**21st WRMISS**

**Noordwijk, The Netherlands**

**Erasmus building**

**6-8 September, 2016**

**ERASMUS said**

There are some people who live in a dream world, and there are some who face reality; and then there are those who turn one into the other.

# Utilization of ground experiments for reliable dose estimate in space

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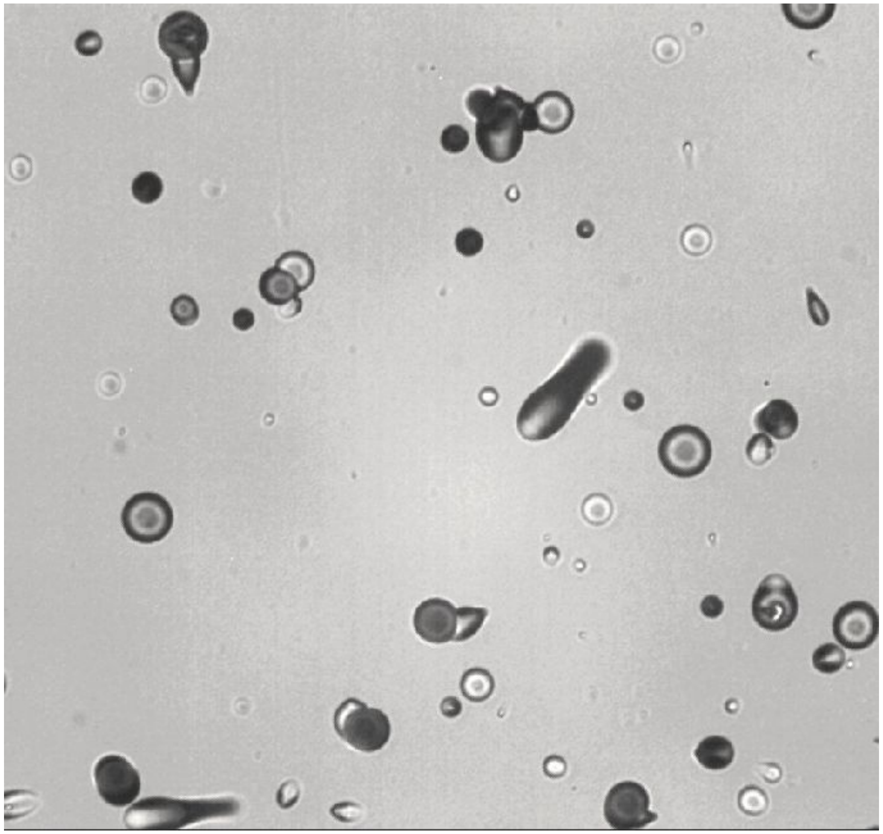
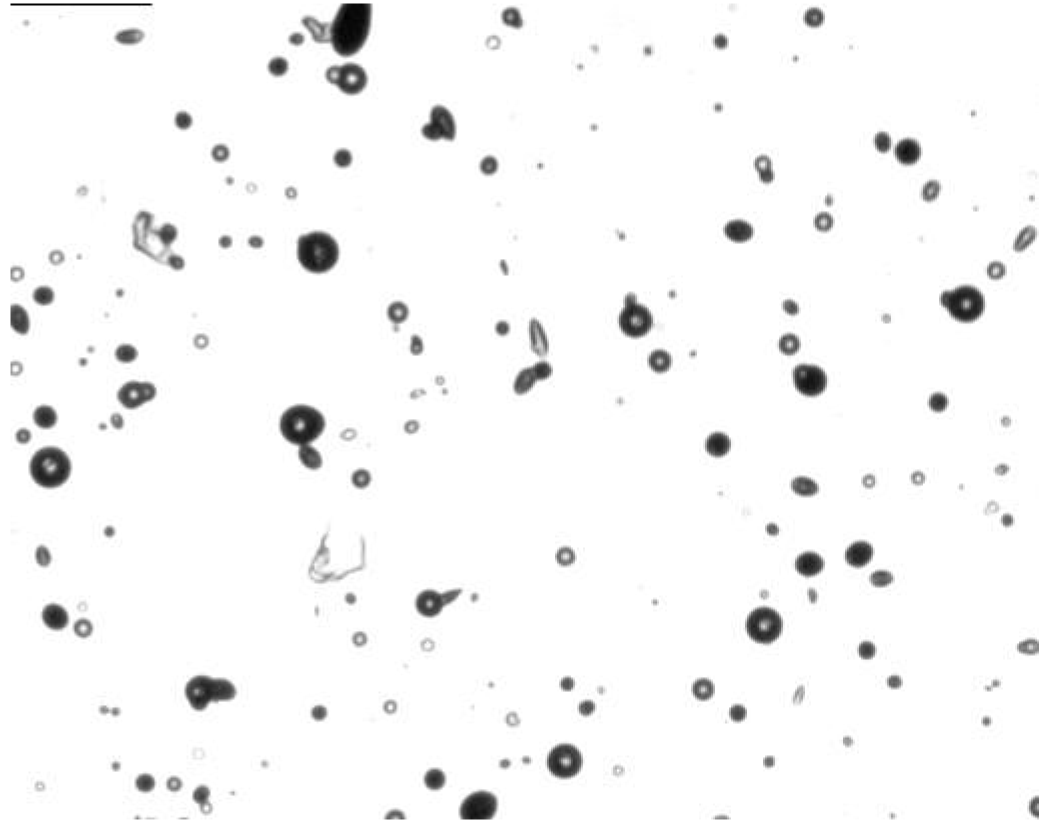




**TASTRAK (PADC) detector, 6h etching, in 6N NaOH at 70 $^{o}$C**

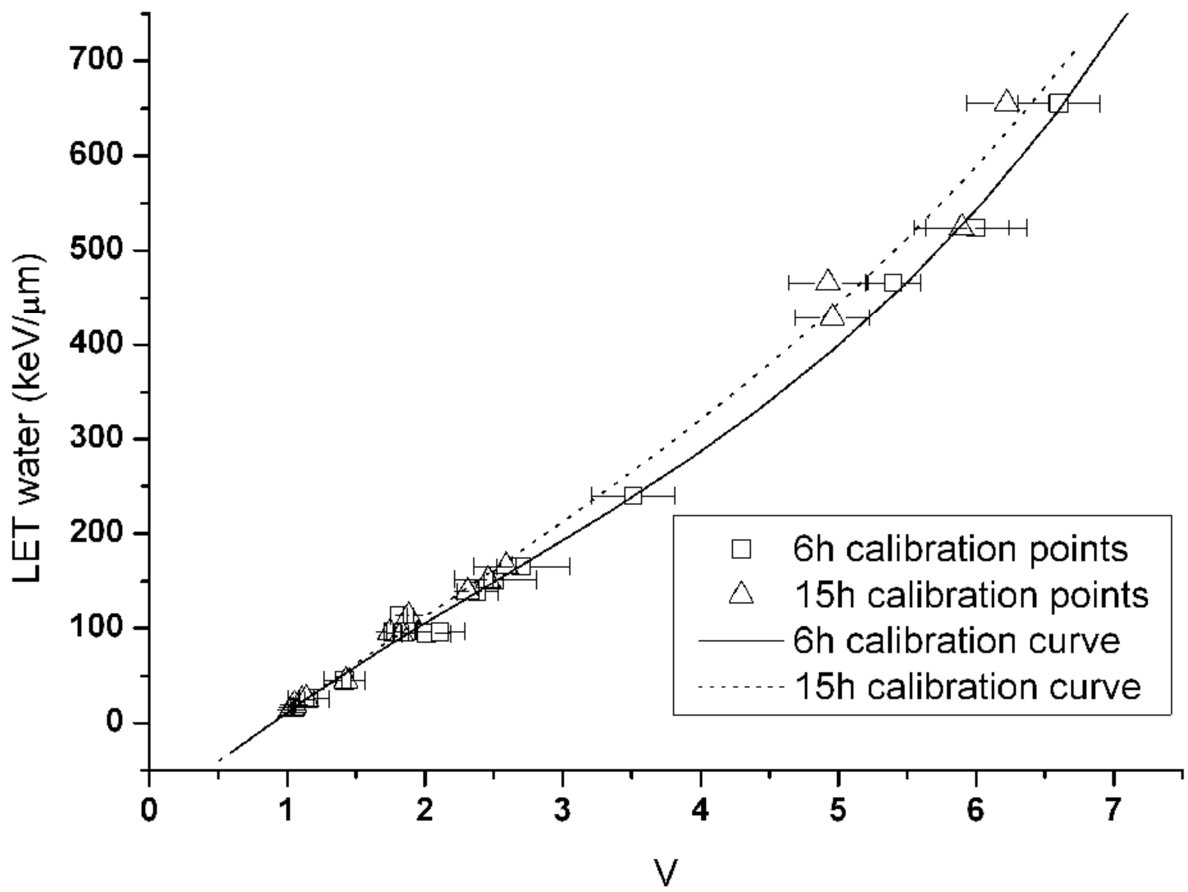
**In what type of radiation field(s) were these detectors exposed?**

**How can we evaluate them?**

**The $LET_\infty$*(V)* calibration curves for different etching times**: convert the track etch rate ratio *(V)* obtained from track parameter measurements to $LET_\infty$ in water, in this way the LET spectra and the dose can be obtained

6h: $LET = -99.8424 + 125.00172\,V - 15.28166\,V^2 + 2.04636\,V^3$, $r^2 = 0.9961$

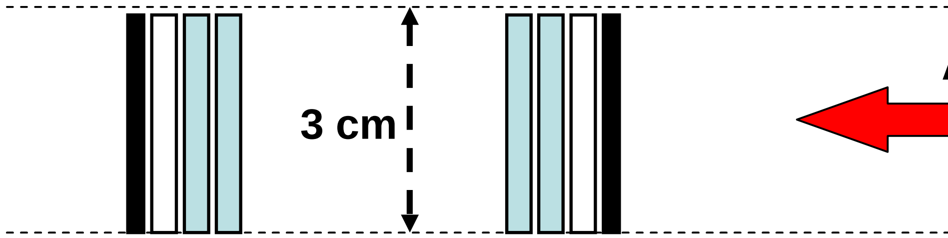
15h: $LET = -96.35071 + 114.90343\,V - 7.77194\,V^2 + 1.27248\,V^3$, $r^2 = 0.9926$

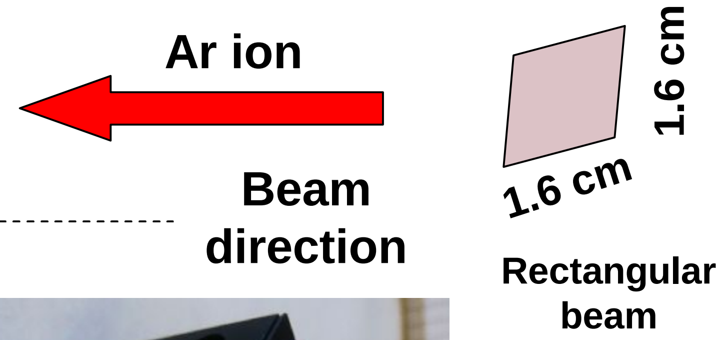



The points are established from exposures with monoenergetic particle beams

An example: **irradiation of a detector stack at HIMAC with Ar ions**

Filters are used to widen the LET range and thus obtain more calibration points, to fill the “gaps” on the calibration curves and also to study the fragmentation of the projectile




**From right to left:**

**Al cover, 0.9 mm**

**Air gap, 3 mm**

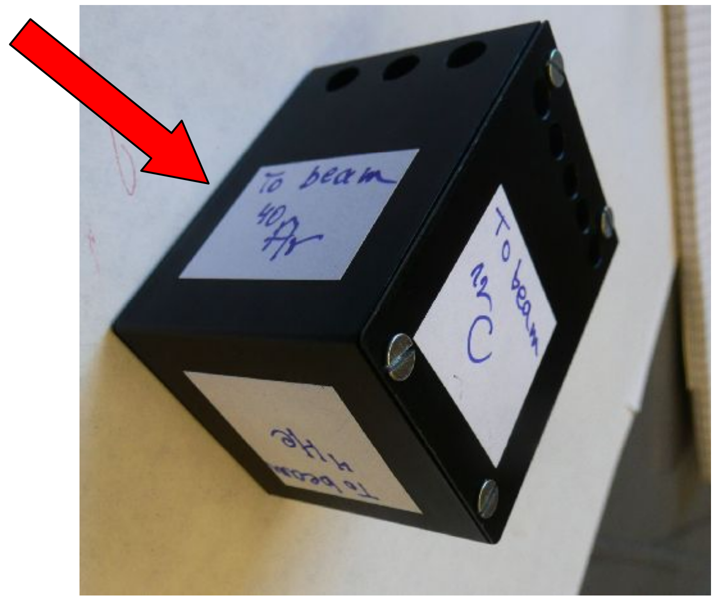
**2 PADC, 2 mm**

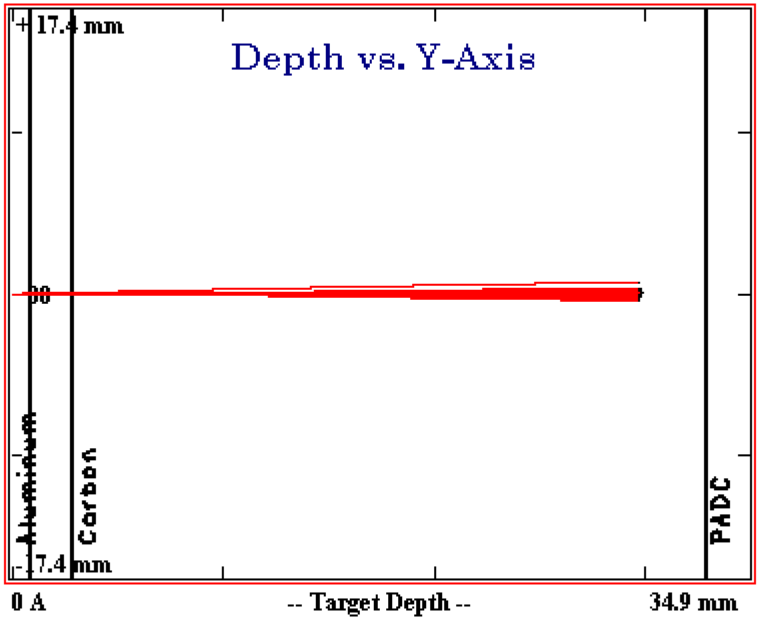
**Carbon, 30 mm**

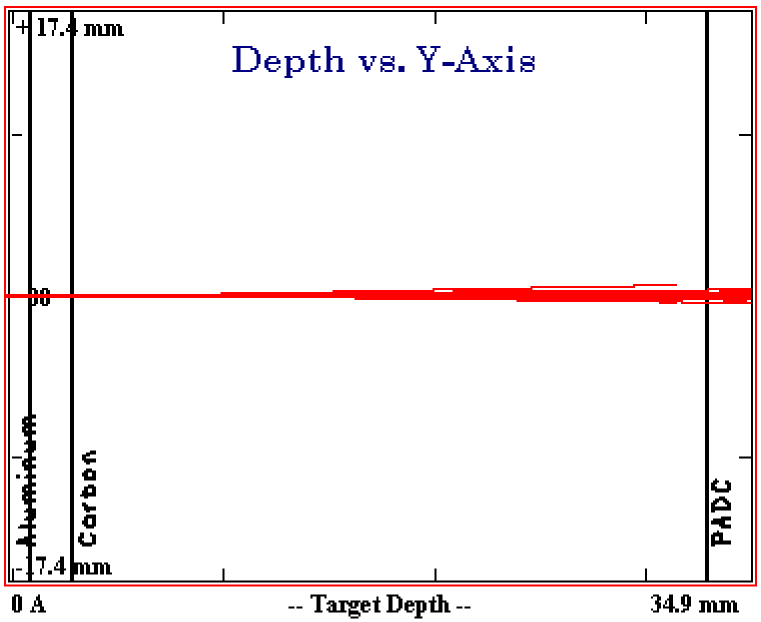
**2 PADC, 2 mm**

Air gap, 3 mm

Al cover, 0.9 mm






**Nominal Ar Ion energy: 290 MeV/amu**

1. **Result of the SRIM calculation: Ar ions do not penetrate the Carbon block.**

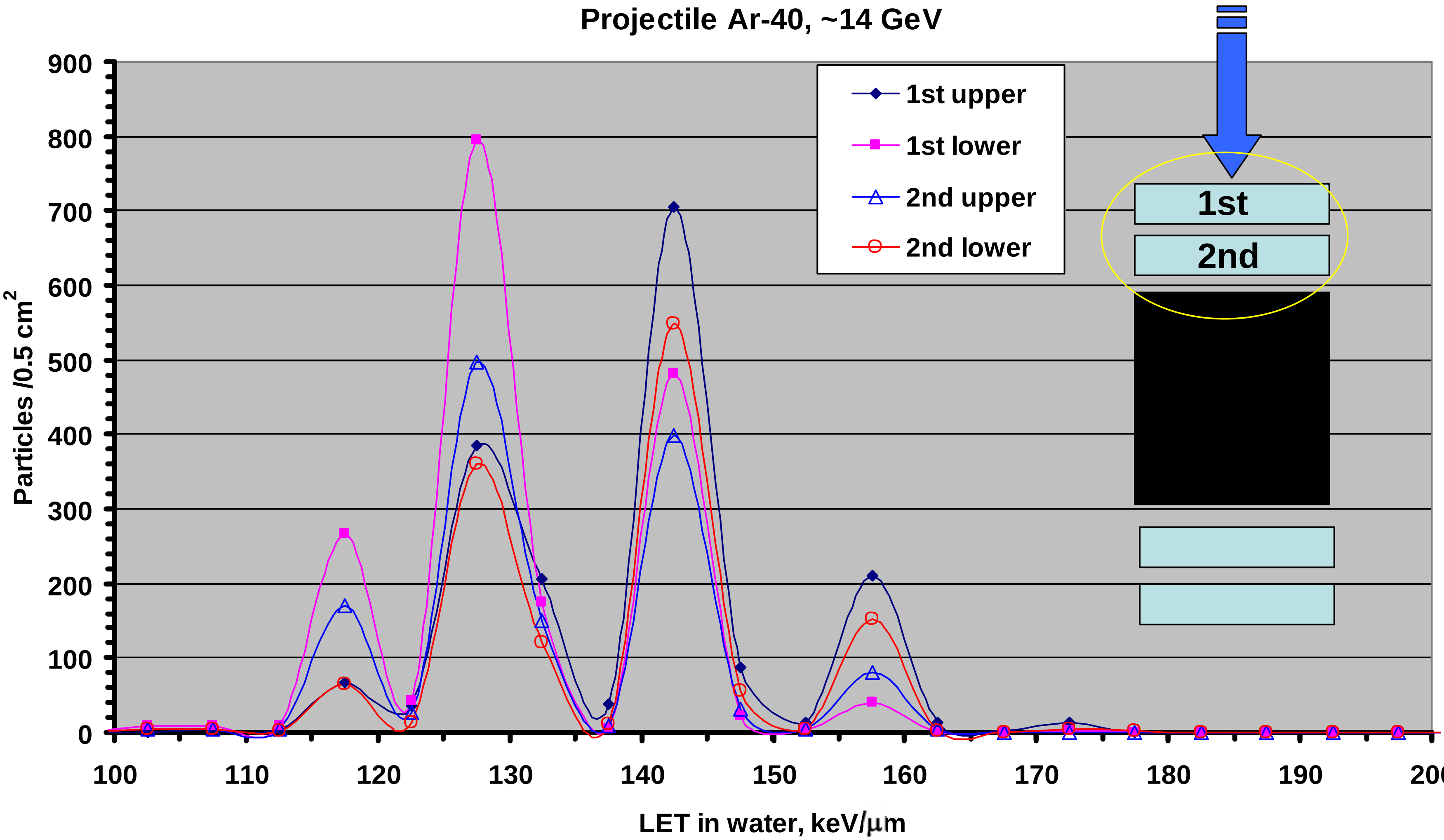
**Therefore only the 1st & 2nd PADC sheets (4 surfaces) were investigated.**

2. **By chance, technician continued measurements and found particle tracks on next PADC surfaces, too**

**This passive stack was exposed together with the active TriTel system and it was found that the actual beam energy was different from the nominal**

**Corrected Ar Ion energy: 330 MeV/amu**

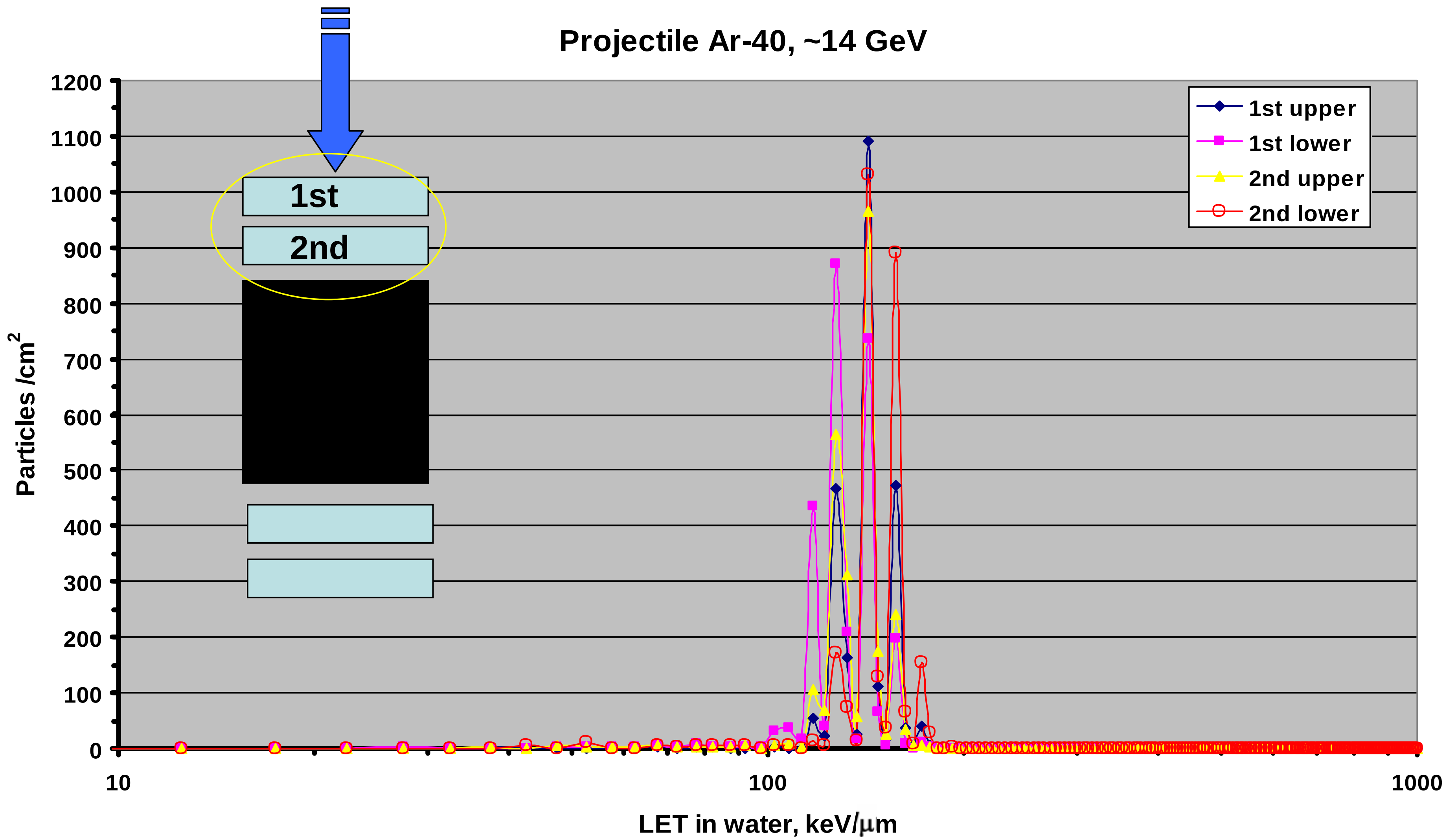
3. **All ions penetrate the entire assembly**



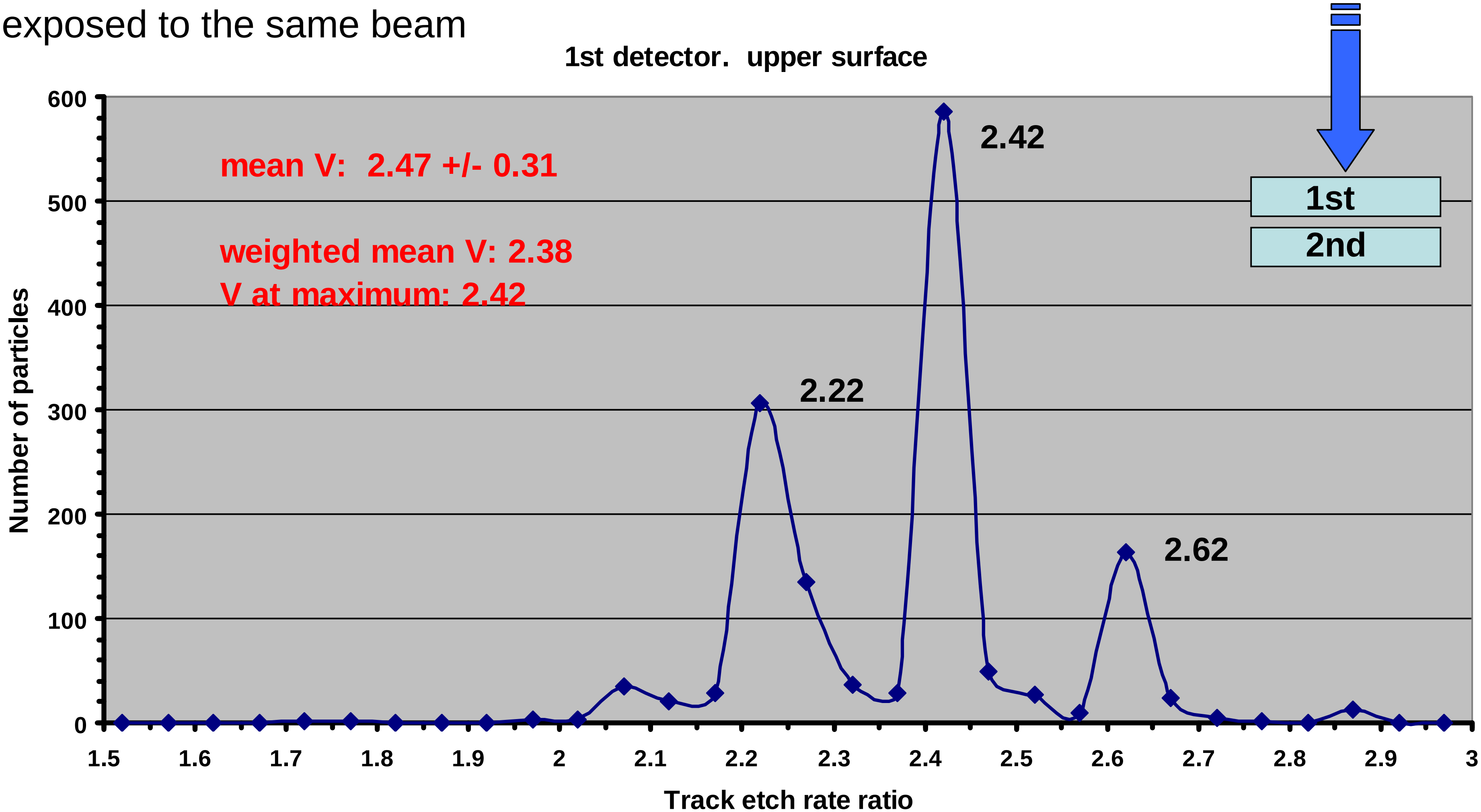

There are 4 peaks on the LET distribution curve instead of 1, which was expected based on the previous experiments with monoenergetic beams

Is it possible that the beam was not monoenergetic or the Al cover on top of the stack caused the fragmentation of the Ar ions?

# The same data, but on log scale

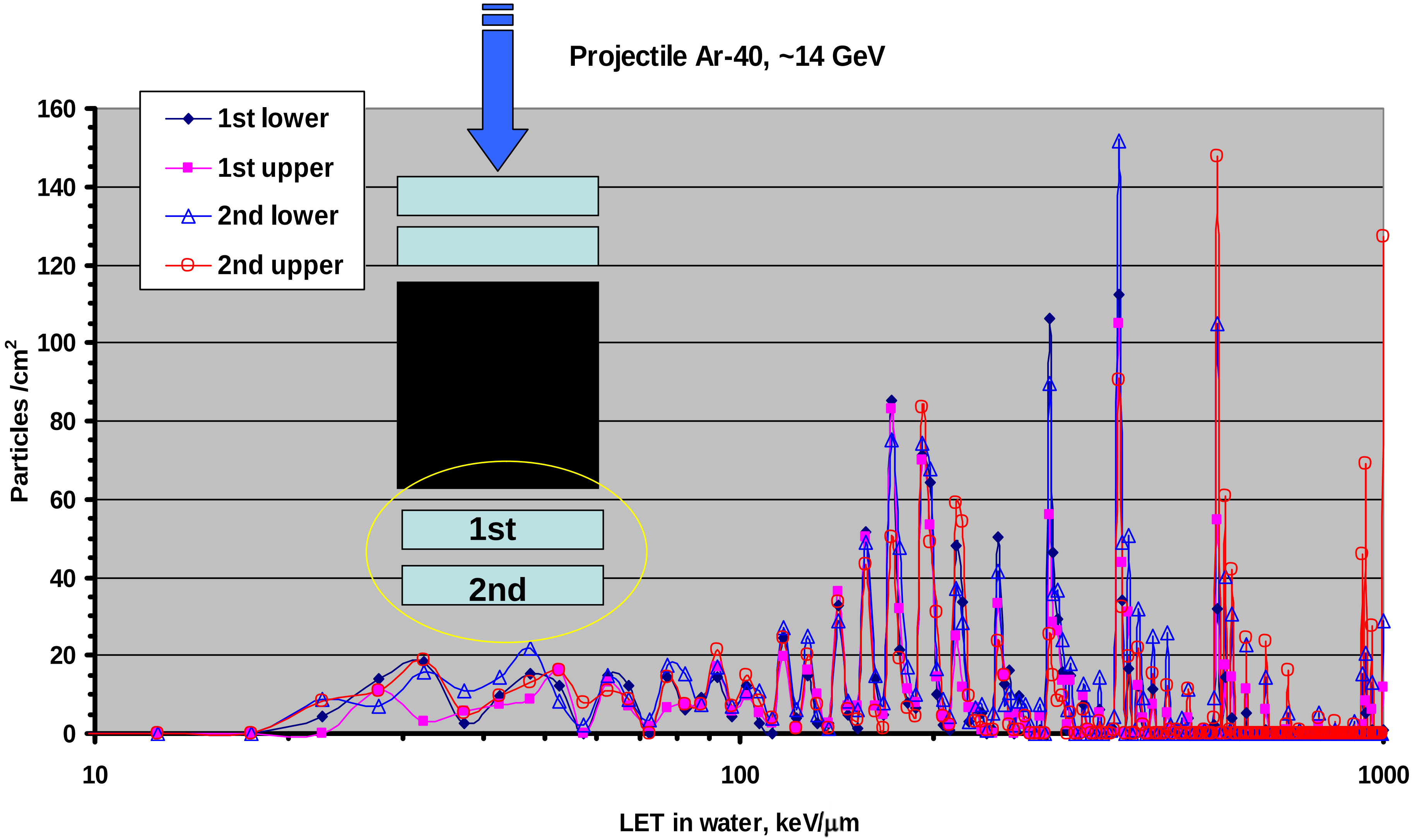


A simple PADC stack composed of only 2 detector sheets, without any filter, was exposed to the same beam




There are more peaks, as well: the constituent elements of the detector may cause the fragmentation of the projectile

Which V value corresdponds to the primary particle and should be used to obtain a calibration point?

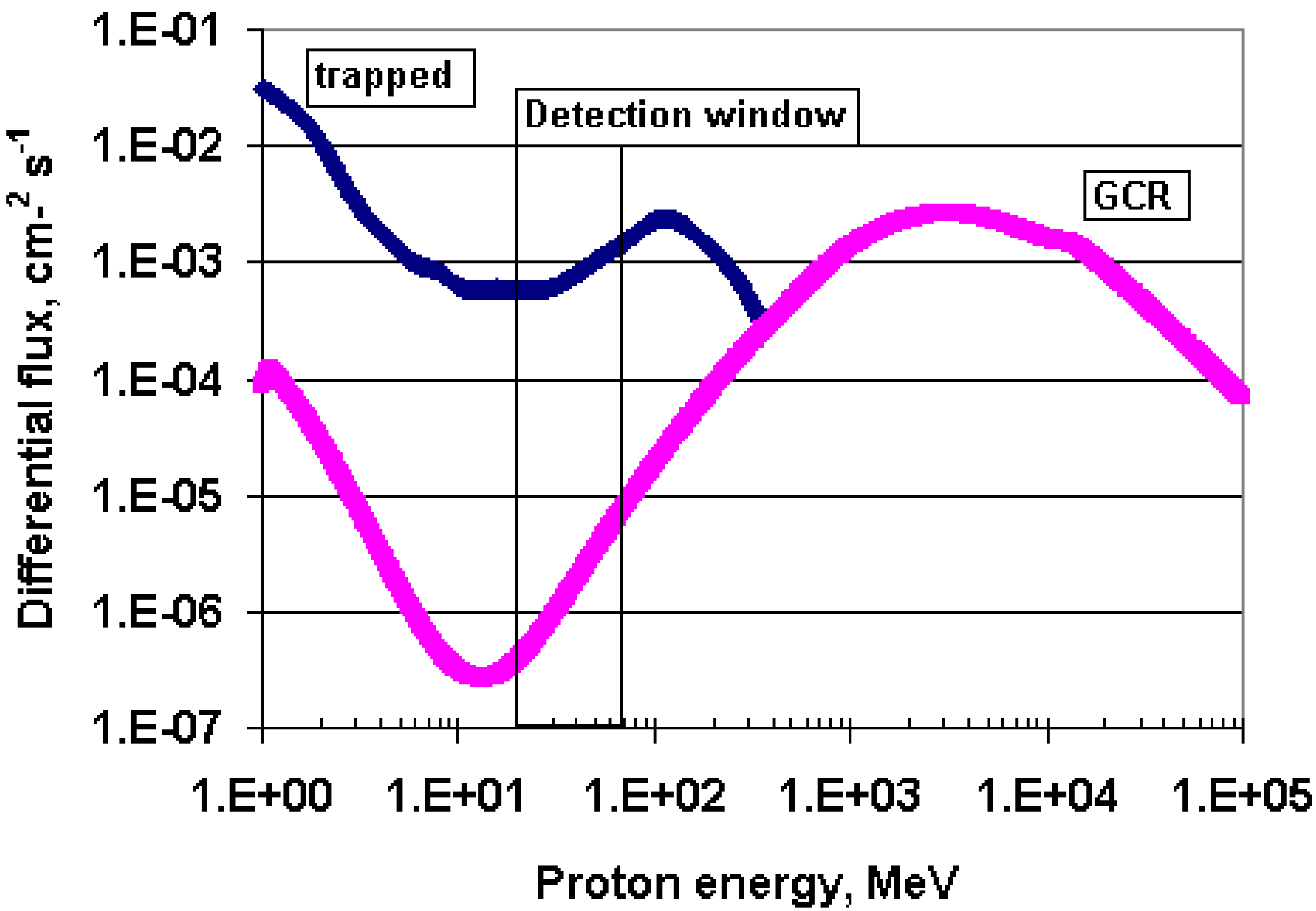



After the C block a variety of fragments are observed from protons up to Ar

**The purpose of the following investigations was to estimate the real number and LET of secondary particles (fragments) produced by high energy trapped and GCR protons in a close tissue equivalent solid state nuclear track detector material (PADC) material composed of $C_{12}H_{18}O_7$, which indicates that ($p \rightarrow {}^{12}C$) is the most important fragmentation interaction.**

**However, the contribution of proton induced fragmentation of ${}^{16}O$ is not negligible**

Since the protons are the most abundant particles in low Earth orbit, the probability of proton detection by a PADC stack has been investigated by calculations. As an example, the incident trapped and GCR proton spectra were calculated by the CREME96 code for the BIOPAN-5 orbit (31 May - 16 June 2005)




The detection window for primary protons (determined by the LET threshold of the detector and the range of the particle) is narrow, but they produce secondaries: recoils and fragments of the constituent elements of the detector material

# Proton induced $^{12}C$ fragmentation

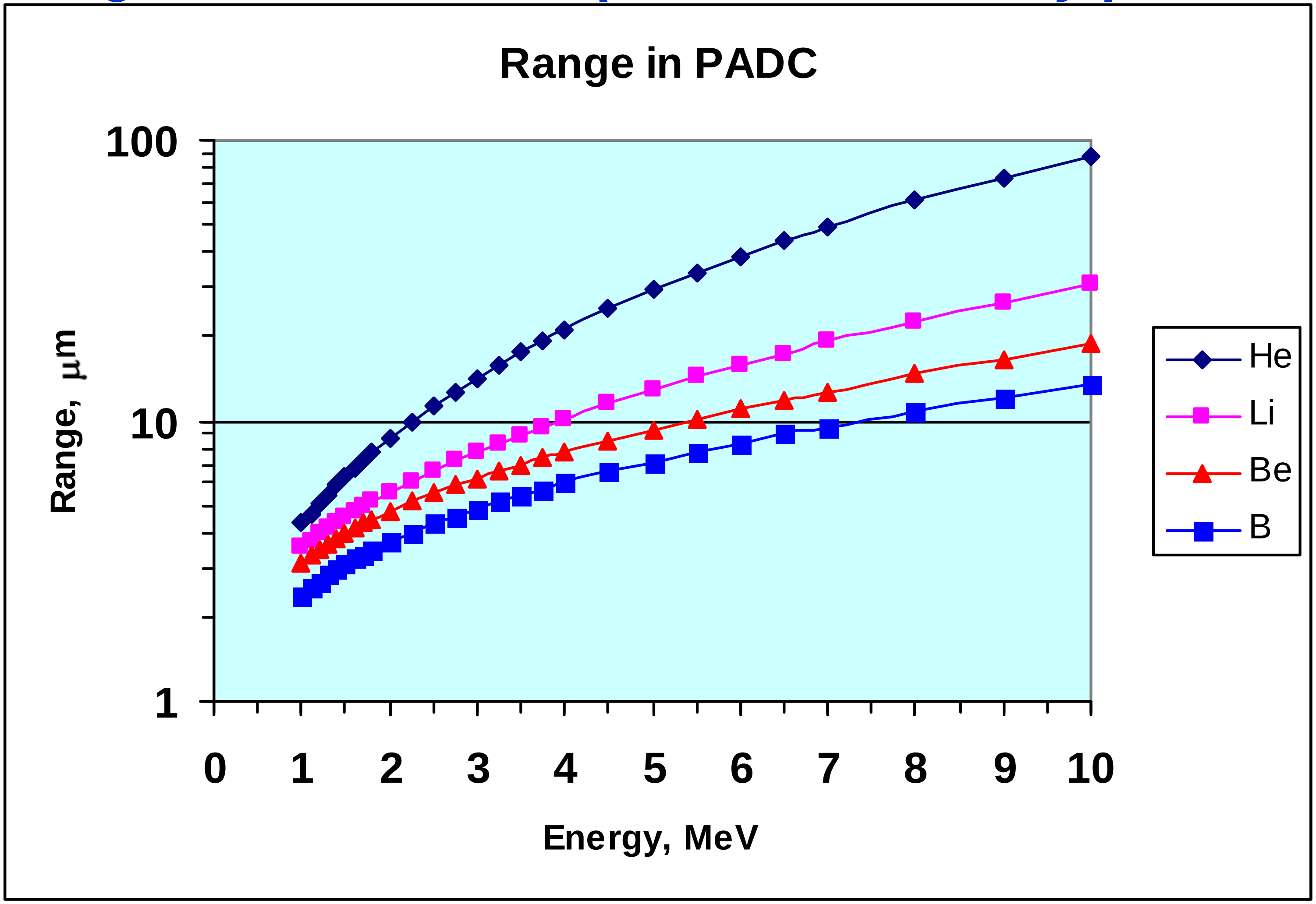
| | $^{6}Li$ + | $^{7}Li$+ | $^{7}Be$+ | $^{9}Be$+ | $^{10}Be$+ | $^{10}B$+ | $^{11}B$+ |
|---|---|---|---|---|---|---|---|
| Possible Coupled particles | $^{7}Be$ | $\alpha$+2p | $\alpha$+D | $^{3}He$+p | 3p | $^{3}He$ | 2p |
| Cross section, mb | 9.8 | 7.8 | 12.2 | 2.5 | 1.8 | 19 | 63 |
| Rel. probability, % | 8.46 | 6.73 | 10.5 | 2.17 | 1.57 | 16.3 | 54.3 |
| $E_{my}$, MeV | ~5 | ~6 | ~7 | ~9 | ~6 | ~6 | ~6 |
| Max. range, µm | ~13 | ~16 | ~13 | ~17 | ~11 | ~9 | ~8 |

**The weighted averaged range $R_e$ = ~ 10 µm**

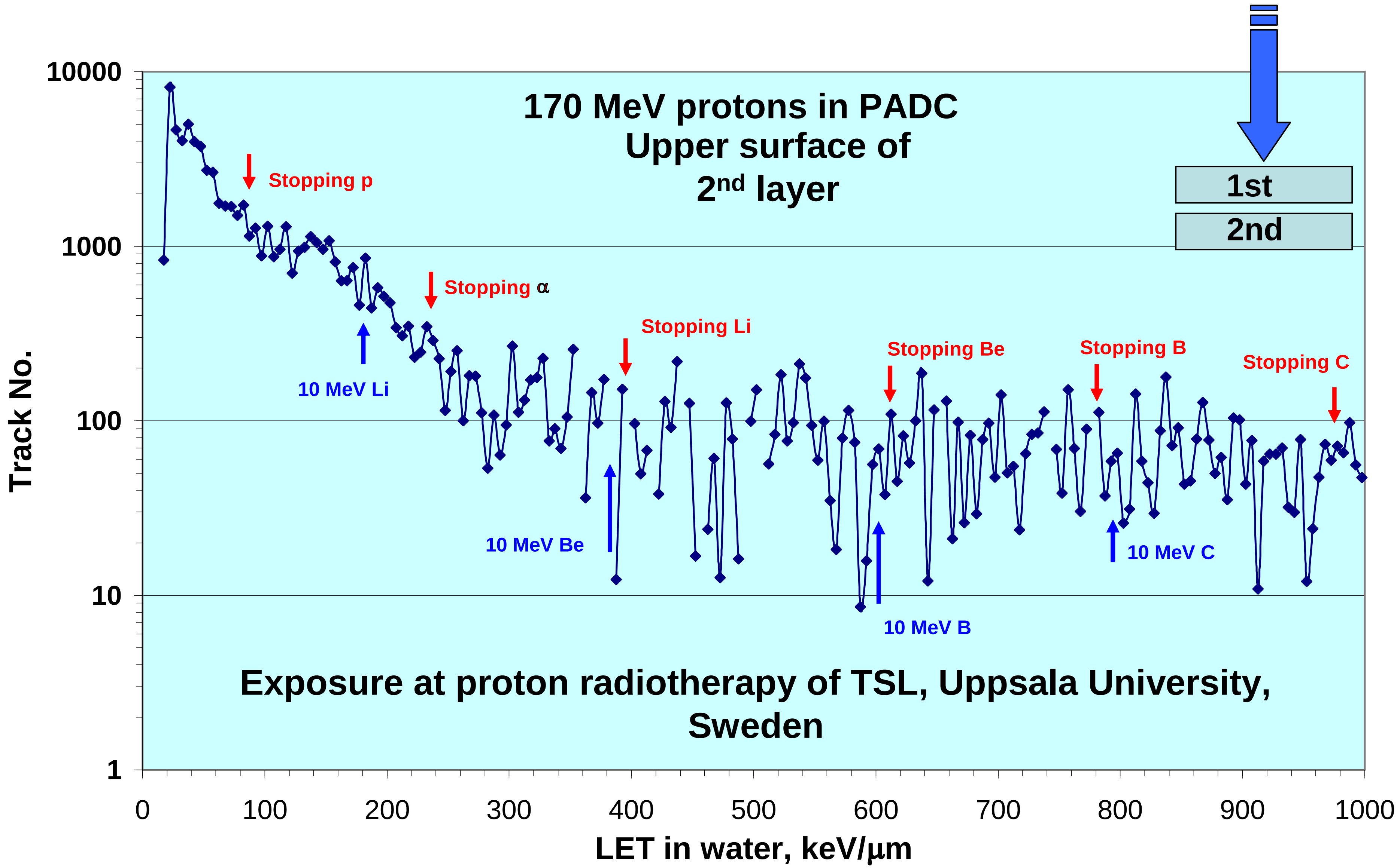
# Some proton induced reactions of $^{16}O$

| Reaction | Q-Value | Reaction | Q-Value |
|---|---|---|---|
| O16(p,d+2α)Be7 | -31203.61 keV | O16(p,n+p+2d+α)Be7 | -57274.71 keV |
| O16(p,n+p+2α)Be7 | -33428.18 keV | O16(p,2n+2p+d+α)Be7 | -59499.27 keV |
| O16(p,t+He3+α)Be7 | -45524.00 keV | O16(p,3n+3p+α)Be7 | -61723.84 keV |
| O16(p,p+d+t+α)Be7 | -51017.47 keV | O16(p,p+2t+He3)Be7 | -65337.86 keV |
| O16(p,n+d+He3+α)Be7 | -51781.23 keV | O16(p,n+t+2He3)Be7 | -66101.61 keV |
| O16(p,n+2p+t+α)Be7 | -53242.04 keV | O16(p,2d+t+He3)Be7 | -69370.52 keV |
| O16(p,2n+p+He3+α)Be7 | -54005.80 keV | O16(p,2p+d+2t)Be7 | -70831.34 keV |
| O16(p,3d+α)Be7 | -55050.14 keV | O16(p,n+p+d+t+He3)Be7 | -71595.09 keV |

# Ranges of the most important secondary particles



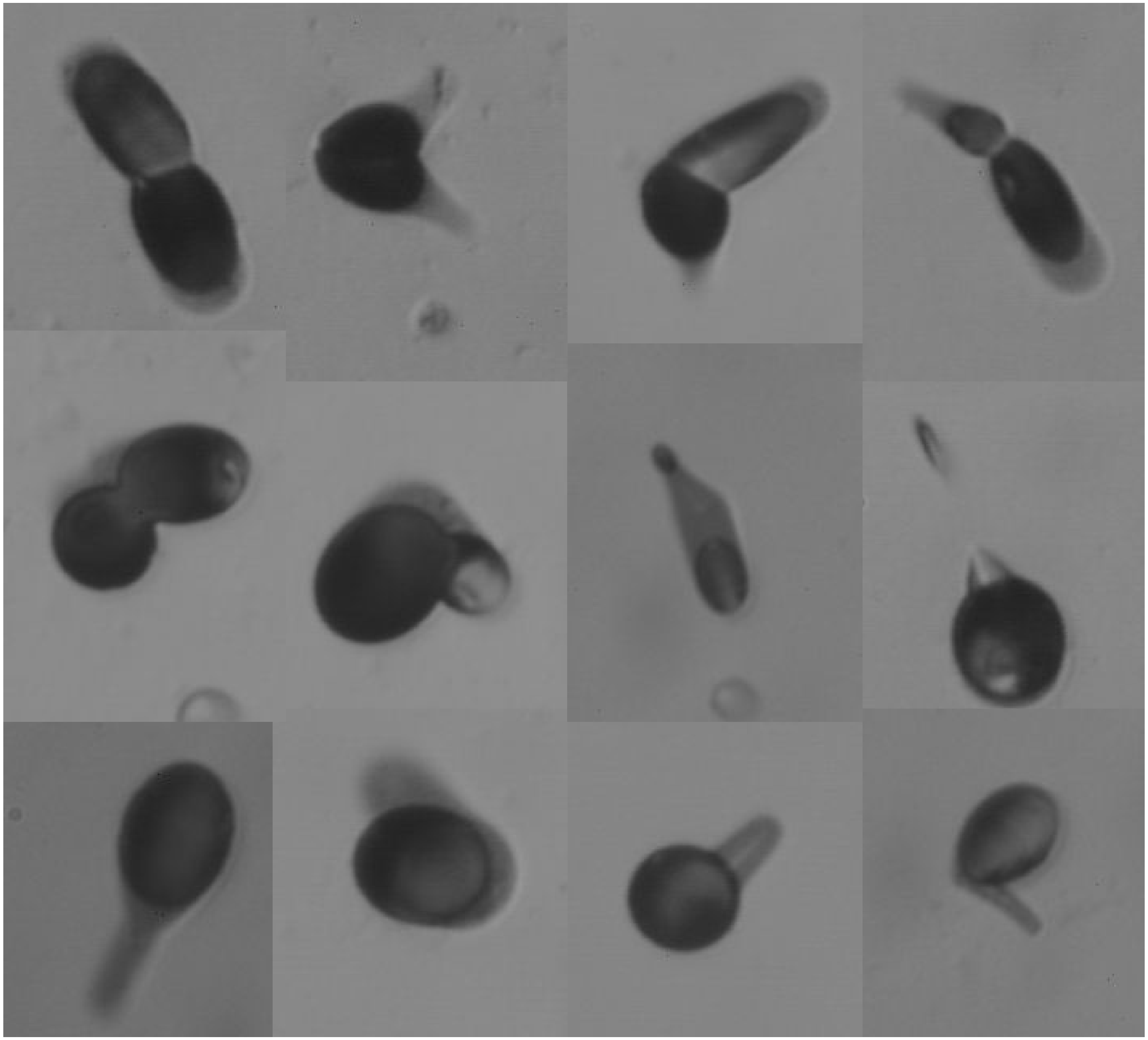

Etching the detectors for 6 and 15 h removes 8 and 20.1 µm from the surface, thus it is expected that the majority of the tracks will be caused by He ions



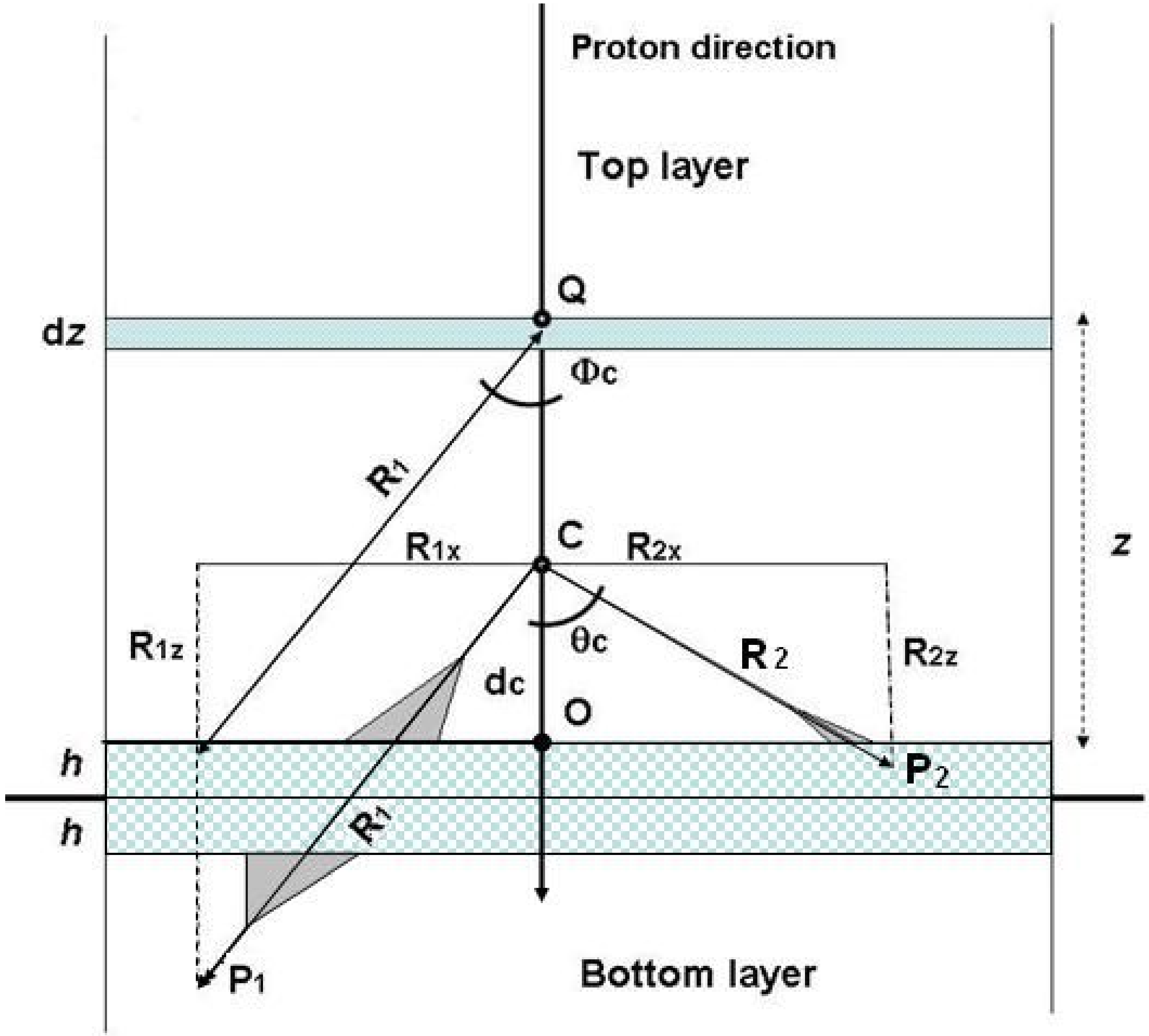

The most probable LET range of a particle is indicated by the lower and upper arrows

**Short range target fragments Z>2 are registered with LET > ~230 keV/µm**

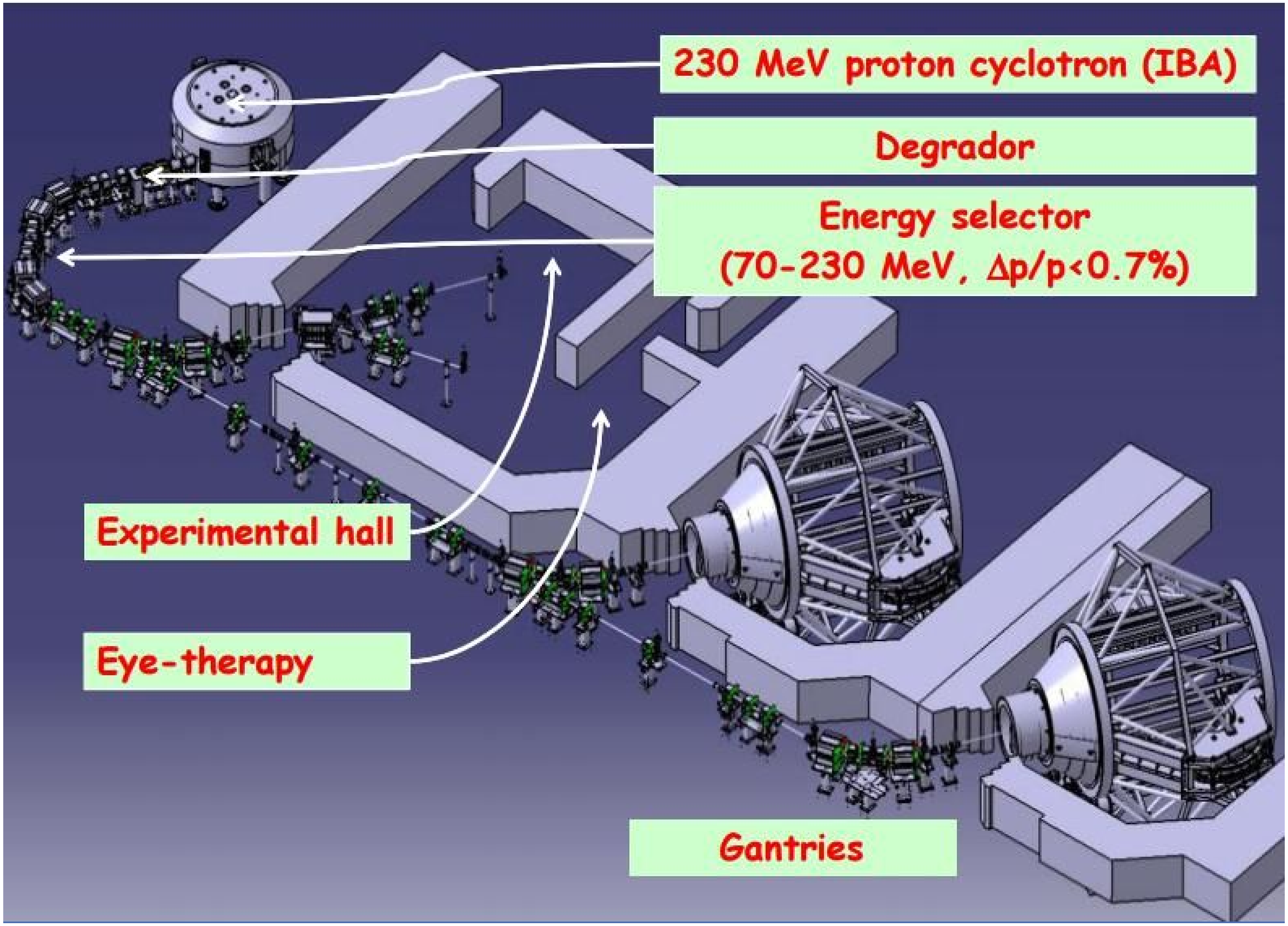
## Some reactions as seen on the surface of the detector



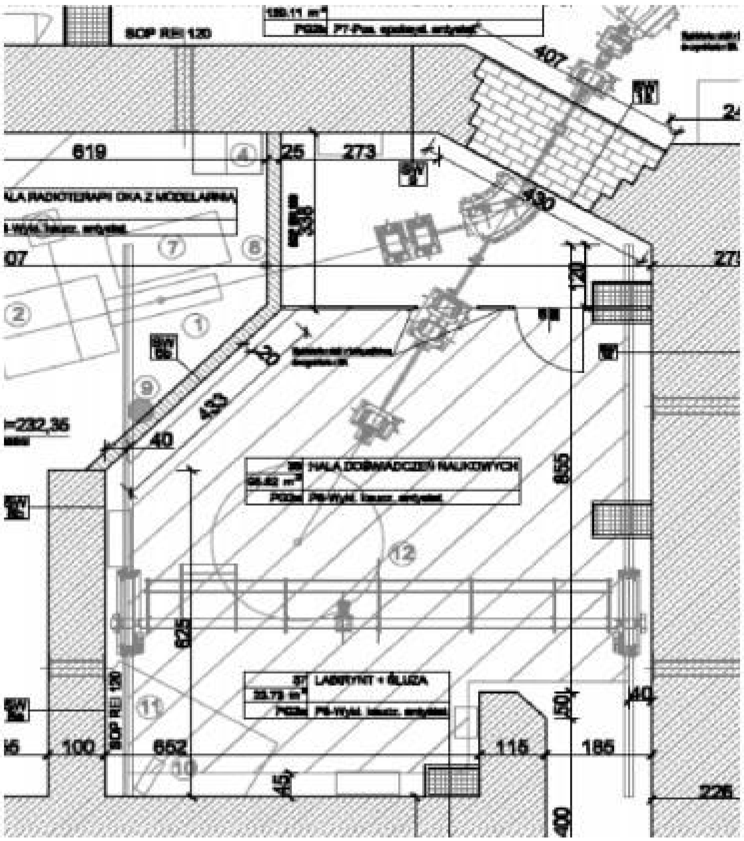
Track formation geometry showing the incident proton and two forward moving fragments induced in point C. Both particles are detected by the upper detector. If point C moves upward then only one particle or above point Q none can be detected.



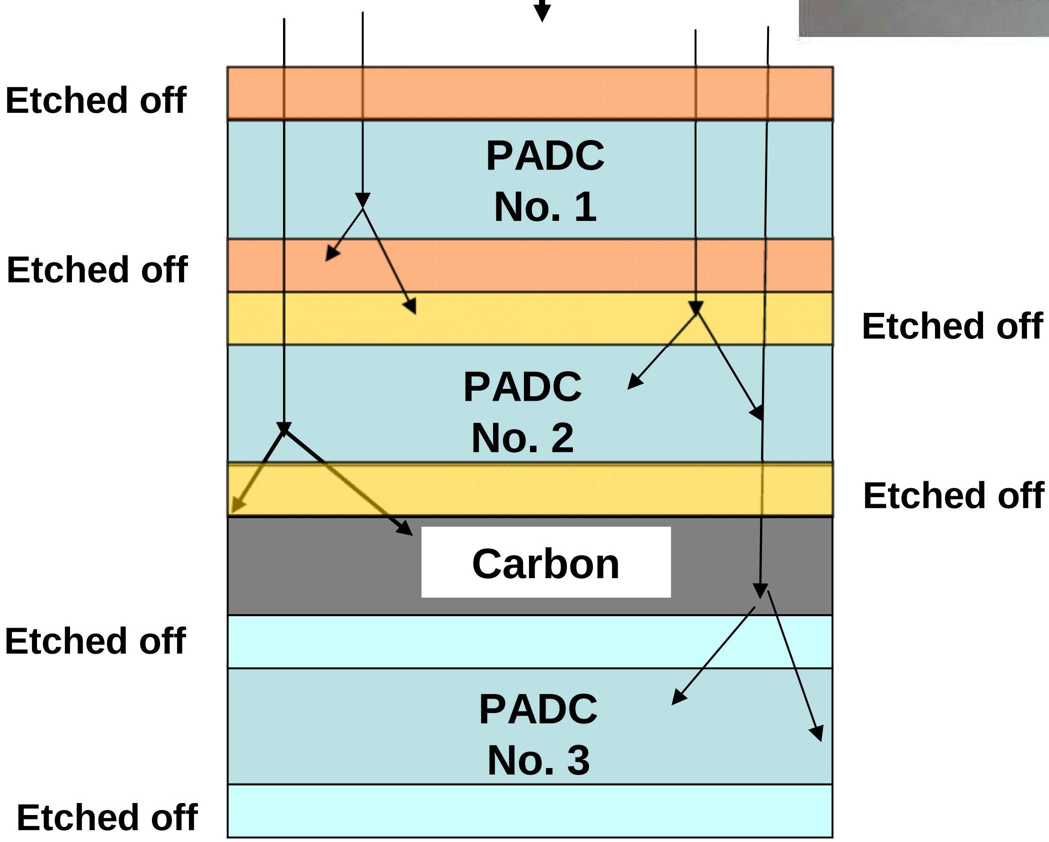
## Proton exposures at the Proteus cyclotron of the Institute of Nuclear Physics, Polish Academy of Sciences - IFJ PAN



# Experimental hall for nuclear physics and radiobiology

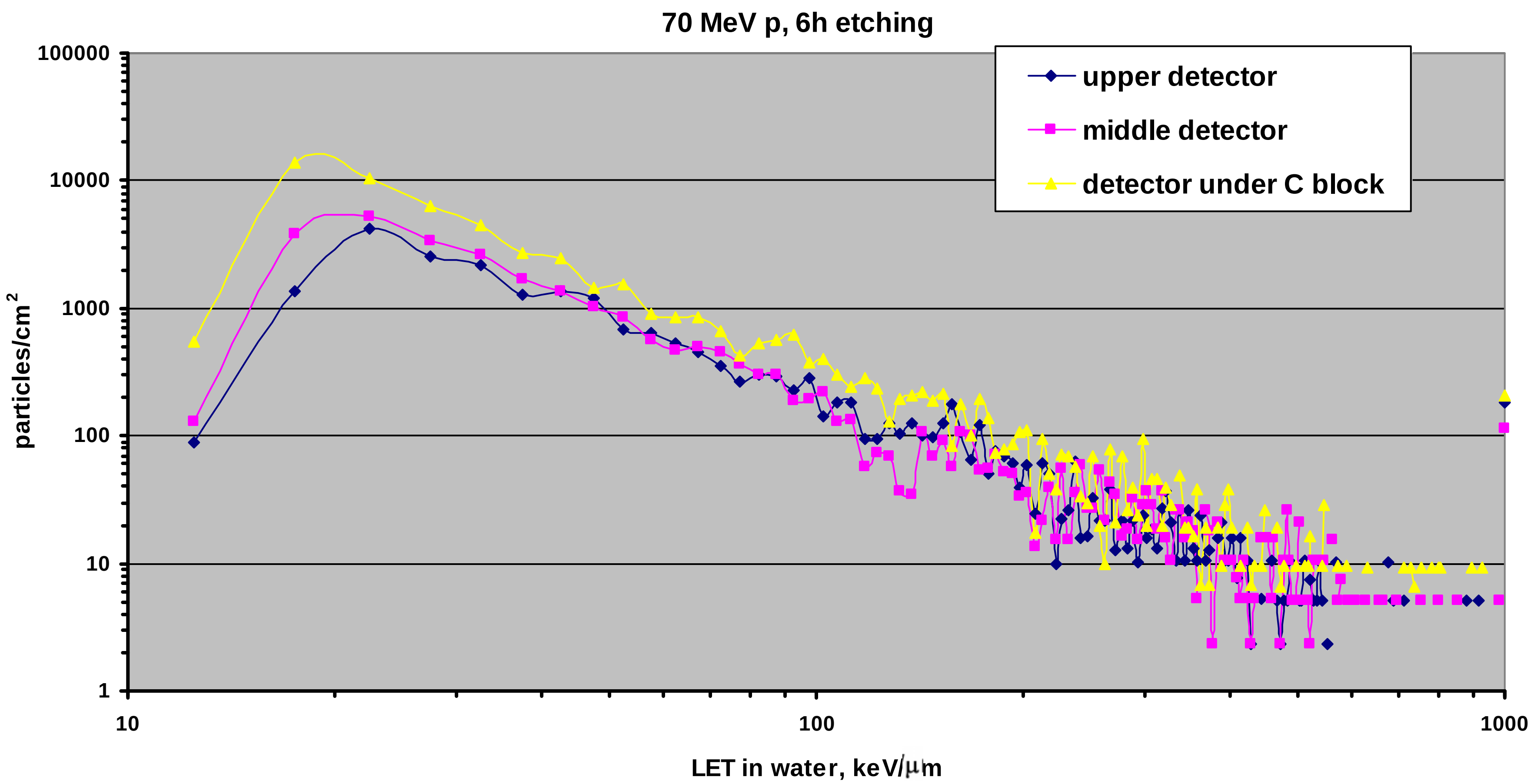



**Direction of incident particles**



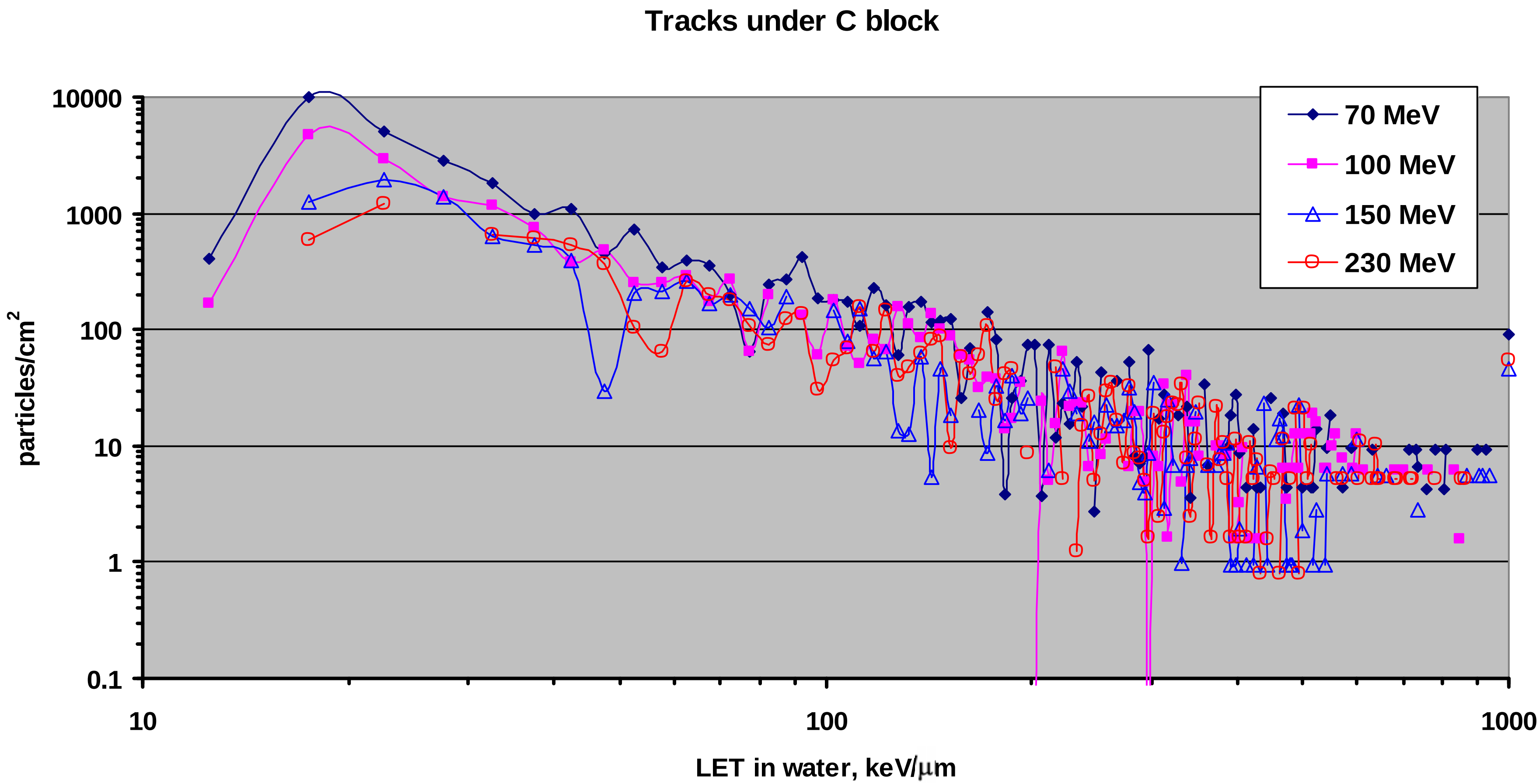

PADC stacks to study high energy particle target fragmentation: fragments are formed in different depths and move forward, some of them are etched off

The high energy, low LET incident protons do not form visible tracks



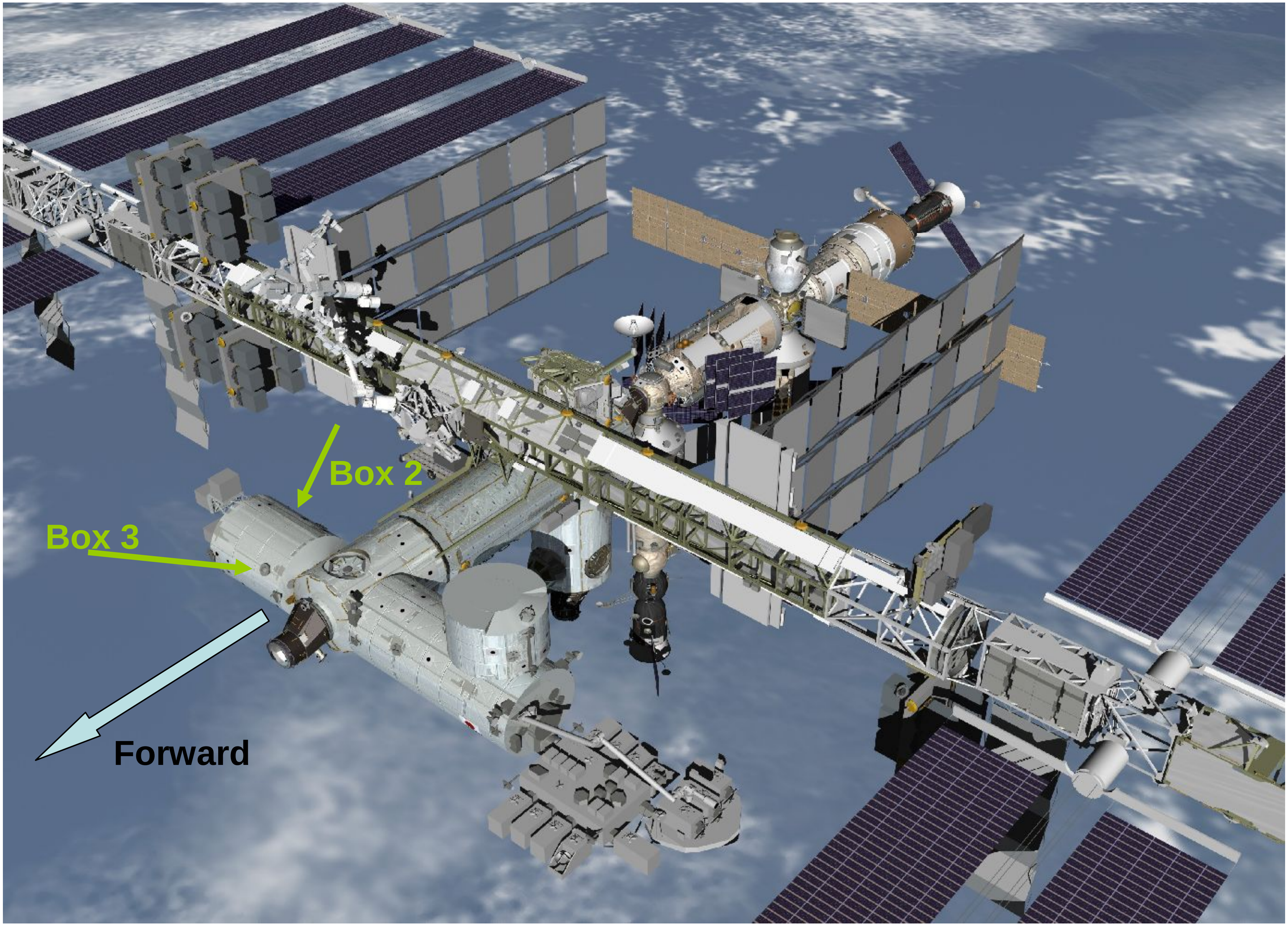

The highest number of tracks can be observed under the carbon block (fragments are formed inside the detector material and inside the C block)

## Comparison of LET spectra of C fragments induced by 70, 100, 150 and 230 MeV protons

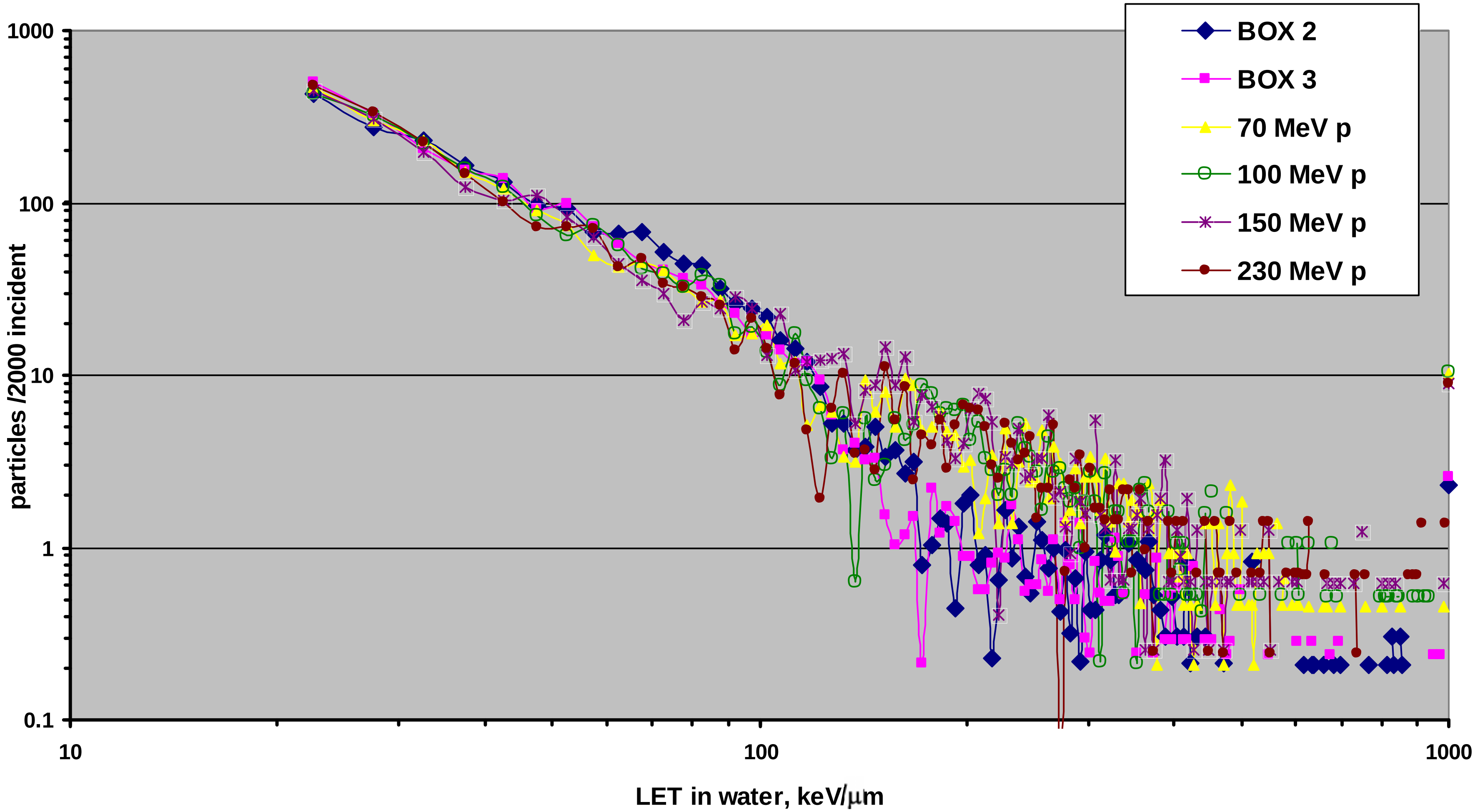



As the proton energy decreases, the number of fragments decreases, as well

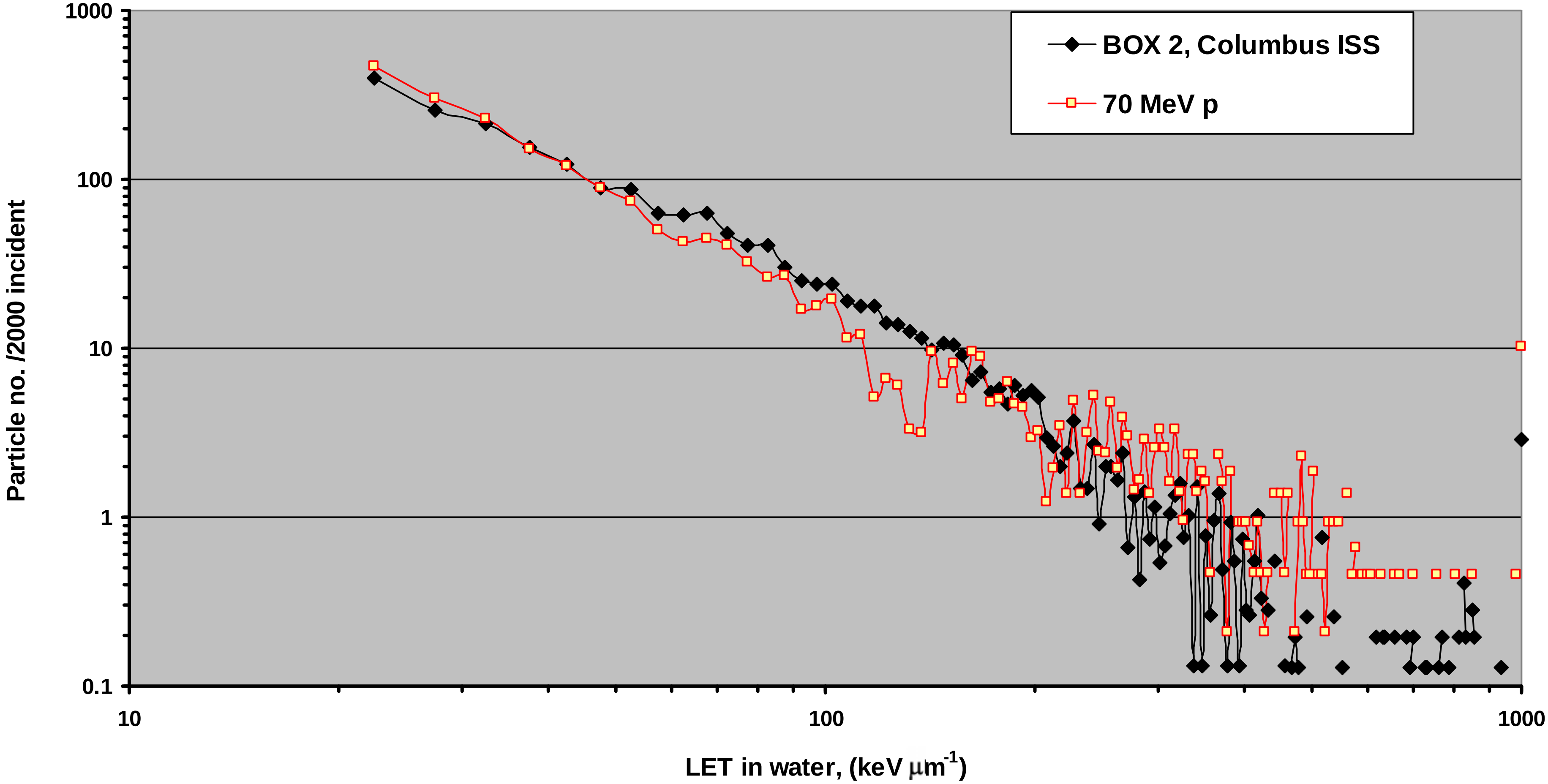
Comparison with the DOSIS-3D detectors flown on the ISS, locations with the highest and lowest doses



## LET spectra of 2000 incident particles, detectors exposed on the ISS and to high energy protons, 6h etching

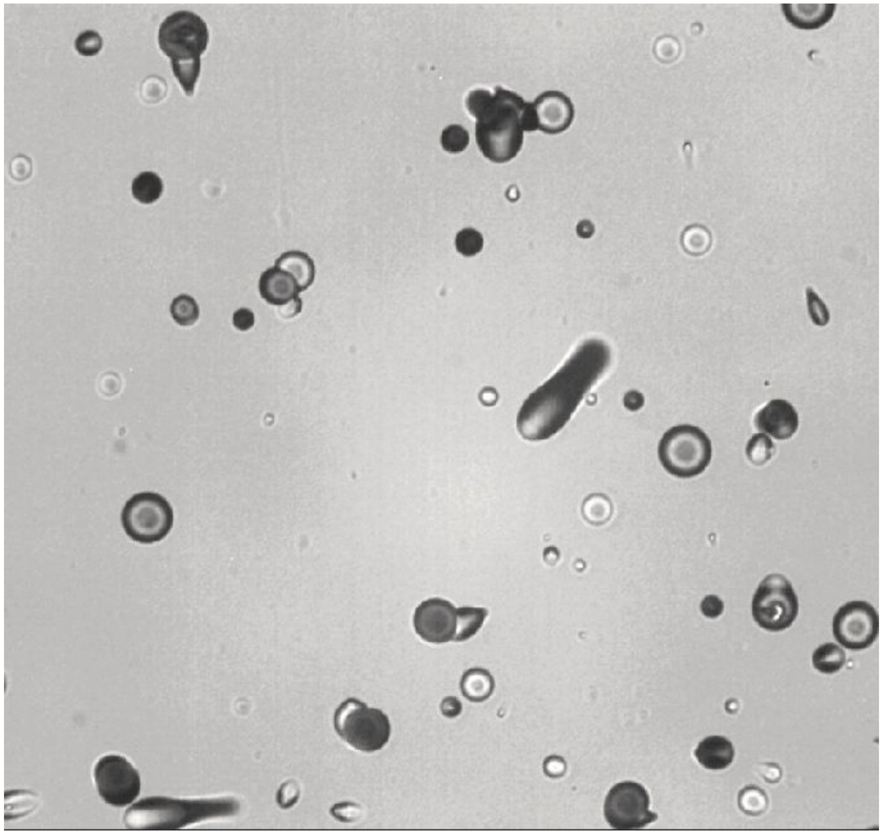



The spectra are similar, however, above ~140 keV/µm the number of fragments observed in space is lower




**Short etching in 6N NaOH at 70 ˚C for 6 h, 8 μm removal, LET threshold ~22 keV/μm**

There is a local minimum in the proton induced spectrum above 100 keV/μm, it was observed at higher proton energies, as well, it should be further investigated



**Mixture of**

**47, 95 and 170 MeV protons**

**ISS, Service Module**

**TASTRAK (PADC) detector, 6h etching, in 6N NaOH at 70 $^{o}$C**

## Simple statements

**During heavy ion calibration attention should be paid at the exact determination of the primary ion and its energy at the target position.**

**The dose estimate, by track detectors, of the energetic protons in space is based on the measurements of target fragments, therefore efforts should be made to separate the tracks of fragments from tracks of GCR particles.**

**A method should be elaborated to determine the fraction of the detected fragments and to establish a method to correct the dose values obtained from fragment measurements**

# Acknowledgements

**The authors are thanking the work of the colleagues at the following accelerators:**

**-Bronowice Cyclotron Centre, Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland**

**-HIMAC, National Institute of Radiological Sciences, Chiba, Japan**

**-The Svedberg Laboratory, Uppsala University, Uppsala, Sweden**

# Thanks for your attention

**And let this be my farewell…..**