# Mean LET response of RRMD-Ⅲ measured for protons from the NIRS cyclotron

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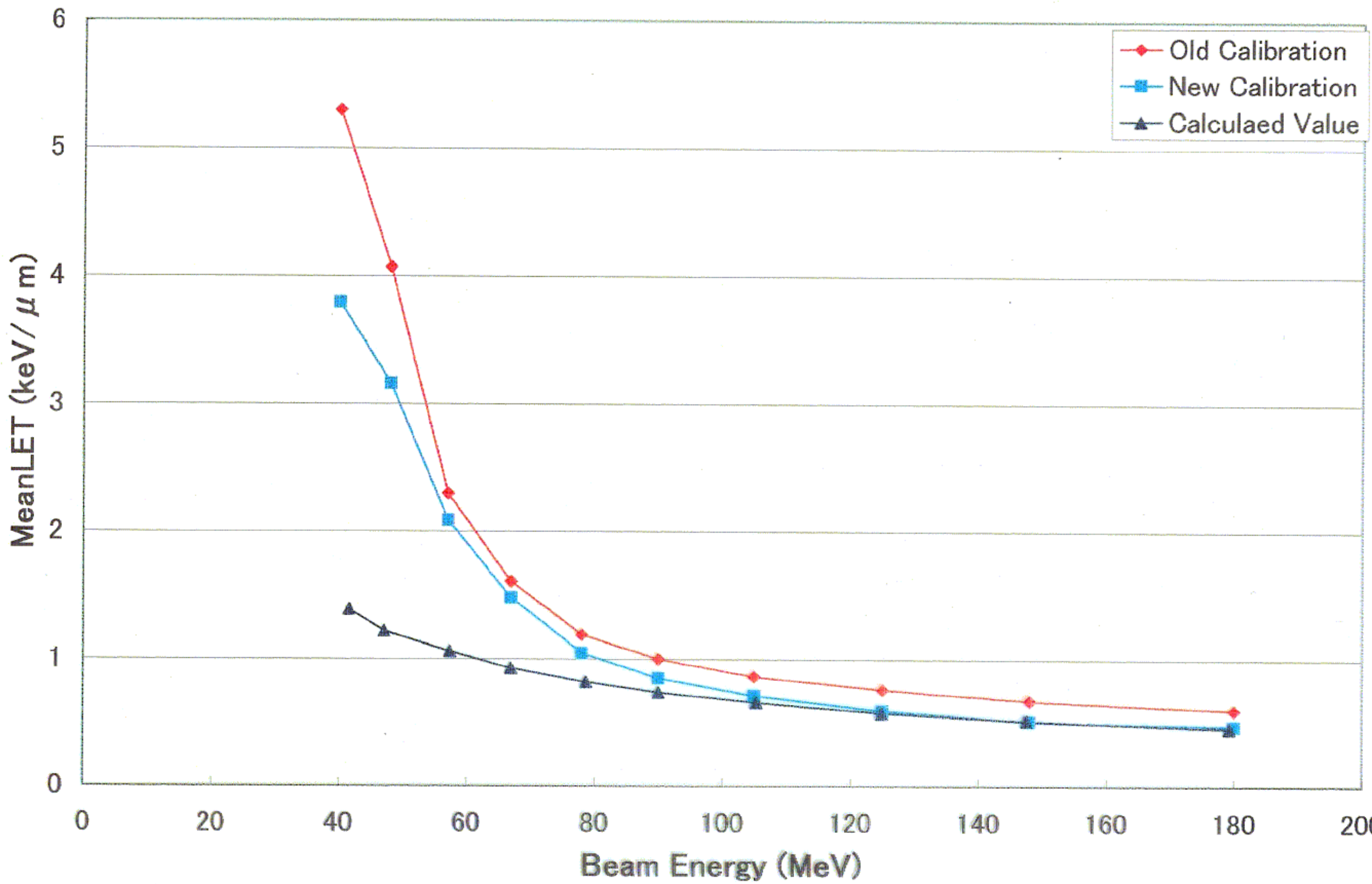
Summary of RRMD-III experiment at Loma Linda:

I. For protons from 180 MeV to 70 MeV, the mean LET obtained by RRMD-III was 30% higher than those calculated by a stopping power formula.

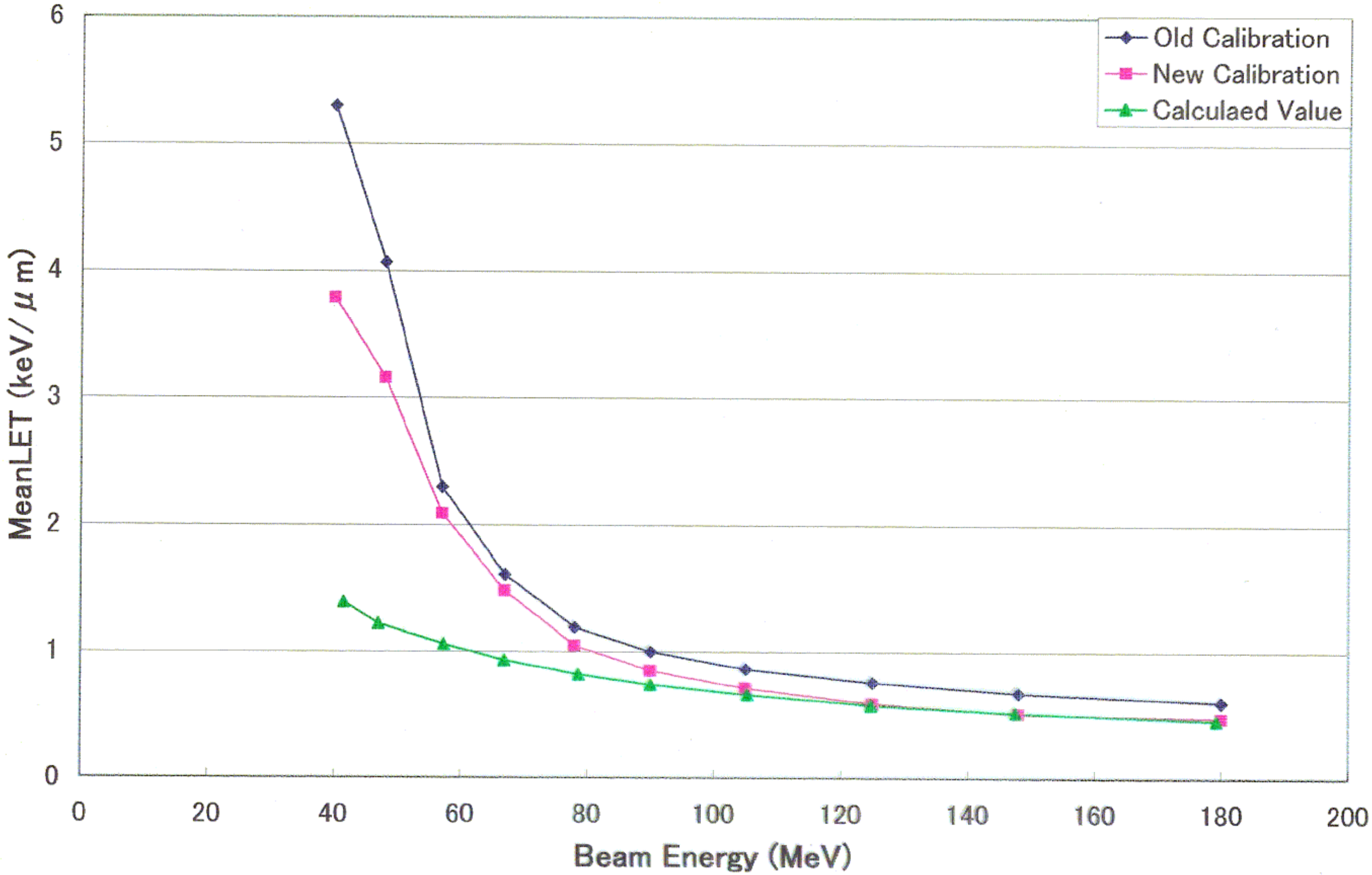
II. For protons below 70 MeV, a large discrepancy in the mean LET between experimental results and the calculation was found.

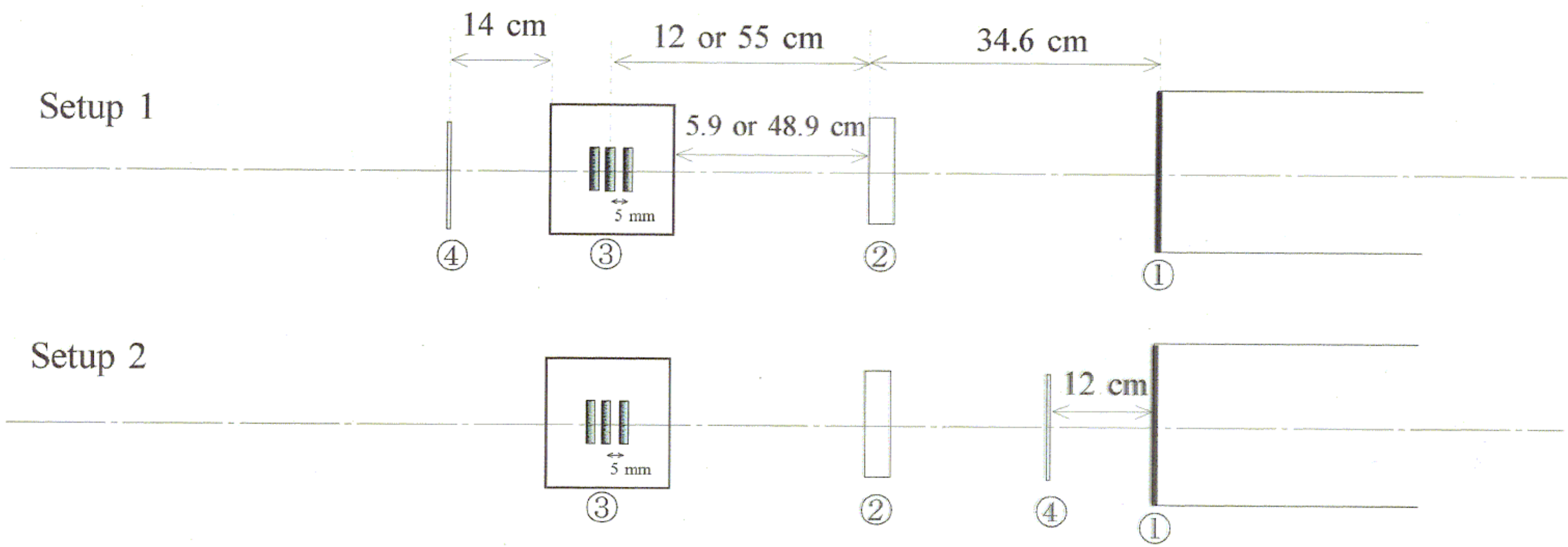
1. As for I, the experimental result obtained by a new calibration curve showed good agreement with the calculation.

2. As for II, for investigating the causes of such a large discrepancy, a new experiment of RRMD-III was achieved by using protons below 70 MeV from the cyclotron at NIRS.



Old Calibration
New Calibration
Calculaed Value
MeanLET (keV/ μ m)
Beam Energy (MeV)
0
1
2
3
4
5
6
0
20
40
60
80
100
120
140
160
180
200


Old Calibration
New Calibration
Calculaed Value
MeanLET (keV/ μ m)
Beam Energy (MeV)
0
1
2
3
4
5
6
0
20
40
60
80
100
120
140
160
180
200




① Beam window (0.1 mm thick Aluminum, 40 mm $\phi$ )

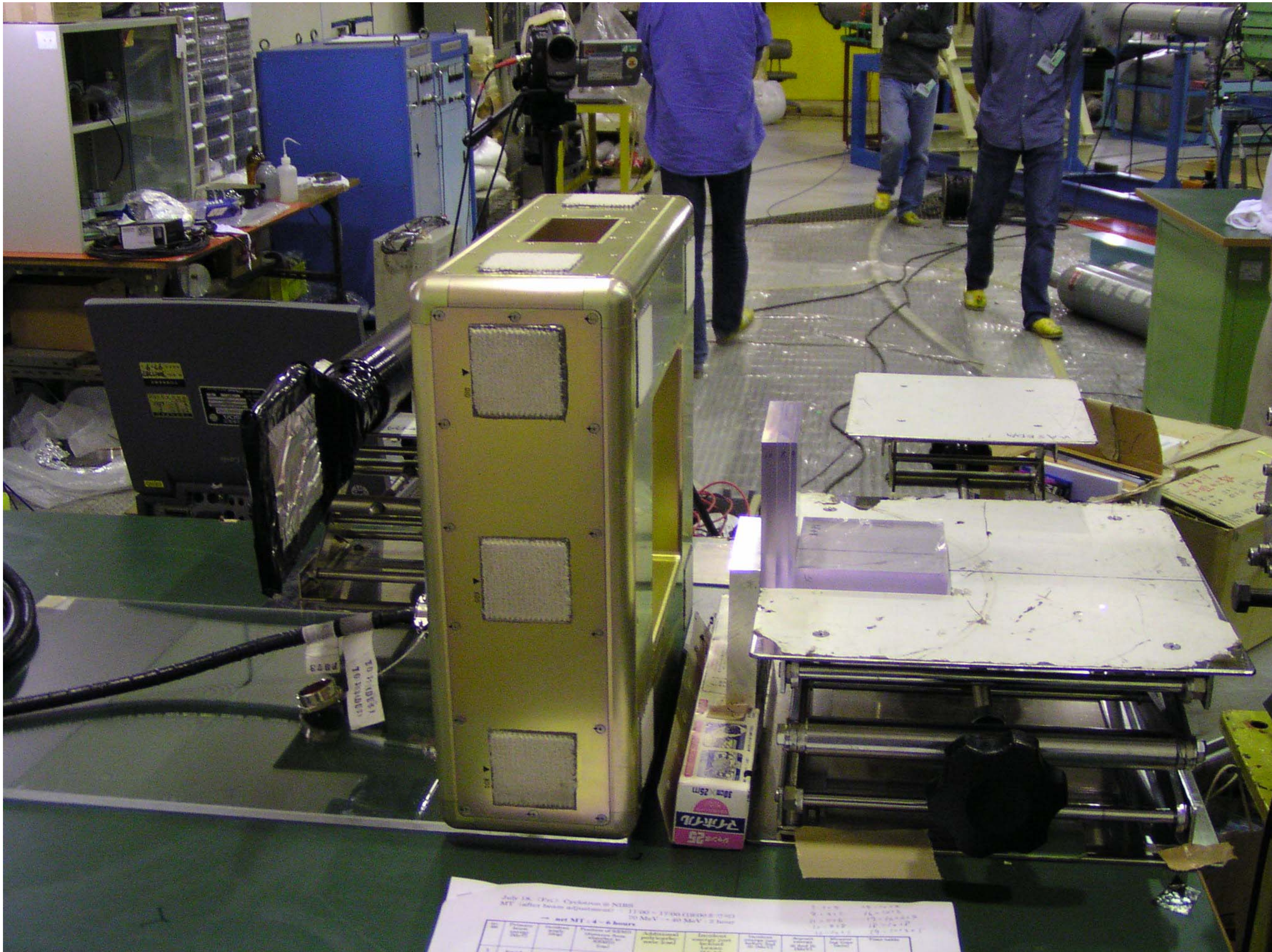
② Absorber (Lexan with various thickness)

③ RRMD-III

④ Plastic scintillator (0.1 mm thick, 10 cm × 10 cm).

For the previous LET calibration, we used heavy ion beams from HIMAC and cosmic muons and assumed that the peak in the energy loss distribution corresponds to be the mean value of the distribution. However, this is in correct. The peak of the distribution is different from the mean value, in specially, for low LET particles like minimum ionizing particles. For correct LET calibration, we must use the most probable value predicted by theory (Landau theory or Vavilov theory).

For the new LET calibration, we used such most probable values predicted by Landau theory for low LET particles and predicted by Vavilov theory for relativistic high LET particles. Here, I like to show you two typical cases of Landau distribution and Vabilov distribution.

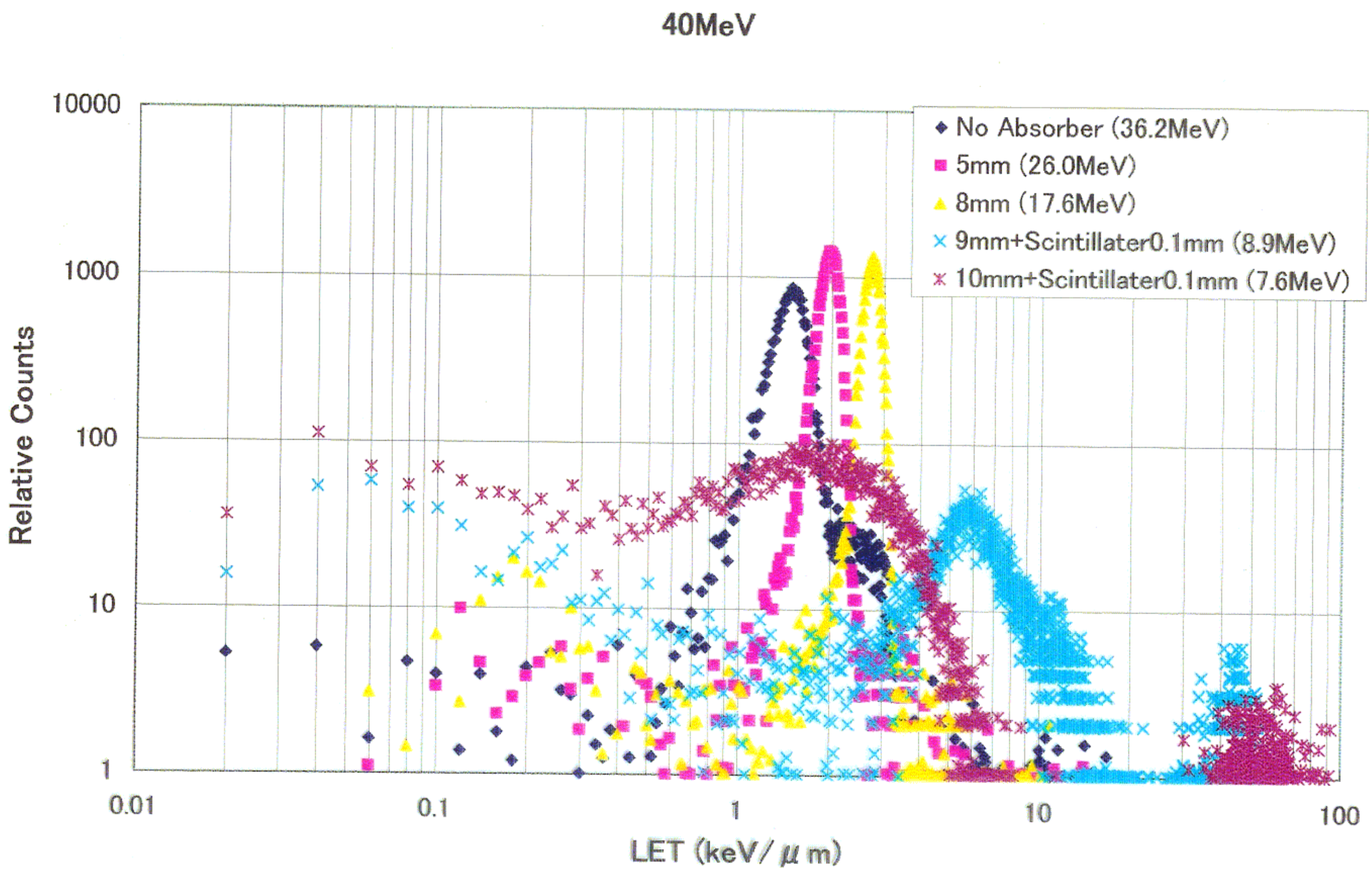


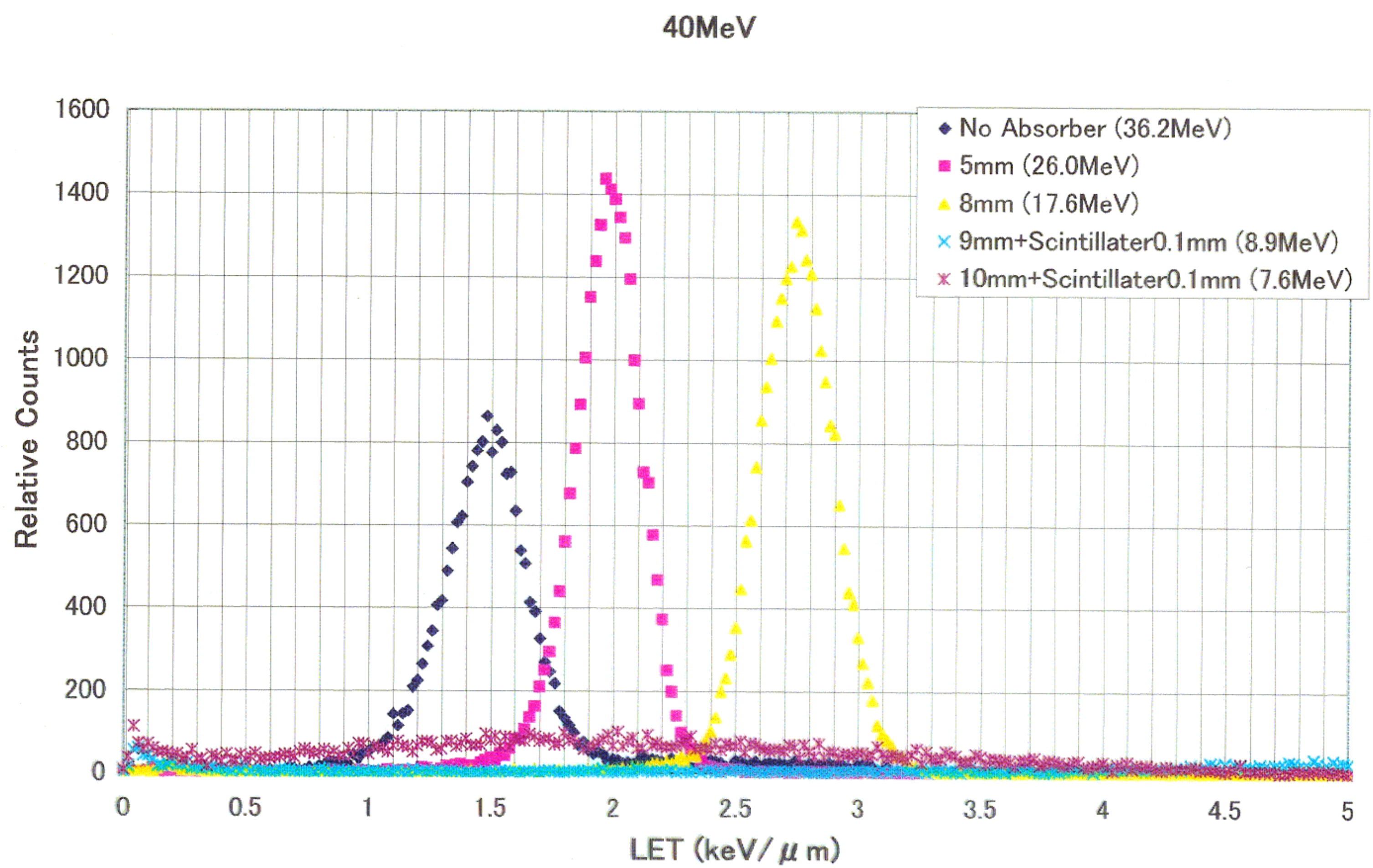
July 18. (Fri.) Cyclotron @ NIRS (final)

→ **net MT : 4 ~ 6 hours**

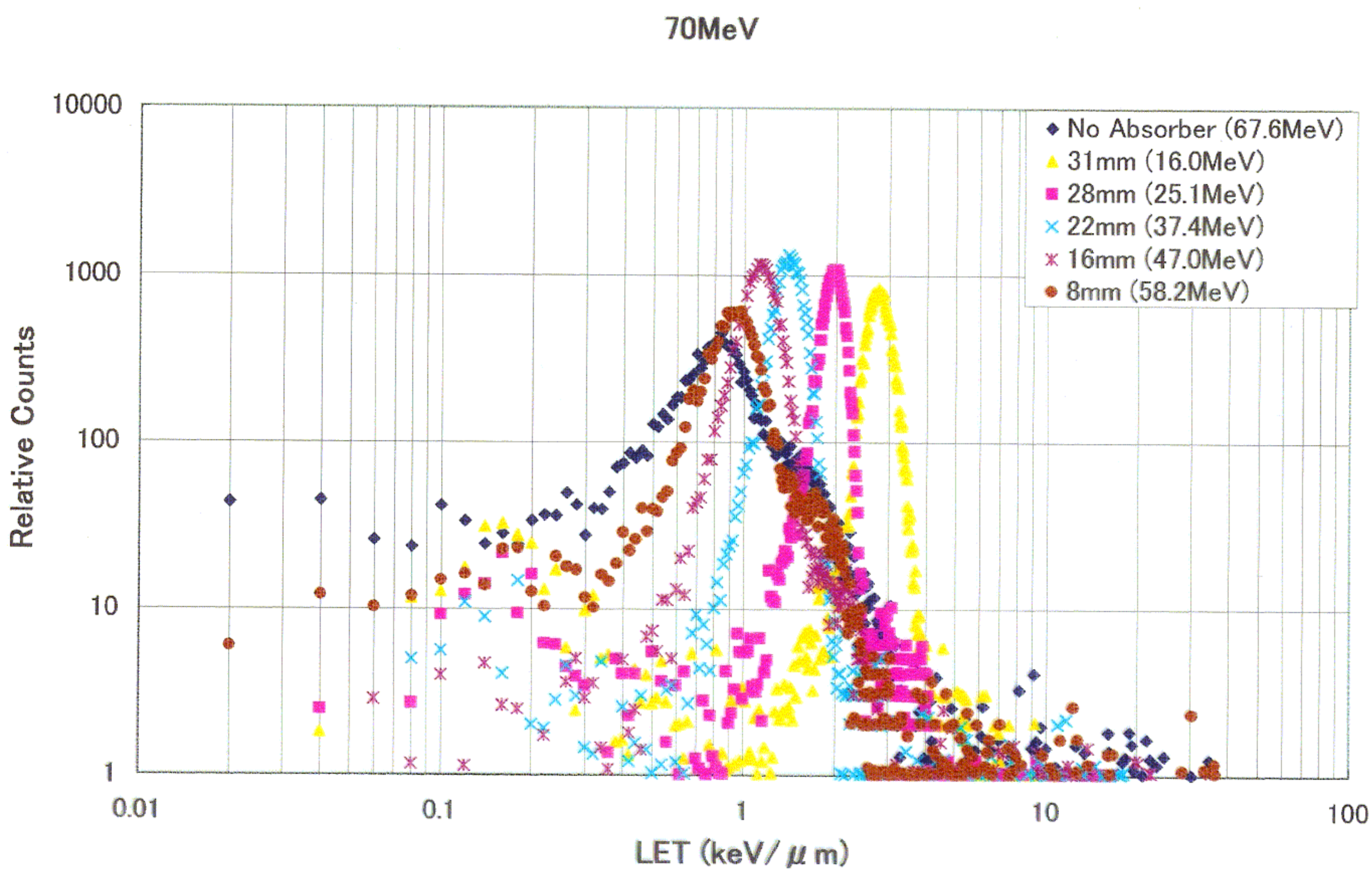
Lexan = 3, 4, 5, 6, 8, 10 × 3, 15 × 2 mm
7 = 3 + 4, 13 = 10 + 3, 18 = 10 + 8
9 = 4 + 5, 14 = 10 + 4, 19 = 10 + 4 + 5
11 = 5 + 6, 16 = 10 + 6
12 = 4 + 8, 17 = 10 + 3 + 4

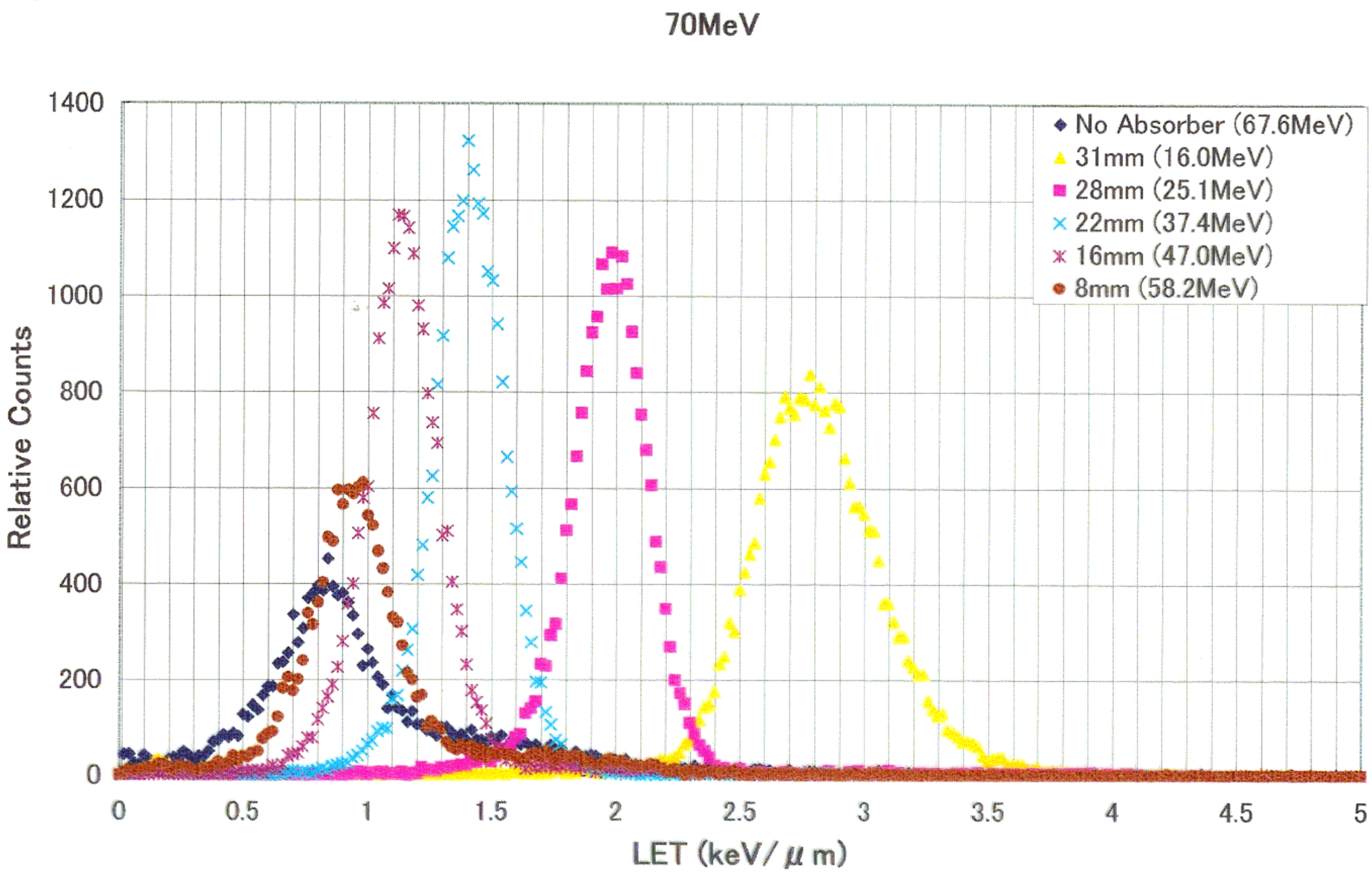
| no. | Primary beam energy [MeV] | Position of a plastic scintillator 0.1 mmt | Position of RRMD (distance from absorber to the center of RRMD) [cm] | Additional polyicarbo-nate [cm] | Incident energy just behind Lexan [MeV] | Incident energy just before 2nd Si [MeV] | deposit energy @ 2nd Si [MeV] | Measuring time [min] |
|---|---|---|---|---|---|---|---|---|
| 1 | 70 | Behind RRMD | 12 | 0.0 | 69.45 | 67.62 (3.4%) | 0.917 | 30 |
| 2 | 70 | Behind | 12 | 2.79 | 28.87 | 25.07 (64.2%) | 2.051 | 30 |
| 3 | 70 | Behind | 12 | 3.10 | 21.13 | 16.00 (77.1%) | 3.072 | 30 |
| 4 | 70 | Behind | 12 | 2.20 | 40.21 | 37.35 (46.6%) | 1.469 | 30 |
| 5 | 70 | Behind | 12 | 1.61 | 49.40 | 46.99 (32.9%) | 1.220 | 30 |
| 6 | 70 | Behind | 12 | 0.79 | 60.27 | 58.22 (16.8%) | 1.030 | 30 |
| 7 | 70 | Behind | 55 | 2.79 | 28.87 | 24.07 (65.6%) | 2.124 | 30 |
| 8 | 70 | Behind | 55 | 2.20 | 40.21 | 36.64 (47.7%) | 1.492 | 30 |
| 9 | test | | | | | | | |
| Switch to 40 MeV | | | | | | | | |
| 9 | 40 | Behind | 12 | 0.0 | 39.14 | 36.22 (9.4%) | 1.507 | 30 |
| 10 | 40 | Behind | 12 | 0.49 | 29.70 | 25.99 (35.0%) | 1.989 | 30 |
| 11 | 40 | Behind | 12 | 0.79 | 22.46 | 17.64 (55.9%) | 2.802 | 30 |
| 12 | 40 | In front | 12 | 0.90 | 15.98 | 8.922 (77.7%) | 6.392 | 20 |
| 13 | 40 | In front | 12 | 1.00 | 11.95 | 7.637 (80.9%) | 7.637 | 20 |
| 14 | 40 | Behind | 55 | 0.49 | 29.70 | 25.02 (37.4%) | 2.054 | 30 |
| 15 | test | | | | | | | |


40MeV
Relative Counts
10000
1000
100
10
1
0.01
0.1
1
10
100
LET (keV/μm)
No Absorber (36.2MeV)
5mm (26.0MeV)
8mm (17.6MeV)
9mm+Scintillater0.1mm (8.9MeV)
10mm+Scintillater0.1mm (7.6MeV)

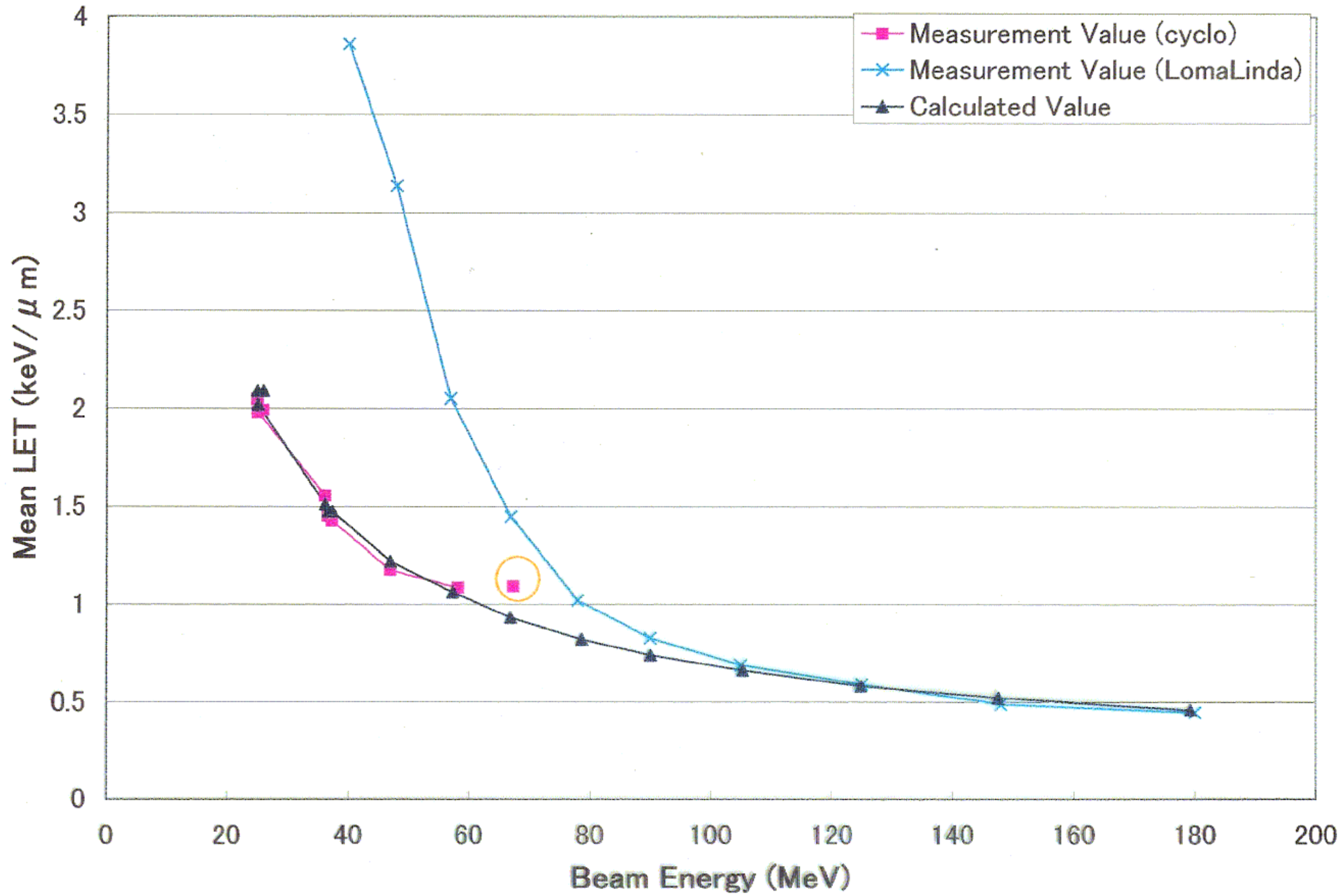


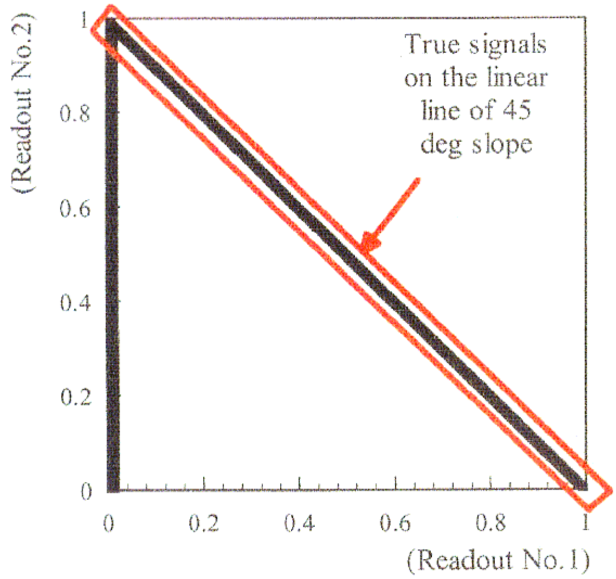
40MeV
1600
1400
1200
1000
800
600
400
200
0
Relative Counts
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
LET (keV/μm)
No Absorber (36.2MeV)
5mm (26.0MeV)
8mm (17.6MeV)
9mm+Scintillater0.1mm (8.9MeV)
10mm+Scintillater0.1mm (7.6MeV)


70MeV
10000
1000
100
10
1
Relative Counts
0.01
0.1
1
10
100
LET (keV/μm)
No Absorber (67.6MeV)
31mm (16.0MeV)
28mm (25.1MeV)
22mm (37.4MeV)
16mm (47.0MeV)
8mm (58.2MeV)

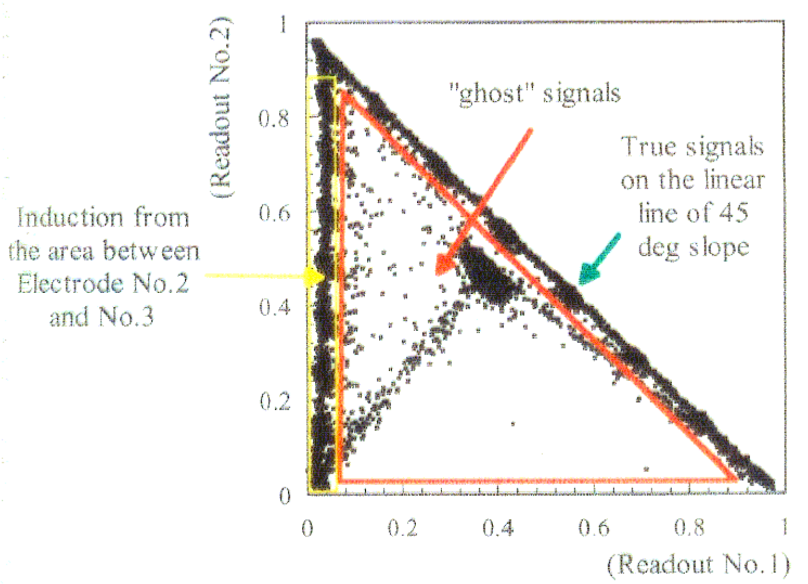


70MeV
Relative Counts
LET (keV/μm)
No Absorber (67.6MeV)
31mm (16.0MeV)
28mm (25.1MeV)
22mm (37.4MeV)
16mm (47.0MeV)
8mm (58.2MeV)
0
200
400
600
800
1000
1200
1400
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5


Measurement Value (cyclo)
Measurement Value (LomaLinda)
Calculated Value
Mean LET (keV/μm)
4
3.5
3
2.5
2
1.5
1
0.5
0
0
20
40
60
80
100
120
140
160
180
200
Beam Energy (MeV)

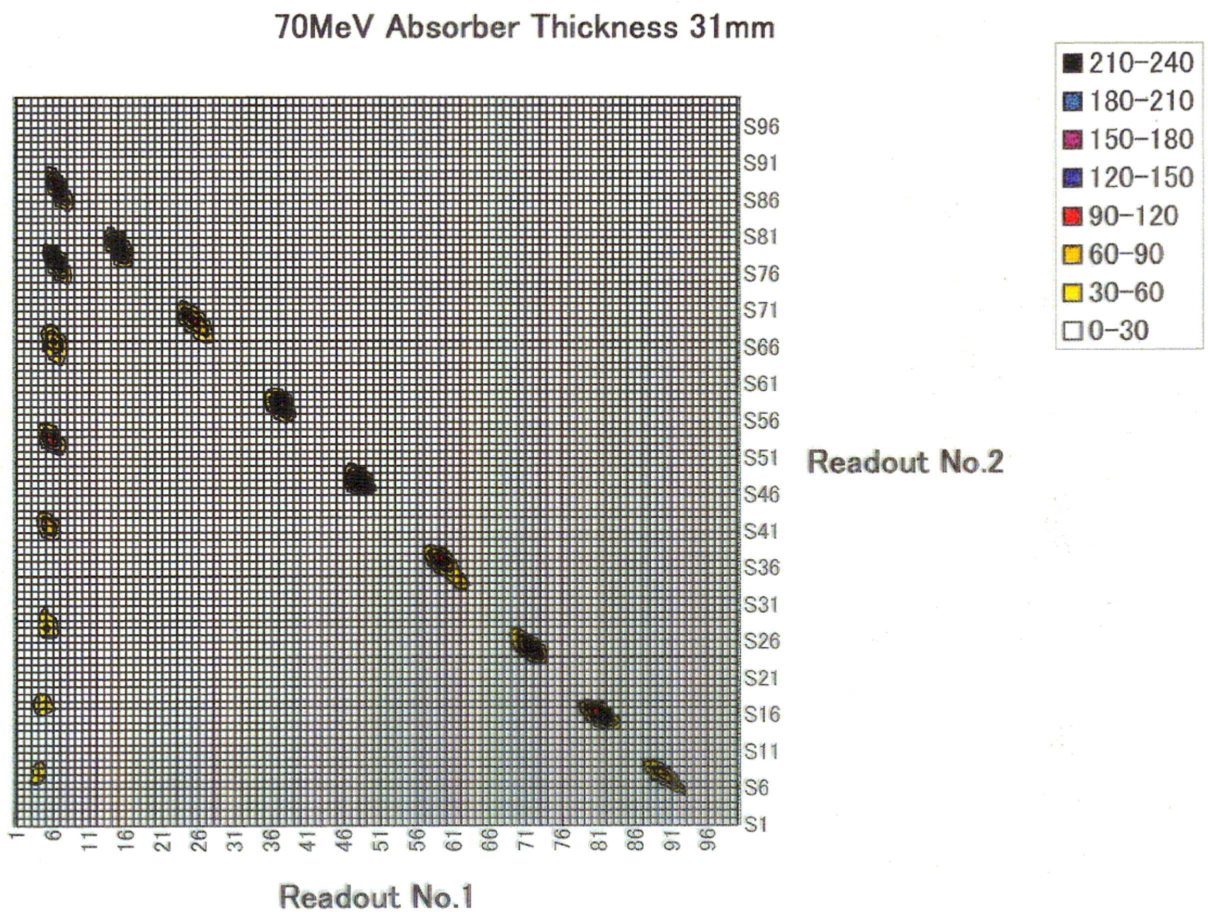



(a) Ideal Case

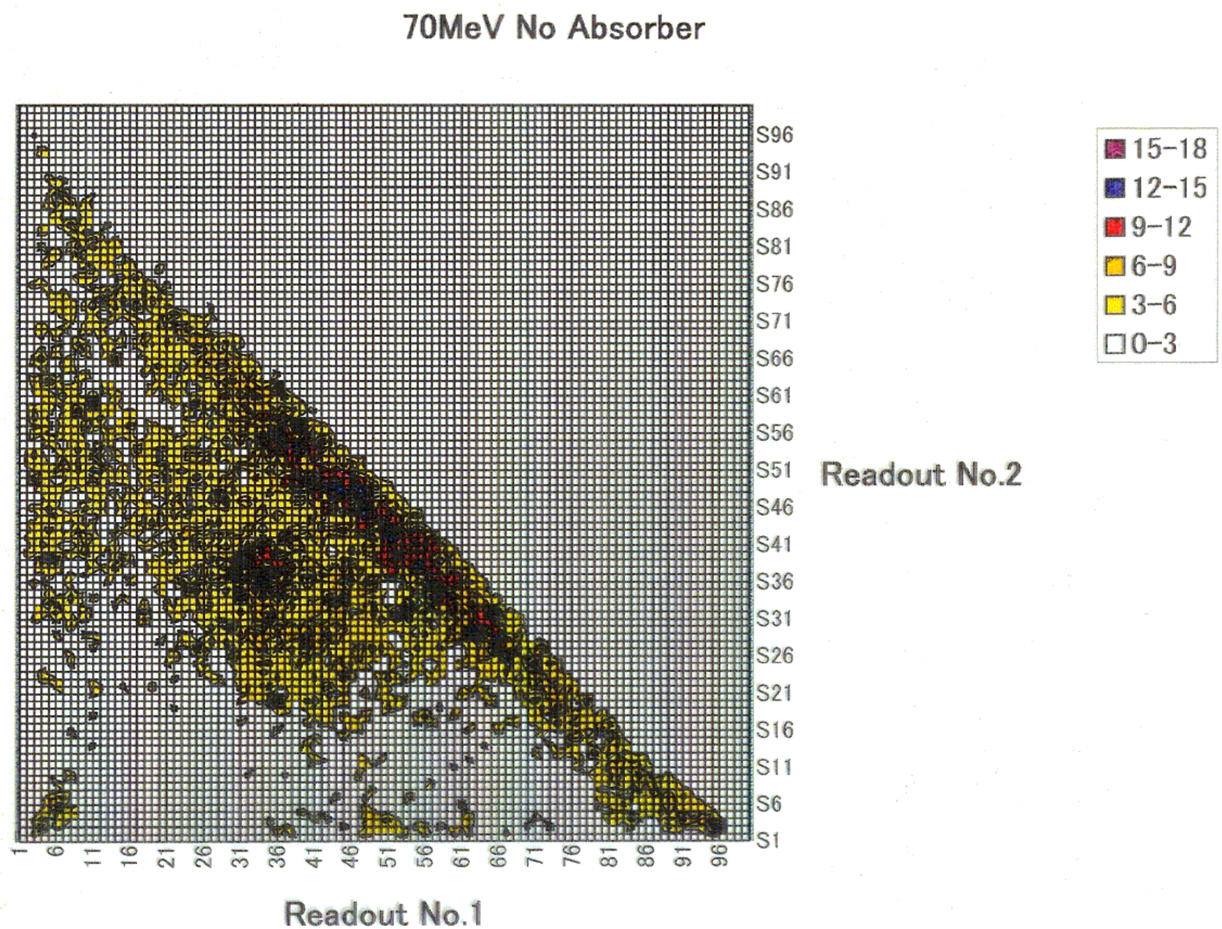


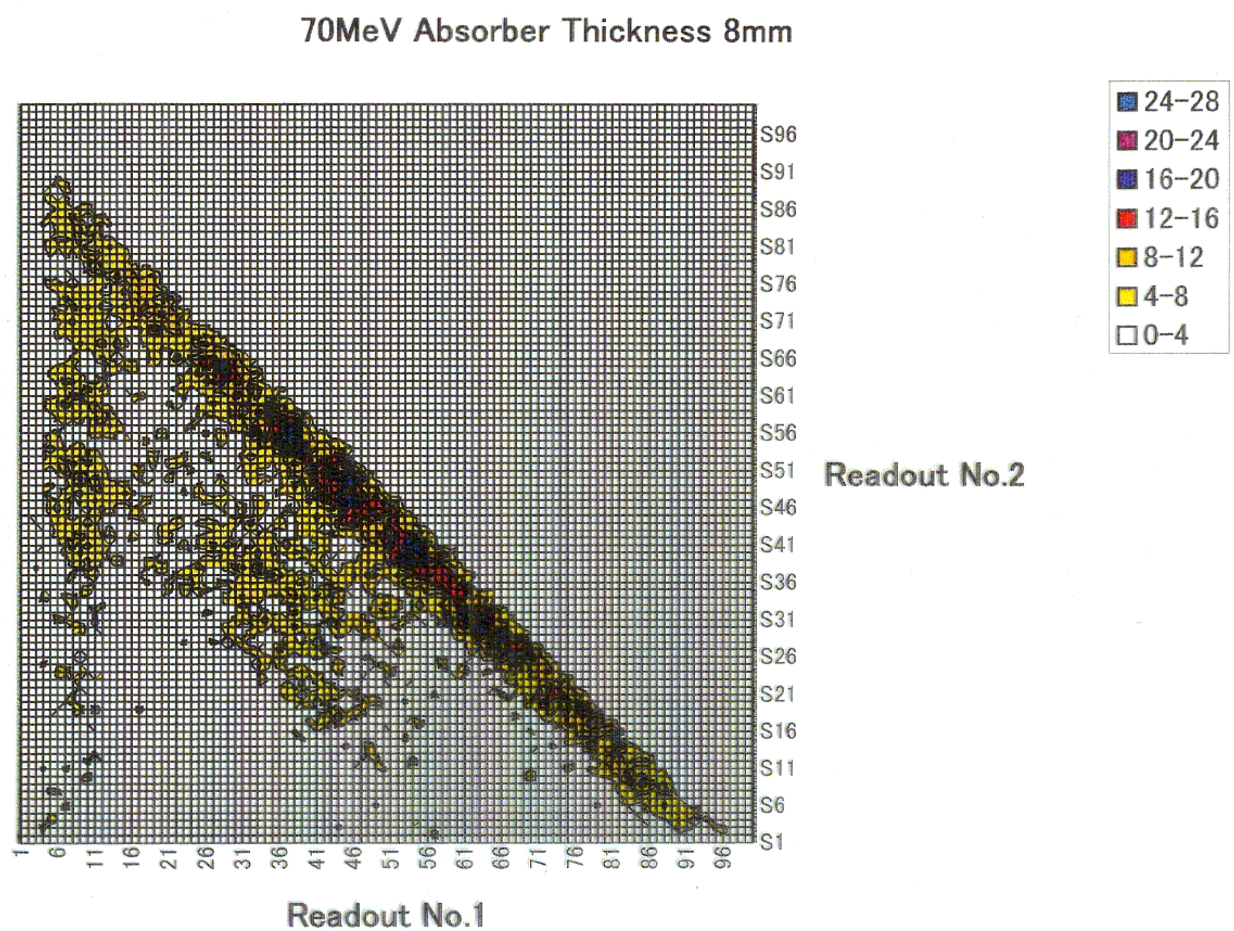

(b) Real plot obtained from exposure of alpha particles

Figure 9. Correlation plots between adjacent readouts. The ideal case is shown in (a) and the plots derived when alpha particles are irradiated over whole DSSD are shown in (b).

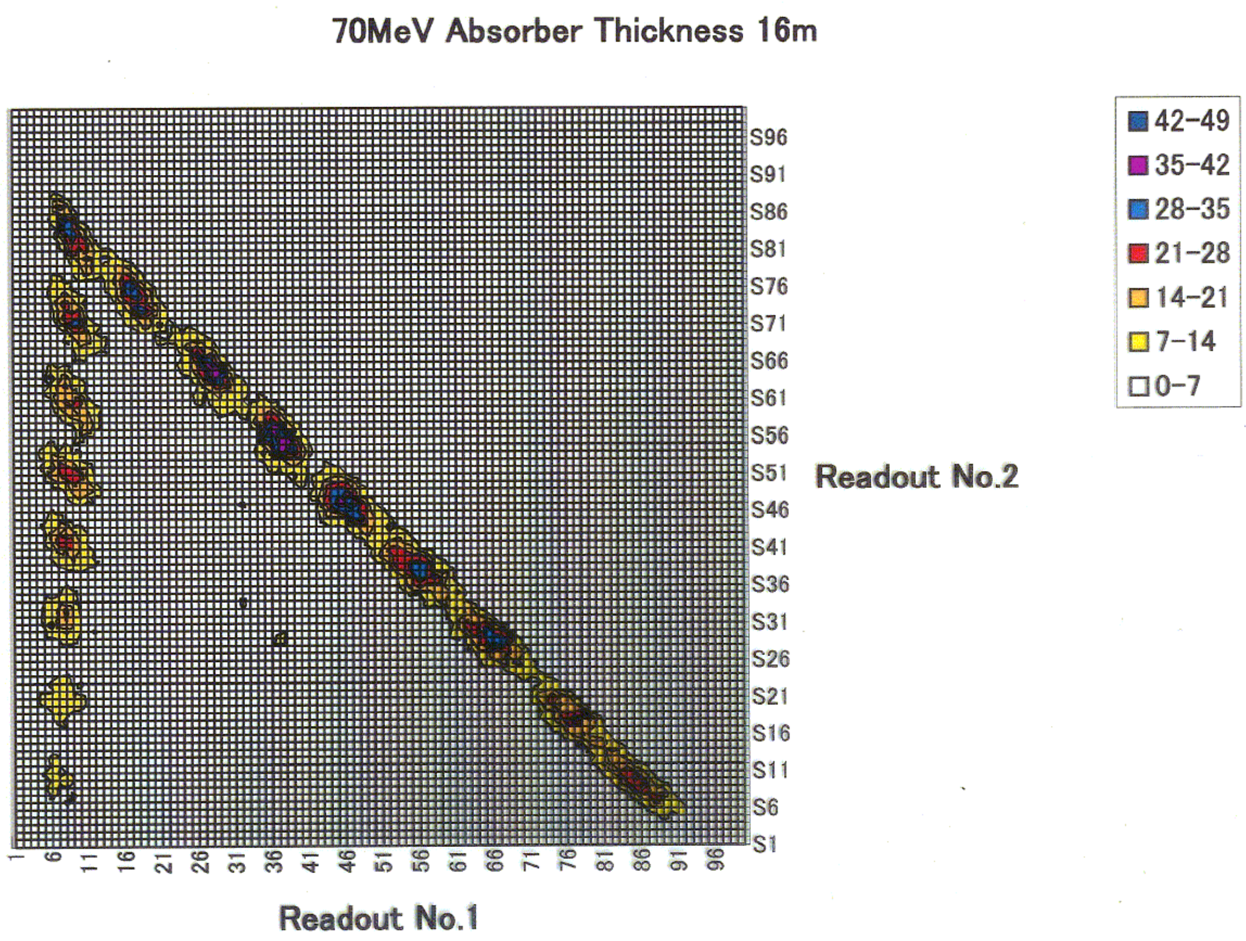


70MeV Absorber Thickness 31mm
210-240
180-210
150-180
120-150
90-120
60-90
30-60
0-30
S96
S91
S86
S81
S76
S71
S66
S61
S56
S51
S46
S41
S36
S31
S26
S21
S16
S11
S6
S1
Readout No.2
1
6
11
16
21
26
31
36
41
46
51
56
61
66
71
76
81
86
91
96
Readout No.1


70MeV No Absorber
15-18
12-15
9-12
6-9
3-6
0-3
Readout No.2
S96
S91
S86
S81
S76
S71
S66
S61
S56
S51
S46
S41
S36
S31
S26
S21
S16
S11
S6
S1
1
6
11
16
21
26
31
36
41
46
51
56
61
66
71
76
81
86
91
96
Readout No.1



70MeV Absorber Thickness 8mm
24-28
20-24
16-20
12-16
8-12
4-8
0-4
S96
S91
S86
S81
S76
S71
S66
S61
S56
S51
S46
S41
S36
S31
S26
S21
S16
S11
S6
S1
Readout No.2
1
6
11
16
21
26
31
36
41
46
51
56
61
66
71
76
81
86
91
96
Readout No.1


70MeV Absorber Thickness 16m
S96
S91
S86
S81
S76
S71
S66
S61
S56
S51
S46
S41
S36
S31
S26
S21
S16
S11
S6
S1
Readout No.2
1
6
11
16
21
26
31
36
41
46
51
56
61
66
71
76
81
86
91
96
Readout No.1
42-49
35-42
28-35
21-28
14-21
7-14
0-7

## Summary

1. 30% gap between the calculation and experiments at Loma Lind was disappeared by the use of new calibration curve
2. The result obtained at NIRS for protons obtained by the combination of 70 MeV and 40 MeV proton beams and several thin absorbers showed good agreement with the result of the energy loss calculation over the energy range from 70 MeV to 20 MeV.
3. A large deviation in mean LET for protons with energies lower than 70 MeV at Loma Linda was caused by largely distorted energy distribution of protons after passing through thick absorber which can not estimate from the simple energy loss calculation including its straggling.