# ICCHIBAN 8: Czech results obtained with thermoluminescent and track etched detectors

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# ICCHIBAN - protocol

| Ion | Energy (MeV/n) | Range in $H_2O$ (cm) | $LET_\infty H_2O$ (keV/μm) |
|---|---|---|---|
| $^{4}He$ | 150 | 15.6 | 2.2 |
| $^{16}O$ | 400 | 20.2 | 19.8 |
| $^{40}Ar$ | 500 | 14.44 | 89.31 |
| $^{56}Fe$ | 200 | 2.1 | 309.7 |

| Exposure | Dose/Fluence | Condition |
|---|---|---|
| 1 | 50 mGy | Bare Beam for TLD/OSL Efficiency |
| 2 | 50 mGy | Behind PMMA[1)] Absorber for TLD/OSL |
| 3 | 5000 $cm^{-2}$ | Bare Beam for CR-39 PNTD calibration[2)] |
| 4 | 5000 $cm^{-2}$ | Behind PMMA Absorber for CR-39 PNTD[2)] |

1) Absorber thickness in $H_2O$ equivalent: 11.47; 10.01; 5.25; and. 0.345 cm for He; O; Ar; and Fe.

2) Higher doses used for 150 MeV/n $^{4}He$ exposures.

# Thermoluminescent detectors (TLD's)

## $Al_2O_3$:C:

- **H*(10) ≥ 1 μSv**
- **rapid decrease of light conversion factor (relative response RR) with LET above ~ 1 keV/μm**

## Czech alumophosphate (AlP) TL glass

- **H*(10) ≥ 10 μSv**
- **slower decrease of relative response RR with LET above ~ 10 keV/μm**

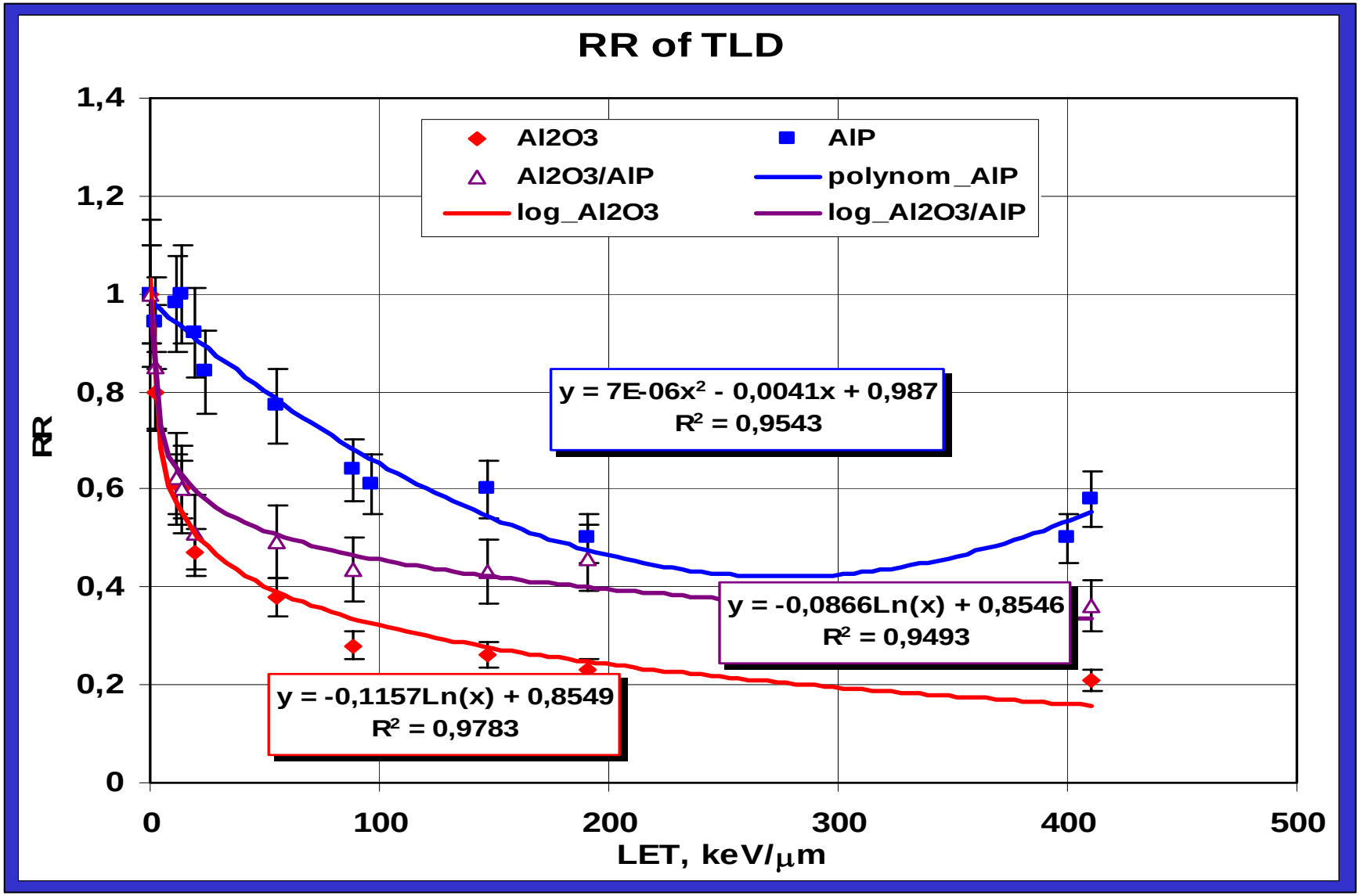
## $CaSO_4$:Dy from INRNE BAS

- **H*(10) ≥ 1 μSv**
- **slower decrease of relative response RR with LET above ~ 10 keV/μm**

# Comparison of relative responses obtained during ICCHIBAN 8 experiment

| Beam | Actual energy | Actual LET | | RR for | |
|---|---|---|---|---|---|
| | MeV/n | keV/µm | $Al_2O_3$:C | Al-P glass | $CaSO_4$:Dy |
| He | 150 | 2.16 | 0.77±0.05 | 0.94±0.08 | 1.01±0.09 |
| He/PMMA | 61[1)] | 4.2 | 1.10±0.08 | 1.37±0.11 | 1.63±0.12 |
| O | 395 | 20.0 | 0.47±0.04 | 0.92±0.07 | 0.95±0.06 |
| O/PMMA | 268[1)] | 25.0 | 0.47±0.04 | 0.92±0.08 | 0.94±0.07 |
| Ar | 440 | 92 | 0.32±0.02 | 0.64±0.05 | 0.59±0.04 |
| Ar/PMMA | 377[1)] | 108 | 0.34±0.03 | 0.68±0.05 | 0.62±0.04 |
| Fe | 130 | 411 | 0.25±0.02 | 0.58±0.04 | 0.44±0.03 |
| Fe/PMMA | 105[1)] | 445 | 0.35±0.03 | 0.77±0.05 | 0.57±0.04 |

# LET dependence of the TL relative response (RR)



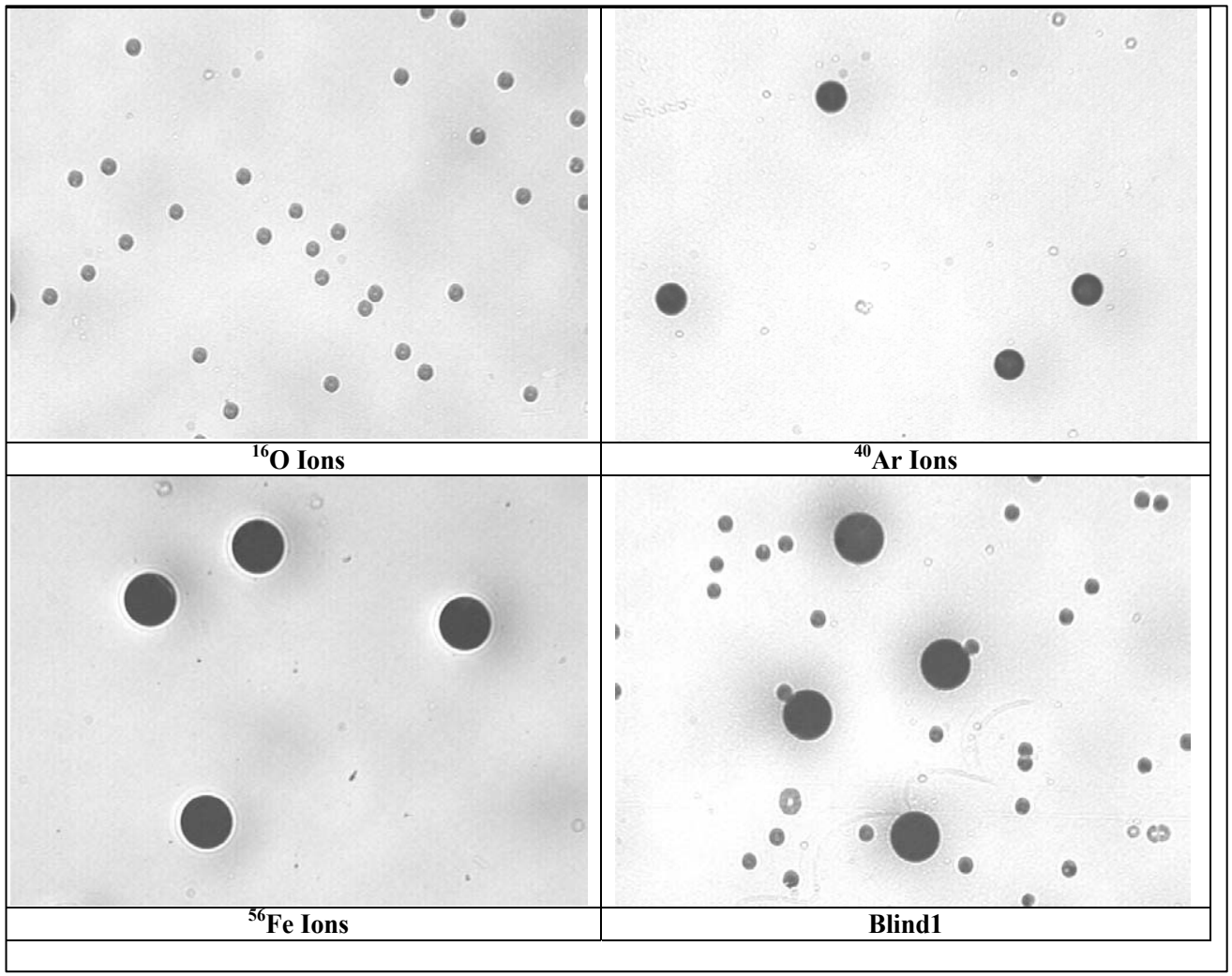
# LET spectrometer based on chemically etched PADC TED

**TED - polyallyldiglycolcarbonate (PADC): Page(0.5mm), Tastrak (0.5 and 1 mm);**
**Etching - 5 N NaOH, 70°C;18 h, $\Delta h \approx 17$ μm;**

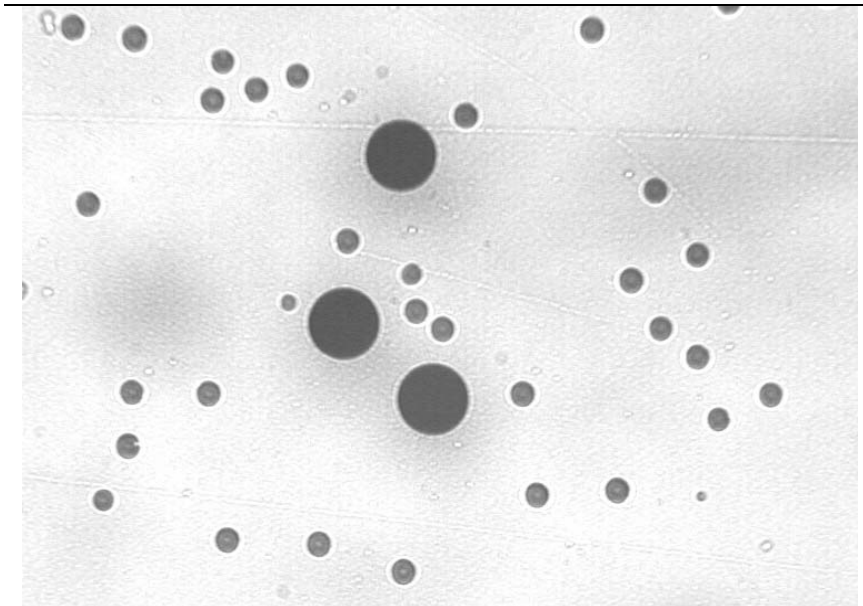
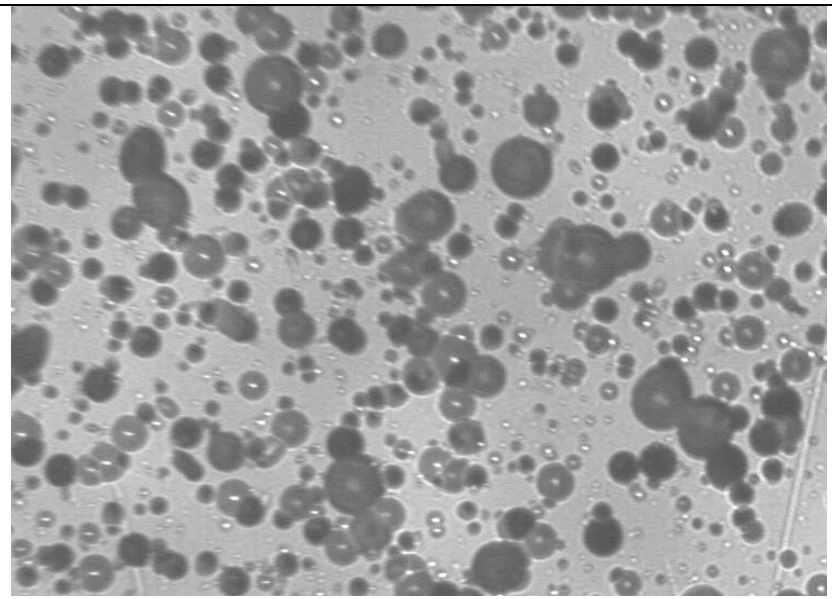
**To determine LET - etching rate ratio $V=V_T/V_B$ established through the determination of track parameters;**

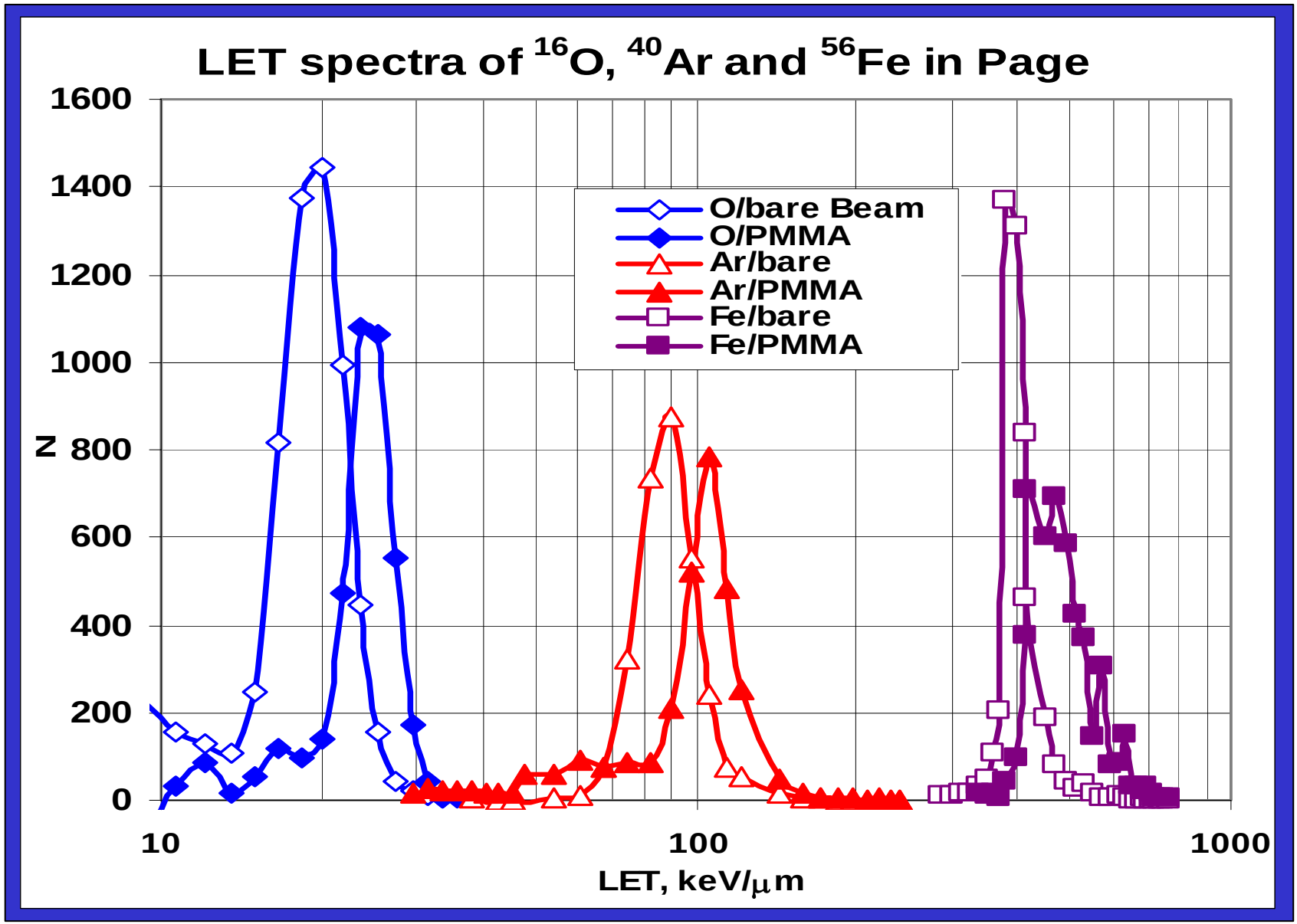
| Material | LET range keV/μm | Range of H mSv |
|---|---|---|
| Page, 0.5 mm thick | 7 – 700 | |
| Tastrak, 0.5 mm thick | 15 – 700 | 1 - 100 |
| Tastrak, 1 mm thick | 22 – 700 | |

# Pictures of tracks etched in Page PADC LET spectrometer and some of exposures - 1



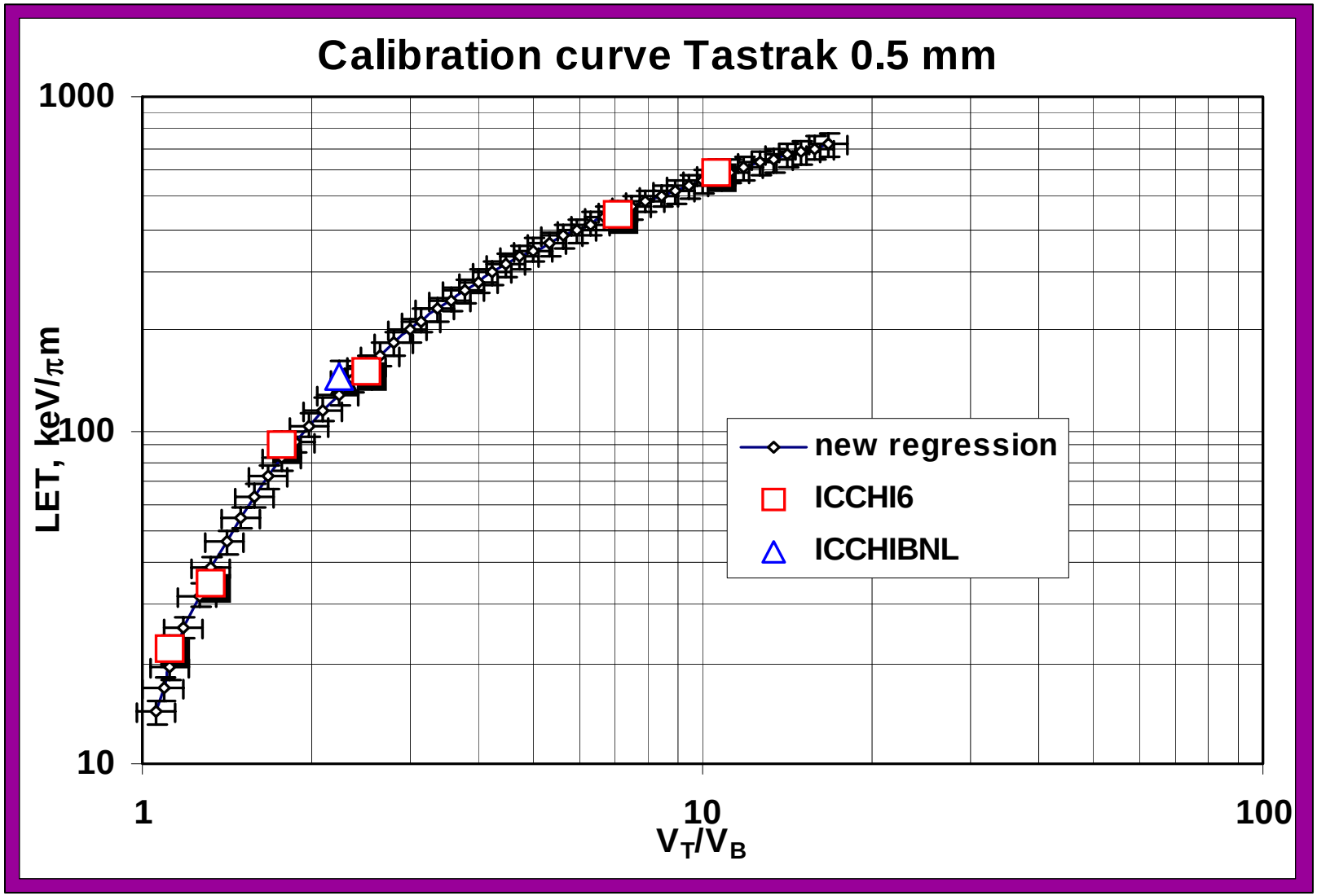
# Pictures of tracks etched in Page PADC LET spectrometer and some of exposures - 2

| | |
|---|---|
|  |  |
| **Blind2** | **Blind3** |


LET spectra of $^{16}O$, $^{40}Ar$ and $^{56}Fe$ in Page
1600
1400
1200
1000
800
600
400
200
0
Z
10
100
1000
LET, keV/μm
O/bare Beam
O/PMMA
Ar/bare
Ar/PMMA
Fe/bare
Fe/PMMA

# Average values of ratio V (= $V_T/V_B$) for PADC materials used for LET spectrometry

| Ion | LET in water | | $V_T/V_B$ for | |
|---|---|---|---|---|
| | keV/μm | Page | Tastrak 0,5 mm | Tastrak 1 mm |
| O | 20.0 | 1.24±0.02 | 1.06±0.02 | 1.10±0.03 |
| O/PMMA | 25.0 | 1.29±0.02 | 1.12±0.02 | 1.20±0.03 |
| Ar | 92 | 1.78±0.03 | 1.78±0.08 | 1.82±0.06 |
| Ar/PMMA | 108 | 1.89±0.03 | 2.01±0.03 | 2.00±0.06 |
| Fe | 420 | 5.50±0.35 | 7.20±0.20 | 6.00±0.36 |
| Fe/PMMA | 460 | 7.33±0.73 | 10.3±0.4 | 10.0±0.45 |


Calibration curve Tastrak 0.5 mm
1000
100
10
LET, keV/μm
1
10
100
V_T/V_B
new regression
ICCHI6
ICCHIBNL

# Comparison of LET values (ICCHIBAN 8) with those from regressions (ICCHIBAN 2,4,6,BNL).

| Ion | $LET_{water}$ keV/μm | LET, keV/μm, for | | | |
|---|---|---|---|---|---|
| | | Page 0.5 mm | | Tastrak 0.5 mm | |
| | | ICCHI 8 | regressed | ICCHI 8 | regressed |
| O | 20.0 | 20.0 | 20.9±2.2 | 14.8 | 14.5±1.7 |
| O/PMMA | 25.0 | 24.8 | 24.7±2.6 | 25.7 | 20.8±1.8 |
| Ar | 92 | 87.0 | 86.7±9.0 | 84.5 | 83.0±8.0 |
| Ar/PMMA | 108 | 103 | 102±13 | 105 | 106±10 |
| Fe | 420 | 397 | 396±17 | 424 | 420±24 |
| Fe/PMMA | 460 | 457 | 463±24 | 490 | 540±33 |

# Registration efficiencies – ICCHIBAN 8, known exposures

| Ion | Shield | Page | Tastrak 0.5 | Tastrak 1.0 | Average |
|---|---|---|---|---|---|
| O | bare | 0.78 | 0.82 | - | 0.80±0.03 |
| | PMMA | 0.52 | 0.44 | - | |
| Ar | bare | 0.44 | 0.44 | 0.58 | 0.49±0.08 |
| | PMMA | 0.44 | 0.33 | 0.36 | |
| Fe | bare | 0.70 | 0.68 | 0.62 | 0.66±0.04 |
| | PMMA | 0.70 | 0.54 | 0.58 | |

# Dose characteristics calculated from LET spectra

## Absorbed dose

$D_{LET} = \Sigma(dN/dL)*L*dL$

## Dose Equivalent

$H_{LET} = \Sigma D_{LET}*Q(L)$

## Quality Factor

$Q = (H_{LET}+D_{pic})/D_{tot}$

**Where:**

**L: Value of LET**

**dN/dL: number of tracks in LET interval dL;**

**Q(L): quality factors from ICRP-60 recommendations;**

**$D_{LET}$: absorbed dose calculated from high LET part of spectra**

**$H_{LET}$: dose equivalent calculated from high LET part of spectra**

**$D_{tot}$: total absorbed dose**

**$D_{pic}$:proton ionisation dose**

# Registration of secondary particles in He-ion beam with LET spectrometry

| Dose D (mGy) | Beam | Registration efficiency tracks per $^4$He | Dose due to secondary particles $D_{sp}$, mGy | $D_{sp}/D$ % |
|---|---|---|---|---|
| Page | bare | $(3.4\pm0.3) \times 10^{-3}$ | 1.31±0.12 | 2.6±0.3 |
| | under PMMA | $(11.3\pm2.3) \times 10^{-3}$ | 5.00±0.65 | 10.0±1.3 |
| Tastrak 0.5 mm | bare | $(1.5\pm0.5) \times 10^{-3}$ | 0.99±0.25 | 2.0±0.5 |
| | under PMMA | $(11.1\pm0.2) \times 10^{-3}$ | 6.4±1.1 | 12.8±2.2 |

# Response of Melinex TED in contact with spallation radiators in He - ion beam

| Radiator | Beam | Track density behind a radiator, $cm^{-2}$ | |
|---|---|---|---|
| | | for D=1 Gy | Per 1 particle |
| $^{197}Au$ | bare | 312±104 *) | 1.1E -06 |
| | PMMA | 332±108 | 1.2E-06 |
| $^{209}Bi$ | bare | 840±180 | 2.9E-06 |
| | PMMA | 1210±210 | 4.2E-06 |

# Blind exposures – Dose estimation based on TLD

| Blind | Direct readings, mGy | | Average $LET_{app}$ | Corrected readings, mGy | | Average value of dose in water |
|---|---|---|---|---|---|---|
| No. | AlP glass | $Al_2O_3$:C | keV/μm | AlP glass | $Al_2O_3$:C | mGy |
| 1 | 9.29 *) | 6.75 | 4.4 | 9.58 | 9.87 | 9.72 |
| 2 | 24.7 | 16.7 | 7.8 | 25.8 | 27.1 | 26.5 |
| 3 | 236.6 | 124.0 | 46 | 295.1 | 300.2 | 297.6 |
| 4 | 17.7 | 16.3 | 0.45 | 17.9 | 17.2 | 17.4 |
| 5 | 17.0 | 10.0 | 22 | 19.0 | 20.2 | 19.6 |
| 6 | 17.1 | 13.0 | 2.6 | 17.5 | 17.5 | 17.5 |

***) 1s relative of read values about ± 5%, uncertainty of corrected procedure estimated to 15%**

# Blind exposures –ICCHIBAN 4 - TLD

| Blind No. | Particle | $D_{H2O}$ refer. | $D_{H2O}$ – TLD[1)] | | | | |
|---|---|---|---|---|---|---|---|
| | | | Read | | Corrected | | Average |
| | | | $Al_2O_3$:C | AlP | $Al_2O_3$:C | AlP | |
| 1 | γ | 25 | 28.6 | 25.3 | 23.6 | 25.8 | 24.7 |
| 2 | γ | 25 | 30.8 | 26.4 | 23.9 | 26.9 | 25.4 |
| 3 | He | 25 | 18.7 | 25.3 | 24.9 | 25.8 | 25.4 |
| 4 | γ, He, C, Ne, Fe | 12 | 10.5 | 12.4 | 12.1 | 12.7 | 12.4 |
| 5 | γ, He, C, Ne, Fe | 10 | 5.47 | 10.0 | 10.3 | 10.5 | 10.4 |
| 6 | C, Ne, Fe | 0.39[2)] | 0.34 | 1.50 | 2.27 | 2.50 | 2.38 |
| 7 | Fe/5 g Al | 1.0[3)] | 0.59 | 2.01 | 2.57 | 2.68 | 2.62 |
| 8 | C | 25 | 17.2 | 24.3 | 25.3 | 25.1 | 25.2 |

[1)]Relative uncertainty (1s) of direct readings ± 5%,
for corrected values estimated as ± 15%.
[2)] only for heavy charged particles [3)] In front of Al – absorber

# Blind exposures –ICCHIBAN 4 – LET TED

| Blind No. | $D_{H2O}$ , mGy from | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | C | | Ne | | Fe | | Total | |
| | ref. | TED | ref. | TED | ref. | TED | ref. | TED |
| 3[1)] | ~ 0 | ~ 0 | ~ 0 | ~ 0 | ~ 0 | ~ 0 | 25 | 22 ± 5[2)] |
| 4 | 0.018 | 0.015±0.002 | 0.050 | 0.031±0.004 | 0.325 | 0.31±0.04 | 0.39 | 0.32±0.04 |
| 5 | 2 | 1.7±0.2 | 2 | 1.8±0.2 | 2 | 2.0±0.2 | 6.0 | 5.5±0.4 |
| 6 | 0.018 | 0.014±0.002 | 0.050 | 0.042±0.006 | 0.325 | 0.32±0.03 | 0.39 | 0.38±0.03 |
| 7 | - | - | - | - | 1[3)] | 1.2±0.2 | 1.0 | 1.2±0.2 |
| 8 | 25 | ≥ 22 | - | - | - | - | 25 | ≥ 22 |

[1)] Irradiated by He-ions, dose estimation by TED based on the secondary charged particles created by nuclear reactions of primary ions;
[2)] here and for other uncertainties - 1 s; [3)] Behind 5 g/cm2 of Al.

# Blind exposures – Dose estimation based on TED (above ~ 10 keV/μm)

**The results of evaluations ad analysis of the LET spectra showed that:**

- Blinds 1 and 2 - two of directly registered ions used (see images);
- Blind No. 3 overirradiated (see image) - probably exposed to at least three from used ions.
- Blind No. 4 – no heavier CP
- Blinds Nos. 5 and 6 exposed, exposure level rather low.

# Dose characteristics calculated from LET spectra

## Absorbed dose

$D_{LET} = \Sigma(dN/dL)*L*dL$

## Dose Equivalent

$H_{LET} = \Sigma D_{LET}*Q(L)$

## Quality Factor

$Q = (H_{LET}+D_{pic})/D_{tot}$

**Where:**

**L: Value of LET**

**dN/dL: number of tracks in LET interval dL;**

**Q(L): quality factors from ICRP-60 recommendations;**

**$D_{LET}$: absorbed dose calculated from high LET part of spectra**

**$H_{LET}$: dose equivalent calculated from high LET part of spectra**

**$D_{tot}$: total absorbed dose**

**$D_{pic}$:proton ionisation dose**

# Blind doses due to the particles registered with PADC-LET spectrometer

| Blind No. | PADC | D, mGy | |
|---|---|---|---|
| | | individual | average |
| 1 | Page | 2.02±0.20 | 1.98±0.21 |
| | T0.5 | 1.88±0.19 | |
| | T1.0 | 2.04±0.21 | |
| 2 | Page | 1.48±0.16 | 1.42±0.15 |
| | T0.5 | 1.39±0.15 | |
| | T1.0 | 1.41±0.15 | |
| 5 | Page | 4.41±0.66 | 4.28±0.92 |
| | T0.5 | 4.14±0.63 | |
| | T1.0 | - | |
| 6 | Page | 3.58±0.59 | 3.84±0.84 |
| | T0.5 | 4.10±0.48 | |
| | T1.0 | - | |

# Blind exposures – summary

| Blind No. | TLD "aver.$LET_{app}$" keV/μm | $D_{total}$ – TLD's results mGy | Dose ≥ 10keV/μm mGy |
|---|---|---|---|
| 1 | 4.4 | 9.7±1.5 | 1.98±0.21 |
| 2 | 7.8 | 26.5±4.0 | 1.42±0.15 |
| 3 | 46 | 298±45 | ? |
| 4 | 0.45 | 17.4±2.6 | ~ 0 |
| 5 | 22 | 19.6±2.9 | 4.28±0.92 |
| 6 | 2.6 | 17.5±2.6 | 3.84±0.84 |

# Conclusions

1. The participation at ICCHIBAN 8 helped us again to improve substantially the evaluation procedures and the interpretation of read data. We consider the results obtained as satisfactory.
2. The experience acquired in all ICCHIBANs will permit us to compose detector's sets for other studies in space and on the Earth's in still more optimal way.
3. Going-on activities related:

- Passive detectors inside MATRJOSHKA-R (12/05-09/06); further exposure since 12/06
- CERN - ICCHIBAN runs with passive detectors
- Nuclotron JINR calibrations

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# Thank you for your attention !