Dosimetry and LET spectrometry in C 290MeV/n HIMAC ion beam by different TED based LET spectrometers, and TLD's

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➢ C-ions 290 MeV/n

➢ Ne-ions 400 MeV/n

- Analysis of obtained results

HIMAC program of NPI ASCR

- **Basic idea** – to start to build LET spectra library for radiobiology experiments in HIMAC ion beams – approved by HIMAC PAC – beginning 2008,

- **Methods used:**

✓ **Experimental:**

❖ LET spectrometers based on TED (CR-39) – above ~ 10 keV/µm

❖ Tissue equivalent proportional counter HAWK – all LET

❖ MDU-Liulin energy deposition spectrometer – up to ~ 30 keV/ µm

❖ Thermoluminescent detectors (TLDs) supplementary information for “low” LET region

✓ **Calculation** - TRIM, PHITS, GEANT, MCNPX?

Irradiation performed April 2008 – general

1. C 290 MeV/n beam:

- TLD's and TED LET spectrometers 19 depths from the entrance (LET ~ 13 keV/µm) up to 3 points behind the Bragg peak (LET ~ 320 keV/µm);
- MDU spectrometer; 02C and 07J units – 7 depths from the entrance up to ~ 46 keV/µm – other WRMISS contribution;

2. Ne 400 MeV/n beam:

- TLD's and TED LET spectrometers 16 depths from the entrance (LET ~ 31 keV/µm) up to 2 points behind the Bragg peak (LET ~ 620 keV/µm);
- MDU spectrometer; 02C and 07J units – 4 depths from the entrance up to ~ 41 keV/µm;

Passive detectors holders (courtesy of N. Yasuda)

LET spectrometer based on a PADC track-etch detectors

- Polyallyldiglycolcarbonate (PADC)–$C_{12}H_{18}O_7$
  - Page, 0.5 mm (Page Moulgings Ltd, England),
  - Tastrak, 0.5 mm (Track Analysis Systems Ltd, Bristol)
  - USF4, 0.6 mm (American Technical Plastics)
  - TD-1, 0.9 mm (Nagase Landauer, Japan),
  - Baryotrak, 0.9 mm (Nagase Landauer, Japan).
- etching in 5 N NaOH at 70^{o}C for 18 hours – for all
- automatic optical image analyzer LUCIA G
- track parameters => determination of the ratio V_T/V_B (V_T – etch rate of damaged material, V_B – etch rate of unaffected bulk material), => LET; correction for critical angle
- range covered: ~ 10 to 700 keV/µm; 1 – 100 mSv

Calibration

- **LET = f(V)**
- **irradiation in heavy charged particle beams at**
  - **HIMAC (NIRS Chiba, Japan) in the frame of ICCHIBAN programs – ICCHIBAN 2, 4, 6, and 8;**
  - **NASA Space Radiation Laboratory (Brookhaven National Laboratory) in the frame of ICCHIBAN BNL;**
  - **Nuclotron of the Laboratory of High Energies, JINR, Dubna**
- **particles: ^{12}C – ^{84}Kr, LET ~ 7.5 – 600 keV/μm**
- **detection thresholds: Page ~ 10 keV/μm, Tastrak ~ 15 keV/μm; TD-1 & USF4 – to be precised, at the moment ~ Page; Baryotrak ~ 30 keV/μm**

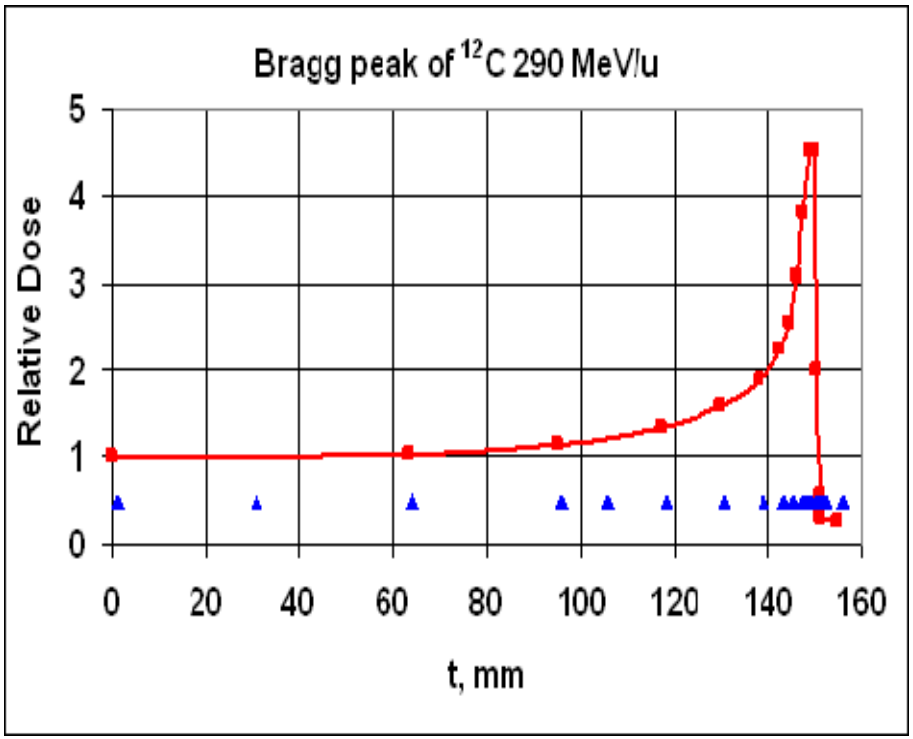
Results - passive detectors

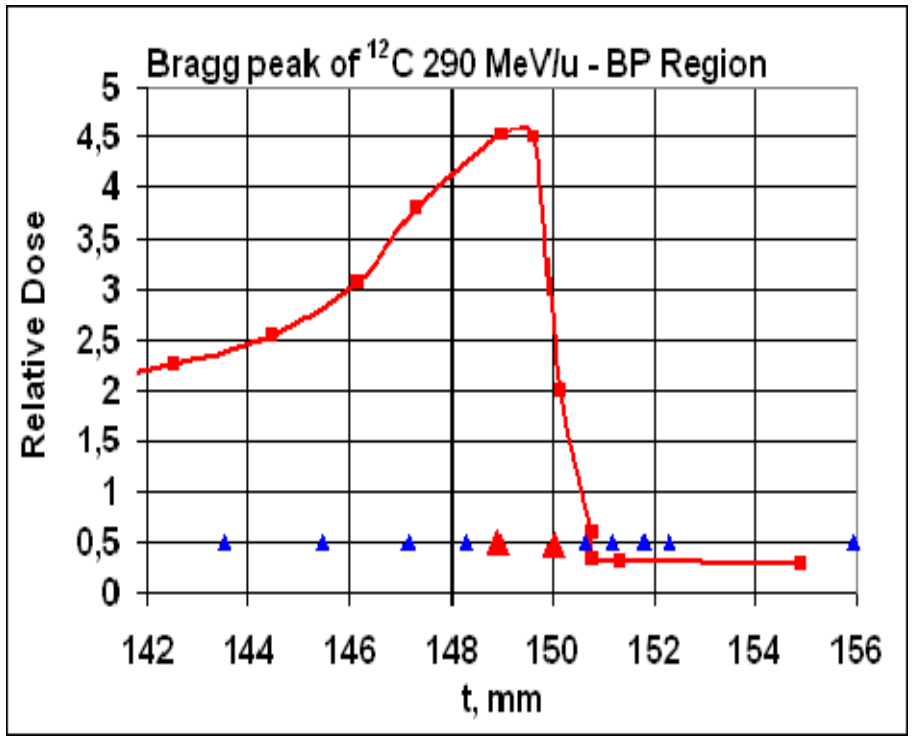
Up to now

C 290/n beam;

- CR-39 TEDs:
  - ❖ Page, 0.5 mm thick, and
  - ❖ USF 4, 0.6 mm thick
- Both TLDs, i.e. Al_2O_3:C, and $CaSO_4$:Dy;

Conditions of Page CR-39 exposure



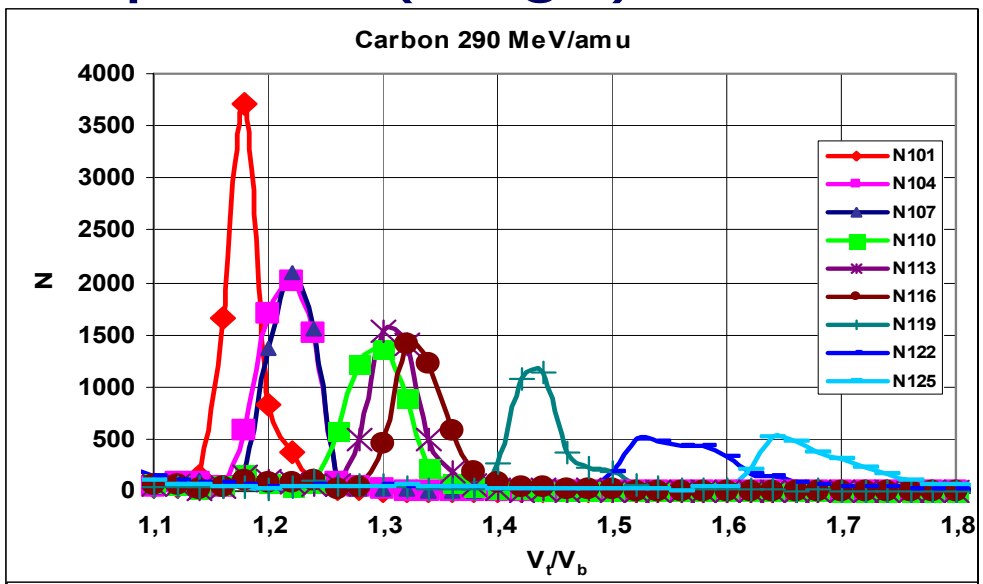


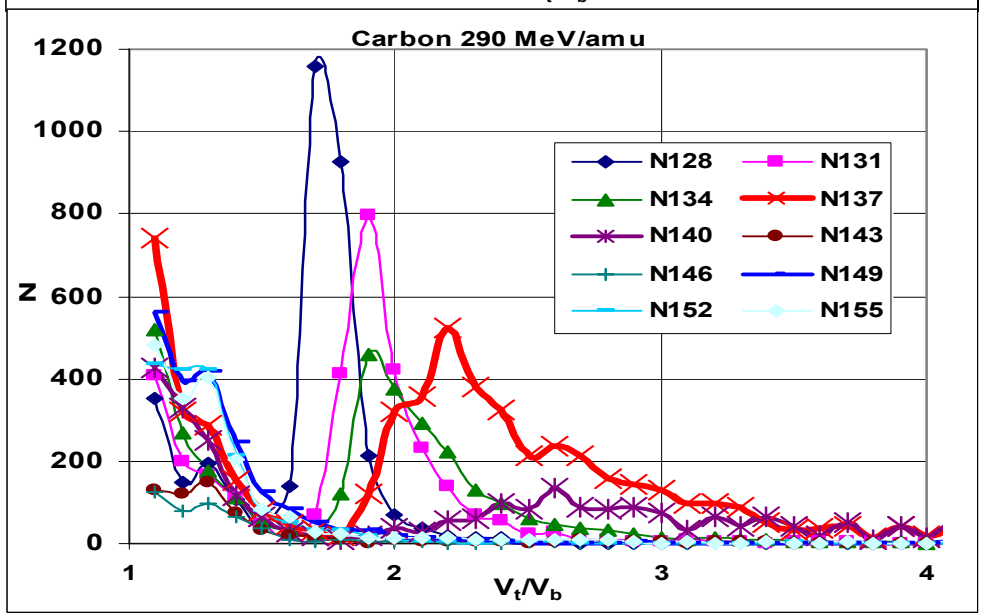
red curves: HIMAC reference values,
blue triangles: detector's positioning

Positioning of detectors; track etch ratio spectra (Page)

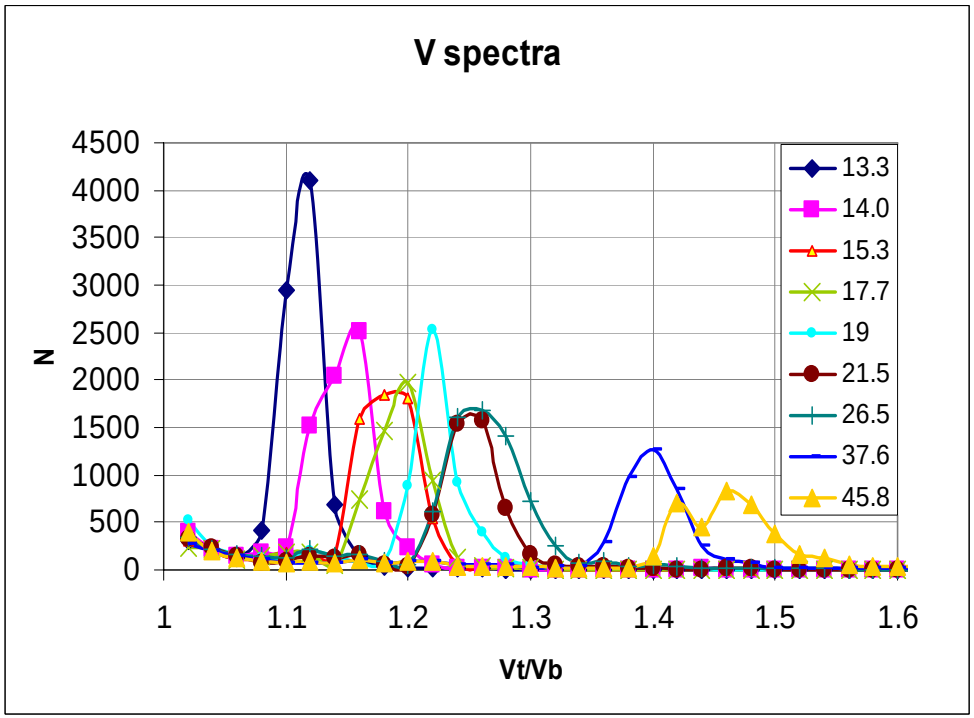
C 290 MeV/n

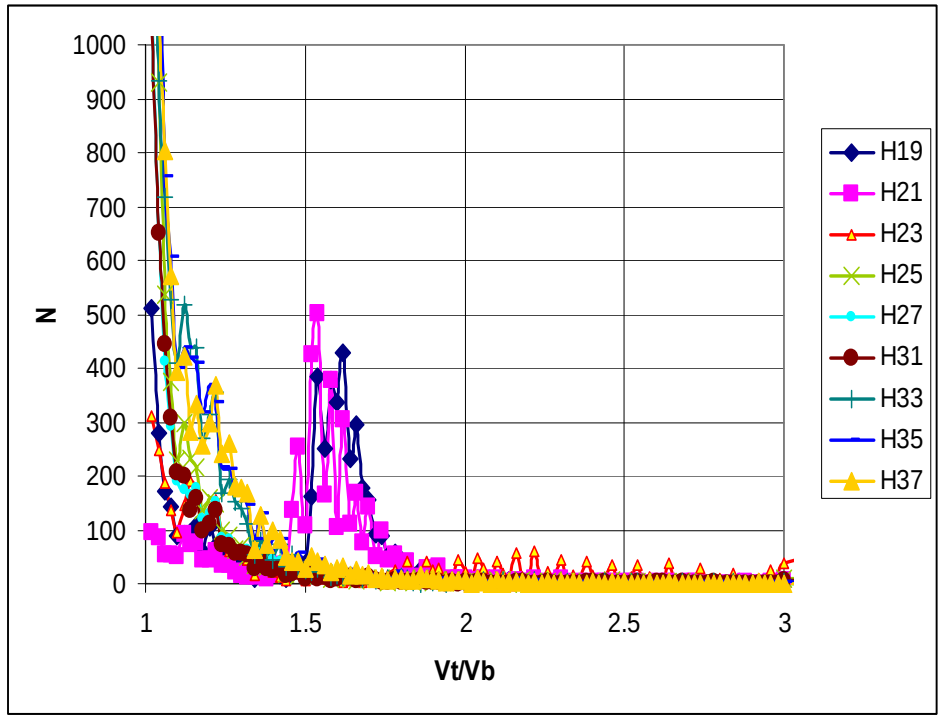
držák	Detector No.	B.F. [mm]	LET [keV*μm^{-1}]	Φ [cm^{-2}]
1C	N101	0,00	13,30	1,00E+05
2C	N104	30,05	14,00	1,00E+05
3C	N107	63,26	15,30	1,00E+05
4C	N110	95,03	17,70	1,00E+05
5C	N113	104,93	19,00	1,00E+05
6C	N116	117,24	21,50	1,00E+05
7C	N119	129,81	26,60	1,00E+05
8C	N122	138,02	37,60	1,00E+05
9C	N125	142,53	45,80	1,00E+05
10C	N128	144,47	53,30	1,00E+05
11C	N131	146,15	65,70	1,00E+05
12C	N134	147,29	85,40	1,00E+05
13C	N137	147,92	119,00	2,00E+04
14C	N140	149,01	300,00	2,00E+04
15C	N143	149,64	320,00	2,00E+04
16C	N146	150,15	99,30	2,00E+04
17C	N149	150,78	29,40	1,00E+05
18C	N152	151,32	29,30	1,00E+05
19C	N155	154,91	27,80	1,00E+05
20C	N158	background		



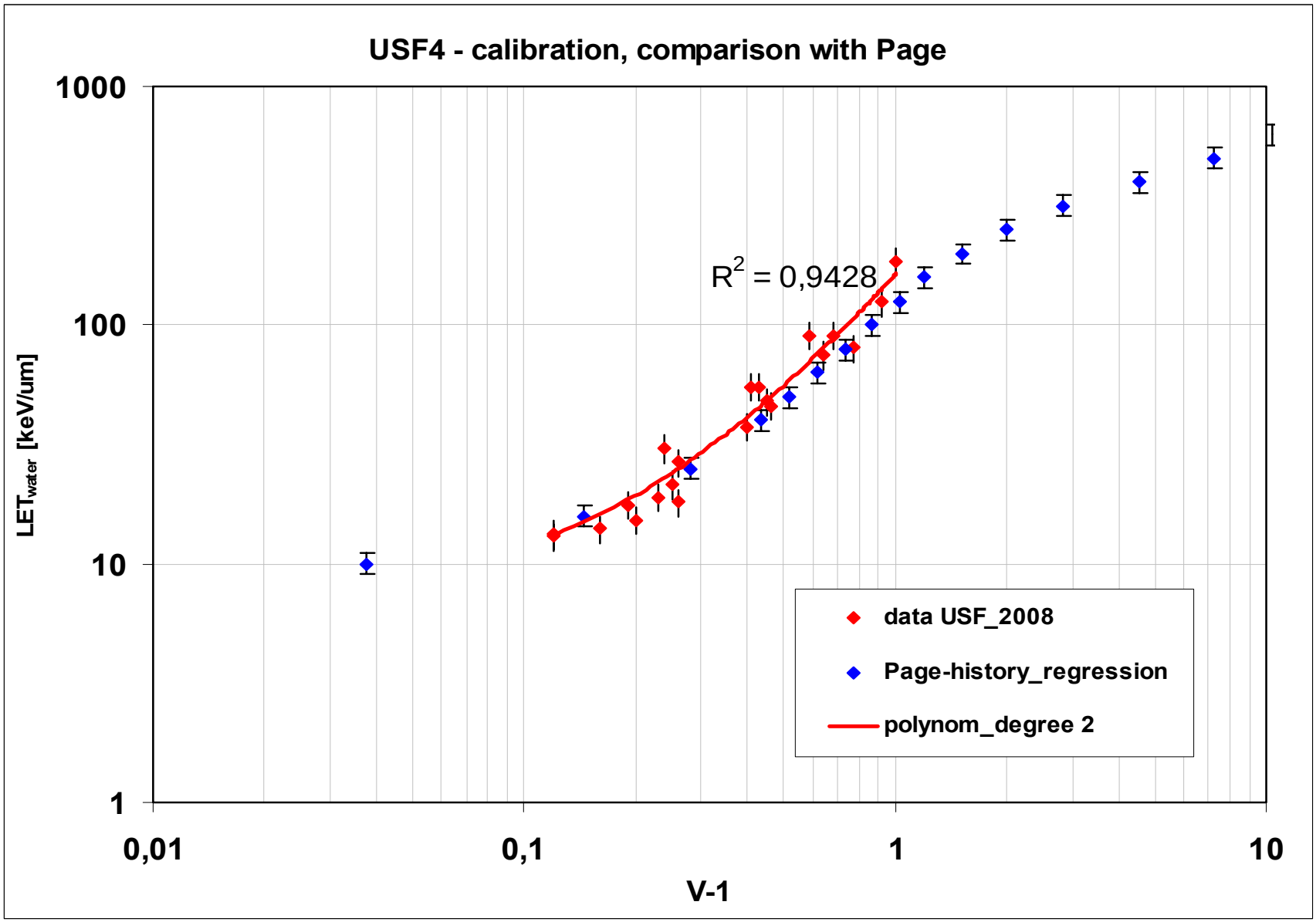


Positioning of detectors; track etch ratio spectra (USF 4)

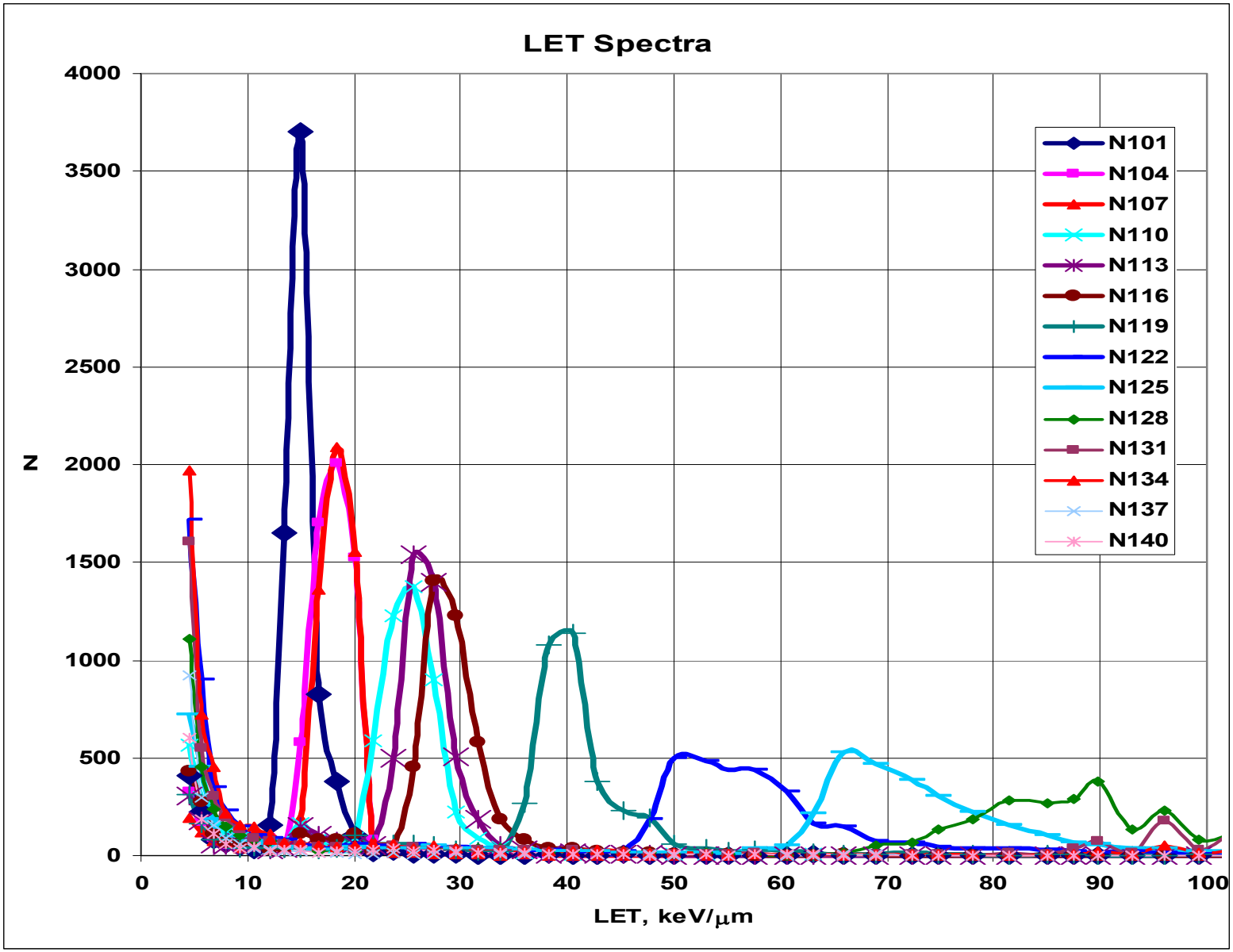




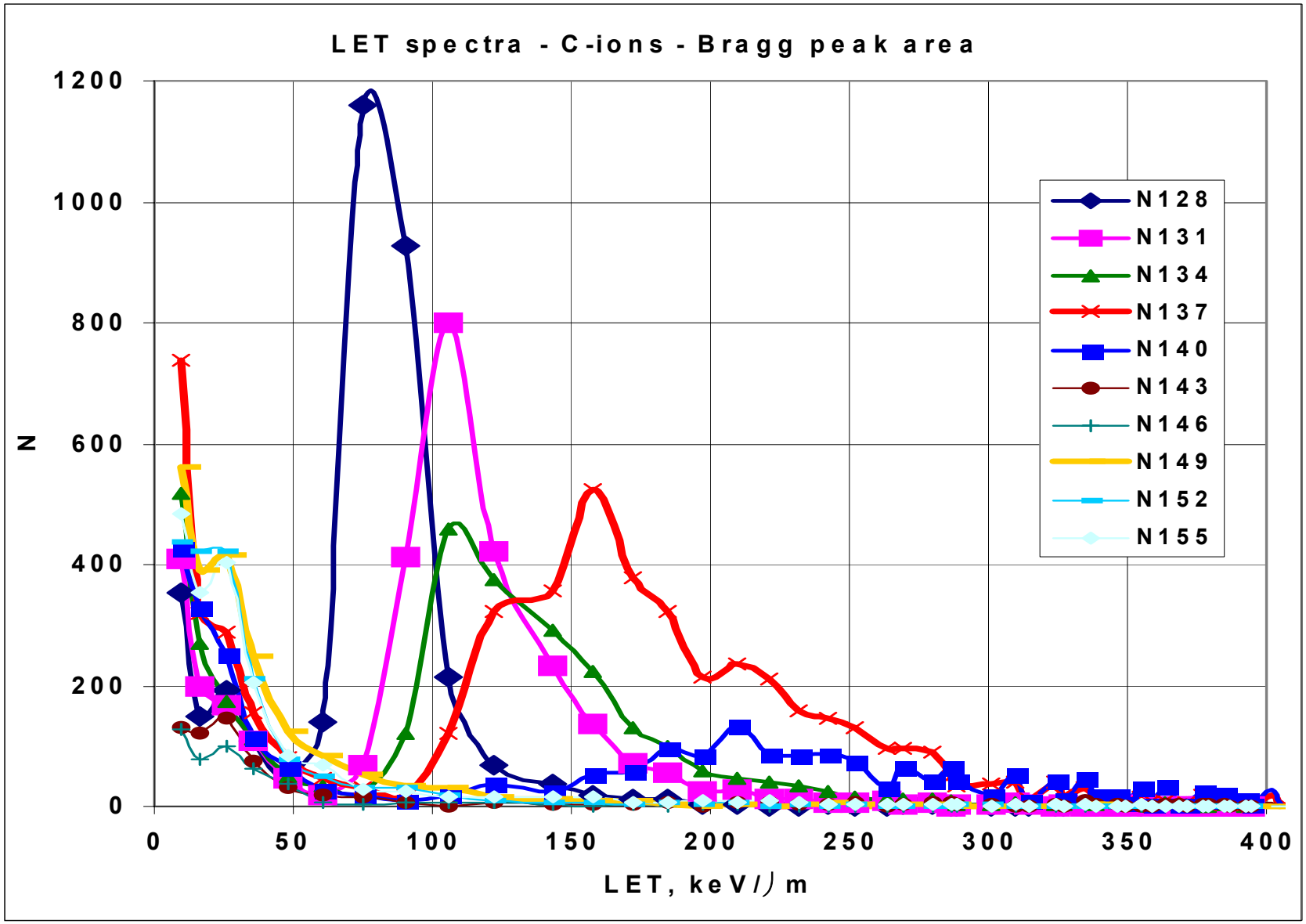
Calibration curves: Page & USF 4



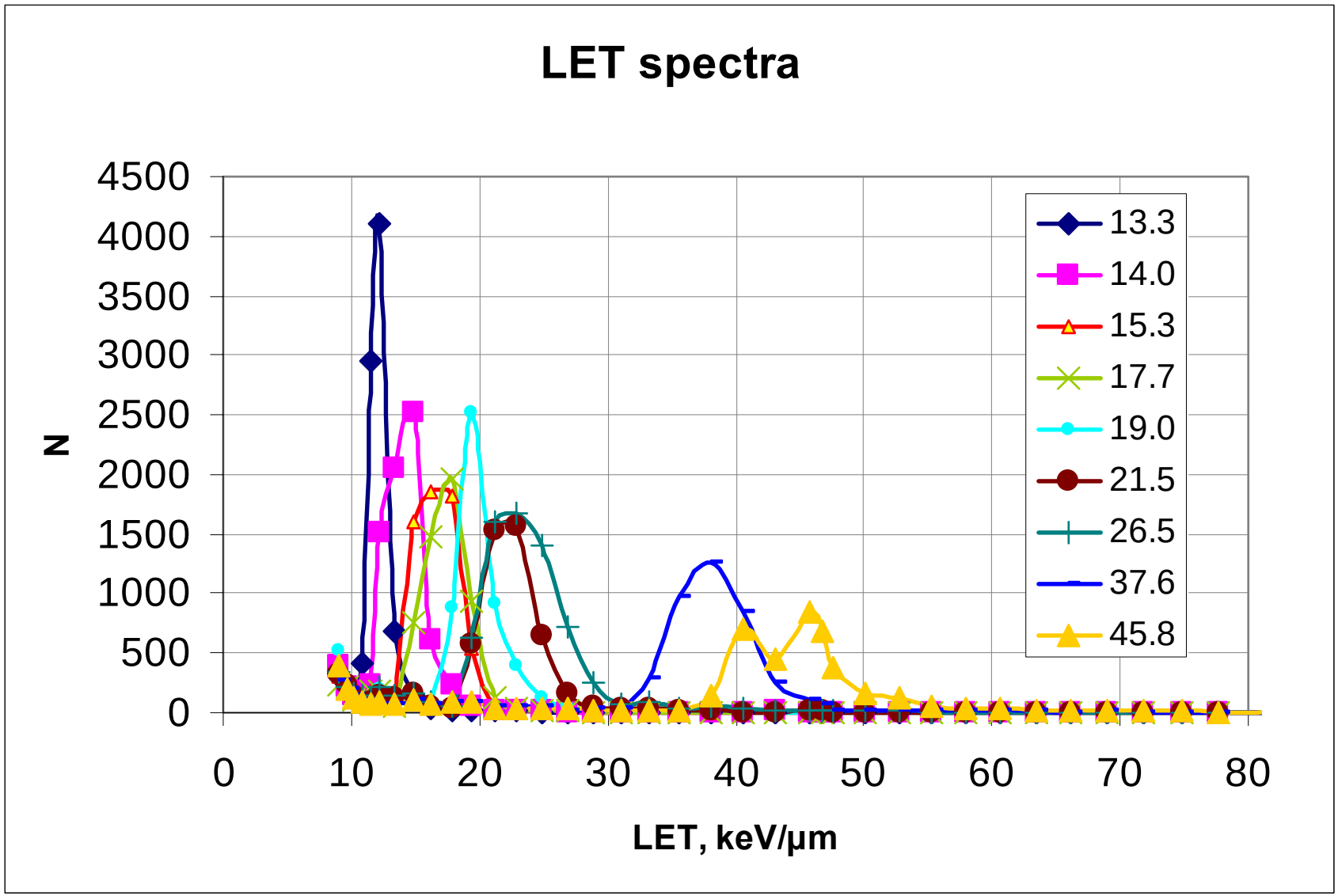
LET spectra (Page) – before BP region



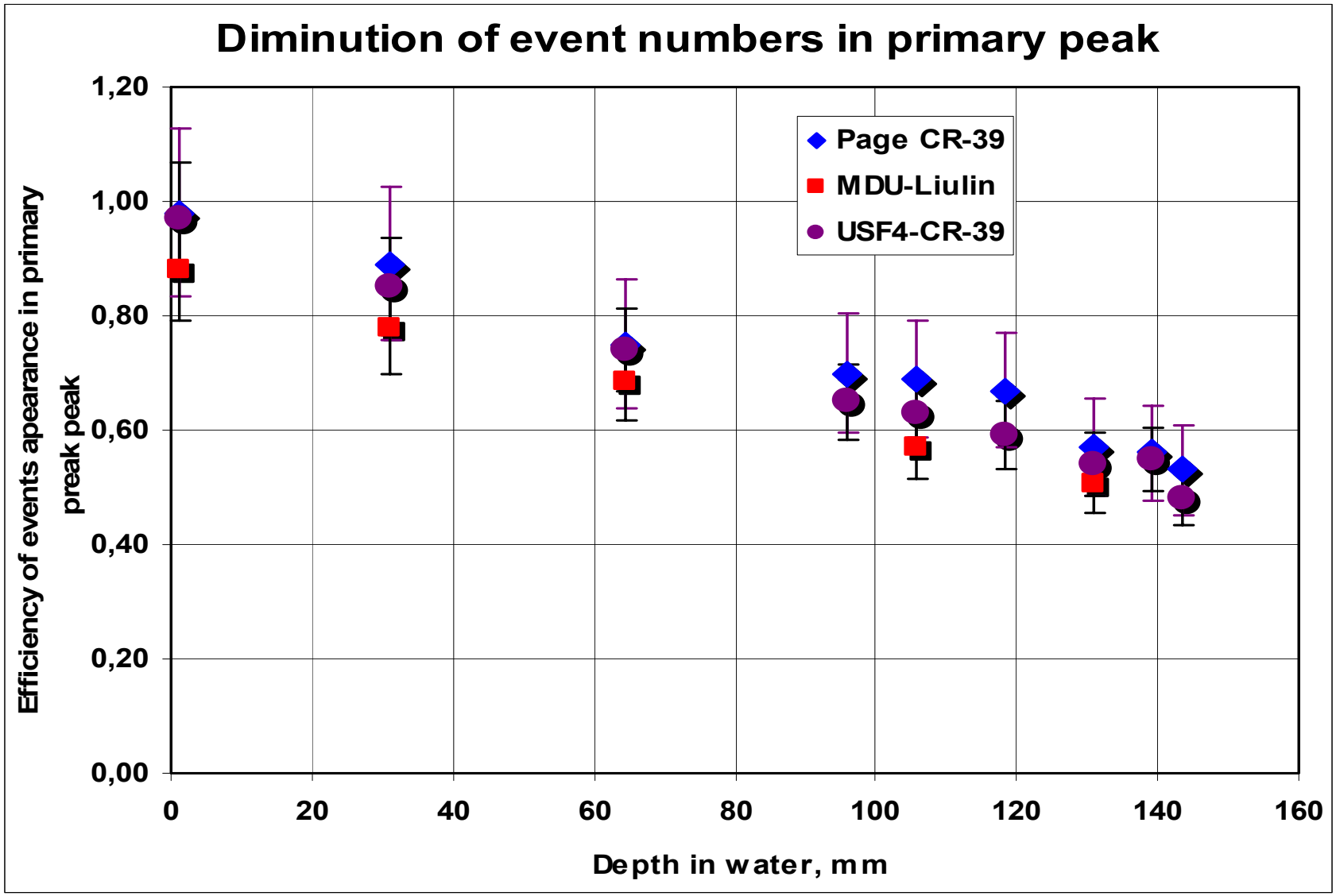
LET spectra (Page) – around the Bragg peak



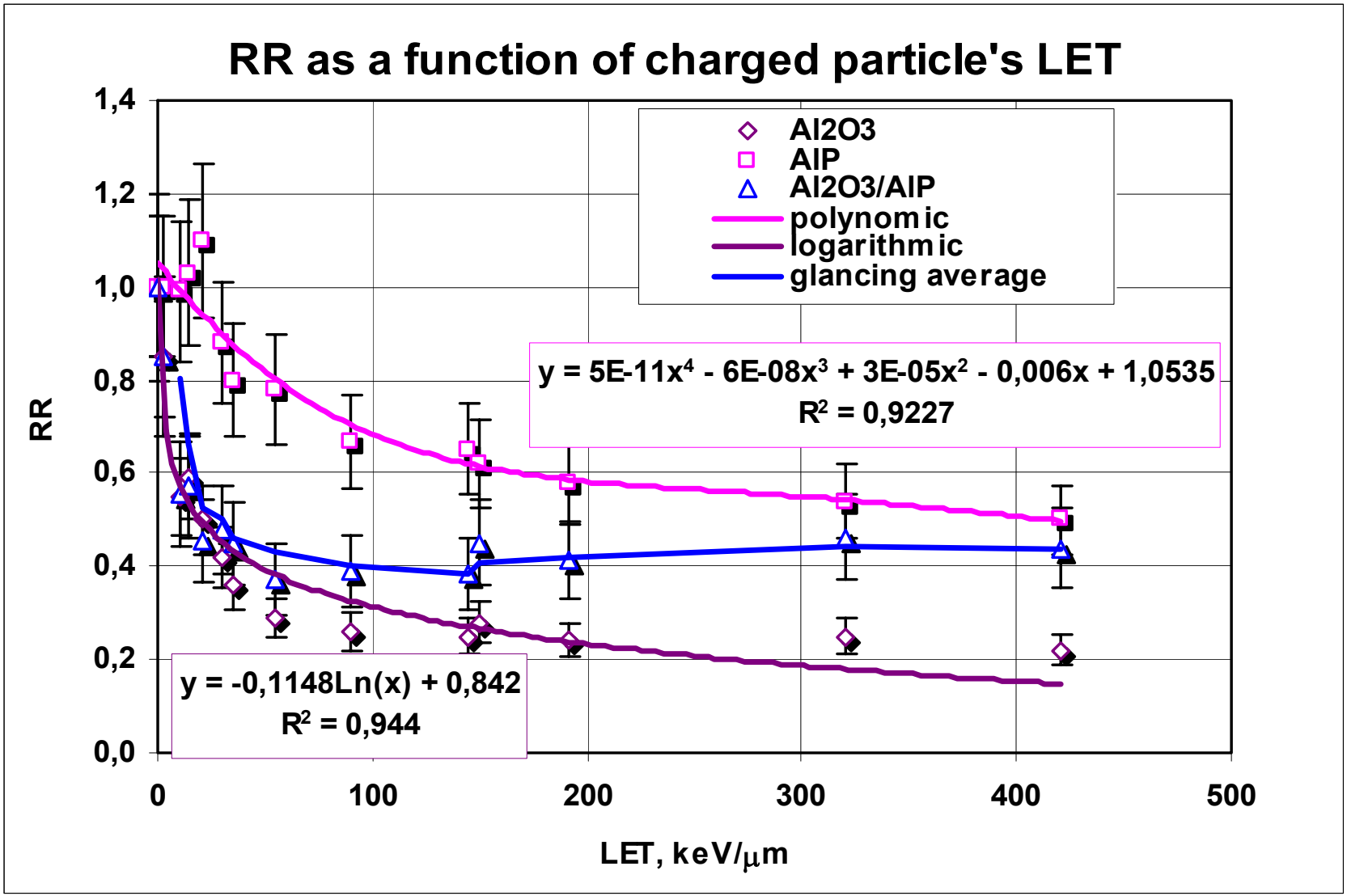
LET spectra (USF 4) for different LET_{ref}



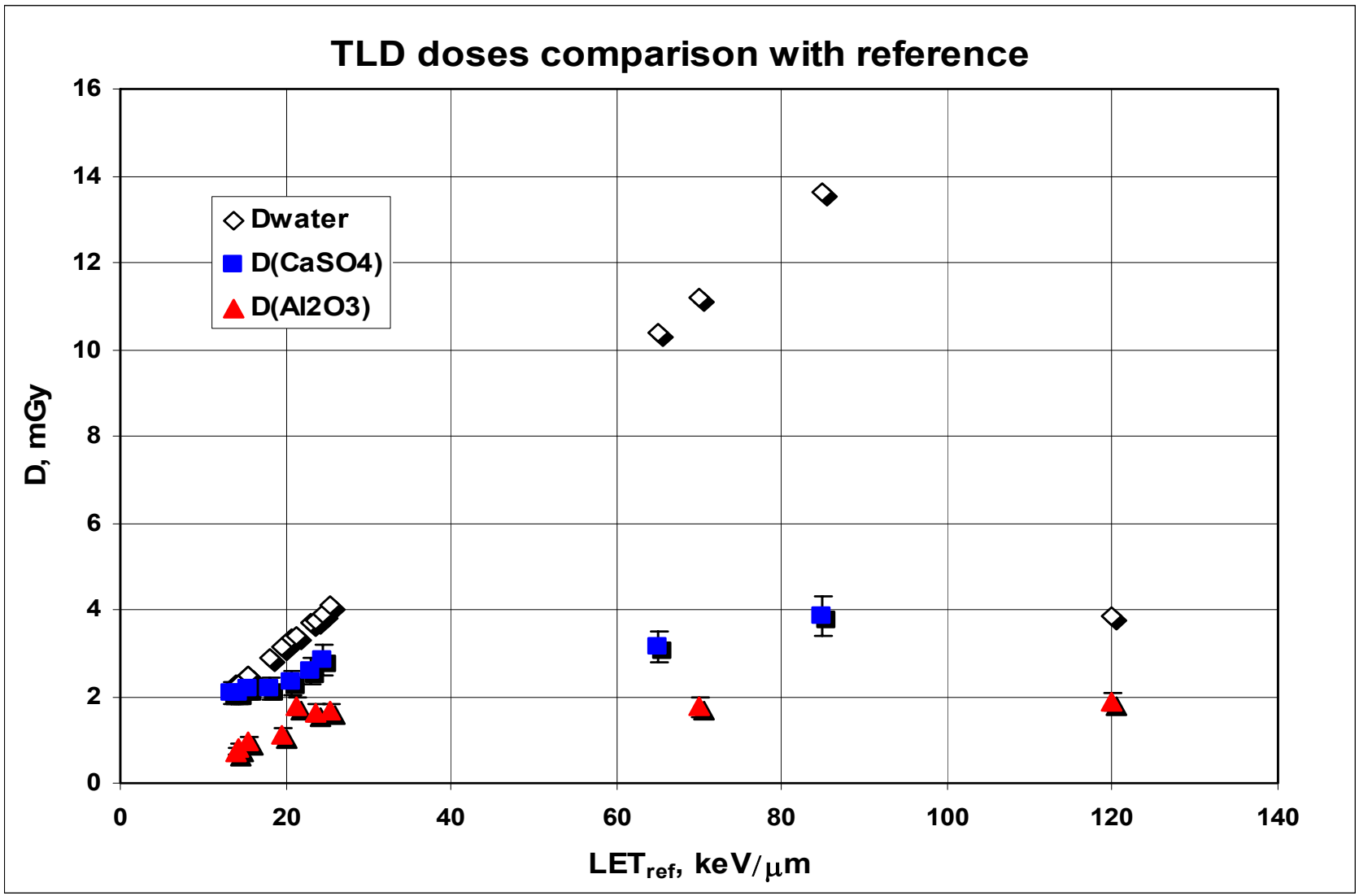
Diminution of event appearance in primary ion area (absolute scale)



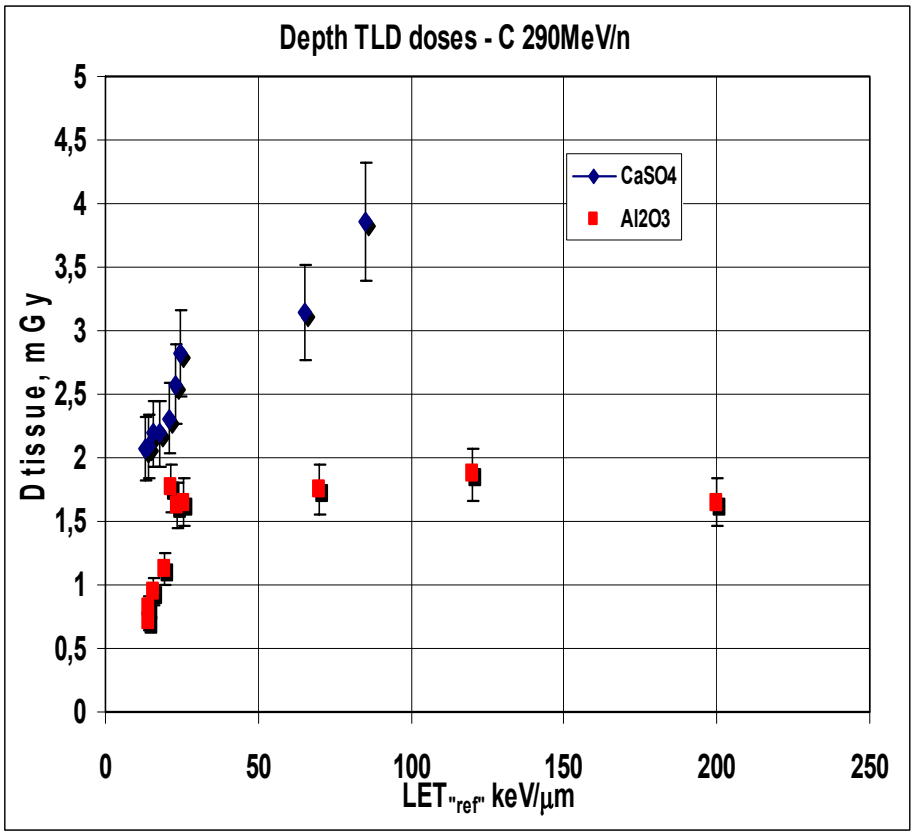
LET dependences of RR for AlP glasses, Al_2O_3:C, and their ratios

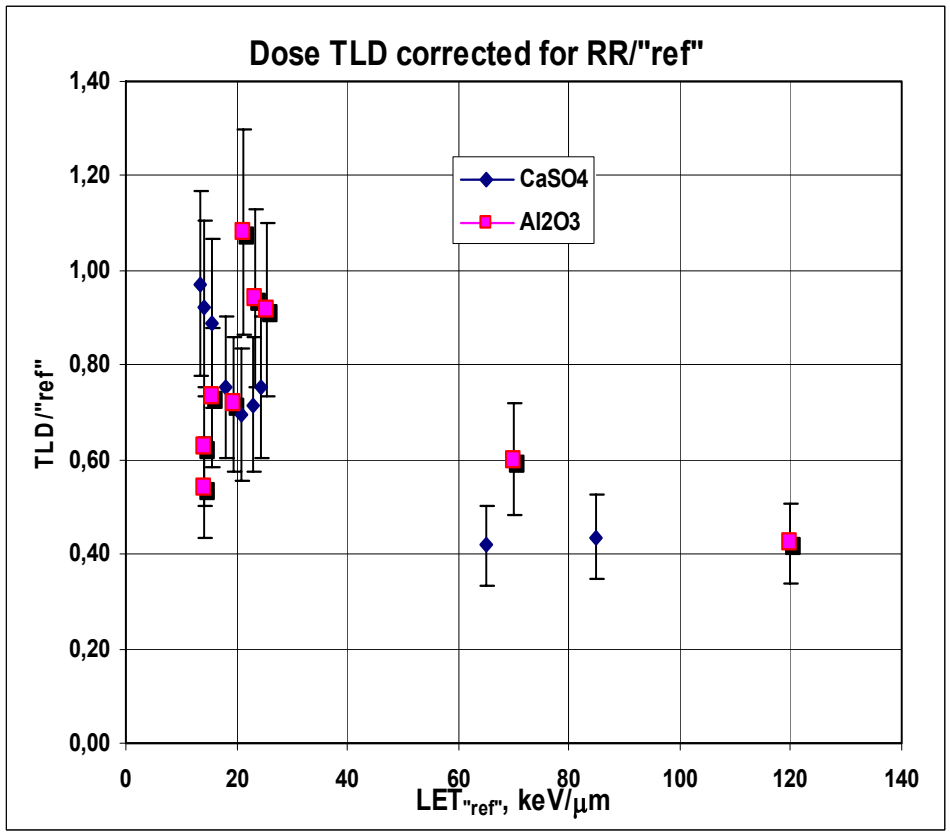


Comparison of TLD doses with those calculated from the C-ion fluence



TLD responses in C290 MeV/n beam





Dose characteristics

$D_{LET} = \int (dN / dL) \,.\, L \,.\, dL$

$H_{LET} = \int (dN / dL) \,.\, L \,.\, Q(L) \,.\, dL$

$BWED = \int (dN / dL) \,.\, L \,.\, r(L) \,.\, dL$

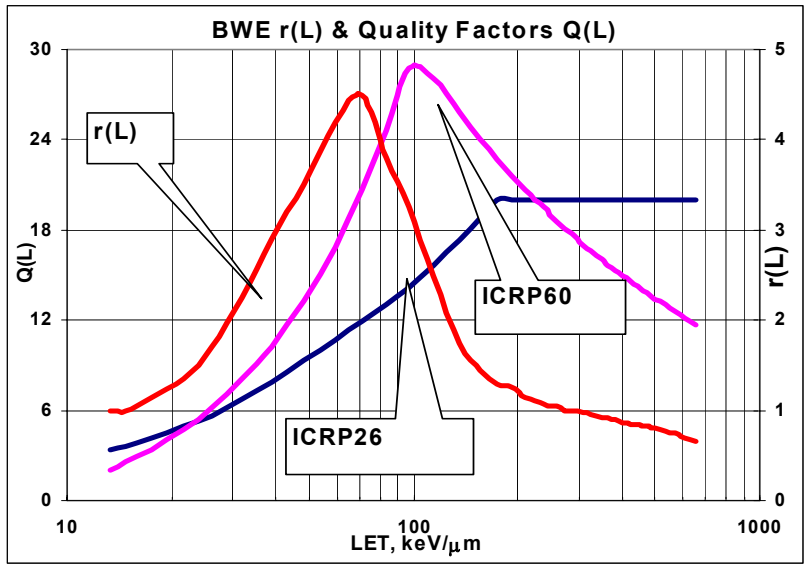
$RBWE = BWED / D$

L – value of linear energy

dN/dL – number of tracks *N* in a *L* interval *dL*

Q(L) – ICRP 60 quality factor

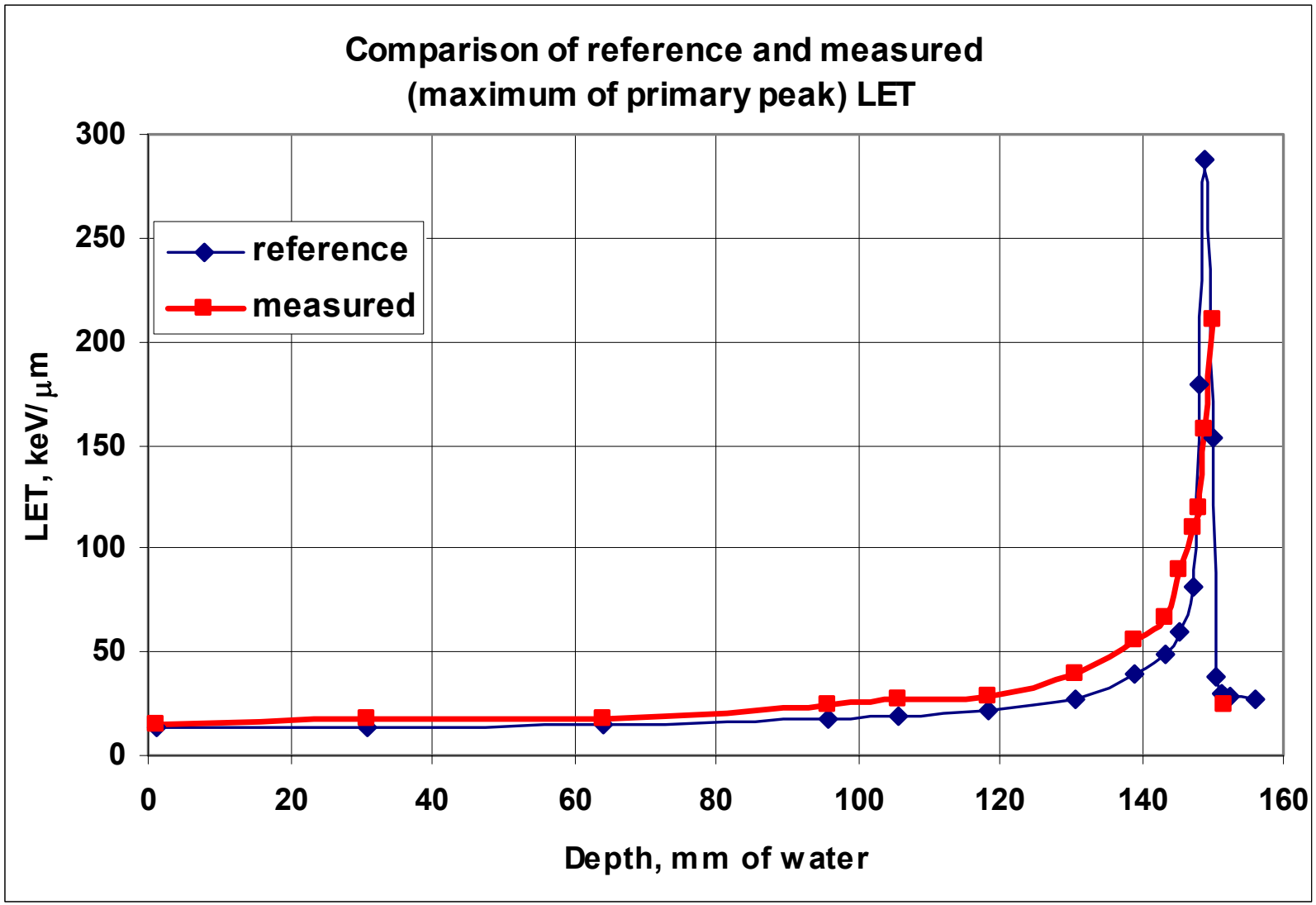
r(L) – biological weighting function transfer



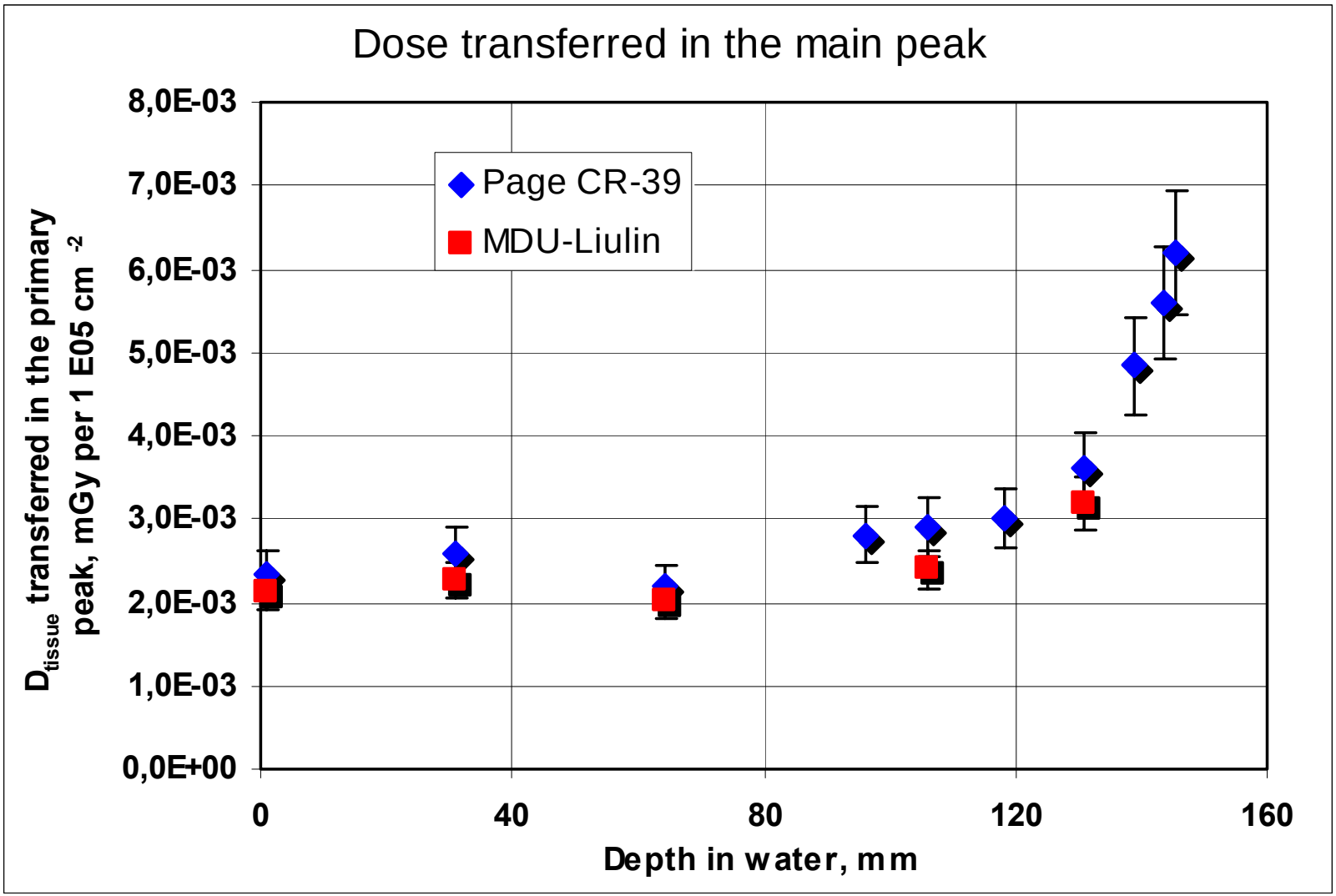
- protocols for *D* and *H* calculations
- errors of doses and dose equivalents – statistical and systematical uncertainties

Pihet P, Menzel HG, Schmidt R, Beauduin M and Wambersie A 1990 A biological weighting function for RBE specification of neutron therapy beams. Intercomparison of 9 European centres *Radiat. Prot. Dosim.* 31 437-444

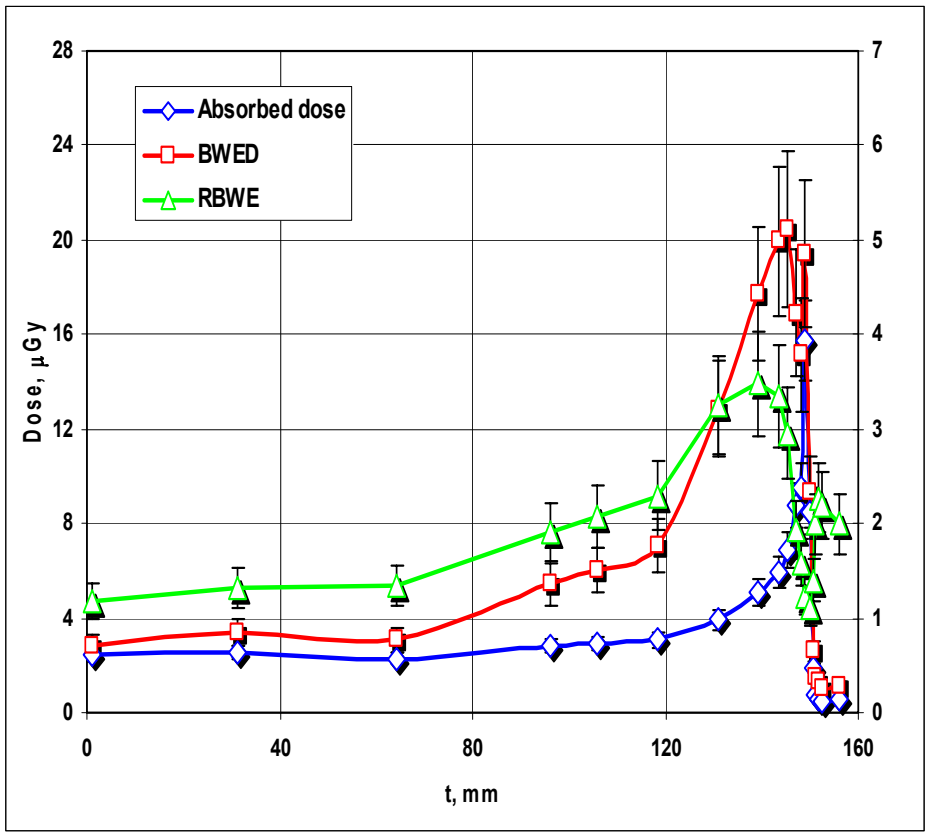
Comparison of depth evolution of LET maxima – Page

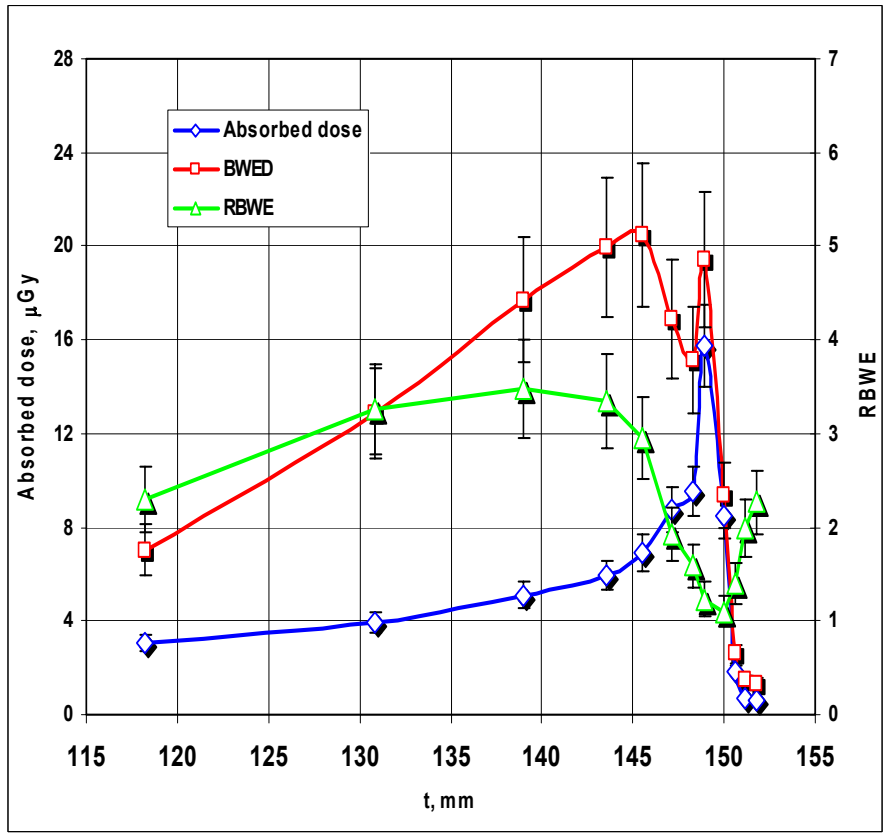


C290 - depth dependence of dose transferred in the peak of primary particles



C290 - depth dependence of dose, and biological efficiencies

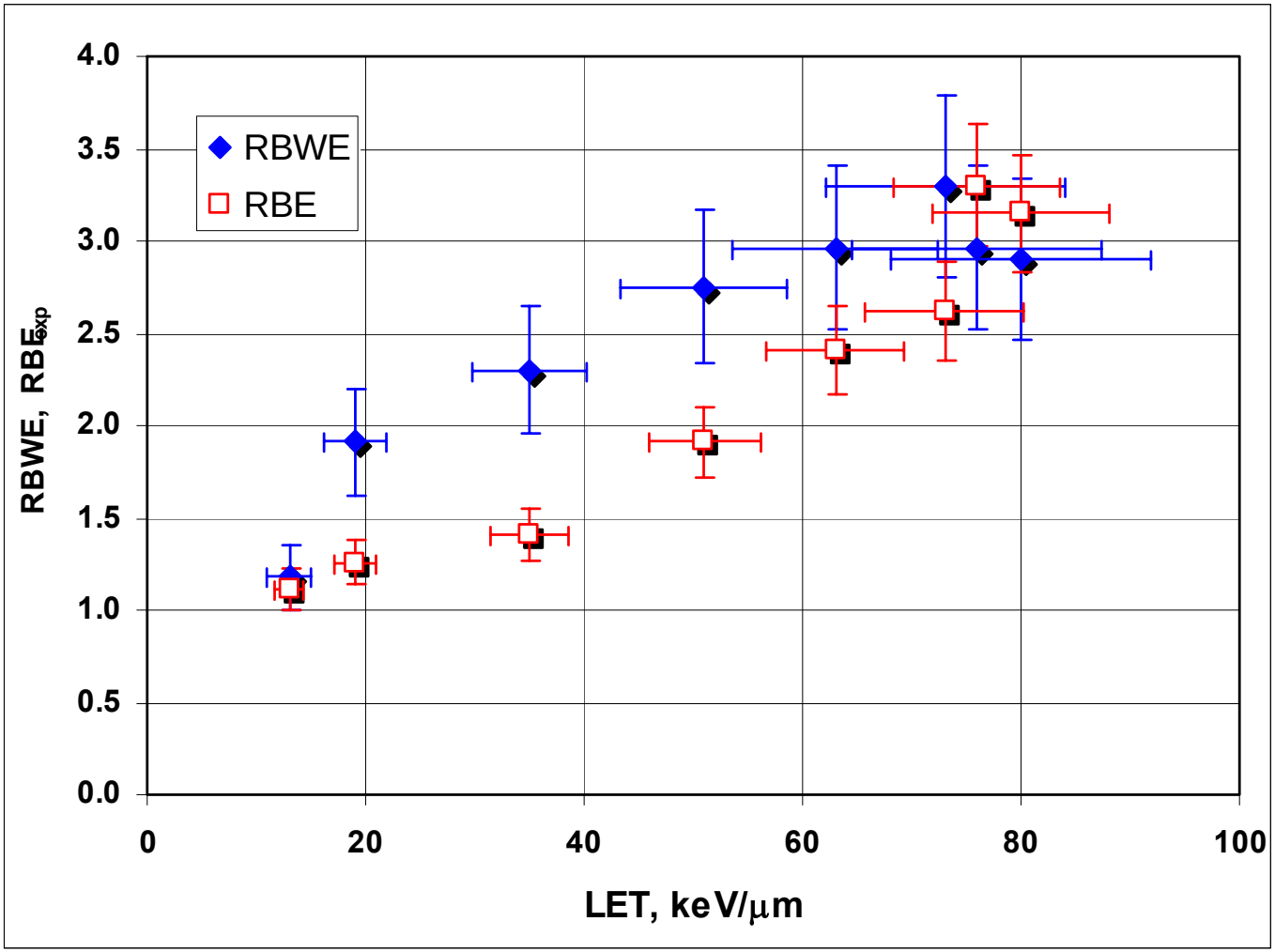




Along the full range

Close to Bragg peak region

Comparison of calculated and measured RBE*)



*) **C. Tsuruoka, M. Suzuki, T. Kanai*b* and K. Fujitaka**: *LET and Ion Species Dependence for Cell Killing in Normal Human Skin Fibroblasts*

RADIATION RESEARCH **163**, 494–500 (2005)

Fragmentations as seen in C 290MeV/u, and Ne 400 MeV/u HIMAC ion beams by MDU-Liulin energy deposition spectrometer

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MDU exposure conditions

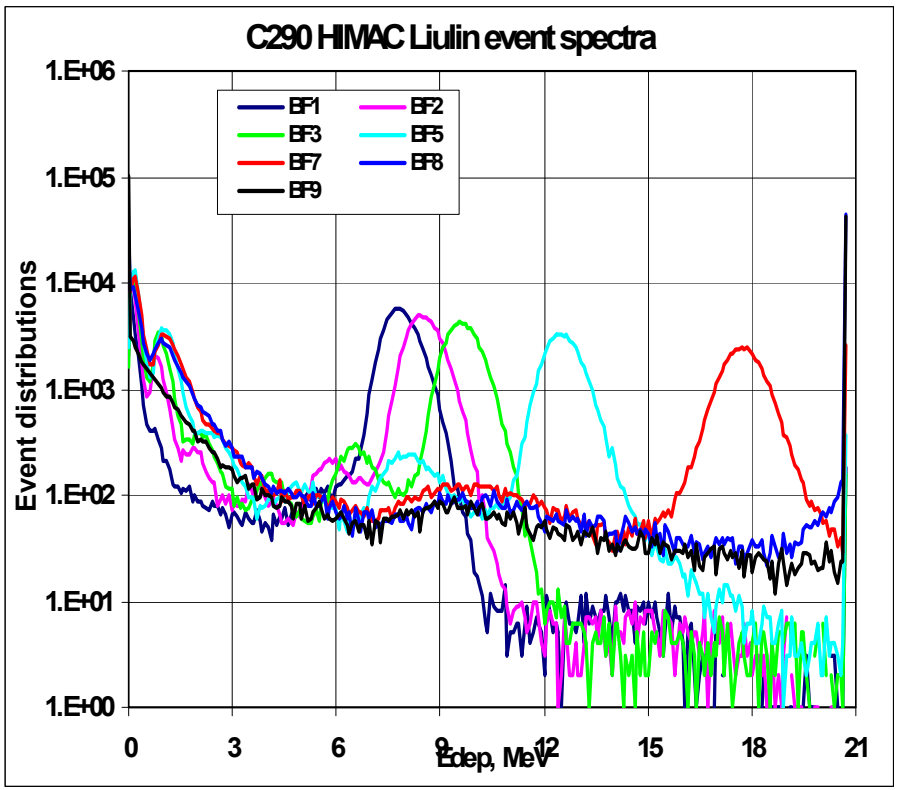
BF No.	C 290Mev/n		Ne 400 MeV/n	
	water equiv., mm	LET_{ref}, keV/µm	water equiv., mm	LET_{ref}, keV/µm
1	0	13.3	0	30.9
2	30.05	14.0	1.1	31.0
3	63.26	15.3	29.84	32.5
5	104.93	19.0	59.84	35.7
7	129.81	26.6		
8	138.02	37.6		
9	144.47	45.8		

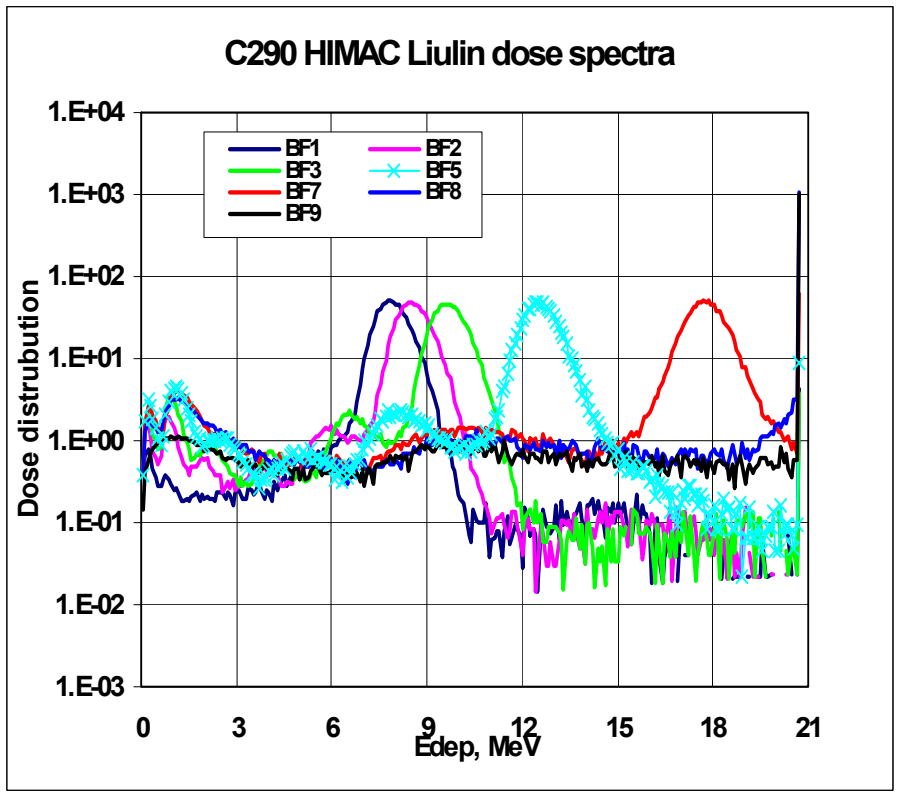
Specific importance of MDU results

- There is no other information on LET spectra below the threshold of CR-39 LET spectrometers (5 – 10 keV/μm) i.e. for E_{dep} below about 7.3 MeV – see Table and following figures;
- TLD signal comes mostly from high LET particles, particularly for lighter ions see previous data

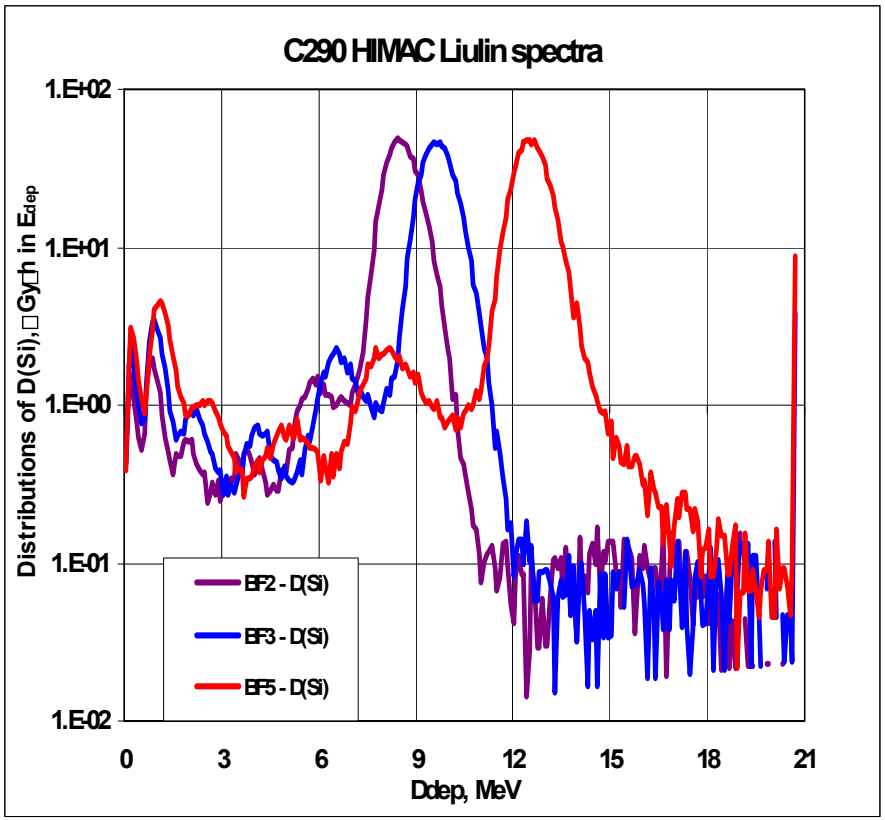
	LET_{ref}, keV/μm	$E_{dep} \leq$ 7.3MeV, %	Events ≤ 7.3MeV, %
1	13,3	18.1	38.5
2	14	8.4	42.3
3	15,3	10.7	53.2
5	19	9.9	61.1
7	26,6	8.6	60.0

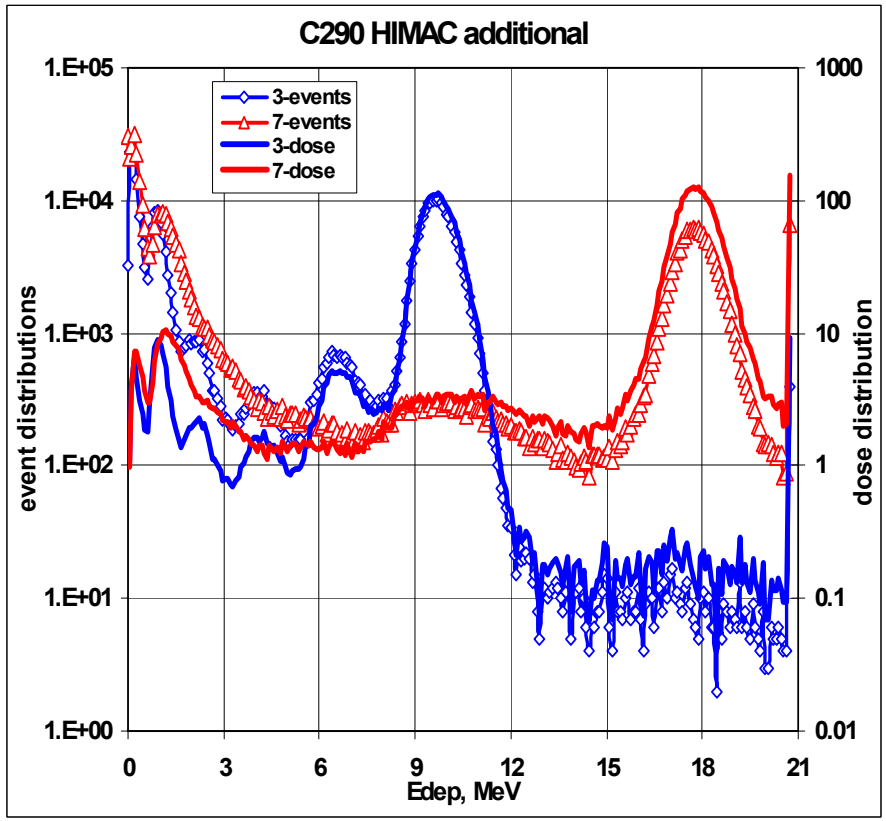
C290 results: Event and energy deposition spectra -1





C290 results: event and energy deposition spectra - 2

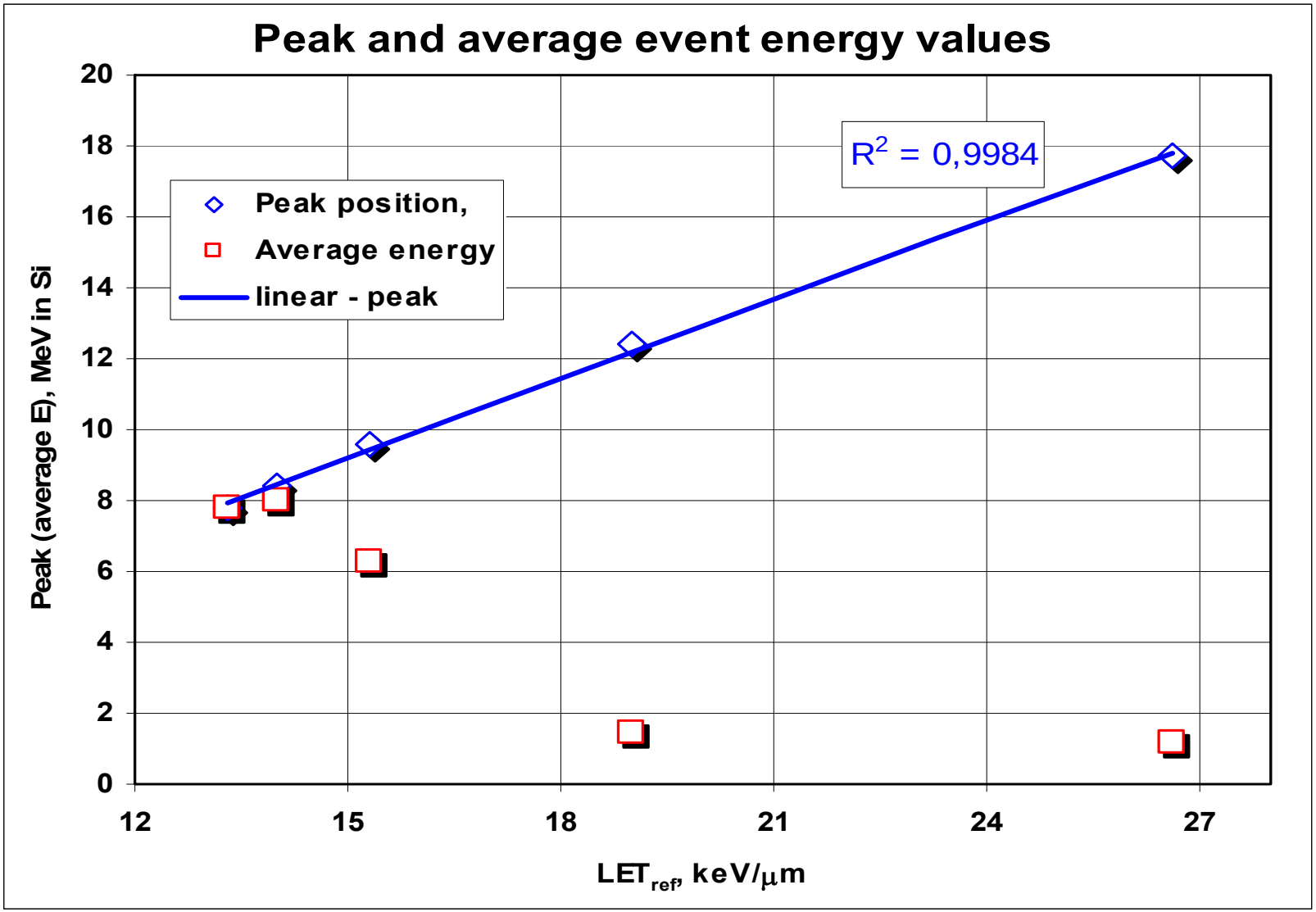




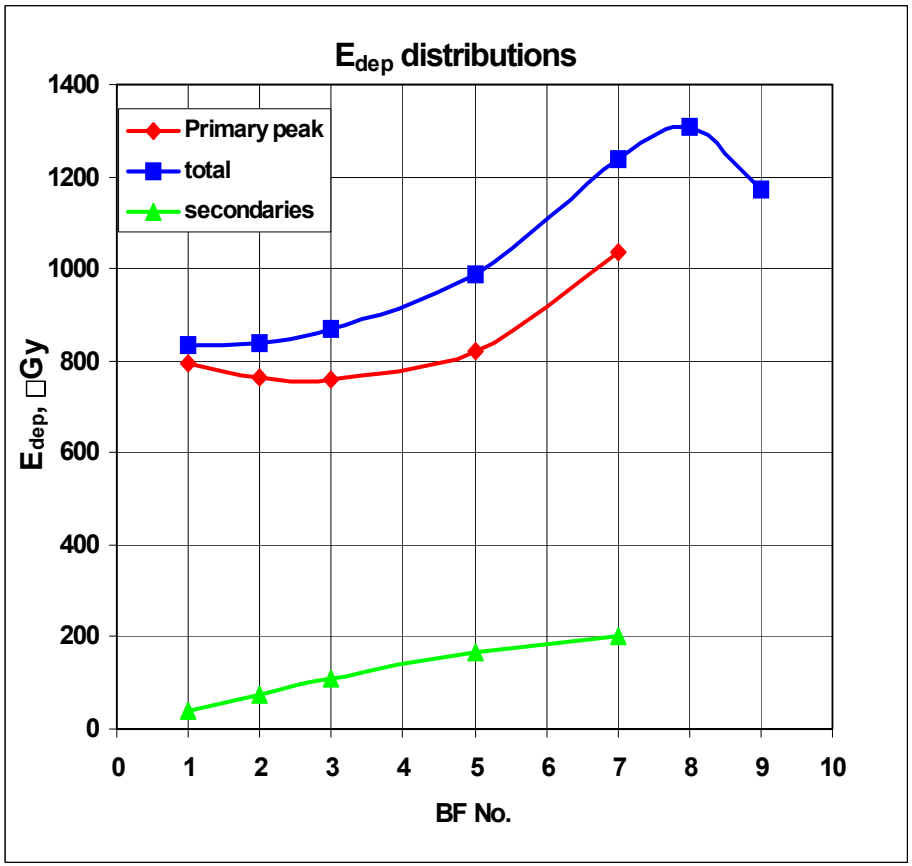
Distribution of events (doses); 1st attempt, C 290 MeV/n, BF No. 3 ~ 63.26 mm H_2O equiv., ~ 15.3 keV/µm

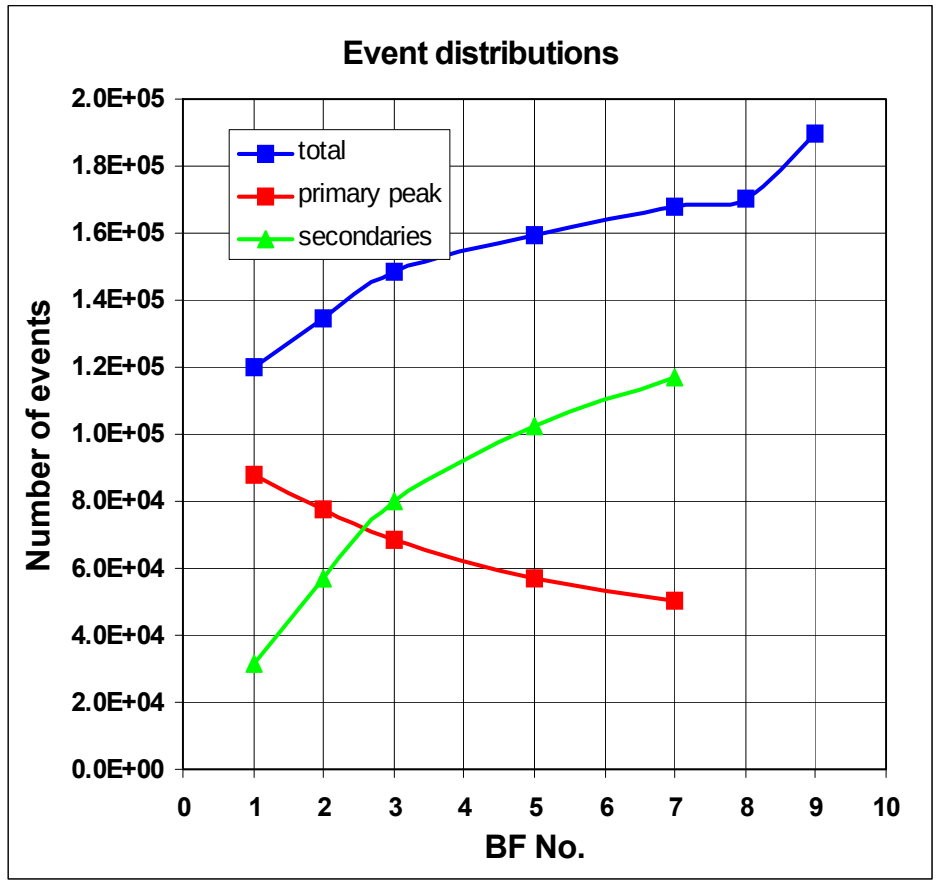
No.	Particle ?	Range of D(Si), MeV	No. of events (rel)	Dose, µGy; (rel.)
1	Protons & lowLET	0-0.53	115928 (0.317)	24.0 (0.0114)
2	He	0.61 – 1.67	52026 (0.143)	62.2 (0.0294)
3	Li	1.75 – 3.30	10913 (0.030)	28.8 (0.0136)
4	Be	3.38 – 5.09	5779 (0.016)	27.7 (0.0131)
5	B	5.19 – 7.94	14379 (0.039)	109.3 (0.0517)
6	C	7.94 – 12.17	165608 (0.452)	1841.6 (0.873)
7	“2 hits”	12.17- 20.72	1340 (0.0037)	17.2 (0.008)
		total	365973 (1.00)	2110.7 (1.0)

C290 - values of peak and average event energy as f(LET_{ref})



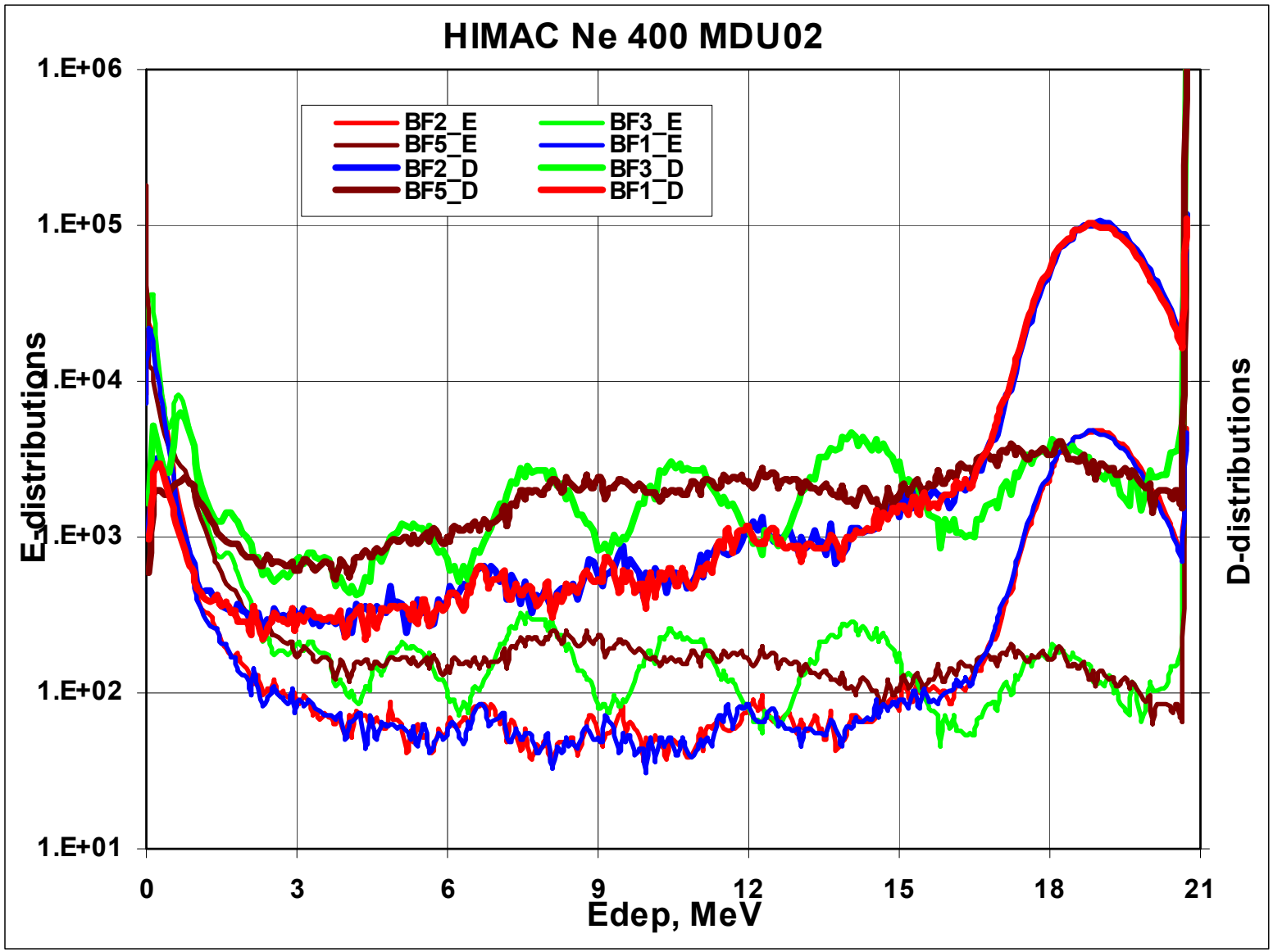
C290 - distributions behind different BF



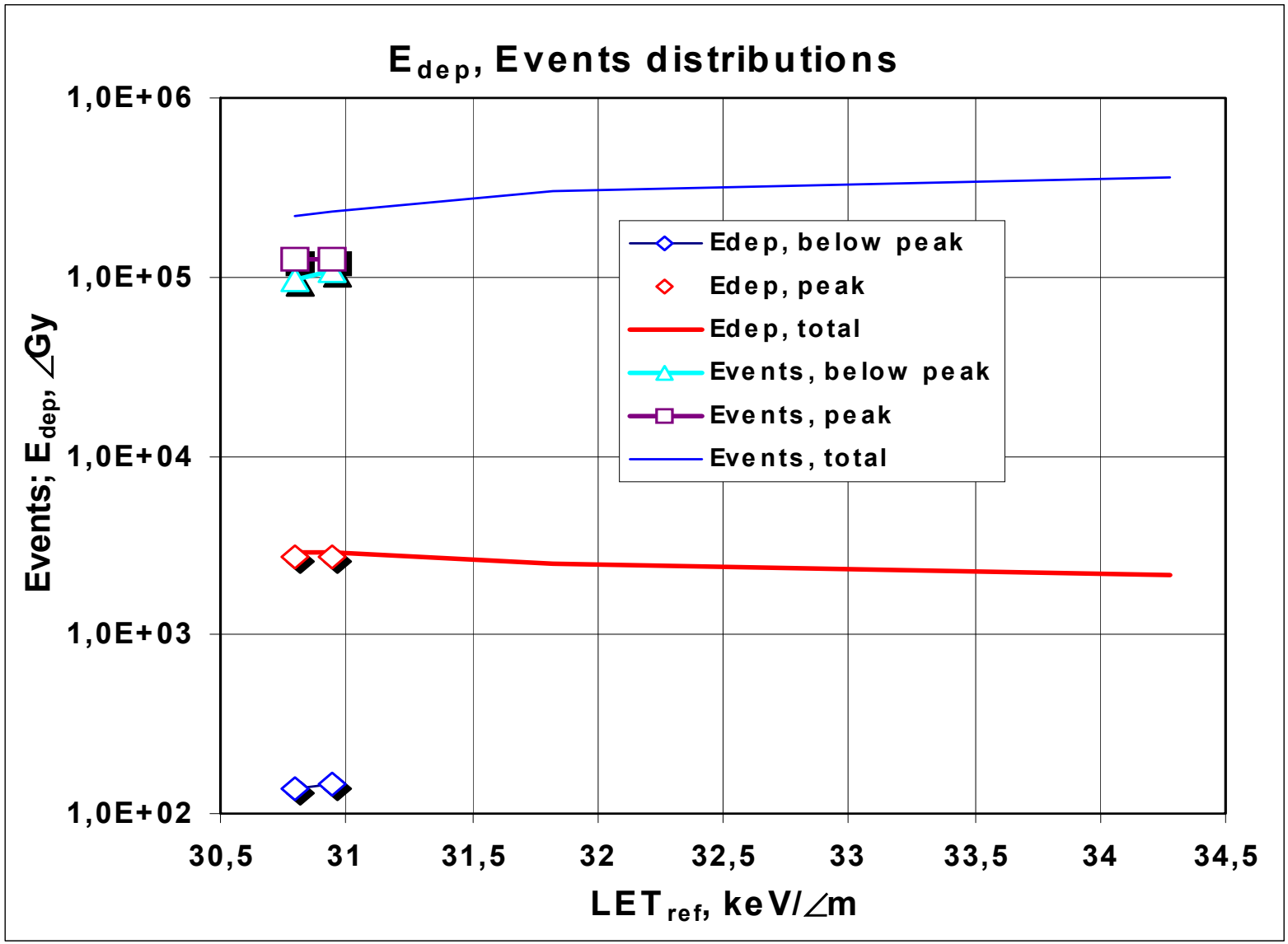


Reference value 1 E05

Event and energy deposition spectra – Ne



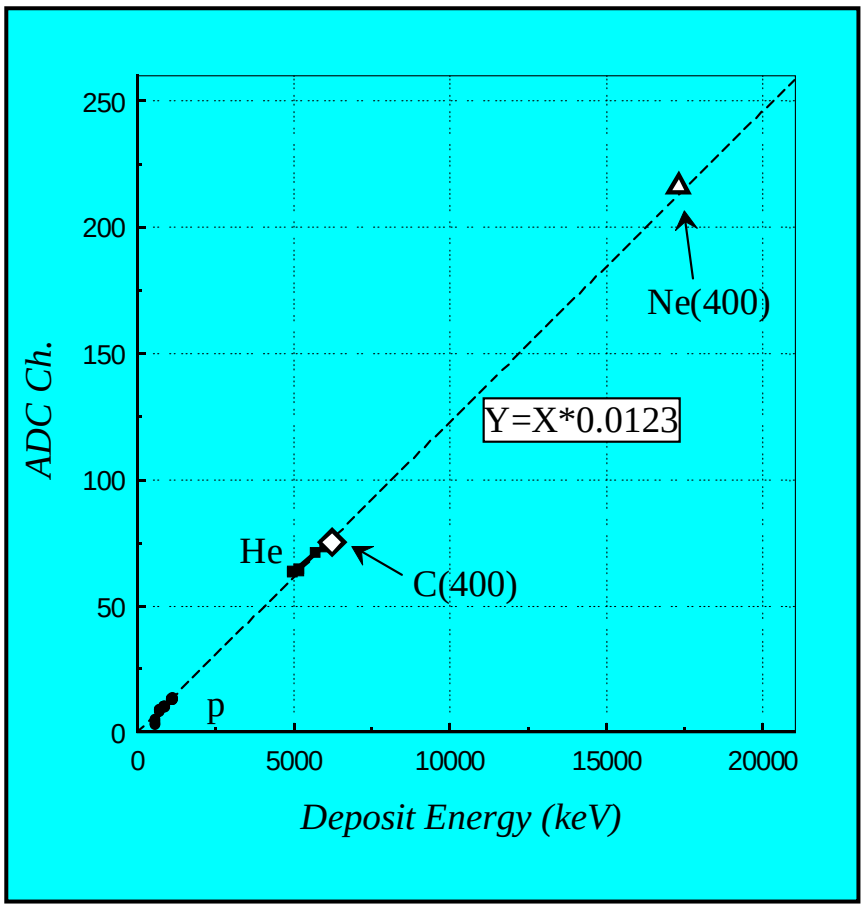
Ne400 - distributions behind different BF: event reference value 2 E05

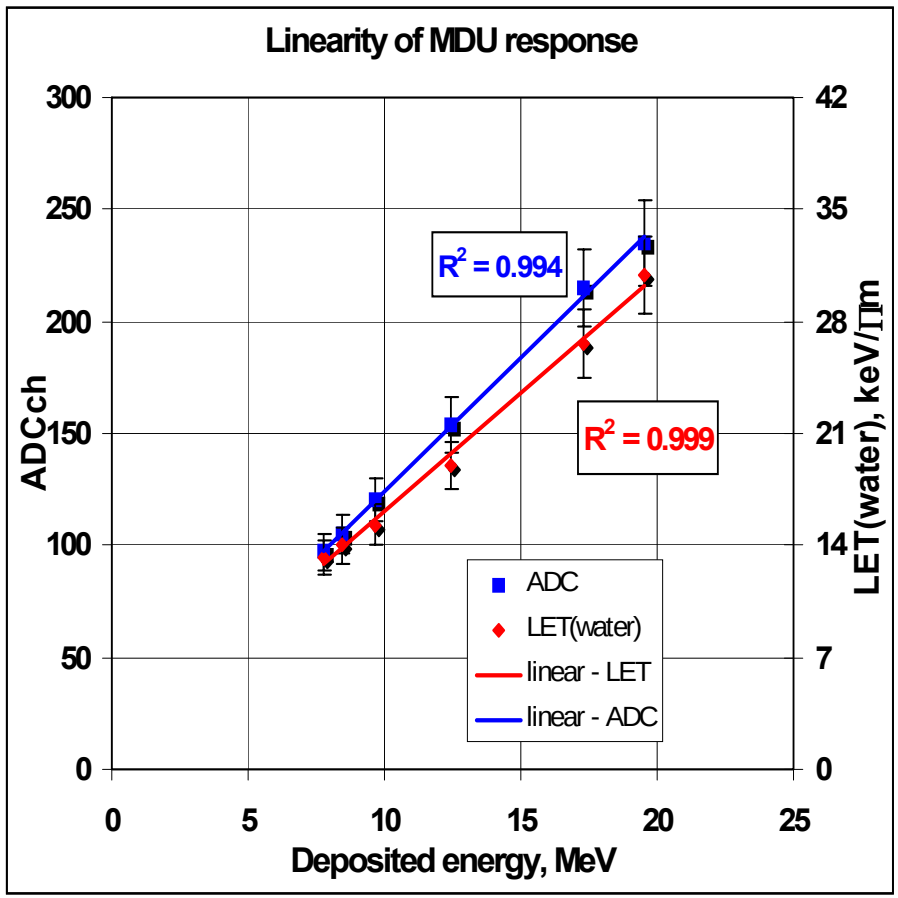


Ne400 - distribution of events (doses); 1st attempt, BF No. 3: 27.88 mm H_2O equiv., ~ 32.5 keV/µm

Particle ?	E dep, µGy(Si)	Events number
He	41.9	45829
Li	11.6	5430
Be	12.1	3450
B	22.2	4140
C	61.8	6898
N	76.5	6073
O	107.5	6554
F	120.6	5801
total	2014.4	84871

Comparison of MDU response linearity

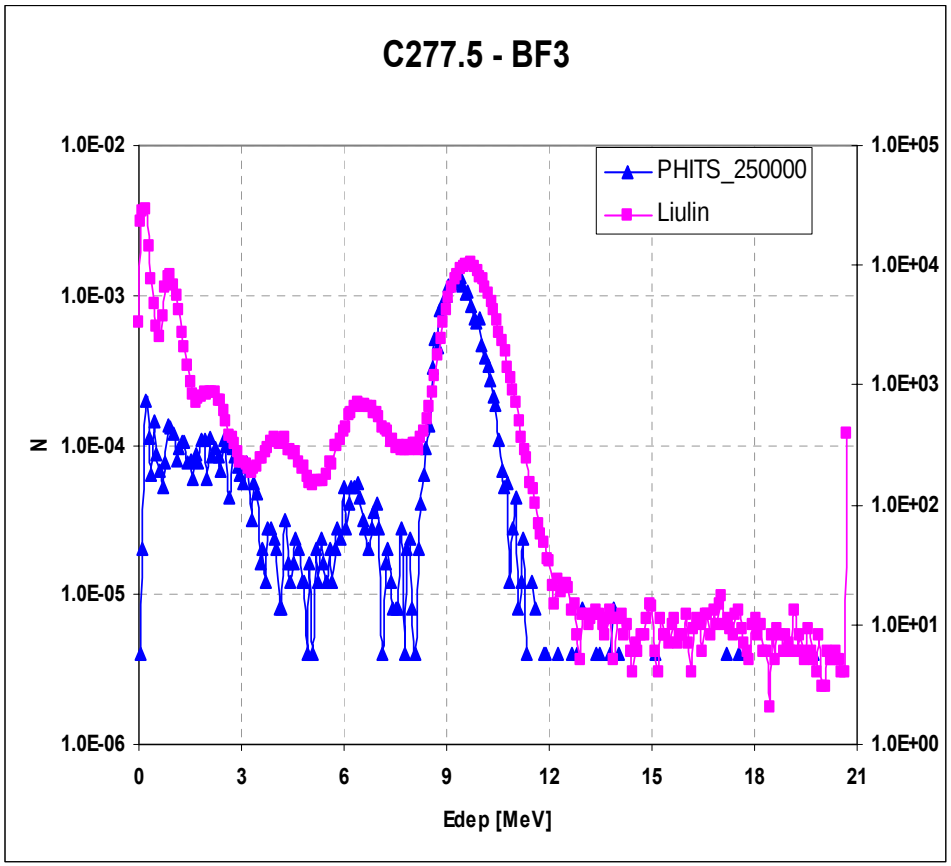


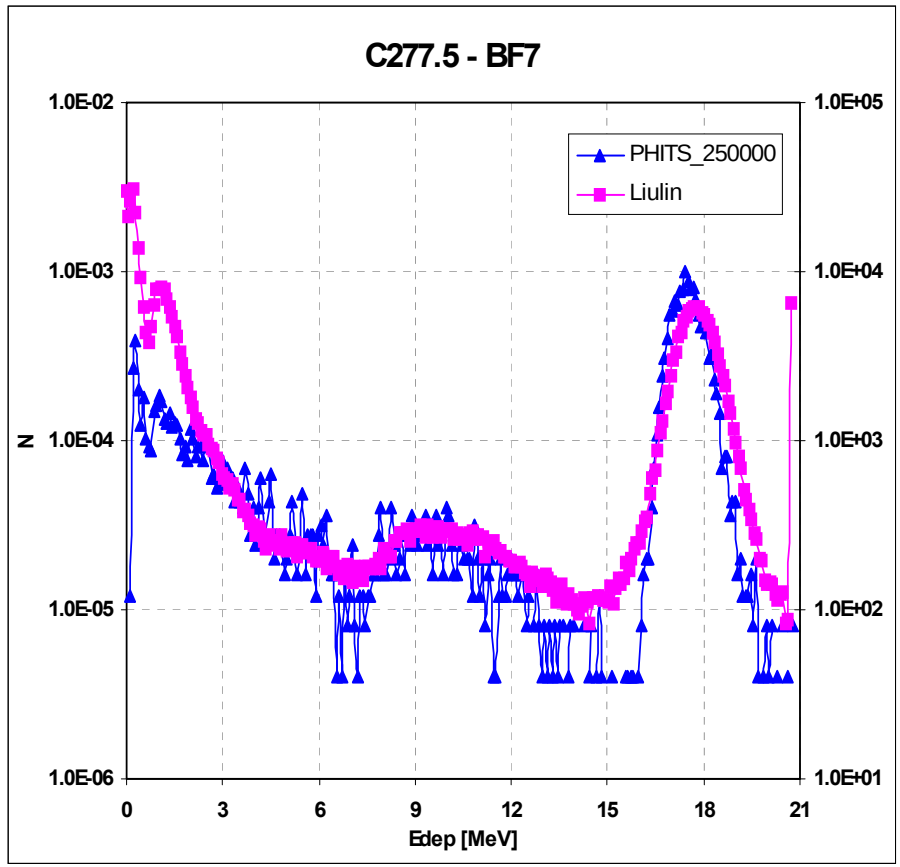


Previous results - Uchihori, et al, Rad. Meas., 35, 127-134, 2002

This study

C290 - comparison with PHITS calculations -1st attempt;





BF3 – 63.3 mm H_2O: ~ 15.3 keV/µm **BF7 - 130 mm H_2O; ~ 26.6 keV/µm**

Remark: no normalisation performed

Conclusions - Liulin

MDU – Liulin reproves its possibilities to acquire data on ionizing energy transfer in complex fields, in high-energy charged particle beams

- These data can be relevant to:

➢ energy transfer in heavy ion therapy beams;

➢ nuclear physics (fragmentations, nuclear interactions); and

➢ radiation protection questions related to

Further analysis to be performed:

A. Comparison of 02C and 07C MDU units

B. Generall tasks:

- Full analysis of E_{dep} spectra as a function of particle and its energy; transform the E_{dep} to LET(water) spectra;
- Comparison of LET(water) spectra obtained with those deduced from CR-39 LET spectrometry data above corresponding thresholds;
- Improvement of the methodology of E_{dep} (LET) spectra calculations by means of PHITS code, comparison with other codes (GEANT?); comparison of measured and calculated E_{dep} (LET) spectra

Conclusions - passive & general

I. Basic characteristics already established (for C 290 MeV/n ion beam):

1. Track etch ratios, LET spectra, doses, and BWED for Page and USF 4 CR-39, and TLD responses along the range
2. Depletion of primary particles along the range – comparison with MDU detector

II. Other studies have to be done:

1. To complete Page and USF4 data with the results for other materials;
2. Full LET spectra and radiobiological efficiencies on the base of combination of CR-39s, MDU, and TLD results for C 290 MeV/n ion beam;
3. All studies mentioned above for Ne 400 MeV/n ion beam
4. Analysis of complete sets of data for both ion beams

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