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SUBJECT: MCNP6 calculations of secondary particle production in a thick Line C exit window for proton radiography (U)

Abstract

In a recent JOWOG 32P talk (2011 May 20) results were presented for MCNP6 calculations of the production of secondary particles in an exit window used for dynamic proton radiography experiments. In this note the quantitative numbers from those calculations are presented along with a description of the model.

I. Introduction with a bit of history

The Clinton P. Anderson Meson Physics Facility at Los Alamos (LAMPF) [the facility is now call LANSCE, Los Alamos Neutron Scattering CEnter] was built over four decades ago to, among other things, make beams of secondary particle (specifically beams of mesons, i.e. pions and muons). This was accomplished by running the high-intensity 800-MeV proton beam from the accelerator through 'pion' production targets. Beams at forward angles (at 35^{O} for EPICS [Energetic PIon Channel and Spectrometer], at 45^{O} for LEP [Low Energy Pion], at 20^{O} for P^3 [Pion Particle Physics] and at 60^{O} for SMC [Stopped Muon Channel]; not all that forward) were directed to secondary target area for experiments. The first two beam channels (EPICS and LEP) viewed a common 3-cm thick graphite target and the latter two channels (P^3 and SMC) were designed to view a 6-cm thick graphite target.

In proton radiography the image is generated by focusing particle trajectories from an object onto an image plane with a magnetic lens at forward angles (i.e. in the range from 0 degrees to ~1 degree). The detector at the image plane, while not necessarily, has generally been an ionizing radiation-to-light converter (i.e. a fast scintillator) and a camera system is arranged to take optical pictures of this scintillator.

Because the transport of the protons through the magnetic lens is in vacuum there is a window immediately upstream of the scintillator. In the case of dynamic experiments (i.e. experiments involving the detonation of high explosives) this typical window might be 1/8″ of glass followed by 1/8″ of aluminum. The bottom line is that this window (1.27 cm of material) could be a particle production target at 0 degrees, and in this note the results of MCNP6 calculations looking at the production on secondary particles are presented.

MCNP6 is a developmental version[1] of MCNP which, in addition to neutrons, photons, and electrons, can transport twenty-four (24) additional particles. Particle production on nuclear targets is currently accomplished using the CEM (Cascade Exciton Model).[2] While trying to do transport runs (for protons, muons, pions, deuterons, tritons, ^{3}He, and alphas) through the whole Line C proton radiography system (diffuser to image plane) it was noticed that the object to diffuser times for all particles, regardless of particle energy, was highly correlated. This indicated that the protons were producing secondary particles near the image plane, hence the study reported here.

II.The MCNP6 Model # 1

The MCNP6 model, for which results will be presented, was quite simple and a sample input is presented in Appendix I. Simply a line beam of mono-energetic protons along the z-axis (starting at -100 cm) was incident on a window as described above (1/8″ of glass followed by 1/8″ of aluminum). The window extended from -0.3175-cm to 0.0-cm (SiO_2 with density 2.65 grams per cc) and from 0.0-cm to +0.3175-cm (Al with density 2.70 grams per cc); this was followed by a drift from 0.3175 cm to 100 cm in void (i.e. vacuum); from 100 cm to 100.2 cm there was LSO (Lu_2SiO_5 with density 7.36 gram per cc).

Results for various particles were tallied in fmesh (track length) tallies that were from -7 cm to +7 cm in both dimensions transverse to the z-axis and from 100.0 cm to 100.2 cm along the z-axis. There were separate fmesh tallies for protons, π^+, π^- (charged pions), deuterons, tritons, helions (^{3}He) and alphas. There is the possibility of other particles or recoiling nuclei but in this study we present results for only these particles.

In addition to the results for the fmesh tallies, results are also presented for a different set of fmesh tallies where an energy dependent multiplier is used for the various particle tallies. In this case the multiplier for a given particle is the dE/dx in LSO at a given energy divided by the value of dE/dx in LSO for a 1-GeV proton. It is thought that this should account for differences in a given particles ionization energy in the LSO scintillator the tallies are overlaid on. The MCNP input for these multipliers can be found in the sample input deck in Appendix I.

III. Results for Model #1

The results of the MCNP6 fmesh tallies are given in Table I as a ration to the proton fmesh tally. These results are also plotted in Figure 1a. Table II gives (plotted in Figure 1b) the results when an energy dependent multiplier (that is different for each particle) is applied. The protons are also multiplied by an energy dependent multiplier.

Energy	π^+		π^-		d		t		^{3}He		α	
(MeV)		Error		Error		Error		Error		Error		Error
800	1.73E-03	1.85E-05	1.34E-03	1.63E-05	3.76E-03	2.73E-05	8.56E-04	1.30E-05	2.11E-04	6.46E-06	2.88E-04	7.56E-06
750	1.55E-03	1.75E-05	1.16E-03	1.52E-05	3.46E-03	2.62E-05	7.74E-04	1.24E-05	1.90E-04	6.13E-06	2.58E-04	8.35E-06
700	1.35E-03	1.63E-05	9.82E-04	1.40E-05	3.17E-03	2.51E-05	6.93E-04	1.17E-05	1.69E-04	5.79E-06	2.28E-04	6.73E-06
650	1.13E-03	1.50E-05	8.06E-04	1.26E-05	2.87E-03	2.38E-05	6.12E-04	1.10E-05	1.48E-04	5.40E-06	1.99E-04	6.3E-06
600	8.96E-04	1.33E-05	6.47E-04	1.13E-05	2.56E-03	2.30E-05	5.33E-04	1.00E-05	1.29E-04	5.10E-06	1.71E-04	5.8E-06
550	6.71E-04	1.15E-05	4.91E-04	9.88E-06	2.28E-03	2.10E-05	4.64E-04	9.59E-06	1.10E-04	4.68E-06	1.45E-04	5.4E-06
500	4.62E-04	9.58E-06	3.49E-04	8.33E-06	1.99E-03	1.99E-05	3.94E-04	8.85E-06	9.31E-05	4.30E-06	1.21E-04	4.91E-06

Table I – The values of the fmesh for the indicated particle as a ratio to the value for protons is given.

Energy	π^+		π^-		d		t		^{3}He		α	
(MeV)		Error		Error		Error		Error		Error		Error
800	2.54E-03	2.11E-05	2.03E-03	1.89E-05	4.55E-02	8.93E-05	1.57E-02	5.24E-05	1.28E-02	4.74E-05	3.15E-02	7.43E-05
750	2.27E-03	1.97E-05	1.74E-03	1.73E-05	4.11E-02	8.40E-05	1.39E-02	4.89E-05	1.14E-02	4.42E-05	2.78E-02	1.08E-04
700	1.97E-03	1.82E-05	1.45E-03	1.56E-05	3.67E-02	7.84E-05	1.22E-02	4.53E-05	9.95E-03	4.09E-05	2.42E-02	6.38E-05
650	1.71E-03	1.70E-05	1.21E-03	1.43E-05	3.33E-02	7.48E-05	1.09E-02	4.3E-05	8.82E-03	3.85E-05	2.14E-02	6.00E-05
600	1.38E-03	1.51E-05	9.70E-04	1.26E-05	2.93E-02	6.9E-05	9.34E-03	3.9E-05	7.55E-03	3.5E-05	1.82E-02	5.5E-05
550	1.04E-03	1.30E-05	7.35E-04	1.09E-05	2.54E-02	6.4E-05	7.96E-03	3.6E-05	6.35E-03	3.20E-05	1.52E-02	4.9E-05
500	7.30E-04	1.07E-05	5.21E-04	9.02E-06	2.18E-02	5.83E-05	6.61E-03	3.21E-05	5.26E-03	2.86E-05	1.25E-02	4.41E-05

Table II – The values of the fmesh for the indicated particle as a ratio to the value for protons is given. This is for the case where each tally has an energy dependent multiplier that is dE/dx over dE/dx of a 1-GeV proton. Note that these tally multipliers are different for each particle type.

One sees by comparing Figures 1 and 2 that there is other an order of magnitude increase in this signal for the case of the energy dependent multiplier. The ratios of the sums are given in Table III, and these figures are those that were presented at the recent JOWOG32P.

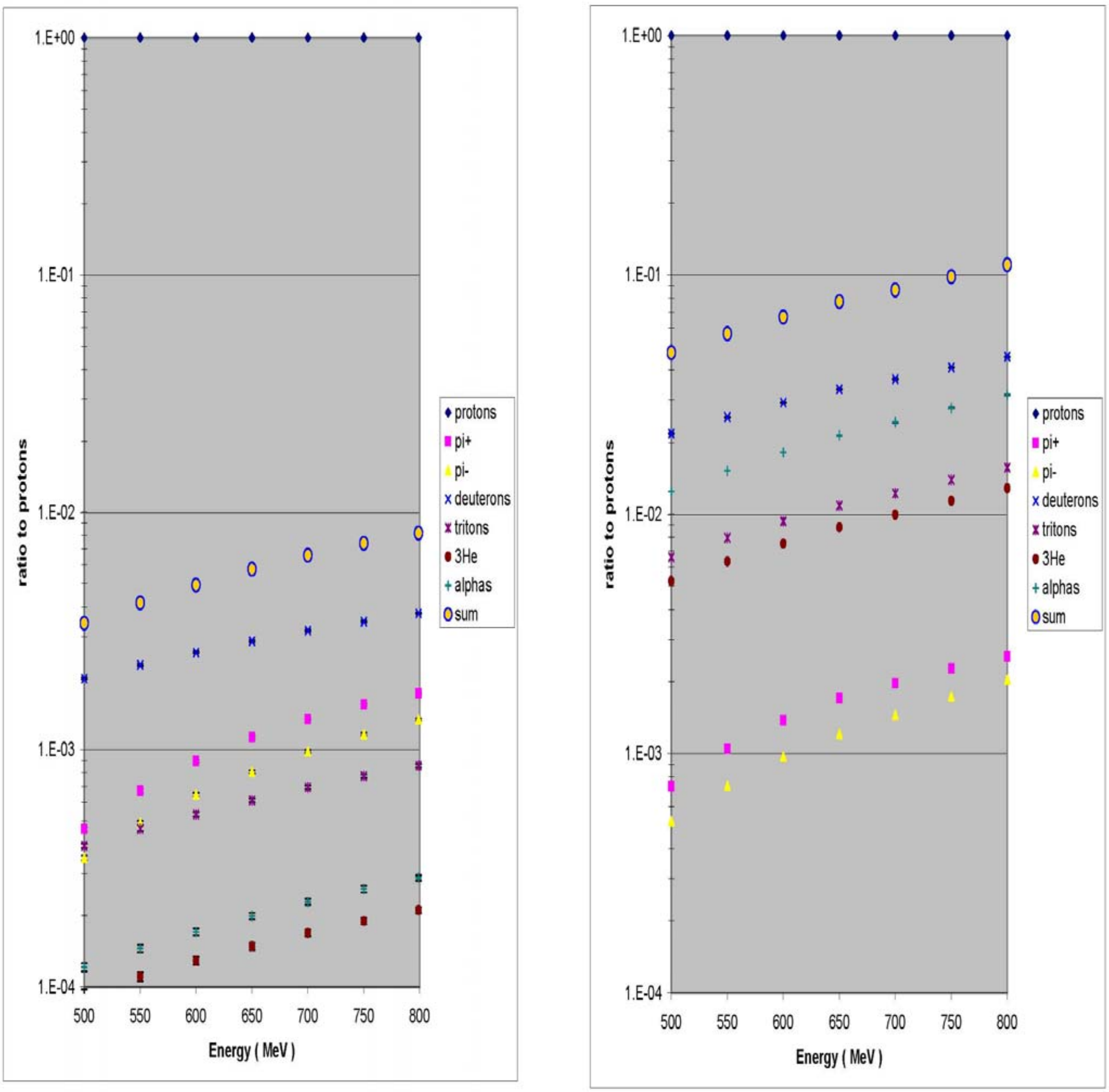

Figure 1a (left) – Ratio of the raw produced particle count (track length) to the proton count (track length) in an fmesh tally that overlays the LSO "detector". This "detector" is one pixel that is 14-cm × 14-cm × 0.2-mm thick in beam direction located at 100 cm from the center of the window (Mode # 1). The particle type is indicated in the legend and sum is the sum of all particles excluding the protons. **Figure 1b** (right) is the same as 1a but the signal (track length) is multiplied by an energy dependent term. This term is the particles dE/dx as a function of energy divided by dE/dx for 1-GeV (1000-MeV) protons. The particle type is indicated in the legend and sum is the sum of all particles excluding the protons.

Energy	Sum without multiplier		Sum with multiplier		Ratio of sum with to sum without	
(MeV)		Error		Error		Error
800	0.00818	0.00004	0.11013	0.00014	13.46	0.07
750	0.00740	0.00004	0.09817	0.00015	13.27	0.07
700	0.00659	0.00004	0.08649	0.00012	13.12	0.07
650	0.00576	0.00003	0.07725	0.00011	13.42	0.08
600	0.00494	0.00003	0.06666	0.00010	13.49	0.09
550	0.00416	0.00003	0.05676	0.00010	13.66	0.10
500	0.00341	0.00003	0.04736	0.00009	13.88	0.11

Table III – The sum of the values in Table I (without multiplier) are compared to the sum in Table II (with multiplier), and the ratio of the two sums is given.

IV. The MCNP6 Model # 2

In preparing this document it was realized that the MCNP6 model with the LSO at 100 cm from the window center did not represent the real situation with the LSO as the detector. The problem was re-run for a more realistic case. In this case the LSO material starts 1-cm downstream of the center of the glass-Al window interface and is otherwise the same as Model #1. A MCNP geometry plot for this second case is shown in Figure 2.

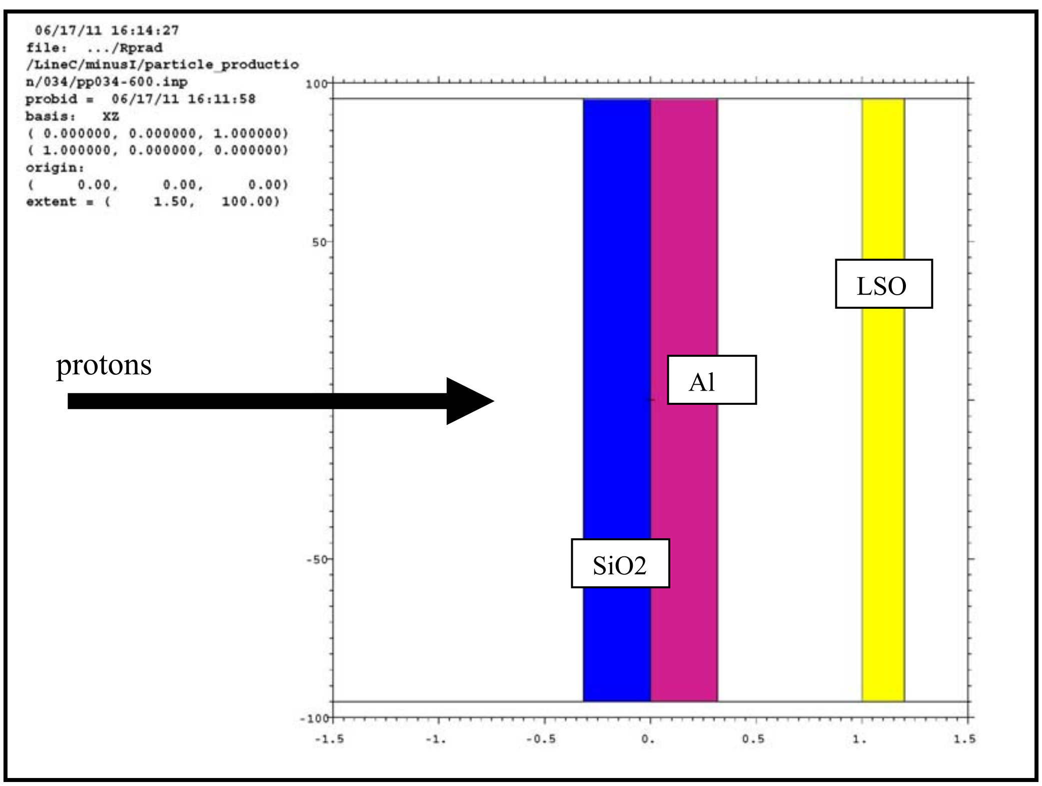

Figure 2 – MCNP geometry for the Model # 2 geometry (dimensions on the plot are in centimeters), note the aspect ratio of the plot is not 1-to-1. Protons are incident on the window (SiO_2 and Al) from the left (indicated by the arrow).

As in the case of Model # 1 results, various particles were tallied in fmesh (track length) tallies that were from -7 cm to +7 cm in both dimensions transverse to the z-axis and from 1.0 cm to 1.2 cm along the z-axis. There were separate fmesh tallies for protons, π^+, π^- (charged pions), deuterons, tritons, helions (^{3}He) and alphas, with and without the energy dependent multiplier.

V. Results for Model #2

The results of the MCNP6 fmesh tallies are given in Table IV as a ratio to the proton fmesh tally for the Model # 2 (Figure 2) geometry. These results are also plotted in Figure 3a. Table V gives (plotted in Figure 3b) the results when an energy dependent multiplier (that is different for each particle) is applied. These multipliers were the same as the multipliers used for the Model # 1 results.

Energy	π^+		π^-		d		t		^{3}He		α	
(MeV)		Error		Error		Error		Error		Error		Error
800	4.51E-03	3.93E-06	2.37E-03	3.07E-06	6.32E-03	3.45E-06	1.07E-03	1.11E-06	2.82E-04	4.26E-07	2.95E-04	2.82E-07
750	4.01E-03	3.72E-06	2.03E-03	2.85E-06	5.88E-03	3.27E-06	9.63E-04	1.04E-06	2.54E-04	4.02E-07	2.64E-04	4.17E-07
700	3.48E-03	3.45E-06	1.69E-03	2.60E-06	5.43E-03	3.08E-06	8.66E-04	9.71E-07	2.28E-04	3.77E-07	2.33E-04	2.39E-07
650	2.90E-03	3.13E-06	1.37E-03	2.33E-06	4.95E-03	2.88E-06	7.64E-04	8.94E-07	2.01E-04	3.49E-07	2.03E-04	2.17E-07
600	2.30E-03	2.77E-06	1.08E-03	2.07E-06	4.44E-03	2.68E-06	6.67E-04	8.21E-07	1.75E-04	3.23E-07	1.74E-04	1.95E-07
550	1.72E-03	2.36E-06	8.02E-04	1.77E-06	3.93E-03	2.47E-06	5.78E-04	7.52E-07	1.49E-04	2.93E-07	1.48E-04	1.74E-07
500	1.19E-03	1.94E-06	5.58E-04	1.46E-06	3.41E-03	2.25E-06	4.89E-04	6.77E-07	1.24E-04	2.61E-07	1.23E-04	1.54E-07

Table IV – The values of the fmesh for the indicated particle as a ratio to the value for protons is given for the indicated proton energy.

Energy	π^+		π^-		d		t		^{3}He		α	
(MeV)		Error		Error		Error		Error		Error		Error
800	5.49E-03	5.20E-06	3.18E-03	4.18E-06	5.88E-02	3.03E-05	1.70E-02	1.47E-05	1.42E-02	1.67E-05	3.00E-02	2.24E-05
750	4.90E-03	4.92E-06	2.70E-03	3.85E-06	5.35E-02	2.82E-05	1.52E-02	1.36E-05	1.27E-02	1.55E-05	2.65E-02	3.25E-05
700	4.28E-03	4.57E-06	2.24E-03	3.48E-06	4.83E-02	2.61E-05	1.34E-02	1.26E-05	1.12E-02	1.43E-05	2.32E-02	1.86E-05
650	3.69E-03	4.28E-06	1.85E-03	3.19E-06	4.41E-02	2.46E-05	1.19E-02	1.19E-05	9.94E-03	1.34E-05	2.05E-02	1.71E-05
600	3.00E-03	3.84E-06	1.47E-03	2.82E-06	3.91E-02	2.25E-05	1.03E-02	1.03E-05	8.57E-03	1.23E-05	1.75E-02	1.5E-05
550	2.29E-03	3.31E-06	1.10E-03	2.42E-06	3.42E-02	2.05E-05	8.83E-03	9.67E-06	7.24E-03	1.11E-05	1.47E-02	1.3E-05
500	1.62E-03	2.74E-06	7.70E-04	2.00E-06	2.94E-02	1.84E-05	7.34E-03	8.57E-06	6.00E-03	9.83E-06	1.20E-02	1.17E-05

Table V – The values of the fmesh for the indicated particle as a ratio to the value for protons is given. This is for the case where each tally has an energy dependent multiplier that is dE/dx over dE/dx of a 1-GeV proton. Note that these tally multipliers are different for each particle type.

One sees in general that the values in Tables IV and V (Model # 2) are greater that the values in Tables I and II (Model # 1) but the ratios of the sum with multiplier to sum without multiplier for Model # 2 (Table VI) are less than the values for Model # 1 (Table III). There are at least two effects: one is the fact that the solid angle for particles off the window getting to the LSO will be greater for Model # 2 than for Model # 1. A second effect is that the energy spectrum of the particles getting to the LSO in the two cases could be and probably is different.

While we have not tabulated the results here, there is a number of charged muons getting to the LSO in the Model # 2 case (these were not recorded in the Model #1 case) – these muons presumably coming from charged-pion decay and are 5% to 8% of the π^+/p ratios and ~0.2% of the π^-/p ratios.

Energy	Sum without multiplier		Sum with multiplier		Ratio of sum with to sum without	
(MeV)		Error		Error		Error
800	0.01485	0.00001	0.12868	0.00004	8.67	< 0.01
750	0.01340	0.00001	0.11550	0.00005	8.62	0.01
700	0.01193	0.00001	0.10252	0.00004	8.59	0.01
650	0.01038	< 0.00001	0.09203	0.00004	8.87	0.01
600	0.00884	< 0.00001	0.07989	0.00003	9.04	0.01
550	0.00732	< 0.00001	0.06831	0.00003	9.33	0.01
500	0.00589	< 0.00001	0.05714	0.00003	9.70	0.01

Table VI – The sum of the values in Table IV (without multiplier) are compared to the sum in Table V (with multiplier), and the ratio of the two sums is given. This is for the MCNP geometry Model # 2 case.

For Model # 2 we have also calculation the image of the particles in the LSO with a mesh that is 1400 pixels -by- 1400 pixels -by- 1 pixel thick covering 14-cm × 14-cm × 0.2-cm. These images divided by the summed image (protons + π^+ + π^- + μ^+ + μ^- + deuterons + tritons + 3He + α) are shown in Figure 4a-i, respectively, on plots that cover two orders of magnitude in the intensity scale; and in Figure 5a-i where the lower bound of the intensity is auto scaled for each plot.

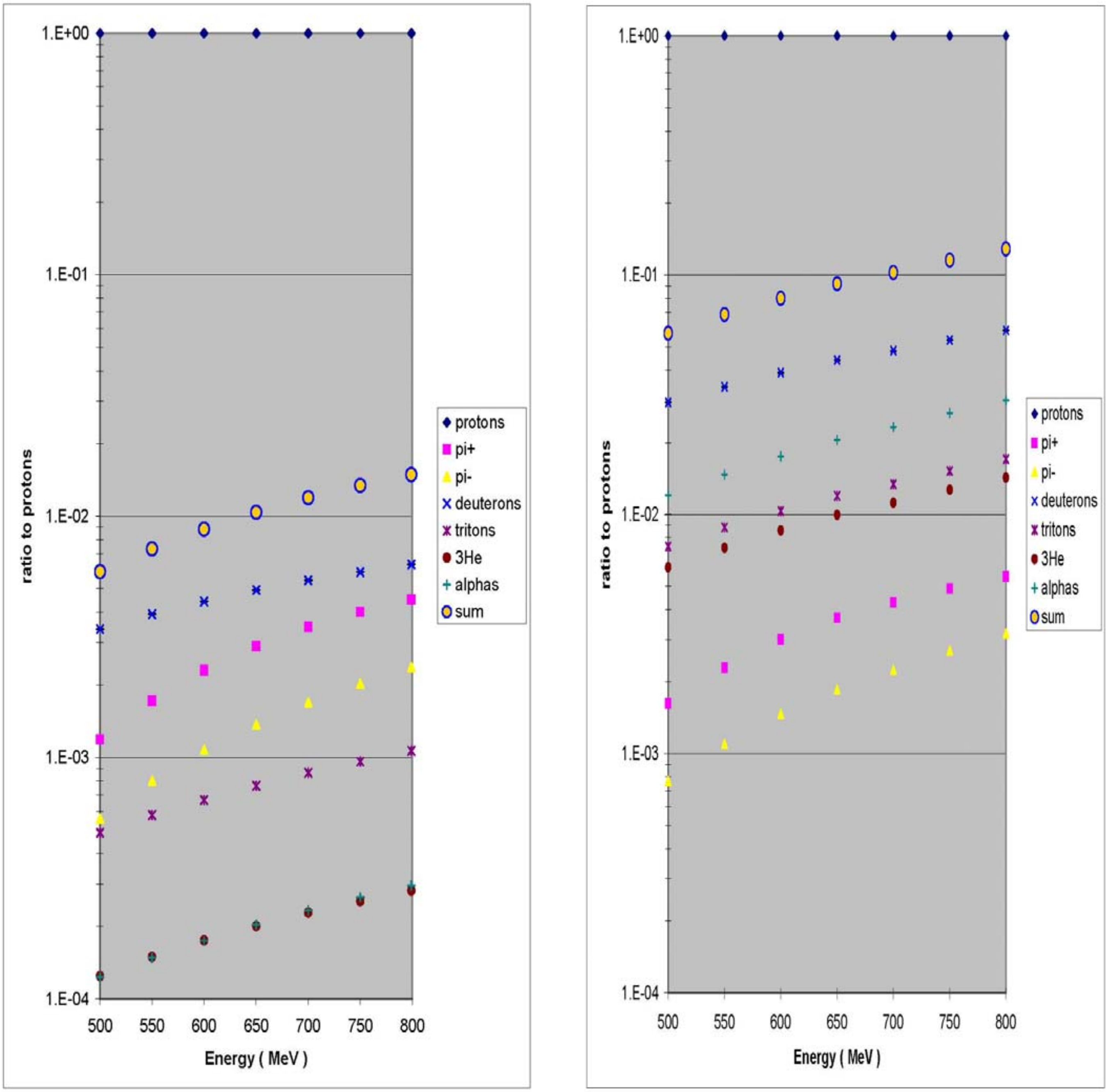

Figure 3a and **3b** (left) – Caption is the same as Figure 1a and 1b except that runs were with MCNP Model #2 (see text) with LSO detector 1 cm from the center of the window.

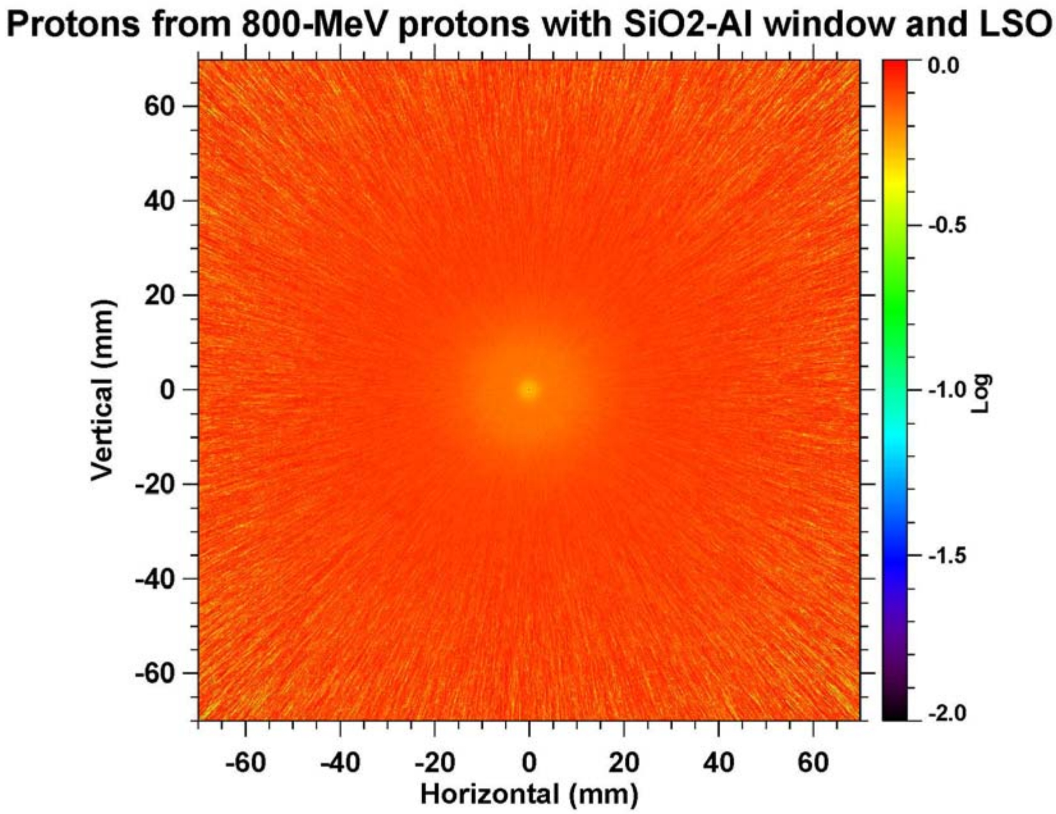

Figure 4a – Ratio of the proton image to the summed image (see text).

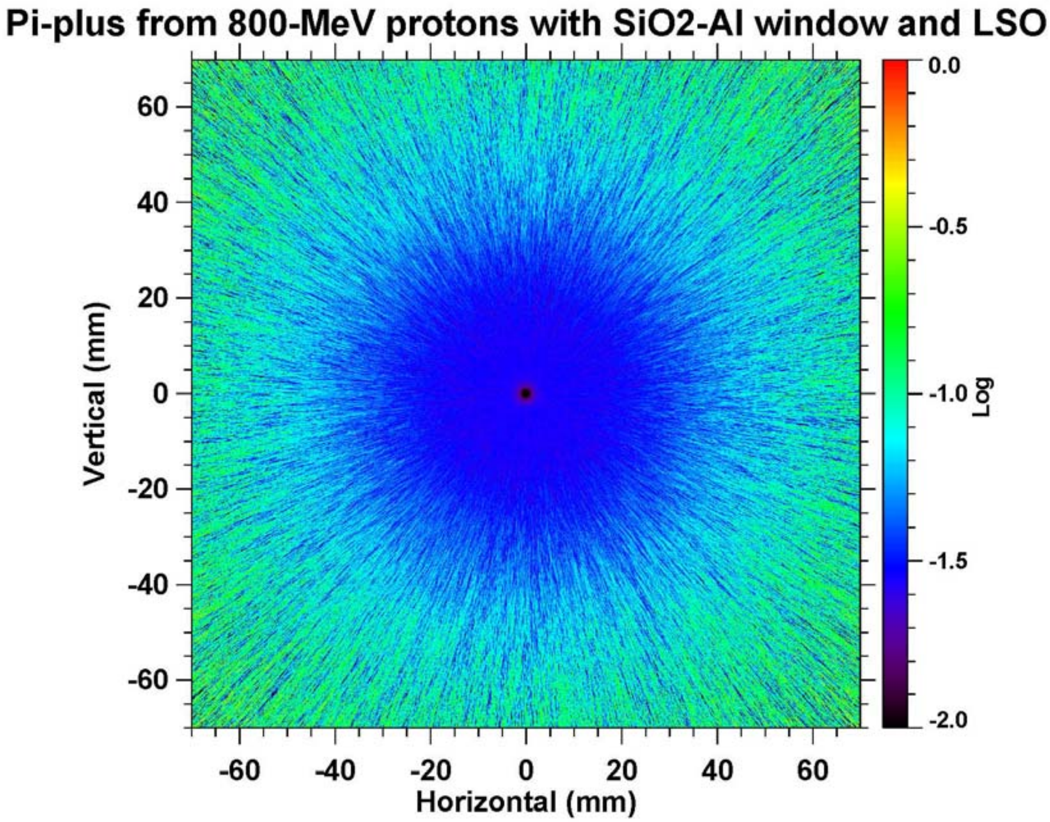

Figure 4b – Ratio of the π^+ image to the summed image (see text).

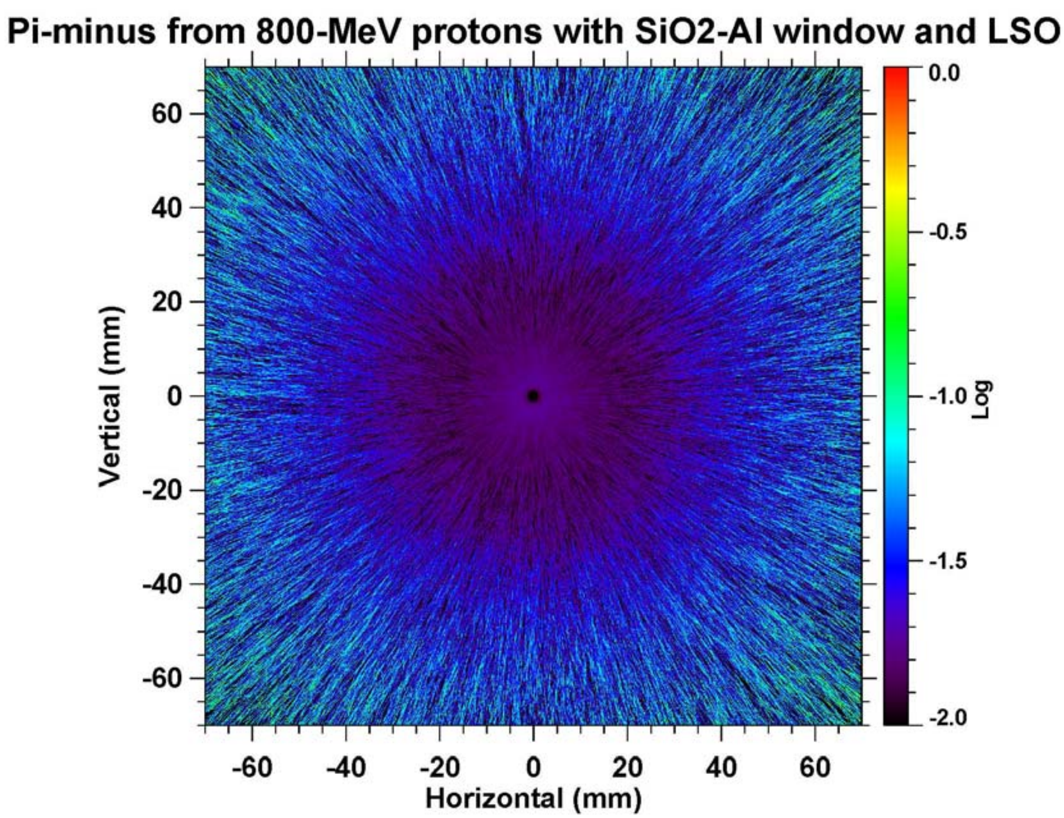

Figure 4c – Ratio of the π^- image to the summed image (see text).

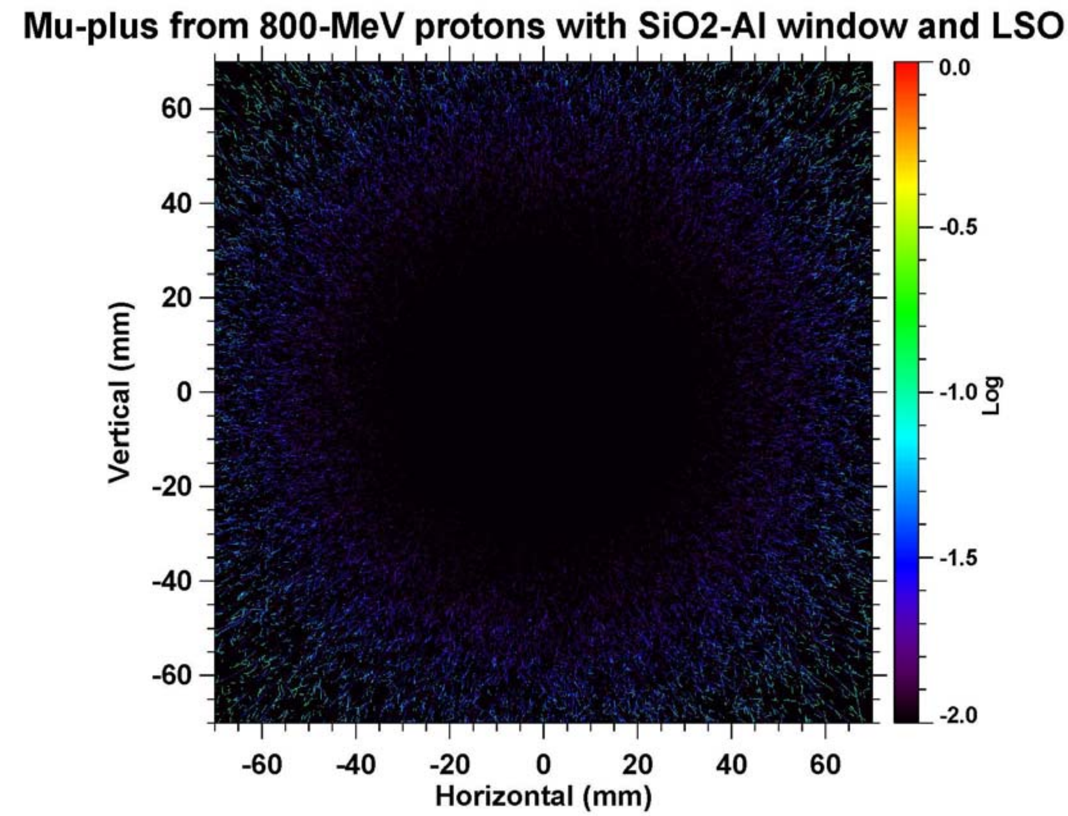

Figure 4d – Ratio of the μ^+ image to the summed image (see text).

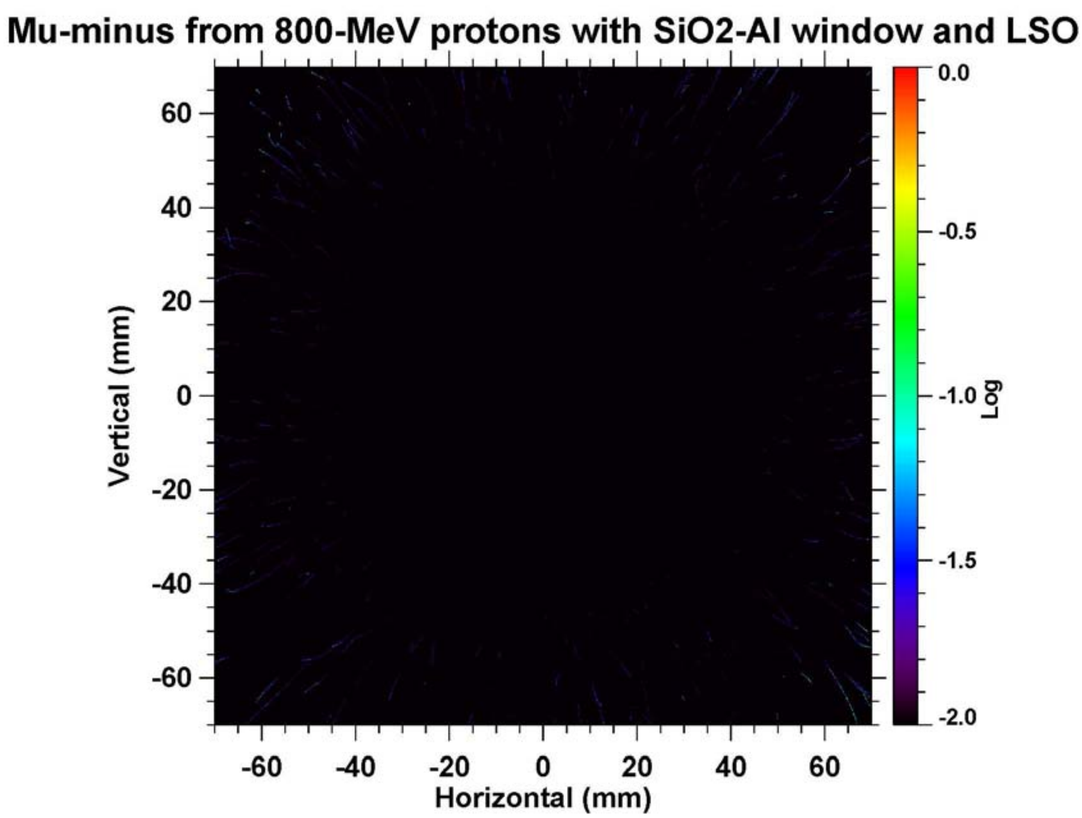

Figure 4e – Ratio of the μ^- image to the summed image (see text).

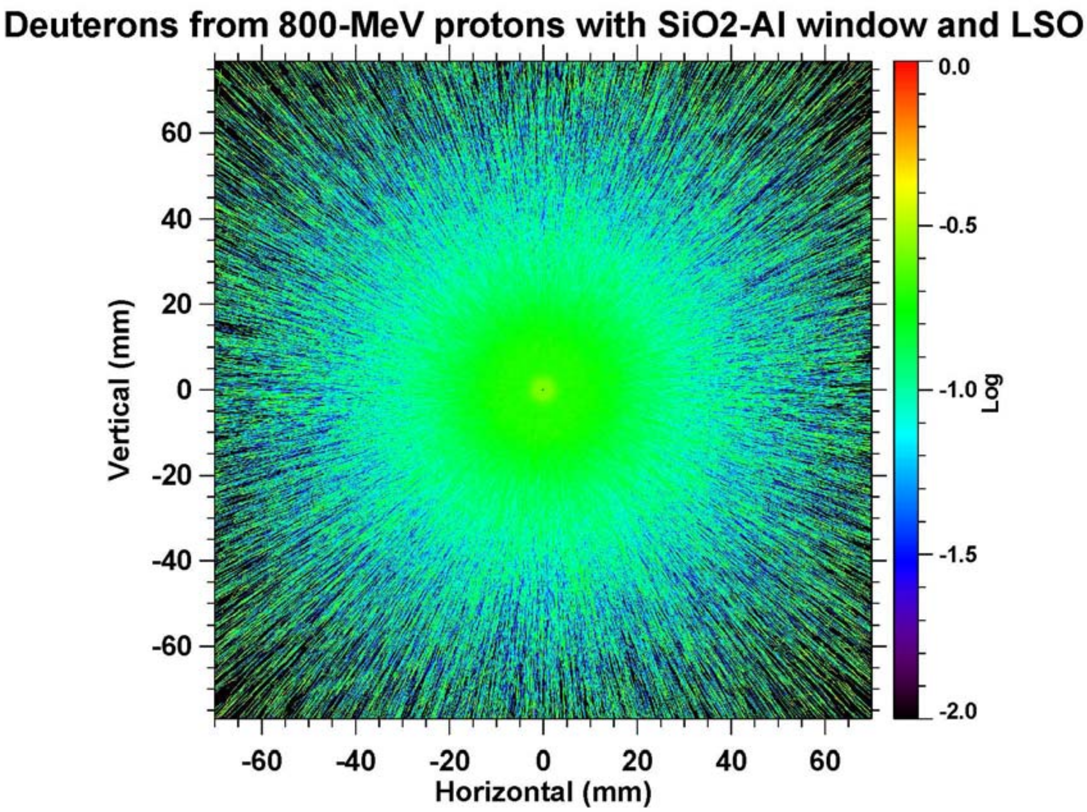

Figure 4f – Ratio of the deuteron image to the summed image (see text).

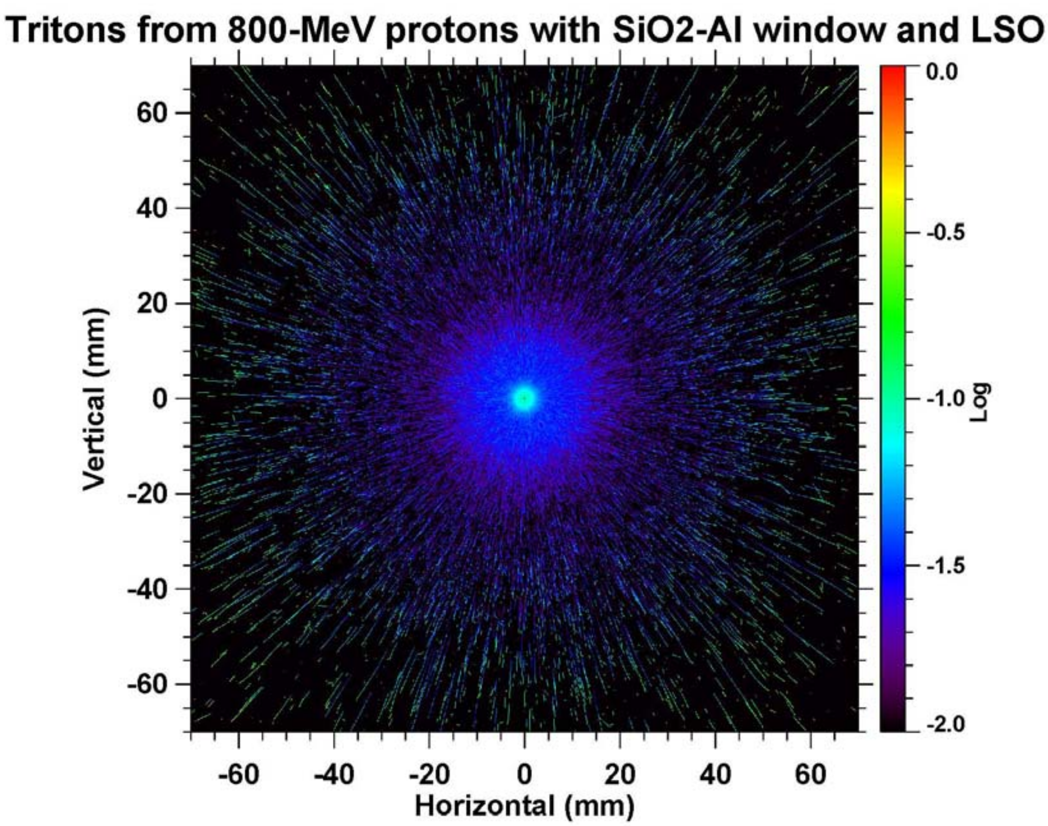

Figure 4g – Ratio of the triton image to the summed image (see text).

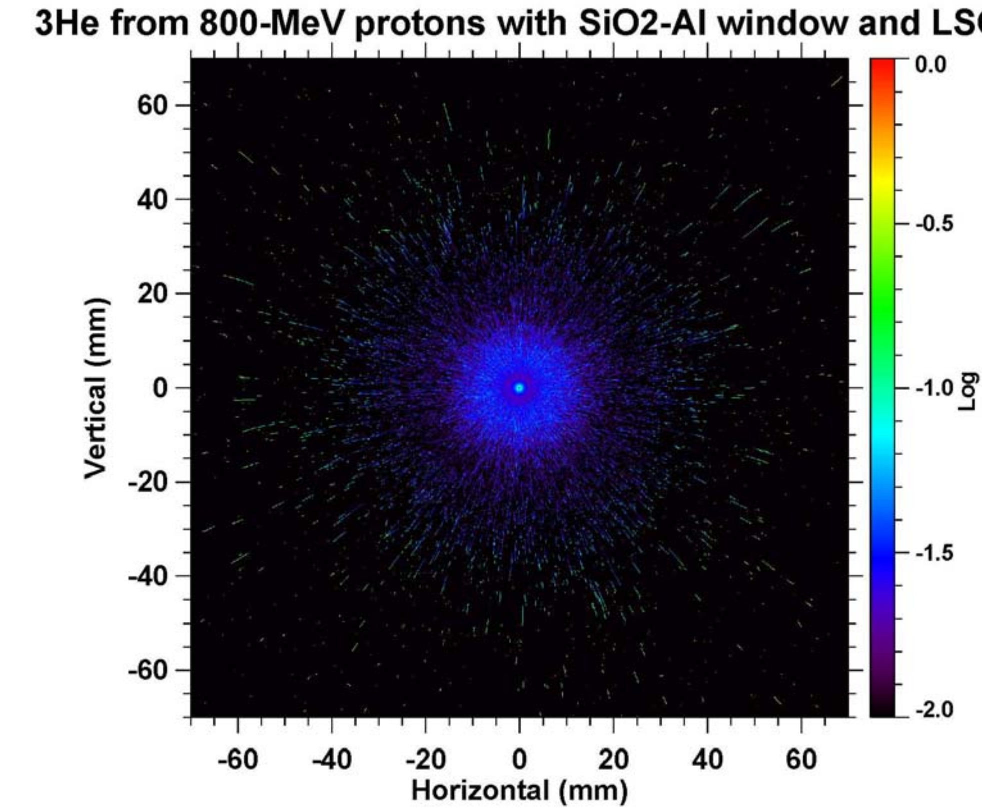

Figure 4h – Ratio of the ^{3}He image to the summed image (see text).

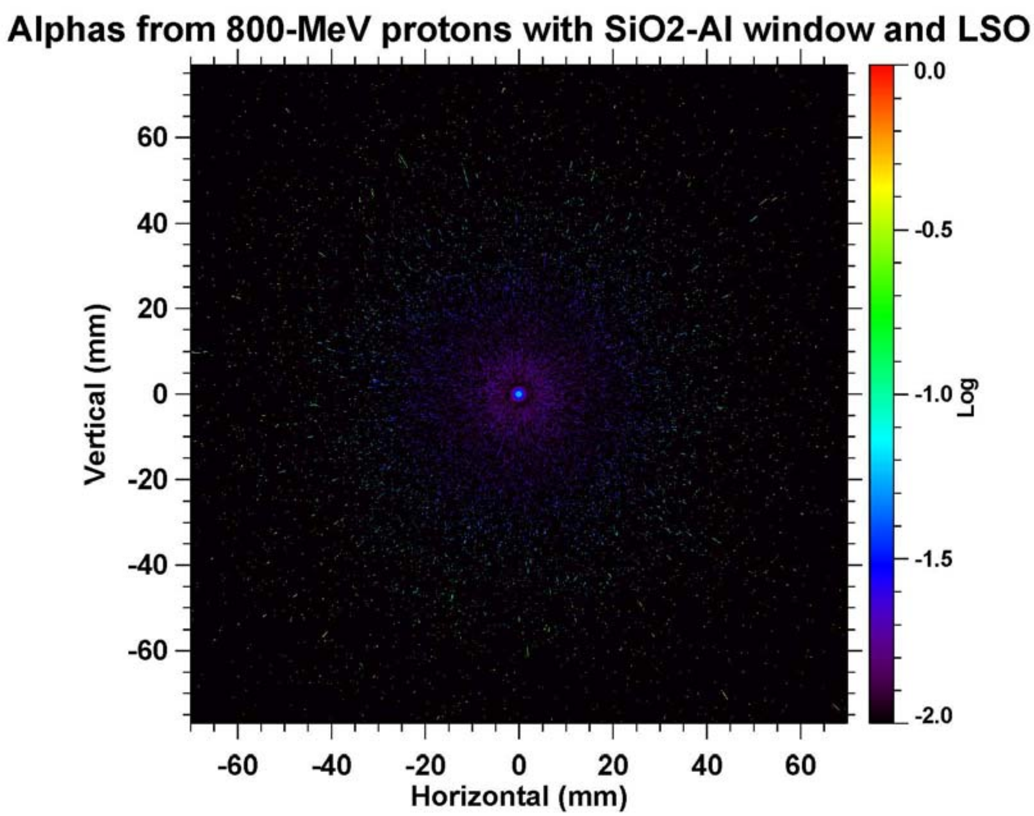

Figure 4i – Ratio of the alpha particle image to the summed image (see text).

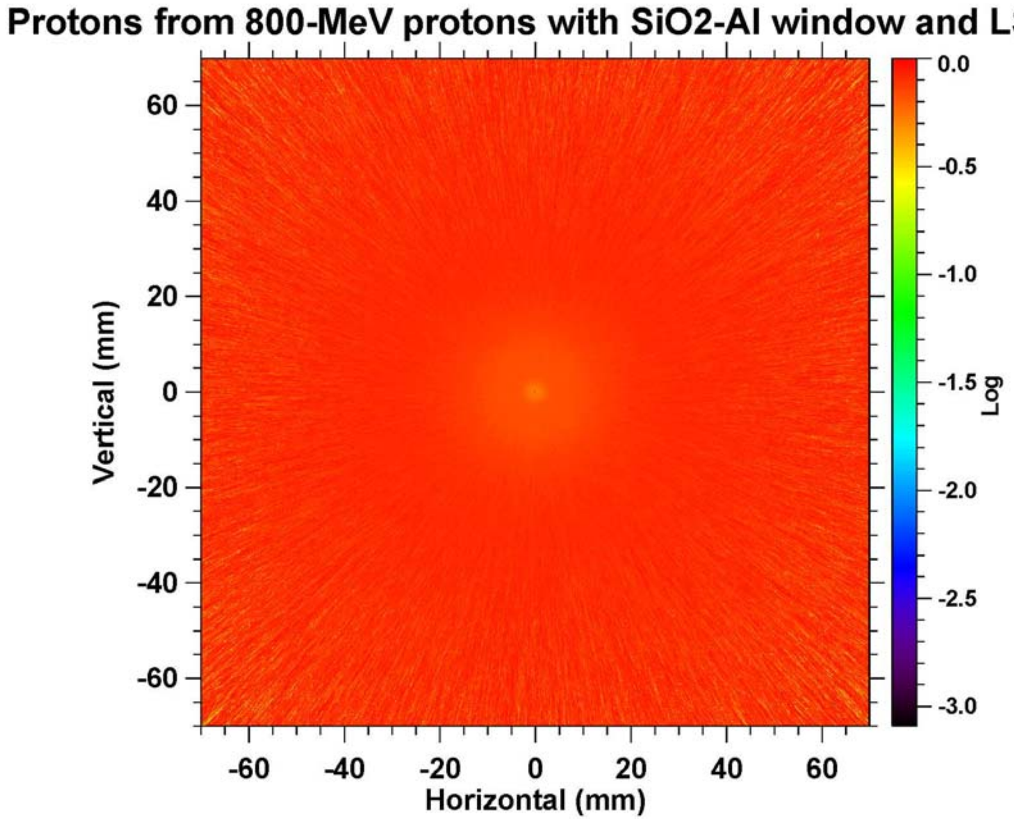

Figure 5a – Ratio of the proton image to the summed image with the lower limit of the intensity scale auto scaled by the plotting program. This is the same data is in Figure 4a.

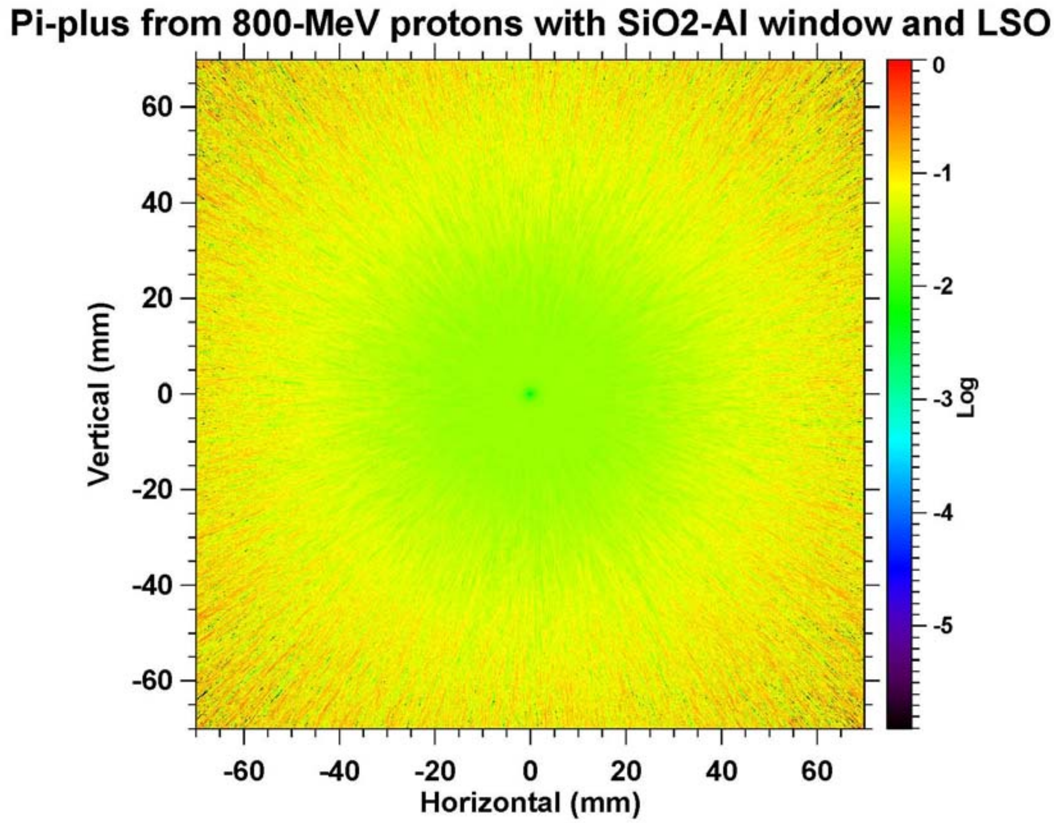

Figure 5b – Ratio of the π^+ image to the summed image with the lower limit of the intensity scale auto scaled by the plotting program. This is the same data is in Figure 4b.

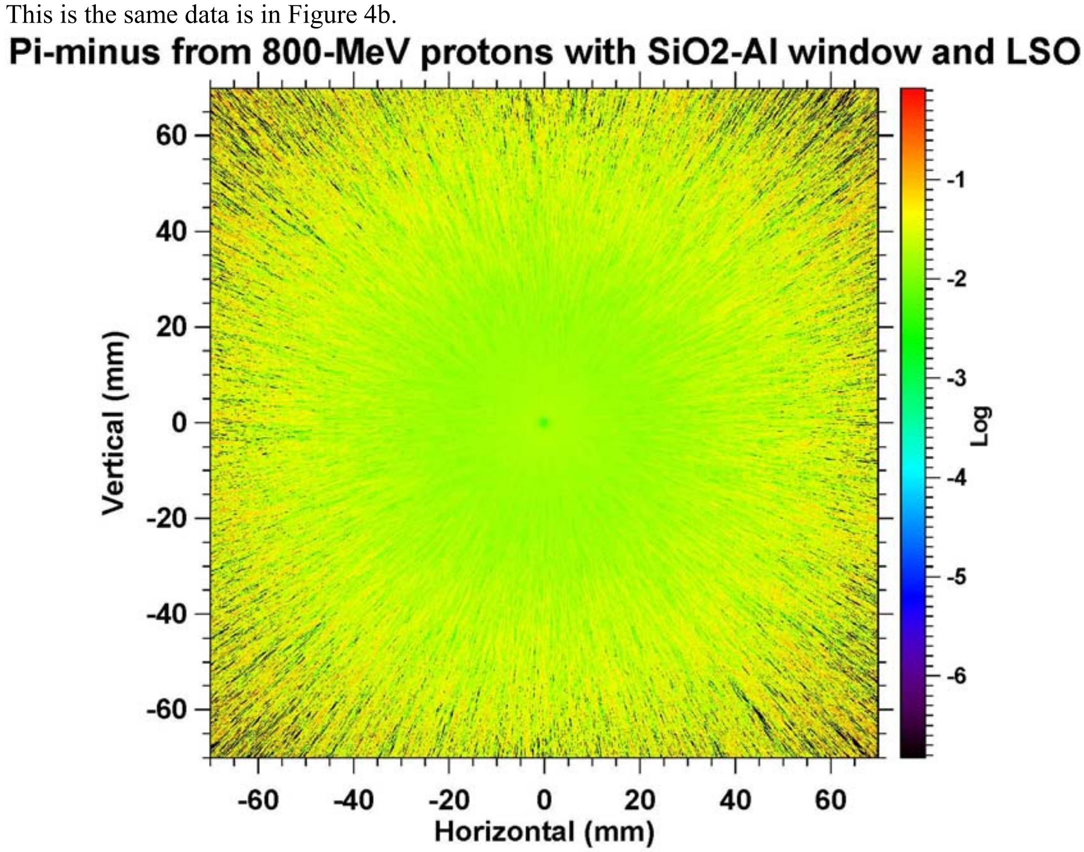

Figure 5c – Ratio of the π^- image to the summed image with the lower limit of the intensity scale auto scaled by the plotting program. This is the same data is in Figure 4c.

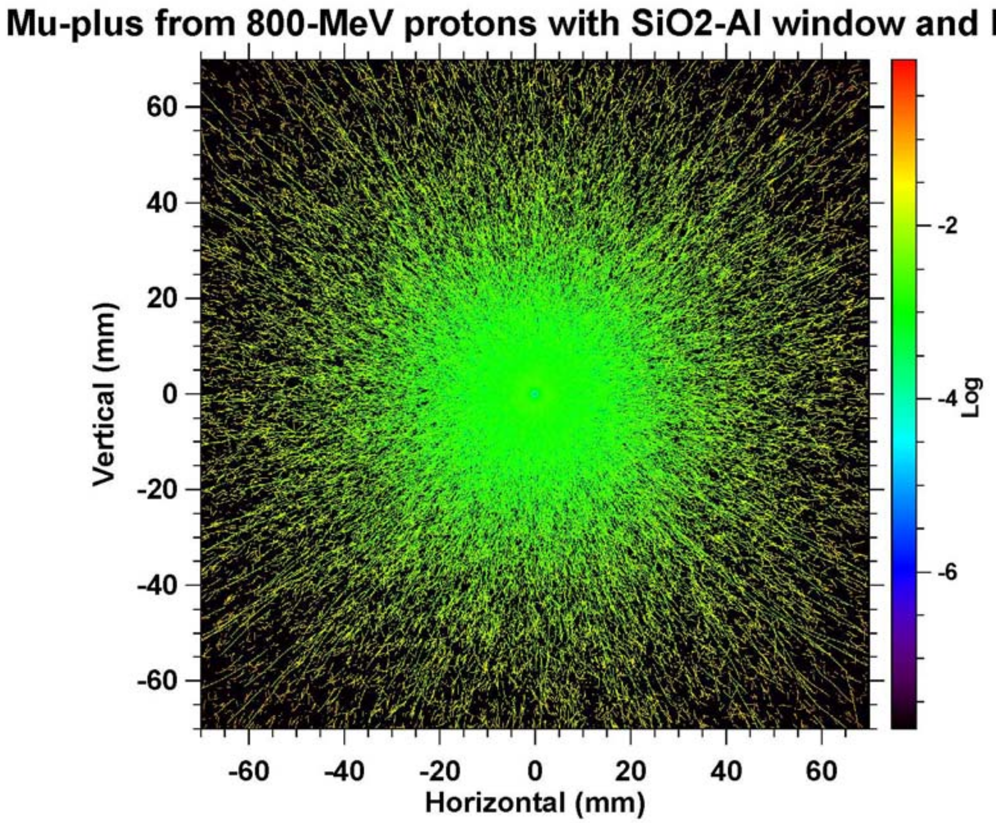

Figure 5d – Ratio of the proton image to the summed image with the lower limit of the intensity scale auto scaled by the plotting program. This is the same data is in Figure 4d.

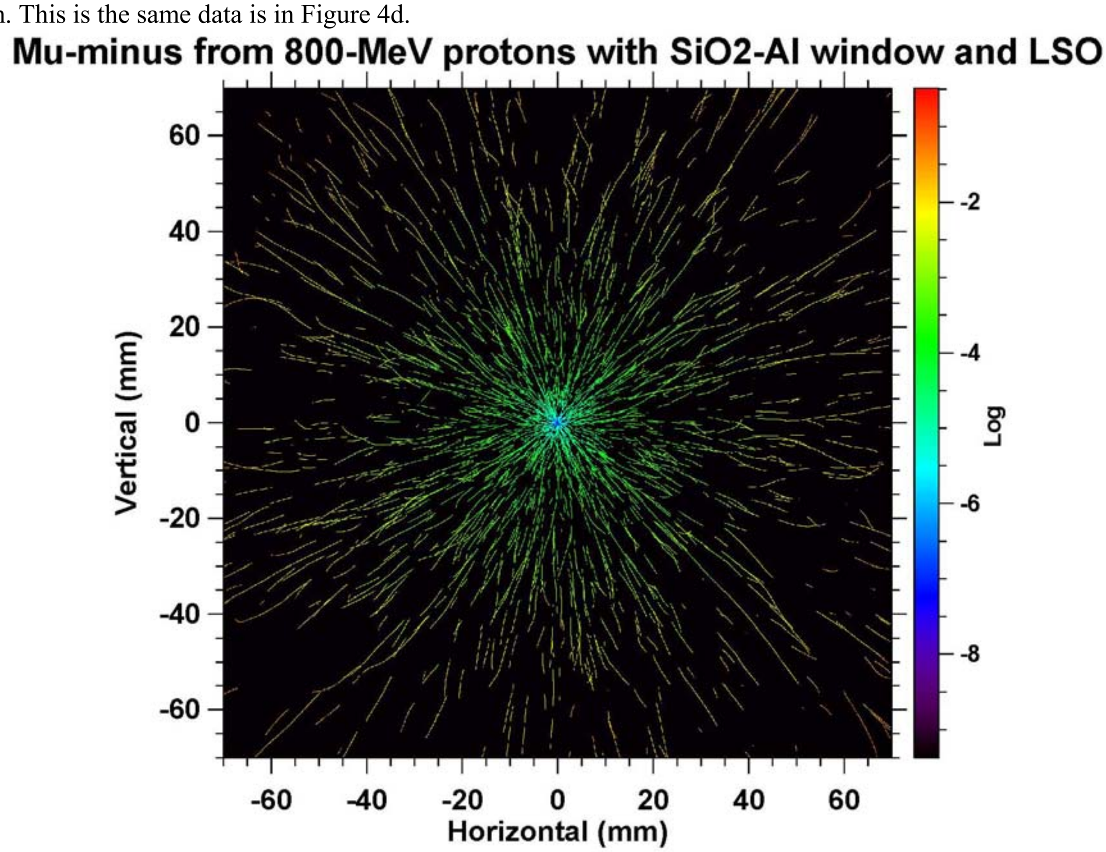

Figure 5e – Ratio of the proton image to the summed image with the lower limit of the intensity scale auto scaled by the plotting program. This is the same data is in Figure 4e.

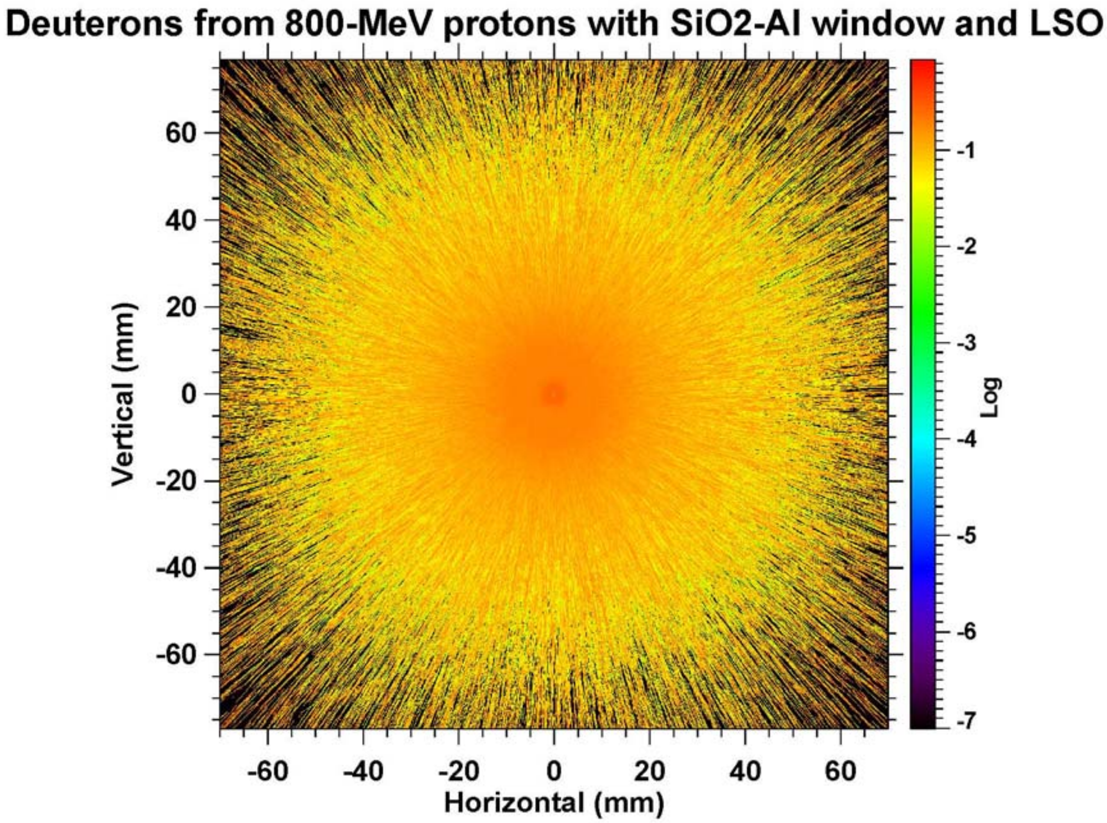

Figure 5f – Ratio of the proton image to the summed image with the lower limit of the intensity scale auto scaled by the plotting program. This is the same data is in Figure 4f.

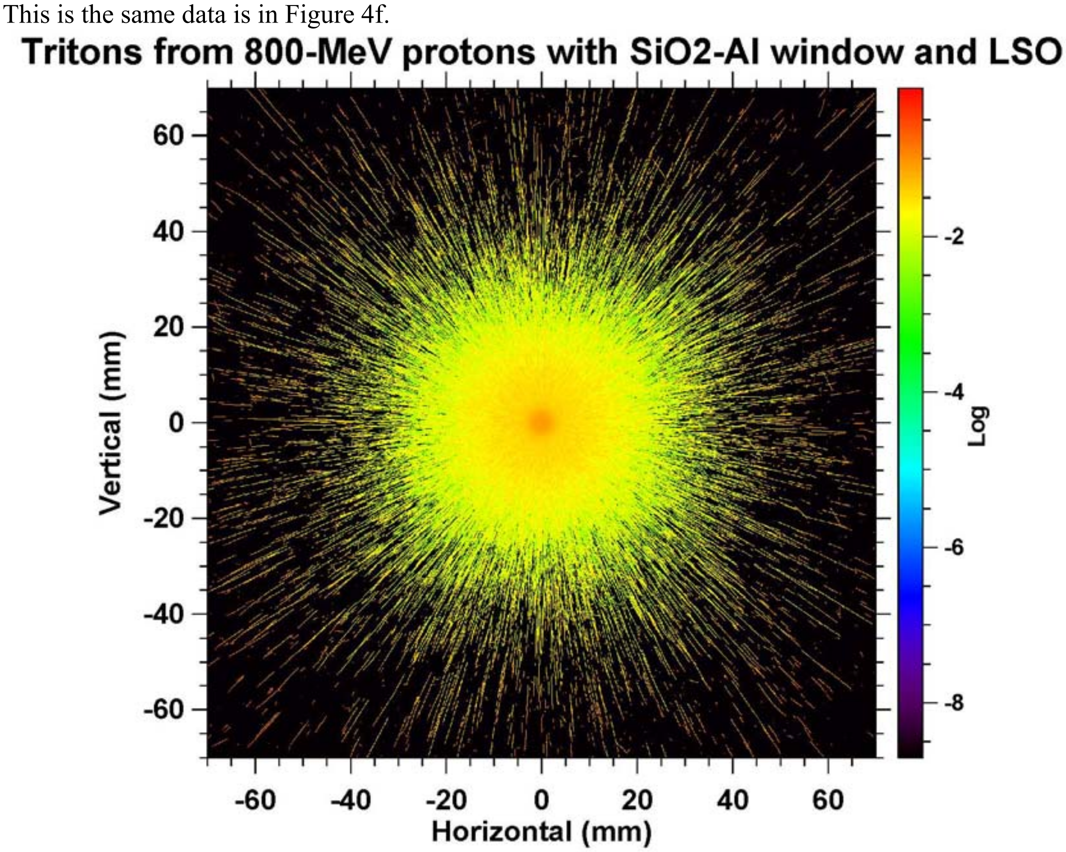

Figure 5g – Ratio of the proton image to the summed image with the lower limit of the intensity scale auto scaled by the plotting program. This is the same data is in Figure 4g.

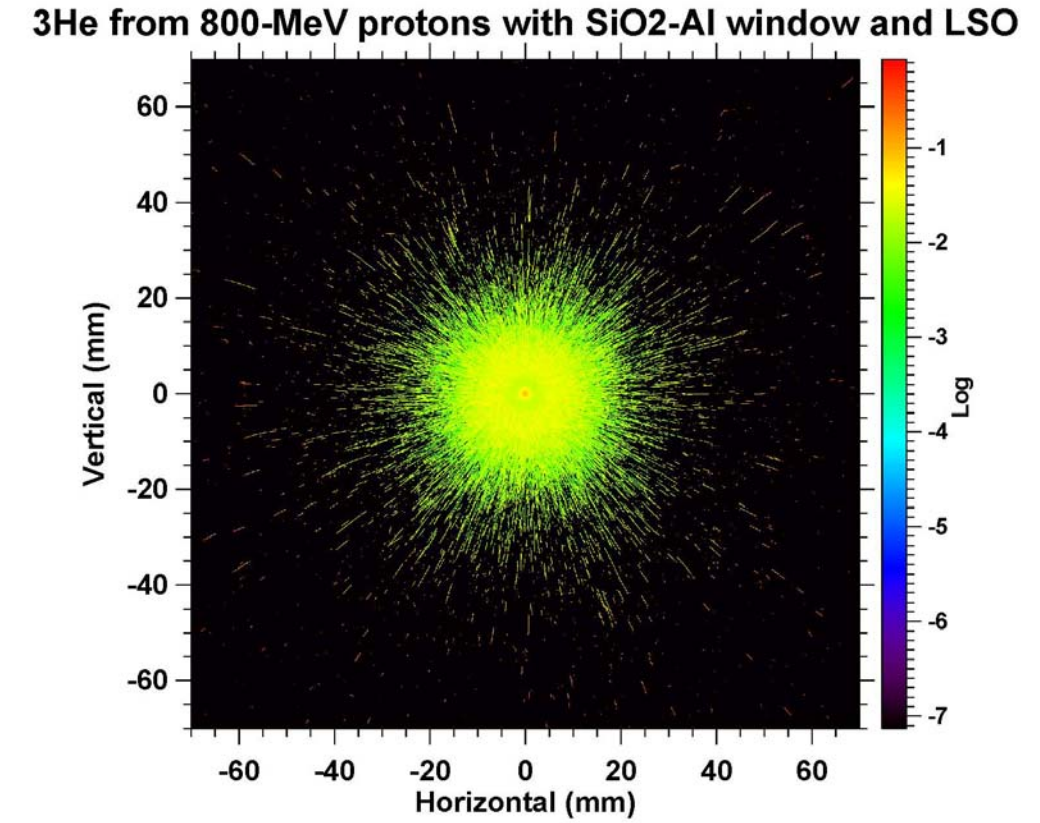

Figure 5h – Ratio of the proton image to the summed image with the lower limit of the intensity scale auto scaled by the plotting program. This is the same data is in Figure 4h.

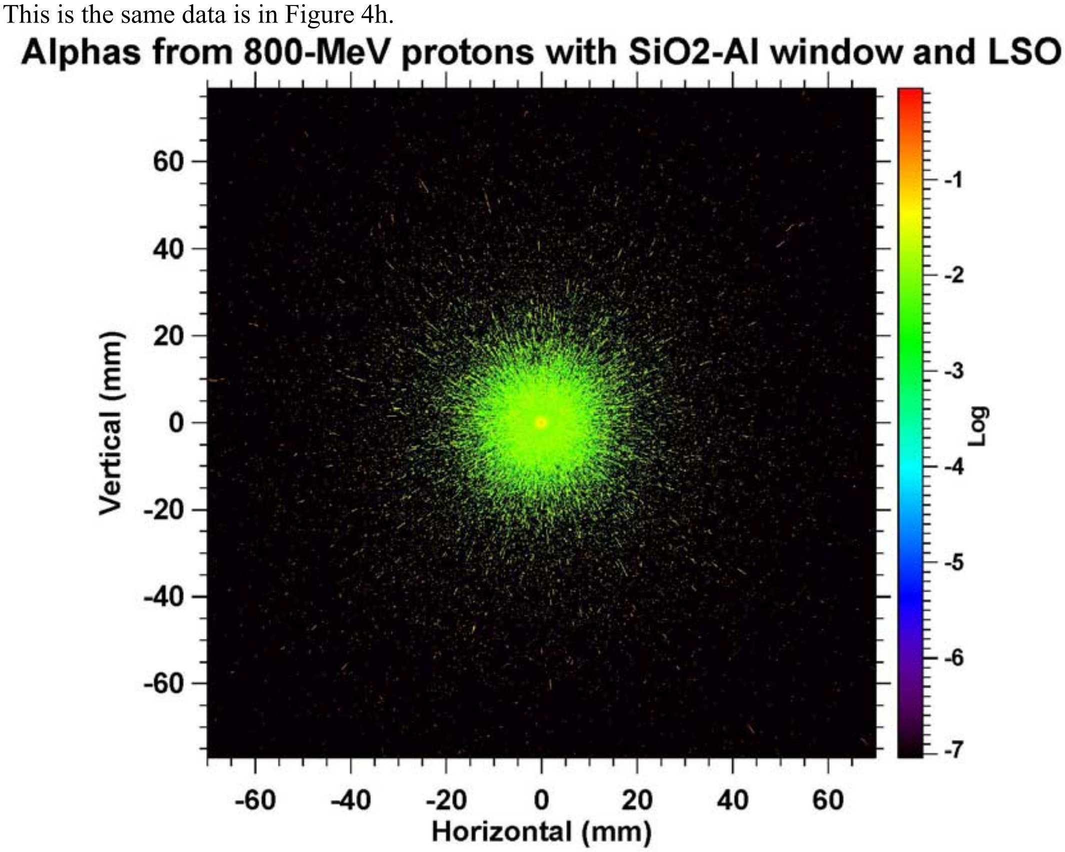

Figure 5i – Ratio of the proton image to the summed image with the lower limit of the intensity scale auto scaled by the plotting program. This is the same data is in Figure 4i.

VI. Conclusions

Monte Carlo calculations with MCNP6 of a protons incident of a thick window (similar to the window used in some proton radiography experiments at Line C) and subsequently transported to a LSO detector show a significant number of secondary particles in the LSO. If a model that accounts for the relative energy loss of the particles in the LSO is applied one sees that the summed signal from the secondary particles is 5% to 12% of the proton signal depending on the incident proton energy.

Tthe effects of these secondary particles should cancel out when the experimenters calculate a transmission by taking the ratio of an object-in run to an object-out run. However, one must be careful since there appears to be energy dependence to the secondary contribution, and the protons energies for the object-in run and the object-out run will probably be different.

The secondary production in the window and subsequent spreading of signal in the LSO scintillator (Figures 4b through 4i) might lead to the effect that has been called "long range blur". The effect of long range blur has been discussed in a couple of documents.[3] These documents discuss the effect at LANSCE Line C (800-MeV protons) and at the Brookhaven AGS (24-GeV/c protons), respectively, and the latter points out that the long range blur is reduced by approximately an order of magnitude at the energy higher energy. If it is secondary particle production causing the effect then the forward peaking at energy proton energies might explain the effect. We intend to perform similar MCNP6 calculations at the higher energy when the cross sections become available in the code – the cross sections currently stop at ~5-GeV proton energy.

It should be noted that the calculations presented in this note do not include delta rays (i.e. fast electrons produced by the energetic charged particles knocking orbiting electrons out of atoms), or heavy ions (i.e. ions heavier than alpha particles that could be produced primarily by the protons interacting with the nuclei of the window material(s). Both of these processes would modify the scintillator signal, but neither process is included in MCNP6 at the moment.

VII. References

1. "Initial MCNP6 Release Overview", T. Goorley et al., LA-UR-11-01766 -- states: "While MCNP6 is simply and accurately described as the merger of MCNP5 and MCNPX capabilities, it is also the result of 4 years of meticulous effort by the MCNP5 and MCNPX code development teams."

The merger is cited is being or nearing completion, but this author will believe this when it is seen at RSICC (Radiation Safety Information Computational Center).

2. "CEM03.03 and LAQGSM03.03 Event Generators for the MCNP6, MCNPX, and MARS15 Transport Codes", S. G. Mashnik, K. K. Gudima, R. E. Prael, A. J. Sierk, M. I. Baznat, and N. V. Mokhov, Joint ICTP-IAEA Advanced Workshop on Model Codes for Spallation Reactions, February 4-8, 2008, ICTP, Trieste, Italy; LA-UR-08-2931; E-print: arXiv:0805.0751v2 [nucl-th]; IAEA Report INDC(NDS)-0530, Distr. SC, Vienna, Austria, August 2008, p. 51.

3. "Long Range Blur correction to Proton Radiography Data", N. S. P. King, K. B. Morley, C. L. Morris and Pete Pazuchanics, Los Alamos National Laboratory (no date and no LA number); "Tile Glow Correction" Chris Morris et al., LANL, LLNL, and Bechtel Nevada (no date and no LA number).

VIII. Acknowledgements

Thanks to my fellow transporters in XCP-7 "Transport Applications" for the occasional discussion of this and similar topics. And also to XCP-3 "Monte Carlo Codes" for the implementation of the new features that allow proton radiography simulations with MCNP6, and in advance for features that are yet to be implemented.

JDZ:jdz

Appendix I — MCNP6 input for Model # 2 geometry

```
file:  .../Rprad/LineC/minusI/particle_production/035/pp035-700.inp
c from .../Rprad/LineC/minusI/particle_production/034/pp034-700.inp
c from .../Rprad/LineC/minusI/particle_production/018/pp018.inp
c
c to 1400x1400-pixel LSO detector that is 14-cm by 14-cm by 0.2-cm thick
c location 1-cm to 1.2-cm downstream of center of window
c
c particle production with 700-MeV protons
c with  'tropt' card
c and proton cutoff set to 10-MeV
c DF cards are dE/dX(E) to proton stopping power at 1-GeV
c
c start cell cards
c
  101    0                -50   101  -102      imp:h=1
  102   14   -2.65        -50   102  -103      imp:h=1
  103   13   -2.70        -50   103  -104      imp:h=1
  104    0                -50   104  -105      imp:h=1
  105   71   -7.36        -50   105  -106      imp:h=1
  106    0                -50   106  -107      imp:h=1
c
   75    0                 50:-101:+107        imp:h=0
c -----------------------------------------------------------------------------
c end of cell cards

c start surface cards
    50    cz     95
c
   101    pz   -100
   102    pz     -0.3175
   103    pz      0.0000
   104    pz      0.3175
   105    pz      1
   106    pz      1.2
   107    pz    100
c -----------------------------------------------------------------------------
c end of surface cards

c start physics cards
c mode h
  mode   h     / * | !      d t s a
c phys:n 1000
  phys:h 1000
  phys:/ 1000
  phys:* 1000
  phys:| 1000
  phys:! 1000
  phys:d 1000
  phys:t 1000
  phys:s 1000
  phys:a 1000
c
c cut:n j   1.00
  cut:h j   5.
  cut:/ j   5.
  cut:* j   5.
  cut:| j   5.
  cut:! j   5.
  cut:d j   5.
  cut:t j   5.
  cut:s j   5.
  cut:a j   5.
c
  tropt nreact=on nescat=on mcscat=fnal1 eloss=strag1
c void
c ---------------------------------------------------------------------------
```

```
  sdef erg=700.   part=5 sur=101 x=0  y=0  z=-100   vec=0 0 1  dir=1
c ---------------------------------------------------------------------------
  rand gen=2
  print -160 -30
c ---------------------------------------------------------------------------
  nps        1000000000
  prdmp j     100000000  1 2    100000000
c ---------------------------------------------------------------------------
  m13   13027 1.                              $ aluminum
  m14   14028 1.     08016  2.                $ SiO2 == glass (rho=2.64 g/cc)
  m71   71175 2.     14028 1.     8016 5.     $ LSO (rho=7.36 g/cc)
c end of material cards
c ---------------------------------------------------------------------------
c
  fc021 exit of problem
   f021:h 105
   e021 0 001 800i 802
c -----------------------------------------------------------------------------
  fc031 exit of problem
   f031:n 105
   e031 0 001 800i 802
c -----------------------------------------------------------------------------
  fc411 pi+ at exit of problem
   f411:/ 105
   e411  00  99i 1000
c -----------------------------------------------------------------------------
  fc511 pi- just after object energy
   f511:* 105
   e511  00  99i 1000
c -----------------------------------------------------------------------------
  fc611 mu+ just after object energy
   f611:! 105
   e611  00  99i 1000
c -----------------------------------------------------------------------------
  fc711 mu- just after object energy
   f711:| 105
   e711  00  99i 1000
c -----------------------------------------------------------------------------
  fc811 deuterons just after object energy
   f811:d 105
   e811  00  99i 1000
c -----------------------------------------------------------------------------
  fc911 tritons just after object energy
   f911:t 105
   e911  00  99i 1000
c -----------------------------------------------------------------------------
  fc1011 3He just after object energy
   f1011:s 105
   e1011  00  99i 1000
c -----------------------------------------------------------------------------
  fc1111 alphas just after object energy
   f1111:a 105
   e1111  00  99i 1000
c -----------------------------------------------------------------------------
c -----------------------------------------------
c -----------------------------------------------
c -----------------------------------------------
   fc154  proton image at IL1
   fmesh154:h   geom=rec  origin=-7 -7   +1.0
         imesh 7 iints 1400
         jmesh 7 jints 1400     kmesh   +1.2  out=cf
  DE154 LIN     5.06578    5.52427    6.02426    6.56950    7.16409    7.81250
                8.51959    9.29068   10.13160   11.04850   12.04850   13.13900
               14.32820   15.62500   17.03920   18.58140   20.26310   22.09710
               24.09700   26.27800   28.65640   31.25000   34.07840   37.16270
               40.52620   44.19420   48.19410   52.55600   57.31280   62.50000
               68.15670   74.32540   81.05250   88.38830   96.38820  105.11200
              114.62600  125.00000  136.31300  148.65100  162.10500  176.77699
              192.77600  210.22400  229.25101  250.00000  272.62701  297.30200
              324.20999  353.55301  385.55301  420.44800  458.50201  500.00000
```

```
           545.25403  594.60400  648.41998  707.10699  771.10498  840.89600
           917.00403 1000.00000
  DF154 LIN    26.08269   24.42458   23.06607   23.06607   20.53502   19.36003
            18.24370   17.18285   16.17851   16.17851   14.32689   13.47228
            12.66411   11.90028   11.17743   11.17743    9.85530    9.24868
             8.67966    8.14292    7.63895    7.63895    6.72014    6.30293
             5.91134    5.54462    5.20113    5.20113    4.57863    4.29743
             4.03476    3.78938    3.56046    3.56046    3.14812    2.96289
             2.79043    2.63060    2.48150    2.48150    2.21463    2.09555
             1.98528    1.88349    1.78915    1.78915    1.62186    1.54794
             1.48000    1.41767    1.36058    1.36058    1.26090    1.21772
             1.17860    1.14331    1.11163    1.11163    1.05821    1.03608
             1.01673    1.00000
c --------------------------------------------------------------------------------
  fc454   pi+      image at IL1
  fmesh454:/   geom=rec  origin=-7 -7   +1.0
         imesh 7 iints 1400
         jmesh 7 jints 1400     kmesh   +1.2  out=cf
  DE454 LIN     5.06578    5.52427    6.02426    6.56950    7.16409    7.81250
             8.51959    9.29068   10.13160   11.04850   12.04850   13.13900
            14.32820   15.62500   17.03920   18.58140   20.26310   22.09710
            24.09700   26.27800   28.65640   31.25000   34.07840   37.16270
            40.52620   44.19420   48.19410   52.55600   57.31280   62.50000
            68.15670   74.32540   81.05250   88.38830   96.38820  105.11200
           114.62600  125.00000  136.31300  148.65100  162.10500  176.77699
           192.77600  210.22400  229.25101  250.00000  272.62701  297.30200
           324.20999  353.55301  385.55301  420.44800  458.50201  500.00000
           545.25403  594.60400  648.41998  707.10699  771.10498  840.89600
           917.00403 1000.00000
  DF454 LIN     6.71911    6.30202    5.91054    5.91054    5.20051    4.87881  $ ratio of pion dE/dx values
             4.57813    4.29698    4.03435    4.03435    3.56011    3.34675  $ to proton dE/dx at 1-GeV
             3.14781    2.96259    2.79015    2.79015    2.48122    2.34276
             2.21435    2.09526    1.98498    1.98498    1.78884    1.70182
             1.62152    1.54759    1.47963    1.47963    1.36017    1.30801
             1.26047    1.21727    1.17812    1.17812    1.11110    1.08277
             1.05764    1.03548    1.01609    1.01609    0.98504    0.97297
             0.96294    0.95483    0.94849    0.94849    0.94066    0.93894
             0.93854    0.93936    0.94129    0.94129    0.94811    0.95282
             0.95829    0.96445    0.97121    0.97121    0.98629    0.99448
             1.00303    1.01189
c --------------------------------------------------------------------------------
  fc554   pi-      image at IL1
  fmesh554:*   geom=rec  origin=-7 -7   +1.0
         imesh 7 iints 1400
         jmesh 7 jints 1400     kmesh   +1.2  out=cf
  DE554 LIN     5.06578    5.52427    6.02426    6.56950    7.16409    7.81250
             8.51959    9.29068   10.13160   11.04850   12.04850   13.13900
            14.32820   15.62500   17.03920   18.58140   20.26310   22.09710
            24.09700   26.27800   28.65640   31.25000   34.07840   37.16270
            40.52620   44.19420   48.19410   52.55600   57.31280   62.50000
            68.15670   74.32540   81.05250   88.38830   96.38820  105.11200
           114.62600  125.00000  136.31300  148.65100  162.10500  176.77699
           192.77600  210.22400  229.25101  250.00000  272.62701  297.30200
           324.20999  353.55301  385.55301  420.44800  458.50201  500.00000
           545.25403  594.60400  648.41998  707.10699  771.10498  840.89600
           917.00403 1000.00000
  DF554 LIN     6.71911    6.30202    5.91054    5.91054    5.20051    4.87881  $ ratio of pion dE/dx values
             4.57813    4.29698    4.03435    4.03435    3.56011    3.34675  $ to proton dE/dx at 1-GeV
             3.14781    2.96259    2.79015    2.79015    2.48122    2.34276
             2.21435    2.09526    1.98498    1.98498    1.78884    1.70182
             1.62152    1.54759    1.47963    1.47963    1.36017    1.30801
             1.26047    1.21727    1.17812    1.17812    1.11110    1.08277
             1.05764    1.03548    1.01609    1.01609    0.98504    0.97297
             0.96294    0.95483    0.94849    0.94849    0.94066    0.93894
             0.93854    0.93936    0.94129    0.94129    0.94811    0.95282
             0.95829    0.96445    0.97121    0.97121    0.98629    0.99448
             1.00303    1.01189
c --------------------------------------------------------------------------------
  fc654   mu+      image at IL1
  fmesh654:!   geom=rec  origin=-7 -7   +1.0
```

```
       imesh 7 iints 1400
       jmesh 7 jints 1400     kmesh   +1.2  out=cf
  DE654 LIN     5.06578    5.52427    6.02426    6.56950    7.16409    7.81250
                8.51959    9.29068   10.13160   11.04850   12.04850   13.13900
               14.32820   15.62500   17.03920   18.58140   20.26310   22.09710
               24.09700   26.27800   28.65640   31.25000   34.07840   37.16270
               40.52620   44.19420   48.19410   52.55600   57.31280   62.50000
               68.15670   74.32540   81.05250   88.38830   96.38820  105.11200
              114.62600  125.00000  136.31300  148.65100  162.10500  176.77699
              192.77600  210.22400  229.25101  250.00000  272.62701  297.30200
              324.20999  353.55301  385.55301  420.44800  458.50201  500.00000
              545.25403  594.60400  648.41998  707.10699  771.10498  840.89600
              917.00403 1000.00000
  DF654 LIN     5.46768    5.12906    4.81208    4.81208    4.23864    3.97987  $ ratio of muon dE/dx values
                3.73813    3.51271    3.30252    3.30252    2.92424    2.75446  $ to proton dE/dx at 1-GeV
                2.59712    2.45038    2.31414    2.31414    2.07065    1.96219
                1.86209    1.76934    1.68382    1.68382    1.53230    1.46558
                1.40439    1.34837    1.29722    1.29722    1.20832    1.17001
                1.13548    1.10451    1.07689    1.07689    1.03084    1.01203
                0.99580    0.98199    0.97036    0.97036    0.95301    0.94702
                0.94266    0.93981    0.93837    0.93837    0.93926    0.94139
                0.94451    0.94855    0.95341    0.95341    0.96525    0.97210
                0.97946    0.98728    0.99551    0.99551    1.01294    1.02205
                1.03136    1.04084
c ------------------------------------------------------------------------------
  fc754   mu-      image at IL1
  fmesh754:|   geom=rec  origin=-7 -7   +1.0
       imesh 7 iints 1400
       jmesh 7 jints 1400     kmesh   +1.2  out=cf
  DE754 LIN     5.06578    5.52427    6.02426    6.56950    7.16409    7.81250
                8.51959    9.29068   10.13160   11.04850   12.04850   13.13900
               14.32820   15.62500   17.03920   18.58140   20.26310   22.09710
               24.09700   26.27800   28.65640   31.25000   34.07840   37.16270
               40.52620   44.19420   48.19410   52.55600   57.31280   62.50000
               68.15670   74.32540   81.05250   88.38830   96.38820  105.11200
              114.62600  125.00000  136.31300  148.65100  162.10500  176.77699
              192.77600  210.22400  229.25101  250.00000  272.62701  297.30200
              324.20999  353.55301  385.55301  420.44800  458.50201  500.00000
              545.25403  594.60400  648.41998  707.10699  771.10498  840.89600
              917.00403 1000.00000
  DF754 LIN     5.46768    5.12906    4.81208    4.81208    4.23864    3.97987  $ ratio of muon dE/dx values
                3.73813    3.51271    3.30252    3.30252    2.92424    2.75446  $ to proton dE/dx at 1-GeV
                2.59712    2.45038    2.31414    2.31414    2.07065    1.96219
                1.86209    1.76934    1.68382    1.68382    1.53230    1.46558
                1.40439    1.34837    1.29722    1.29722    1.20832    1.17001
                1.13548    1.10451    1.07689    1.07689    1.03084    1.01203
                0.99580    0.98199    0.97036    0.97036    0.95301    0.94702
                0.94266    0.93981    0.93837    0.93837    0.93926    0.94139
                0.94451    0.94855    0.95341    0.95341    0.96525    0.97210
                0.97946    0.98728    0.99551    0.99551    1.01294    1.02205
                1.03136    1.04084
c ------------------------------------------------------------------------------
  fc854   deuteron image at IL1 -- d's are the largest fraction of other stuff
  fmesh854:d   geom=rec  origin=-7 -7   +1.0
       imesh 7 iints 1400
       jmesh 7 jints 1400     kmesh   +1.2  out=cf
  DE854 LIN     5.06578    5.52427    6.02426    6.56950    7.16409    7.81250
                8.51959    9.29068   10.13160   11.04850   12.04850   13.13900
               14.32820   15.62500   17.03920   18.58140   20.26310   22.09710
               24.09700   26.27800   28.65640   31.25000   34.07840   37.16270
               40.52620   44.19420   48.19410   52.55600   57.31280   62.50000
               68.15670   74.32540   81.05250   88.38830   96.38820  105.11200
              114.62600  125.00000  136.31300  148.65100  162.10500  176.77699
              192.77600  210.22400  229.25101  250.00000  272.62701  297.30200
              324.20999  353.55301  385.55301  420.44800  458.50201  500.00000
              545.25403  594.60400  648.41998  707.10699  771.10498  840.89600
              917.00403 1000.00000
  DF854 LIN    46.99316   43.84974   40.86316   40.86316   35.35503   32.83821  $ ratio of deuteron dE/dx
               30.45042   28.19230   26.07328   26.07328   23.06054   21.76551  $ to proton dE/dx at 1-GeV
               20.52985   19.35507   18.23888   18.23888   16.17406   15.21982
```

```
             14.32294   13.46847   12.66044   12.66044   11.17413   10.49369
              9.85235    9.24588    8.67708    8.67708    7.63658    7.16322
              6.71806    6.30098    5.90950    5.90950    5.19951    4.87786
              4.57721    4.29610    4.03353    4.03353    3.55937    3.34606
              3.14718    2.96202    2.78962    2.78962    2.48081    2.34240
              2.21404    2.09500    1.98478    1.98478    1.78873    1.70176
              1.62150    1.54761    1.47970    1.47970    1.36034    1.30822
              1.26072    1.21756
c --------------------------------------------------------------------------------
  fc954   triton   image at IL1
  fmesh954:t   geom=rec  origin=-7 -7   +1.0
         imesh 7 iints 1400
         jmesh 7 jints 1400     kmesh   +1.2  out=cf
  DE954 LIN     5.06578    5.52427    6.02426    6.56950    7.16409    7.81250
                8.51959    9.29068   10.13160   11.04850   12.04850   13.13900
               14.32820   15.62500   17.03920   18.58140   20.26310   22.09710
               24.09700   26.27800   28.65640   31.25000   34.07840   37.16270
               40.52620   44.19420   48.19410   52.55600   57.31280   62.50000
               68.15670   74.32540   81.05250   88.38830   96.38820  105.11200
              114.62600  125.00000  136.31300  148.65100  162.10500  176.77699
              192.77600  210.22400  229.25101  250.00000  272.62701  297.30200
              324.20999  353.55301  385.55301  420.44800  458.50201  500.00000
              545.25403  594.60400  648.41998  707.10699  771.10498  840.89600
              917.00403 1000.00000
  DF954 LIN    63.82817   59.91015   56.16025   56.16025   49.15790   45.91025  $ ratio of triton dE/dx
               42.82045   39.88614   37.11004   37.11004   32.01544   29.66841  $ to proton dE/dx at 1-GeV
               27.46039   25.38572   23.95152   23.95152   21.33982   20.12637
               18.97208   17.87300   16.83272   16.83272   14.91396   14.02916
               13.18993   12.39757   11.64733   11.64733   10.27243    9.64296
                9.04943    8.49191    7.96623    7.96623    7.00925    6.57388
                6.16580    5.78267    5.42411    5.42411    4.77385    4.47999
                4.20520    3.94859    3.70890    3.70890    3.27715    3.08300
                2.90226    2.73404    2.57816    2.57816    2.29787    2.17273
                2.05674    1.94937    1.85027    1.85027    1.67385    1.59580
                1.52399    1.45801
c --------------------------------------------------------------------------------
  fc1054   3He      image at IL1
  fmesh1054:s   geom=rec  origin=-7 -7   +1.0
         imesh 7 iints 1400
         jmesh 7 jints 1400     kmesh   +1.2  out=cf
  DE1054 LIN    5.06578    5.52427    6.02426    6.56950    7.16409    7.81250
                8.51959    9.29068   10.13160   11.04850   12.04850   13.13900
               14.32820   15.62500   17.03920   18.58140   20.26310   22.09710
               24.09700   26.27800   28.65640   31.25000   34.07840   37.16270
               40.52620   44.19420   48.19410   52.55600   57.31280   62.50000
               68.15670   74.32540   81.05250   88.38830   96.38820  105.11200
              114.62600  125.00000  136.31300  148.65100  162.10500  176.77699
              192.77600  210.22400  229.25101  250.00000  272.62701  297.30200
              324.20999  353.55301  385.55301  420.44800  458.50201  500.00000
              545.25403  594.60400  648.41998  707.10699  771.10498  840.89600
              917.00403 1000.00000
  DF1054 LIN  251.35355  236.69599  222.48483  222.48483  195.55695  182.91138  $ ratio of helion dE/dx
              170.79847  159.23402  148.24679  148.24679  127.99319  118.63409  $ to proton dE/dx at 1-GeV
              109.81699  101.52535   95.79416   95.79416   85.34892   80.49541
               75.87840   71.48250   67.32202   67.32202   59.64778   56.10900
               52.75274   49.58344   46.58300   46.58300   41.08420   38.56652
               36.19267   33.96295   31.86046   31.86046   28.03308   26.29187
               24.65978   23.12746   21.69341   21.69341   19.09277   17.91749
               16.81848   15.79222   14.83359   14.83359   13.10683   12.33043
               11.60751   10.93476   10.31132   10.31132    9.19032    8.68987
                8.22594    7.79659    7.40023    7.40023    6.69472    6.38256
                6.09534    5.83149
c --------------------------------------------------------------------------------
  fc1154   alpha    image at IL1
  fmesh1154:a   geom=rec  origin=-7 -7   +1.0
         imesh 7 iints 1400
         jmesh 7 jints 1400     kmesh   +1.2  out=cf
  DE1154 LIN    5.06578    5.52427    6.02426    6.56950    7.16409    7.81250
                8.51959    9.29068   10.13160   11.04850   12.04850   13.13900
               14.32820   15.62500   17.03920   18.58140   20.26310   22.09710
```

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              24.09700   26.27800   28.65640   31.25000   34.07840   37.16270
              40.52620   44.19420   48.19410   52.55600   57.31280   62.50000
              68.15670   74.32540   81.05250   88.38830   96.38820  105.11200
             114.62600  125.00000  136.31300  148.65100  162.10500  176.77699
             192.77600  210.22400  229.25101  250.00000  272.62701  297.30200
             324.20999  353.55301  385.55301  420.44800  458.50201  500.00000
             545.25403  594.60400  648.41998  707.10699  771.10498  840.89600
             917.00403 1000.00000
  DF1154 LIN 301.14149  285.98364  270.49441  270.49441  240.57549  226.23997 $ ratio of alpha dE/dx values
             212.38032  199.03174  186.25032  186.25032  162.27752  151.12927 $ to proton dE/dx at 1-GeV
             140.61071  130.57880  121.09534  121.09534  103.69260   97.26703
              91.85572   86.69168   81.76917   81.76917   72.63794   68.41291
              64.41078   60.62861   57.03621   57.03621   50.41296   47.37011
              44.49215   41.78218   39.22719   39.22719   34.54728   32.40993
              30.40391   28.51857   26.74653   26.74653   23.52734   22.06799
              20.70093   19.42070   18.22400   18.22400   16.05998   15.08374
              14.17299   13.32413   12.53271   12.53271   11.10994   10.47421
               9.88132    9.33070    8.82005    8.82005    7.90815    7.50345
               7.12849    6.78267
c ------------------------------------------------------------------------------
C -------|---------|---------|---------|---------|---------|---------|---------|---------|
```