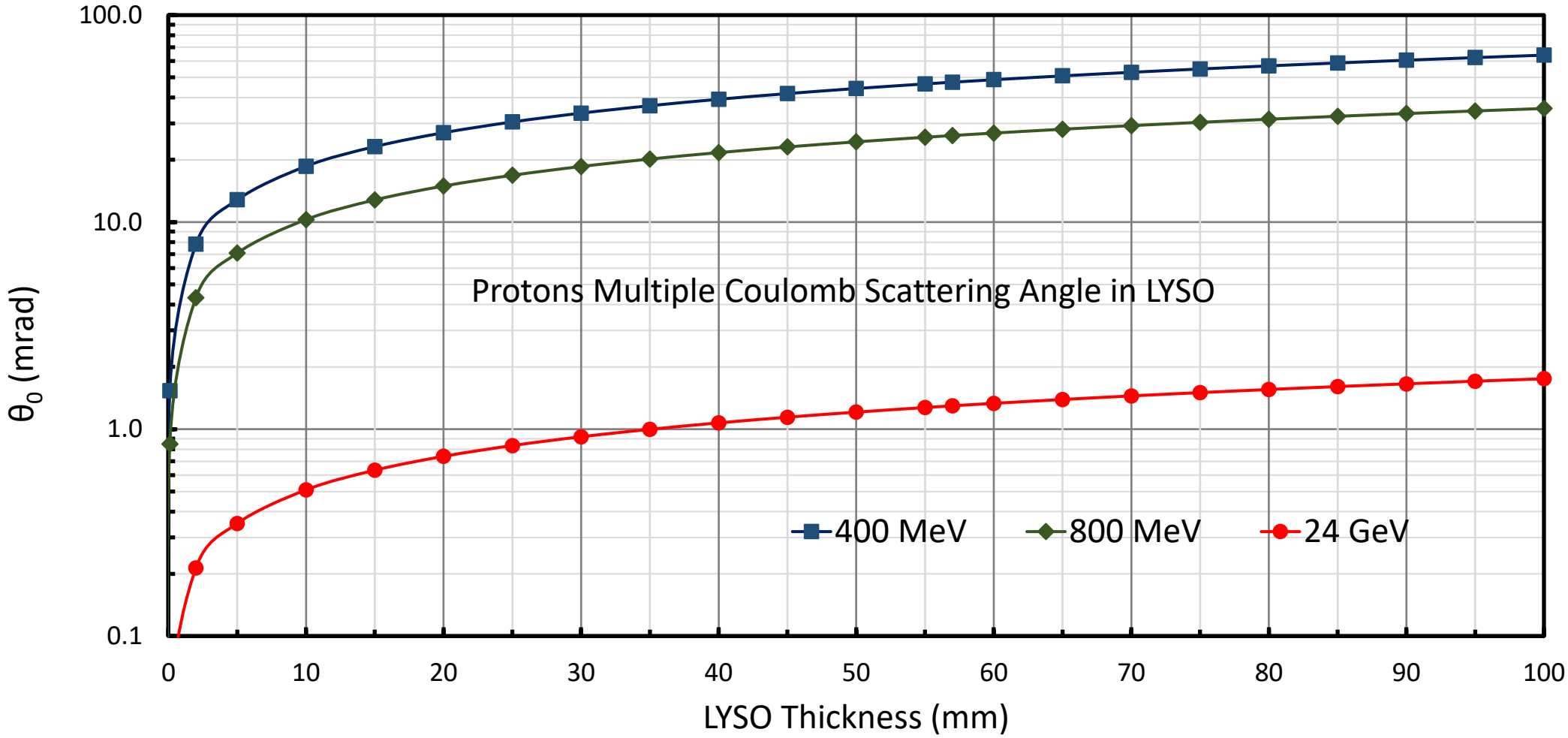
Ratio between the Back and Front Fluence

Fluence at back decreases by 30%/33% from Be-7/Na-22 foil data
Consistent with beam broadening due to multiple Coulomb scattering

Group	Front Avg Fluence Be-7 (cm^{-2})	± Error (cm^{-2})	Front Avg Fluence Na-22 (cm^{-2})	± Error (cm^{-2})	Back Avg Fluence Be-7 (cm^{-2})	± Error (cm^{-2})	Back Avg Fluence Na-22 (cm^{-2})	± Error (cm^{-2})	B/F Ratio Be-7	± Error	B/F Ratio Na-22	± Error
1	2.41E+13	1.6E+12	2.08E+13	7.9E+11	1.82E+13	1.5E+12	1.51E+13	7.6E+11	0.76	0.08	0.73	0.05
2	1.81E+13	1.5E+12	1.32E+13	7.2E+11	1.18E+13	1.6E+12	8.53E+12	7.5E+11	0.65	0.10	0.65	0.07
3	2.39E+13	1.8E+12	1.73E+13	8.0E+11	1.65E+13	1.6E+12	1.12E+13	7.7E+11	0.69	0.08	0.65	0.05
								Avg =	**0.70**	**0.05**	**0.67**	**0.03**

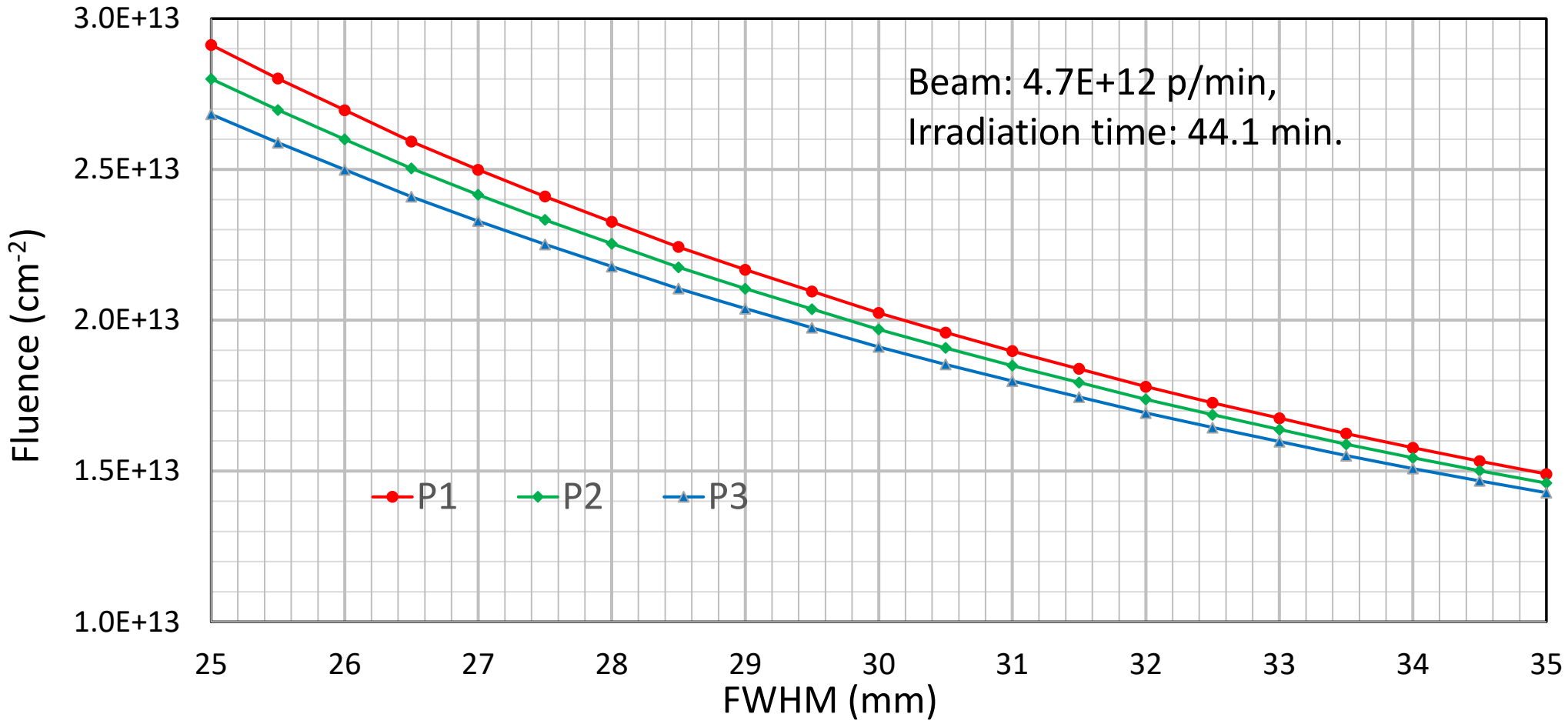
Proton Multiple Coulomb Scattering in LYSO

Multiple scattering angle after 57 mm LYSO is 47.4 mrad, or 2.7 deg, for 400 MeV protons



Fluence Reduction after 57 mm LYSO

FWHM of beam is 26 + 2×57×tan(θ) = 31.4 mm after 57 mm LYSO, causing ~30% reduction



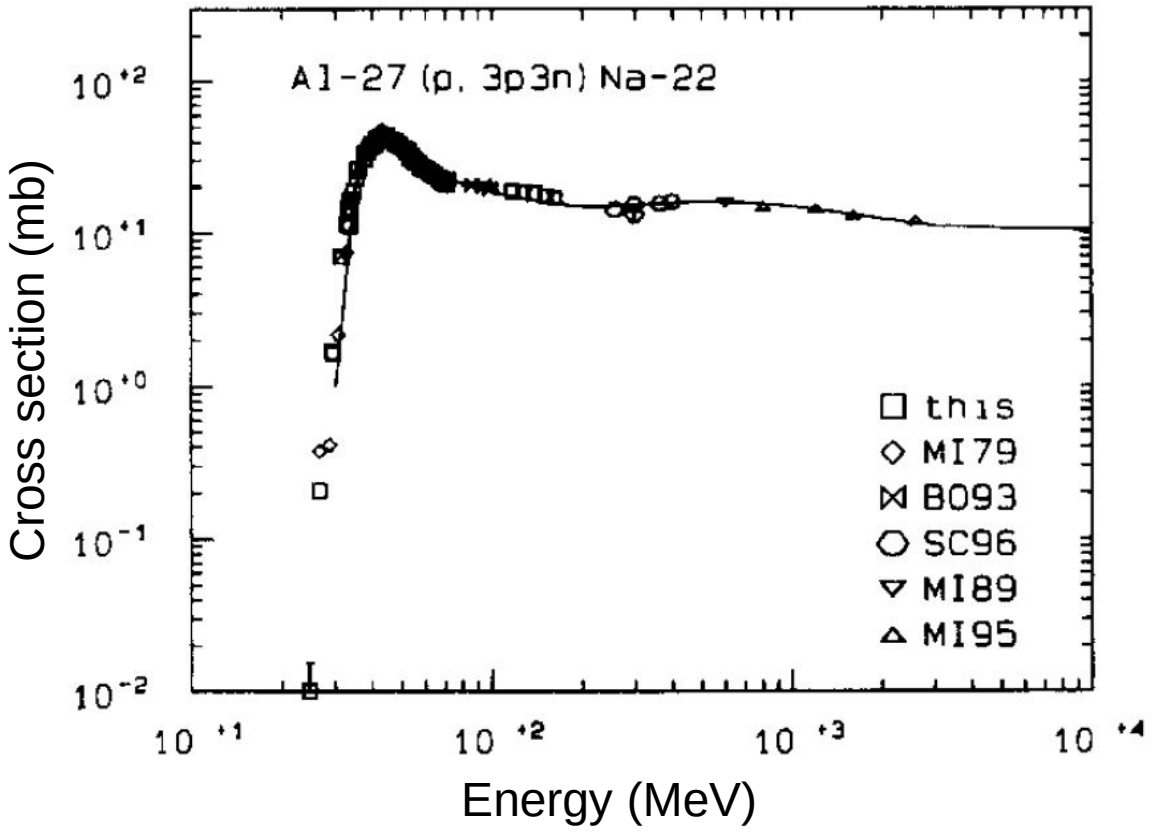
Proton dE/dx in LYSO

dE/dx of protons in LYSO crystals is calculated by using its density (7.4 g/cm3), Zeff (64.8) and the data of Sn(Z=50) and Pb (Z=82) shown in Fig. 27.3 in PDB Chapter 27
400 MeV protons loses 70 MeV via dE/dx after 57 mm LYSO: 330 MeV

Facility	E_k (MeV)	βγ	dE/dx in LYSO (Z_{eff}=64.8) (MeV $g^{-1}cm^2$)	dE/dx in LYSO (MeV/cm)	Dose Coeff* (rad/p/cm^2)	Dose @ 2.5E+13 (Mrad)	E in BTL (MeV)
FNAL	400	1.02	1.67	**12.3**	2.67E-08	0.67	3.7
LANL	800	1.56	1.33	**9.8**	2.12E-08	0.53	2.9
CERN	24000	26.56	1.49	**11.0**	2.38E-08	0.60	3.3

Cross-Sections at 330 and 400 MeV

Al(p,x)Na22 cross-sections: no significant change between 330 and 400 MeV
Al(p,x)Be7: 2.6±0.4 mb at 330 MeV and 3.1±0.4 mb at 400 MeV, or ~20% at the back



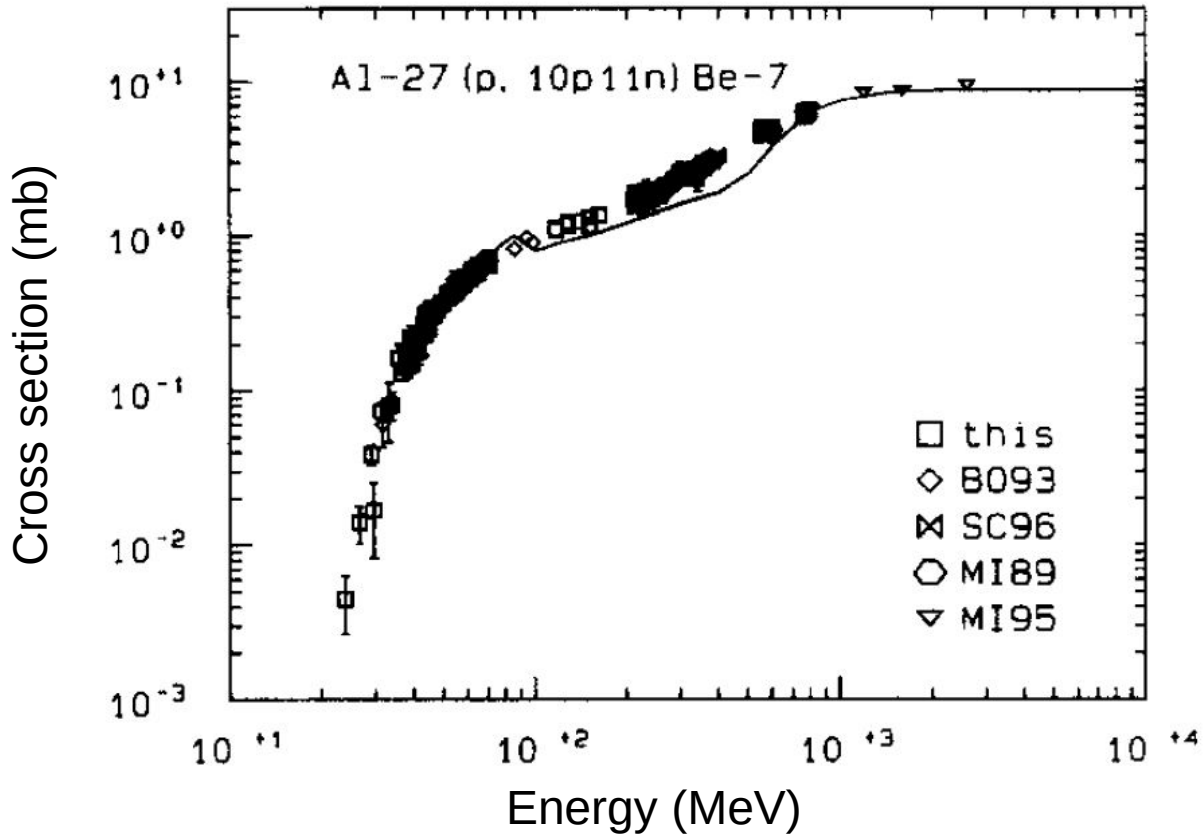


Fig. 3 in the paper “R. Michel et. al., Nuclear Instruments and Methods in Physics Research B 129 (1997) 153- 193”

Summary

The error weighted average fluence from eighteen foils at front and back is (1.88±0.05), (1.19±0.05) and (1.61±0.05) $\times 10^{13}$ p/cm^2 respectively for the Group 1, 2 and 3, smaller than the required 2.5 $\times 10^{13}$ p/cm^2.

The fluence at back is 30%/33% lower than front for both Be-7 and Na-22, which is consistent with beam broadening due to multiple Coulomb scattering. The fluence at front is used as the nominal fluence.

The fluence from the Be-7 data is 30% and 35% larger than that from Na-22 for both front and back foils, which appears due to different calibration.

dE/dx caused cross-section variation can not explain the difference between the Be-7 and Na-22 data.

Because of the large counting error due to small foil mass, it is difficult to extract detailed beam profile from nine foils.

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