Peak temperature ratio of TLD glow curves to investigate the spatial variation of LET in a clinical proton beam

University of Chicago – CDH Proton Center LET study

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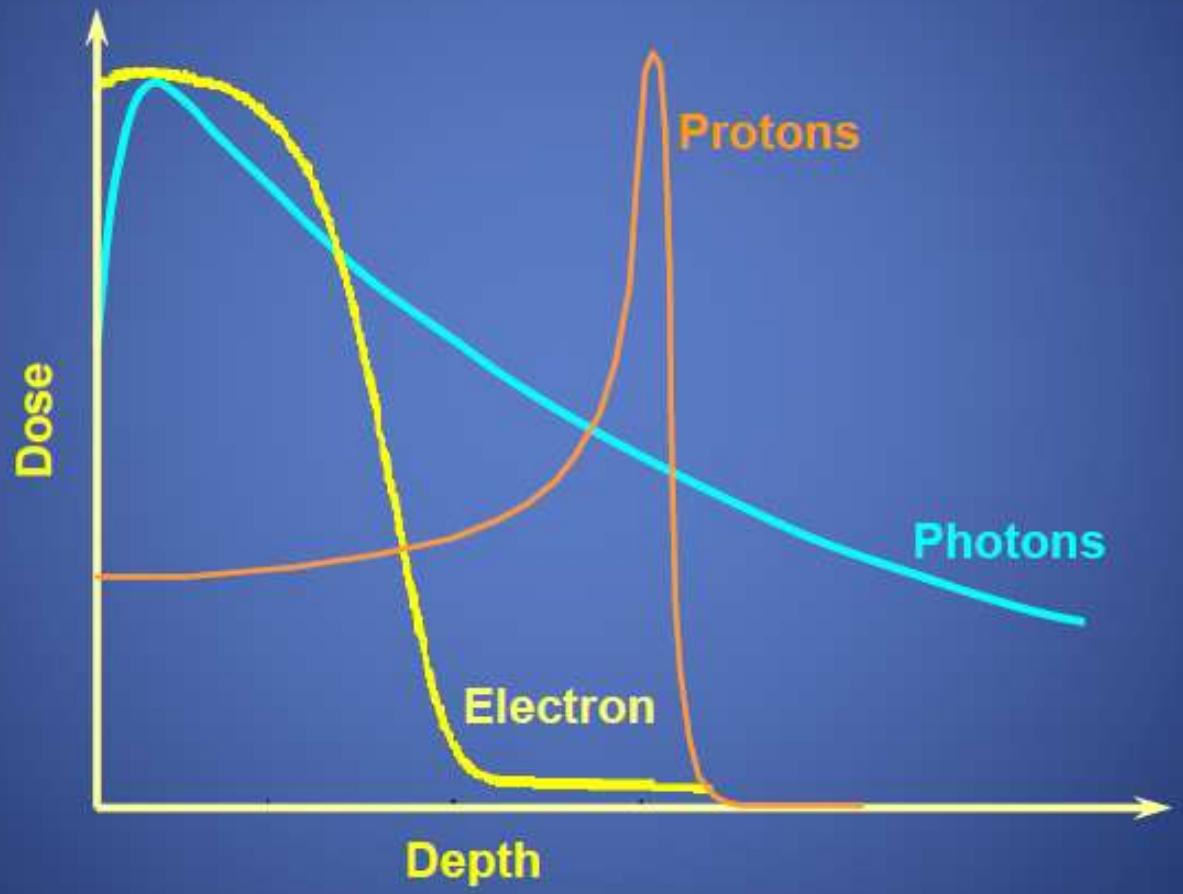
Purpose

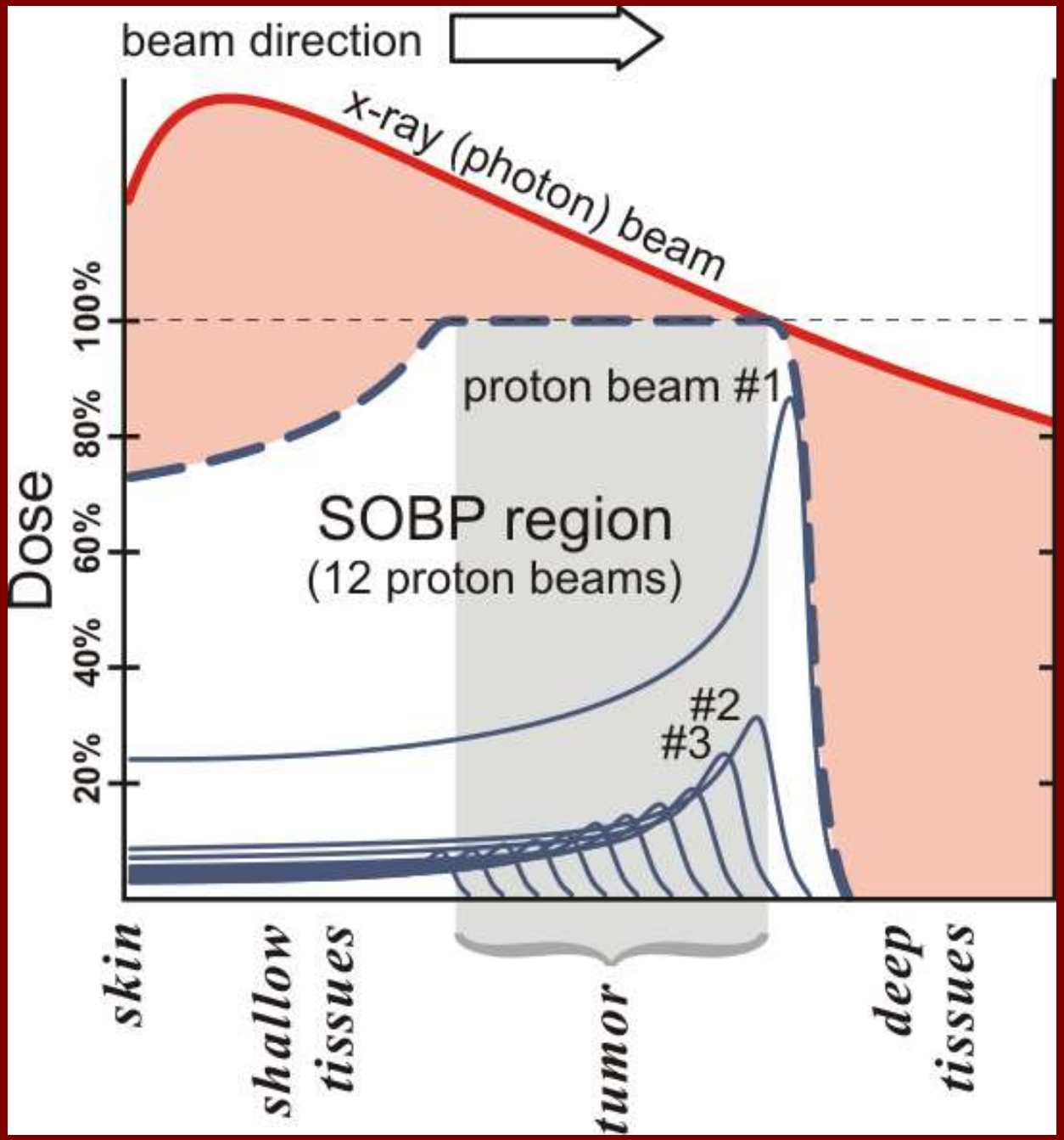
1. Investigate the possibility of using two peak analysis in TLDs to measure LET of a proton beam
2. Use two peak analysis in TLDs to measure the spatial variation of LET in the SOBP of a clinical proton beam
3. Use two peak analysis in TLDs to measure the LET in the distal dose fall-off region in a clinical proton beam

Depth dose curves



Bragg Peak

Dose Line Profile: depth_dose
Bragg Peak
proton pt A
Low entrance
No exit dose
Dose [%]
Distance [cm]
0
20
40
60
80
100
0
5
10
15
20
25


beam direction
x-ray (photon) beam
proton beam #1
SOBP region
(12 proton beams)
#2
#3
Dose
100%
80%
60%
40%
20%
skin
shallow tissues
tumor
deep tissues

Proton Therapy Advantages:

Conformal dose distribution→dose escalation

Significantly lower integral dose

Proton Therapy Concerns:

Out-of –field dose mostly from neutrons → Typically ↓with ↑field size

In field dose patient dose (neutrons) ↑ proton energy and field size

Variation of LET along the length of the proton beam

Why determine low and high LET components?

LET related to RBE

)

Biological damages depends on:

1.Absorbed dose

2.Spatial distribution of absorbed dose

3.Relative biological effectiveness (RBE)

Proton therapy uses a generic, spatially invariant RBE = 1.1

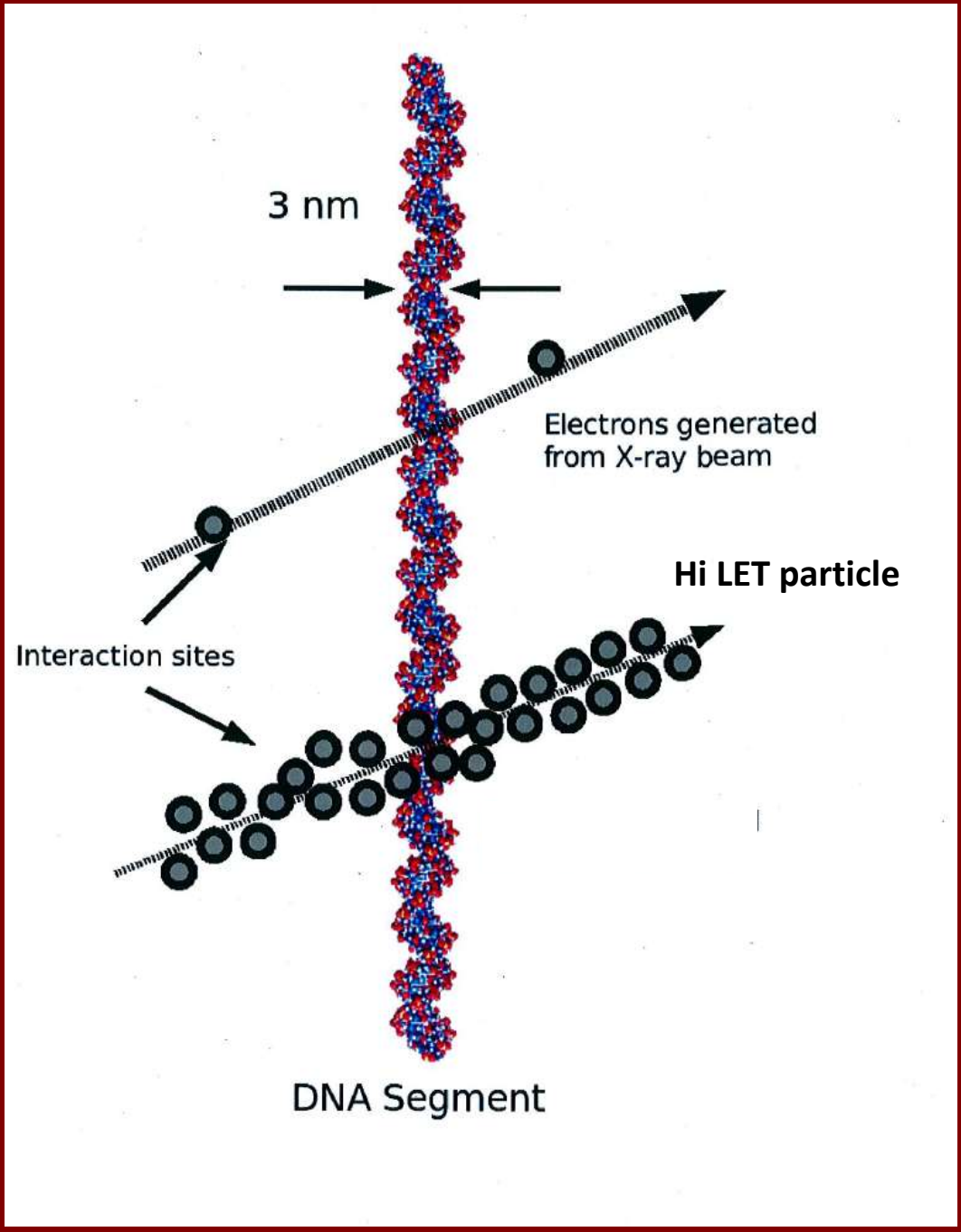
Evidence that RBE increases with LET →
The LET may vary in different portions of the SOBP

Relative Biological Effectiveness

- The amount of radiation dose is expressed in terms of absorbed energy; dose in Gy is a measure of energy absorbed/unit mass of tissue
- However, equal doses of different types of radiation *DO NOT* produce equal biological effects
- Key to the difference lies in the pattern of energy deposition at the microscopic level

Relative Biological Effectiveness (RBE)

$$\text{RBE} = \frac{\text{Dose of std rad (250 kVp x-rays) to produce Biol Eff}}{\text{Dose of test rad to produce the same Biol Eff}}$$


3 nm
Electrons generated
from X-ray beam
Hi LET particle
Interaction sites
DNA Segment

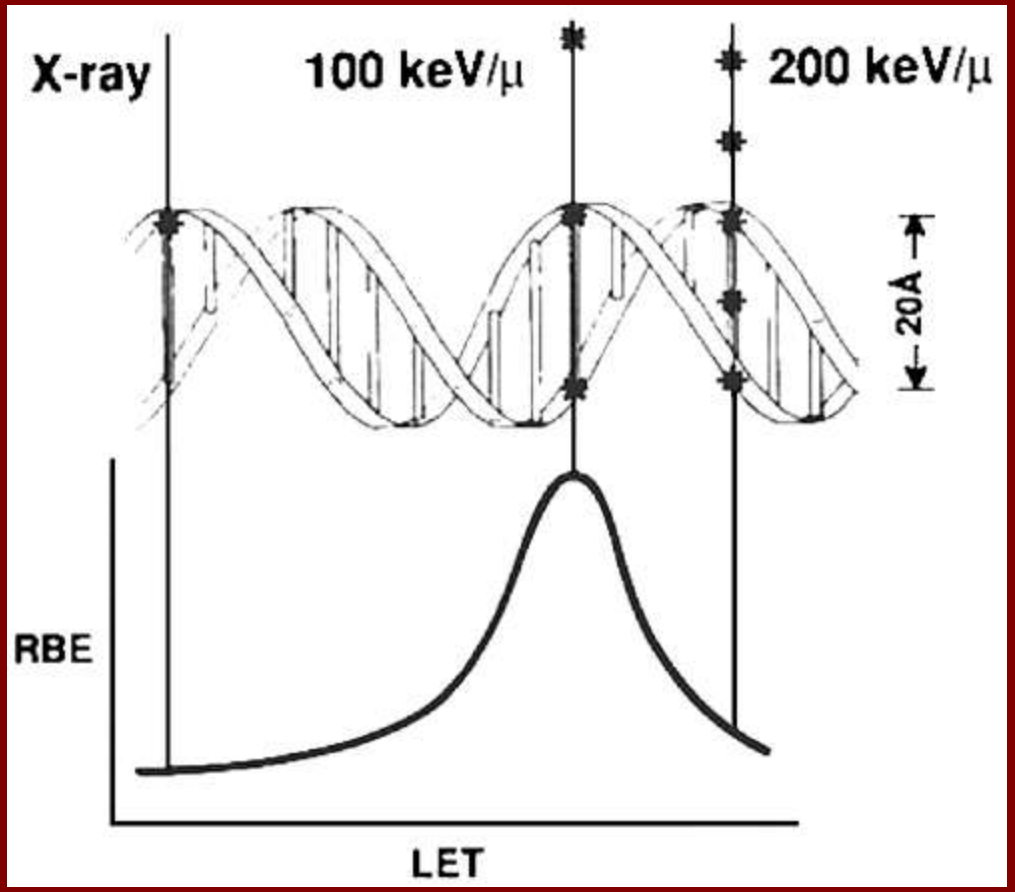


Diagram illustrating why radiation with a LET of 100 keV/μm has the greatest RBE for cell killing, mutagenesis, or oncogenic transformation. For this LET, the average separation between ionizing events coincides with the diameter of the DNA double helix (i.e., about 20A or 2 nm). Radiation of this quality is most likely to produce a double-strand break from one track for a given absorbed dose

Linear Energy Transfer (LET)

- LET is the energy transferred per unit length of track
- Unit is the kiloelectron volt per micrometer (keV/μm) of unit density material
- LET is an average value that can be calculated in different ways

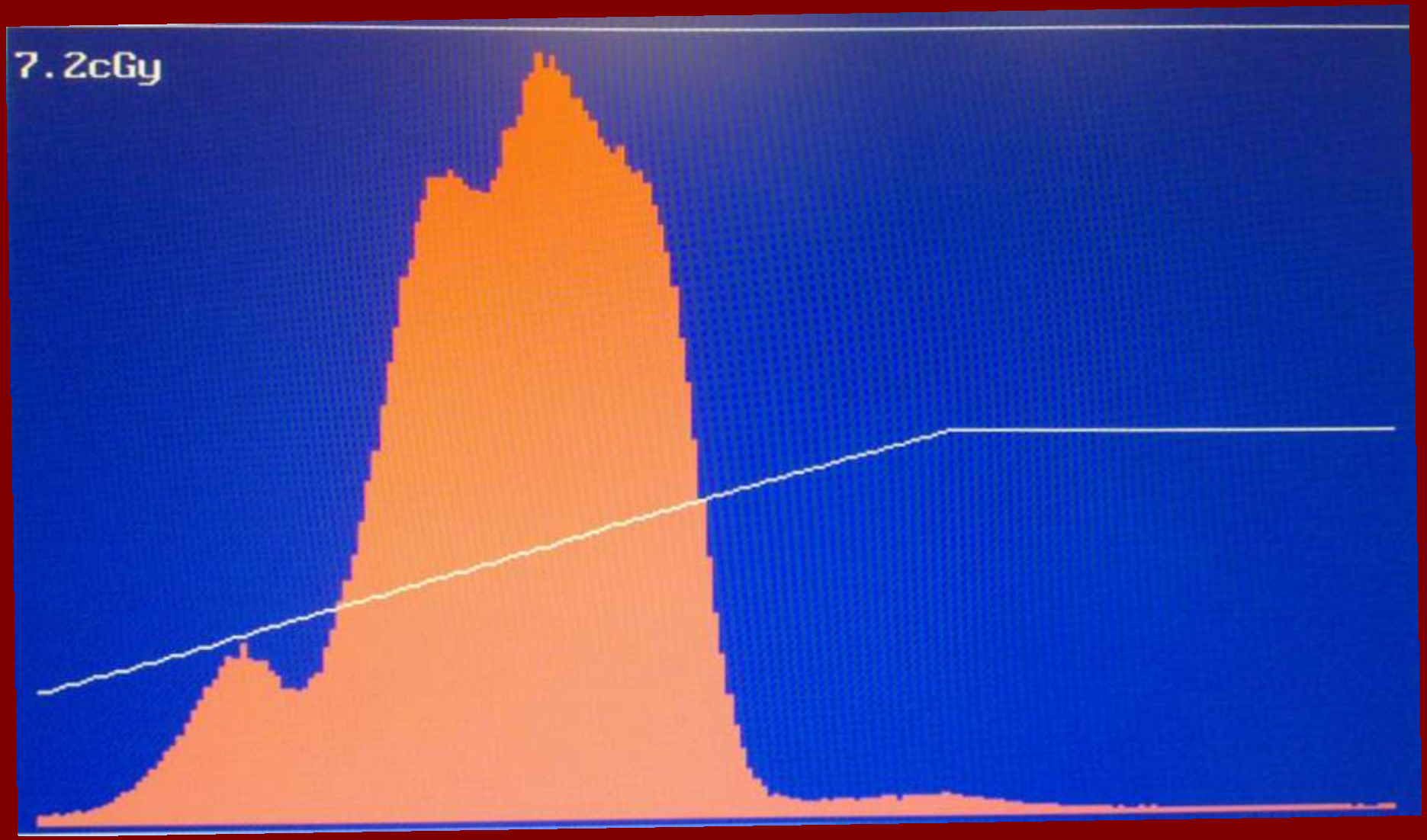
Linear Energy Transfer (LET)

- Track average: obtained by dividing the track into equal lengths, calculating the energy deposited in each length, and finding the mean

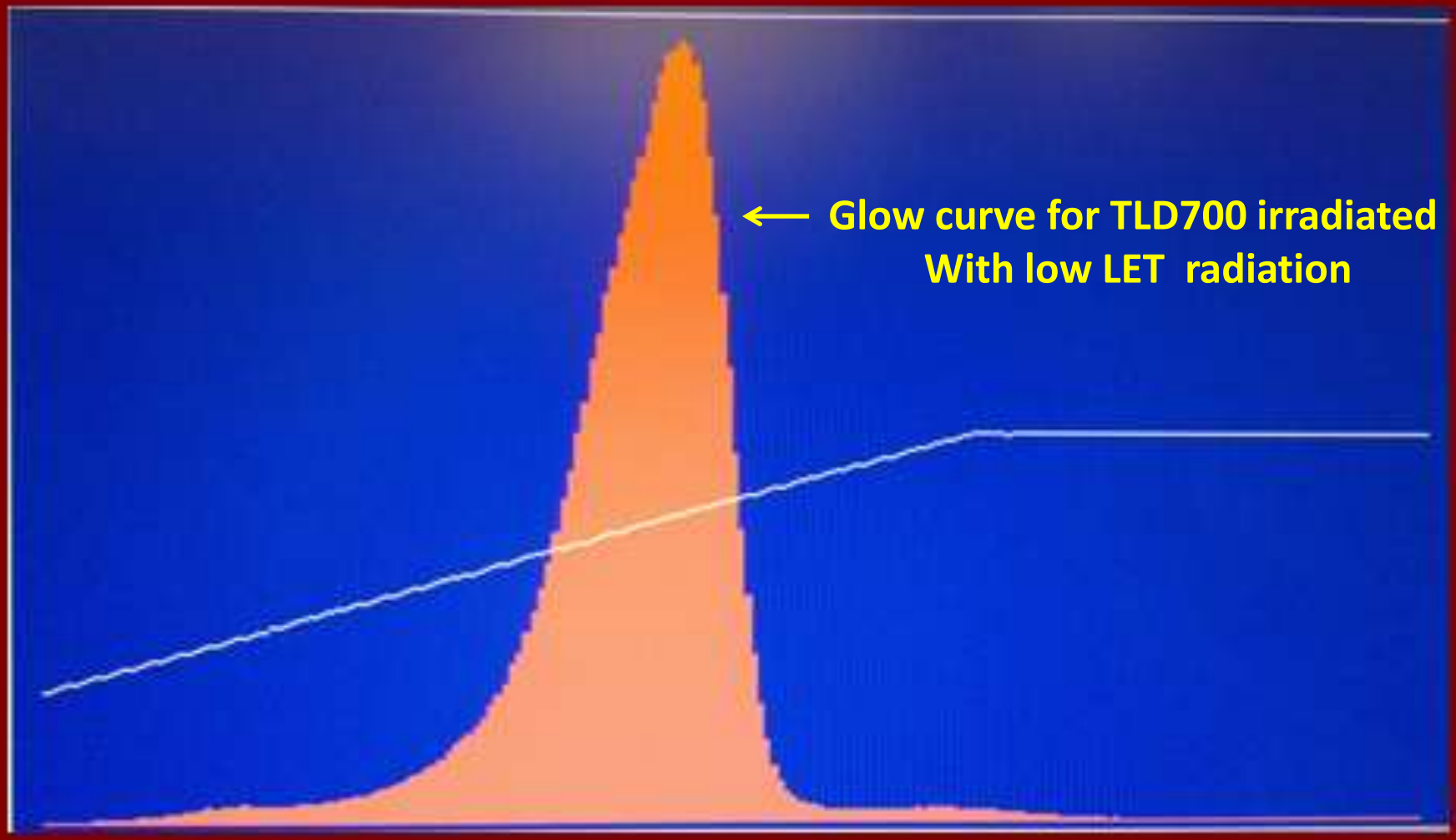
- Energy average: obtained by dividing the track into equal energy increments and averaging the lengths of track over which these energy increments are deposited

Examples of radiation and their LET

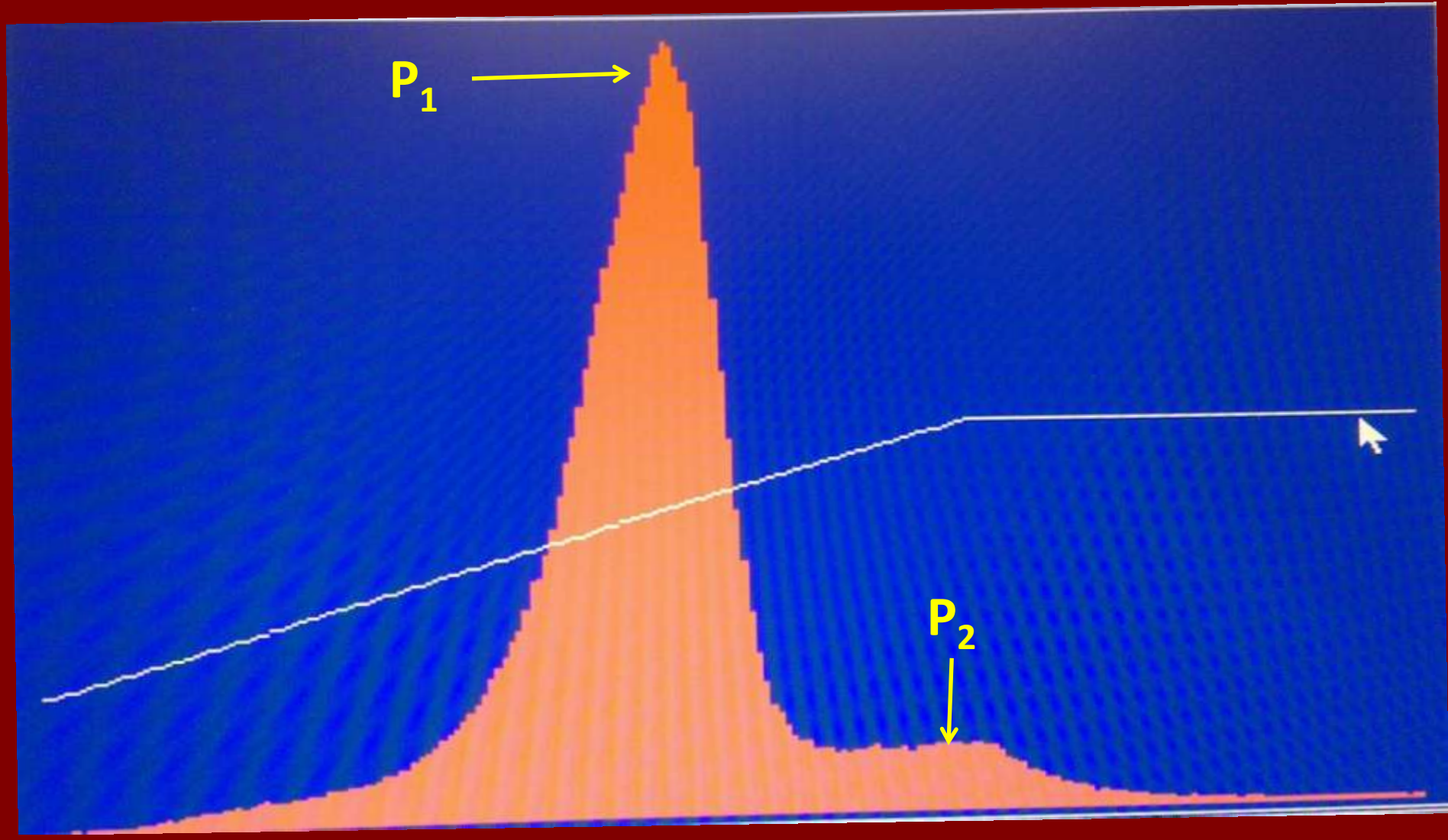
Particle	Effective Energy (MeV)	LET KeV/µ
Photon	0.025	6
Photon	0.057	1.6
Photon	0.075	1.8
Photon	1.25 (Co-60)	**0.25**
Photon	2.0	**0.30**
Photon	6.0	**0.30**
Electron	12.0	**0.40**
Proton	10.0	4.7
Proton	150	**0.5**
Neutron	1.0	80
Neutron	14	40
Alpha	2.5	166
Heavy nuclei	Various energies	200-1000



TLD 700 glow curve after ≈ 0.10 Gy from 6 MV without the 80^0C anneal following the 400^0C anneal



Glow curve for 6 MV irradiation using the annealing procedure of 400^0 C for 1 hr followed by 18-24 hr at 80^0C

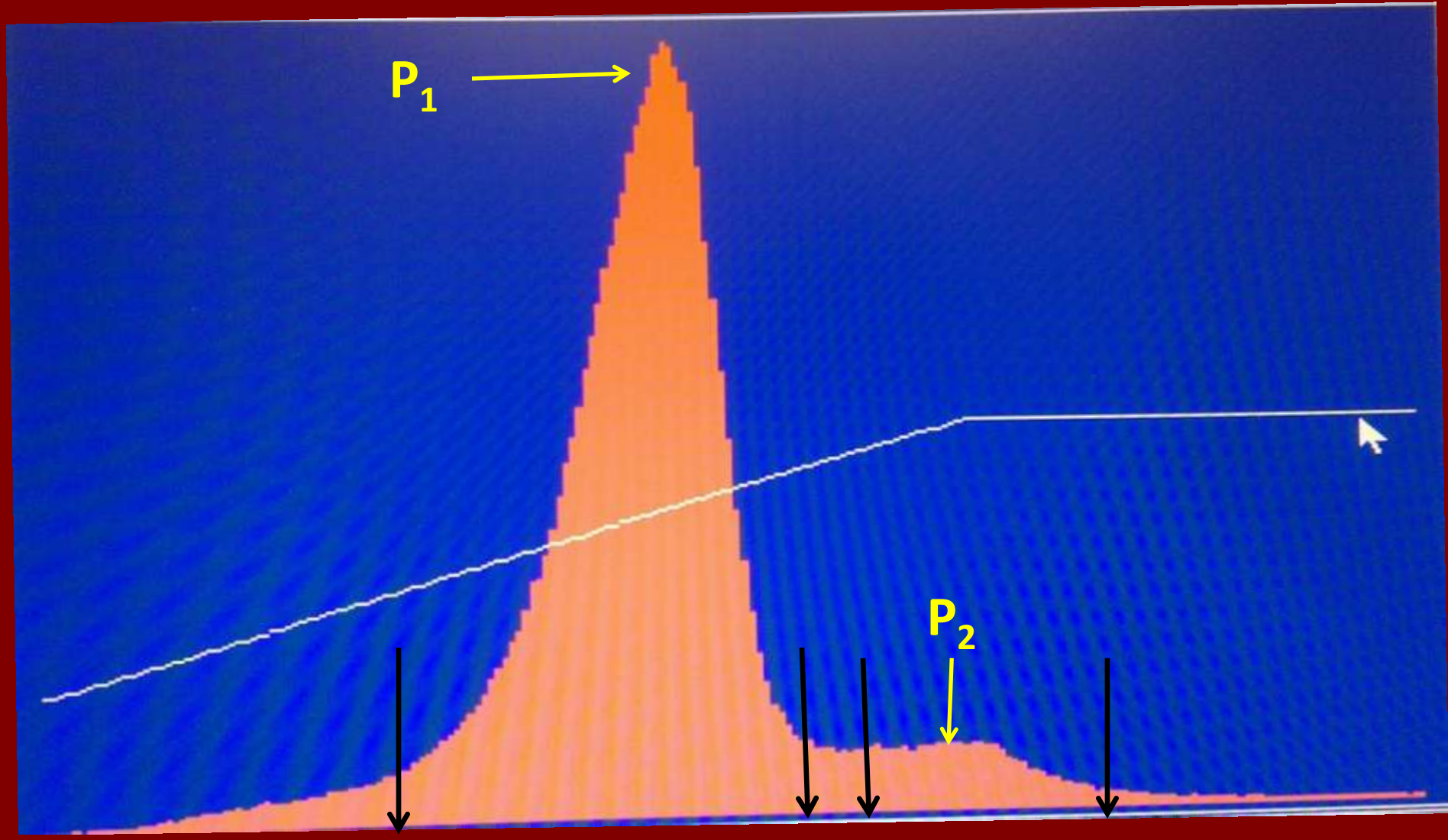


Glow curve for TLD700 irradiated in a clinical proton beam showing Peak 1 and Peak 2

High Temperature Ratio =

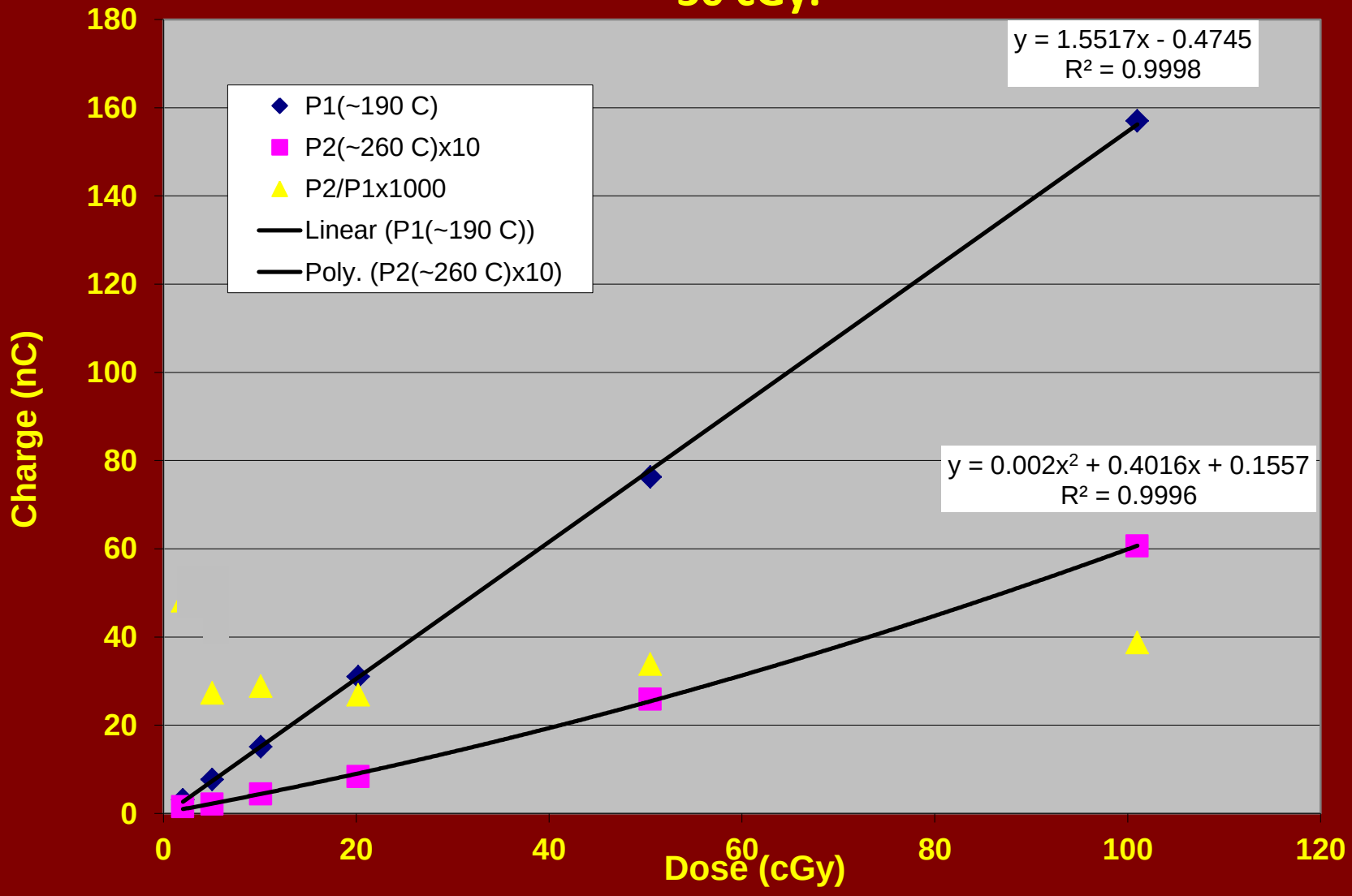
HTR = Area under P2/Area under P1

= P2/P1



Glow curve for TLD 700 irradiated in a clinical proton beam

TLD700 dose response of peaks P_1 and P_2 illustrating the sensitivity differences between the two peaks. P_2 exhibits supralinearity above 30 cGy.



Critical requirement:

Relate HTR (P2/P1) to LET

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THE LET DEPENDENCE OF LiF:Mg,Ti DOSEMETERS AND ITS APPLICATION FOR LET MEASUREMENTS IN MIXED RADIATION FIELDS

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Abstract — Several types of standard TLDs were irradiated in various fields of high energy heavy ions and the TL emission in the high temperature region (peaks 6 and 7) was analysed in comparison with that of ^{60}Co radiation. The parameter determined is defined as the high temperature ratio (HTR). Irradiations were carried out in the JINR (Dubna) with fluoride ions in the energy range from 65 to 275 MeV.amu^{-1} and carbon ions with energies from 100 MeV.amu^{-1} up to 3650 MeV.amu^{-1}. Additionally, irradiations with protons (10 and 62 MeV) were performed. The results show the well known decrease of peak 5 efficiency with increasing LET of the absorbed radiation. The LET dependence of the parameter HTR and of the peak 5 efficiency in the range from 0.35 up to 180 keV.μm^{-1} are presented. Based on these calibrations, the HTR method allows the measurement of the average LET in mixed radiation fields and therefore the estimation of biologically relevant dose. Results from measurements on space station MIR are also presented.

Table 1. Summary of irradiations carried out for the LET calibration.

Radiation	Experiment	Energy ($MeV.amu^{-1}$)	Dose av. LET ($keV.\ \mu m^{-1}$ tiss.)	HTR TLD-100	HTR TLD-600	HTR TLD-700
^{60}Co	AIAU	1.25 MeVγ	0.31	1 ± 0.05	1 ± 0.05	1 ± 0.05
Protons	PSI 96	62	1.04 ± 0.05	1.19 ± 0.02	1.17 ± 0.02	1.13 ± 0.01
^{12}C	JINR 95	3650	7.39 ± 0.37	1.91 ± 0.16	1.89 ± 0.14	1.89 ± 0.08
^{12}C	JINR 94	600	9.04 ± 0.45	2.58 ± 0.11	2.71 ± 0.17	2.23 ± 0.09
^{12}C	JINR 95–96	300	12.6 ± 0.6	3.41 ± 0.28	3.21 ± 0.29	3.56 ± 0.28
Protons	PSI 96	10	16.6 ± 0.7	3.96 ± 0.10	3.32 ± 0.08	3.57 ± 0.05
^{12}C	JINR 96	100	26.6 ± 1.3	4.83 ± 0.32	5.1 ± 0.37	5.34 ± 0.17
^{19}F	JINR 92	275	29.6 ± 1.5	4.92 ± 0.21	5.18 ± 0.02	4.97 ± 0.07
^{19}F	JINR 92	123	50.6 ± 2.5	5.60 ± 0.13	6.19 ± 0.15	5.41 ± 0.14
^{19}F	JINR 92	65	85.6 ± 4.3	6.17 ± 0.17	7.05 ± 0.23	6.30 ± 0.17
Neutrons	AIAU	Thermal	129 ± 6.5		8.65 ± 0.43	
Alphas	AIAU	1.125	174 ± 8.7		10.3 ± 0.43	

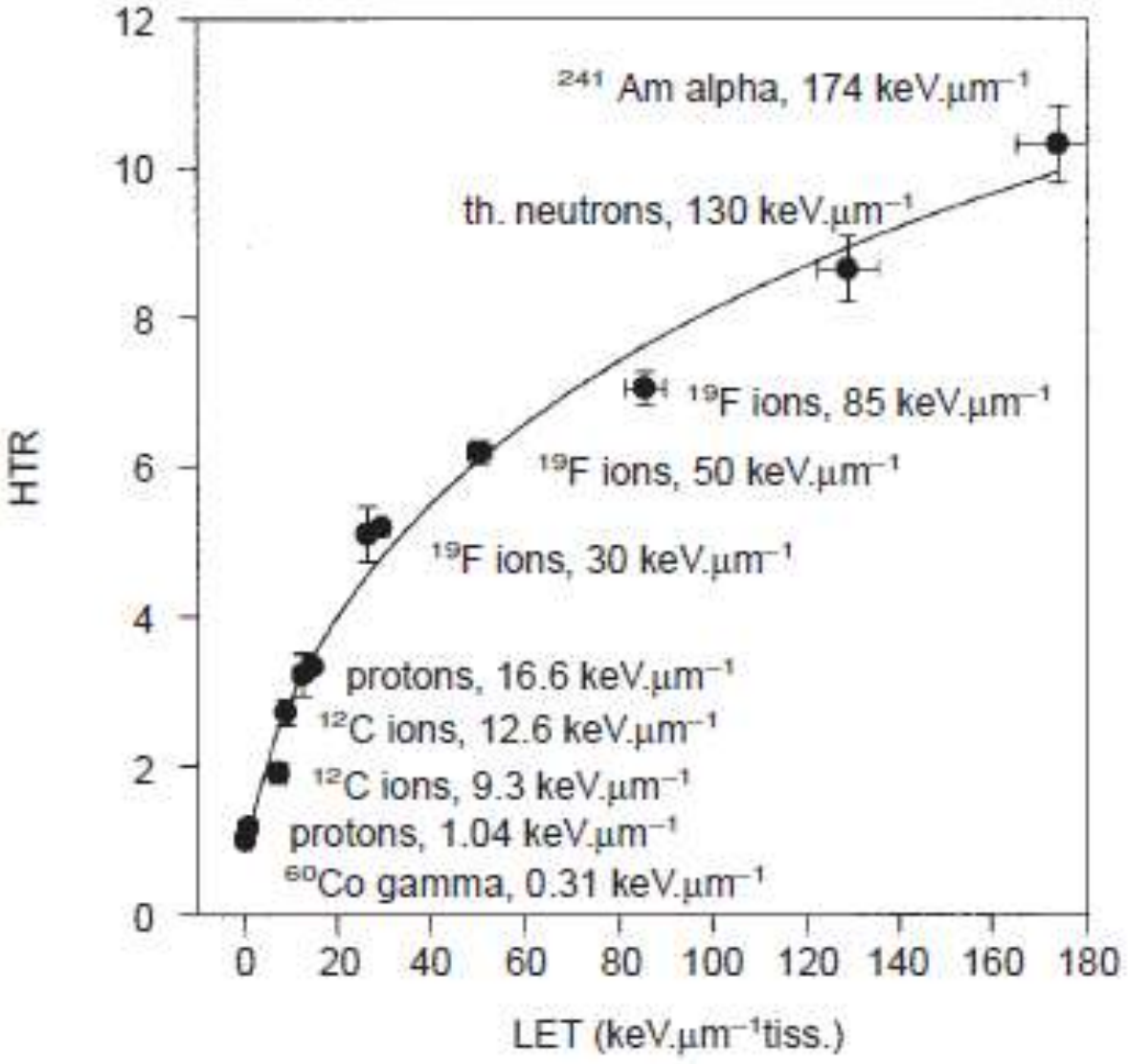
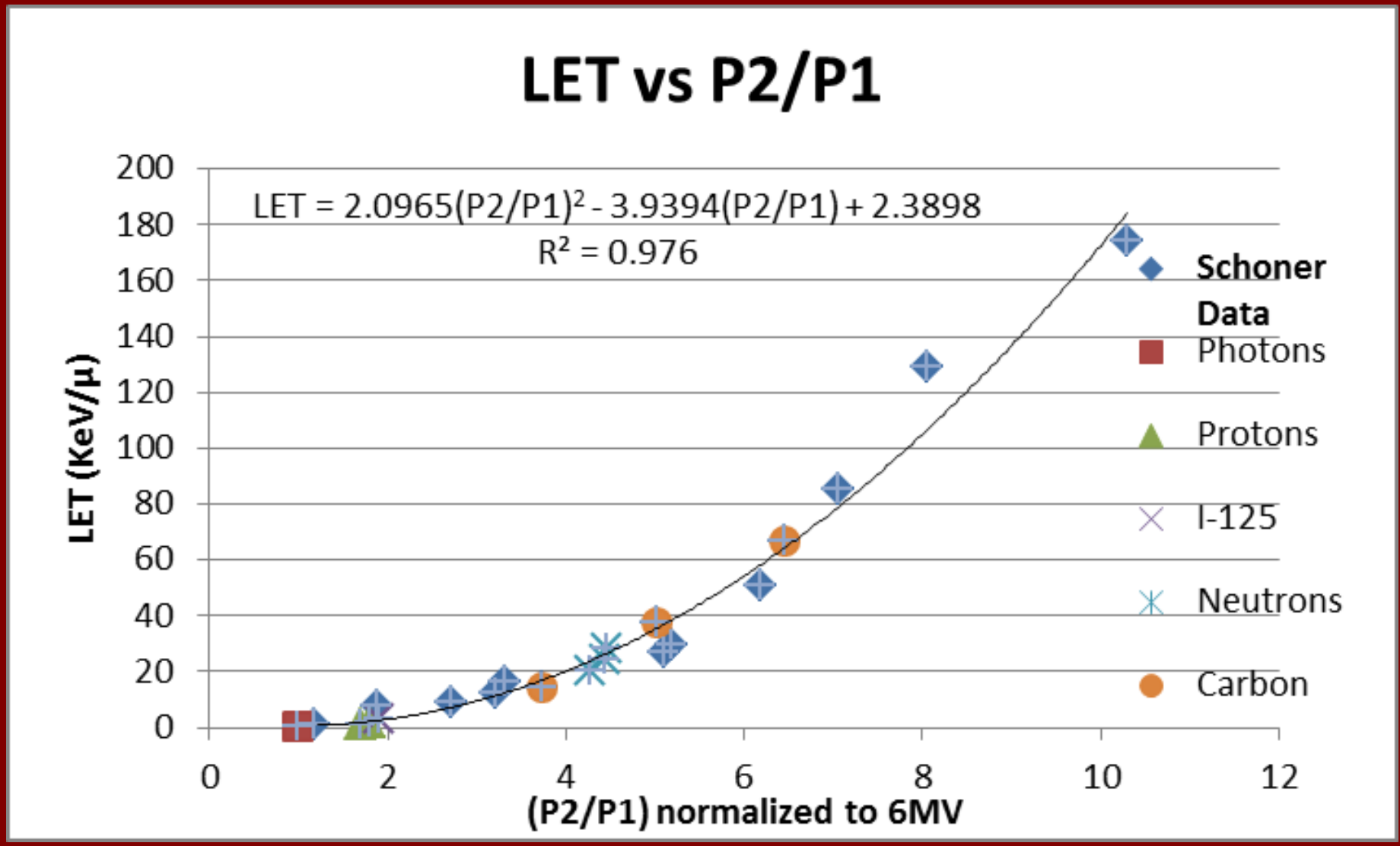
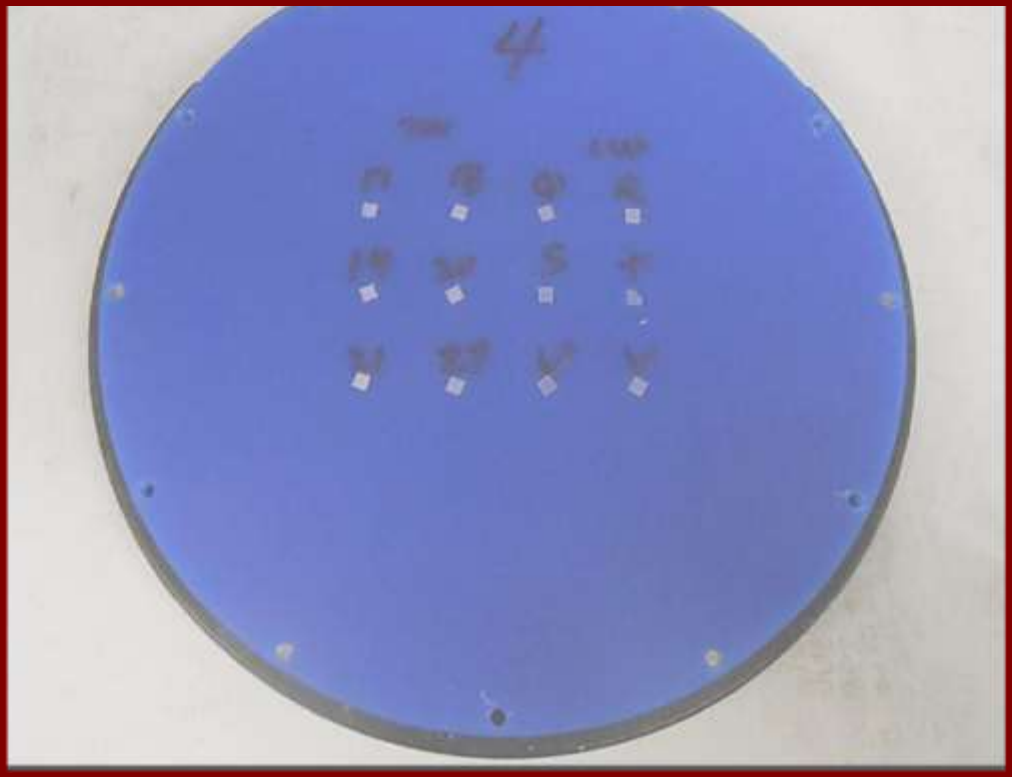
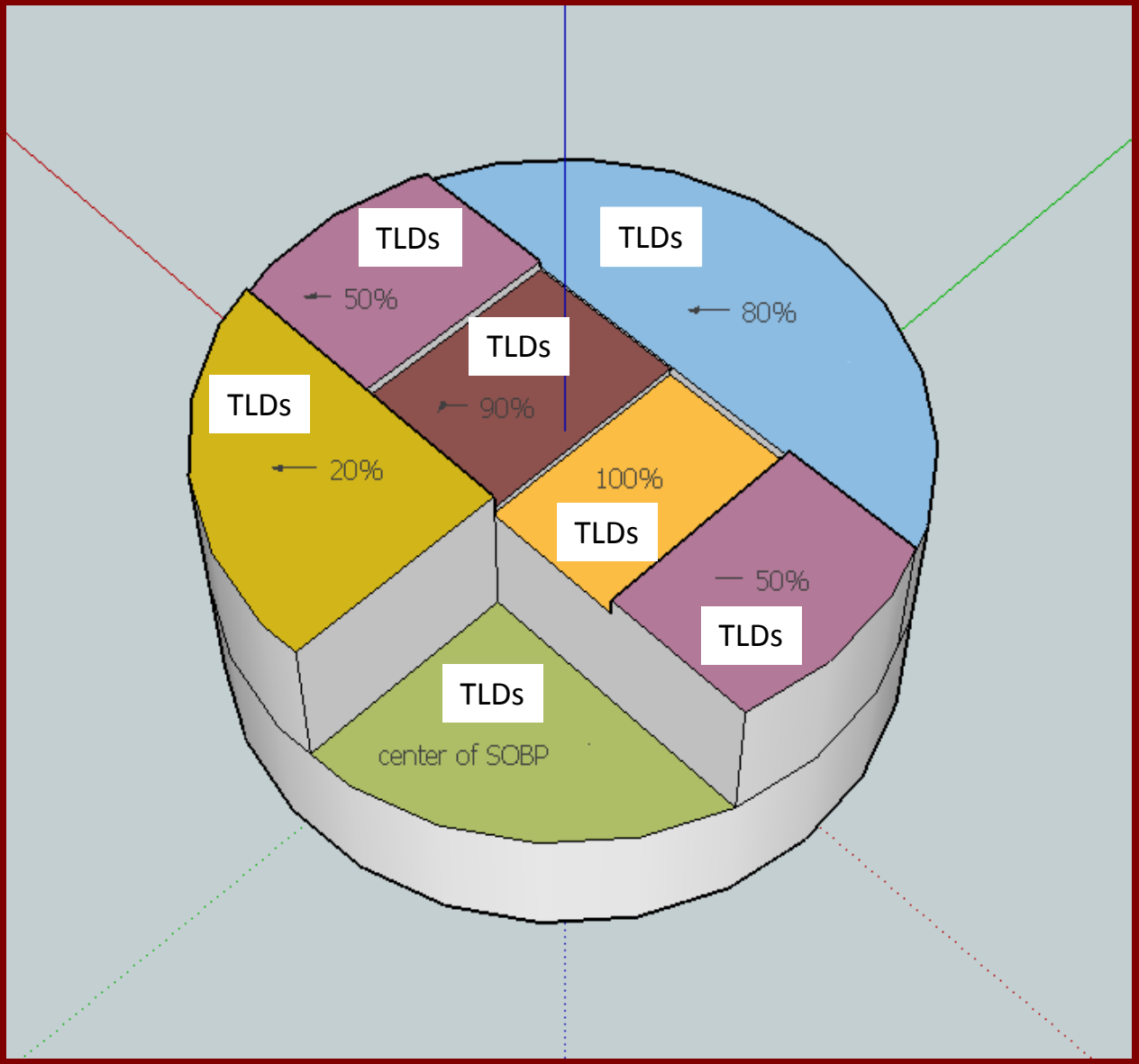


Figure 3. High temperature ratio HTR plotted against LET of absorbed radiation for TLD-600.


LET vs P2/P1
LET = 2.0965(P2/P1)² - 3.9394(P2/P1) + 2.3898
R² = 0.976
LET (KeV/μ)
(P2/P1) normalized to 6MV
0
20
40
60
80
100
120
140
160
180
200
0
2
4
6
8
10
12
Schoner Data
Photons
Protons
I-125
Neutrons
Carbon

in the SOBP to measure the LET

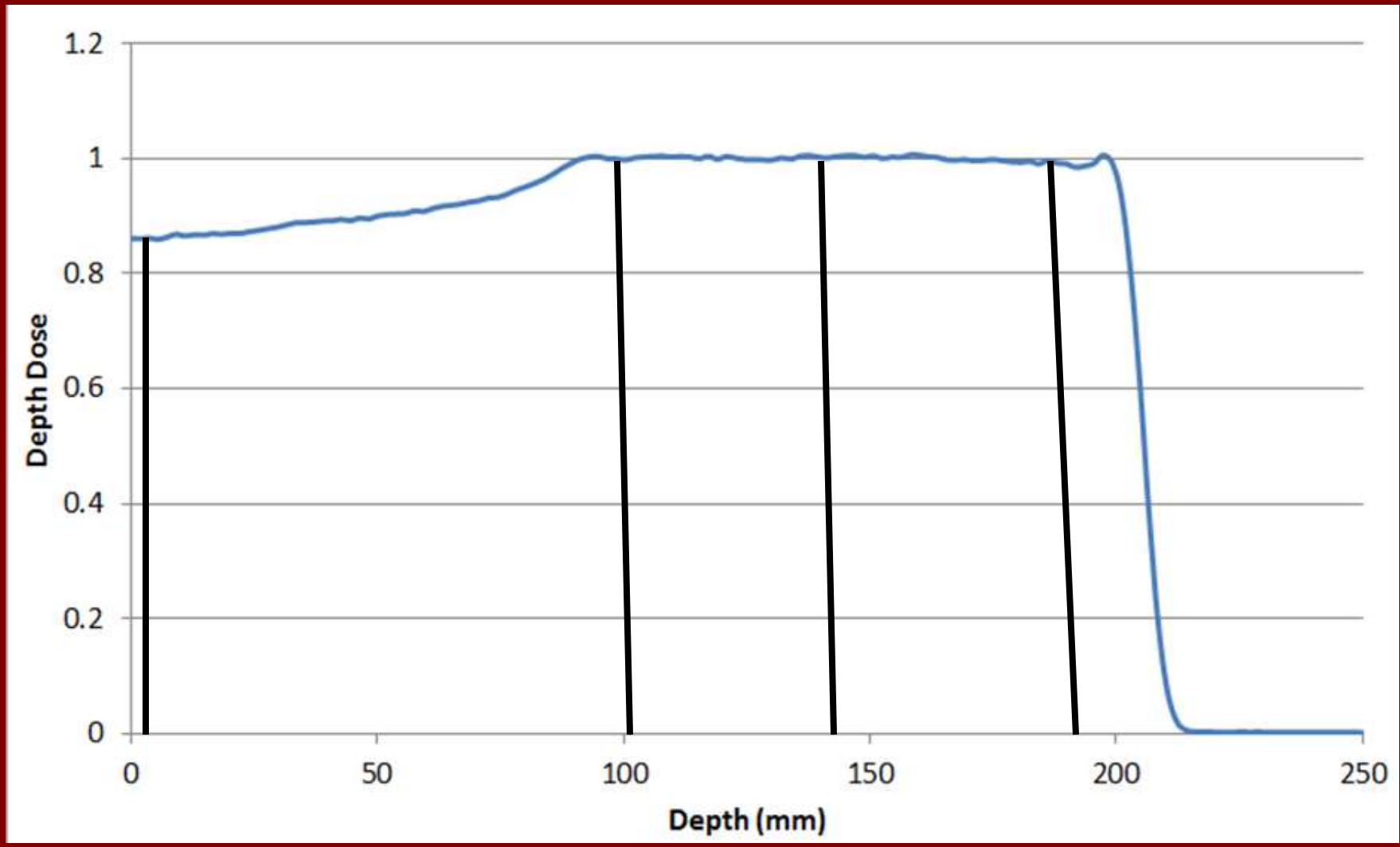




Schematic diagram of the wax phantom showing the location of the TLDs for measurements in the dose fall-off region of the distal SOBP

Location of TLDs in the wax phantom at the various depths in the dose fall-off region of the distal SOBP

Sealed wax phantom containing TLDs used in obtaining the LET from TLD measurements of P2/P1 in the dose fall-off region of the distal SOBP


1.2
1
0.8
0.6
0.4
0.2
0
Depth Dose
0
50
100
150
200
250
Depth (mm)

Spatial variation of LET values obtained from TLD measurements in the SOBP

z cm	HTR $(P2/P1)^{P}_{6MV}$	LET KeV/μ	Dose cGy
19	1.25 ± 0.019	.74 ± .07	22.4 ± .7
10	1.46 ± 0.021	1.11 ± .10	28.4 ± .9
4	1.51 ± 0.021	1.22 ± .11	29.4 ± 1.0
2	1.65 ± 0.04	1.60 ± .14	29.7 ± 1.0

z is the distance from the Bragg peak
Proton range: 20 cm
Modulation: 12

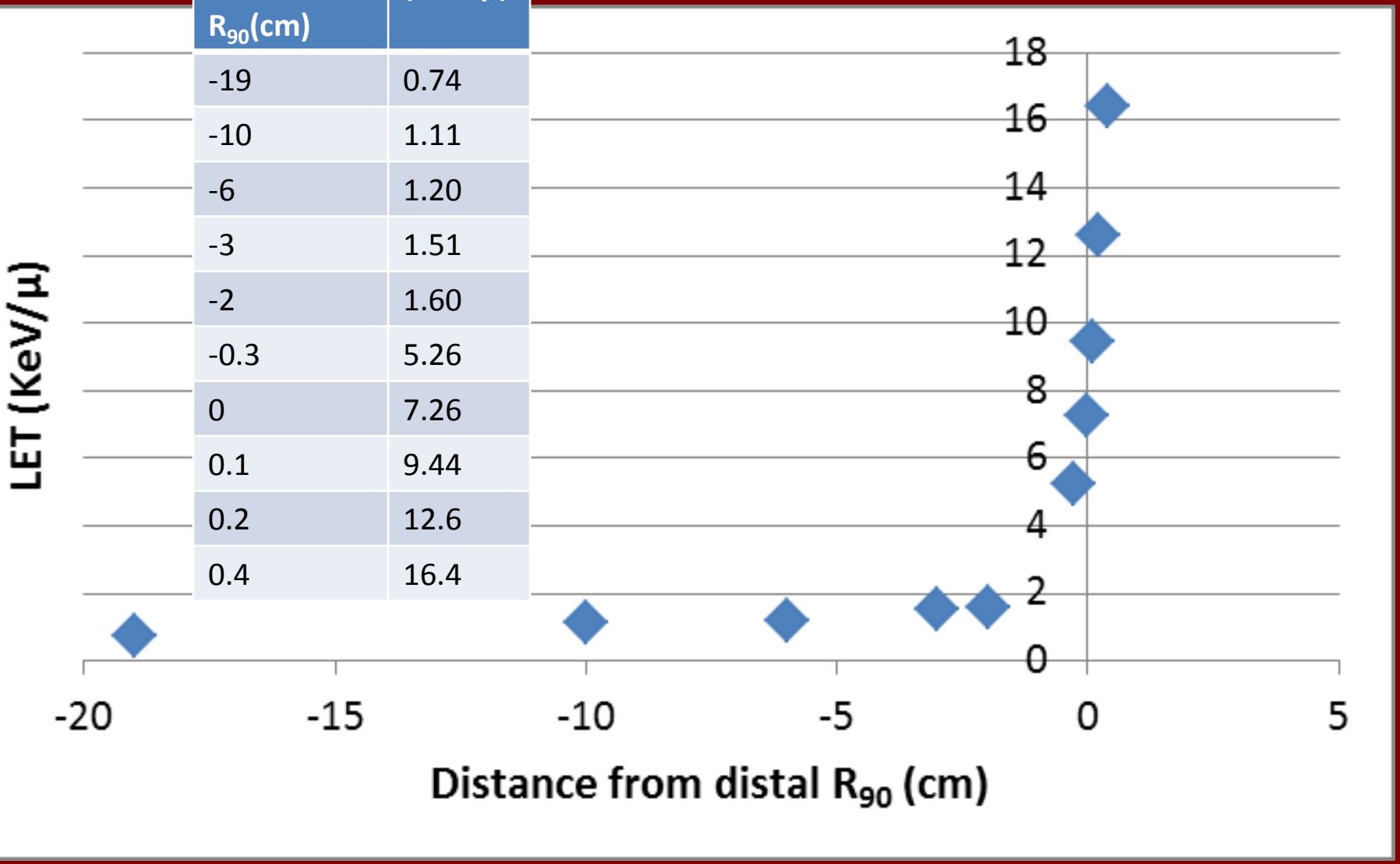
Summary of the LET values obtained from TLD measurements in the dose fall-off region of the distal SOBP

WET cm	≈ PDD	HTR $(P2/P1)^{p}_{6MV}$	LET KeV/μ
3.0	Center of SOBP	1.62 ± .04	1.51 ± .12
5.9	100	2.44 ± .03	5.26 ± .19
6.1	90	2.73 ± 0.04	7.26 ± .30
6.2	80	3.00 ± 0.05	9.44 ± .41
6.3	50	3.34 ± 0.07	12.6 ± .70
6.5	20	3.69 ± 0.11	16.4 ± 1.2

Proton range : 6.1 cm
SOBP width: 6.0 cm
Modulation: 6 cm

Variation of LET in the SOBP at distances from the distal R_{90} (cm) from measurements of P2/P1 in irradiated TLD700

Distance from R_{90}(cm)	LET (KeV/μ)
-19	0.74
-10	1.11
-6	1.20
-3	1.51
-2	1.60
-0.3	5.26
0	7.26
0.1	9.44
0.2	12.6
0.4	16.4



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Response analysis of TLD-300 dosimeters in heavy-particle beams

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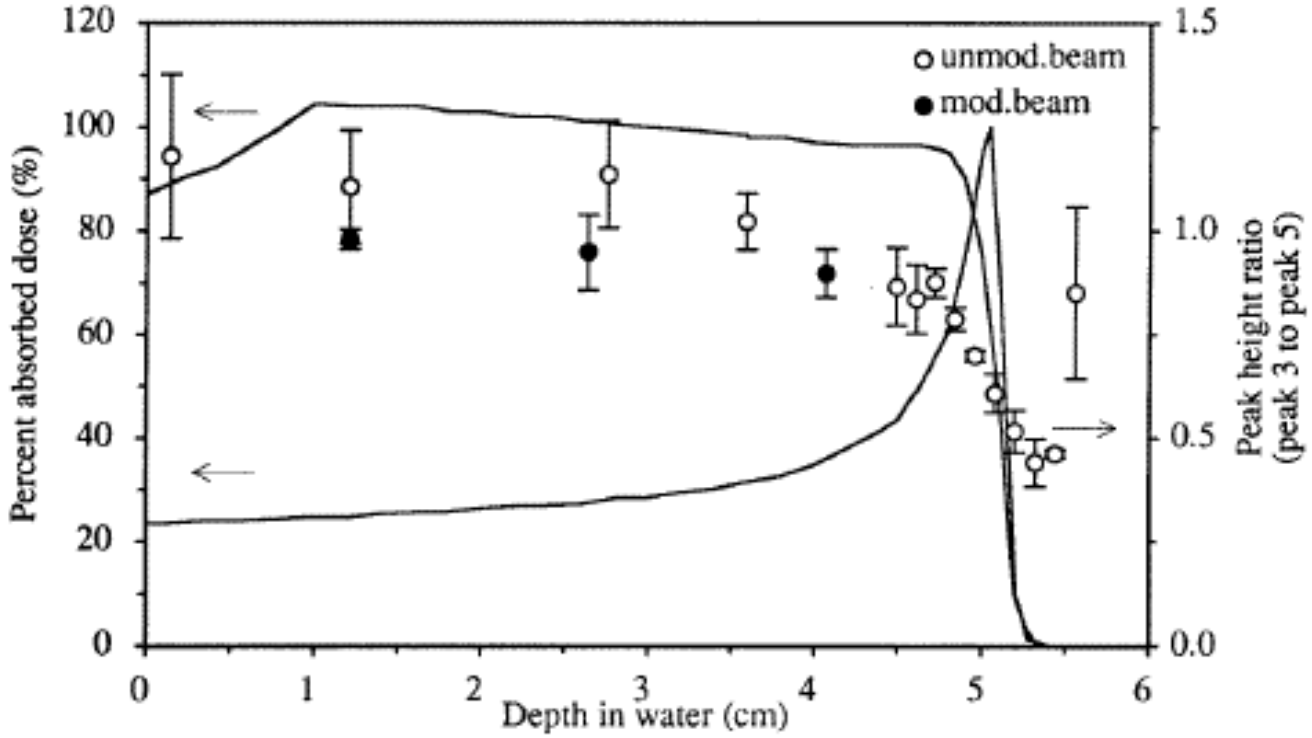

Figure 5. Peak height ratio of peak 3 to peak 5 versus the equivalent depth in water in the unmodulated and modulated 85 MeV proton beams.

Plot of P1/P2

P2/P1 varies from 1.01 → LET varies from 2 → 8Kev/μ

Conclusions:

1. Two peak analysis of TLD 700 glow curve provides information on proton LET due to the increased sensitivity of P2 in TLD700 to LET radiation
2. A calibration curve relating (P2/P1) ratios to LETs is required to extract proton LETs
3. The spatial variation of LET in the SOBP and in the distal dose fall-off region was obtained from measurements of P2/P1 in irradiated TLD700
4. Since radiation LET is related to RBE, LET values obtained from P2/P1 measurements in irradiated TLD700 can provide radiobiological information for proton beams

Thank you for your attention

Questions ???