Dosimetric characterization with 62 MeV protons of a silicon segmented detector for 2D dose verifications in radiotherapy

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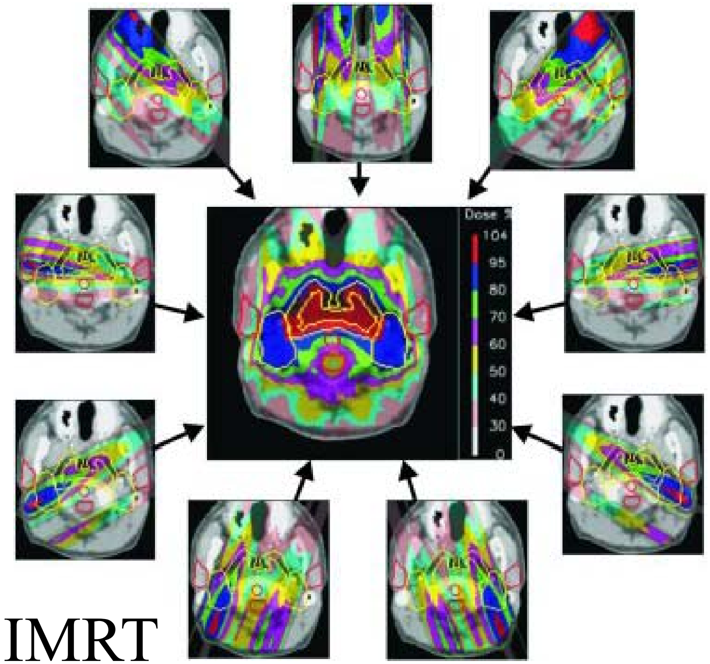
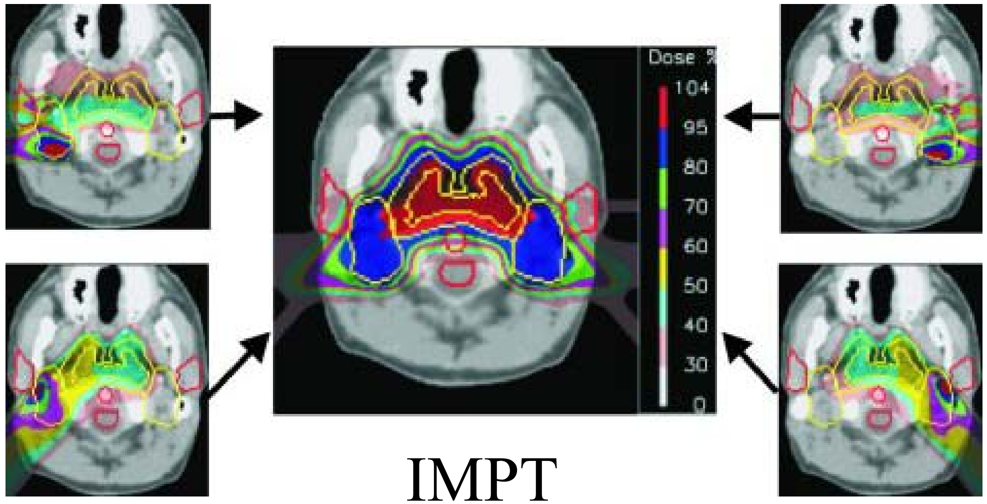
Outline

- MAESTRO
- Detector
- Dosimetric characterization with protons

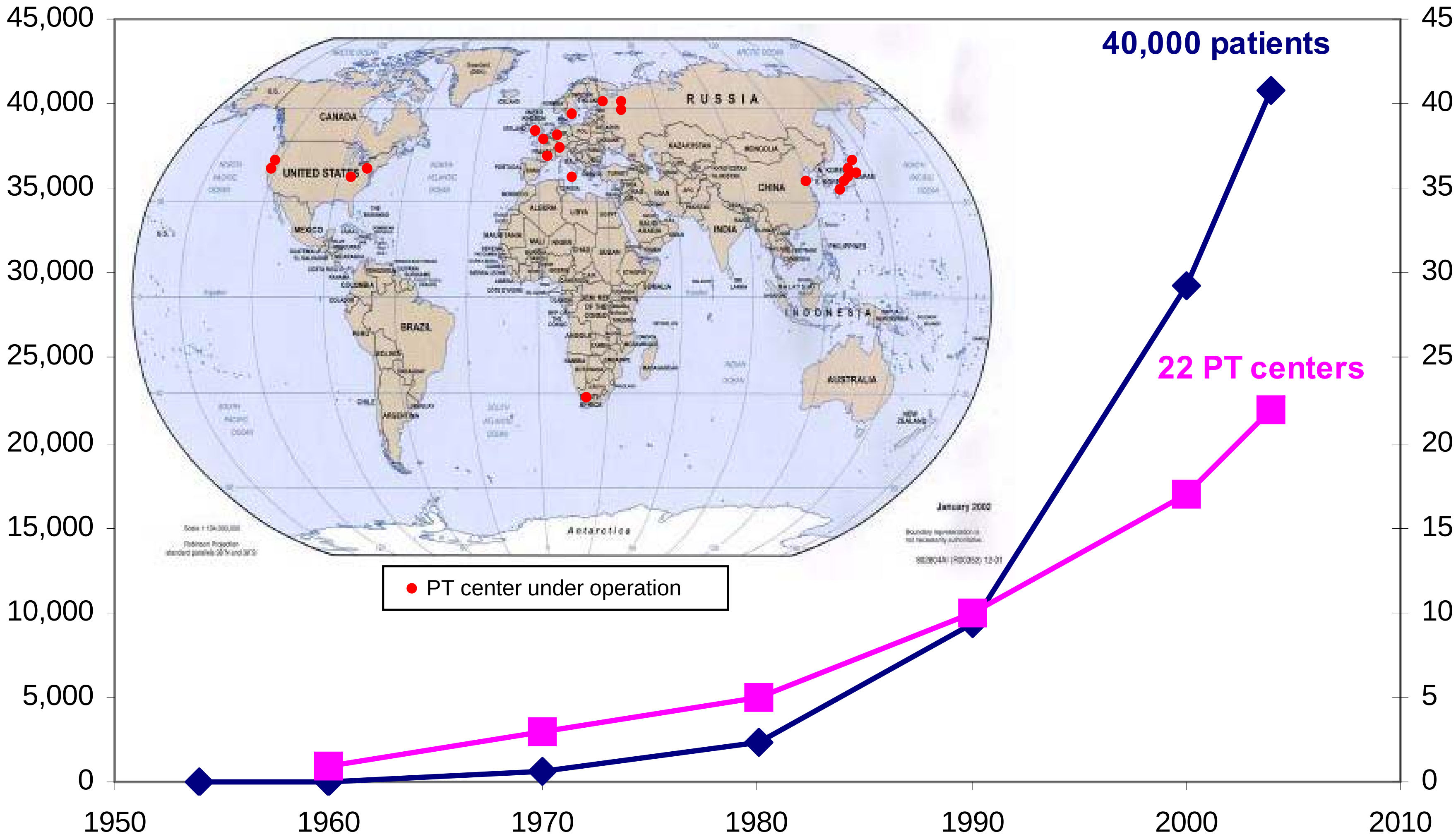
Clinical dosimetry in radiotherapy is well known matter but high conformal radiotherapy modalities (IMRT, Stereotactic treatments with photons and protons, IMPT) pose problems due to the small radiation fields with high dose gradients, to the variation in space and time of the dose rate and to the variation in space and time of the beam energy spectrum.

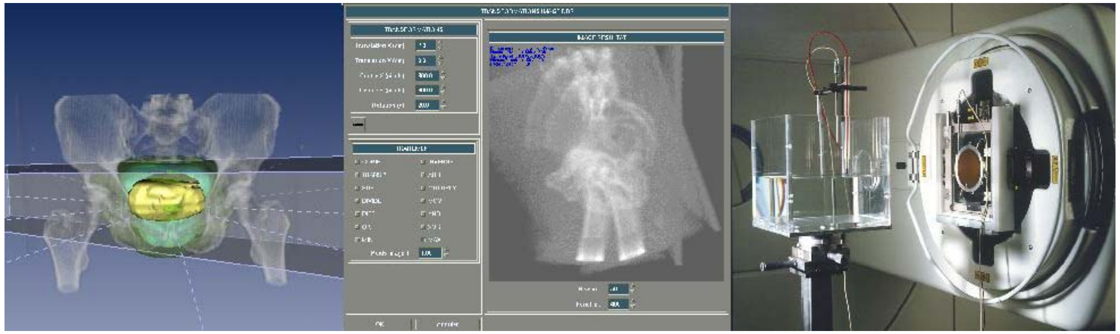


IMRT



IMPT


40,000 patients
22 PT centers
PT center under operation
45,000
40,000
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0
45
40
35
30
25
20
15
10
5
0
1950
1960
1970
1980
1990
2000
2010
CANADA
UNITED STATES
RUSSIA
CHINA
INDIA
BRAZIL
AUSTRALIA
Antarctica
January 2002

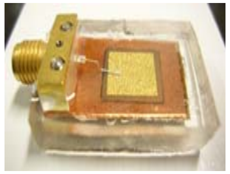


In the framework of the European Integrated project **MAESTRO**

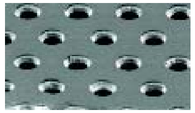
(Methods and Advanced Equipment for Simulation and Treatment in Radio-Oncology, no. LSHC-CT-2004-503564),

a dosimetric detector adequate for 2D pre-treatment dose verifications was developed.

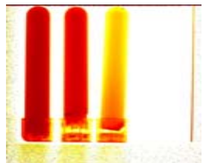
- The research is focused on point, 2D and 3D dosimeters.



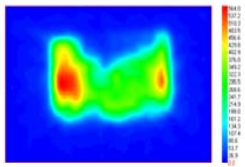
- *Diamond sensors for miniature dosimeters*
- *Optical Fibre Dosimeter*



- ***2D large area ionisation planar silicon detectors***
- ***Gas detectors***
- ***Pixel Ionisation Chambers for Proton therapy & IMRT***
- ***Large area thermoluminescent dosimeters***



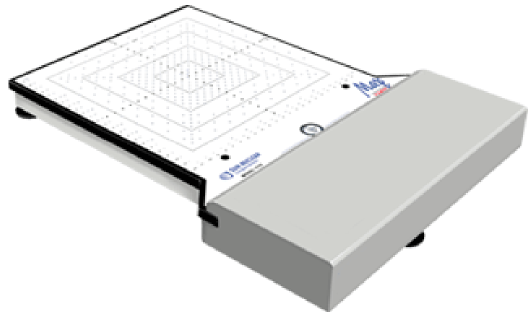
- ***Gel dosimetry optical readout systems by optical computed tomography***
- ***Three-Dimension Dosimetry with Plastic***



MAESTRO 2D validation protocol and procedures

1) Detector working in integration mode	**9) Linearity vs. absorbed dose** Requirement: < 1% in 0.1- 2000 cGy range
2) Spatial resolution: sensor size Requirement: 1-2 mm (photons) 1 mm (protons)	**10) Background signal** Requirement: < 0.1% of radiation induced signal
3) Spatial resolution: granularity Requirement: 1-2 mm (photons) 1 mm (protons)	**11) Energy dependence** Requirement: < 1% photons in 4–25 MV range Protons in 20-200 MeV range
4) Dose rate dependence Requirement: < 1% in the range 1- 400 cGy/min	**12) LET Dependence** Requirement: < 1%
5) Short-term precision Requirement: response repeatability < 0.5%	**13) Water equivalence**
6) Fast detector response Requirement: detector able to follow the linac output variation	**14) Angular dependence** Requirement: < 1%
7) Detector area Requirement: ≥ 20 cm x 20 cm	**15) Transparency** for beam monitoring devices
8) Radiation hardness Requirement: as much as possible	**16) Reproducibility** (different element of matrix) Requirement: < 1%

The requirements on the ideal detector for dose evaluation in radiotherapy are such that only few solutions exist but no one has the combined performance on high sensitivity, small dimensions and separation distance, tissue equivalence with high precision response and perfect stability.



445 silicon diodes

22X22 cm^2 diodes Pitch 1.0 cm

1024 cylindrical ionization chambers

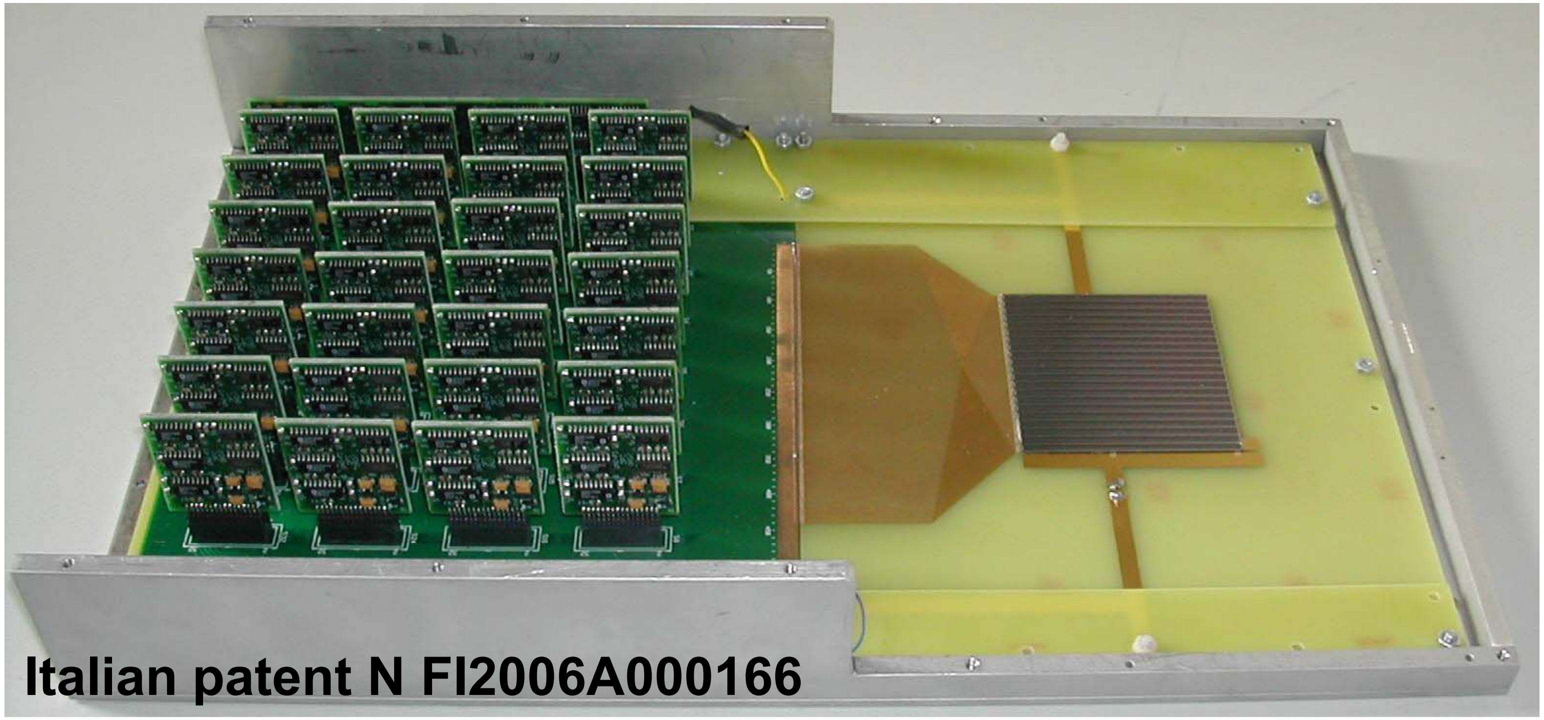
24 x 24 cm^2 Pitch 7.5mm

729 ionization chambers

27x27 cm^2 Pitch 10 mm

Our goal was to develop a device adequate for 2D pre-treatment in phantom dose verifications in conformal radiotherapy on a beam-by-beam basis.

Accurate determination of the 2D absorbed dose distribution requires detectors with **high spatial resolution**, a **response independent** of the **dose rate**, of the **energy**, **fast**, **stable in time**, with a **good linearity** and **high dynamic range**.



It is a modular detector, based on a monolithic silicon segmented sensor, with a n-type implantation on an epitaxial p-type layer. Each **pixel** element is **2x2 mm^2** and the distance **center-to-center** is **3 mm**. The sensor is composed of 21x21 pixels. **Area 6.29x6.29 cm^2**.

Attractives of Si:

a) linear relationship between photon energy and e/h pairs;

b) high sensitivity (Si ~3.6 eV/pair)⇨small active volume⇨<u>high spatial resolution</u>;

c) well developed technology for the production of segmented monolithic planar detectors.

Material Problems and solutions

Commercial single-pad Si dosimeters: dependence of sensitivity on dose.

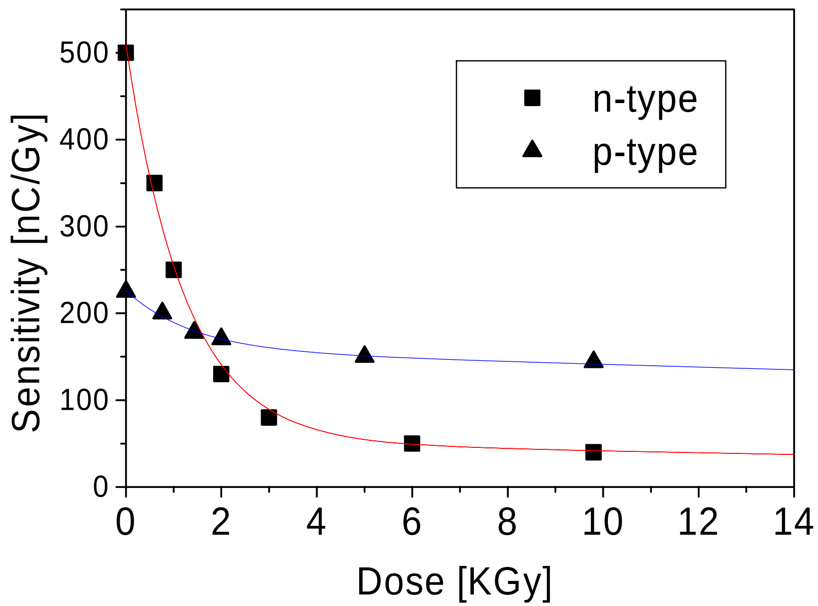
Key idea: to fix the pixel active volume by limiting its lateral size and depth to values shorter than diffusion length after irradiation at the higher operative dose.

Sensitivity of silicon is quite high, and the subsequent reduction in signal strength is of no concern.

In practice: lateral size limited by a guard ring structure; active thickness limited by implanting the pixels upon a 50 μm thick epitaxial layer.

$S \propto L = \sqrt{(D\,\tau)}$, D diffusion coefficient , τ minority carrier lifetime:

$$1/\tau = 1/\tau_0 + K\,D$$



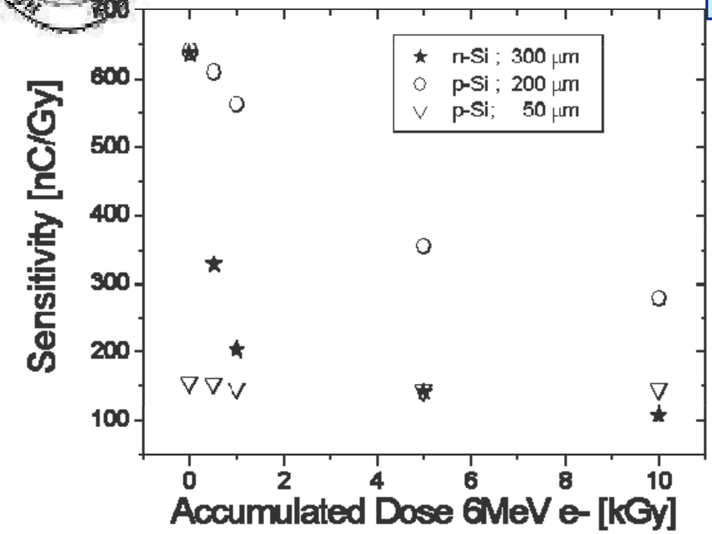
G.Rikner et al.Phys. Med. Biol. 28, 1983, 1261-12670

Standard Si dosimeters

➔ Pre-irradiation up to 10kGy

➔ Frequent Calibration

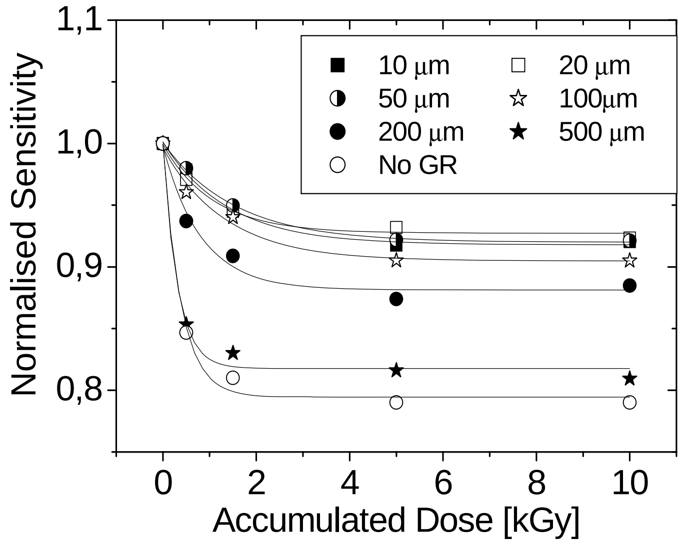
Choice of Si material and pixel geometry



-Irradiation of test samples with 6 MeV electrons.

-Comparison of samples of different materials (Cz, FZ, epi), resistivity and type (n/p).

-p-type Epi diodes show the higher radiation hardness in terms of sensitivity reduction.



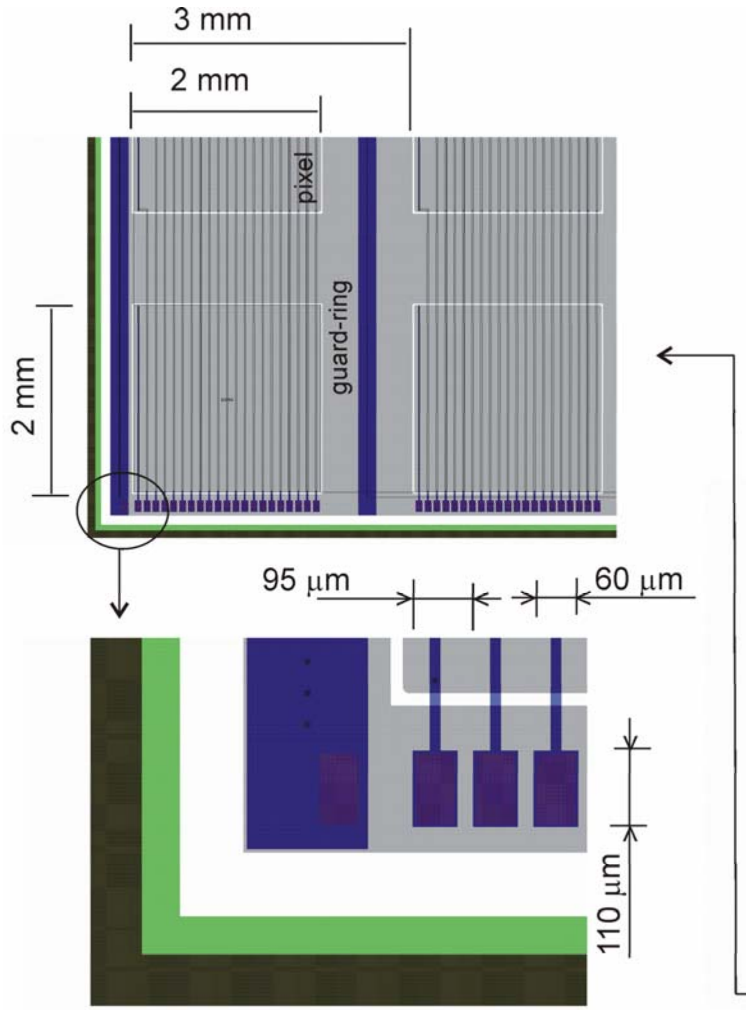
-Measurements on p type, **50 μm thick**, epi samples with a different pad to guard-ring distance *X*.

-A **close guard ring (20 μm)** excludes the contributions from the lateral area diffusion.

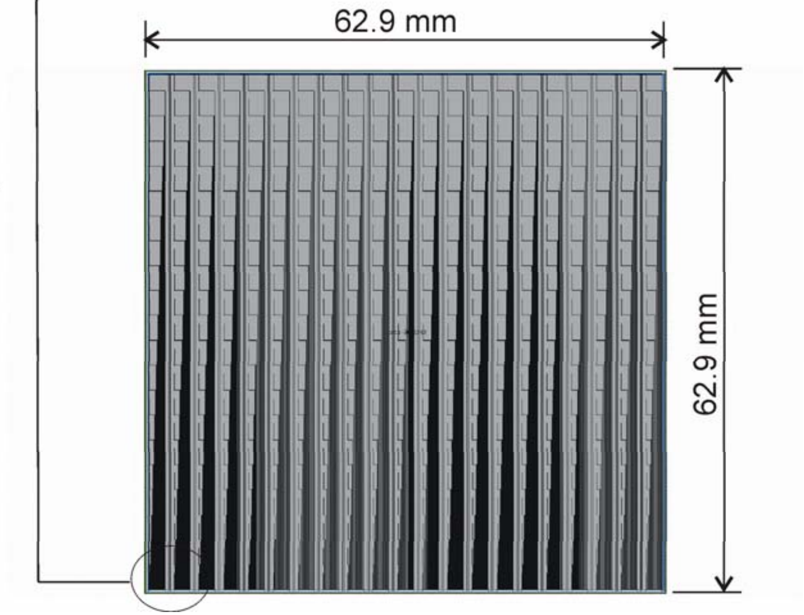
-Sensitivity slightly decreases for Doses up to 1.5 kGy (3.5 % for X=10 **μm**) and it is almost constant up to 10 kGy (within 1.8%).

Epitaxial silicon devices for dosimetry applications , Bruzzi M, Bucciolini M, Casati M., Menichelli D., Talamonti C., Piemonte C., Svensson BG., Appl. Phys. Lett. 90, 172109 2007

Design and production of silicon modules



441 Si *n+p* diodes, 50 µm epi layer on p MCz.
Active area: 6.29x6.29 cm^2.
Segmentation: 21x21 pixel (2×2 mm^2, 3 mm pitch).
Overmetal strips to 441 pads along one single side.
Diffused guardring structure at 20 µm from pads.
DC coupling.

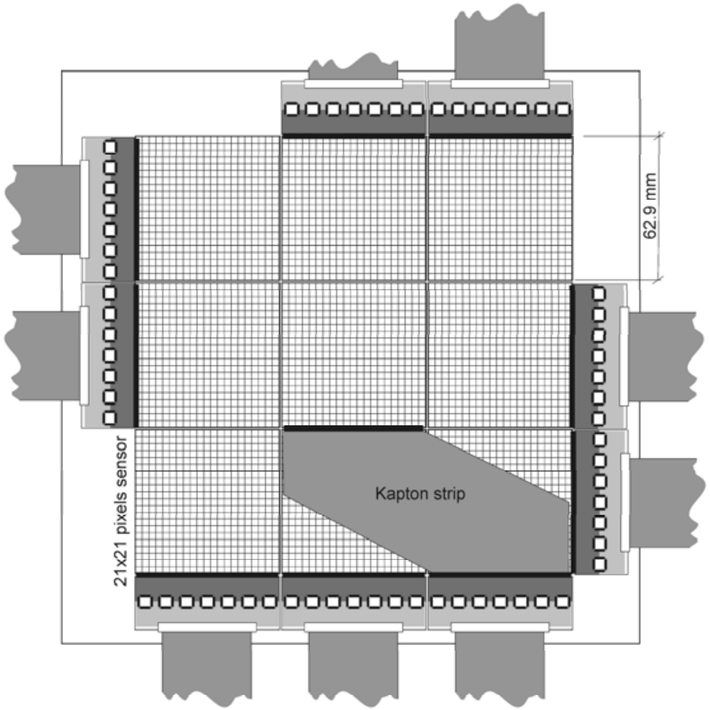


9-modules design:

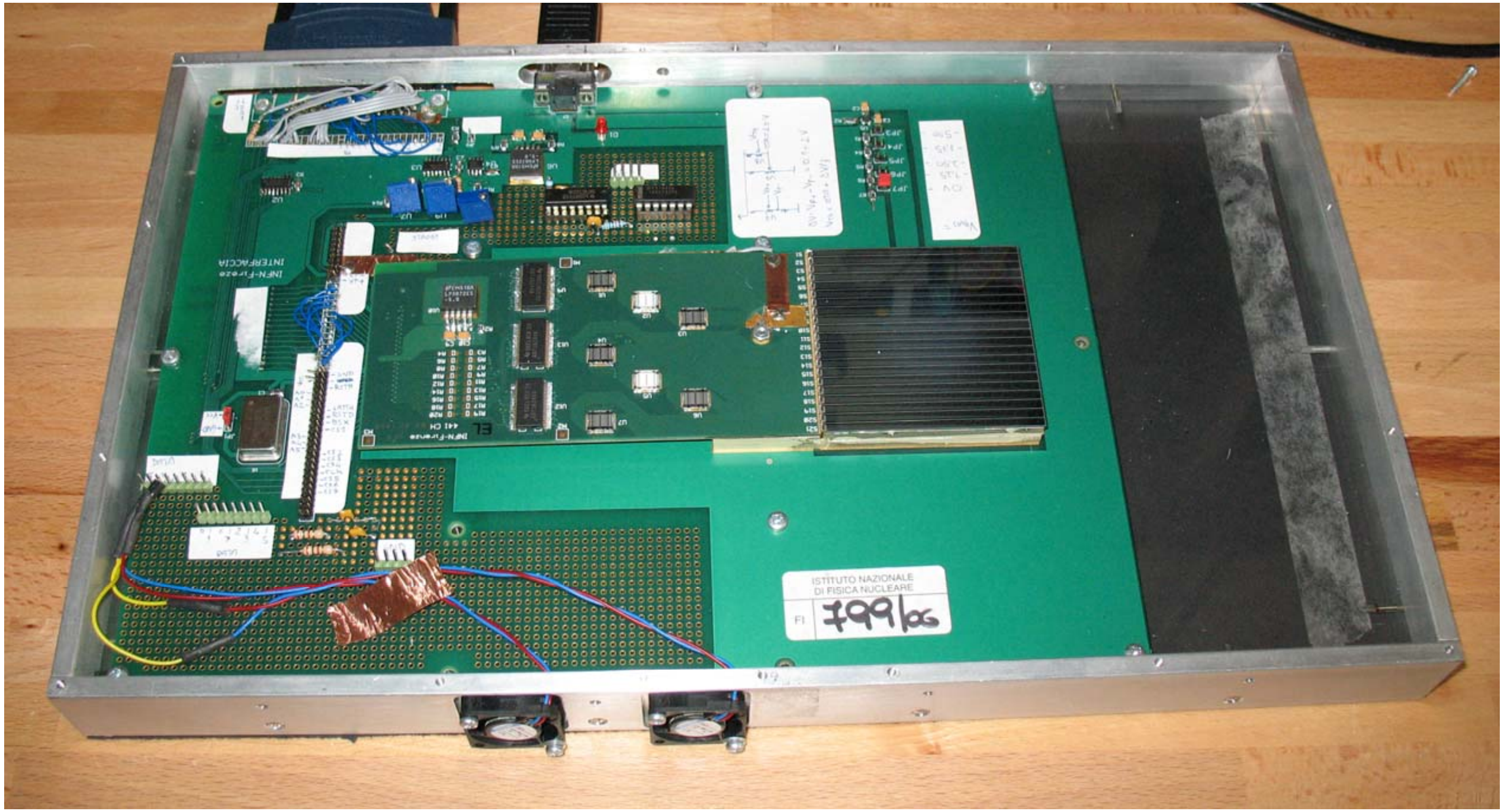
A single module cut from each wafer.

Nine modules will be used to cover an area of about 20×20 cm^2.

System complexity: ~4k channels



441ch TERA-based prototype



Device			State	Completed /to be completed by:
Silicon Module (15 6x6 samples from IRST)		✓	Designed, manufactured and tested	Aug. 2005
441 ch prototype with discrete electronics		✓	Assembled and tested	March 2006
ASIC choice and testing		✓	Done	June 2006
441 ch prototype with integrated electronics	Design	✓	Done	Sept. 2006
	Part manufacturing	✓	Done	Jan. 2007
	Assembling	✓	Done	May 2007
	Debug	O	In progress	May 2007
	Beam test	X	To be done	Sept. 2007
Full detector 4k ch	Design	✓X	Done, in part	during 2008
	Part manufacturing	OX	In progress, in part	
	Assembling	X	To be done	
	Debug	X	To be done	
	Beam Test	X	To be done	

Dosimetric characterization
Photon beam

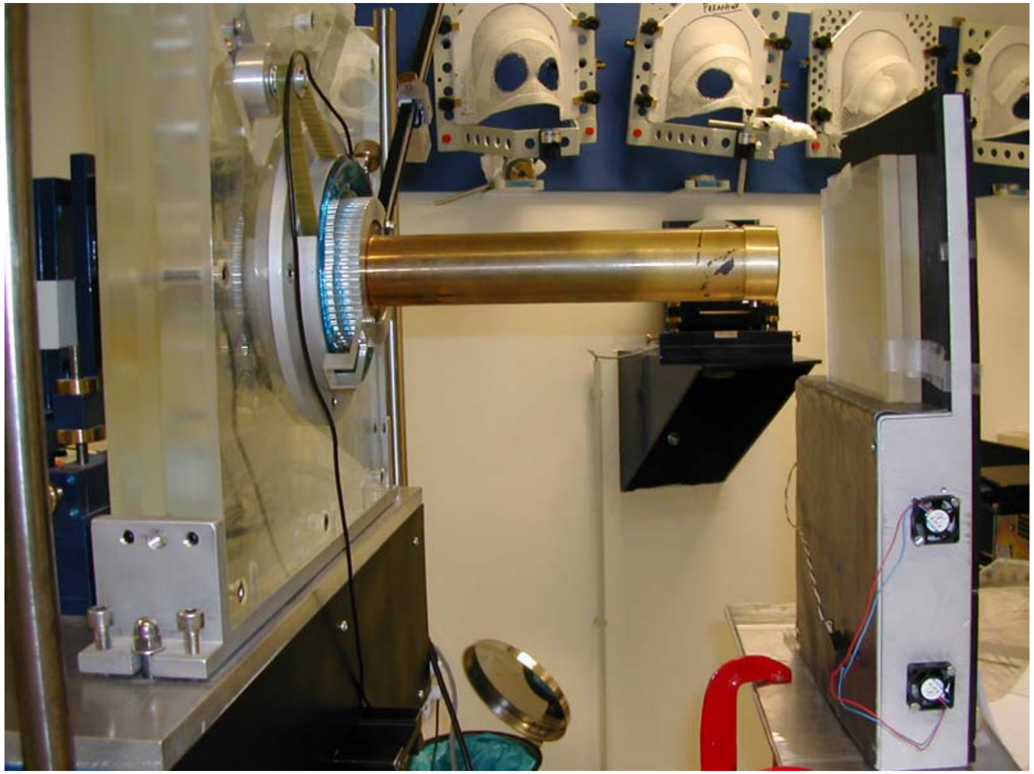
The module was irradiated with 6, 10, 25 MV photon beams from Precise LINAC (ELEKTA)

The dosimetric characterization has been performed following the protocol and the procedures defined inside MAESTRO Project.

Almost all the channels exhibit performances within the project specifications repeatability < 0.5%, reproducibility < 1%, deviation from linearity < 1%, dose rate dependence < 1%.

Preliminary results of dosimetric characterization of a silicon segmented detector for 2D dose verifications in radiotherapy, C. Talamonti, M. Bruzzi, M. Bucciolini, L. Marrazzo, D. Menichelli Nucl.Instrum.Meth A (in press).

Dosimetric characterization: Proton Experimental setup



The module was irradiated with 62 MeV protons for medical applications at INFN-LNS Catania

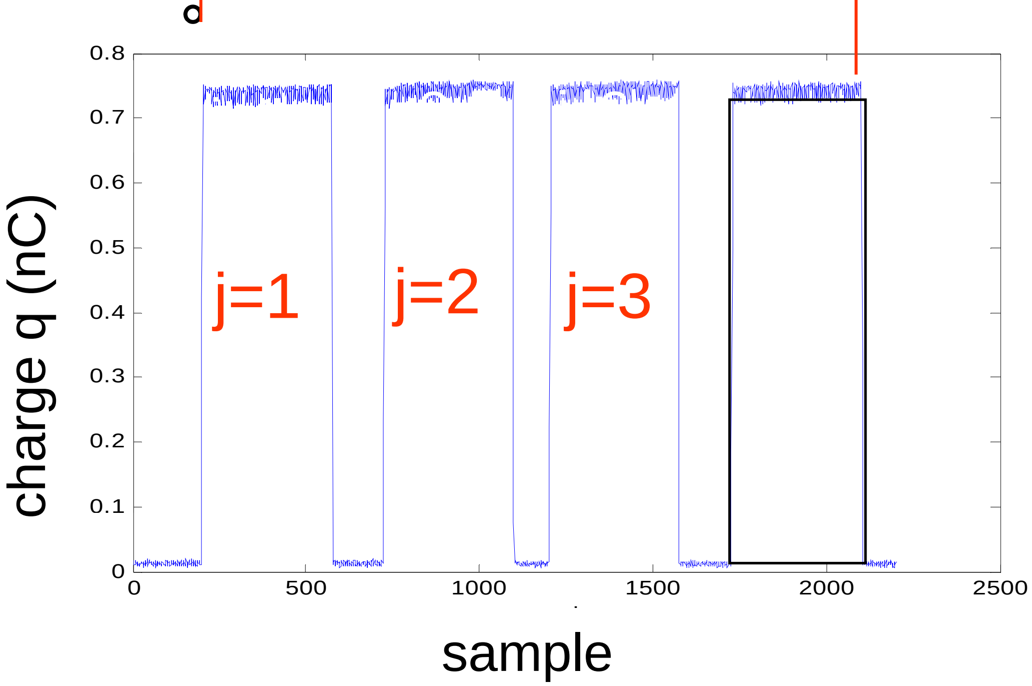
During one irradiation several samples (q) are acquired (time >>T=205 ms). They are summed off line (Q).

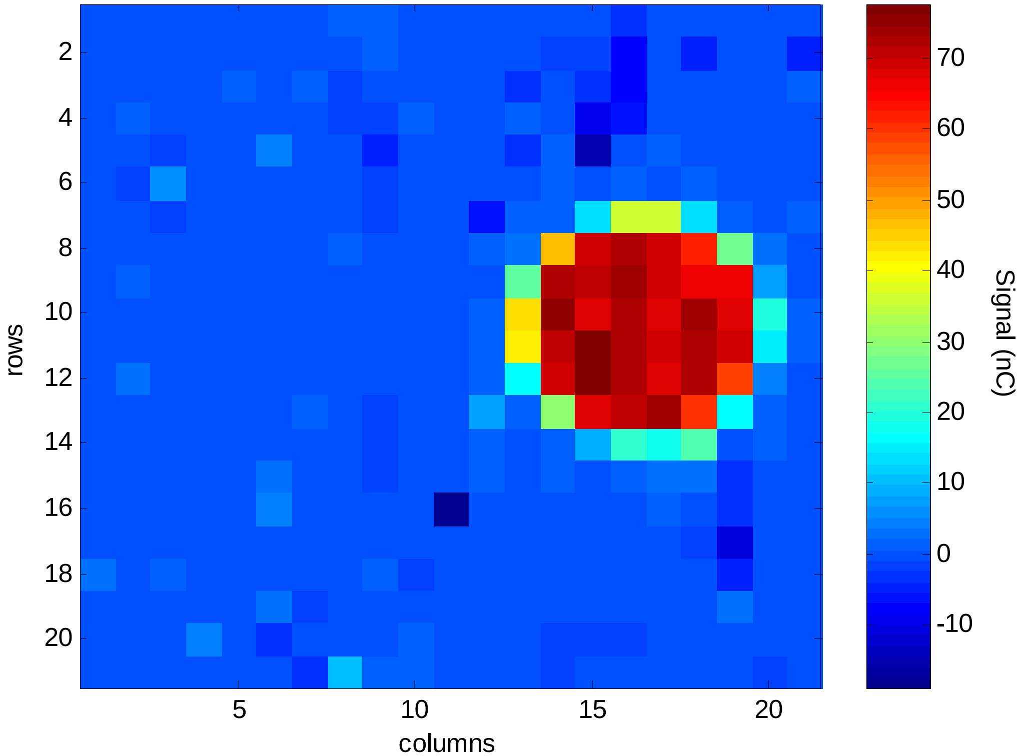
$$q_{ni} \equiv 1nF \times V_{ni}$$

$$Q_{nj} = \sum_i q_{ni}$$

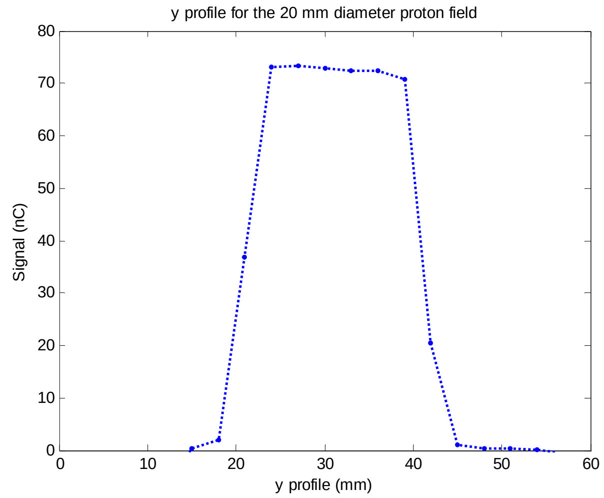
The signal is expressed in C, assuming the integration on a conventional capacity of 1nF.

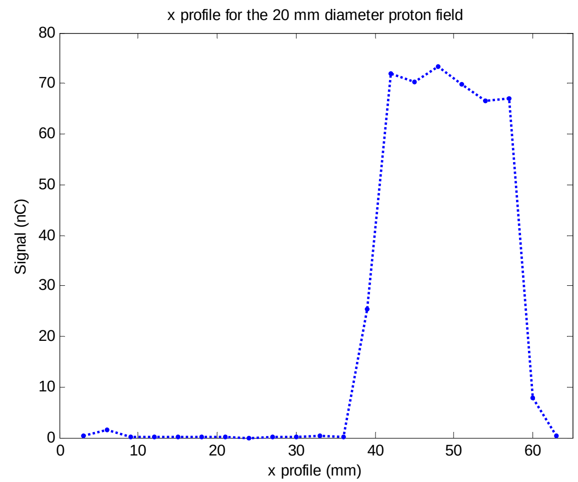
Fluctuations during irradiations because of noise of the device and dose rate instability of the beam.





Field size 20 mm diameter





Repeatability

Dose rate (Gy/min)	Repeatability	
	σ% (%)	$N_{0.5}$ (%)
0.18	0.8	58%
2.5	0.2	100%
6.8	0.2	100%
14	0.5	70%

- $\sigma_n < 0.5\%$ for most of the channels in the radiation field if $R_N \geq 2.5$ Gy/min.

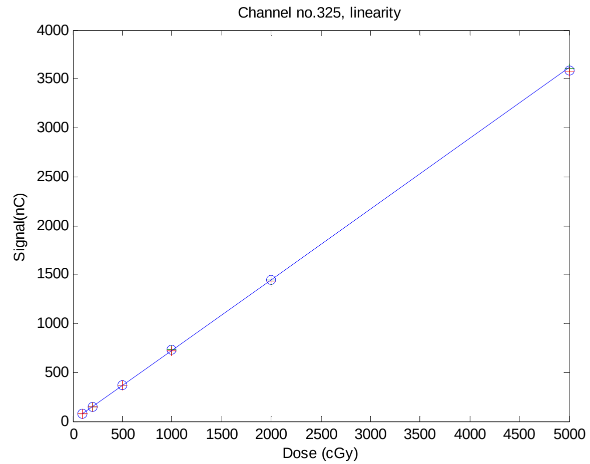
MAESTRO requirement: σ% < 0.5 %

$N_{0,5}$ is the percentage of pixels with σ(%) < 0.5%.

Linearity

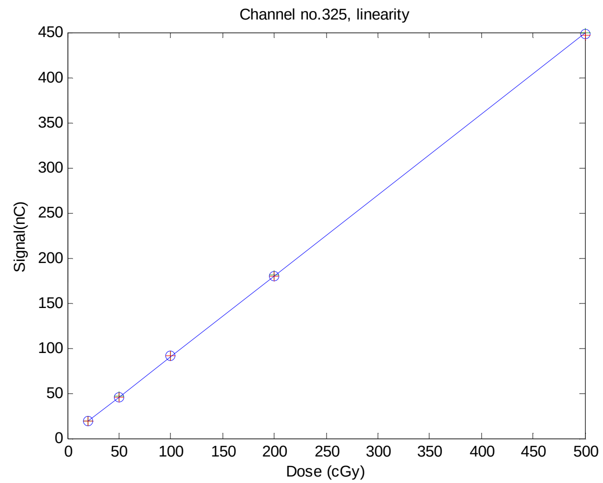
Nominal dose rate (Gy/min)	$<d_n>_n$ (%)	N_1 (%)	$<a_n>_n$ (nC/cGy)	$<\delta a_n>_n$ (nC/cGy)
14	1	65	0.723	0.002
2.5	1	57	0.895	0.001

Dose rate
14 Gy/min



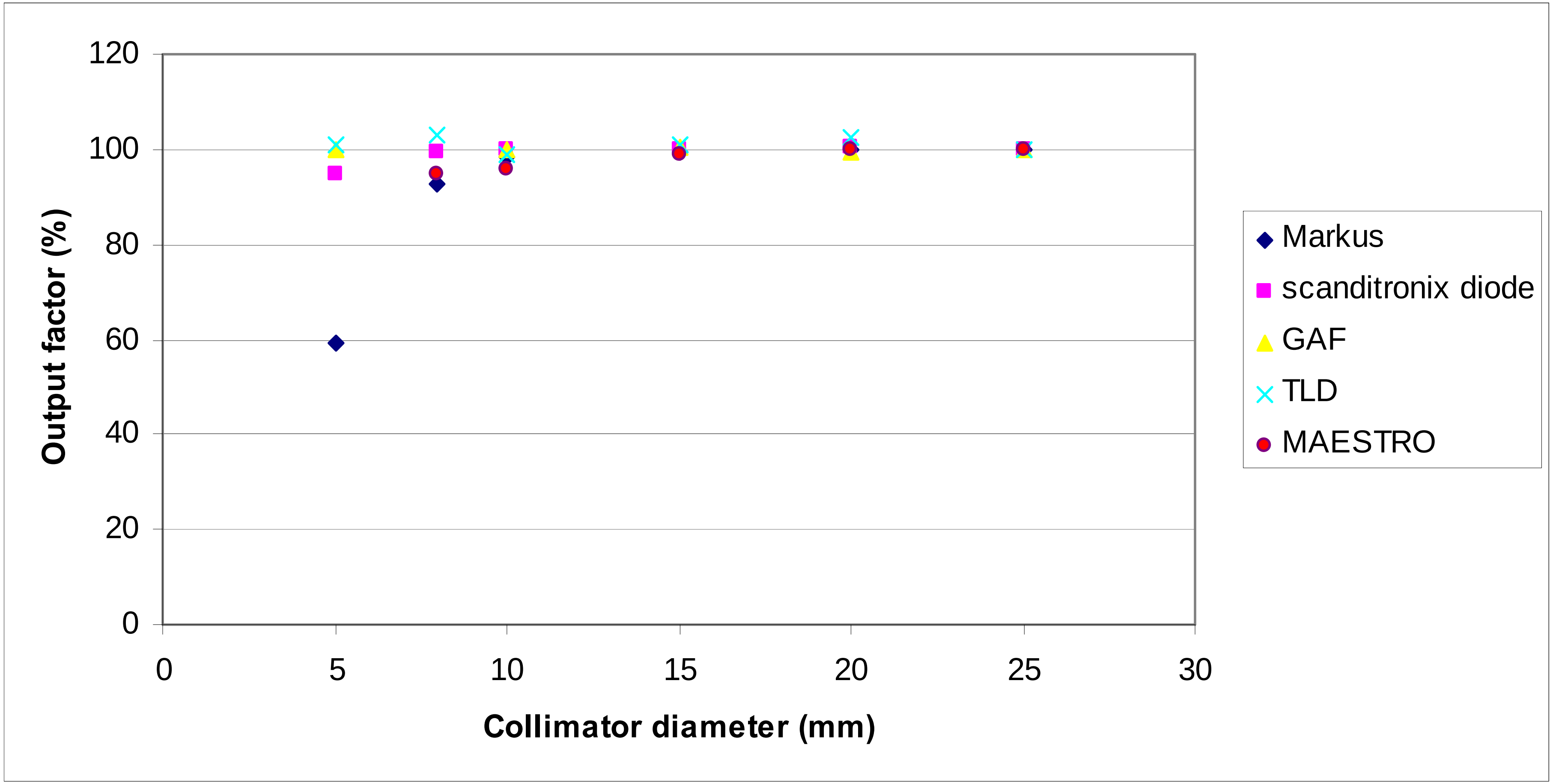
Range 20- 5000 cGy

Dose rate
2.5 Gy/min

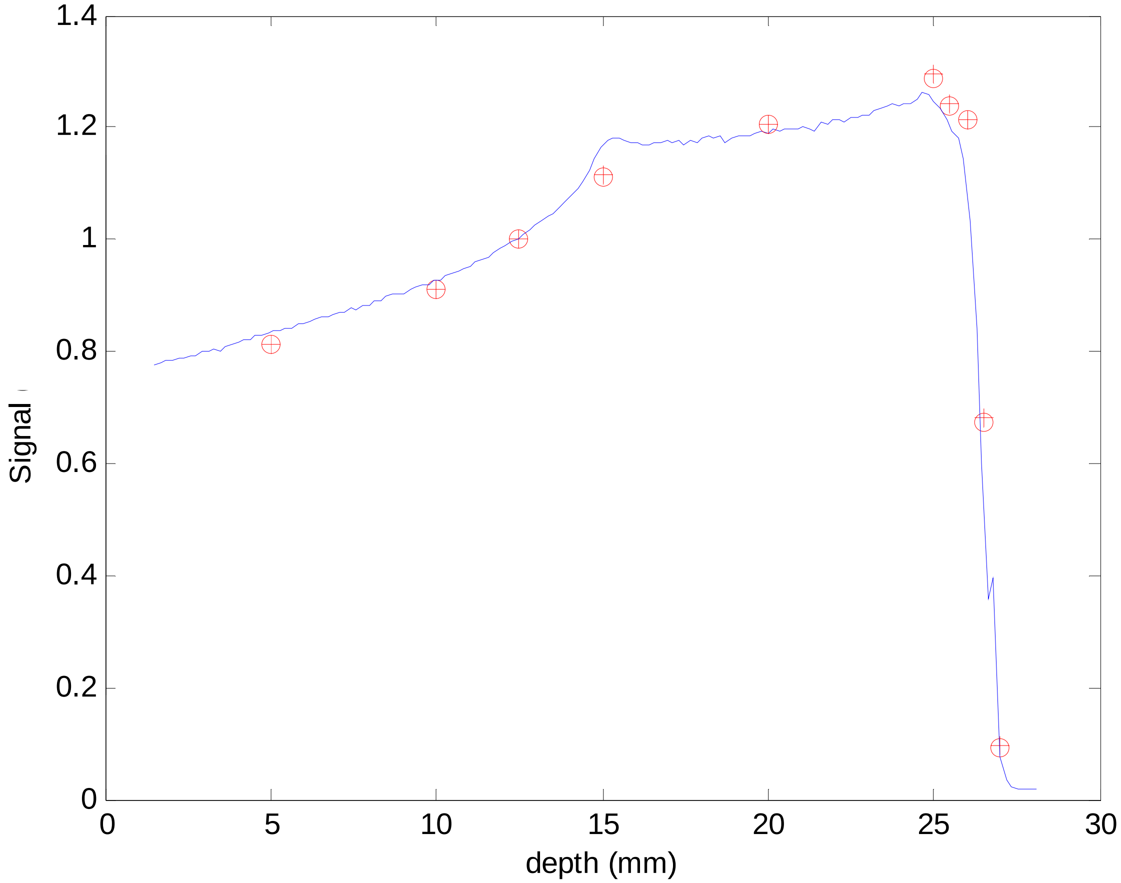


MAESTRO requirement: d<1 %

Output factors (protons)



Depth dose measurements (protons)



Spread Out Bragg Peak

CATANA:
62 MeV proton beam

Measurements in PMMA

Radiation damage

Photons:

The device was exposed to a radiation dose of about 0.5 kGy and the reduction in sensitivity is about 2%. This result agrees with the results of experiments performed on single diodes of the same materials.

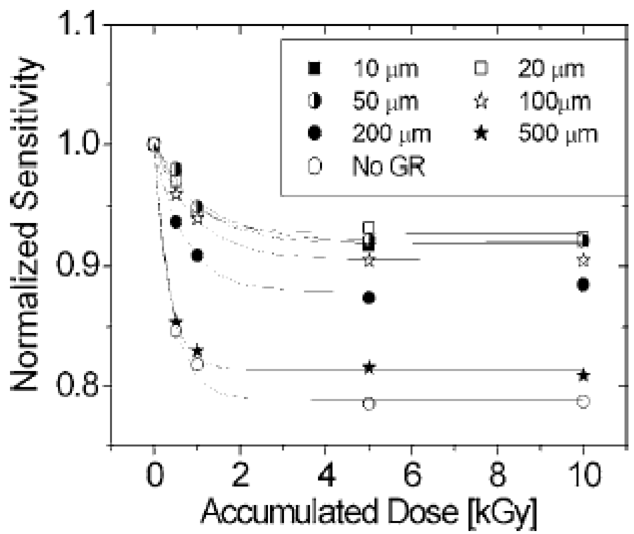


FIG. 2. Sensitivity of epitaxial (w=50 μm) dosimeters as a function of the dose delivered by 6 MeV electrons, normalized to the zero-dose value. Samples with different electrode-to-guard ring distances (d=10–500 μm) and a diode without guard ring have been tested.

Considering the results obtained with the single diode, we expect that the sensitivity still decreases with the accumulated dose.

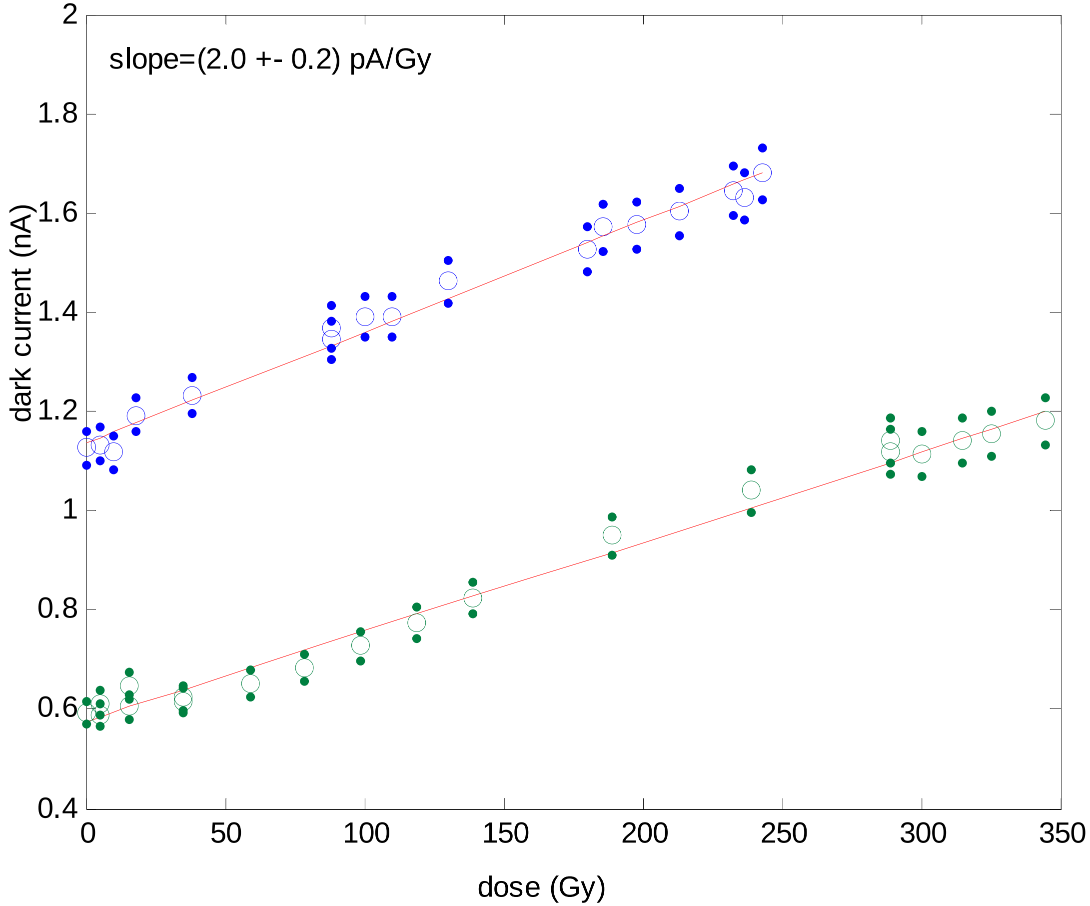
Epitaxial silicon devices for dosimetry applications , Bruzzi M, Bucciolini M, Casati M., Menichelli D., Talamonti C., Piemonte C., Svensson BG., Appl. Phys. Lett. 90, 172109 2007

Protons:

The device was exposed to a radiation dose of about 0.6 kGy and the reduction in sensitivity is about 1,5%.

We still haven't performed any tests on proton damage of the single diode. We can just compare this result with the electron curve and this result agrees with the results already shown. After a sensitivity decrease<of about 7% observed up to 1.5 kGy, its sensitivity remains constant within 1.8% up to 10 kGy.

The sensitivity should still decrease with the accumulated dose up to 1.5 kGy


slope=(2.0 +- 0.2) pA/Gy
dark current (nA)
dose (Gy)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0
50
100
150
200
250
300
350

Conclusions

- We described the device developed inside the MAESTRO project
- It is suitable for measurements with proton beams also with low energy protons that correspond to the highest LET.
- Next step is to characterize the new prototype with a discreet electronics
- We are also planning   to performer study of radiation damage with proton beam on the single diode