TRAINING COURSE ON EXPERIMENTAL MICRODOSIMETRY

Principle of silicon-based microdosimetry

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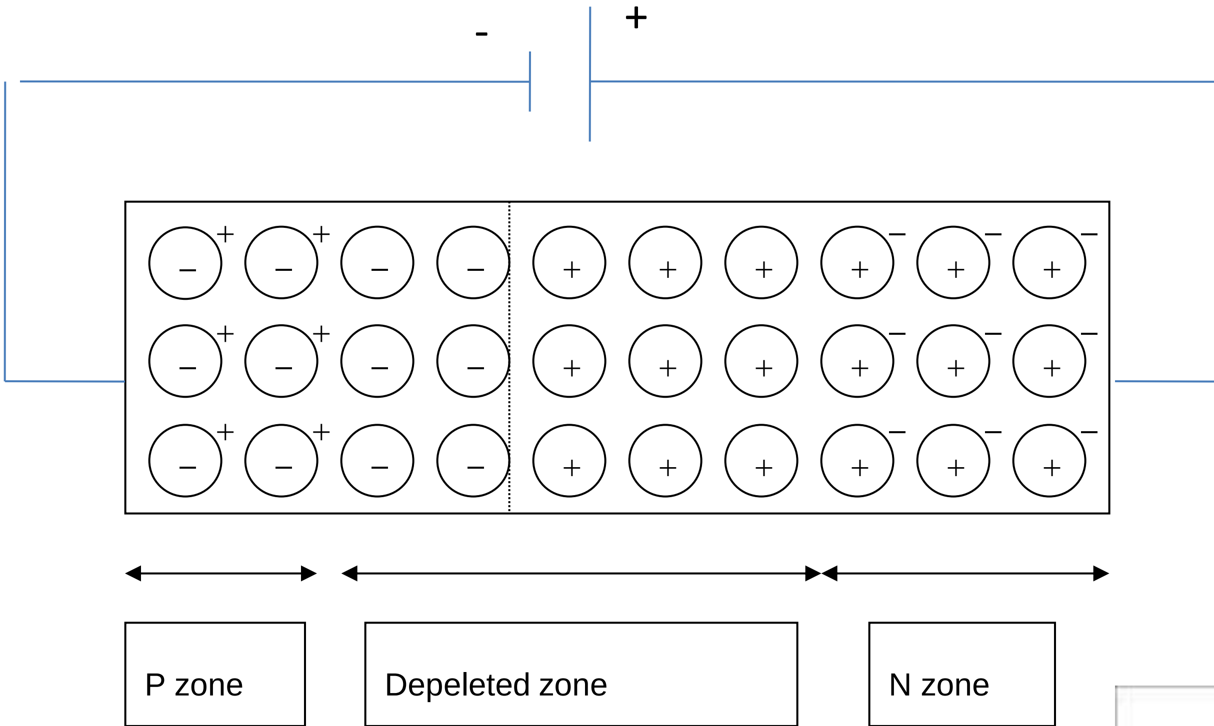
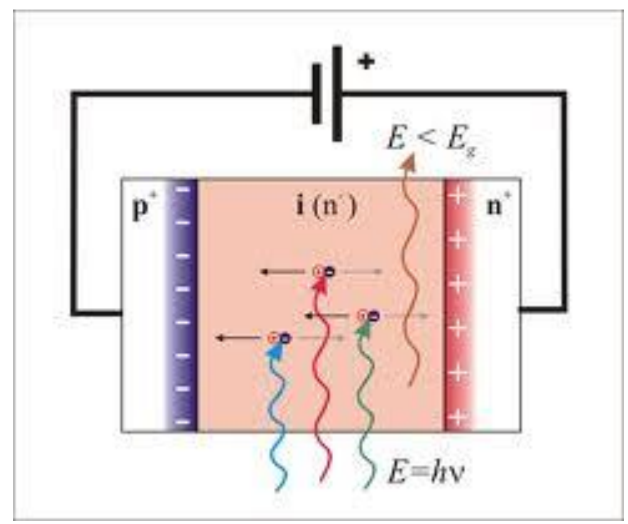
uthor name, Institute



-
+
P zone
Depeleted zone
N zone



+
$E < E_g$
p^+
i (n^-)
n^+
$E=h\nu$

SILICON MICRODOSIMETRY

PN diodes

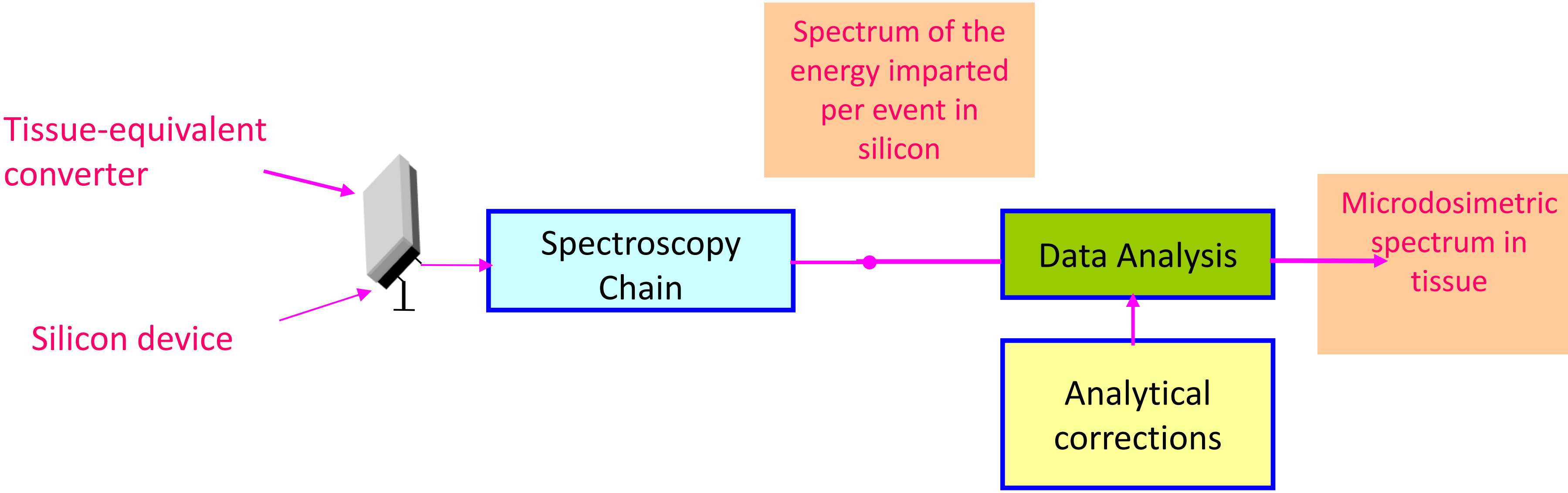
[1] J. F. Dicello, H. I. Amols, M. Zaider, and G. Tripard, *A Comparison of Microdosimetric Measurements with Spherical Proportional Counters and Solid-state Detectors*, Radiation Research 82 (1980) 441-453.
[2] M. Orlic, V. Lazarevic, and F. Boreli, *Microdosimetric Counters Based on Semiconductors Detectors*, Radiat. Prot. Dosim. 29 (1989) 21-22.
[3] A. Kadachi, A. Waheed, and M. Obeid, *Perfomance of PIN photodiode in microdosimetry*, Health Physics 66 (1994) 577-580.
[4] A. Kadachi, A. Waheed, M. Al-Eshaikh, and M. Obeid, *Use of photodiode in microdosimetry and evaluation of effective quality factor*, Nuc. Instrum. Meth. A404 (1998) 400-406.

The differences from the lineal energy spectra measured with the TEPC (Tissue Equivalent Proportional Counter) were mainly ascribed to the shape and the dimensions of sensitive volumes

Complex charge collection process

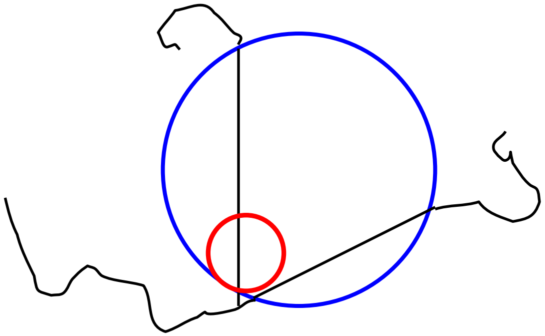
INTRODUCTION (I)

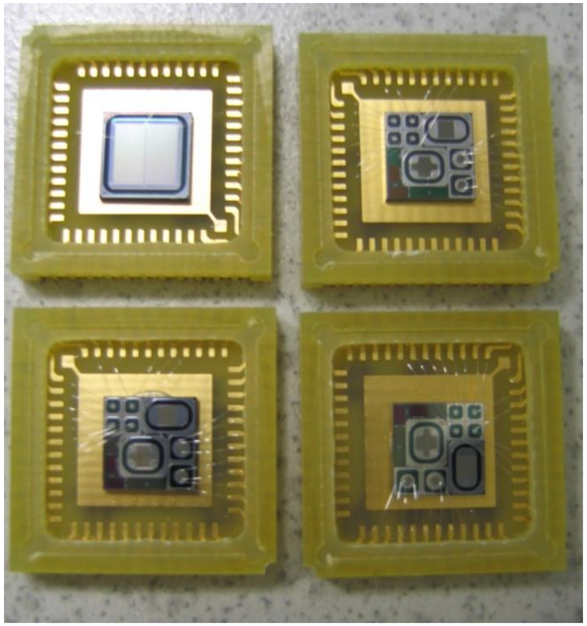
- The micrometric sensitive volumes which can be achieved with silicon detectors led these devices to be studied as microdosimeters.
  - ✓ coupled to TE converters, microdosimetry of neutron fields;
  - ✓ bare (no converter): they can be used for measuring the quality of radiation therapy beams and SEE assessment.



INTRODUCTION (II)

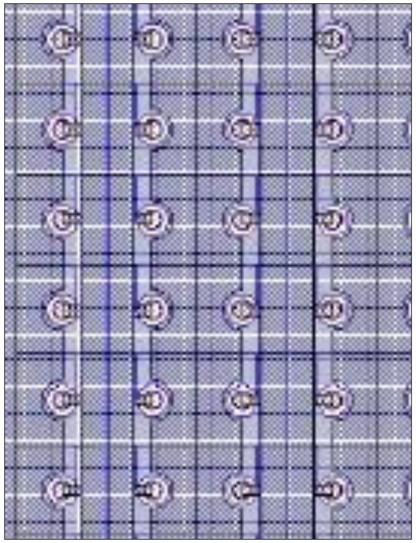
- Advantages:
  - ✓ wall-effects avoided;
  - ✓ compactness;
  - ✓ cheapness;
  - ✓ transportability;
  - ✓ low sensitivity to vibrations;
  - ✓ low power consumption.





INTRODUCTION (III)

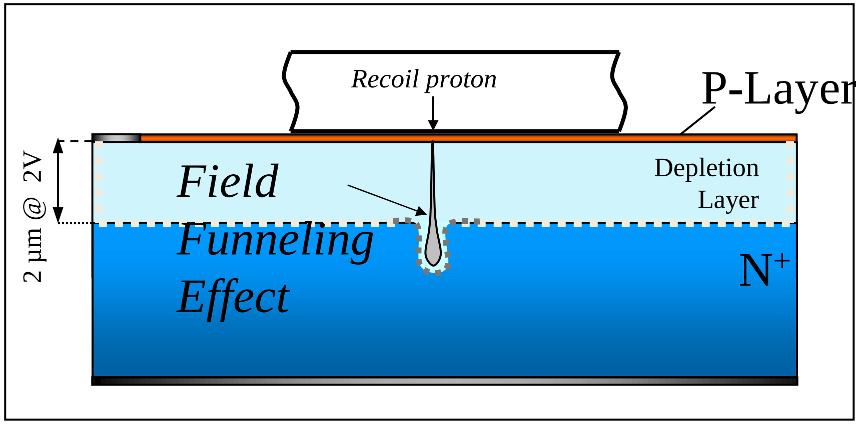
- Problems:
  - ✓ the sensitive volume has to be confined in a region of well-known dimensions (field-funnelling effect);
  - ✓ corrections for tissue-equivalency (energy dependent);
  - ✓ correction for shape equivalency of the track distribution (for TEPC comparison);
  - ✓ angular response;
  - ✓ the electric noise limits the minimum detectable energy (high capacitance);
  - ✓ the efficiency of a single detector of micrometric dimensions is very poor (array of detectors);
  - ✓ radiation hardness.



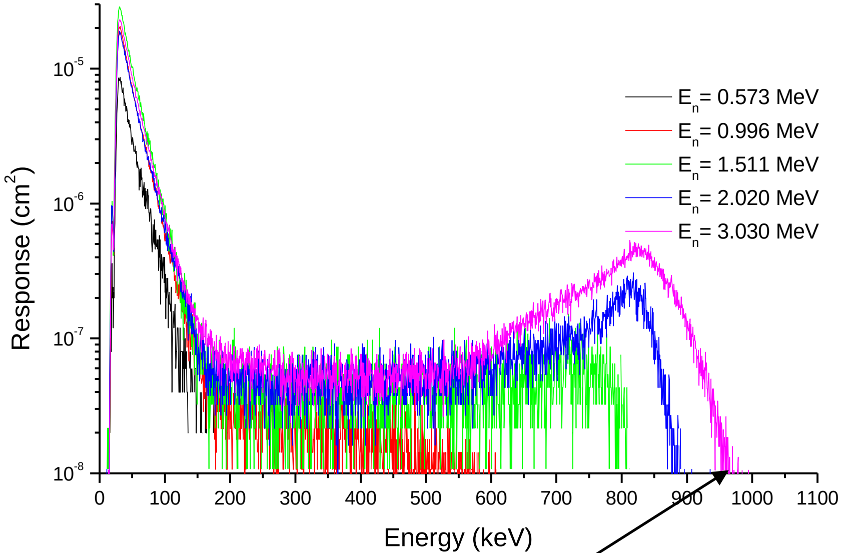
THE FIELD-FUNNELING EFFECT

- FFE: a local distortion of the electric field in the sensitive zone, induced by high-LET particles, which leads to charge collection outside the depleted region.

Depletion layer thickness: 2 μm @ 2 V



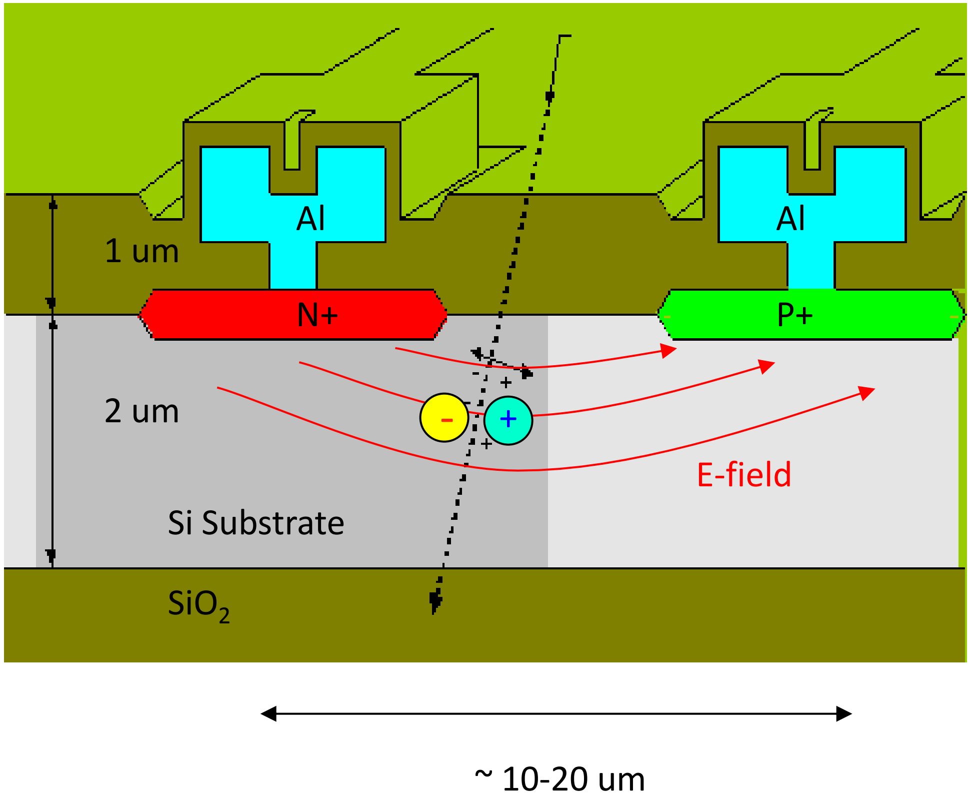
- Example: p-n diode coupled to a polyethylene converter, irradiated with monoenergetic neutrons:

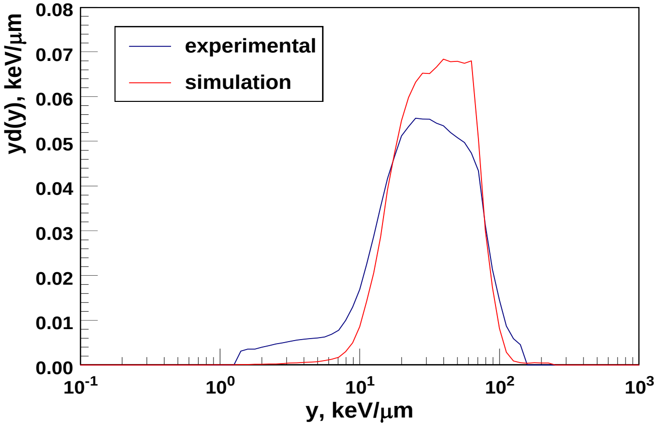


Active thickness: ~ 12 μm

THE FIELD-FUNNELING EFFECT: SOLUTIONS

- Array of diodes fabricated using the silicon on insulator (SOI) technology (Rosenfeld et al.).
  - ✓ This technique allows to obtain sensitive volumes of well defined dimensions, independent of the field funnelling effect;
  - ✓ Different structures with a sensitive volume 2, 5 and 10 µm in thickness were fabricated.
  - ✓ The absorbed dose distributions from different neutron fields were compared to simulations performed with the GEANT code and measurements with a standard TEPC, resulting in a satisfactory agreement.

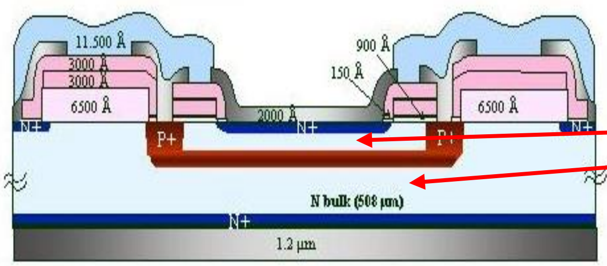




All figures in this slide
Courtesy of A. Rosenfeld, Wollongong University, Australia

THE FIELD-FUNNELING EFFECT: SOLUTIONS

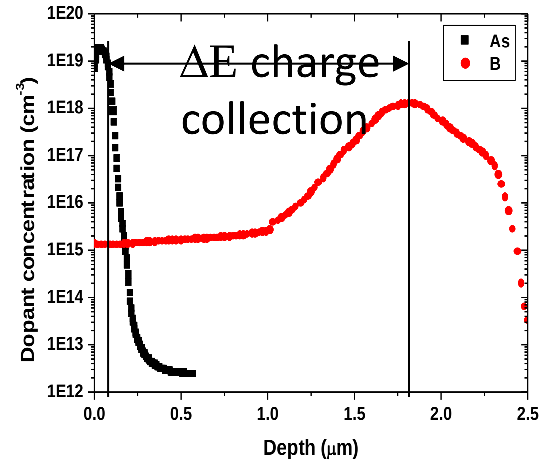
- Monolithic silicon telescope (ST-Microelectronics, Catania, Italy):
  - ✓ the p+ cathode acts as a “watershed” for charge collection, thus minimizing the FFE.

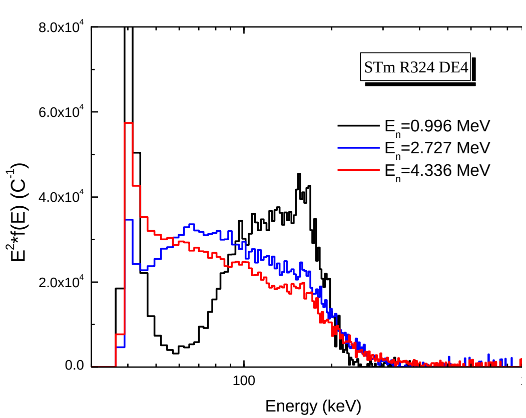


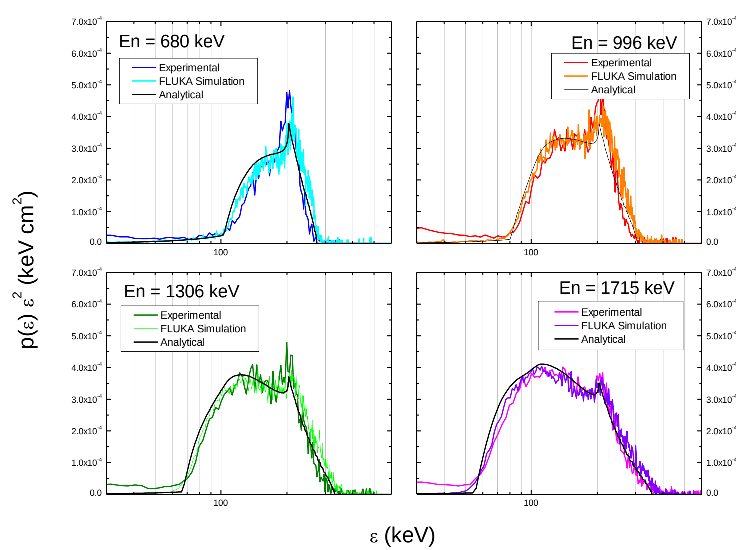
Sensitive area: 1 mm^2

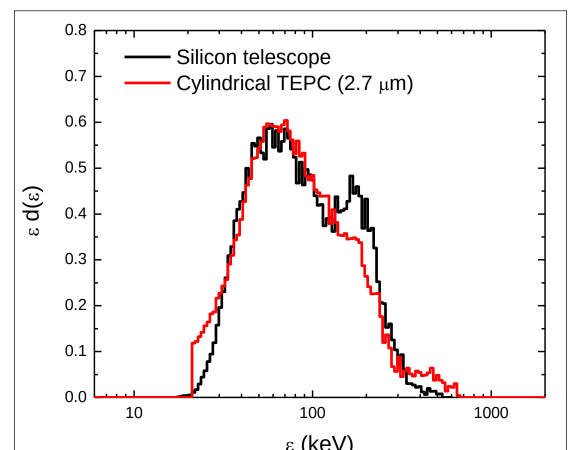
ΔE thickness: ~1.9 µm

E thickness: ~ 500 µm



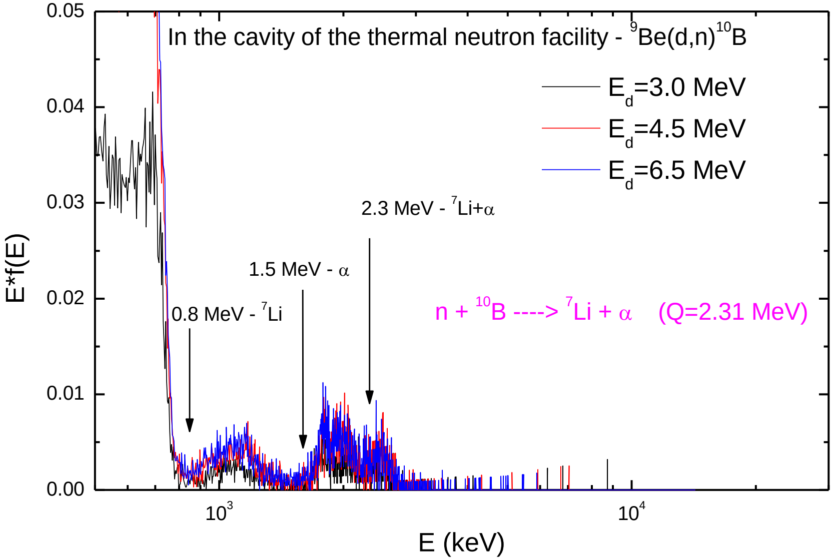


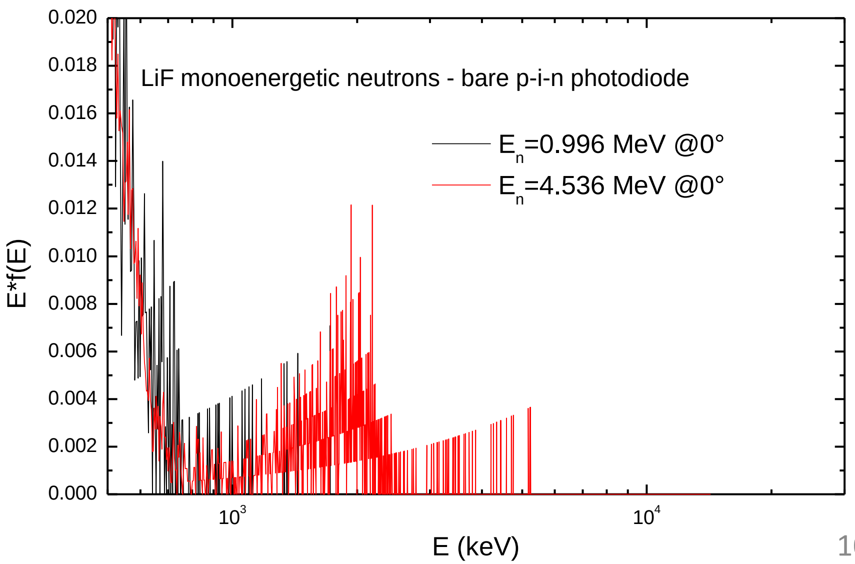




EFFECTS ON SILICON AND DOPANTS

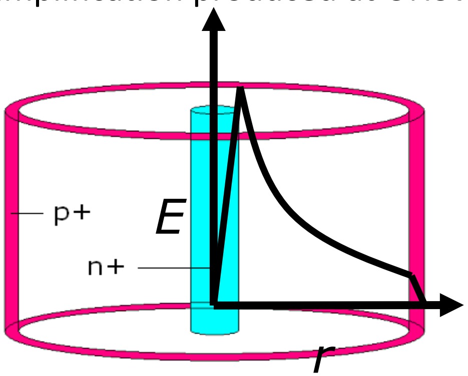
- Contributions of nuclear reactions induced on a p-i-n diode by thermal and fast neutrons were measured in the past.
  - ✓ secondary particles from neutron reactions on ^{10}B were observed (rate 2.2×10^{-6} s^{-1}per unit fluence rate of thermal neutrons vs. $\approx10^{-5}$ s^{-1} recoil-protons);
  - ✓ secondary particles generated by fast neutrons on silicon were also observed.
    - → $^{28}Si(n,p)^{28}Al$ (E_{th} 4.0 MeV);
    - → $^{28}Si(n,\alpha)^{25}Mg$ (E_{th} 2.75 MeV).
  - ✓ Further investigation is necessary for new devices.
  - ✓ Only ^{11}B was implanted in the silicon telescope:
    - → During irradiation on the thermal column of the TAPIRO reactor, no events from $^{10}B(n,\alpha)^{7}Li$ were observed.

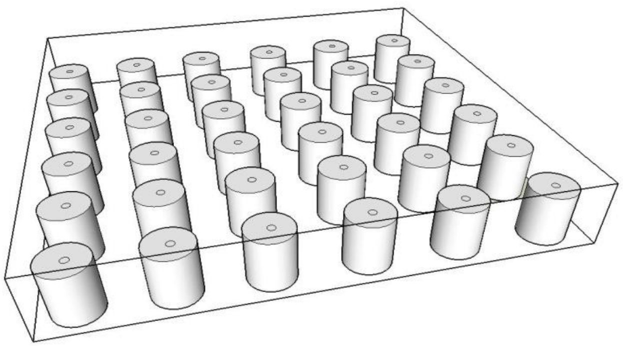


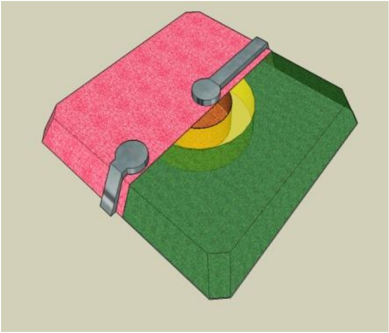


Si MESA MICRODOSIMETERS

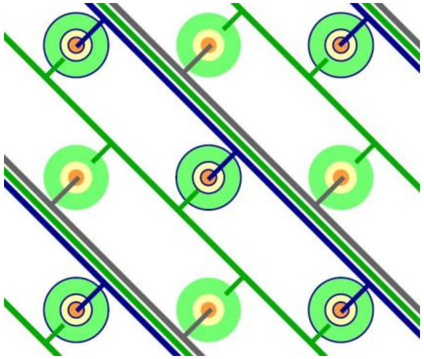
- 3D silicon mesa p-n junction array with internal charge amplification produced at UNSW SNF.

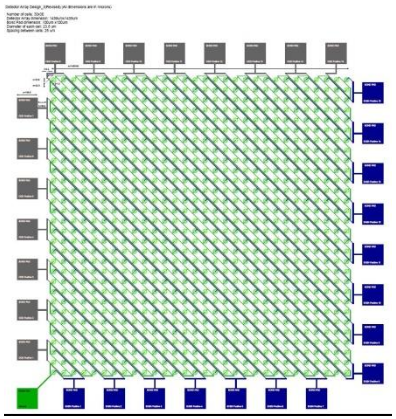






Single mesa 3D SV





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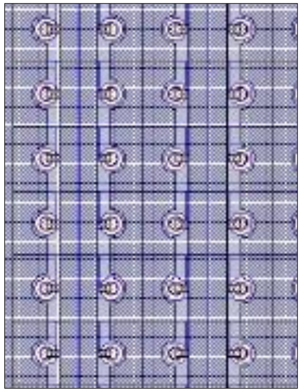
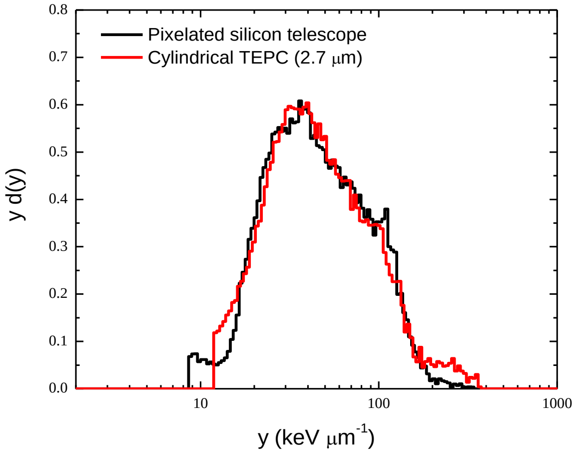
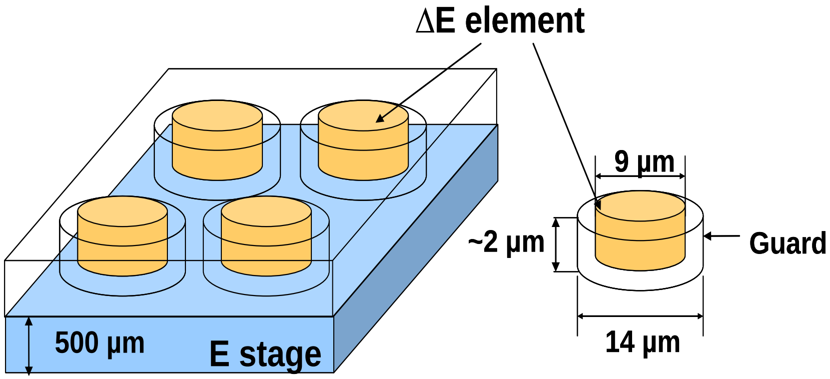
SEGMENTED SILICON TELESCOPE

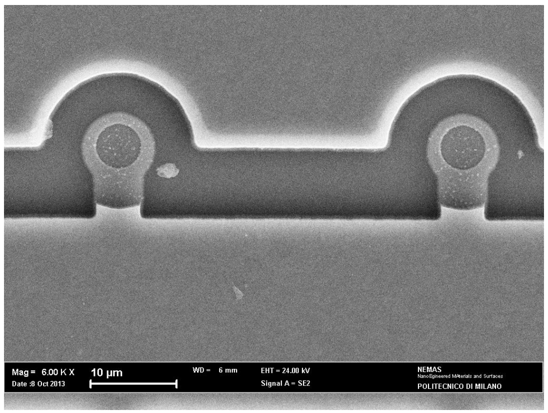
- In the following the main problems related to a silicon microdosimeter will be discussed mainly referring to the:
- segmented silicon telescope:
  - ✓ constituted by a matrix of cylindrical ΔE elements (about 2 µm in thickness) and a single residual-energy E stage (500 µm in thickness);
  - ✓ the nominal diameter of the ΔE elements is about 9 µm and the width of the pitch separating the elements is about 41 µm.
  - ✓ more than 7000 pixels are connected in parallel to give an effective sensitive area of about 0.5 mm^2.
  - ✓ minimum detectable energy is limited to about 20 keV by the electronic noise.
  - ✓ the ΔE stage acts as a microdosimeter and the E stage plays a fundamental role for assessing the full energy of the recoil-protons, thus allowing to perform a LET-dependent correction for tissue-equivalency.

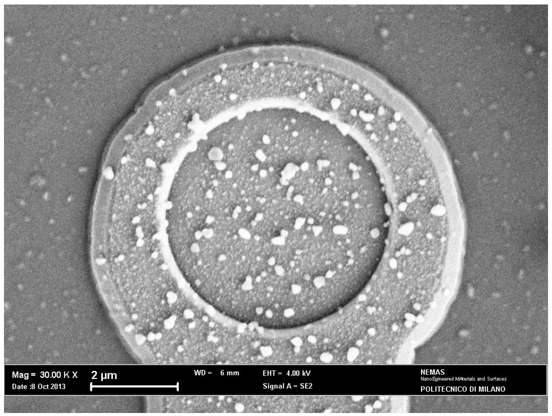


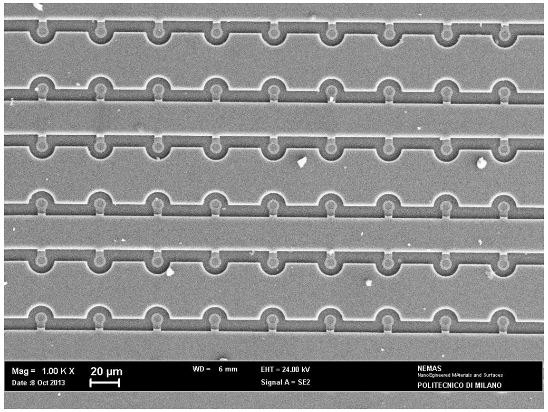


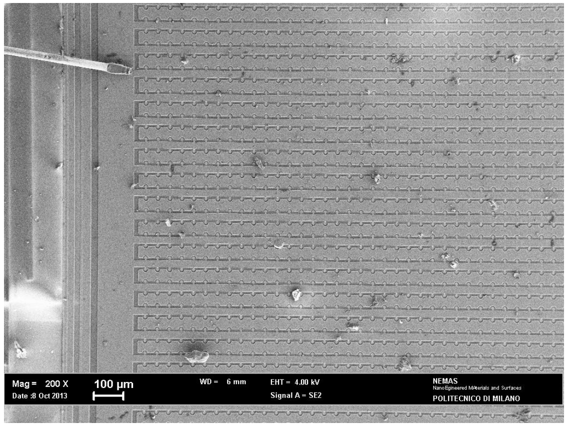


SEGMENTED TELESCOPE: SEM IMAGES



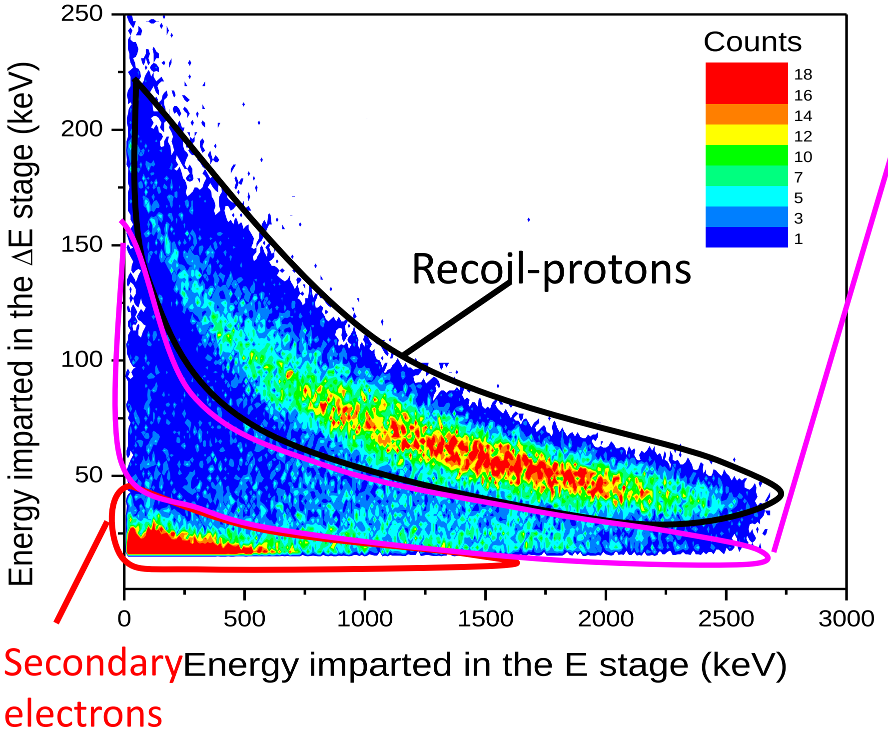






SEGMENTED SILICON TELESCOPE: SCATTER-PLOT

- 2.7 MeV neutron irradiation of the telescope coupled to A-150 plastic;
- The signals from the ΔE and the E stage were acquired with a 2-channel ADC in coincidence mode.



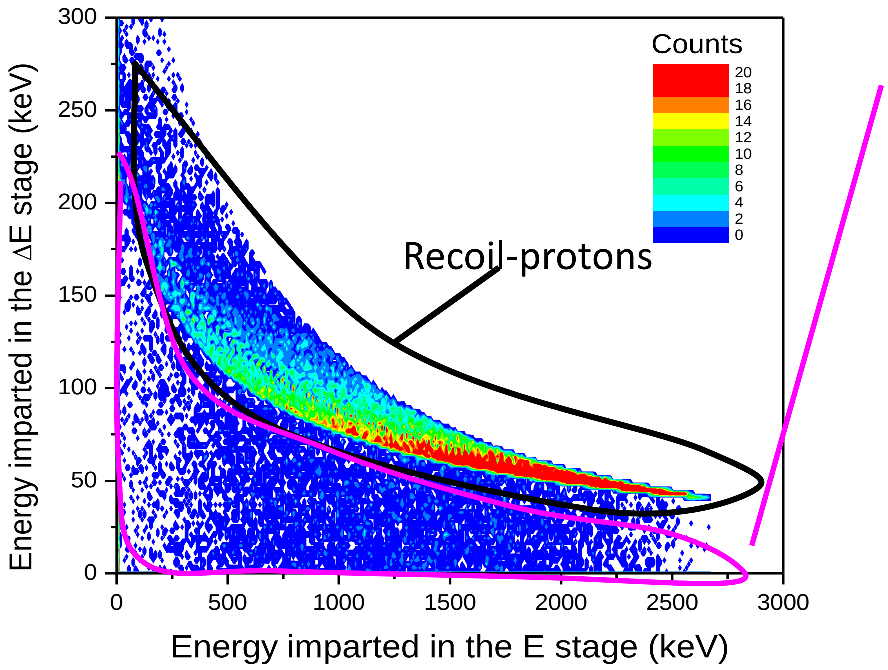
Recoil-protons

May be due to:
-Track length distribution;
Charge sharing.

Contribution of about 5.5%

SEGMENTED SILICON TELESCOPE: SIMULATION

- The response of a cylindrical element of the ΔE stage was simulated with a MC algorithm;
- The algorithm takes into account the geometrical structure of the telescope, but does not reproduce border effects.
- Secondary electrons from photon interactions on the materials surrounding the detector were not accounted for.



Recoil-protons

Calculated contribution of about 5%

due to the track length distribution!

Charge sharing can be neglected

TISSUE-EQUIVALENCE AND GEOMETRIC CORRECTIONS

- In order to derive microdosimetric spectra similar to those acquired by a TEPC, corrections are necessary;
- Tissue equivalence:
  - ✓ a LET-dependent tissue equivalence correction can be assessed through a telescope detector:
    - → by measuring event-by-event the energy of the impinging particles;
    - → by discriminating the impinging particles.
- Shape equivalence:
  - ✓ basing on parametric criteria from the literature, the lineal energy *y* was calculated by considering an equivalent mean cord length.

TISSUE-EQUIVALENCE CORRECTION

Analytical procedure for tissue-equivalence correction:

$$E_d^{Tissue}(E_p, l) = E_d^{Si}(E_p, l) \cdot \frac{S^{Tissue}(E_p)}{S^{Si}(E_p)}$$

Energy deposited along a track of length l by recoil-protons of energy E_p in a tissue-equivalent ΔE detector

Scaling factor :
stopping powers ratio

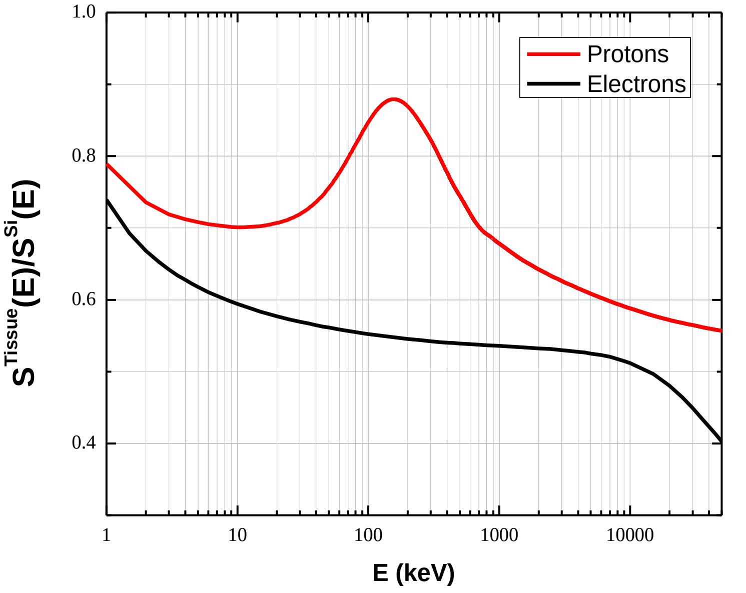
TISSUE-EQUIVALENCE CORRECTION

The scaling factor $\dfrac{S^{Tissue}(E)}{S^{Si}(E)}$

depends on the energy and type of the impinging particle

E stage of the telescope and ΔE-E scatter-plot allow an energy-dependent correction for protons

the thickness of the E stage limits the TE correction to recoil-protons below 8 MeV (alphas below 32 MeV)

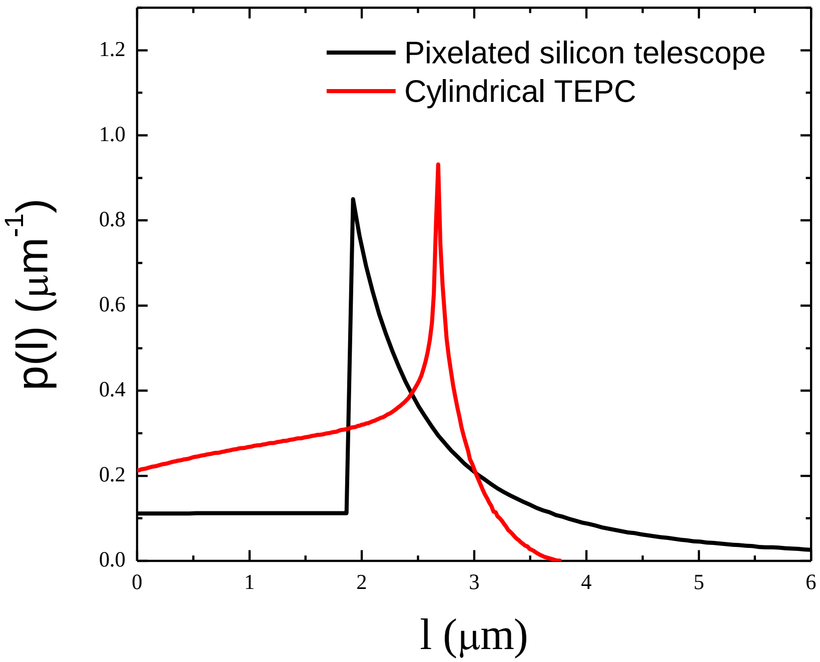


Electrons release only part of their energy in the E stage

ELECTRONS: average value over a wide energy range (0-10 MeV) = 0.53

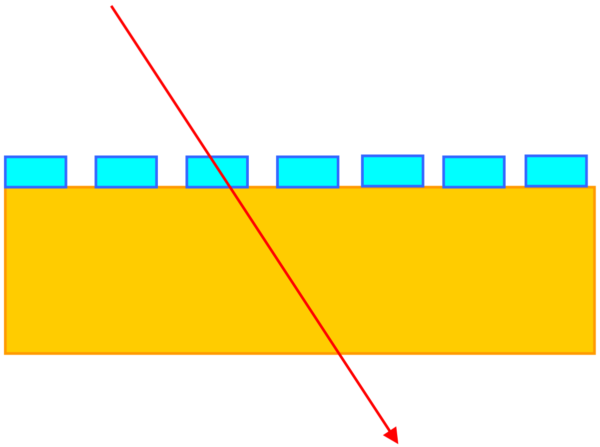
SHAPE ANALYSIS

- The correcting procedure can be based on cord length distributions, since ΔE pixels are cylinders of micrometric size in all dimensions (as the TEPCs).;
  - ✓ This correction is only geometry-dependent (no energy limit).



COMPARISON WITH A CYLINDRICAL TEPC

- The microdosimetric spectra were compared to the one acquired with a cylindrical TEPC at the same positions inside a PMMA phantom.
  - ✓ L. De Nardo, D. Moro, P. Colautti, V. Conte, G. Tornielli and G. Cuttone, RPD 110 (2004)



- Proximal part and across the SOBP:
- Corrections:
- Protons cross both the ΔE and the E stage.

1) Tissue- equivalence:
   a scaling factor was applied:

$$\varepsilon_{\Delta E}^{Tissue}(E) = \varepsilon_{\Delta E}^{Si}(E) \cdot \frac{1}{E_{max}} \int_0^{E_{max}} \frac{S^{Tissue}(E)}{S^{Si}(E)} dE \Rightarrow \varepsilon_{\Delta E}^{Tissue}(E) = \varepsilon_{\Delta E}^{Si}(E) \cdot 0.574$$

2) Shape equivalence:
   by equating the dose-mean energy imparted per event for the two cylindrical sites:

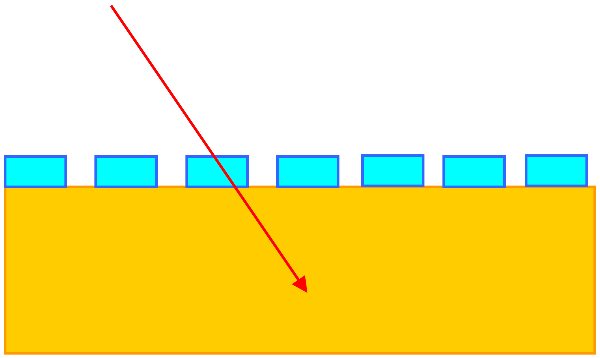
$$\bar{\varepsilon}_D^{\Delta E} = L \cdot \bar{l}_D^{\Delta E} = \bar{\varepsilon}_D^{TEPC} = L \cdot \bar{l}_D^{TEPC} \Rightarrow \eta = \frac{\bar{l}_D^{TEPC}}{\bar{l}_D^{\Delta E}} = 0.533$$

DISTAL PART OF SOBP

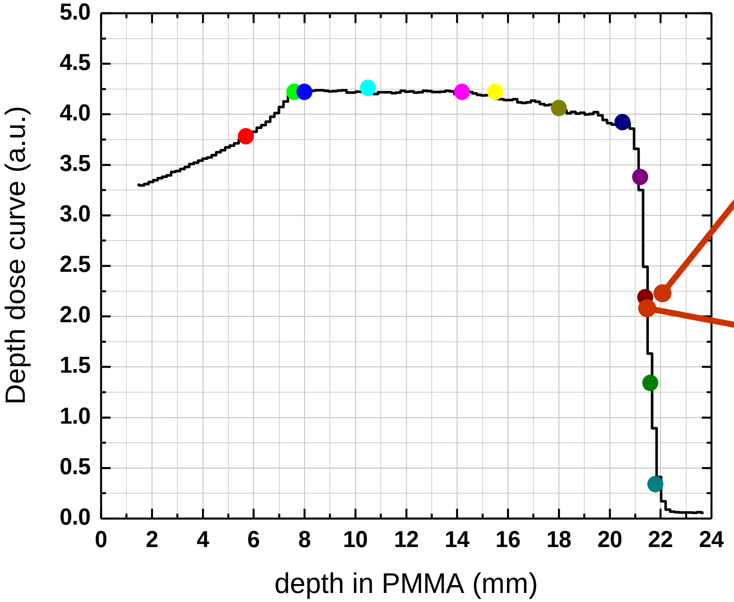
- Distal part of the SOBP: most of protons stop in the E stage
- An energy dependent correction for TE can be applied from the event-by-event information from the two stages:

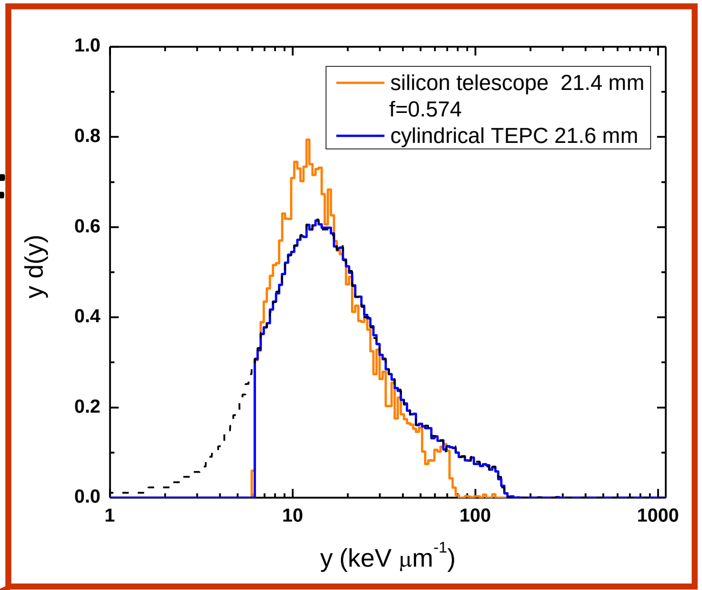
$$\varepsilon_{\Delta E}^{\text{Tissue}}(E) = \varepsilon_{\Delta E}^{\text{Si}}(E) \cdot \frac{S^{\text{Tissue}}(E)}{S^{\text{Si}}(E)}$$

$$E \cong \varepsilon_{\Delta E}^{\text{Si}}(E) + \varepsilon_{E}^{\text{Si}}(E)$$

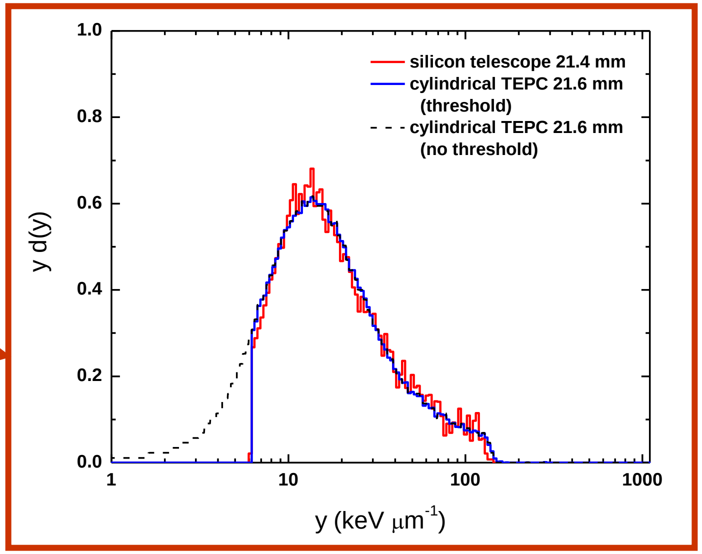


DISTAL PART OF





Constant scaling factor



Energy-dependent correction

ENERGY THRESHOLD IMPROVEMENT

The main limitation of the system is the high energy threshold imposed by the electronic noise.

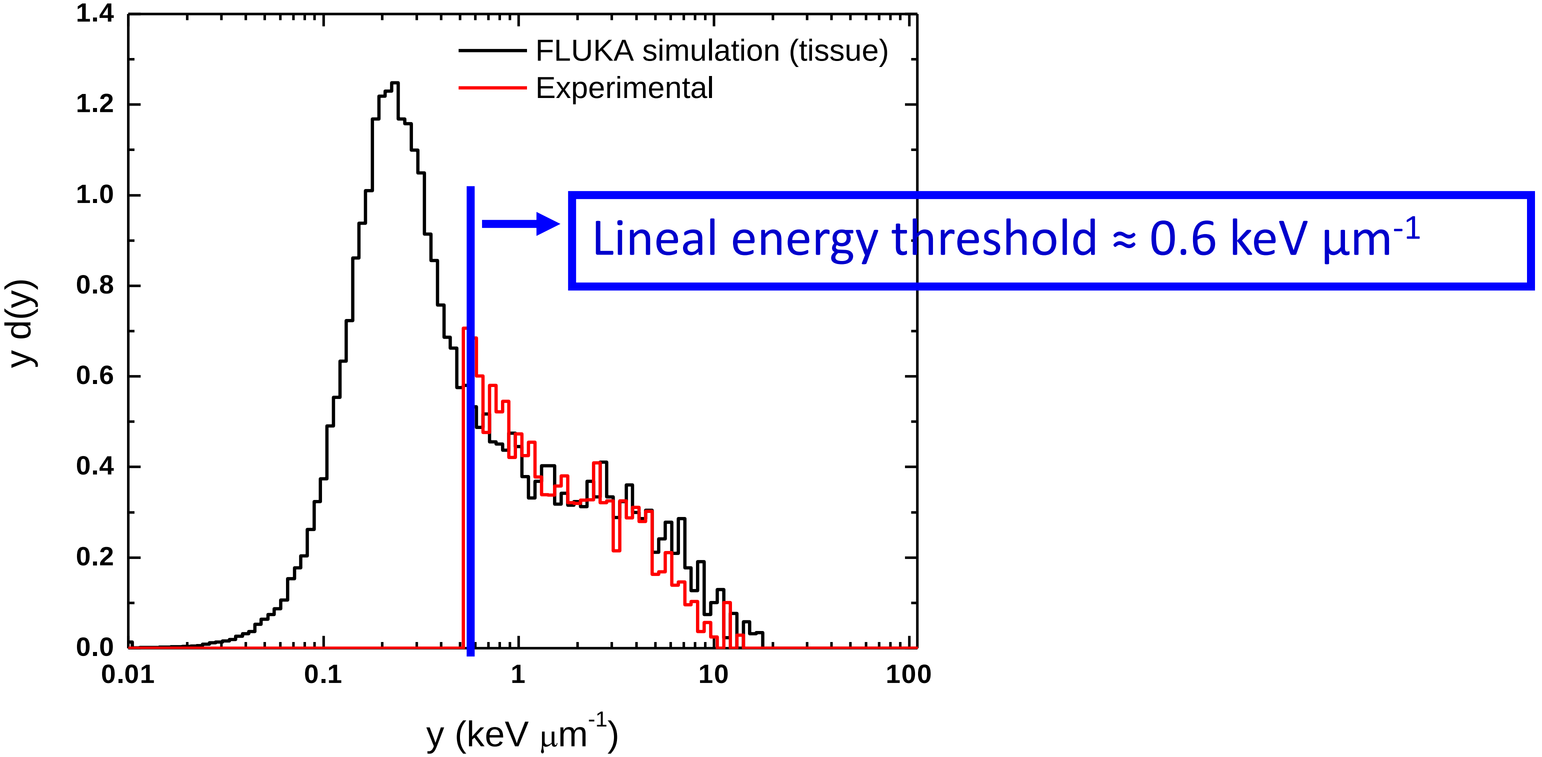
New design of the segmented telescope with a ΔE stage with a lower number of cylinders connected in parallel and an E stage with an optimized sensitive area

1. Decrease the energy threshold below 1 keV μm^{-1}
2. Optimize the counting rate of the two stages

A feasibility study with a low-noise set-up based on discrete components was carried out in order to test this possibility

ENERGY THRESHOLD IMPROVEMENT

A telescope constituted by a single ΔE cylinder coupled to an E stage was irradiated with β particles emitted by a ^{137}Cs source.



CONCLUSIONS

- Silicon detectors show interesting features for microdosimetry, anyway still some problems have to be solved:
  - ✓ electronic noise (minimum detectable lineal energy);
  - ✓ radiation hardness when exposed to high-intensity hadron beams.

Additional Slides

SHAPE ANALYSIS

The equivalence of shapes is based on the parametric criteria given in the literature (Kellerer).

By assuming a constant linear energy transfer L:

$$\bar{\varepsilon}_D = L \cdot \frac{\int_0^\infty l^2 \cdot p(l)\,dl}{\bar{l}} = L \cdot \bar{l}_D$$

By equating the dose-mean energy imparted per event for the two different shapes considered:

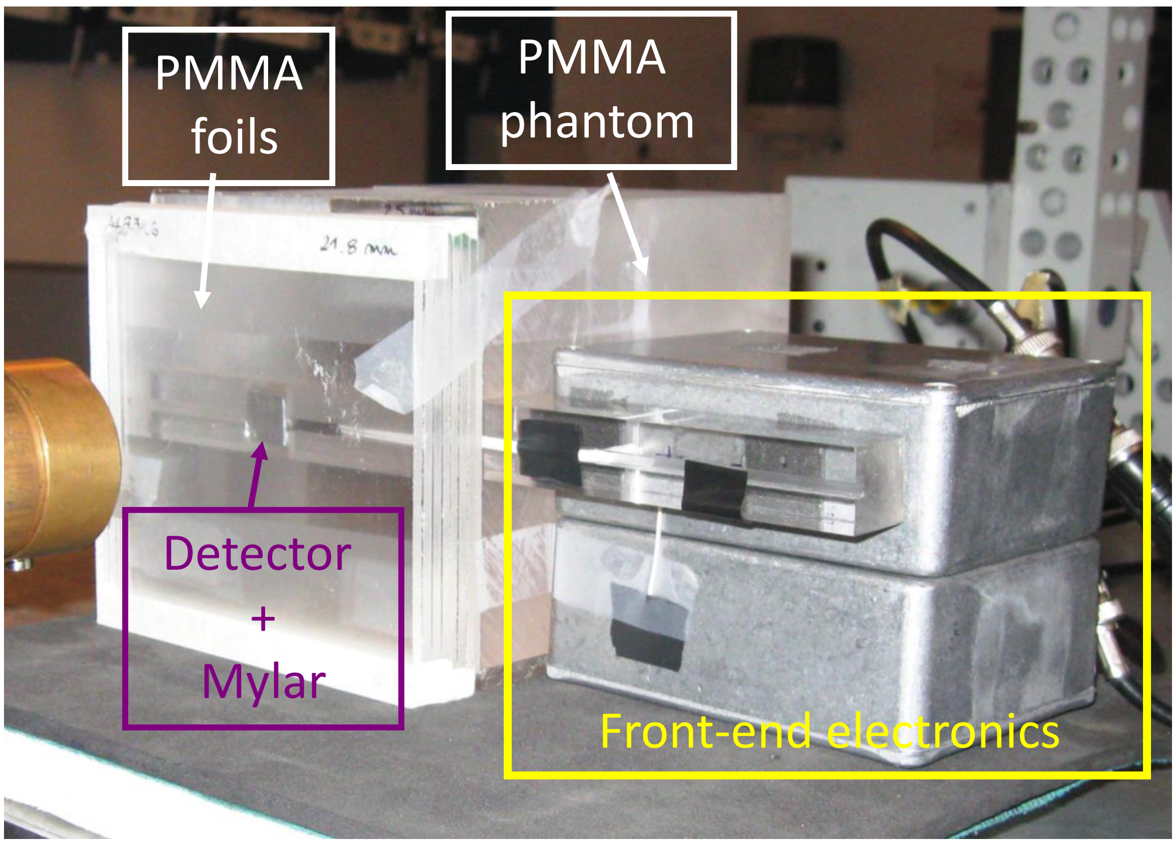
$$\bar{\varepsilon}_D^{\Delta E} = L \cdot \bar{l}_D^{\Delta E} = \bar{\varepsilon}_D^{\mathrm{TEPC}} = L \cdot \bar{l}_D^{\mathrm{TEPC}} \quad \Rightarrow \quad \eta = \frac{\bar{l}_D^{\mathrm{TEPC}}}{\bar{l}_D^{\Delta E}} = 0.533$$

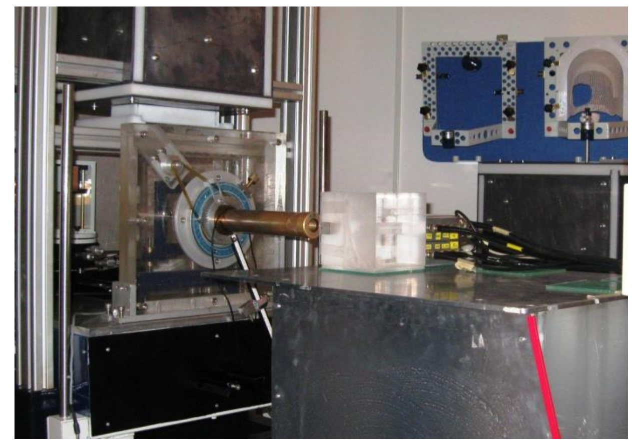
Dimensions of ΔE stages were scaled by a factor η …
… the lineal energy y was calculated by considering an equivalent mean cord length equal to:

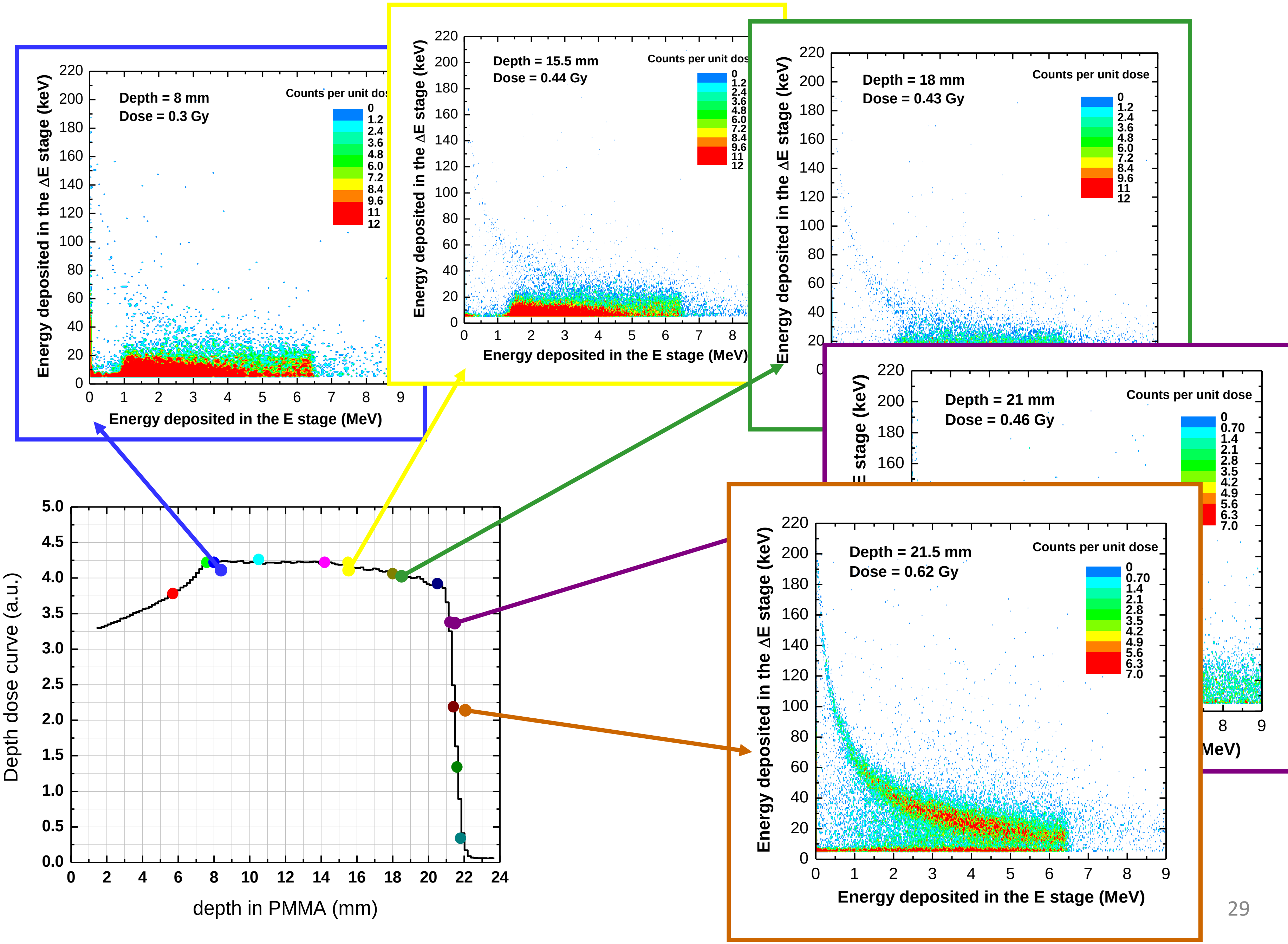
$$\bar{l}_{\Delta E,\mathrm{eq}} = \bar{l}_{\Delta E} \cdot \eta$$

IRRADIATIONS AT THE CATANA FACILITY

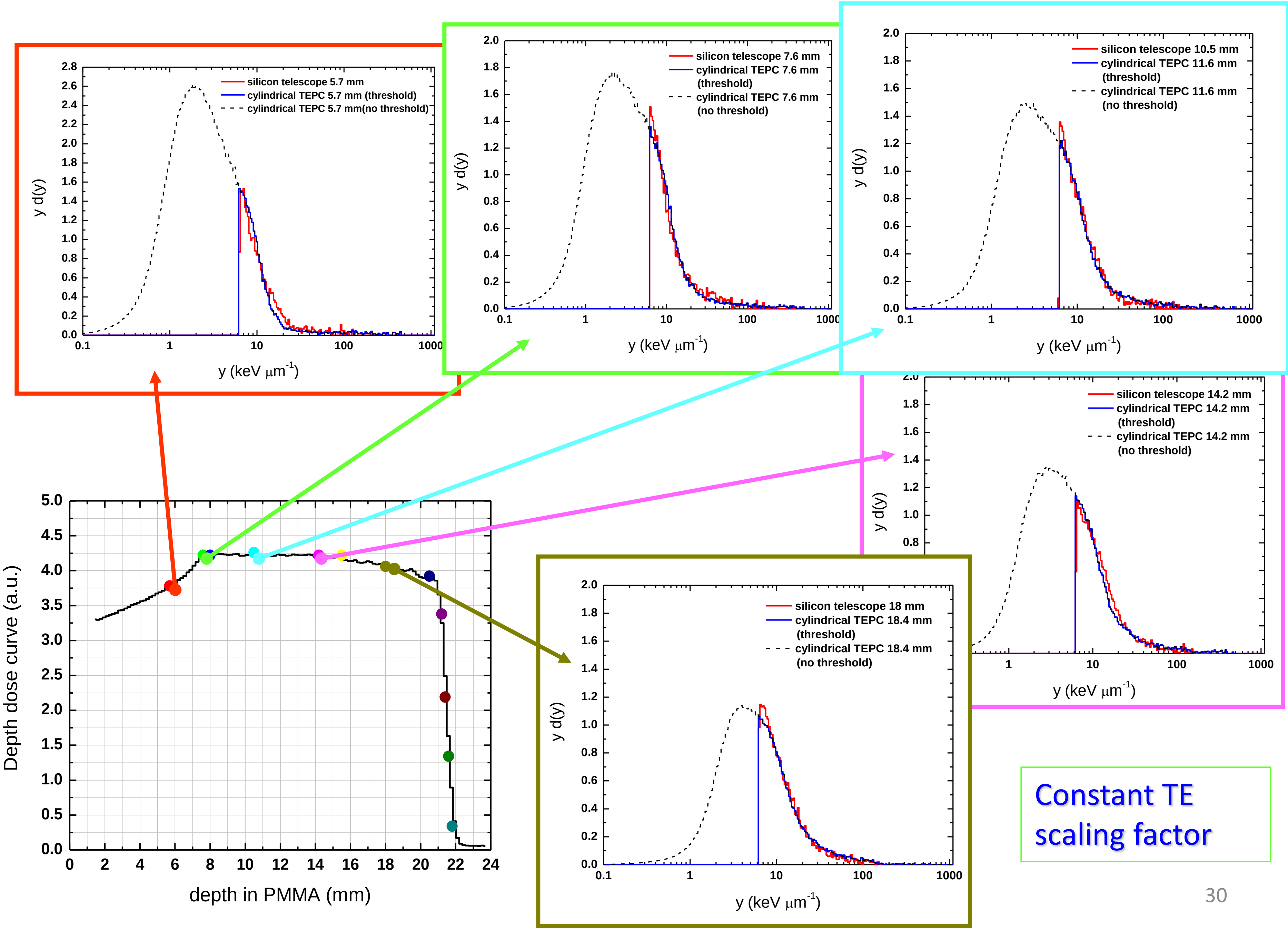
- The segmented silicon telescope was irradiated inside a PMMA phantom exposed to the 62 MeV proton beam at the INFN-LNS CATANA facility.



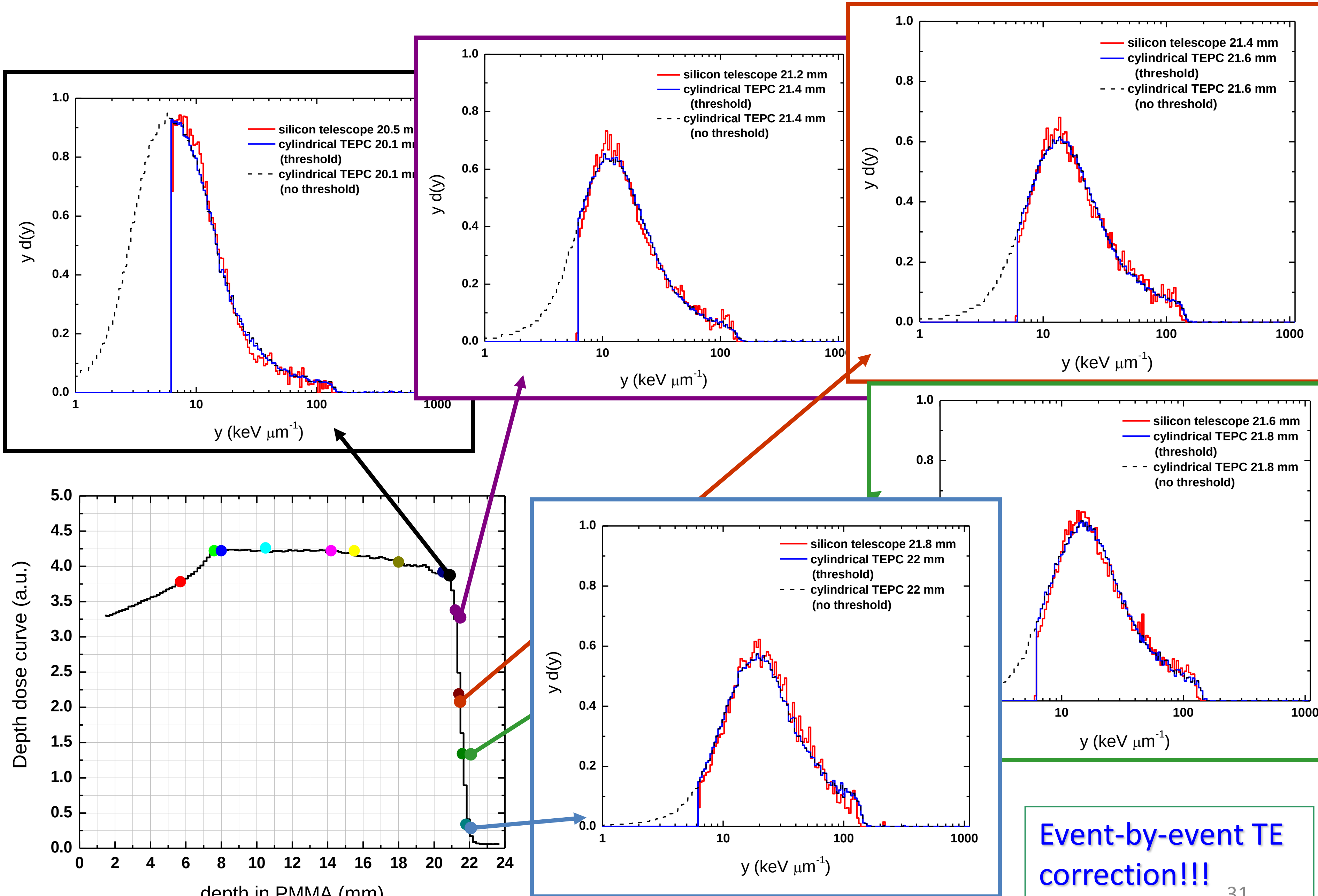




Depth = 8 mm
Dose = 0.3 Gy
Depth = 15.5 mm
Dose = 0.44 Gy
Depth = 18 mm
Dose = 0.43 Gy
Depth = 21 mm
Dose = 0.46 Gy
Depth = 21.5 mm
Dose = 0.62 Gy
Counts per unit dose
Energy deposited in the ΔE stage (keV)
Energy deposited in the E stage (MeV)
Depth dose curve (a.u.)
depth in PMMA (mm)



Constant TE scaling factor



Event-by-event TE correction!!!

PRELIMINARY MEASUREMENTS W