G. CUTTONE

Laboratori Nazionali del Sud – INFN Catania (I)

From the ionization chamber to the on-line microstrip devices:

the status of the art of detectors in proton therapy under the experience gained at the CATANA facility

Scuola Nazionale "Rivelatori ed Elettronica per Fisica delle Alte Energie, Astrofisica, Applicazioni Spaziali e Fisica Medica“

INFN Laboratori Nazionali di Legnaro, 20-24 Aprile 2009

TALK OUTLINE

1. Absolute and relative dosimetry in proton therapy: starting point for the dosimetric commissioning

2. Ten years of detector characterisation

3. What future for clinical proton beam detectors?

DETECTOR DEVELOPMENT AND CHARACTERIZATION

STILL A NEED IN RADIATION THERAPY AND, IN PARTICULAR, IN A YET PIONEERING TECHNIQUE LIKE PROTON THERAPY

↓

ABSOLUTE AND RELATIVE DOSIMETRY

(Dosimetric commissioning)

CONTINOUS R&D WORK

A complete description of each detector is impossible!

Dosimetric commissioning: absolute & relative dosimetry

<u>Absolute Dosimetry</u>: Energy Released in Water (Gray)

<u>Relative Dosimetry</u>: Three dimensional dose distribution measurements

$\Downarrow$

Considering the high gradient dose, conformation and small fields often used the detectors have to be kindly characterized in terms of spatial resolution, energy or fluence dependence to be use in hadrontherapy.

Relative and Absolute Dosimetry are fundamental for:

Customizing of TPS
Monitor Unit Calculation
Quality Control

DETECTOR OVERVIEW

Activity started in 1996 with the first test on 30 MeV protons and continued with 62 MeV protons

Gas detector (ionisation chambers)

Film detectors

Solid state detectors

10 year of work

43 papers in review journals

61 conference proceeding

Farmer

Exradin

Pin Point

Markus

Advanced Markus

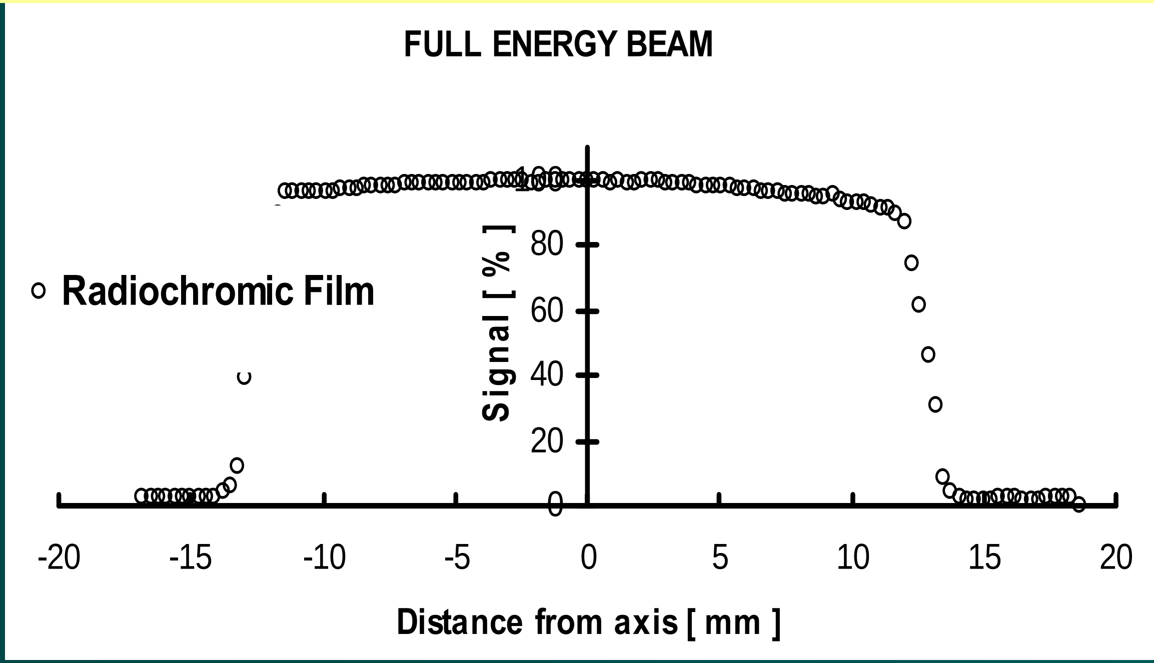
Radiographic films

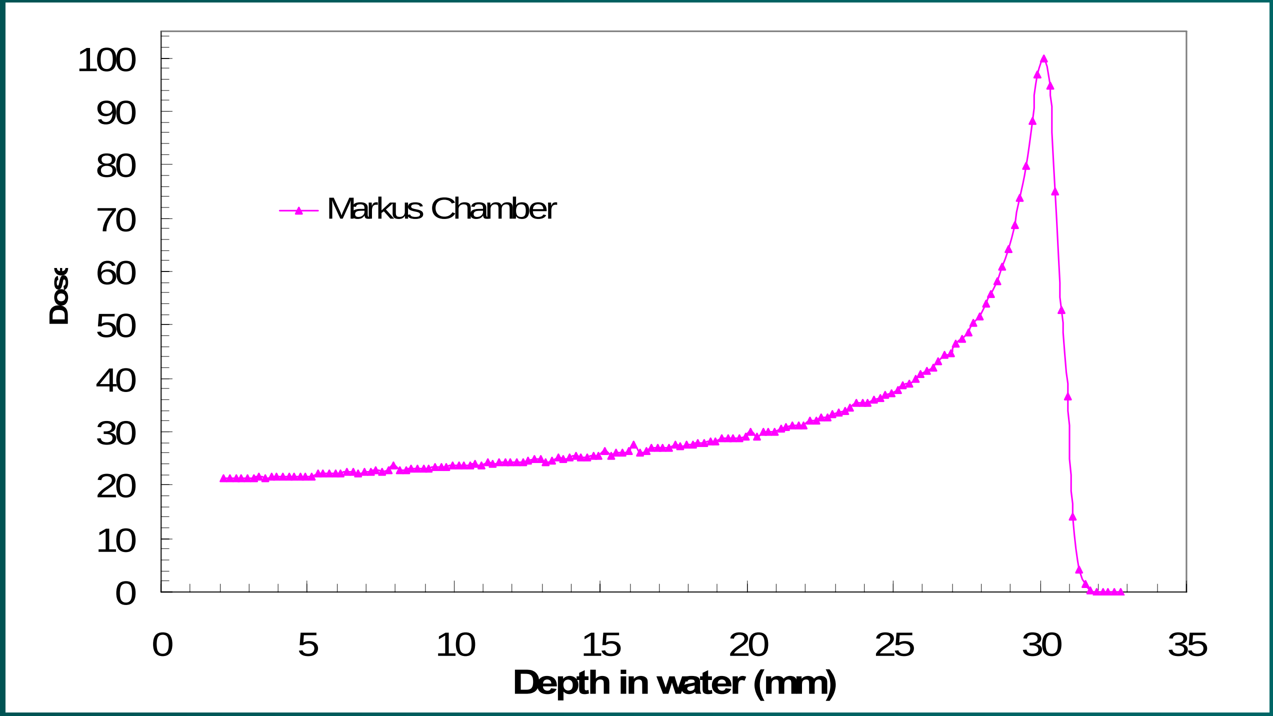
GAF Chromic films

(MD52, EBT, …

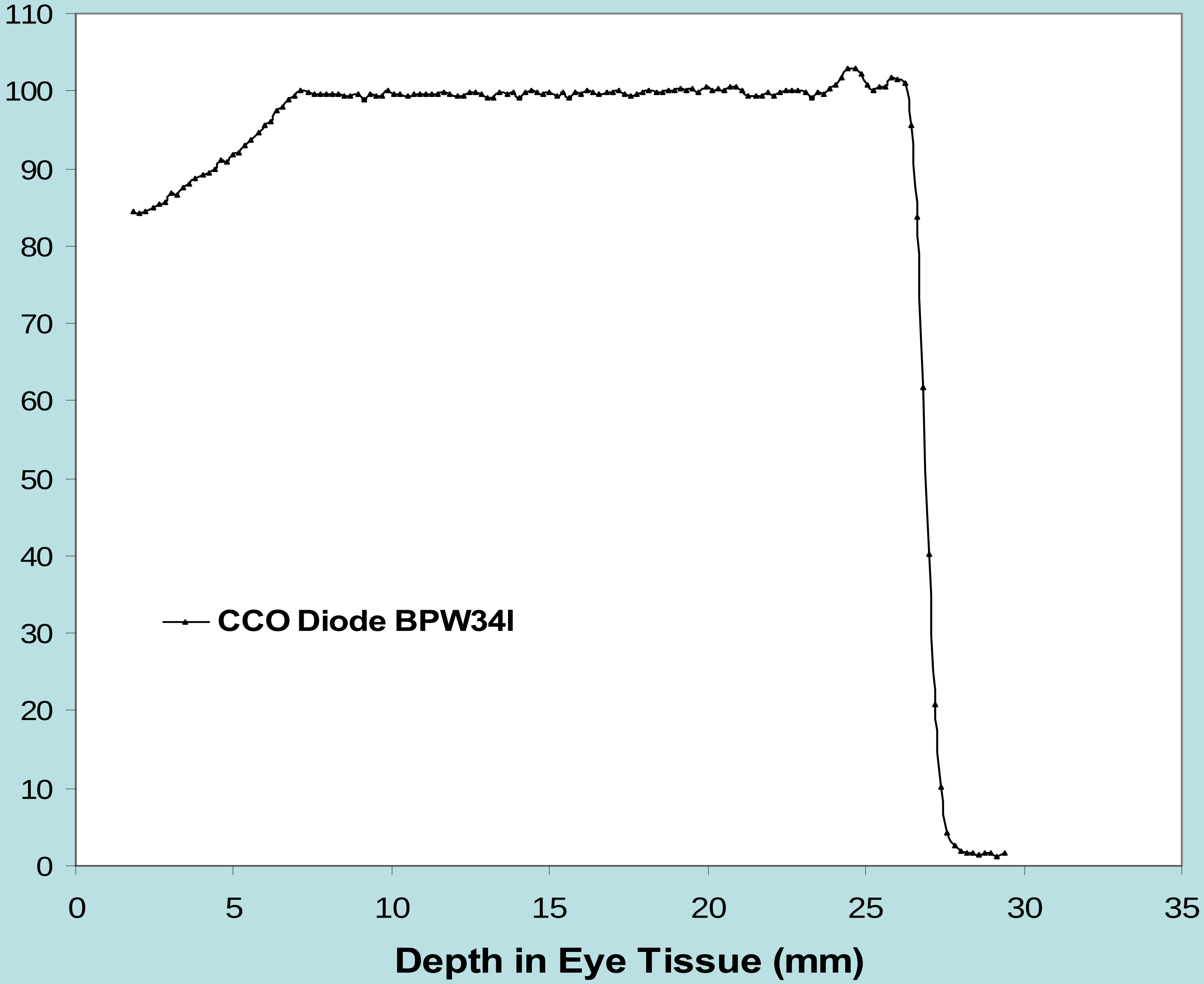
- Plastic scintillators
- Diamond detector
- TLD
- MOSfet
- Silicon diode
- Silicon microstrip

62 MeV experimental proton beam





62 MeV experimental proton beam



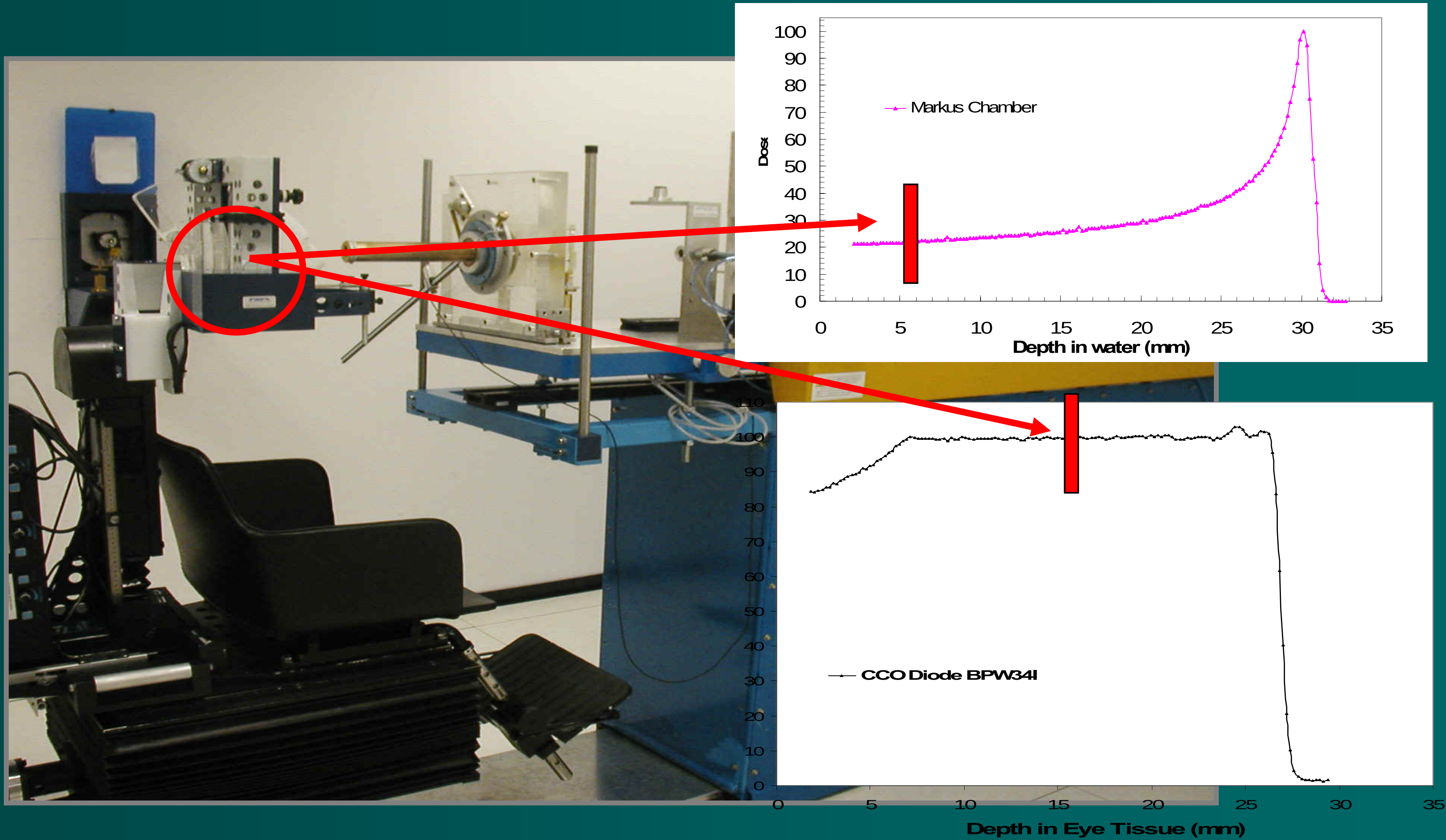
WHAT WE NEED FROM A DOSEMETER?

- Tissue equivalence ($\langle Z \rangle = 6$, $\langle Z/A \rangle = 0.5$)
- Linearity vs absorbed dose
- Independence from dose rate
- Independence from energy
- Radiation hardness
- Spatial resolution (< 1 mm)
- Small size: no perturbation of the proton fluency (Bragg-Gray theory)

MEASUREMENT CONFIGURATION

Detector placed at isocenter on a special table mounted on the treatment chair

MEASUREMENT CONFIGURATION



Detector placed at isocenter on a special table mounted on the treatment chair

ABSOLUTE DOSIMETRY

ICRU 59 AND TRS 398 IAEA RECOMMENDATION

⇓

" FOR MEASUREMENTS OF DEPTH-DOSE DISTRIBUTION IN PROTON BEAMS

THE USE OF PLANE-PARALLEL CHAMBERS IS RECOMMENDED"

⇓

Parallel plate *MARKUS PTW* is the golden standard for depth dose measurements

Dosimetric commissioning: absolute & relative dosimetry

ADVANCED MARKUS CHAMBER

❶ V_P = 400 V ➔ $V \times cm^{-1}$ = 4000 ➔ k_S = 1.00 (1÷100 Gy/min.).

❷ Pressure equilibrium ≤ 10 sec

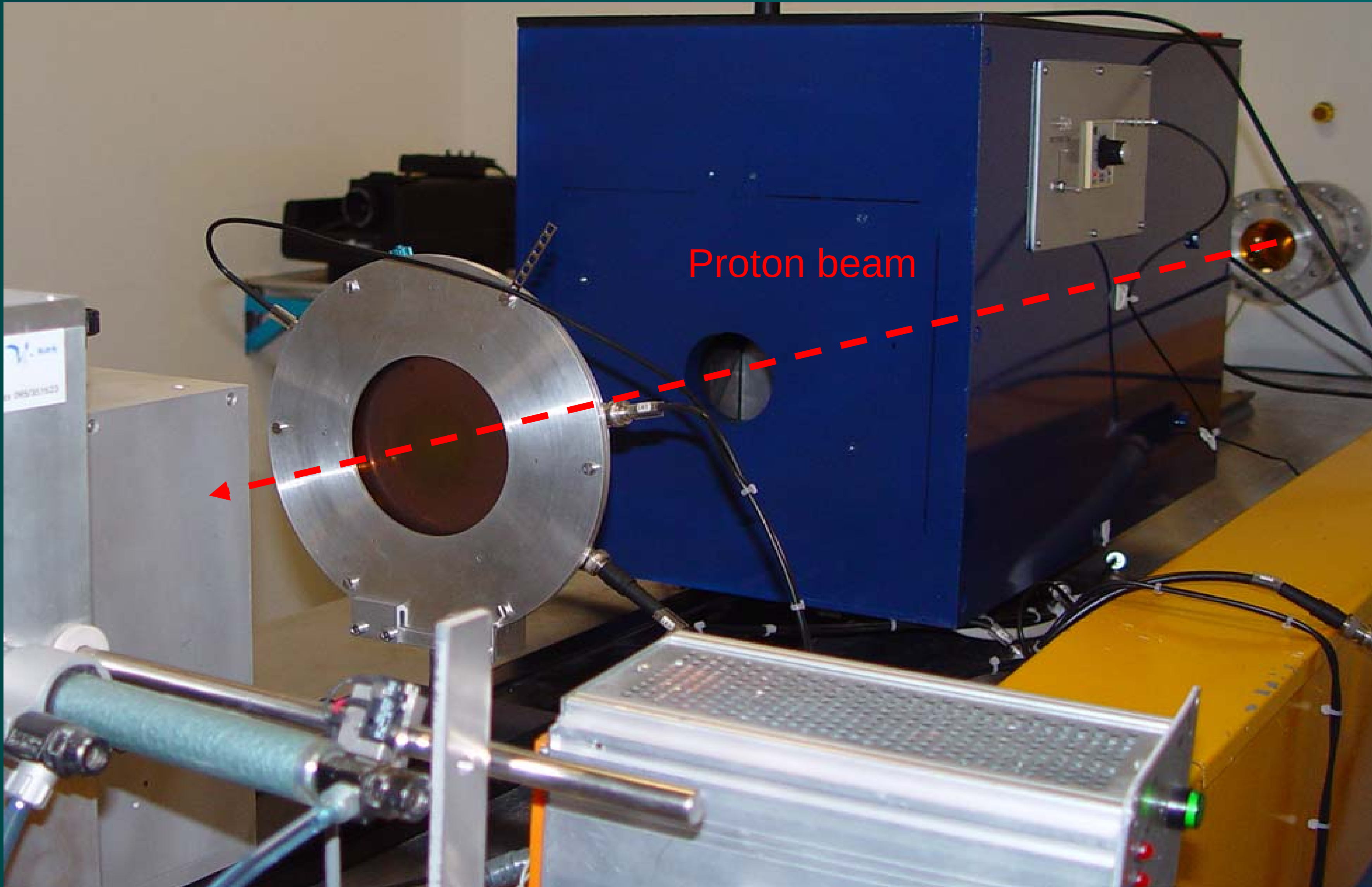
❸ Temperature equilibrium = 2-3 min./K

➍ Response: 670 pC/Gy

➎ Directional dependence: smaller than 0.1% for tilting of the chamber by up to 10º

➏ Electrode Acrylic (PMMA), graphite coated 5 mm Ø

➐ Leakage current ± 4 fA

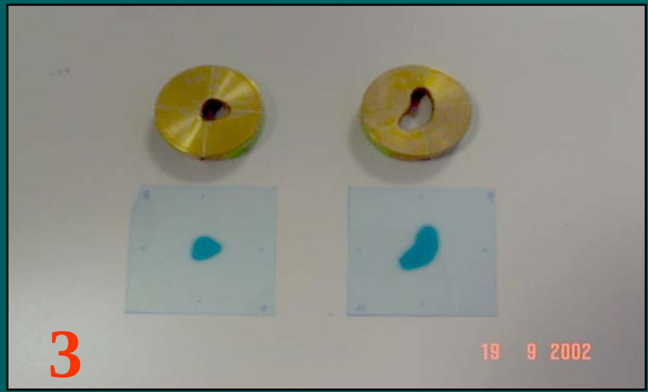


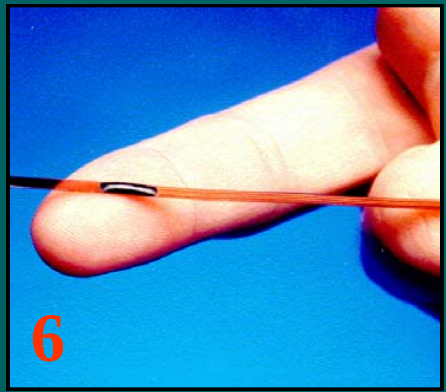
Ionisation, free air monitor chamber calibrated against the Markus:

Sensibility: 5 pC

Reprucibility: 0.5 %

DETECTOR FOR RELATIVE DOSIMETRY





1) Film Kodak: XV and EDR2 2) TLD 3) Radiochromic Film

4) Scanditronix Diode 5) PTW Natural Diamond 6) Mosfet

- In collaboration with ISS (S. Onori..) and DFC Florence (M. Bucciolini...)

RELATIVE DOSIMETRY: FILM DETECTORS

GAFCHROMIC® EBT Configuration

CLEAR POLYESTER - 97 microns

ACTIVE LAYER - 17 microns

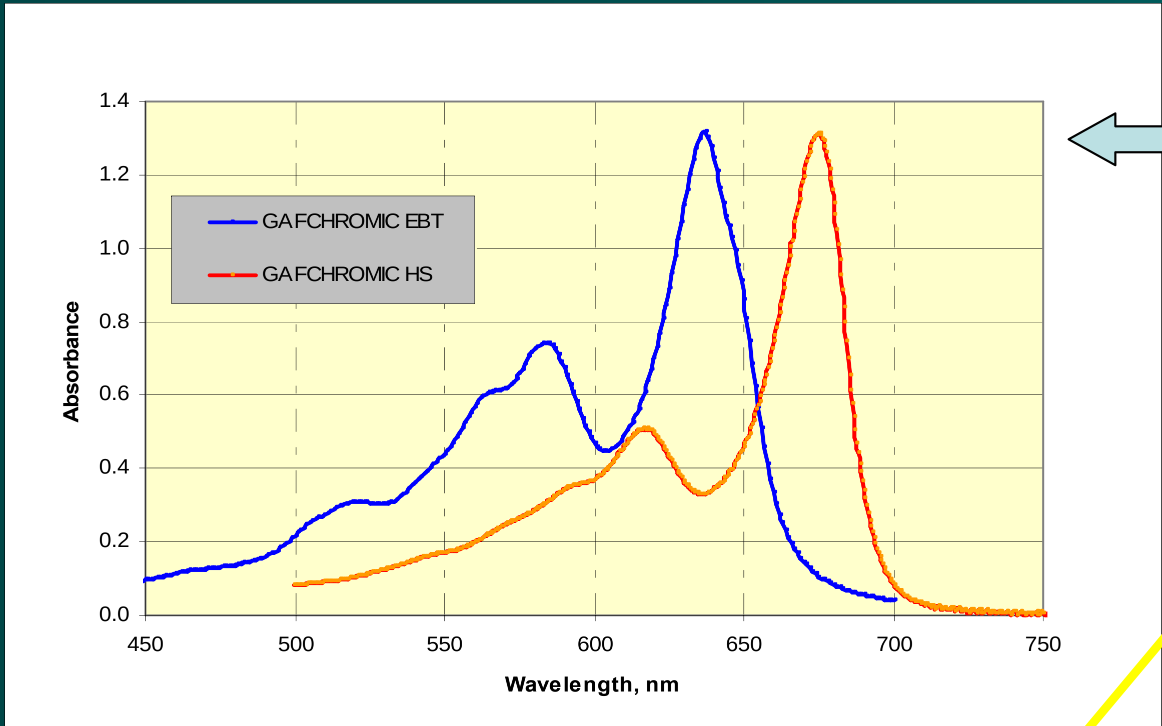
SURFACE LAYER - 6 microns

ACTIVE LAYER - 17 microns

CLEAR POLYESTER - 97 microns

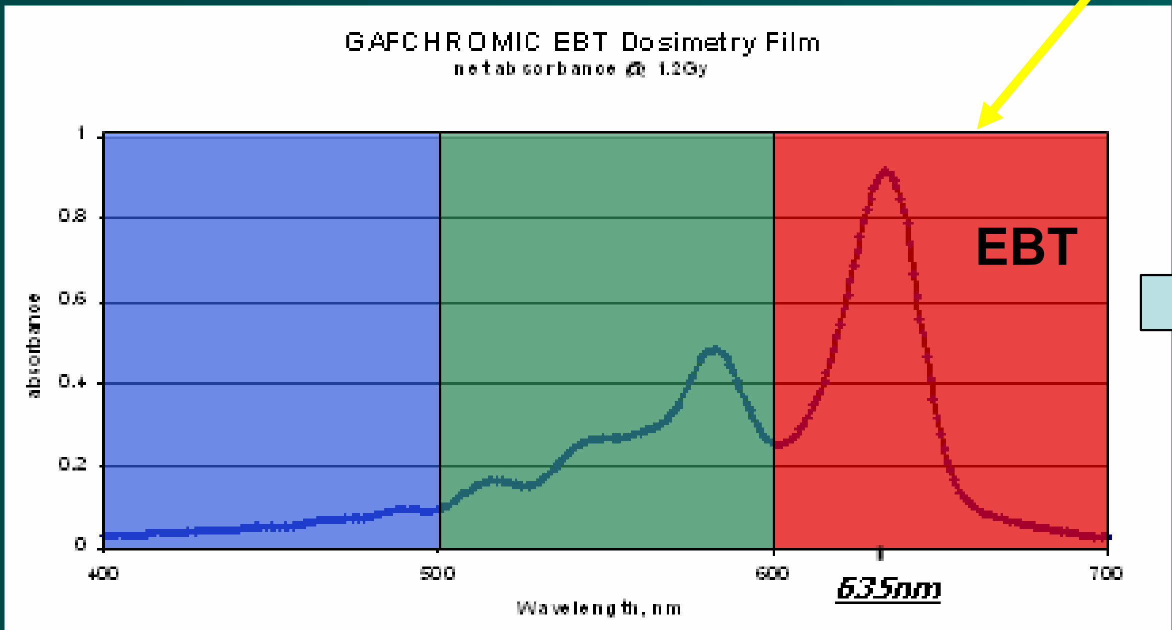
1) Transmission densitometer
2) Colour scanner

SPECTRA OF NEW AND OLD RADIOCHROMIC FILMS



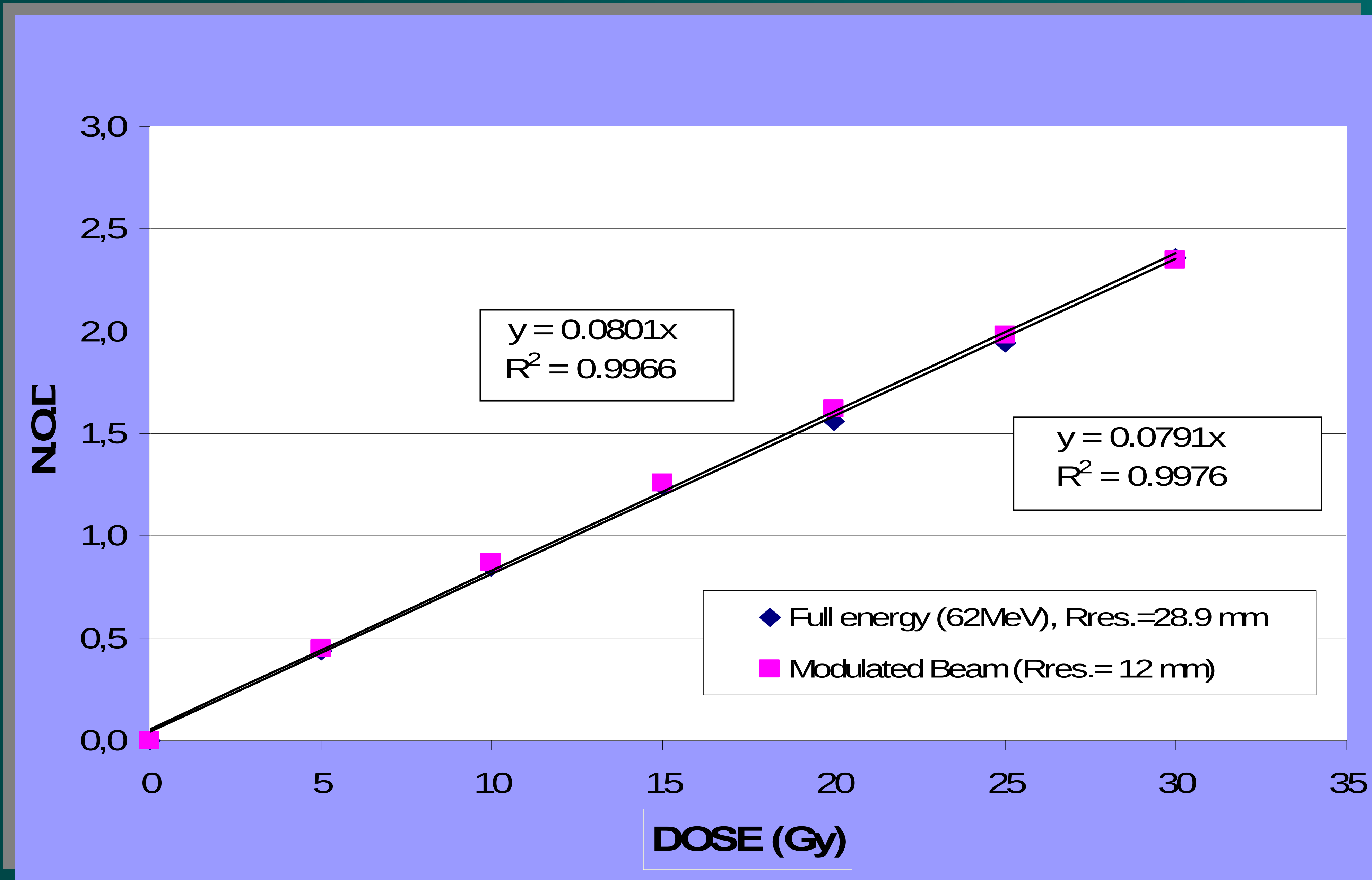
OLD: HS ISP
NEW: EBT ISP

RESPONSE ENHANCED BY MEASUREMENT WITH RED LIGHT

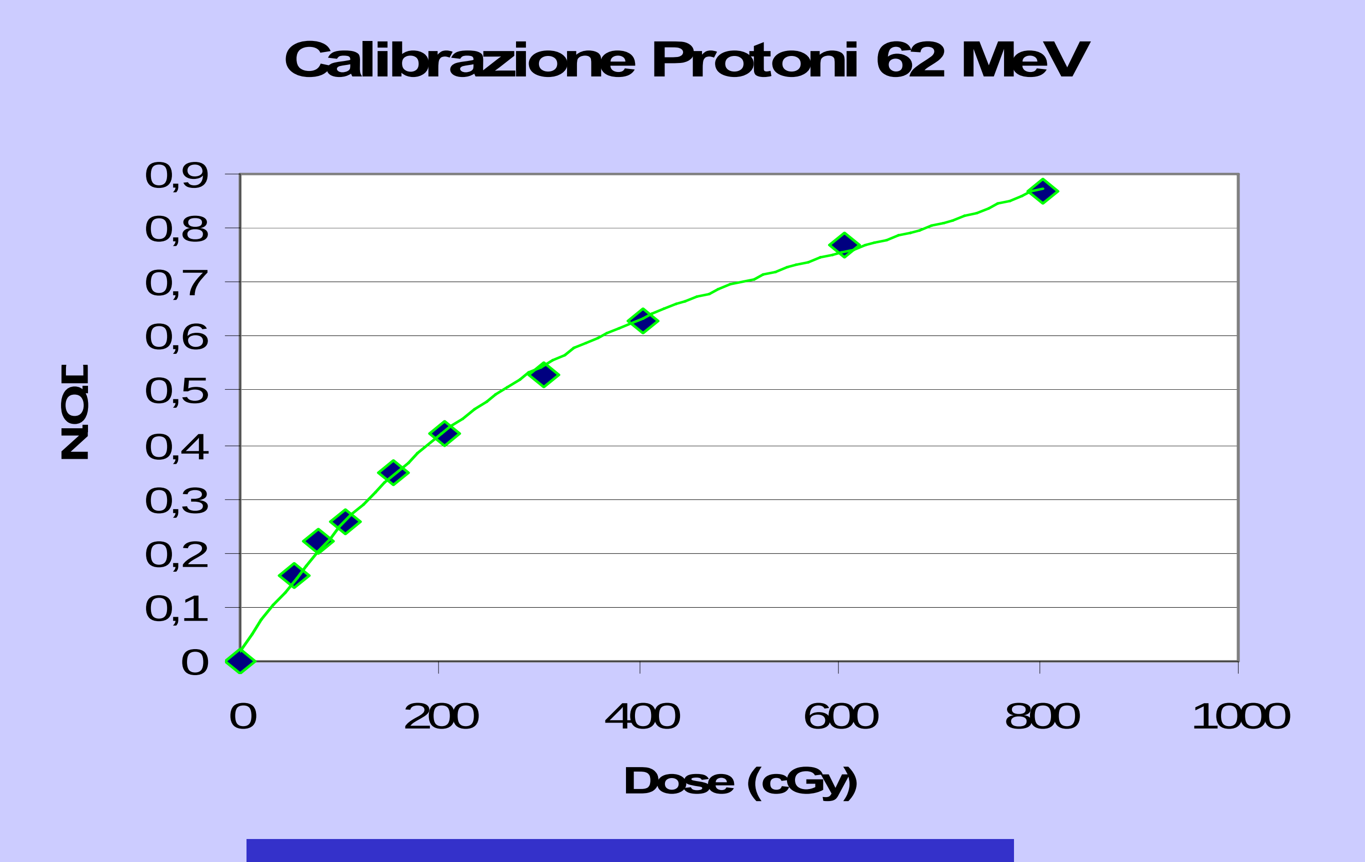


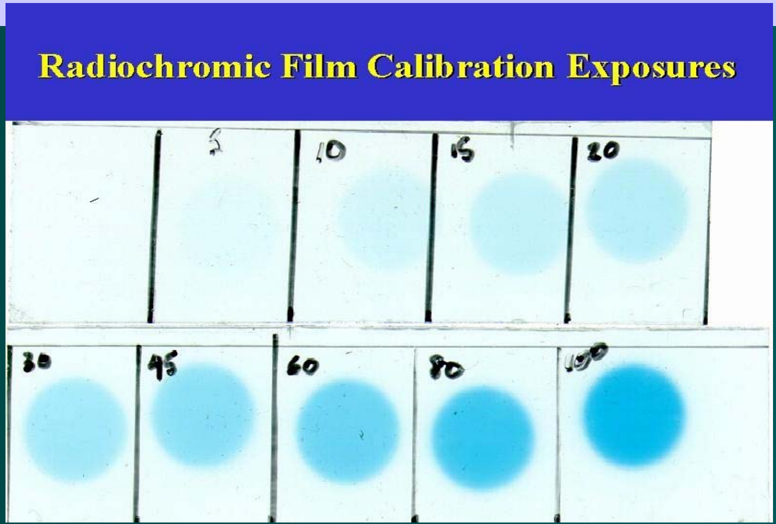
EPSON flatbed color scanner

ENERGY INDEPENDENCE HS GAF



DOSE CALIBRATION



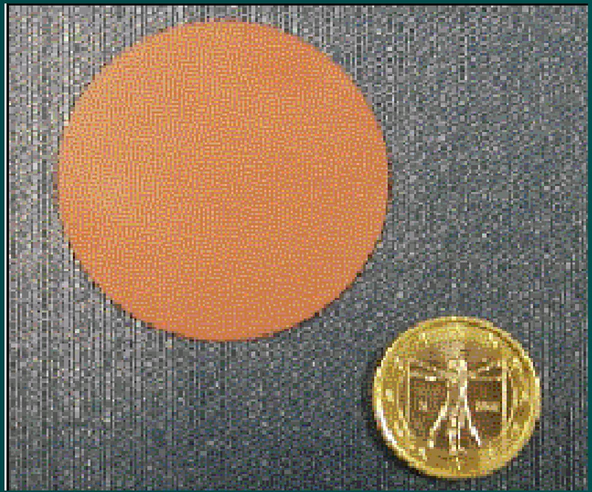


EBT GAF

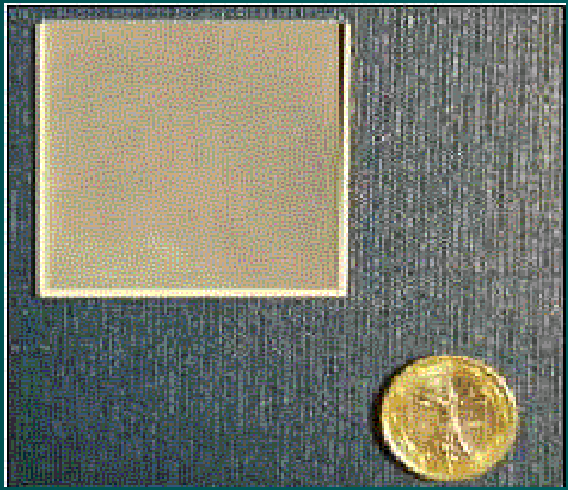
EPSON flatbed color scanner

RED CHANNEL

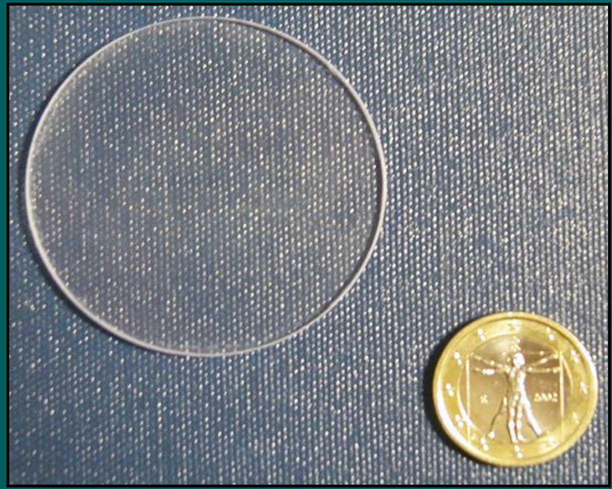
RELATIVE DOSIMETRY: plastic scintilators



Alumina (Al2O3)



Caesium Iodide (CsI)



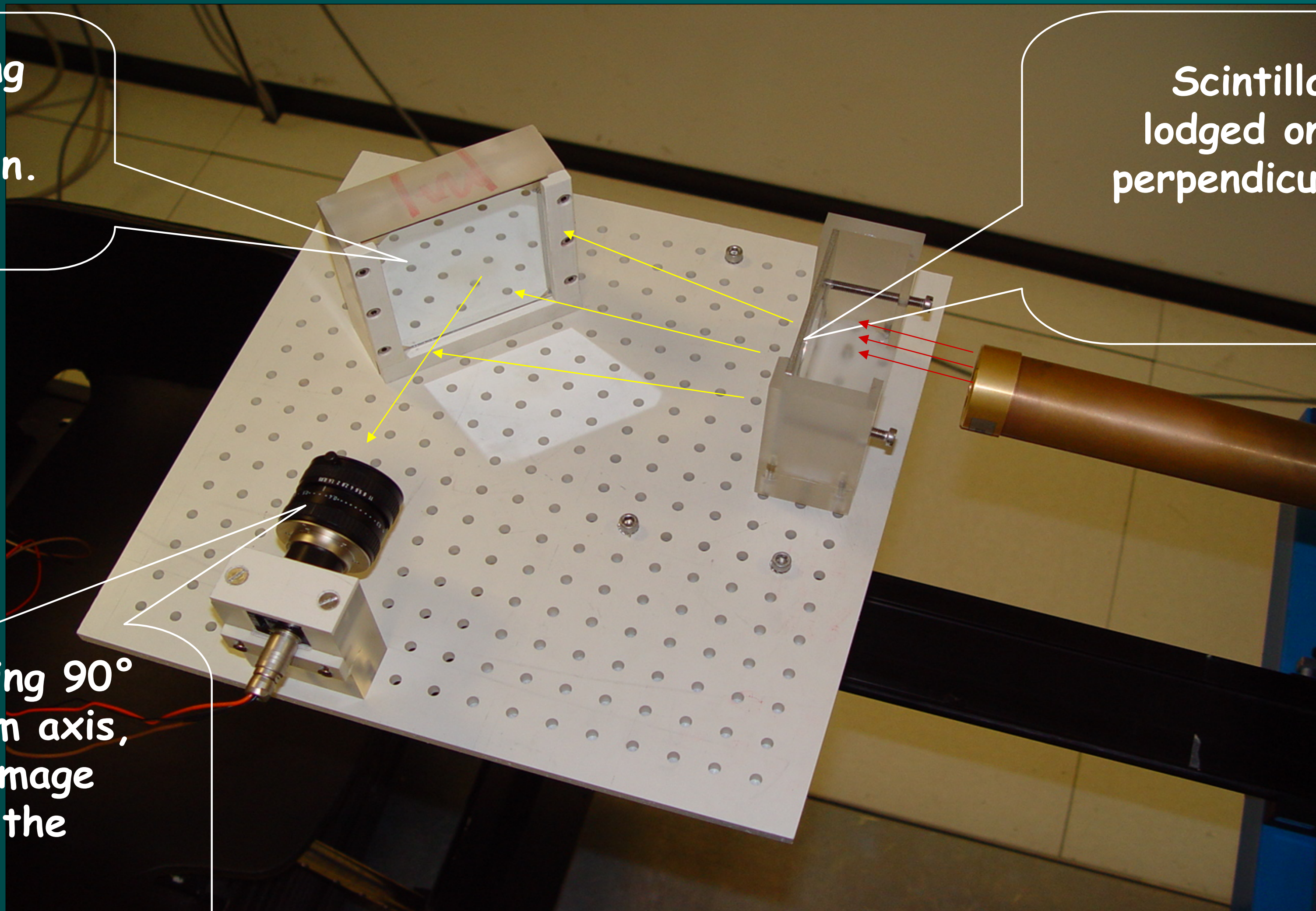
Plastic scintillator
BC 400

- **Alumina:** poor in light efficiency;
- **Caesium Iodide:** excellent light efficiency, but scarce homogeneity;
- **BC 400:** good brightness and homogeneity;

BC 400 has been chosen for our experimental purposes.

DETECTOR ARRANGEMENT

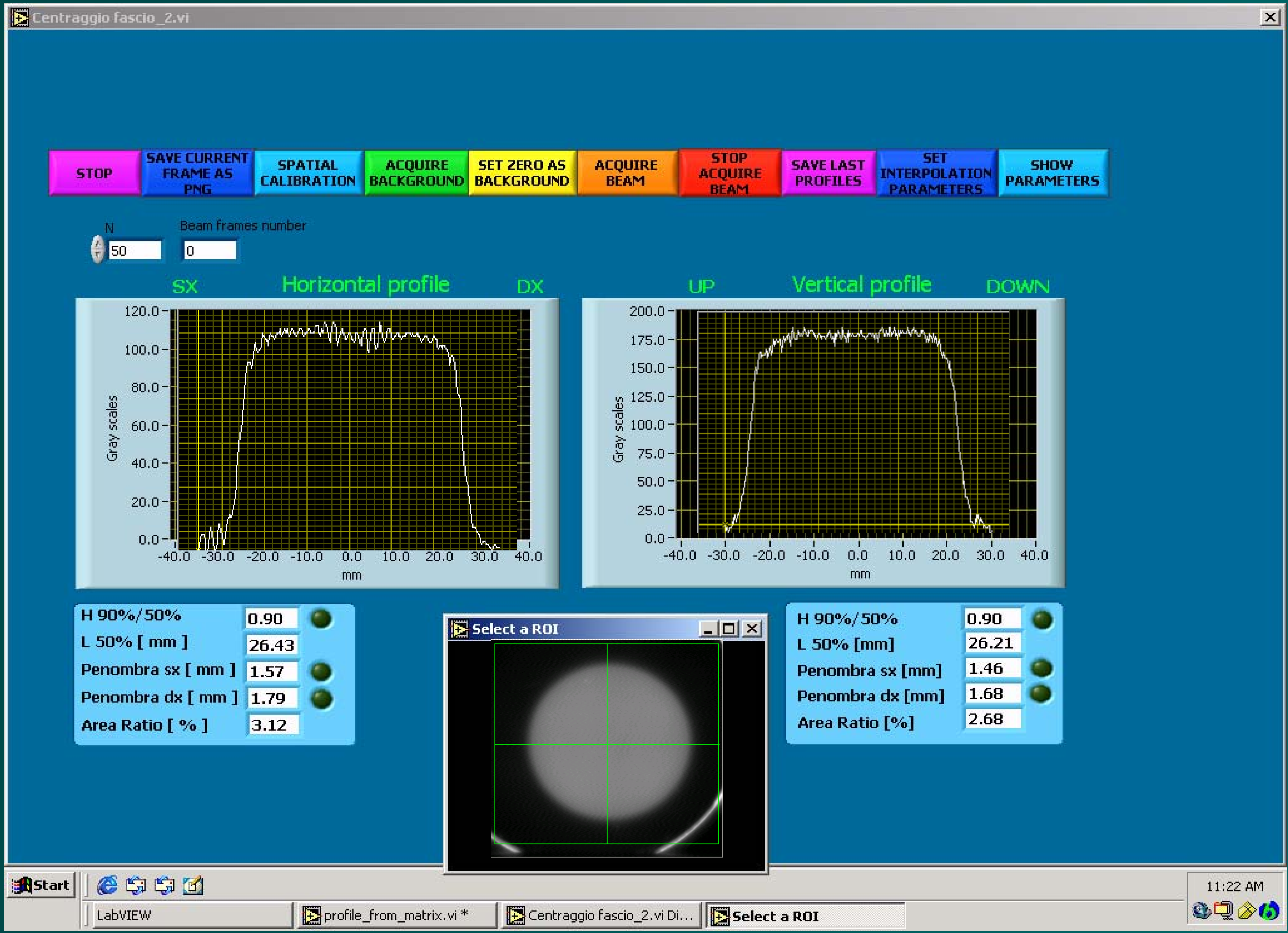
Mirror forming 45° with the beam direction.



Scintillating screen lodged on a support, perpendicularly to the beam axis.

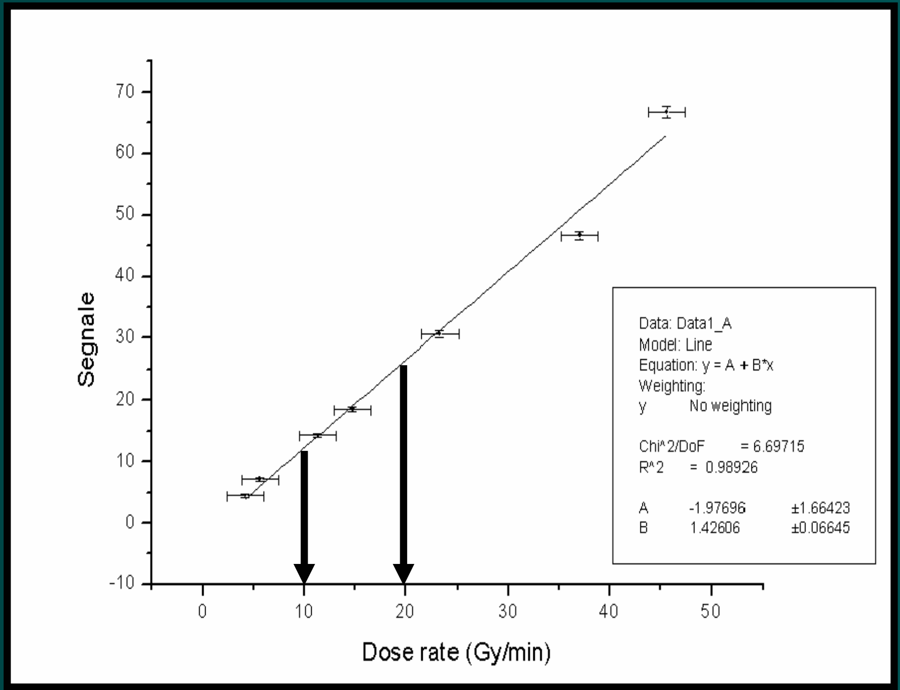
Camera forming 90° with the beam axis, framing the image reflected by the mirror.

LabView Environment



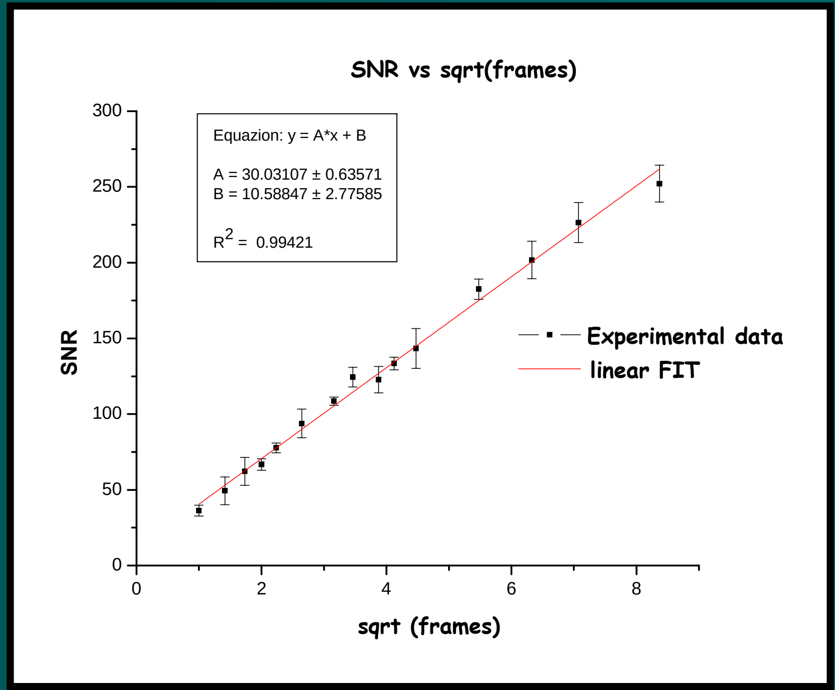
CHARACTERIZATION

LINEARITY



Linearity in the treatment range
(10 ÷ 20 Gy/min)

SIGNAL TO NOISE RATIO



Castleman says: SNR (N)= N^0.5*SNR(1)

Experimental results
are in good agreement
with theoretical
considerations

RELATIVE DOSIMETRY: diamond detectors (synthetic and natural)

PROPRIETA'	DIAMANTE	SILICIO
Gap [eV]	5.5	1.12
Campo di rottura [V/cm]	10^7	$3{\cdot}10^5$
Hole mobility [cm^2/Vs]	1200	450
Velocità di saturazione [cm/s]	$2.2{\cdot}10^7$	$0.8{\cdot}10^7$
Mobilità elettronica [cm^2/Vs]	1800	1450
Vita media dei portatori minoritari [s]	10^{-9}	$2.5{\cdot}10^{-3}$
Costante dielettrica ε_r	5.7	11.9
Numero atomico effettivo Z_{eff}	6	14
Energia per creare un coppia elettrone-lacuna [eV]	13	3.6
Energia di Wigner [eV]	43	13-20

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Energia di Wigner [eV]	43	13-20

Low dark current

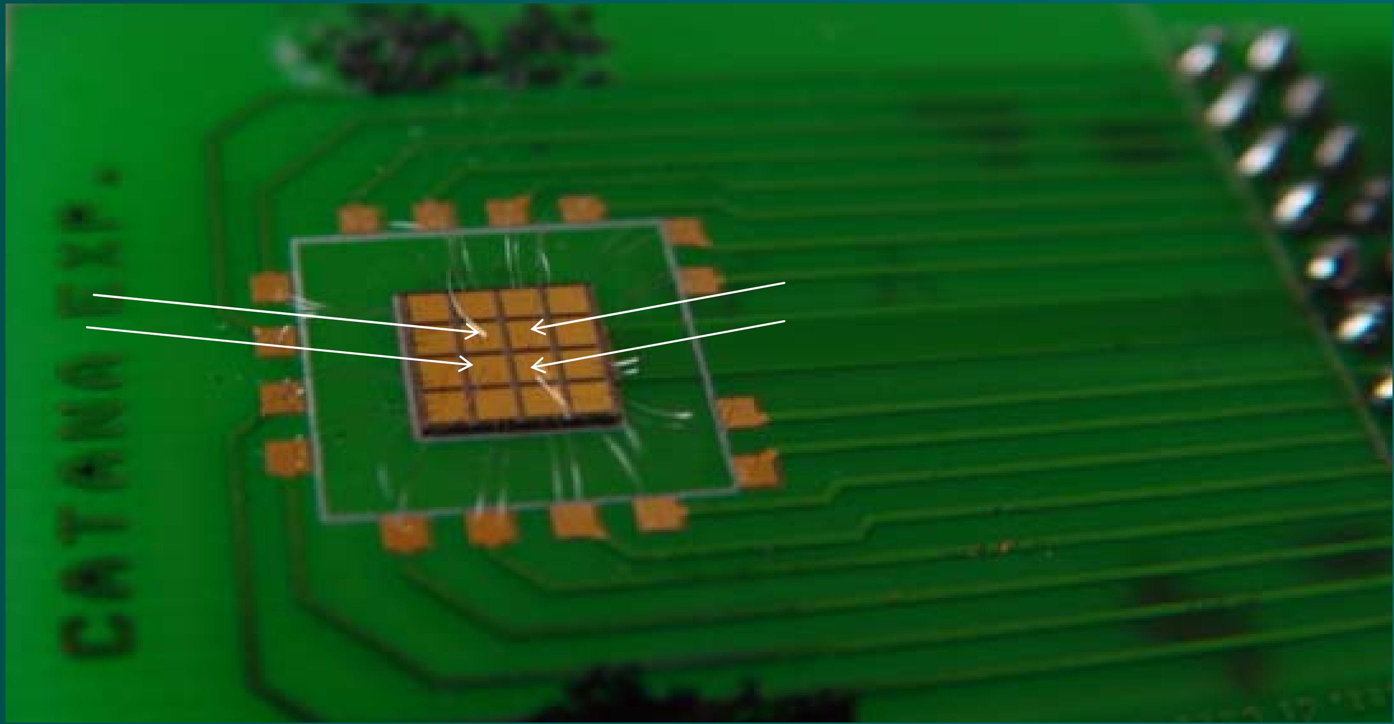
Fast responce time

Tissue equivalence

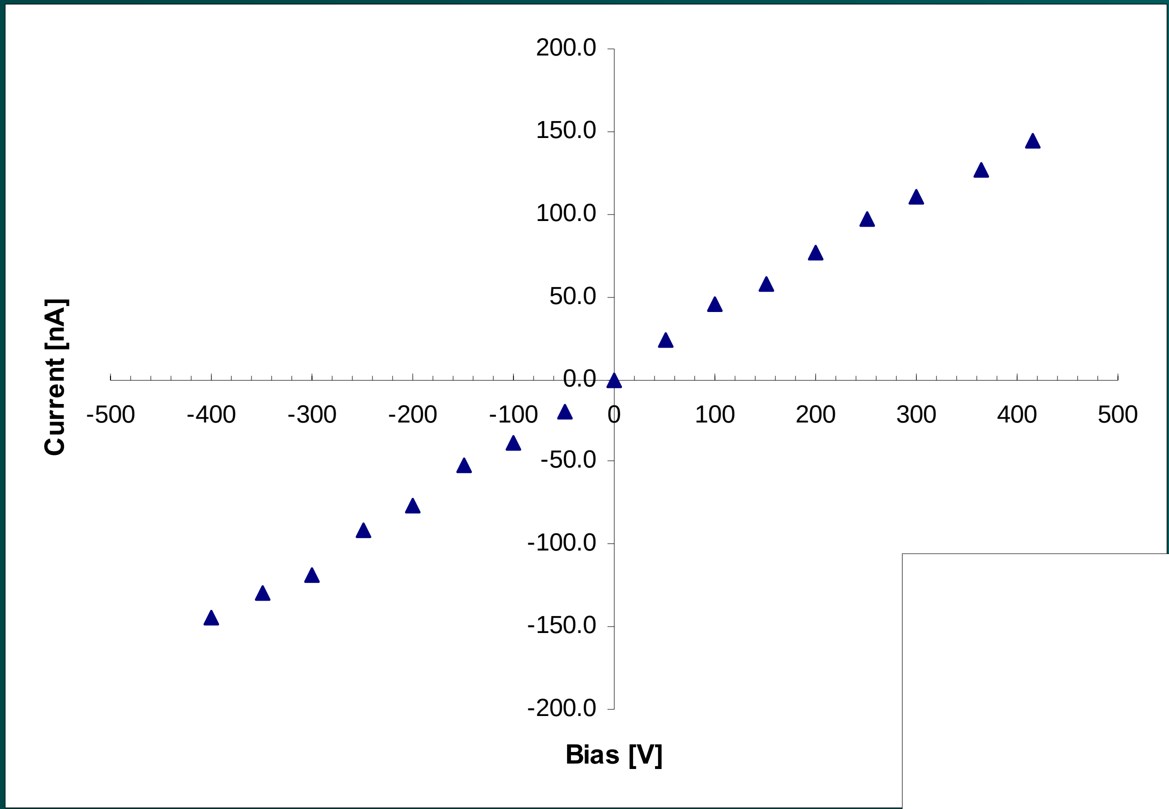
Radiation hardness

ON-LINE CONFIGURATION (CVD diamond)

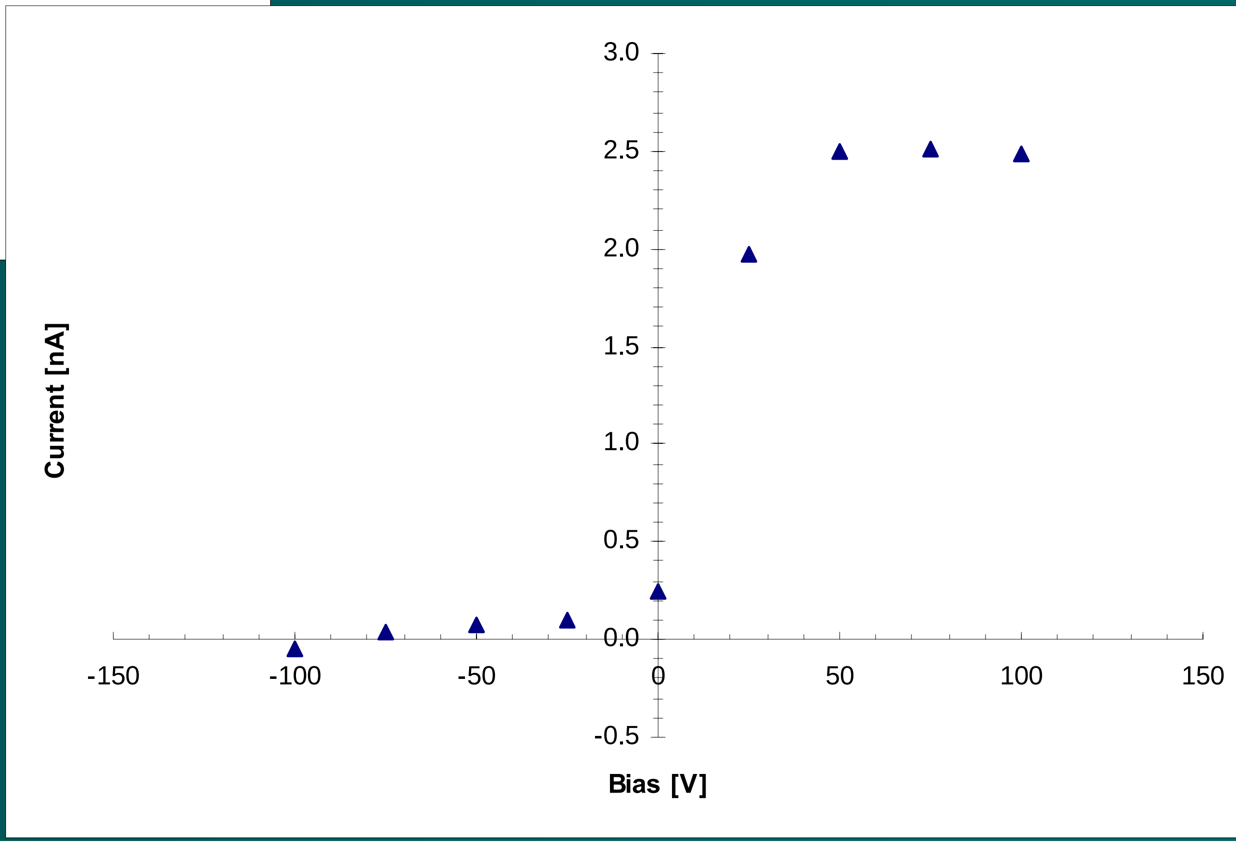
De Beer's diamond sample with two bonding solution



ON LINE CONFIGURATION: CVD vs NATURAL

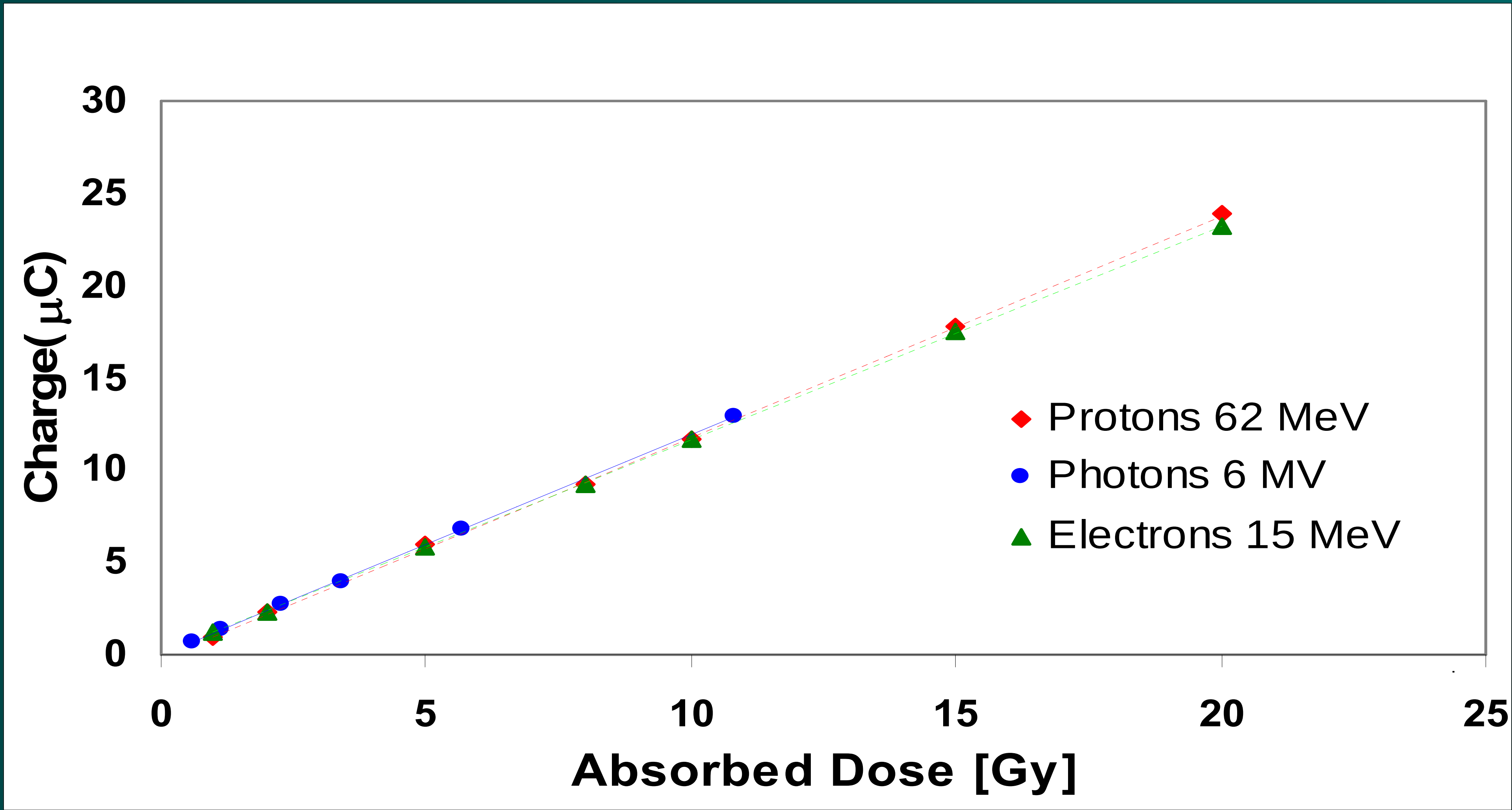


CVD



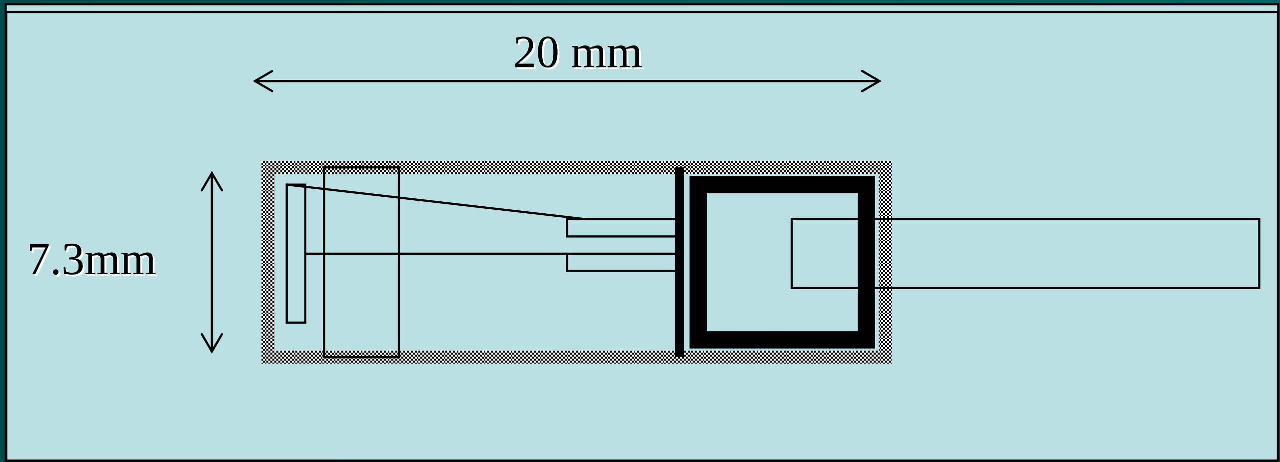
Diamante
Naturale

RESPONCE vs ABSORBED DOSE (CVD diamond)



PTW NATURAL DIAMOND

TWO PTW DIFFERENT DETECTORS HAVE BEEN STUDIED

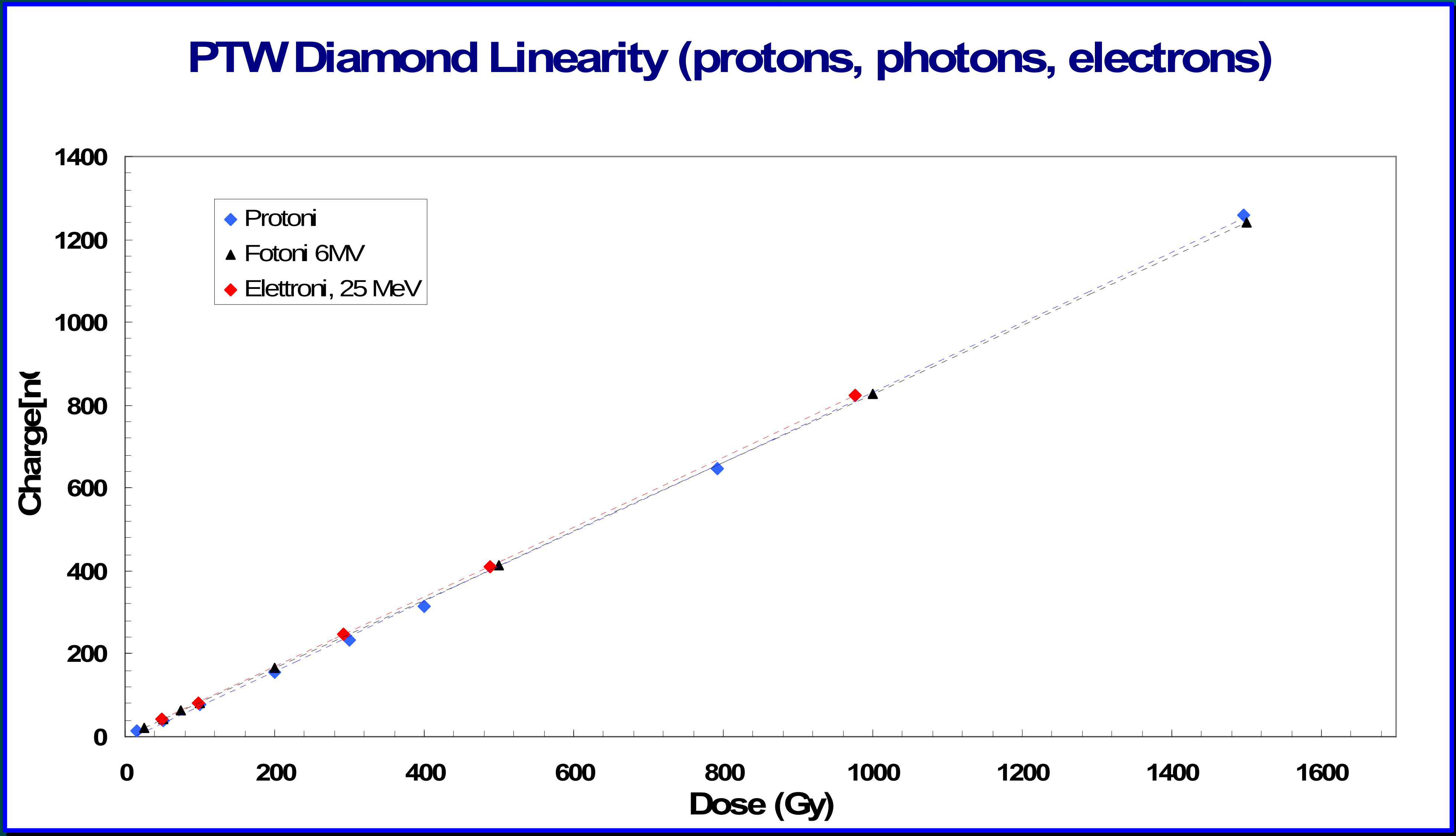


- **Sensitive area:** **4.3/4.5 mm^2**
- **Sensitive volume:** **1.3/1.4 mm^3**
- **Thickness of sensitive volume:** **0.30/0.31 mm**
- **Operating bias:** **100 V**

In photon and electron beams the relative differences have been studied and already published (see De Angelis C et al. Med. Phys. 2002; 29(2): 248-254.)

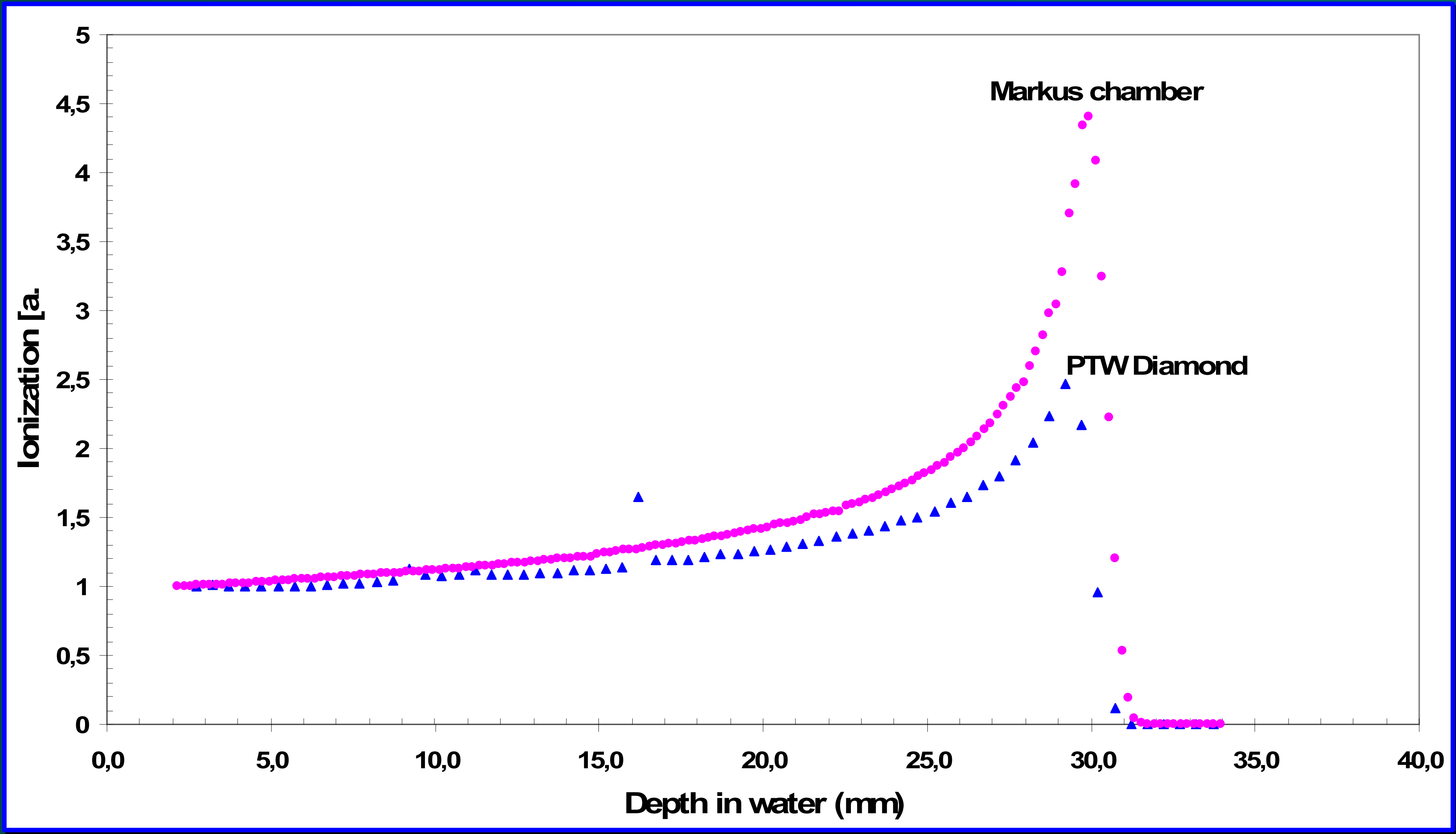
In proton beams the measured repeatability is 0.1%

PTW NATURAL DIAMOND

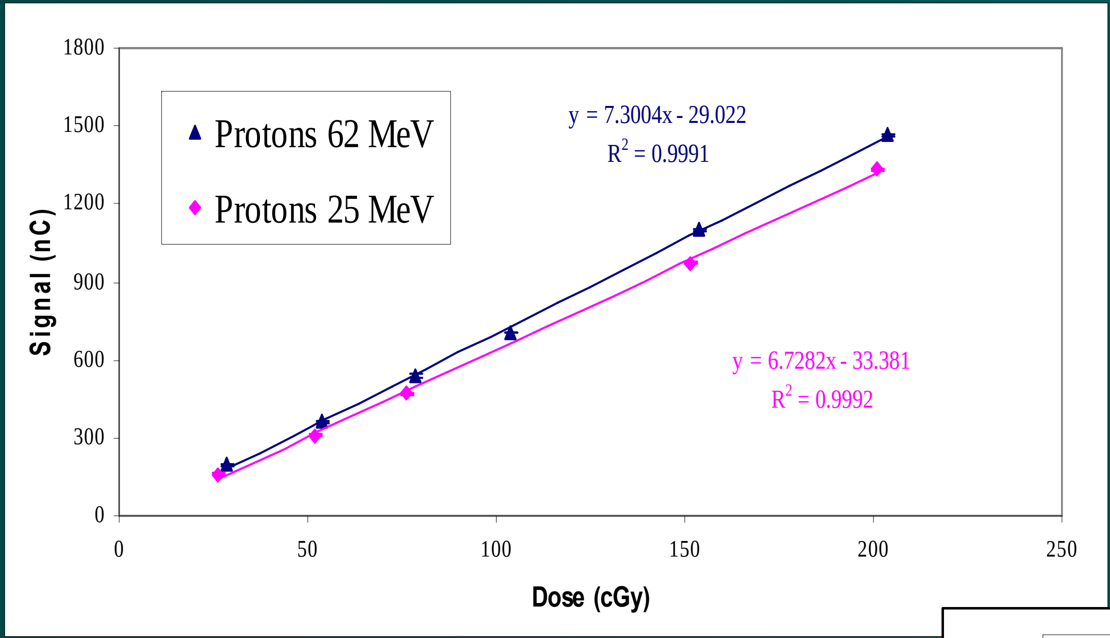


PTW NATURAL DIAMOND

Bragg Peak Measurements

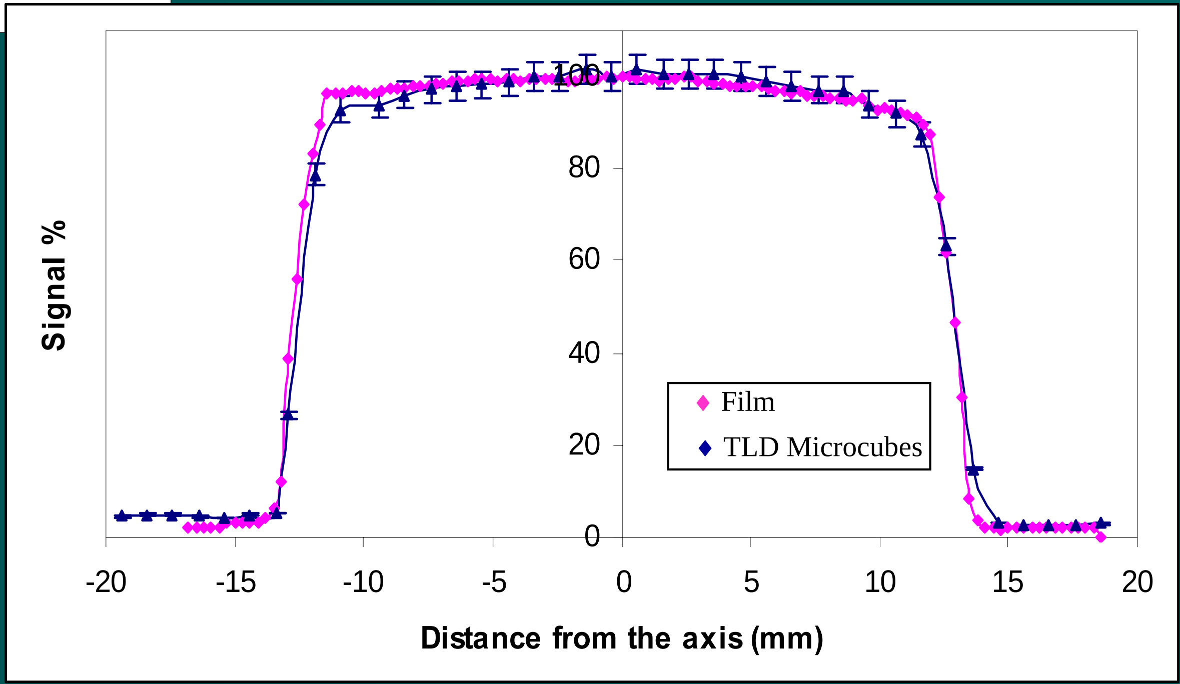


TLD characterization in proton beam



The linear region of the calibration curves covers the same dose range (0.2 ÷ 2 Gy) for all energies tested

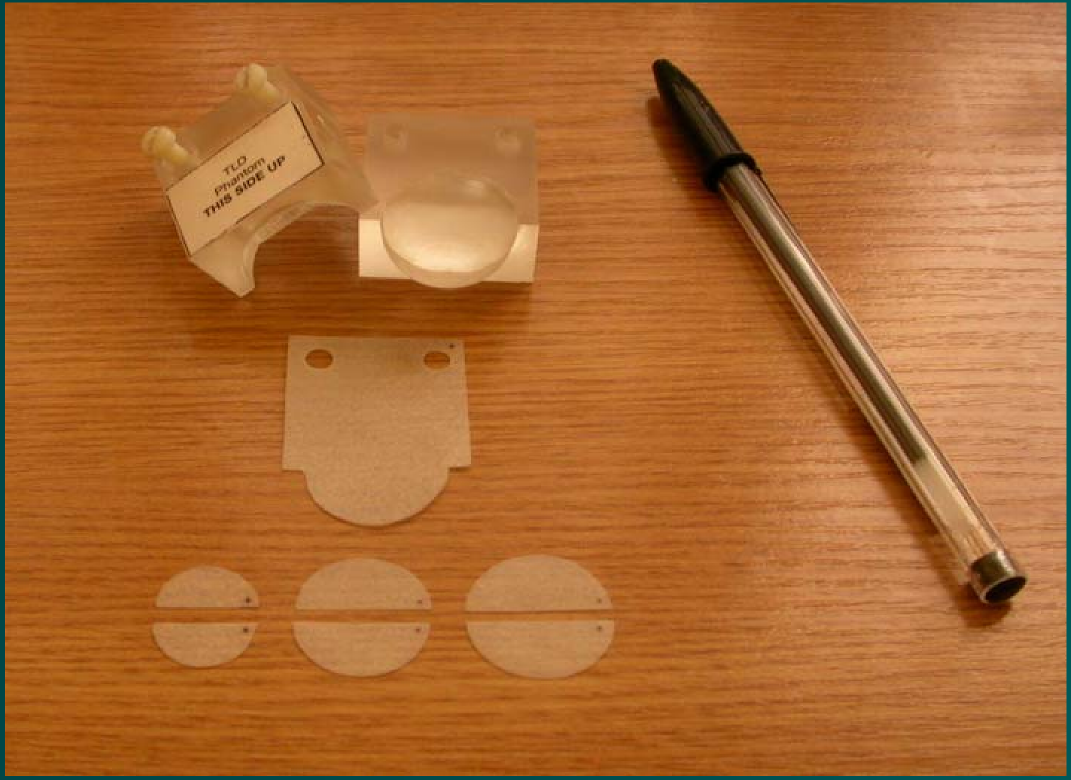
Good agreement for lateral profile between TLD and radiographic film

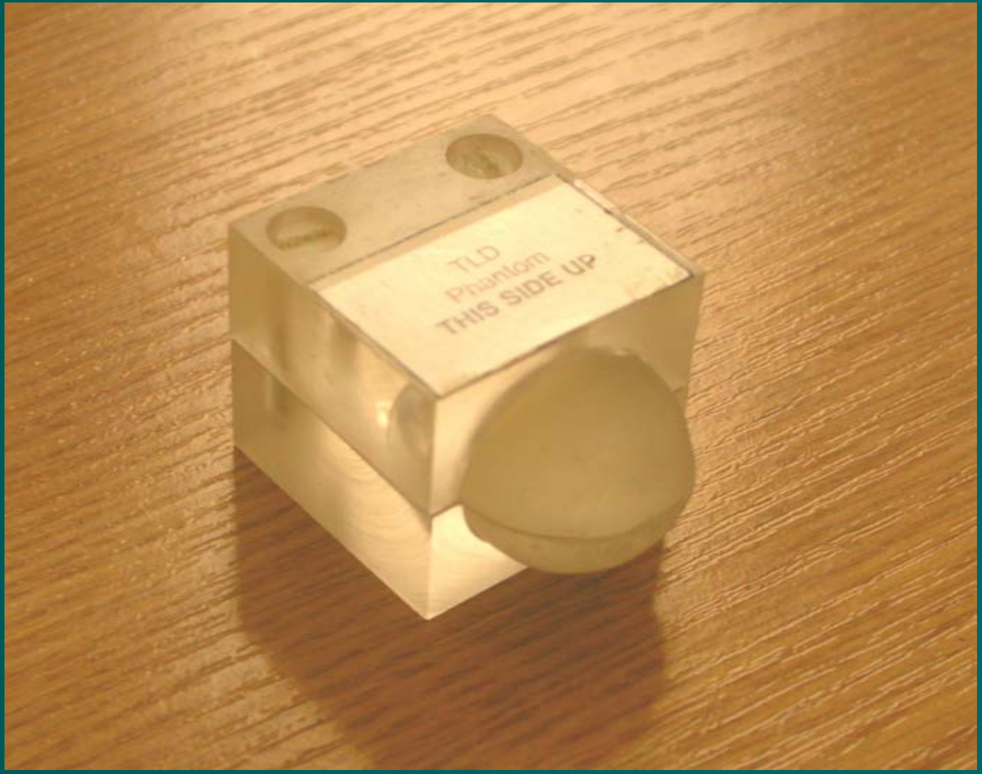


RELATIVE DOSIMETRY: surface TLD detector

PHANTOM & DETECTORS

- 0.27mm mean thickness,
- 7 detectors in each set,
- 10 detector sets.

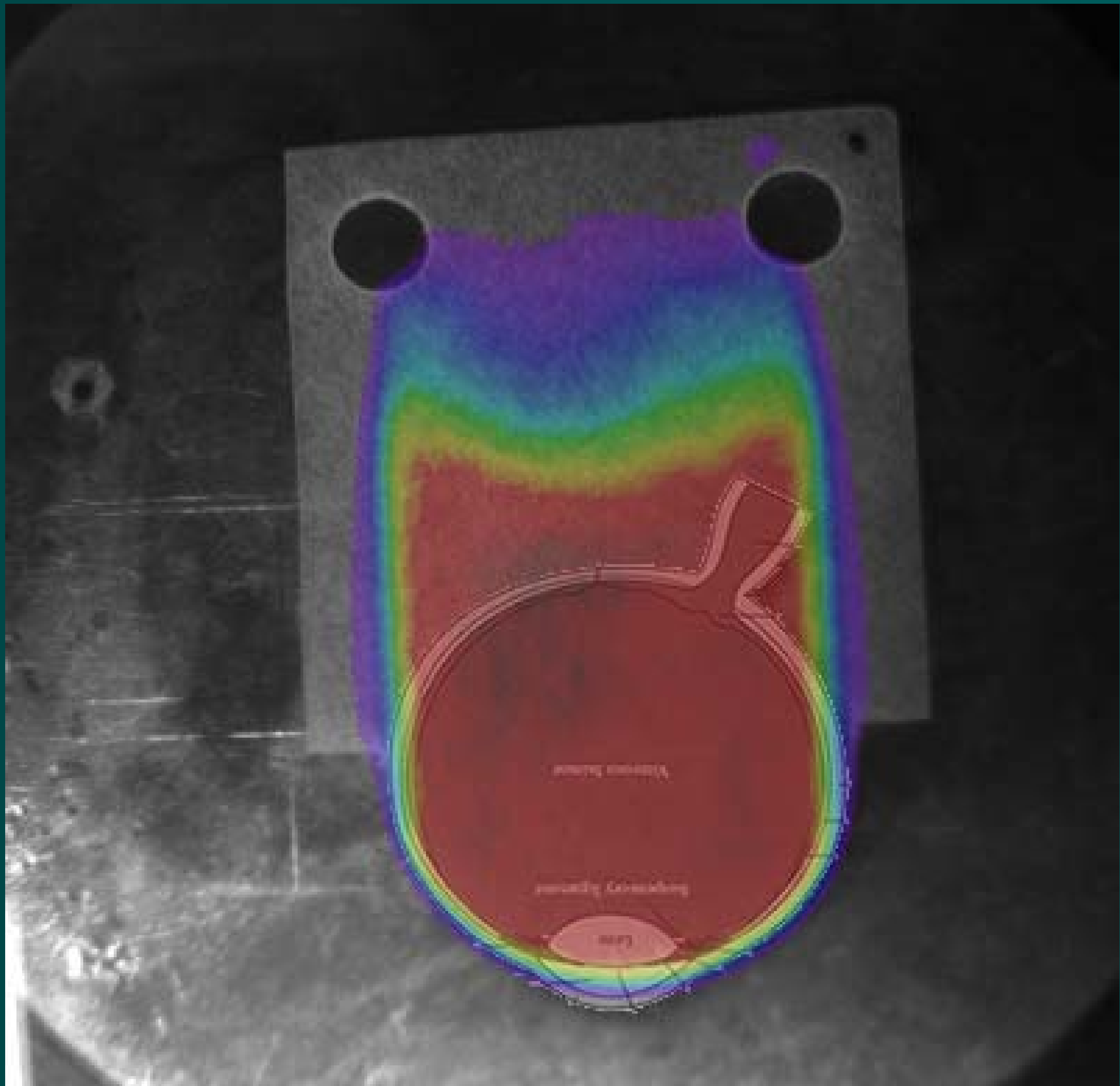




6 sets irradiated!

in dose range 4.5 – 18Gy

READOUTS



READOUTS

(visible photo and heated)

↓

NOISE SUBTRACTION

↓

HOT PIXELS & ZERO BACKGROUND SETTINGS

↓

THICKNESS CORRECTIONING FACTORS (RELATIVE TO CALIBRATION DETECTORS)

↓

CALIBRATION

(Co60 SOURCE UP TO 20Gy)

SILICON DIODE

SCANDITRONIX Silicon Diode

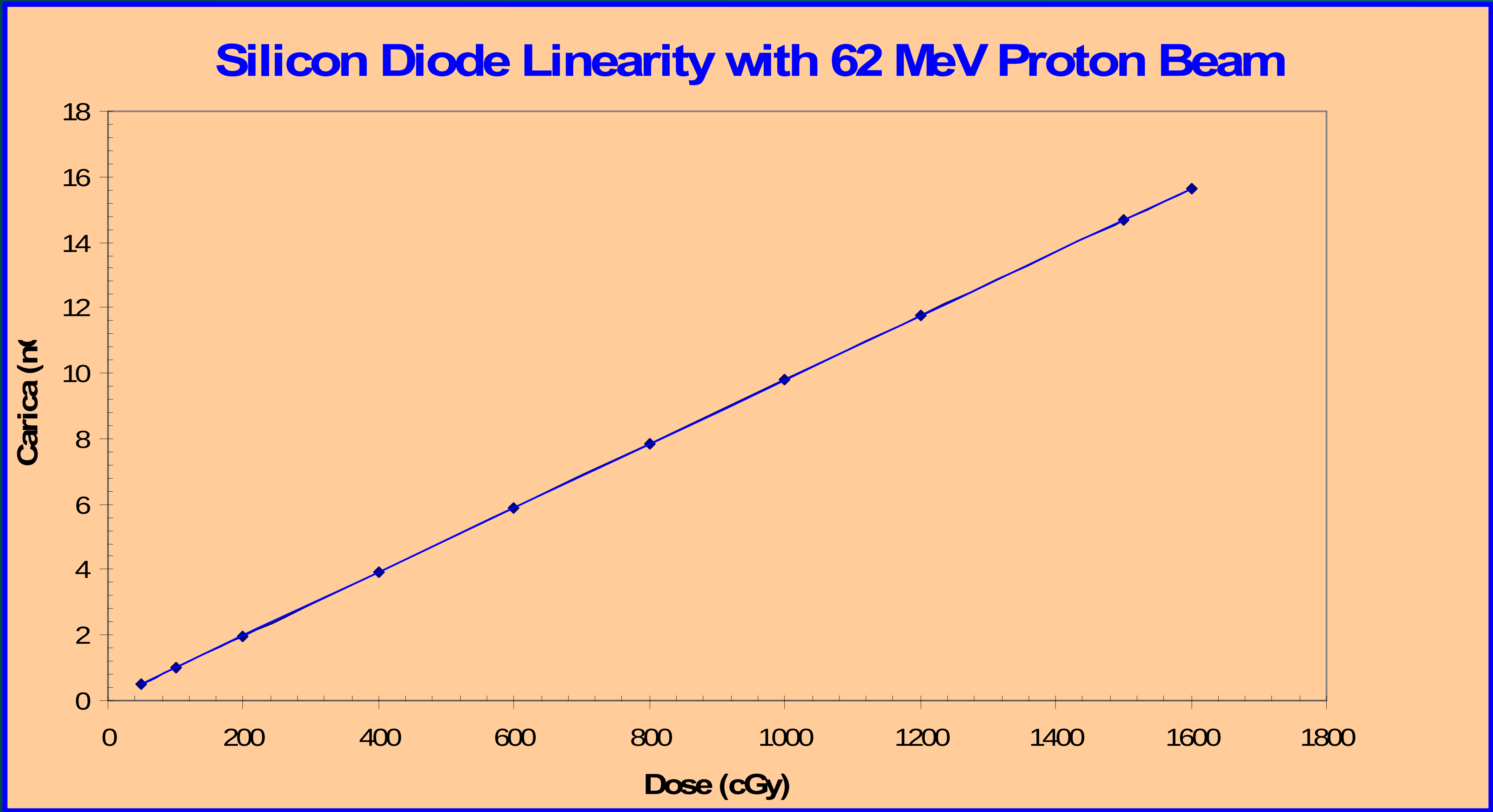
Two different p-type Scanditronix detectors having the following features have been studied:

- Thickness: 0.06 mm
- Sensitive Area: 0.28 mm^2
- Sensitive Volume: 0.017 mm^3
- Materials tickness in front of the detectors: 0.42/0.54 mm
- Center Distance from Detector Surface: 0.546/0.684

Both samples were preirradiated in proton beams, before shipping.

Measured repeatibility (10 meas. at 4 Gy): 0.2%
Sensitivity change after 300 Gy irradiation 0.7%

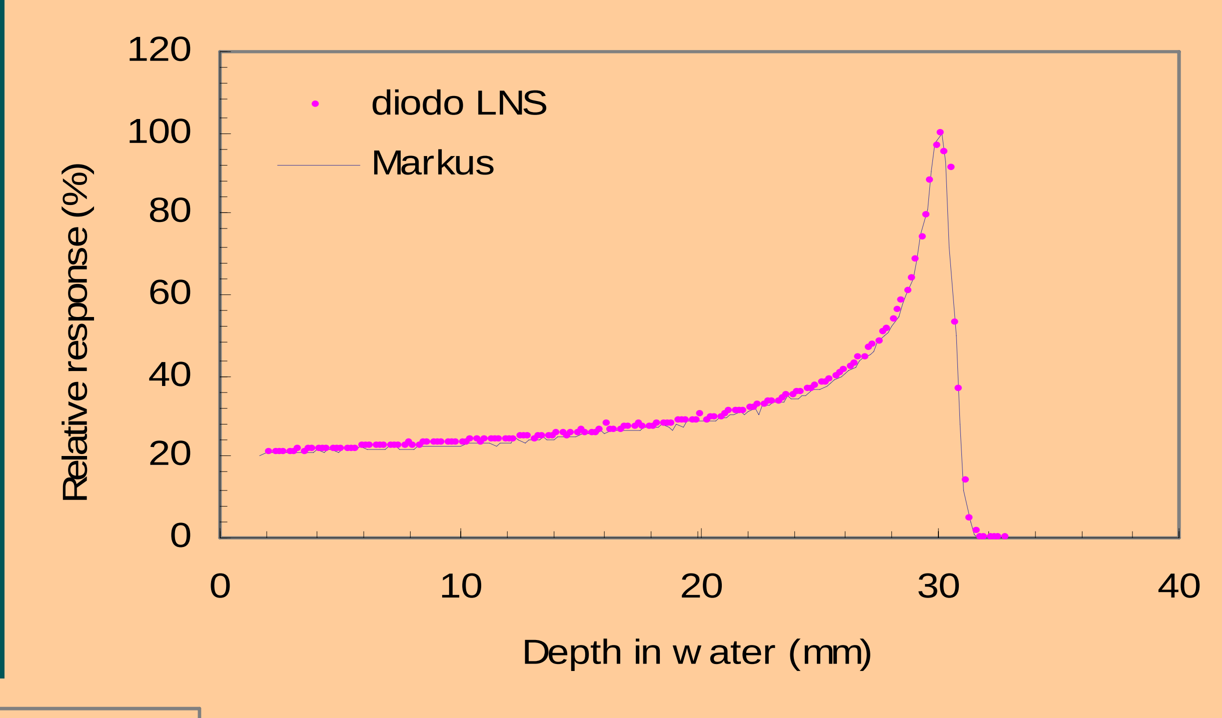
SILICON DIODE

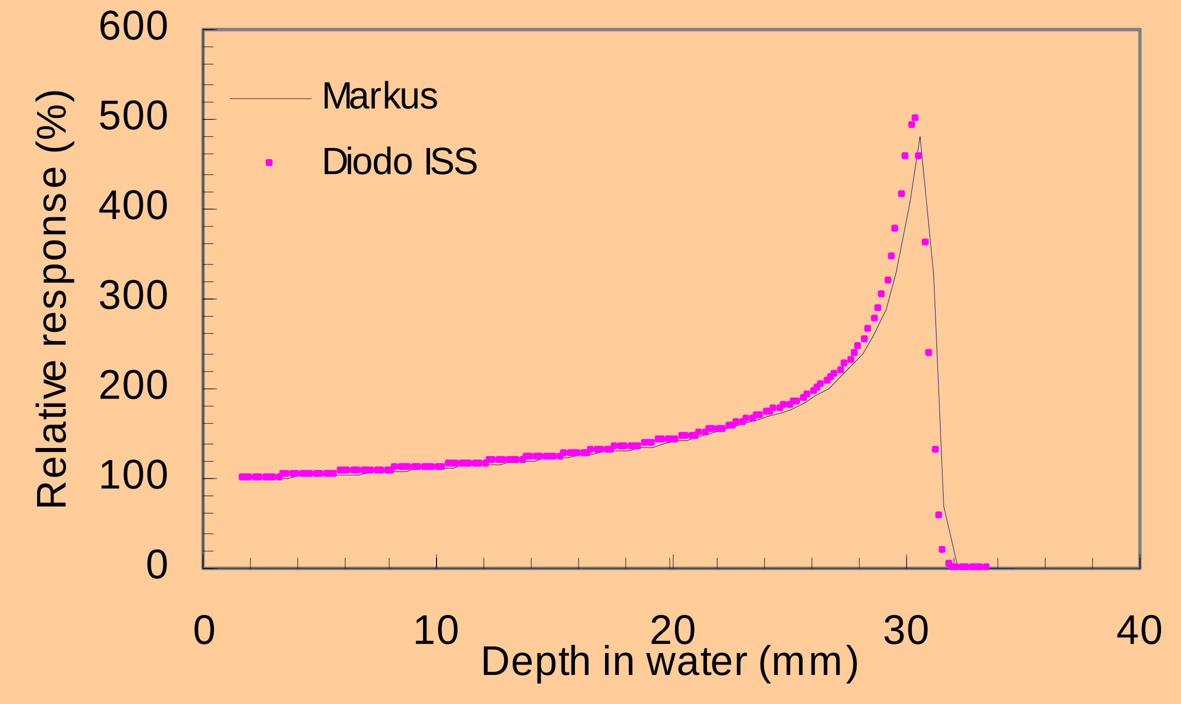


SILICON DIODE: full energy Bragg peak

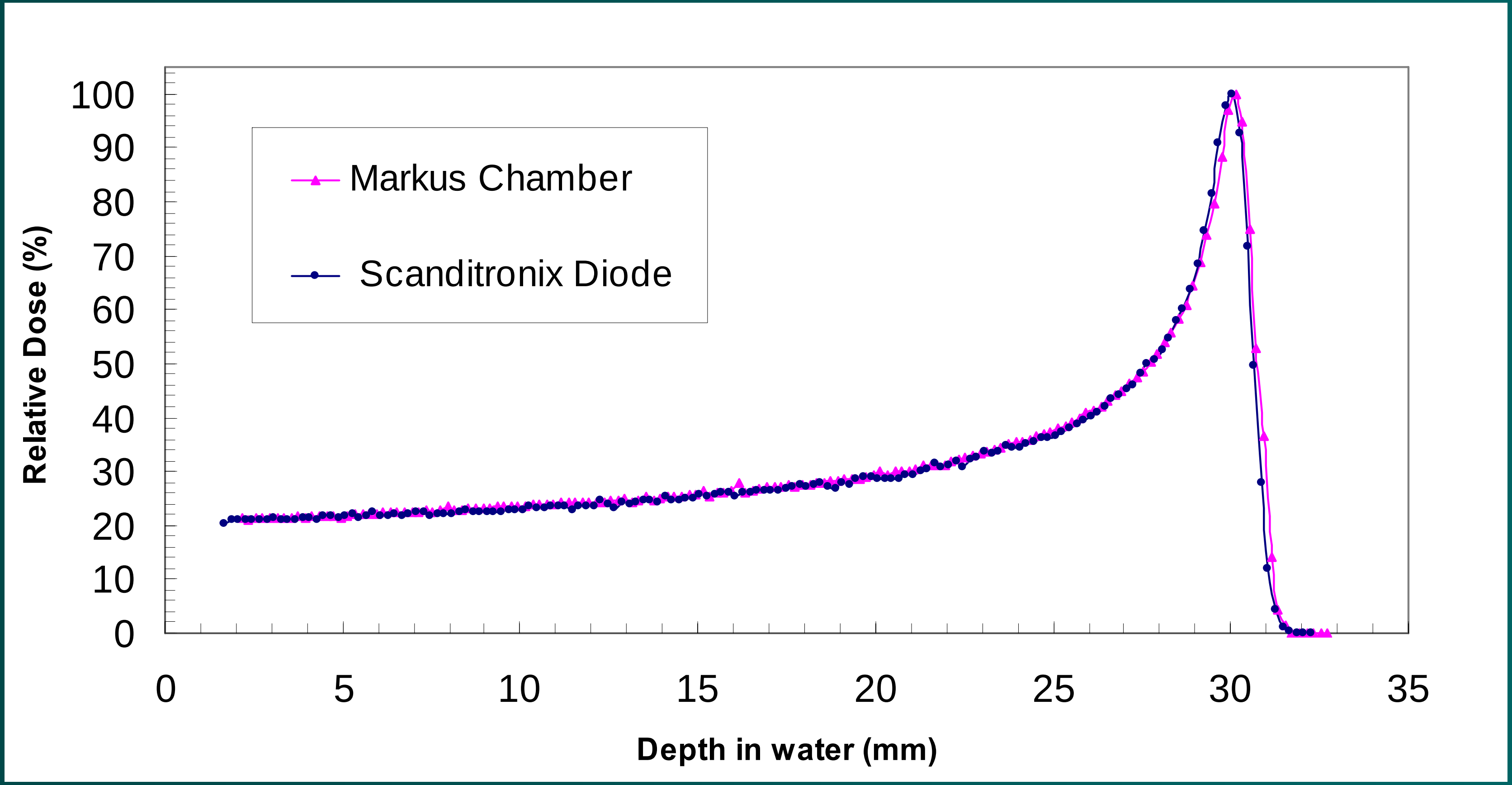
The two detectors give different positions of the peak.

An overestimation of the peak has been noted (up to 6%).





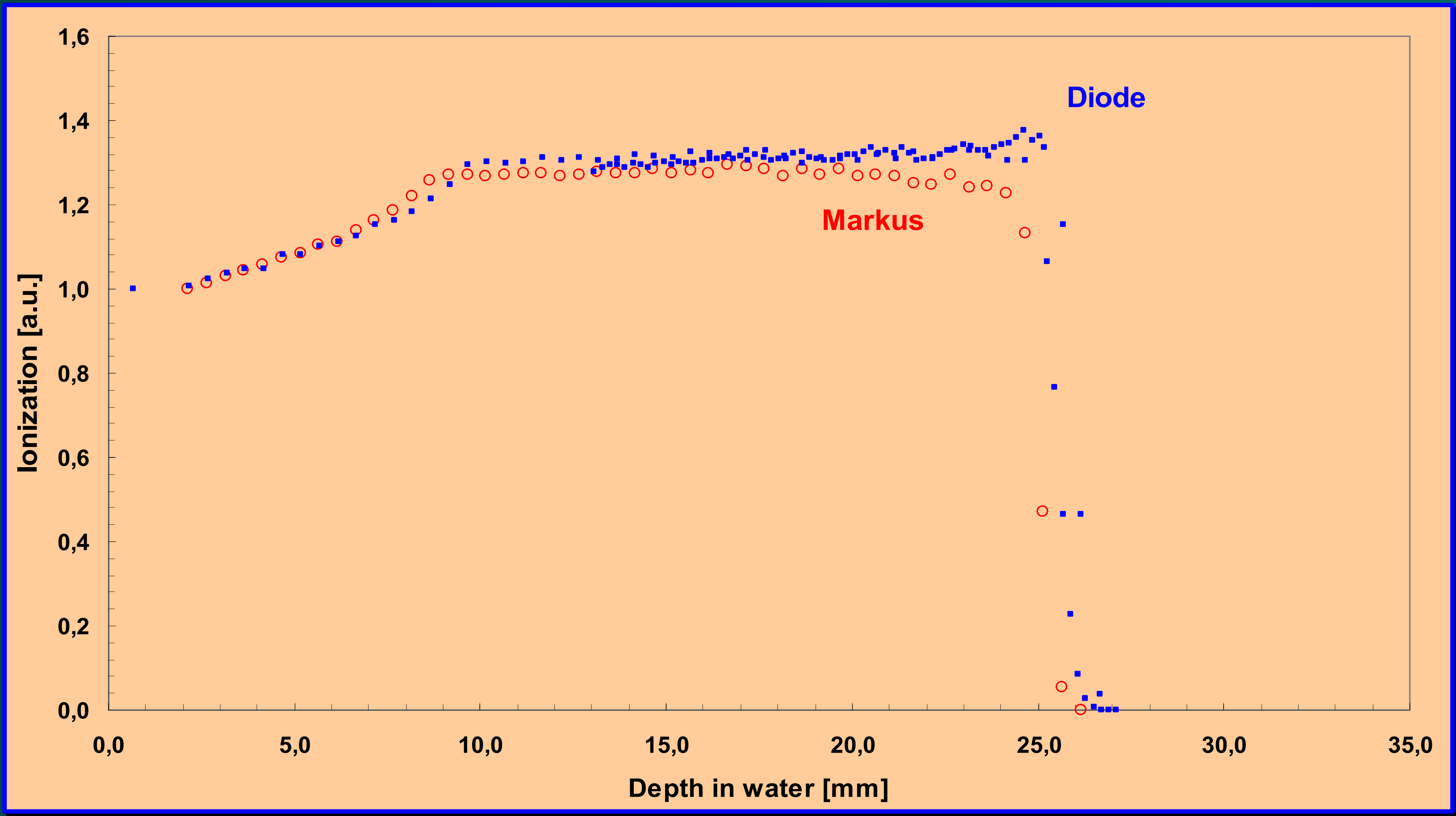
Scanditronix Diode characterization in proton beam



- Detector diameter: 0.6 mm (t = 60 μm)
- Detector Material: Hi-pSi, high doped p-type silicon

(*preirradiated* for use in proton beams)

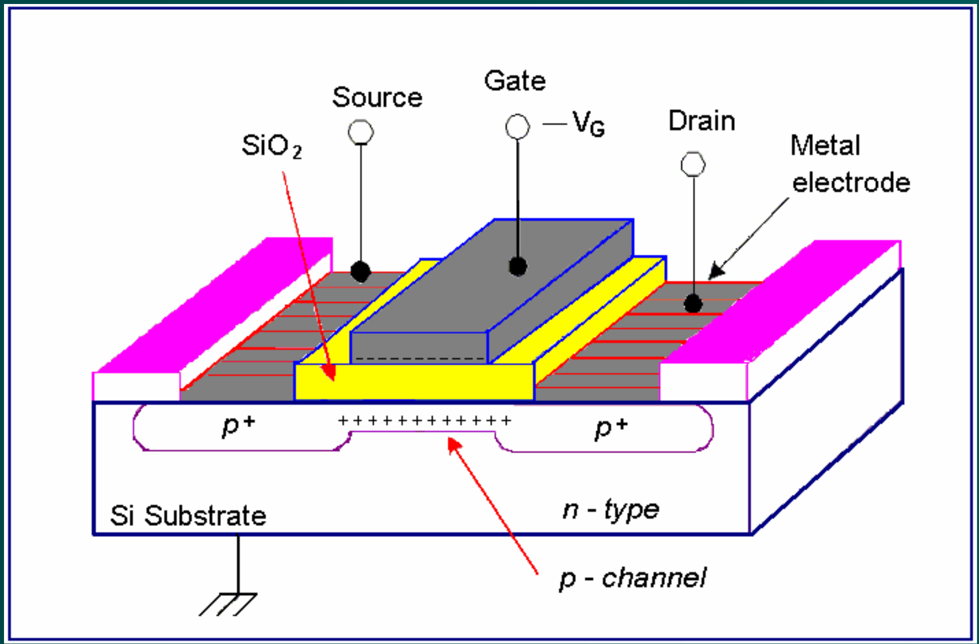
SILICON DIODE: Spread Out Bragg Peak

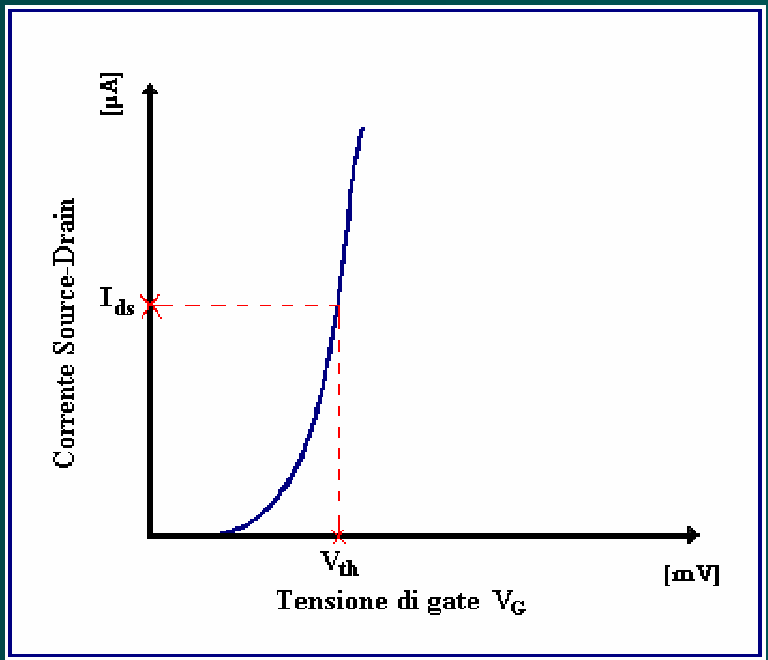


RELATIVE DOSIMETRY: silicon diode and MOSFET

MOSFET e MicroMOSFET

MOSFET (Metal Oxide Semiconductor Field Effect Transistor)





Why a MOSFET:

- stable, reproducible
- linear vs absorbed dose
- dose-rate independence
- on-line reading
- temperature indipendence
- no fluence perturbation
- small size

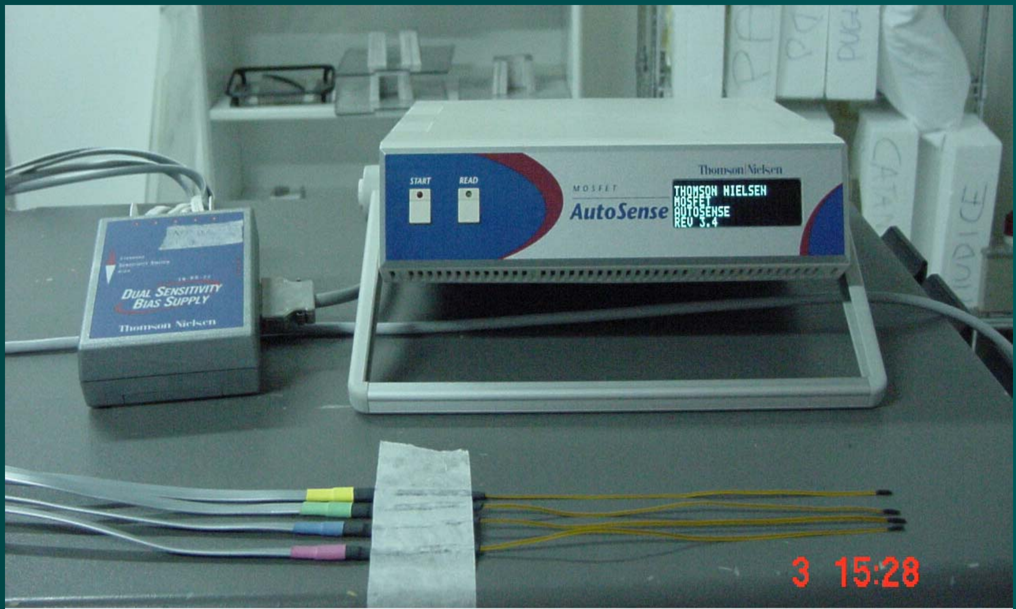
It is OK for *in-vivo* dosimetry

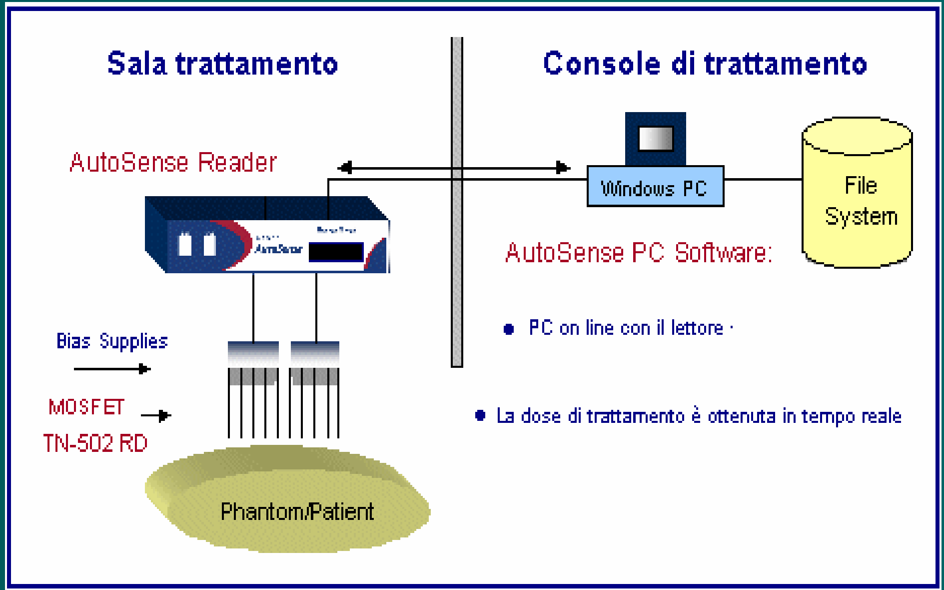
INSTRMENTATION

- Autosense™ reader
- *"Dual Sensitivity Bias Supply"* (up to 5 MOSFETs)

2 sensibility modality: *High e Standard*

- MOSFET TN-502RD

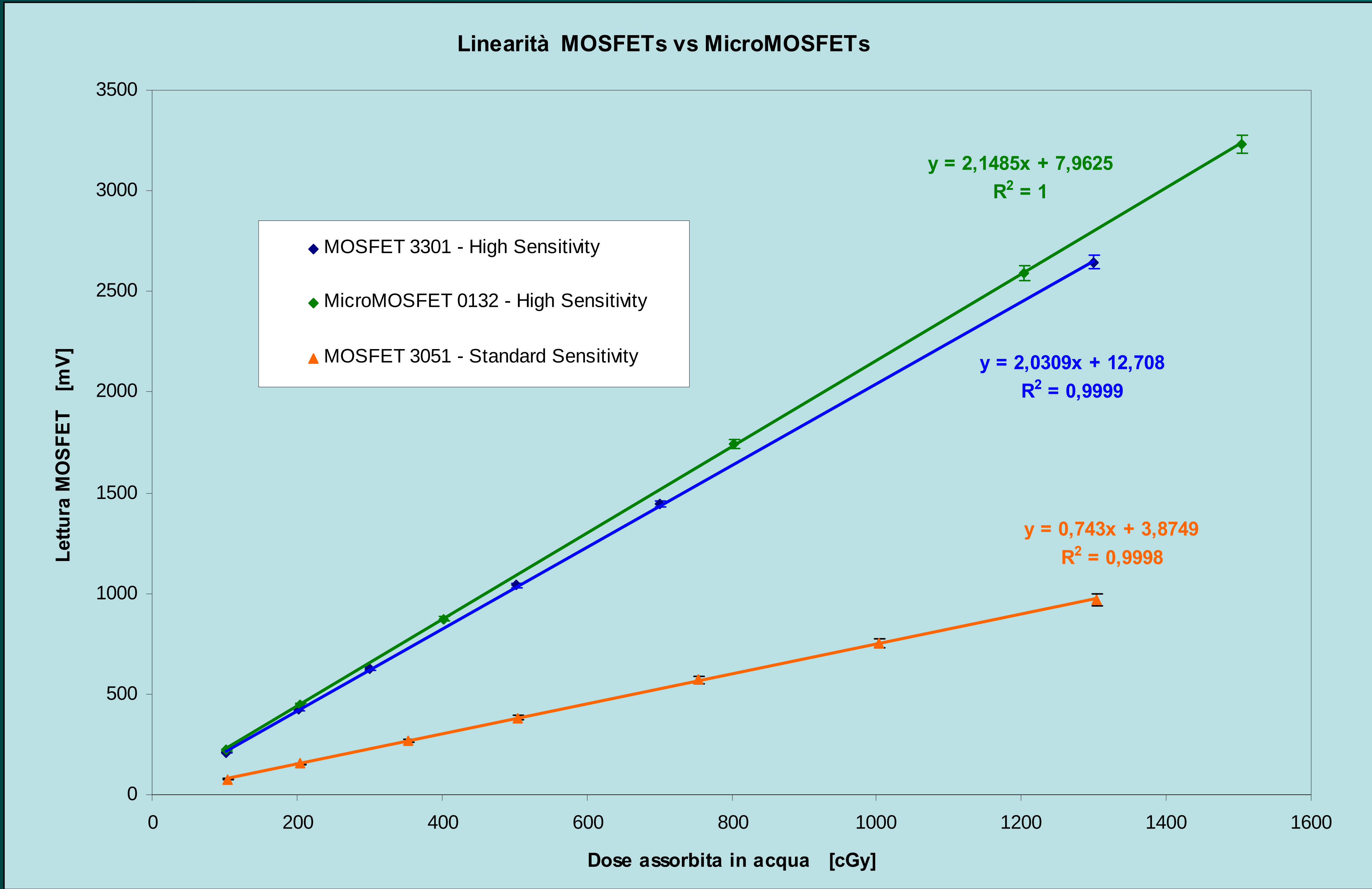




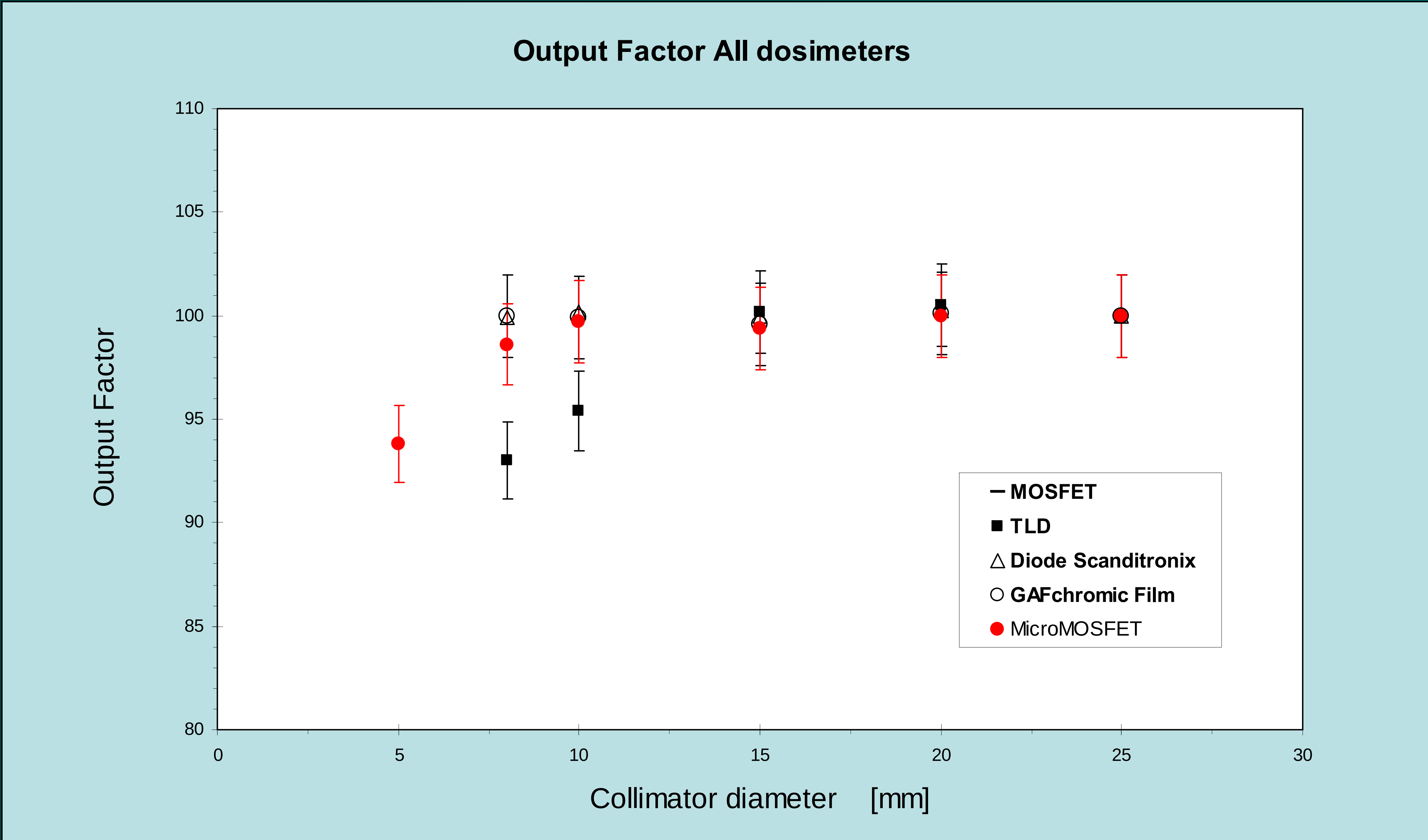
Thomson Nielsen

AutoSense™ PCSoftware V. 1.1

RESPONCE vs ABSORBED DOSE

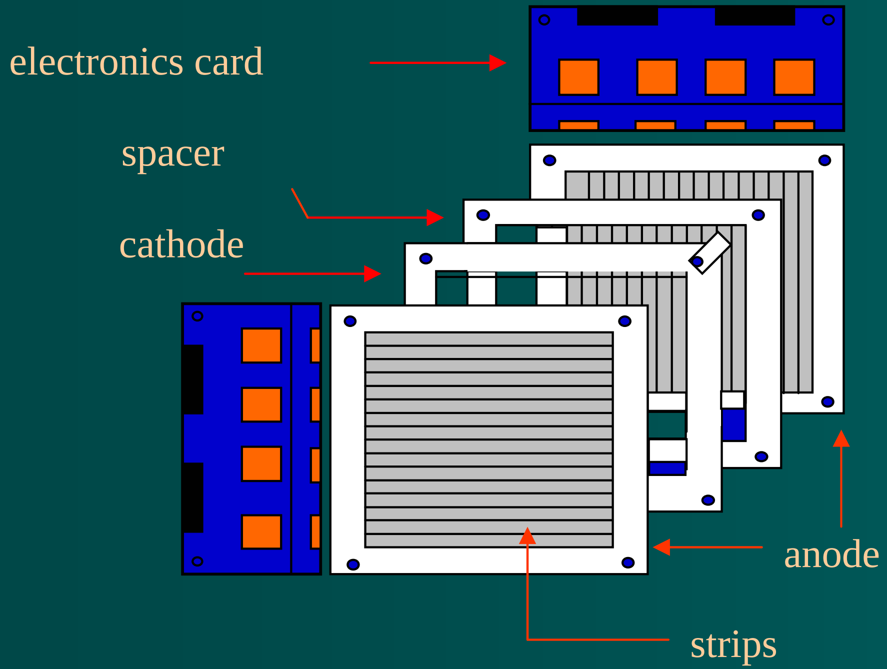


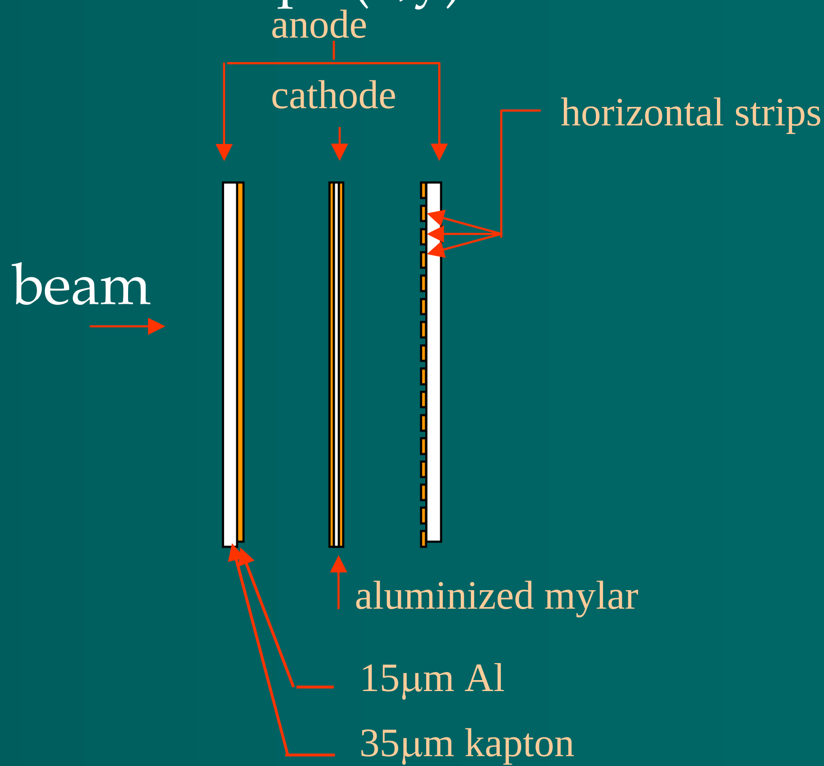
A STUDY OF THE OUTPUT FACTORS



THE MOPI ONLINE MONITOR

2 ionization chambers with anode segmented in strips (x,y)



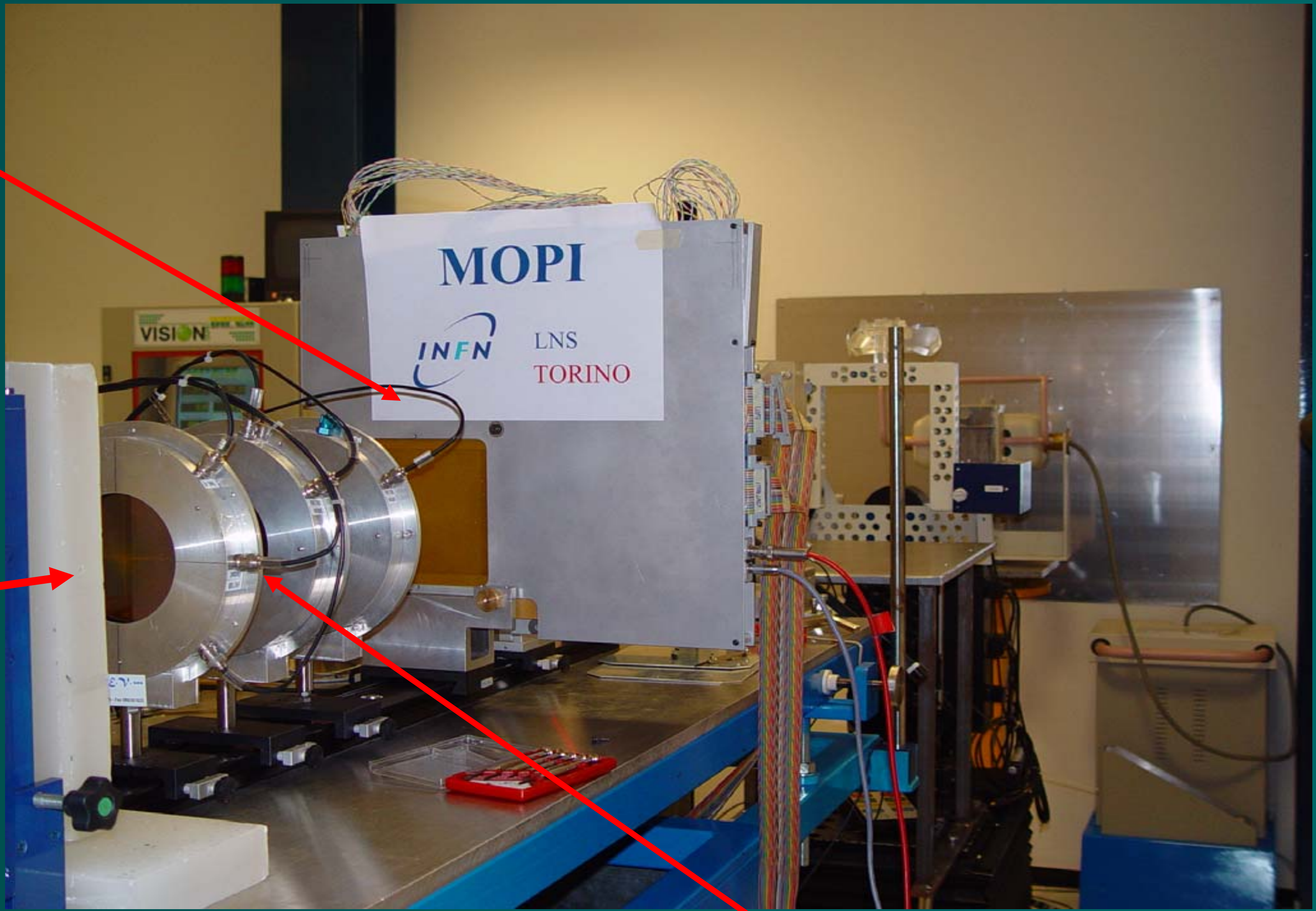


Sensitive area	12.8X12.8 cm^2
Total thickness	~ 200 μm H_2O equiv.
Number of strips/chamber	256
Strip width	400 μm
Pitch	500 μm
Readout rate	up to 4 kHz (1 Hz)

THE MOPI ONLINE MONITOR:TEST SET-UP

x-y ion. strip chambers
MOPI

p beam

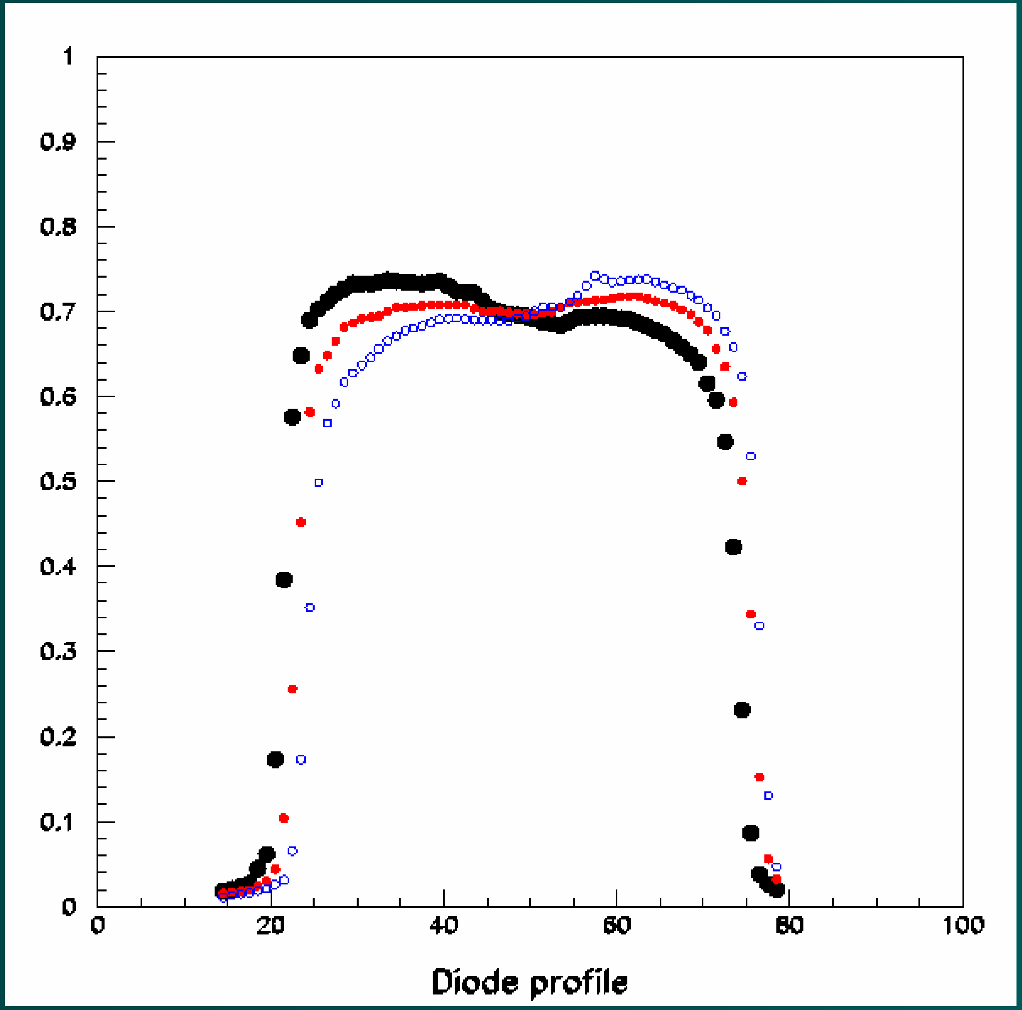


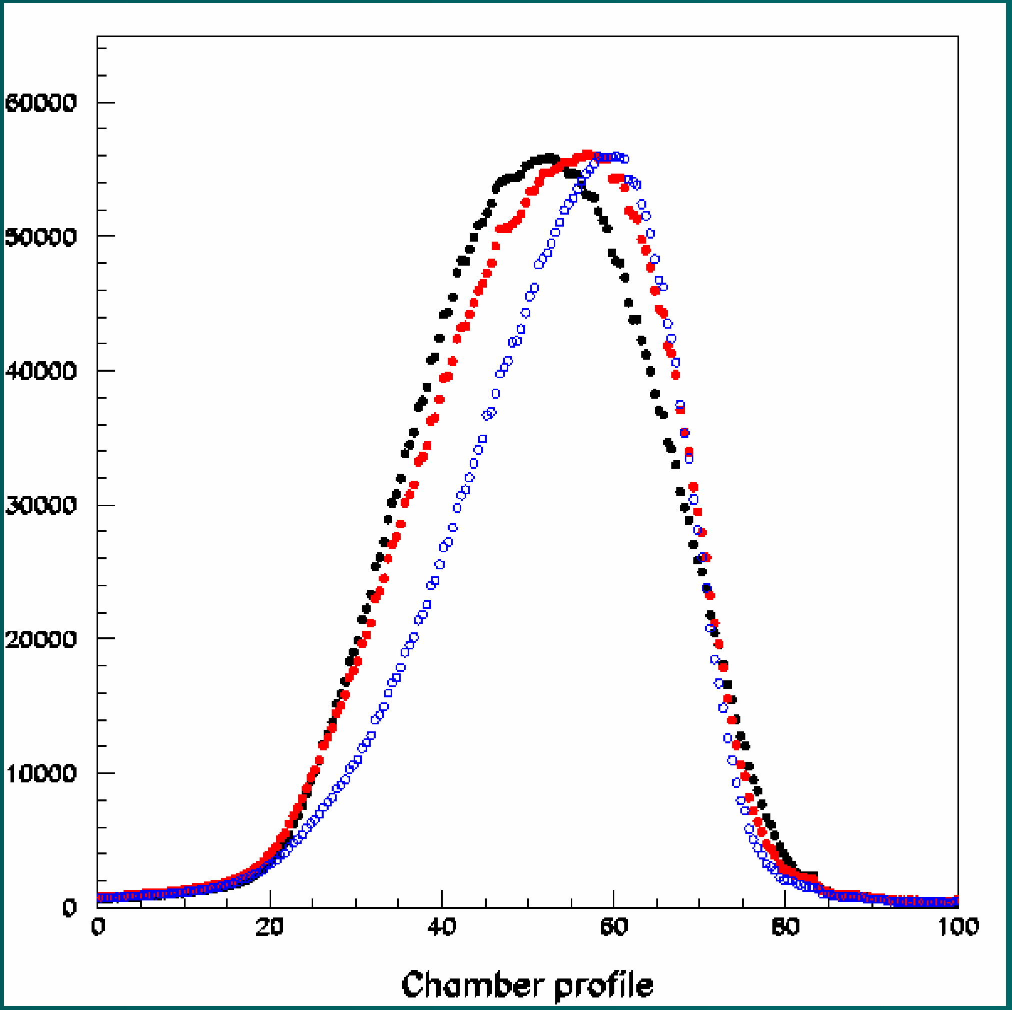
ionization chambers

THE MOPI ONLINE MONITOR

Three different currents of the beam steering magnet

a.u.





What is the future?

- **Proton computed tomography (PCT)**
- **MEDIPIX**
- **On line PET (DOPET)**
- **…….**

WHY proton Computed Tomography (pCT) ?

TOMOGRAPHIC IMAGE RECONSTRUCTION USING HIGH ENERGY PROTON BEAMS

MAIN IUSSUES IN PROTON THERAPY QUALITY

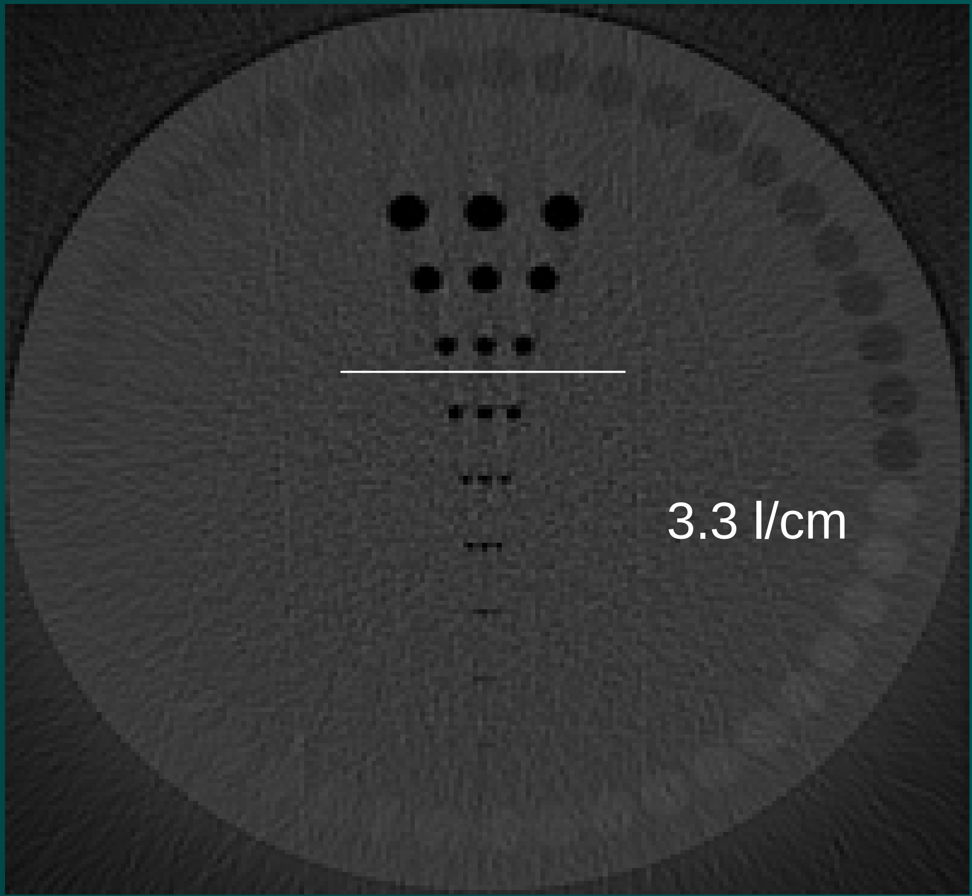
- Patient positioning
- Dose planning

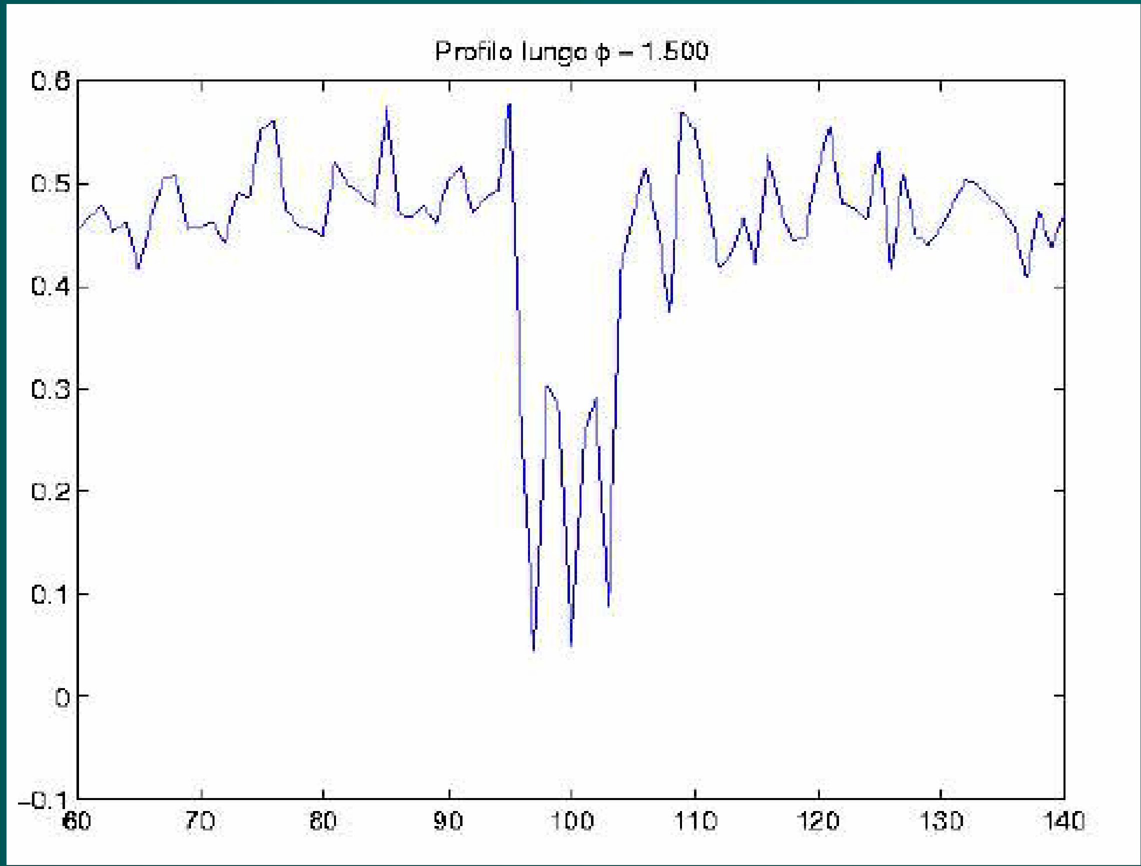
Actually TPS are based on the xCT images as input and this bring a sensible amount of imprecision

THE ROLE OF MONTE CARLO

- Study of the proton paths inside objects
- Study of the algorithms for image reconstructions

GEANT4 tomographic image

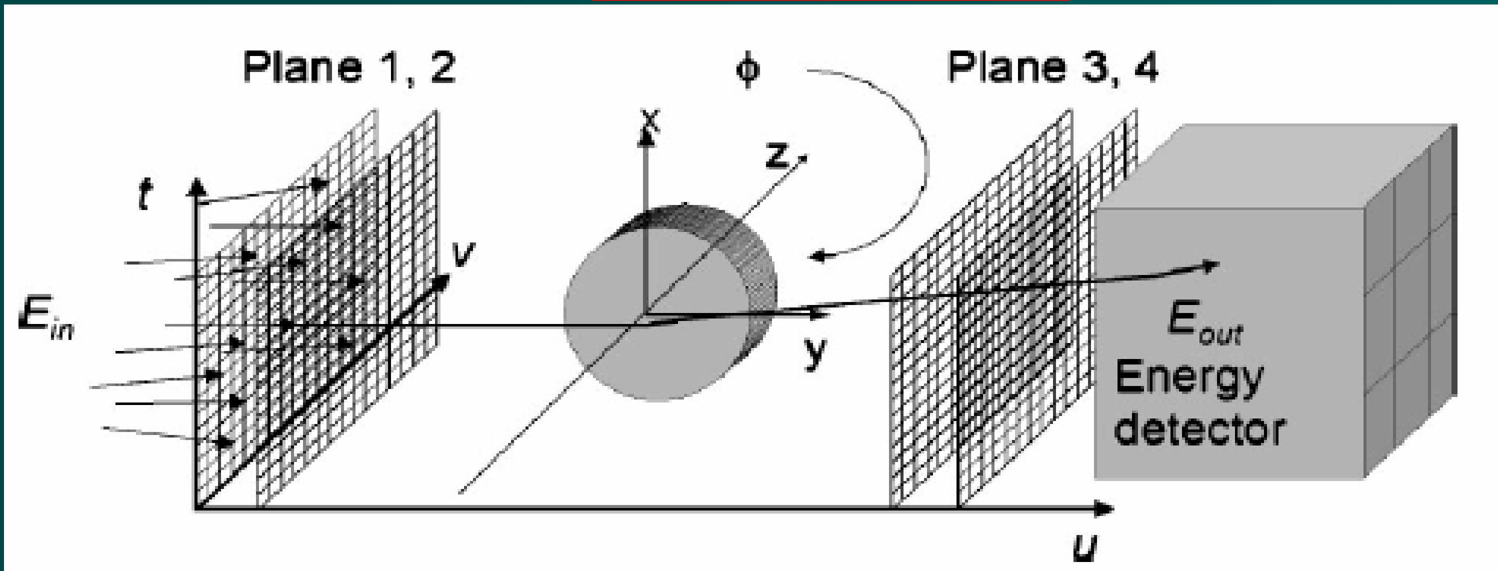




200 MeV, 179 projections at 1°, 5M Histories, 20 cm circular phantom

EXPERIMENTAL SOLUTION FOR SINGLE TRAKING

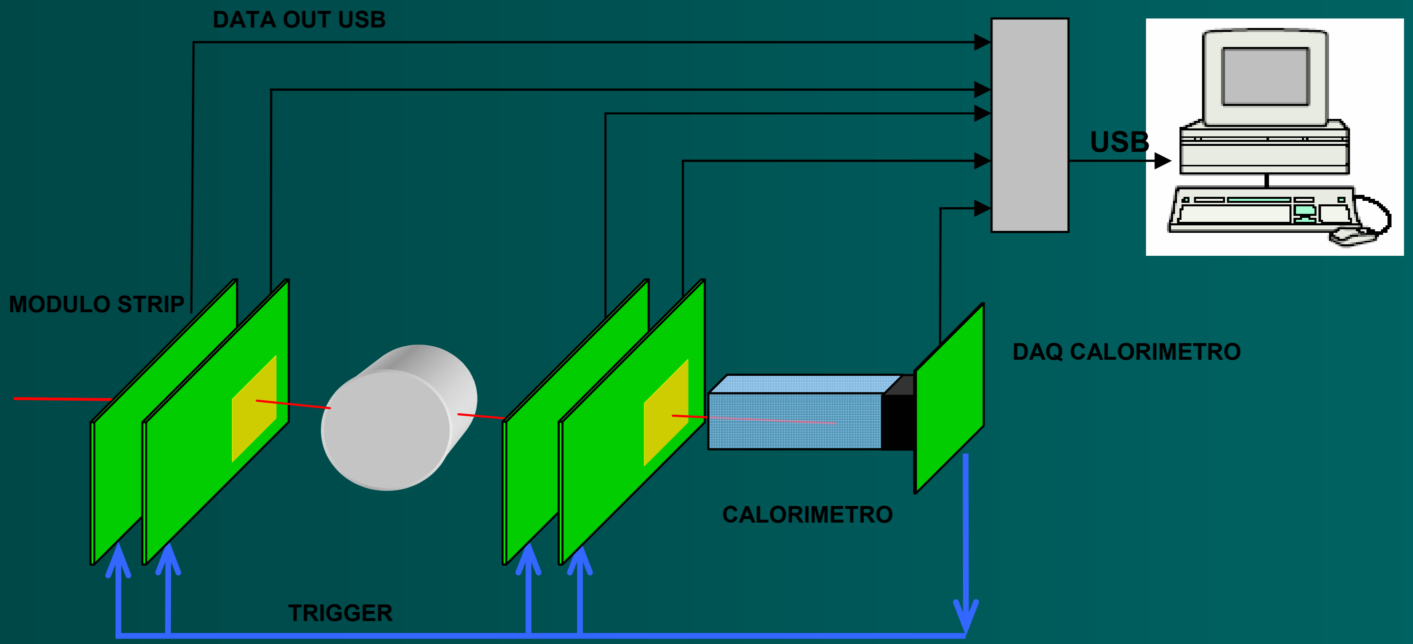
All the studies and prototypes developed in the last years are based on the principle of follow each single proton traversing the medium to investigate



The "single tracking" approach should permit to improve the spatial risolution up to 1 mm or less

$$\int_L \eta_e(\vec{r})\, d\vec{r} = K \int_{E_{out}}^{E_{in}} \frac{dE}{S(E)}$$

THE PRIMA (PRoton IMAging DETECTOR



Single tracking

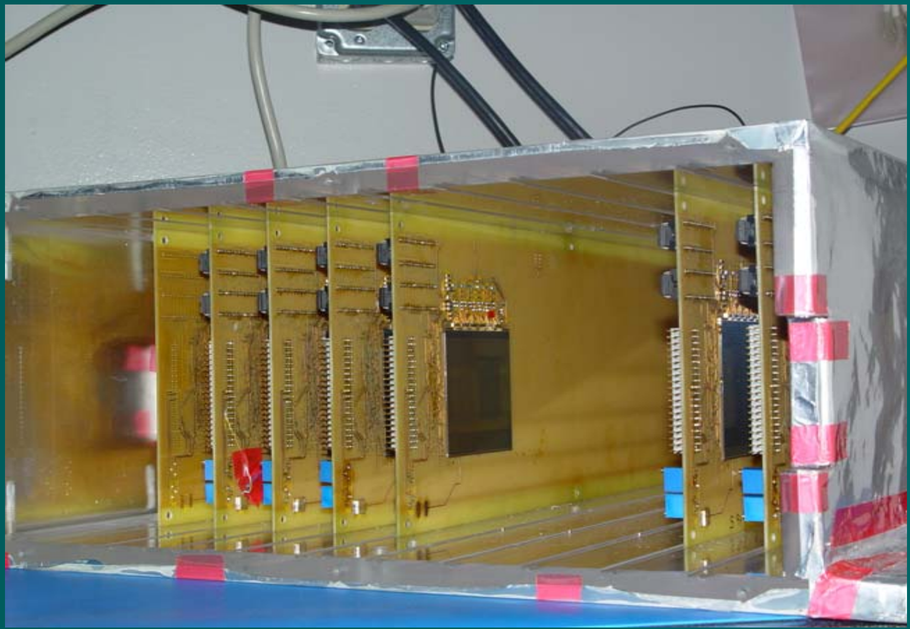
Acquisition rate up to 1 MHz

Detector: 2 orthogonal microstrip; 200 um picth x 256 strips; about 5x5 cm of active area

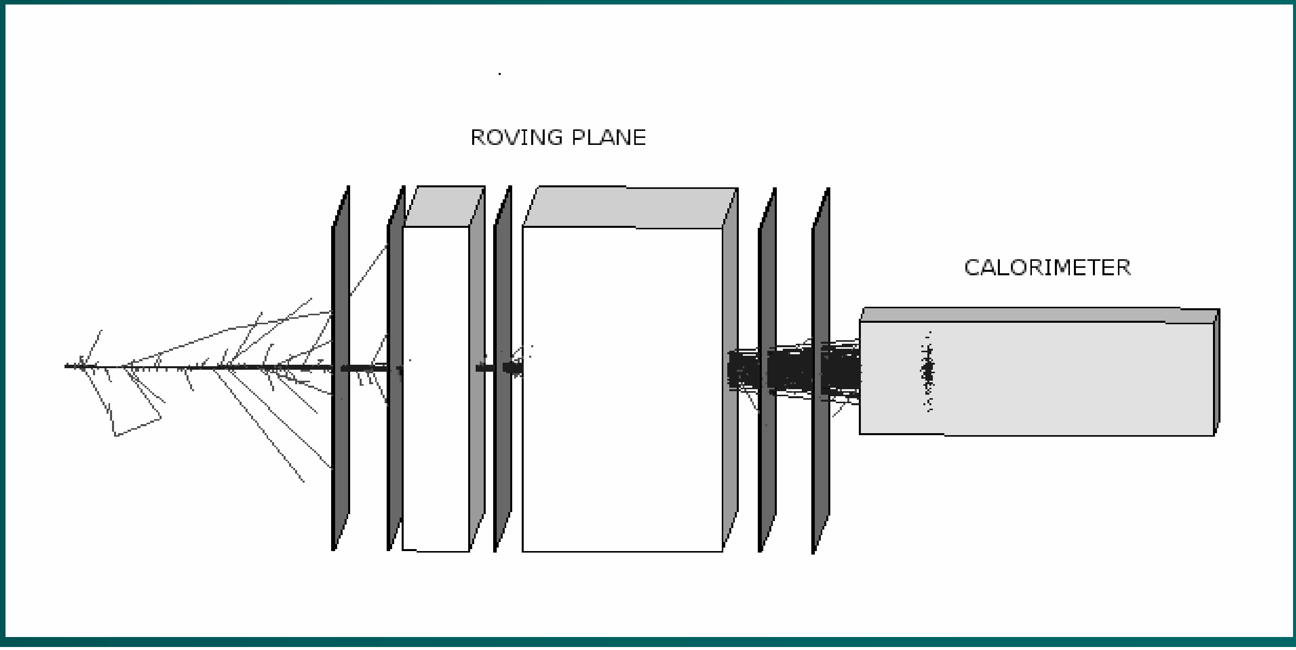
Trigger from the calorimeter

THE ROLE OF MONTE CARLO

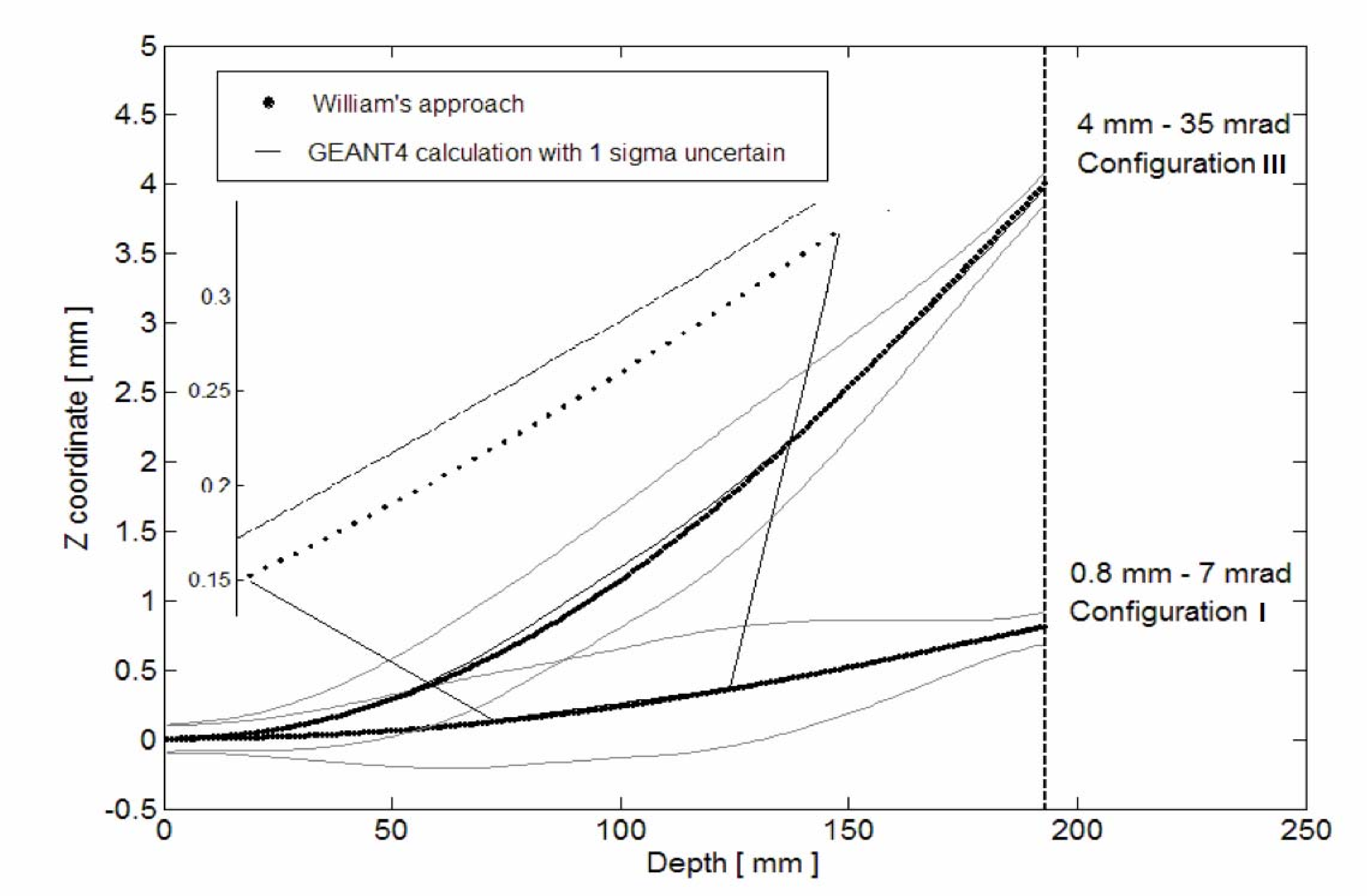
Experiment: 250 MeV proton beams (LLUMC)



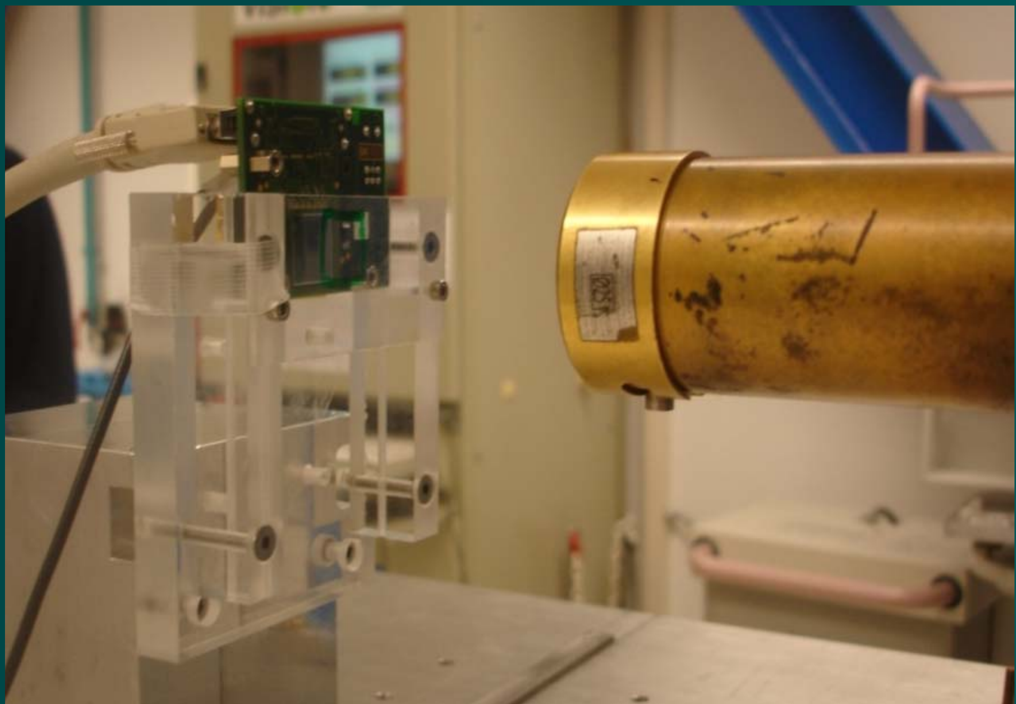
Our Geant4 application and results on detector study



THE ROLE OF MONTE CARLO



The detector is based on a 300 µm thick silicon pixel detector bump-bonded to the Medipix2 readout chip (MPX2MXR version) to form an assembly of 256 x 256 square pixels at a pitch of 55 µm. The active area of the detector is 2 cm^2. Each cell of the read-out chip comprises a low noise preamplifier, two pulse height discriminators and a 14 bit counter. The maximum counting rate per pixel is 1 MHz. The chip operates in single event counting mode, that is only the events releasing an energy above a threshold are counted. The threshold is adjustable at the pixel level with 3-bit resolution.

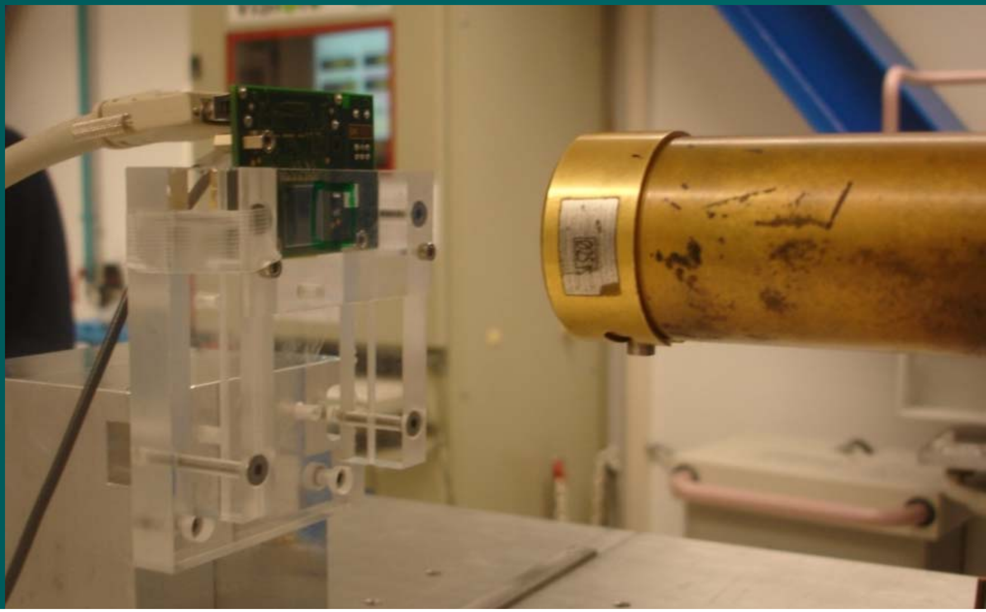


The tests have been performed with the 62 MeV proton beam. In the first test the count rate measured by our detector has
been compared to the one acquired by a reference detector based on a YAP scintillator.
Good agreement between the two counters (the measured count rate of both
detectors was 550 events/mm^2 pA),

G. Bisogni et al. INFN Pisa

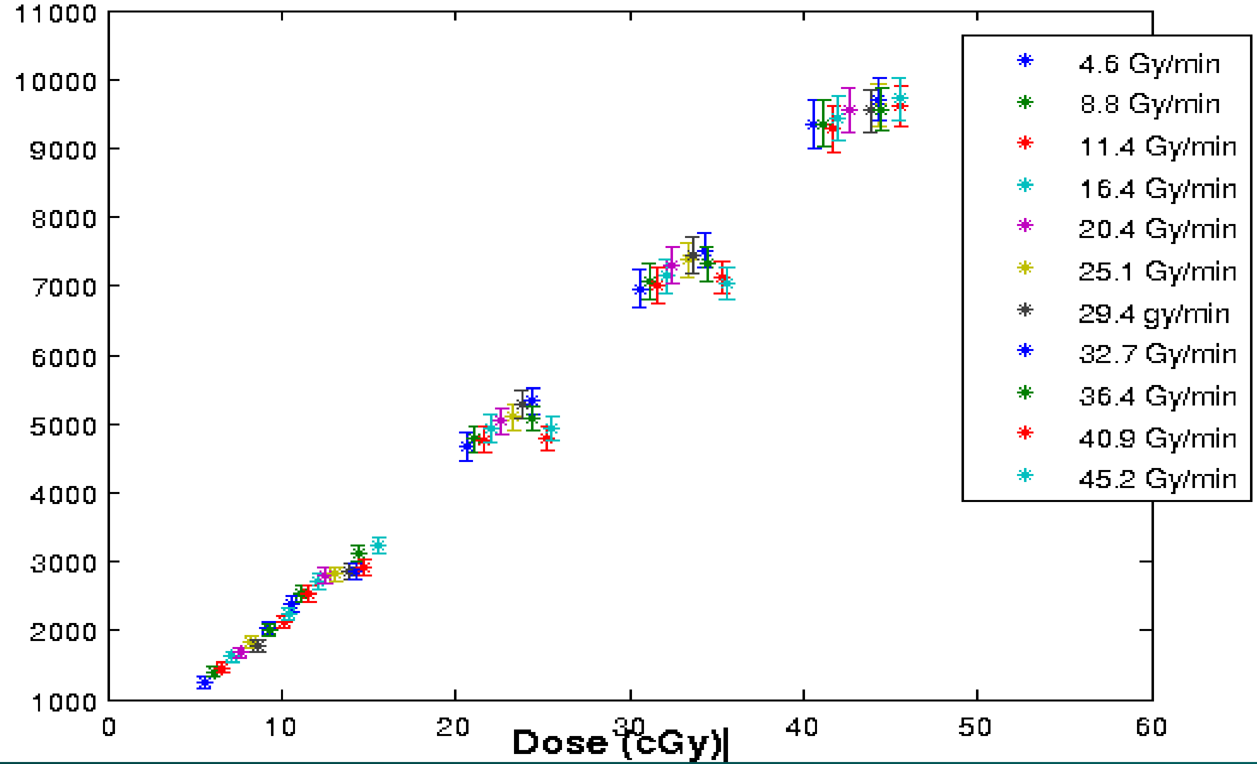
SET-UP

- Fascio Catana protoni da 62 MeV senza modulazione
- Rivelatore MPX2 (Si 300 um spessore, 55 um pixel, single event counter)
- Collimatori in ottone
  - Diametro 5 mm, uno e due fori



MISURE EFFETTUATE

- Stima del rate di protoni sul rivelatore
  - Misura effettuata confrontando il rate misurato da uno scintillatore YAP di Nunzio con il rate misurato da MPX2
- Misure di conteggi in funzione del tempo di acquisizione
- Misure di conteggi in funzione di dose e dose rate
- Misure di allargamento dei profili dopo vari spessori di lucite



Count rate as a function of the dose for different dose rates

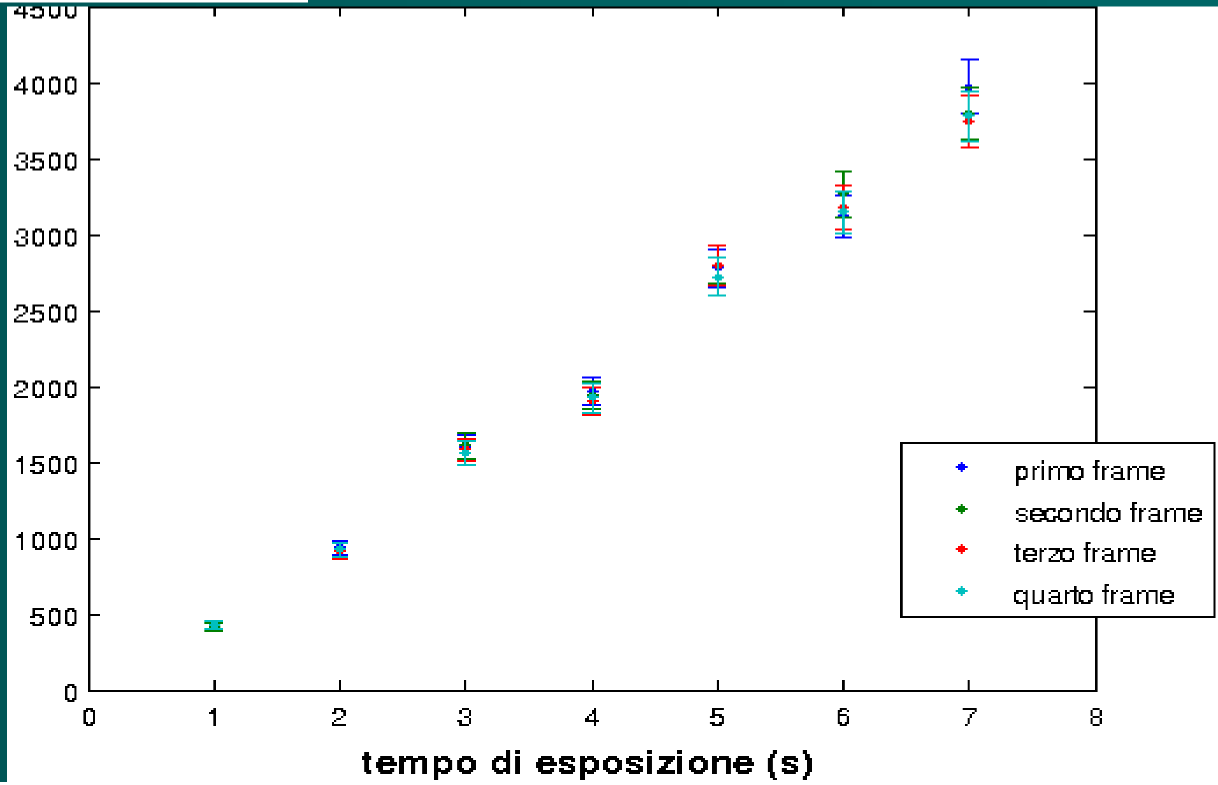
Linear and independent on the dose rate up to 35 Gy/min

Clinical dose rate 15 Gy/min

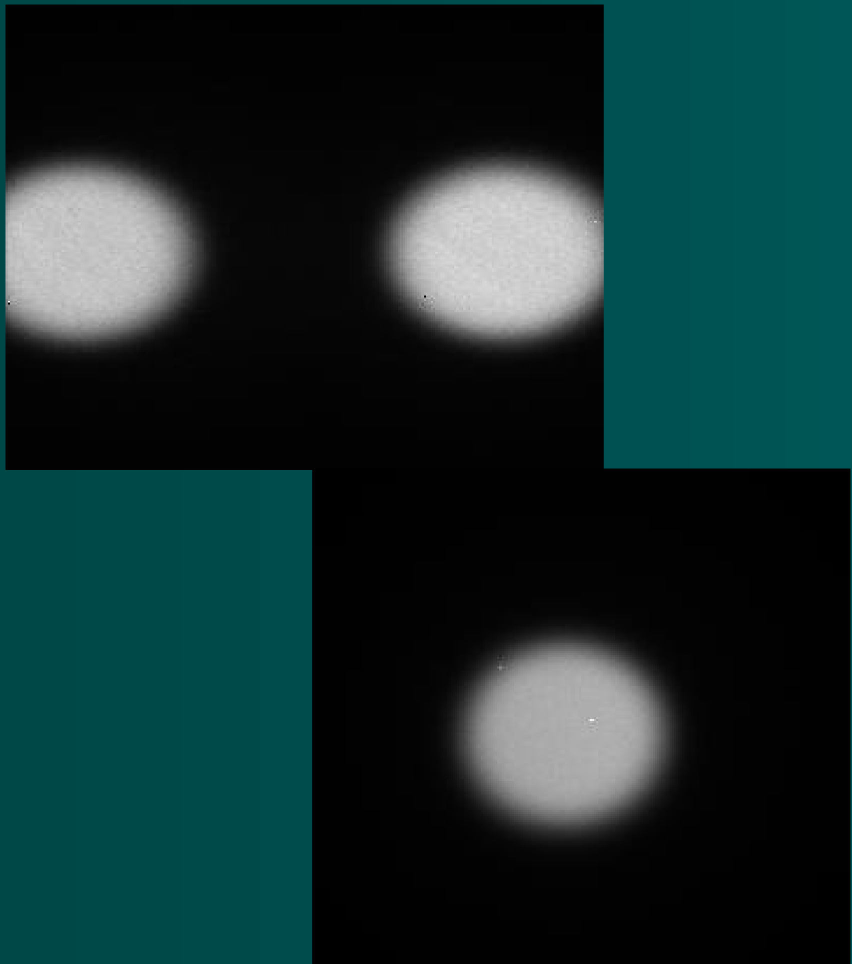
Above 35 Gy/min saturation effects are observed

Count rate as a function of the exposure time and reproducibility

Linear over exposure time range and reproducible



“RADIOGRAFIA” DEL FASCIO



- Collimatori fori da 5 mm
- Soglia discriminatore 190 keV
- Dose rate 0.15 Gy/sec

STIMA DEL RATE DI PROTONI SUL RIVELATORE

- La misura di rate con lo YAP e’ stata fatta fissando la corrente del fascio a 3 pA
- Il dose rate stimato e’ di 3 $*10^{-4}$ Gy/sec
- Tale valore e’ stato scelto per minimizzare il contributo degli eventi di pile-up sul rivelatore
- Risultati:
  - Collimatore un foro da 5 mm:
    - Event rate medio = 10 kHz/pA
  - Collimatore due fori da 5 mm:
    - Event rate medio = 20 kHz/pA
  - **Event rate atteso per pixel= 1.6 sec^{-1} * pA^{-1}**

EVENT RATE MPX2

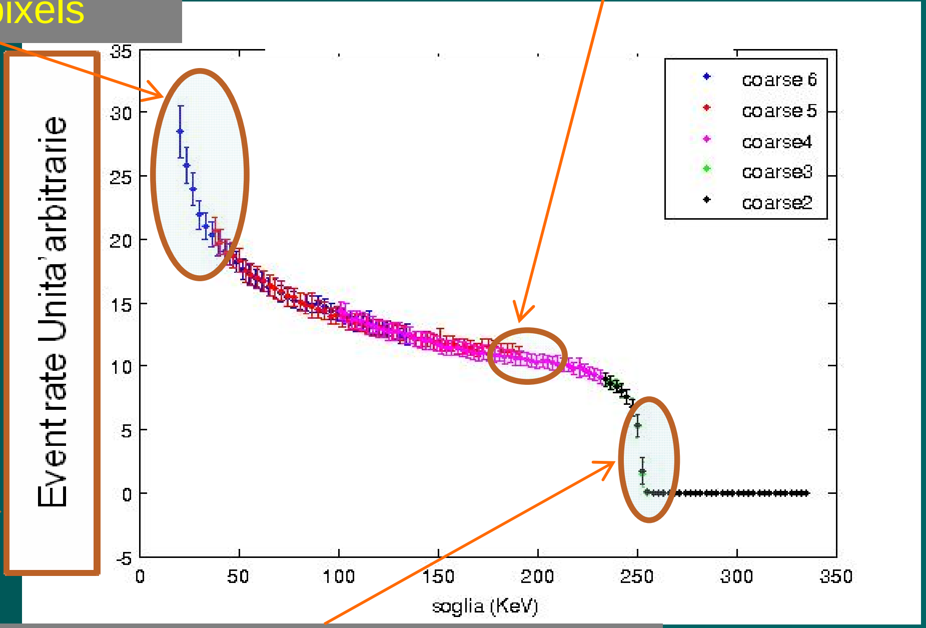
- Corrente fissata a 3 pA
- Il dose rate stimato e' di
  3 $*10^{-4}$ Gy/sec

- Soglia discriminazione 190 keV
  - Event rate misurato:
    - **1.7 sec^{-1} * pA^{-1}**

- La corrente portata a 1 nA
- Dose rate stimato 0.1 Gy/sec
- variata con continuità la soglia del chip da 10 keV fino a 250 KeV (lim max, saturazione preamplificatore)

Eventi multipli
Dovuti alla
Divisione di carica
Tra piu' pixels

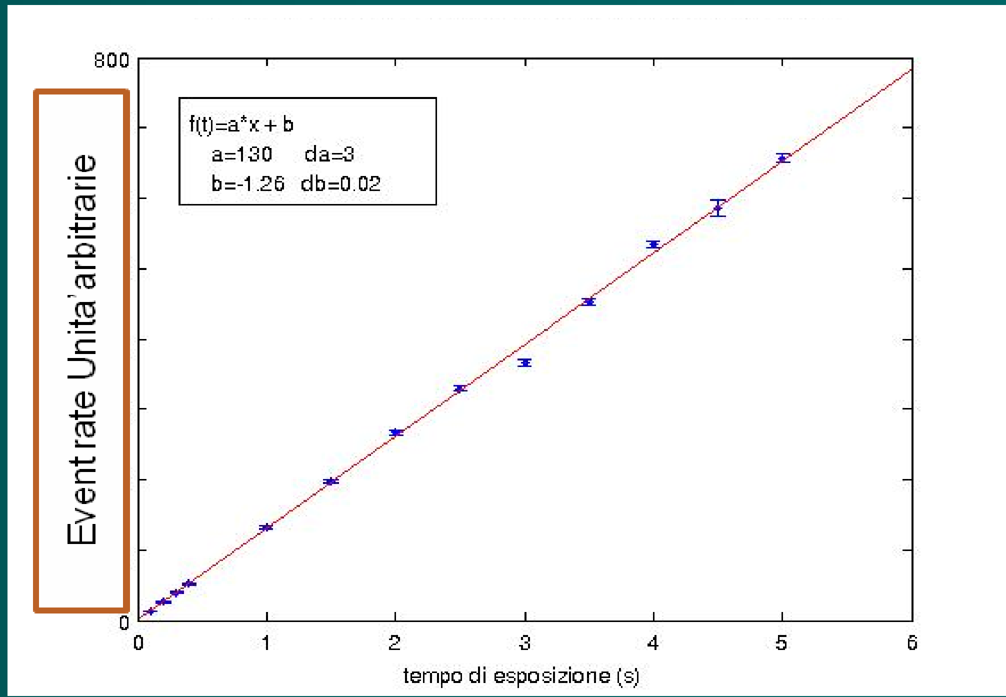
Fissando la corrente a 1 nA e la soglia a 190 keV event rate = 1.8 sec^{-1} * pA^{-1}



Saturazione preamplificatore

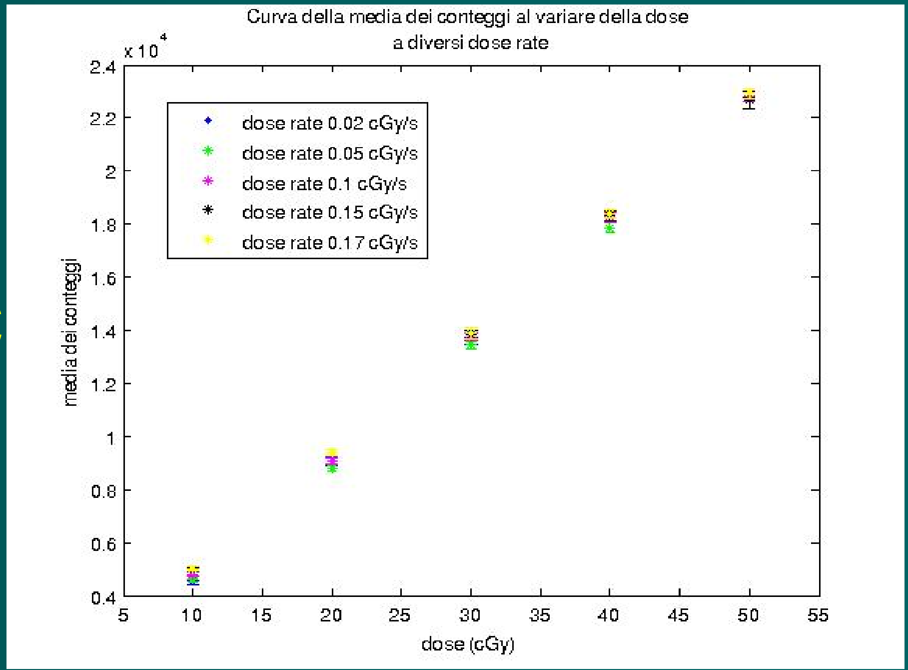
EVENT RATE VS DURATA GATE

- Abbiamo fissato la soglia a 190 keV e la corrente del tubo a 1 nA
- Dose rate stimato = 0.1 Gy/sec
- Variata la durata del gate di acquisizione da 0.1 a 5 sec



EVENT RATE VS DOSE

- Fissata la soglia a 190 keV e la durata del gate di acquisizione a 10 sec
- Misurato event rate sul rivelatore in funzione della dose a diversi dose rate



IMMAGINI CON SPESSORI LUCITE

Immagini ottenute ponendo davanti al rivelatore spessori crescenti di lucite (da 5 a 20 mm)

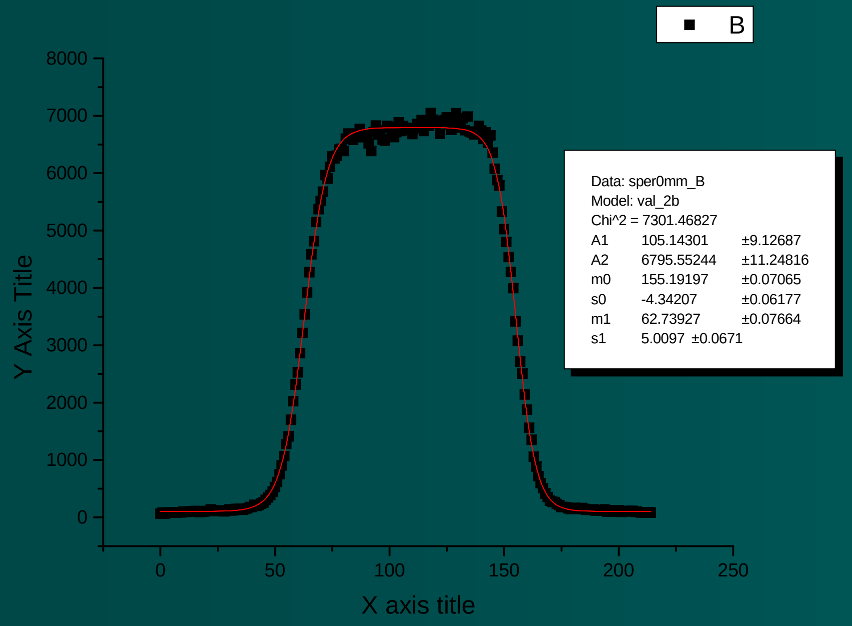
0 mm 5 mm 10 mm 15 mm 20 mm

Soglia 190 keV
Dose in ingresso 30 cGy
Dose rate 0.15 Gy/sec

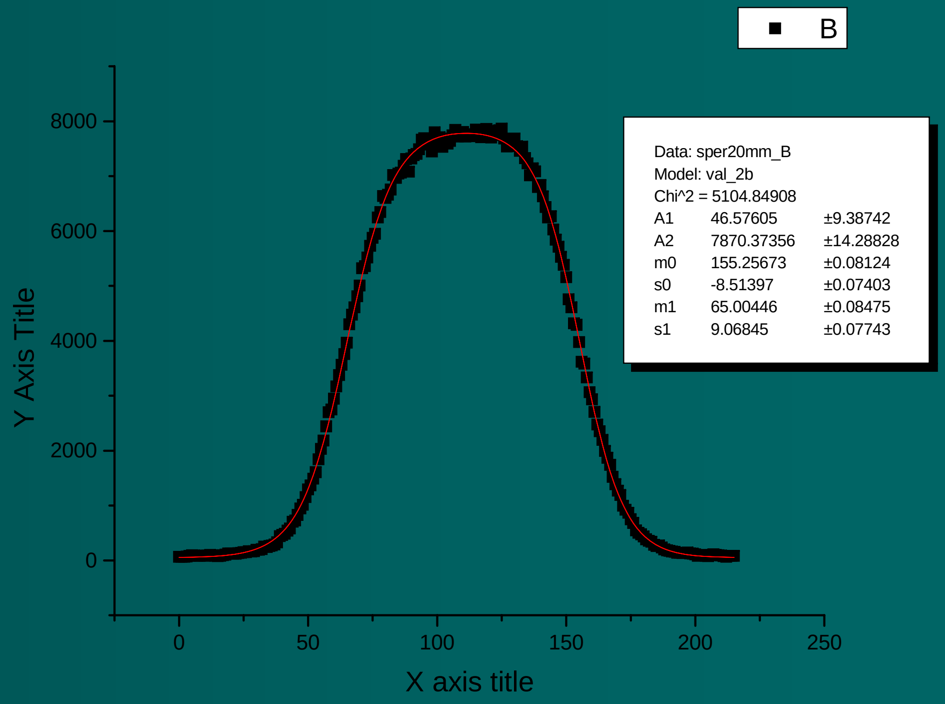
PROFILI ORIZZONTALI

- Profili orizzontali lungo la riga passante epr il centro delle immagini

Experimental NO PMMA



Experimental 20mm PMMA



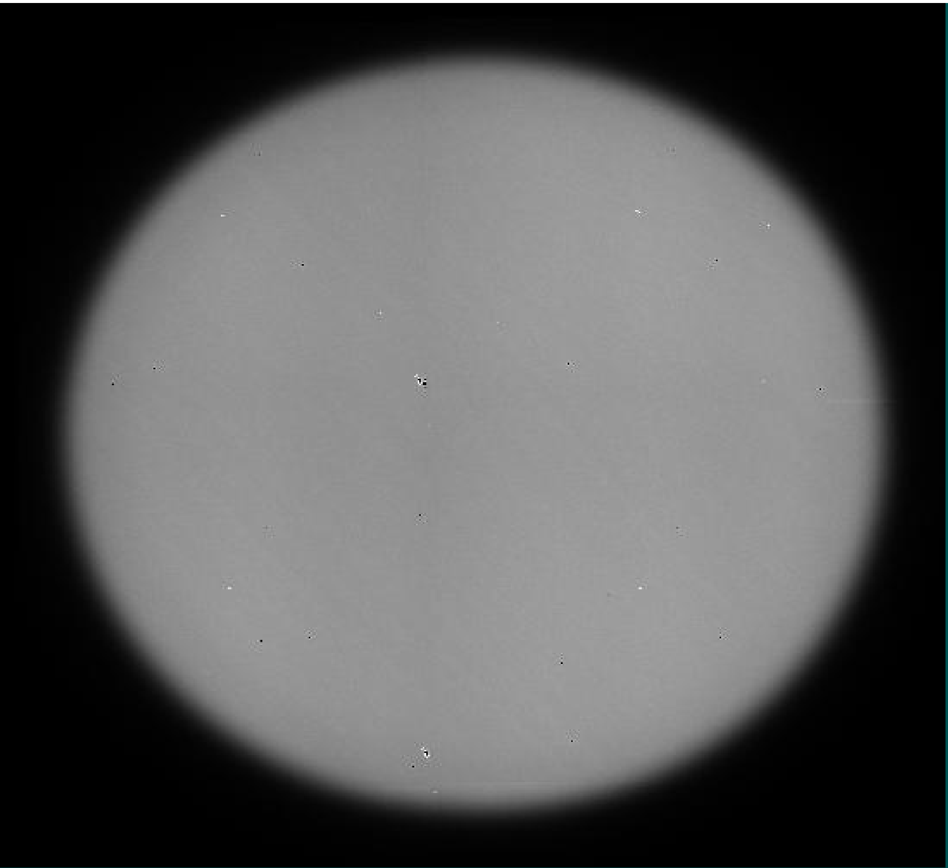
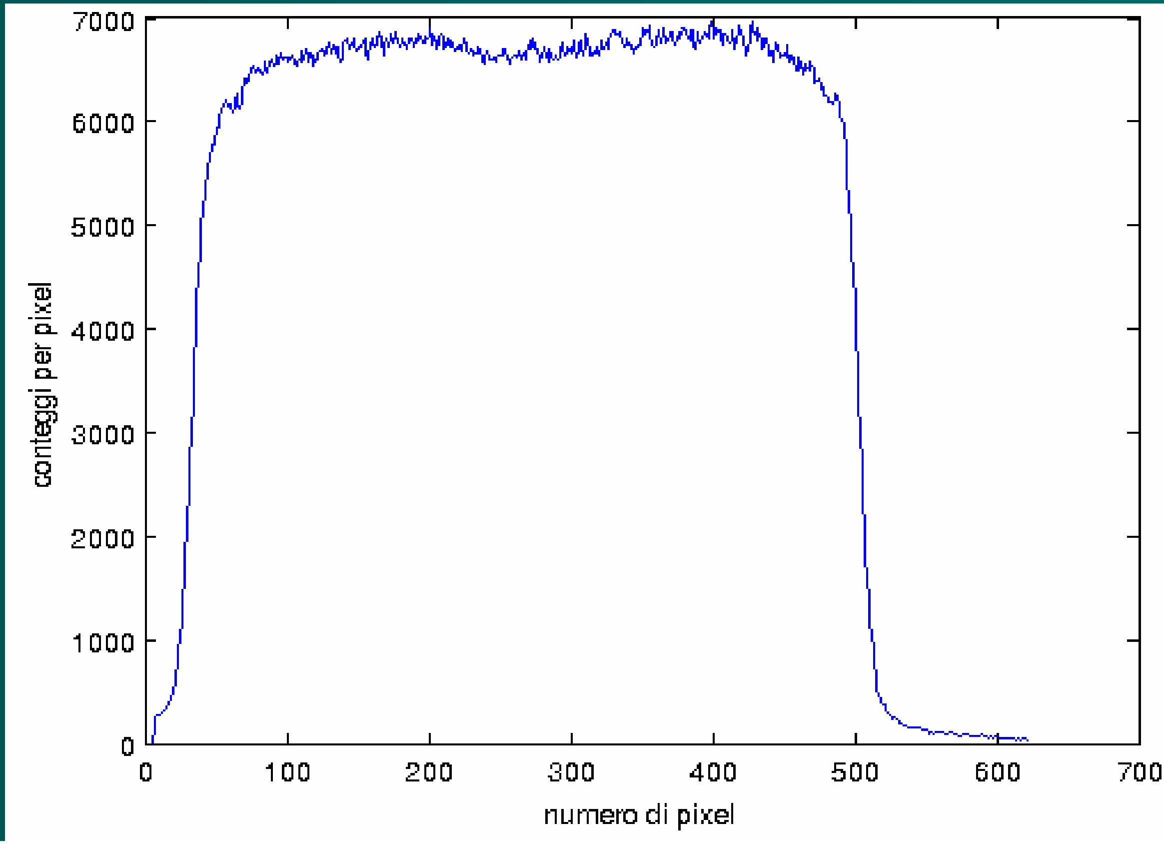


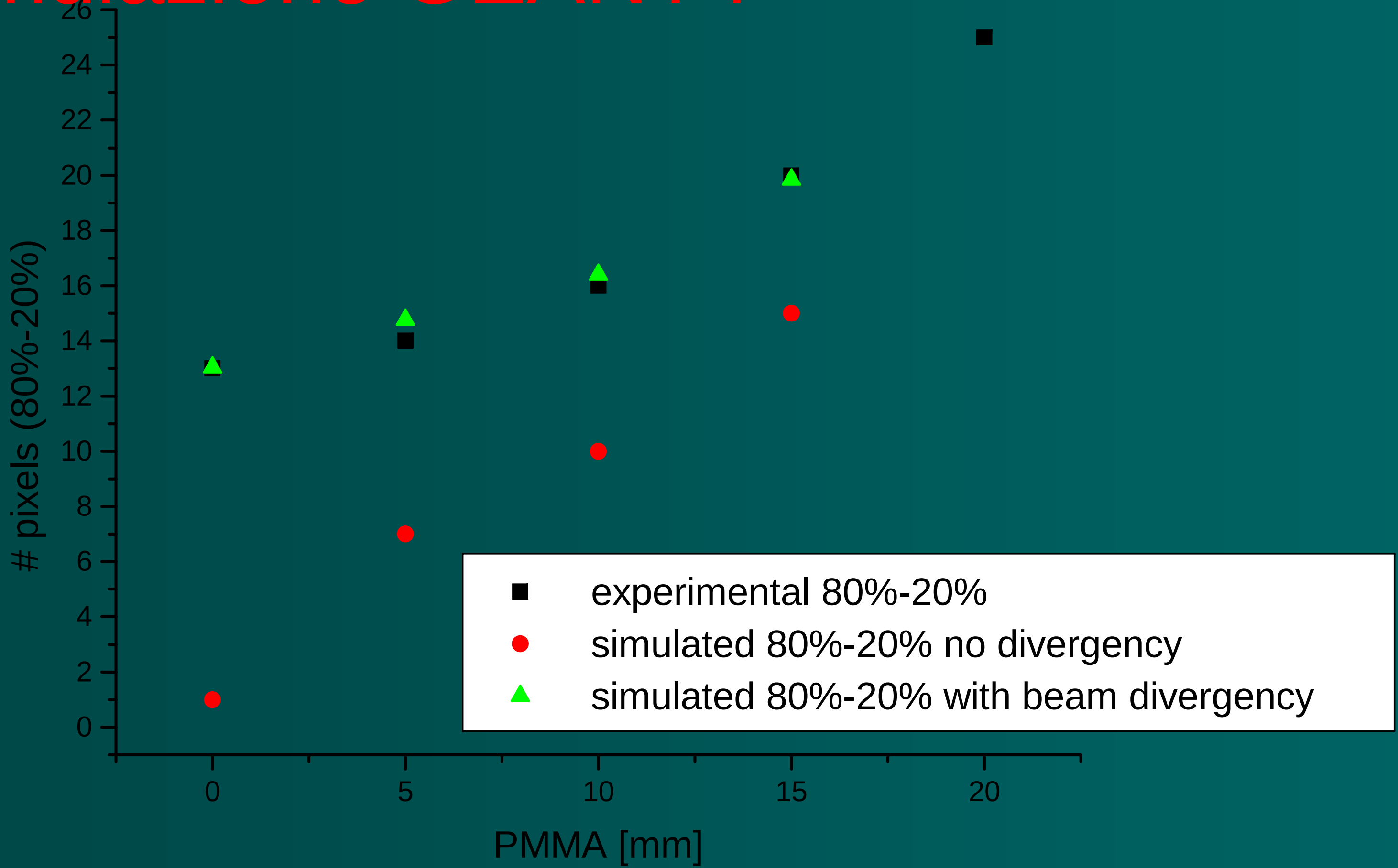
Image of the beam cross section obtained by scanning our detector across the beam area. The image size is **30 x 30 mm ^2** and it has been obtained in 9 steps. The dose for each step was 30 cGy.

Vertical profile of the counts for the central column



“PENOMBRA” 20-80

- Confronto dati sperimentali con simulazione GEANT4



Stringent necessity of monitoring

The higher physical selectivity of ion therapy demands higher precision in the monitoring of the applied treatment due to:

- fractioned therapy
- shifts of the patient
- local tissue reduction

For these reasons in vivo information on the range of ions are desirable, but the complete stopping of the ions in patient prevents the application of electronic portal imaging methods as used in conventional radiotherapy.

Possibilities:

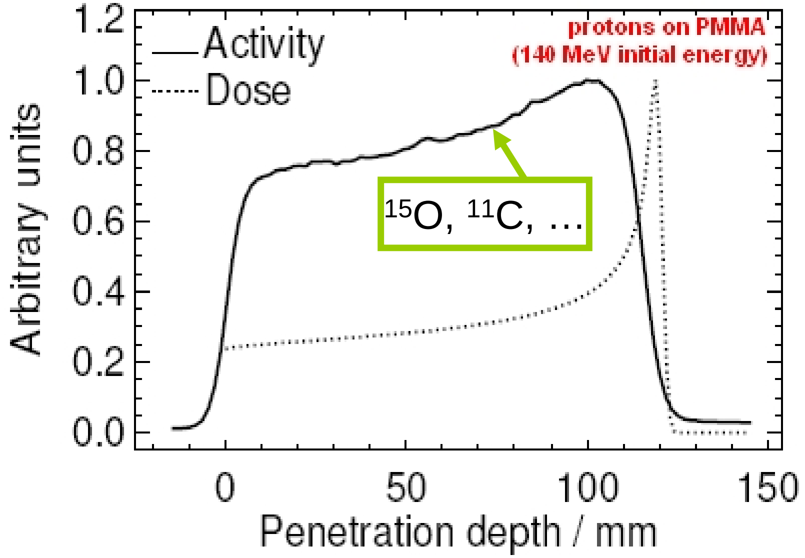
- radiographic imaging of high energy transmitted protons prior to therapeutic irradiation (hadron CT)
- In-beam PET (DOPET- INFN and University of Pisa)

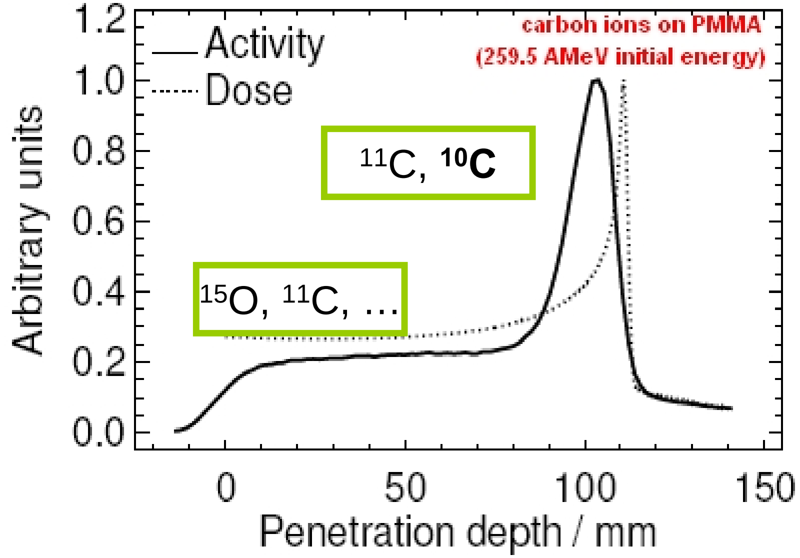
A. Del Guerra, F. Attanasi, N. Belcari, S. Moehrs, V. Rosso, S. Vecchio, G.A.P. Cirrone, G. Cuttone, P. Lojacono, F. Romano, N. Lanconelli.

β^+- emitter target and projectile fragments:

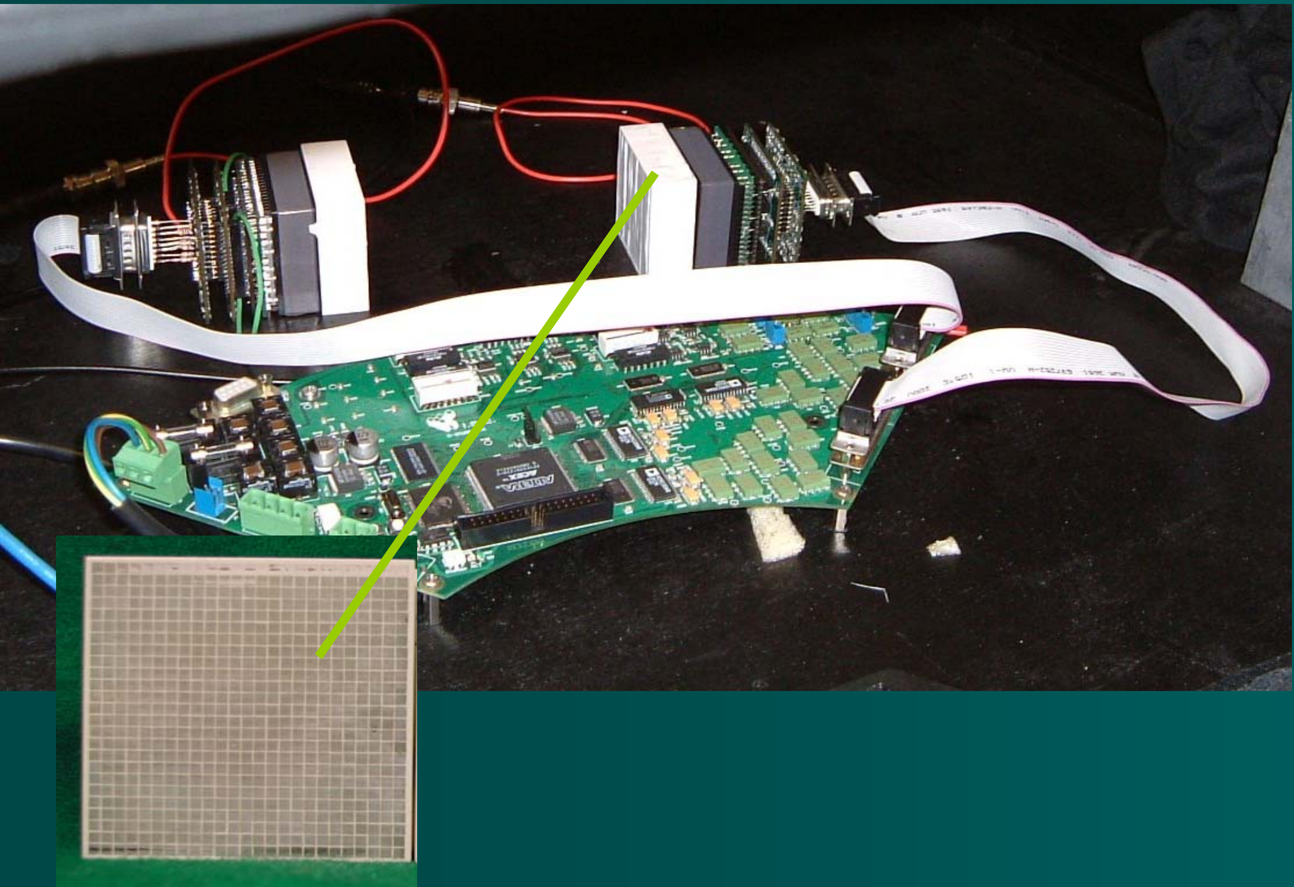
- **Protons:**
  - **$^{16}O\ (p,n)\ ^{15}O$ $T_{½\,15\text{-}O}$=121.8 s** **$^{12}C\ (p,n)\ ^{11}C$ $T_{½\,11\text{-}C}$ =1222.8 s**
  - **15-20 MeV threshold for p-induced nuclear reactions that cause poor spatial correlation between β^+-activity and dose depth profile**
- **Carbon:**
  - **X (^{12}C, ^{11}C+n) X X (^{12}C, ^{10}C+2n) X $T_{½\,10\text{-}C}$ =19.3 s ^{16}O (^{12}C, X) ^{15}O+n ^{12}C (^{12}C, X) ^{11}C +n**
  - **Superior biological effectivenes**

- **The induced β+activity can be measured with a PET tomograph.**





The in-beam PET-tomograph prototype



• LYSO crystal matrix, 21 x 21 pixels 2.152 mm x 2.152 mm each (Hilger Crystals)

•Crystal thickness: 18 mm

•Two planar heads, each with an active area of 45 mm x 45 mm

•Distance between the heads: 7+7 cm

Nominal energy: 62 MeV

Final collimator: 25 mm Ø

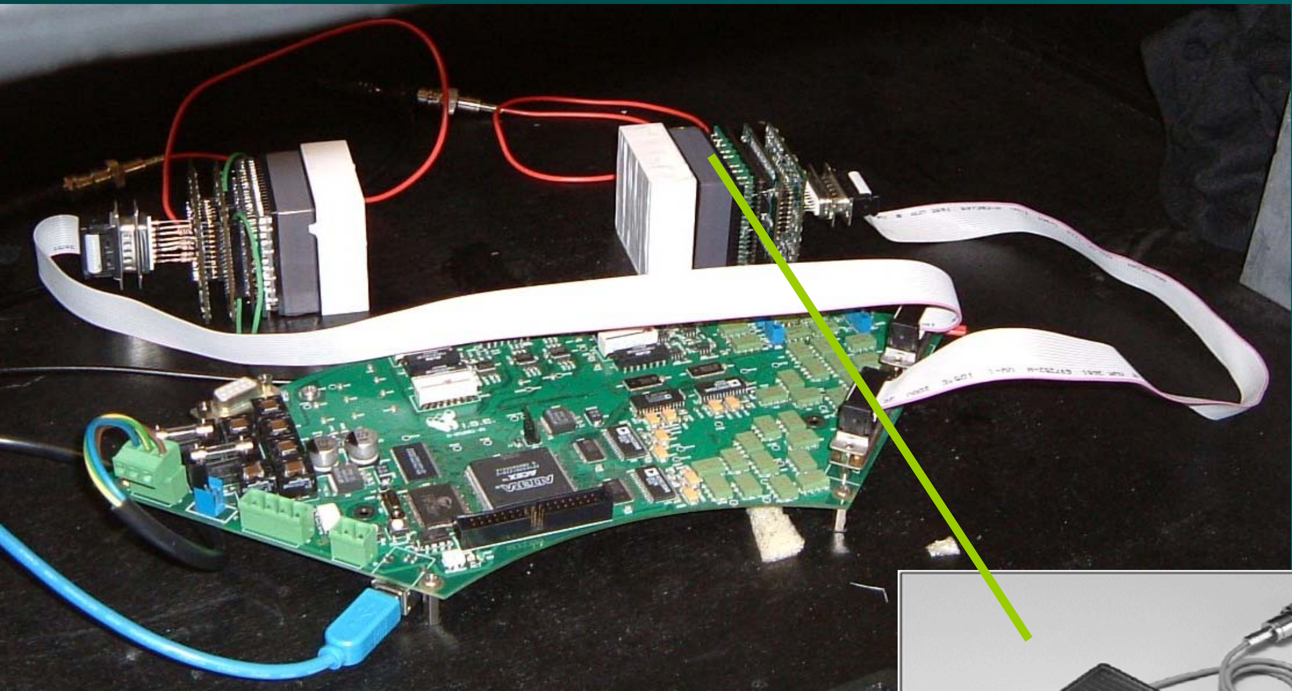
Full energy

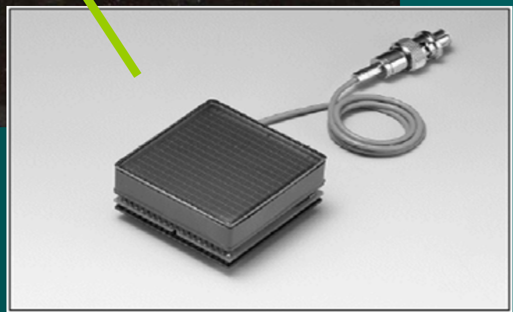
Dose: 30Gy peak

T-irr= 20sec.

T-acquis = 20sec

The in-beam PET-tomograph prototype



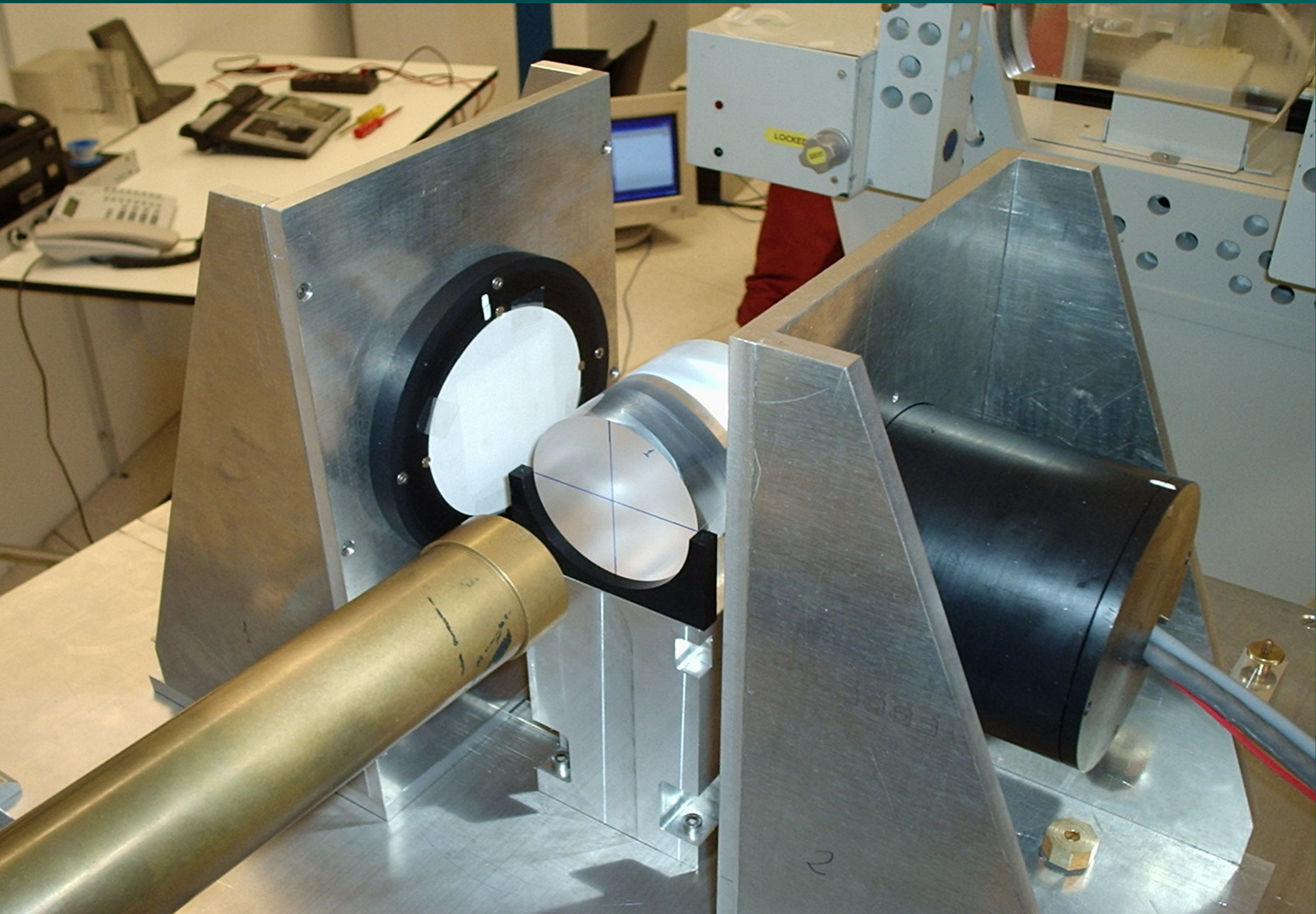


•Two planar heads, each with an active area of 45 mm x 45 mm
•Distance between the heads: 7+7 cm

Nominal energy: 62 MeV
Final collimator: 25 mm Ø
Full energy
Dose: 30Gy peak
T-irr= 20sec.
T-acquis = 20sec

• LYSO crystal matrix, 21 x 21 pixels 2.152 mm x 2.152 mm each (Hilger Crystals)
•Crystal thickness: 18 mm
•64-anode PMT (Hamamatsu)
•“multiplexed” read-out electronics: 64-inputs/4 outputs

The in-beam PET-tomograph prototype



•Two planar heads, each with an active area of 45 mm x 45 mm
•Distance between the heads: 7+7 cm

Nominal energy: 62 MeV
Final collimator: 25 mm Ø
Full energy
Dose: 30Gy peak
T-irr= 20sec.
T-acquis = 20sec

The experiments on homogeneous phantoms

The feasibility of range monitoring

- **SOBPs irradiation of PMMA phantoms were performed using different range shifters along the beam line so that each irradiation differed from the other ones only in the proton range, with variations less than 2 mm.**

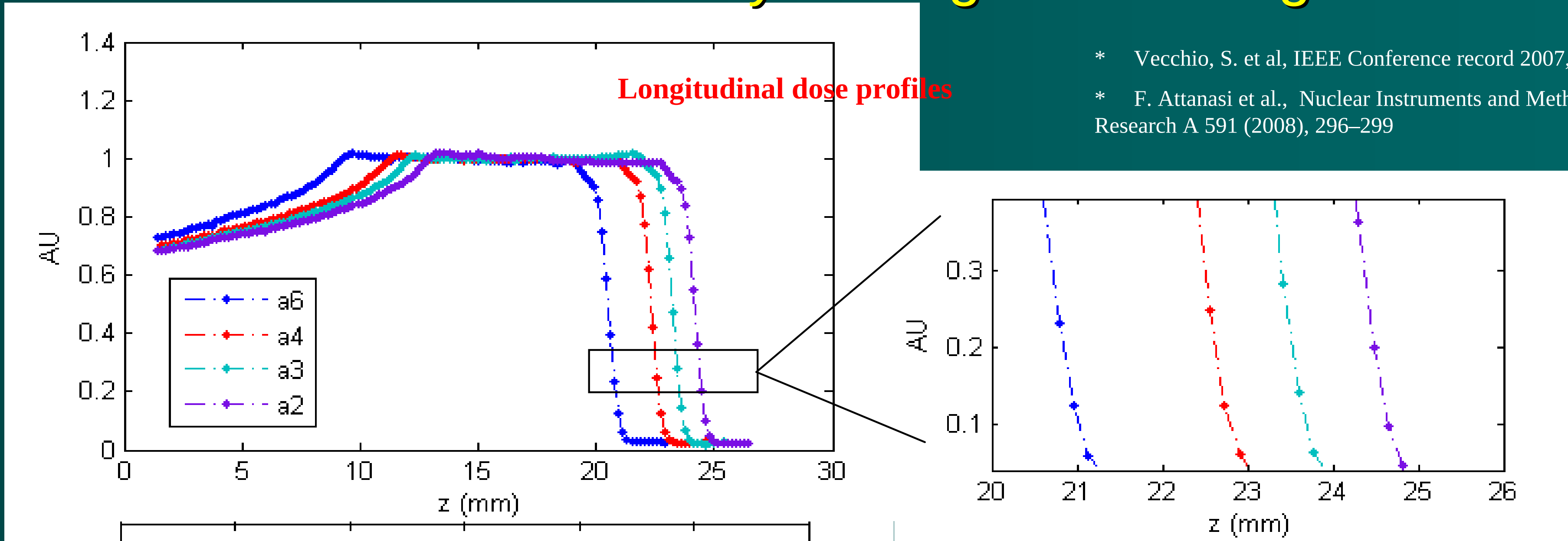
Range shifters

Label	Material	Equivalent thickness in PMMA (mm)
a2	Aluminum	1.9
a3	PMMA	2.9
a4	PMMA	3.9
a6	PMMA	5.8

- Preliminary dosimetric measurement of each selected dose configuration was performed for accurate irradiation planning.

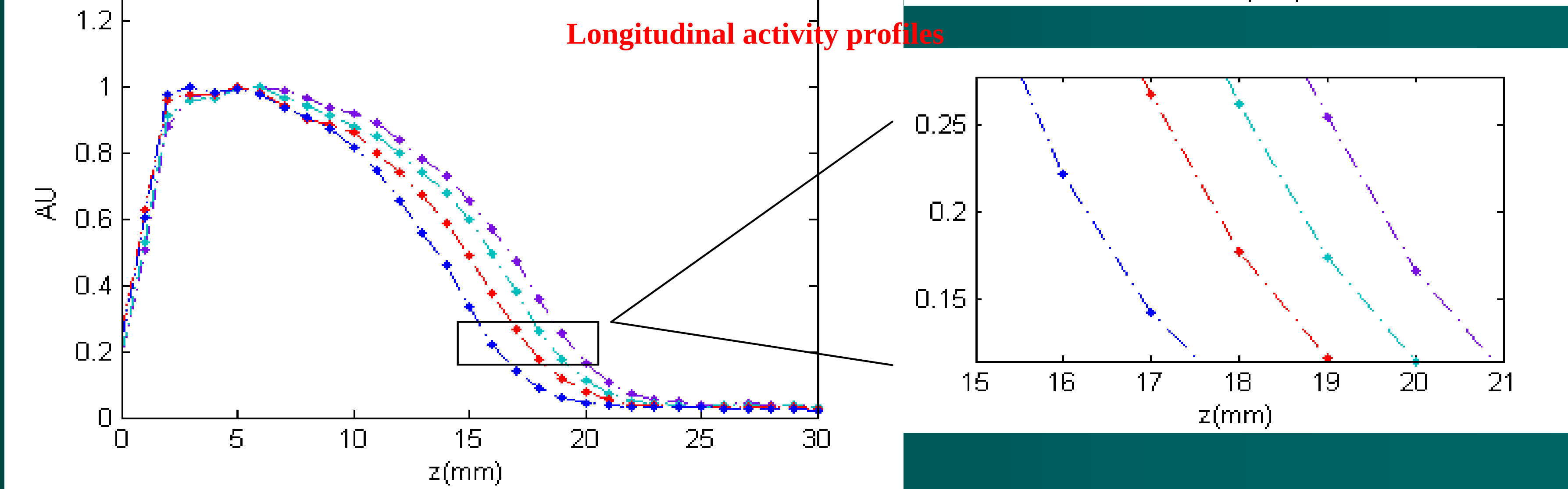
The experiments on homogeneous phantoms

The feasibility of range monitoring

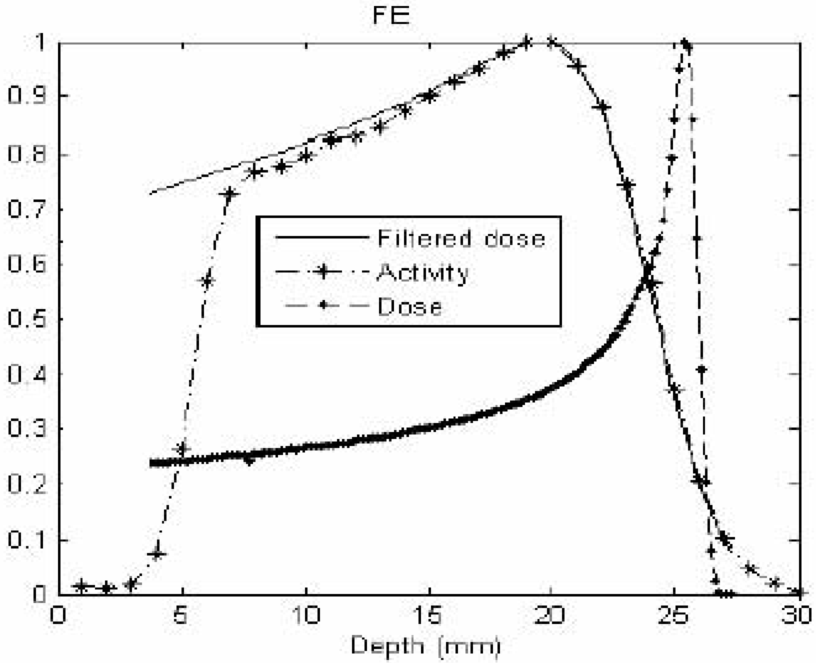


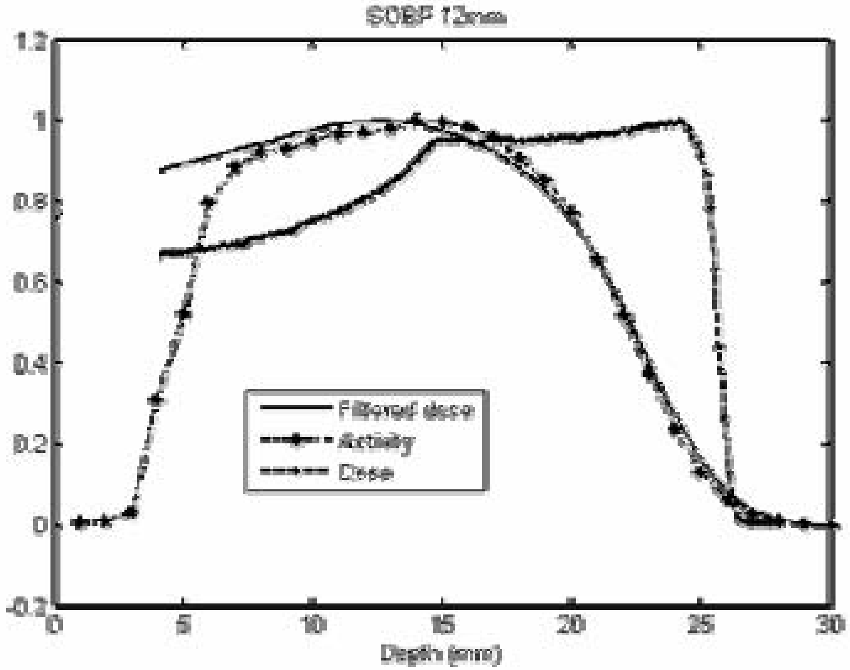
* Vecchio, S. et al, IEEE Conference record 2007, cdrom: m13-61.

* F. Attanasi et al., Nuclear Instruments and Methods in Physics Research A 591 (2008), 296–299



Unfolding: preliminary results



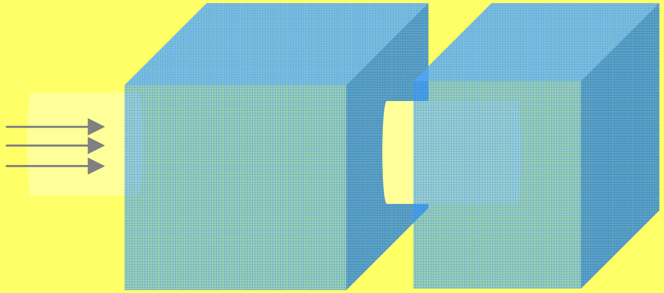


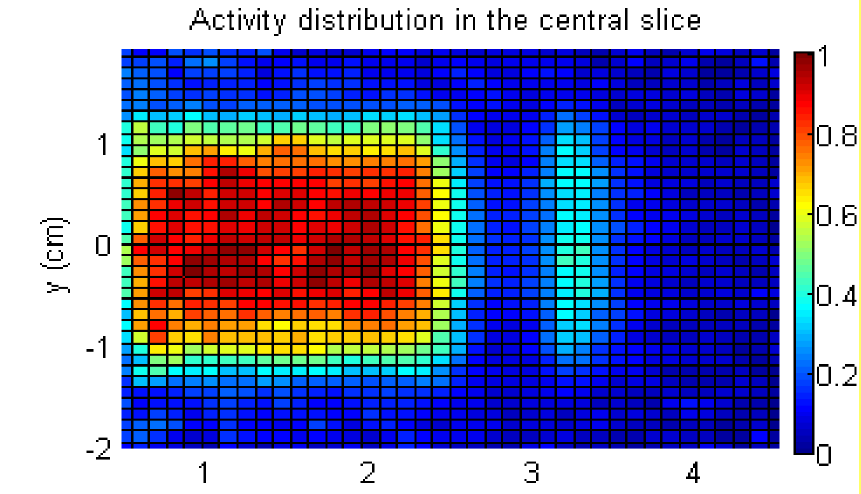
Filter extrapolated from the data available for the Full Energy Bragg peak and mesured activity

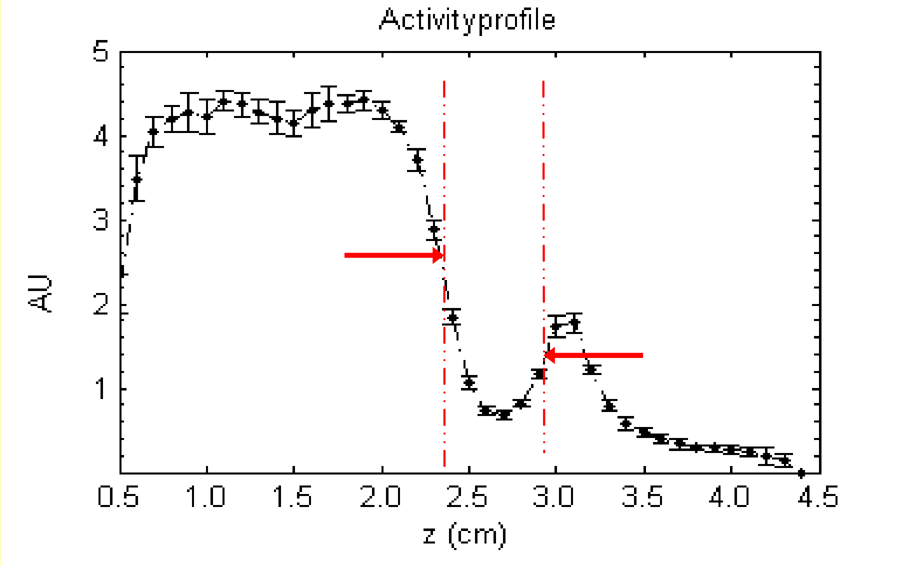
Filtered dose: β+ activity distribution obtained from the application of the filter function to measured dose depth profiles

Resolution of air gaps in PMMA phantoms within the irradiation field

PMMA phantom with 0.5 cm Air_Gap at 2 cm depth;



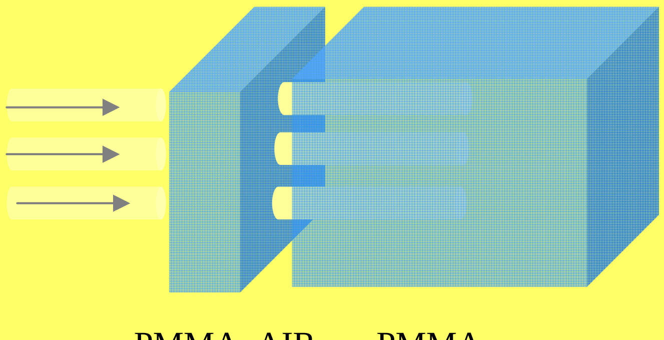


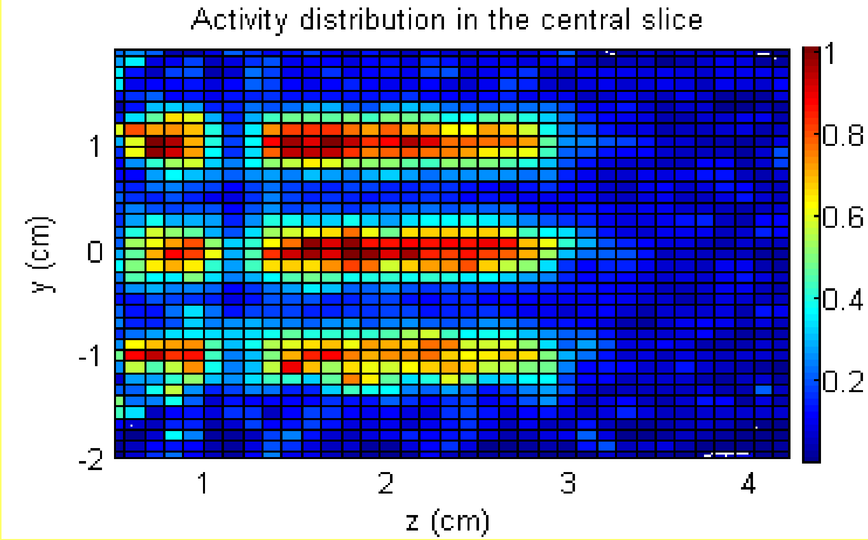


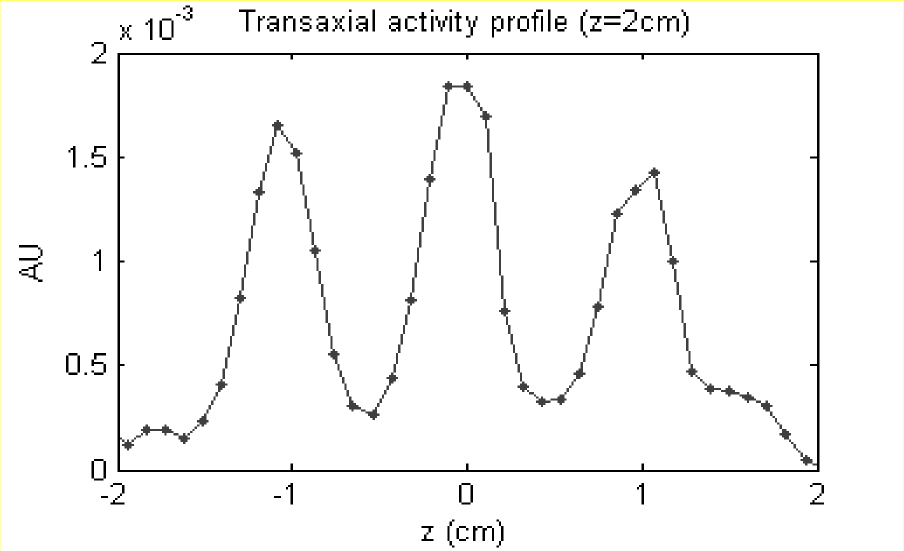
- Phantom irradiation:
  - Bragg peak dose: 30 Gy
  - Irradiation time: 18 s;
- Beam cross sention: 2.5 cm Ø;
- Acquisition time: 20 min;

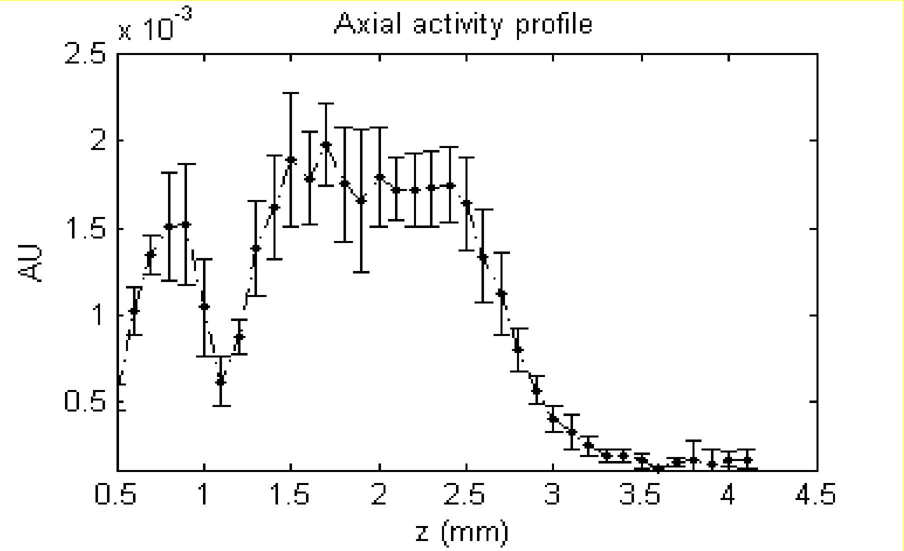
Resolution of air gaps in PMMA phantoms within the irradiation field

• Final three holes collimator: 0.5 cm Ø each;

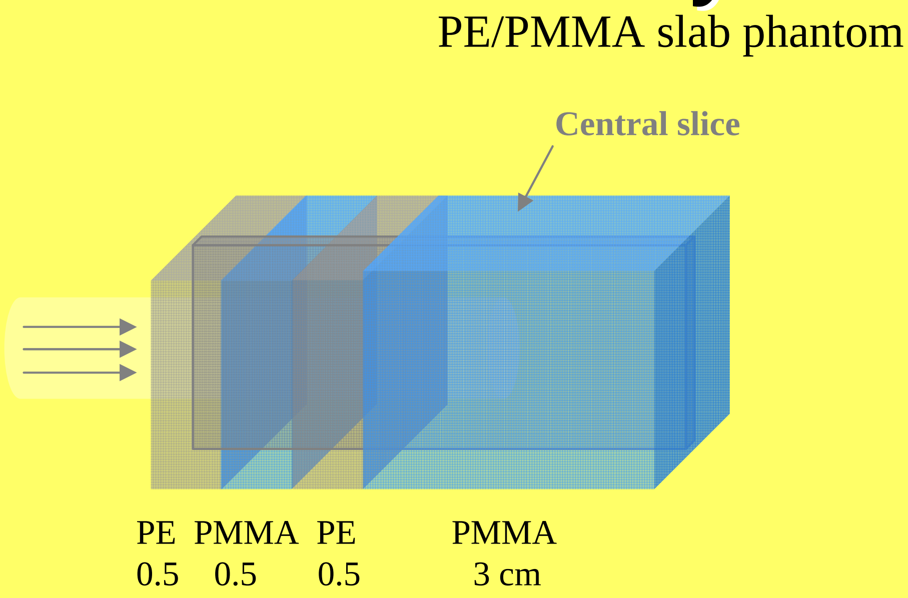


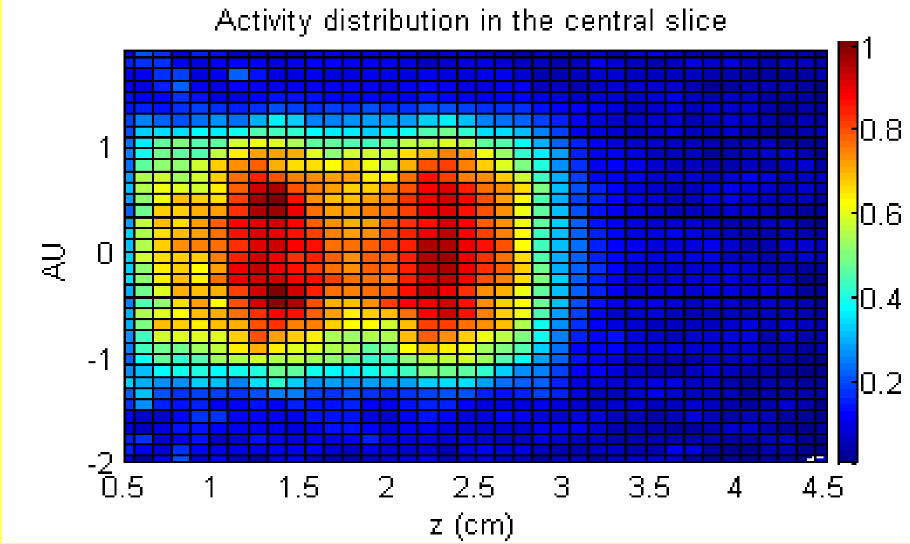


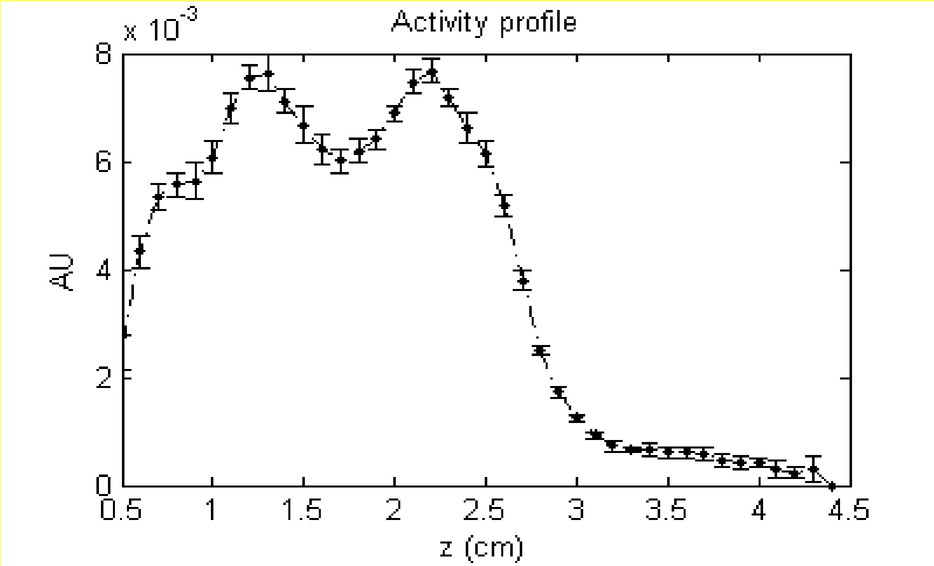




The experiments on slab phantoms
Sensitivity of the PET method



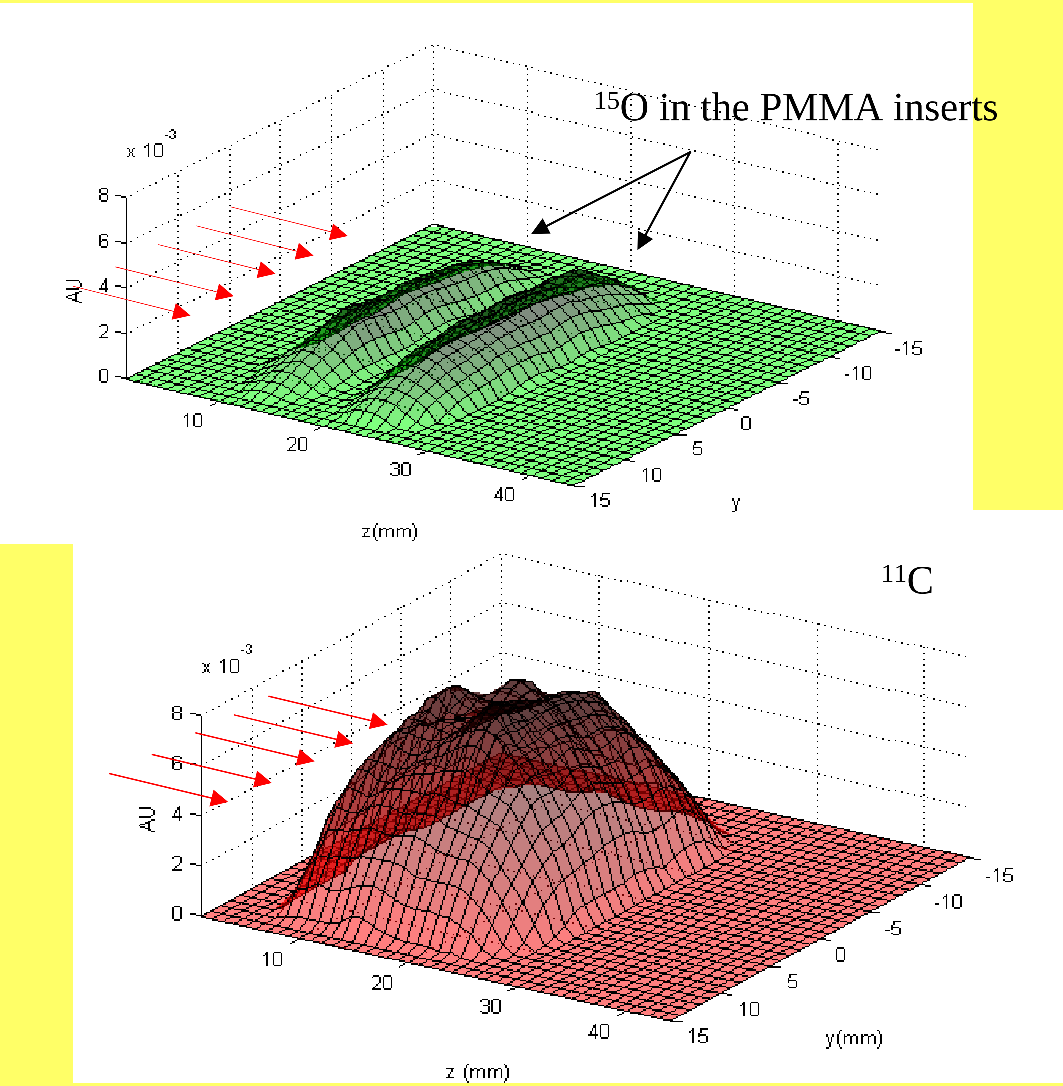




- Monoenergetic irradiation:
  - Bragg peak dose: 30 Gy;
  - Irradiation time: 18 s;
- Beam cross sention: 2.5 cm Ø;
- Acquisition time: 20 min;

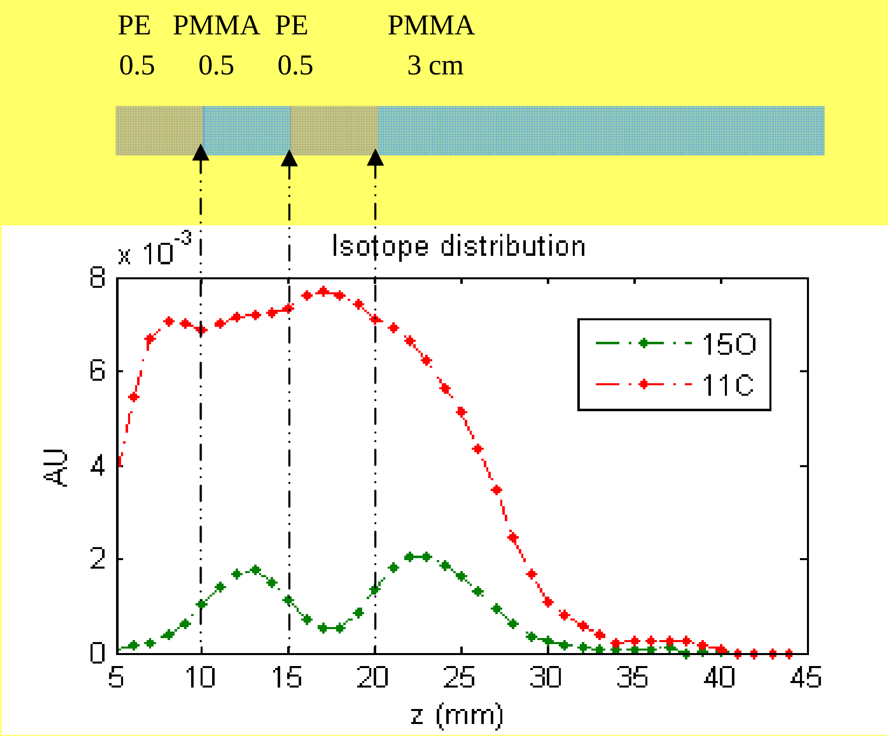
The experiments on slab phantoms
Sensitivity of the PET method

Reconstructed isotope distributions in the central area



PE $\quad ^{12}C\,(p,\ pn)\,^{11}C$

PMMA $\begin{cases} ^{12}C\,(p,\ pn)\,^{11}C \\ ^{16}O\,(p,\ pn)\,^{15}O \end{cases}$



BASTEI (beta activity measurements at the Therapy with Energetic ions) is in use at GSI.

2 heads 42x21 cm2

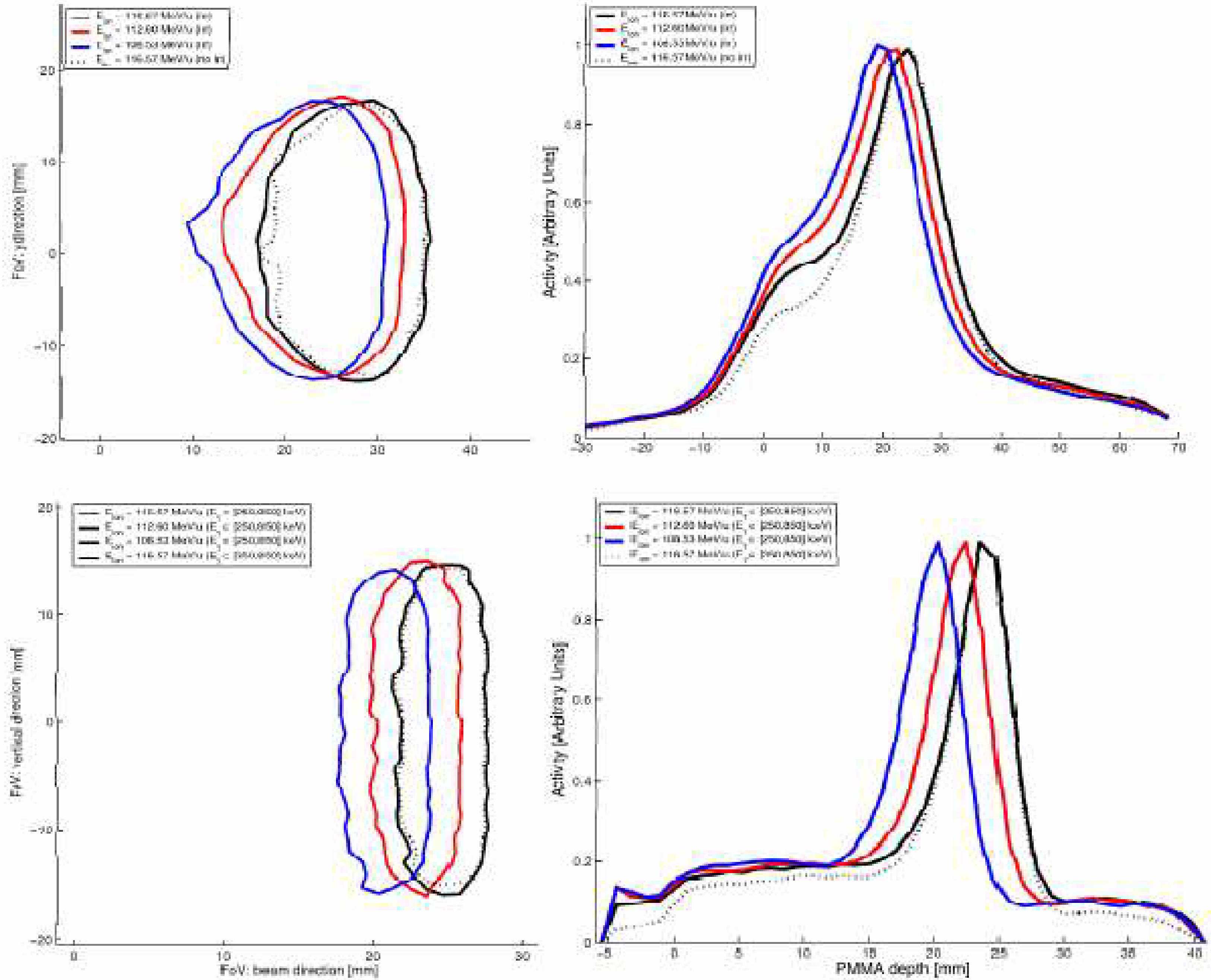
8x8 BGO christals: 6.7x6.7x20mm3

A cylindrical PMMA phantom (7cm diameter, 7cm length) was irradiated with 3 mono-energetic 12C beams (108.53 112.60 116.57 AMeV).
A square section beam of 28mm in side was adopted and a total dose of 60Gy was delivered for each energy. The acquisition time was set at ~30 minutes for both PET systems.

Preliminary

Simultaneous irradiations with ^{12}C

Energy	[AMeV]	108.53	112.60	116.57
Range	[mm]	21.9	23.6	25.3




Thank you
for your attention