Recent results on the development of a p-type 2D Silicon dosimeter for Intensity Modulated Radiotherapy

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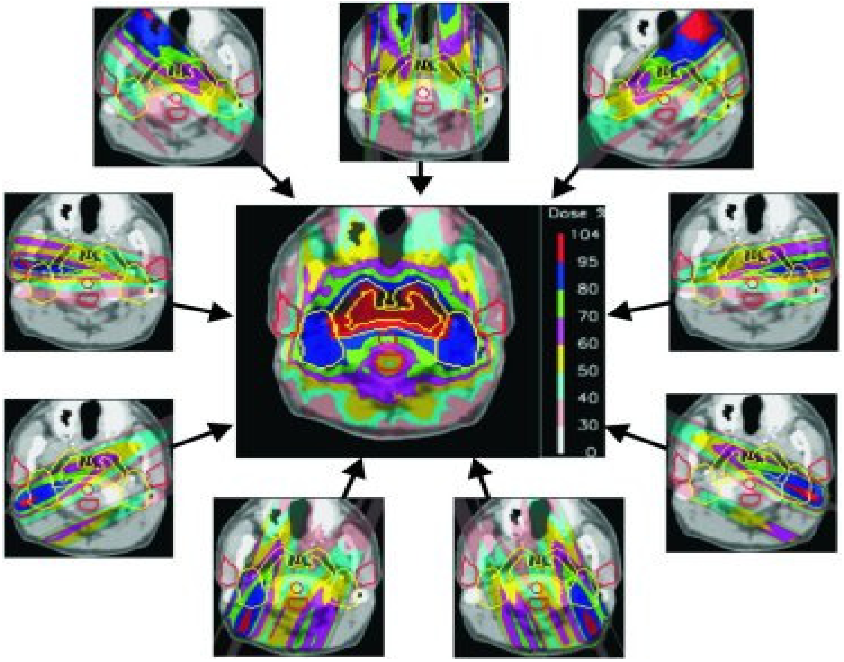
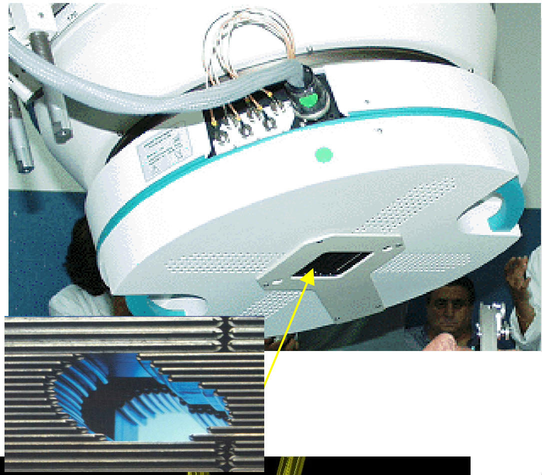
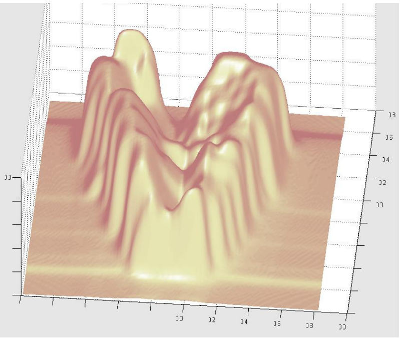
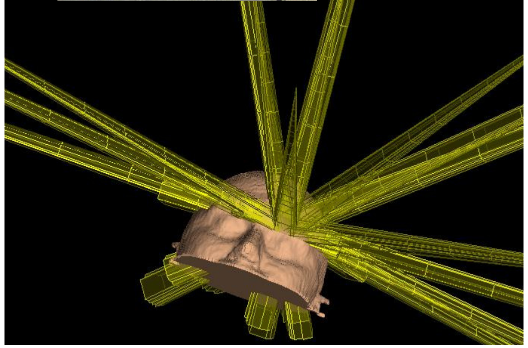
6th "Trento" Workshop on Advanced Silicon Radiation Detectors (3D and P-type Technologies) FBK – irst, Trento, Italy, March 2-4, 2011

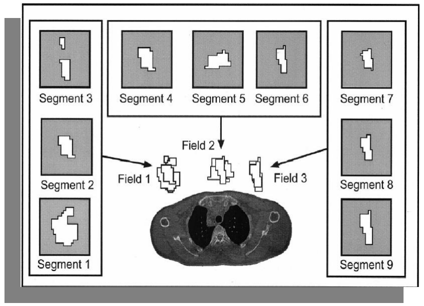
Clinical dosimetry in radiotherapy is well known matter but high conformal radiotherapy modalities (IMRT, Stereotactic treatments with photons and protons, IMPT) pose problems due to the **small radiation fields** with **high dose gradients**, to the **variation in space and time of the dose rate** and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





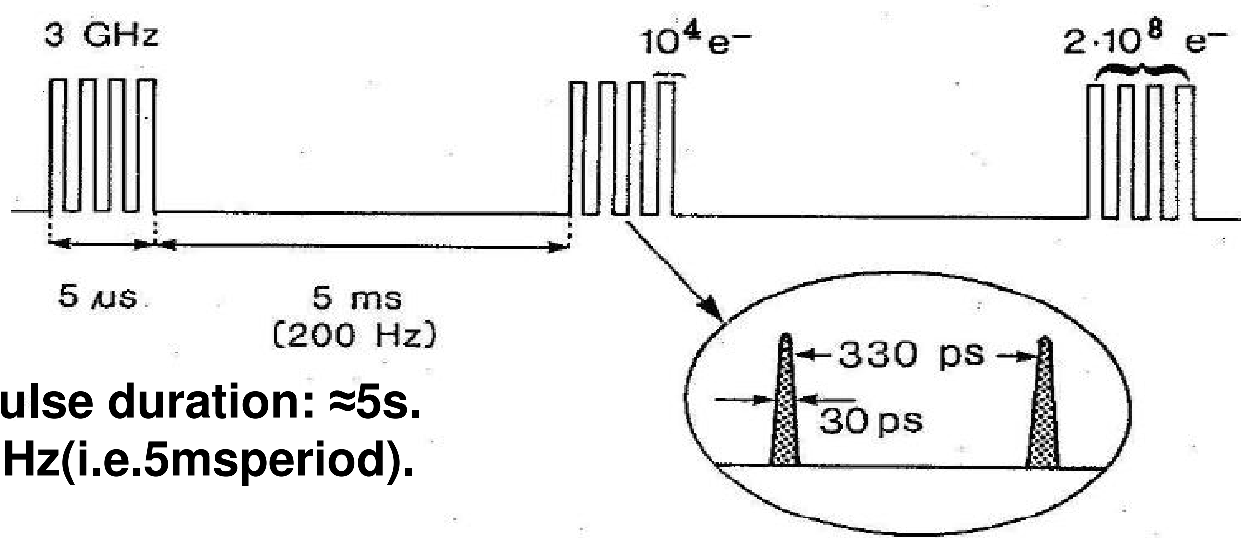






LINAC beam structure

Radiation: electrons or Bremsstrahlung photons



(Macro) pulse duration: ≈5s.
PRF:~200Hz(i.e.5msperiod).

(Micro) pulse frequency:~3GHz(i.e.330ps period).
(Micro)pulse duration:~30ps.
Beam quality: 6-18MV (photons)
6-18MeV (electrons)
Doserate: 3-6Gy/min (flattened).
10-50Gy/min (unflattened).
Dose: 0.3-0.5mGy/pulse (flattened)
0.8-4mGy/pulse (unflattened)

The silicon choice

Advantages:

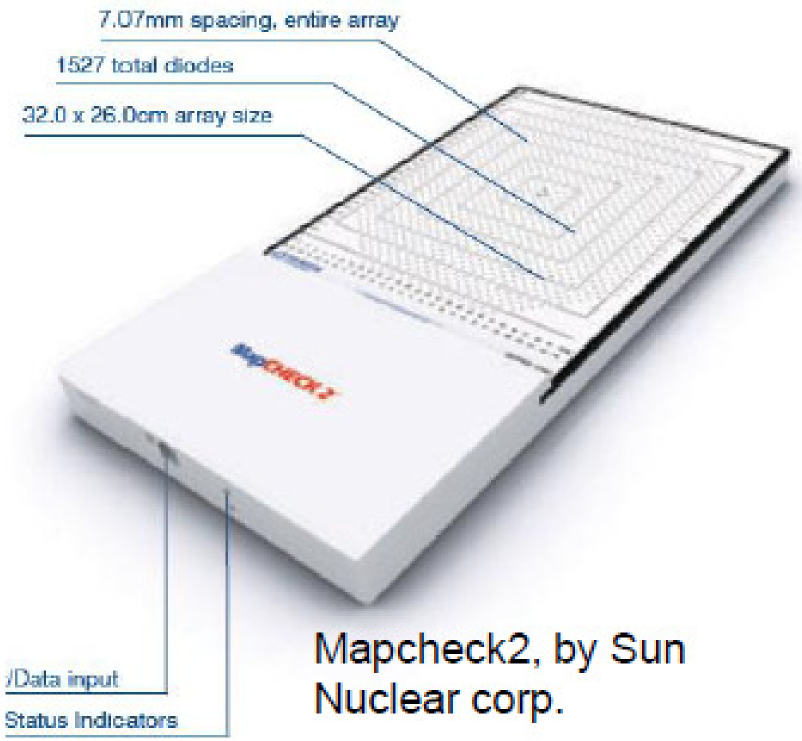
- High sensitivity (about 18000 times higher than air filled IC with same active volume).
- Well developed manufacture technology.
-high spatial resolution.
- work in null bias mode (in-vivo applications possible).

Drawbacks:

- Sensitivity decrease with accumulated dose due to increase of concentration of recombination centers (recalibrations needed).
- Dose rate dependency due to centers saturation at high dose rates.
- Energy dependence, since Si is not "water equivalent" (Z=14).

Present use of Si diodes in dosimetry
i) Radiation field analysis (especially profile measurement).
ii) Direct patient dosimetry ("in vivo" diodes).

Arrays of single diodes are already commercially available for 1D and 2D measurements, granuaity is limited due to assembling difficulties.



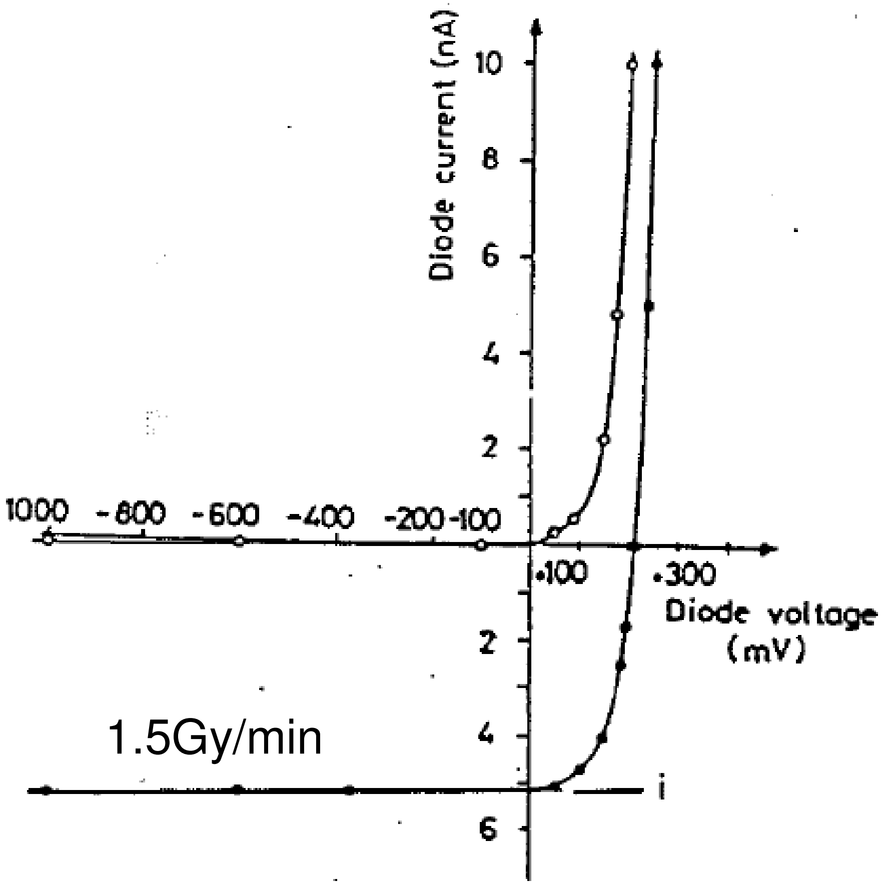
Mapcheck2, by Sun Nuclear corp.

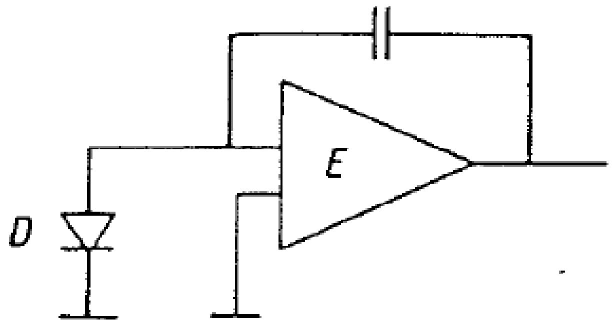
IBA dosimetry LDA99.

Sensor:	n-type diode, Pt doped;
Detectors active area:	0.64mm^2;
Active volume:	0.019mm^3;
Sensitivity:	32nC/Gy;

Sensor:	p-type;
Diode spacing:	5mm;
Detectors active area:	3mm^2;
Sensitivity:	35nC/Gy;

Si dosimeter working principle: Photovoltaic Mode





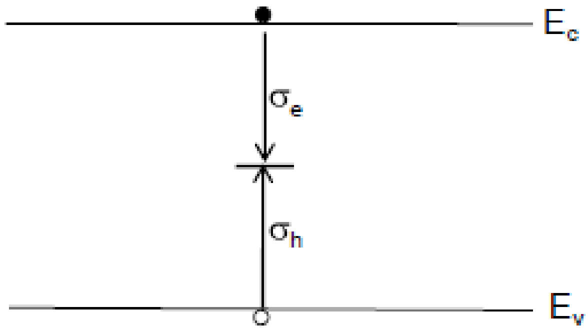
a) null bias;
b) DC coupling;
c) Sampling time and reset fixed by digital electronics (usually T≈10ms);
d) Only integrated charge measured.

Sensitivity of the device scales with diffusion length: $$L_{e,h} = \sqrt{D_{e,h}\tau_{e,h}}$$

$$D_{e,h} = \mu_{e,h} K \cdot T/e$$

The issue of radiation damage in Si dosimeters

Indirect recombination via midgap levels dominant in Si…



.. a two-step process where both electron and hole are captured by the centre

Carrier lifetimes are given by $\tau_{e/h} = \dfrac{1}{\sigma_{e/h} v_{e/h} N_t}$.

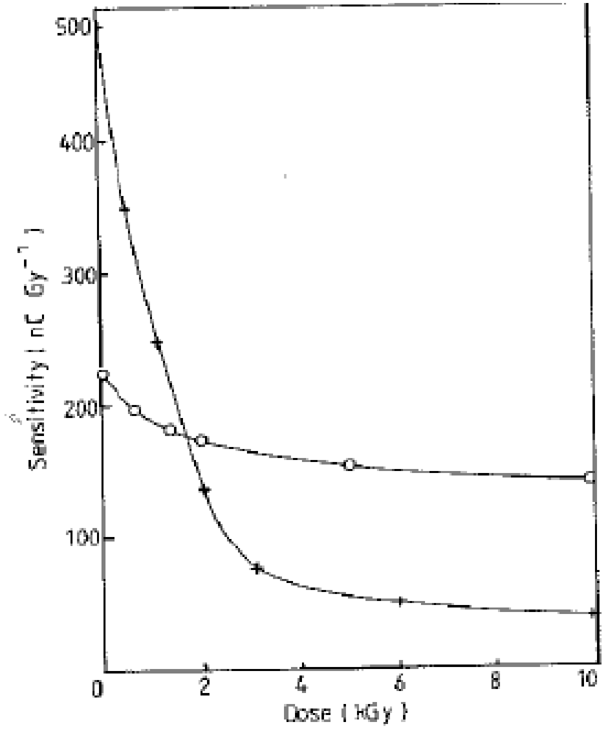
$\sigma_{e,h}$= capture cross sections
$v_{the,h}$= thermal velocity
N_t= concentration

As N_t grows with irradiation τ and L decrease with the accumulated dose.

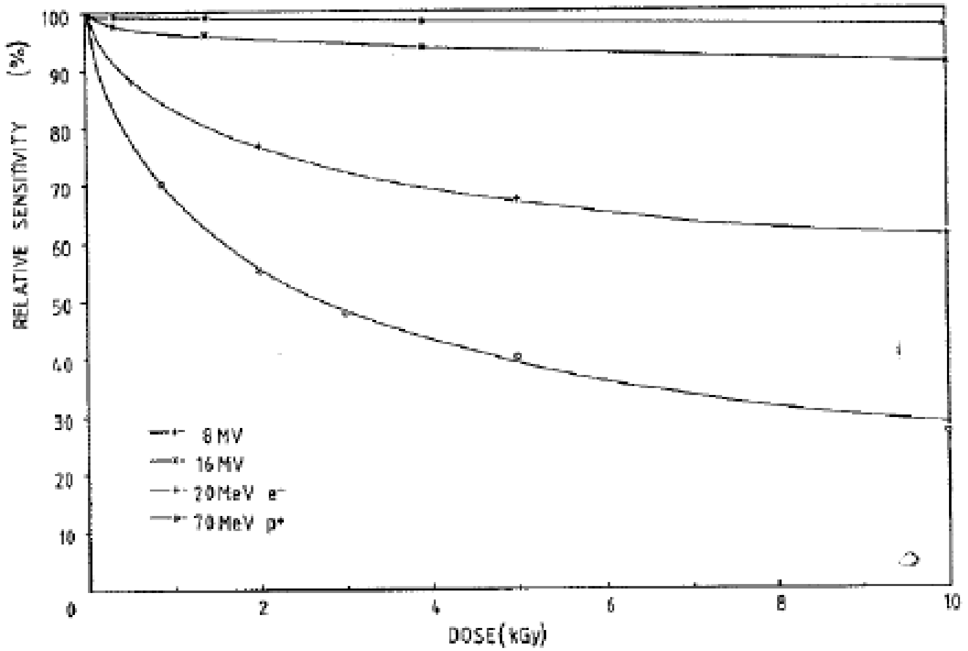
This leads to a decrease in sensitivity during device lifetime → recalibration needed

Radiation hardness of Si dosimeters

First radiation hardness solution (≈1980) has been pre-irradiation before use. In fact, since $S \alpha N_t^{-1/2}$ pre-irradiation reduces the slope of sensitivity vs. dose curve. Usually 10kGy are adopted as a typical pre-irradiation.

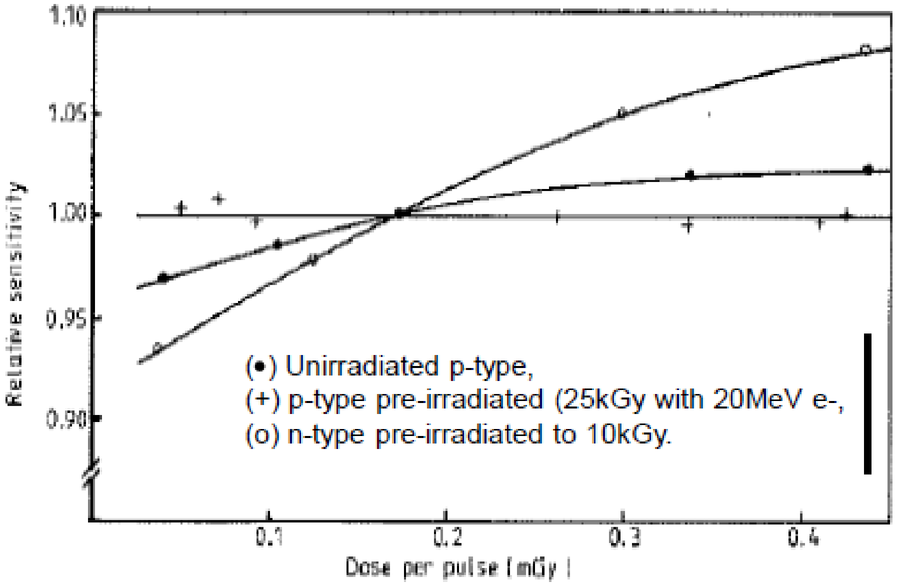


Sensitivity in a Co field of a p-type (o) and n-type (+) detectors, preirradiated with 20MeV electrons.
After Grusell andd Rikner , 1984, Acta RAdiologica Oncology 23, 465-469.



Relative radiation damage effects caused by high energy radiation in p-Si detectors.
After Rikner G. et al., 1983, Nucl. Instr. and Meth. A, 217, 501-5.

Another radiation hardness solution (≈ 1980) was: working with p-type materials.



After Rikner G. and Grusell E., 1983, Phys. Med. Biol., 1261-67.

In fact, dominant center produced by electron irradiation has cross sections:

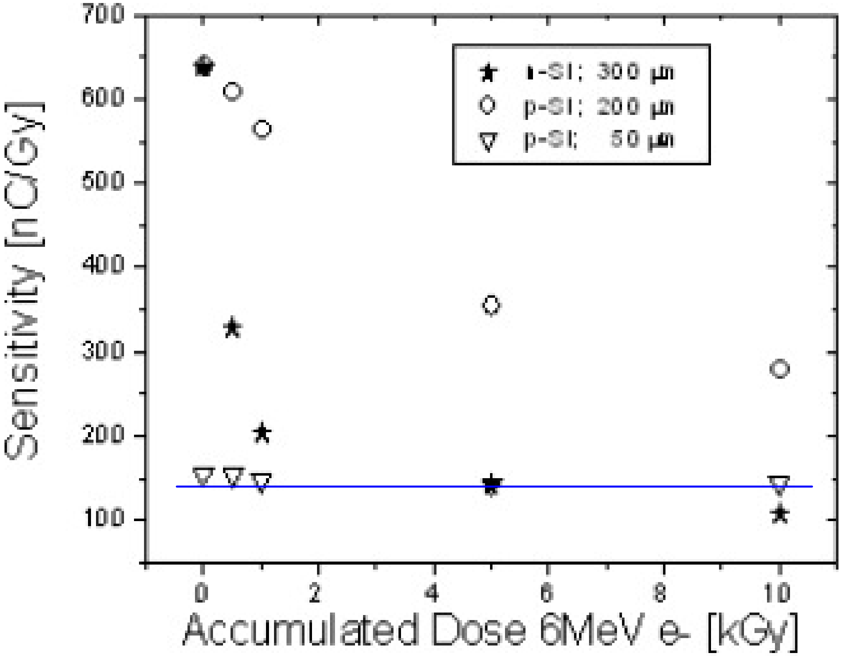
$$\sigma_e=1.62\times10^{-16}\mathrm{cm}^2,$$
$$\sigma_h=8.66\times10^{-16}\mathrm{cm}^2.$$

see Shi J., Simon W. E., 2003, Med. Phys. 30, 2509-19 and cited refs.

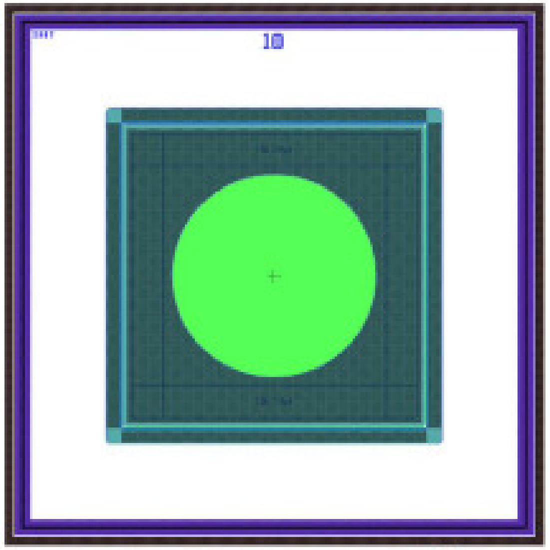
This means that for this center is easier to capture holes. As diffusion is ruled by minority carriers, to get a transport less influenced by irradiation minority carriers must be electrons, thus material has to be p-type.

Our Solution : low resistivity epitaxial p-type Si on MCz substrates

Concept: active region is limited in any direction to a value shorter than L_e at the highest dose of interest. Epitaxial Layer is used to limit active depth, guard-ring to limit active area.

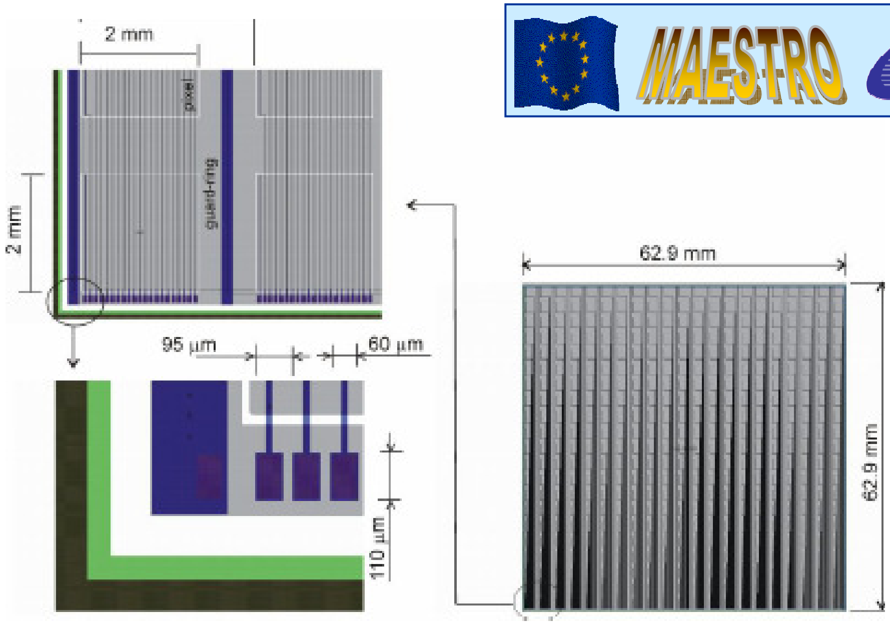


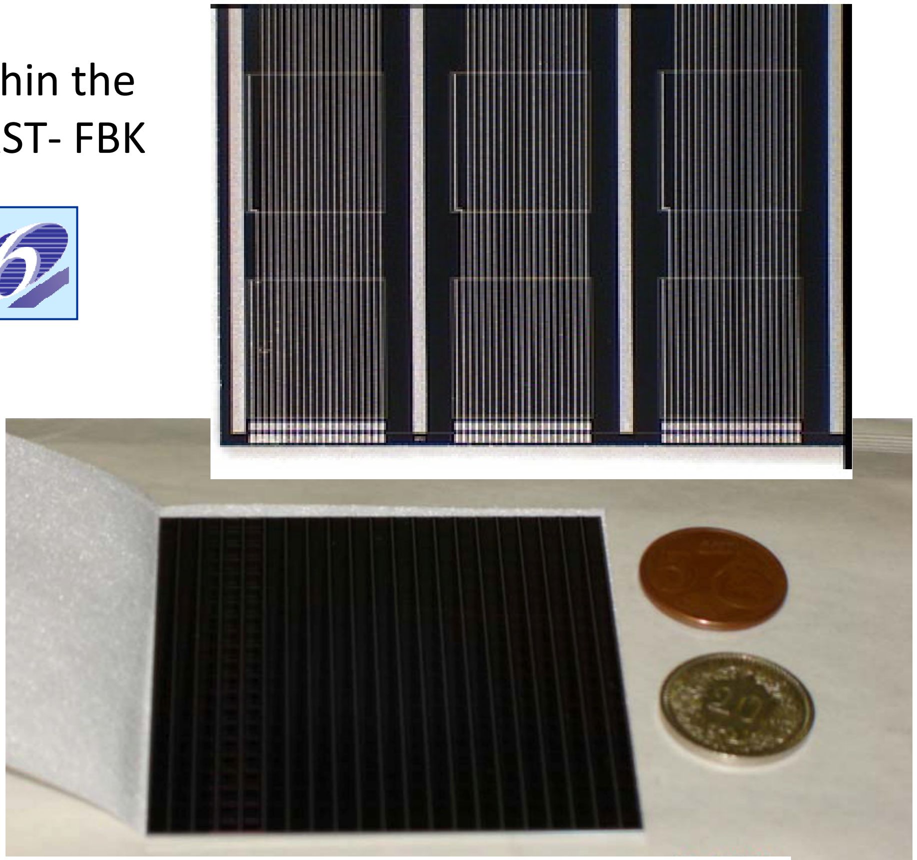
M. Bruzzi et al., "Epitaxial silicon devices for dosimetry applications," Appl. Phys. Lett., vol. 90 (2007) 172109 1-3.



Active area	~$9mm^2$
pad-grd distance:	10-500 µm
Epi layer:	50µm thickness 50Ωcm resistiv p type

Detector Developed by University of Florence within the European project MAESTRO - Manufactured by IRST- FBK





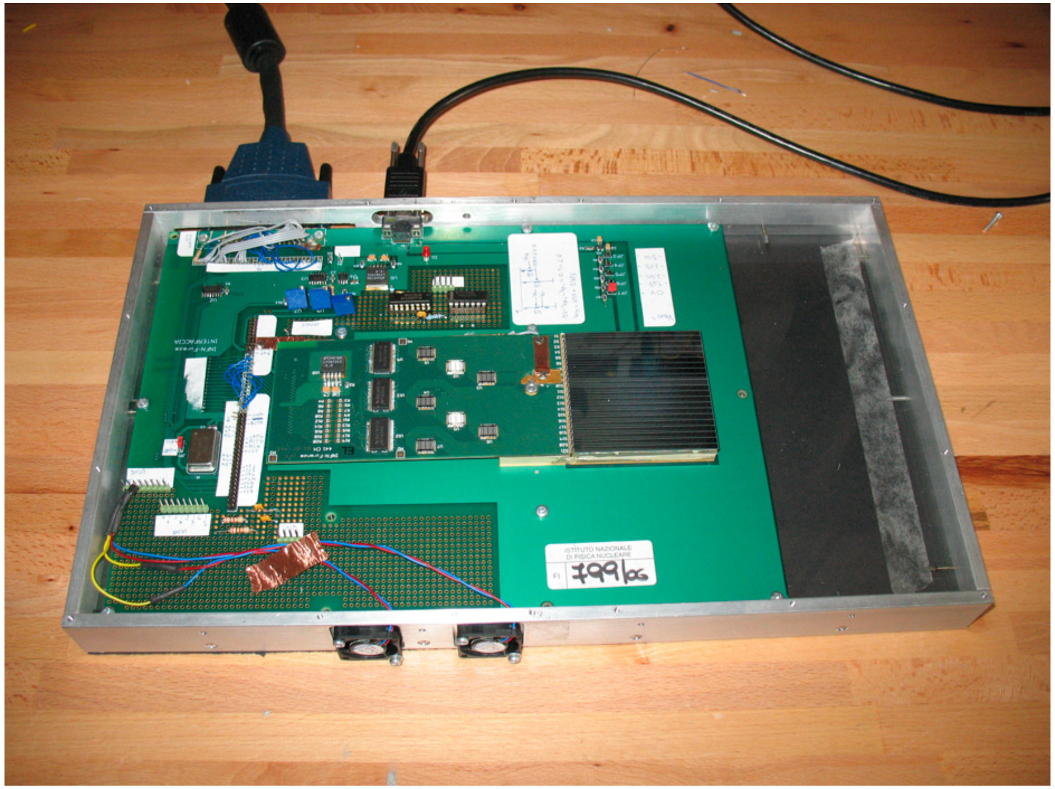
No granularity limits. Anyway complexity of readout electronics is proportional to the number of channels.

Italian patent FI2006A000166.
European application PCT-IB2007-001850.
Nationalization in US and EU under way

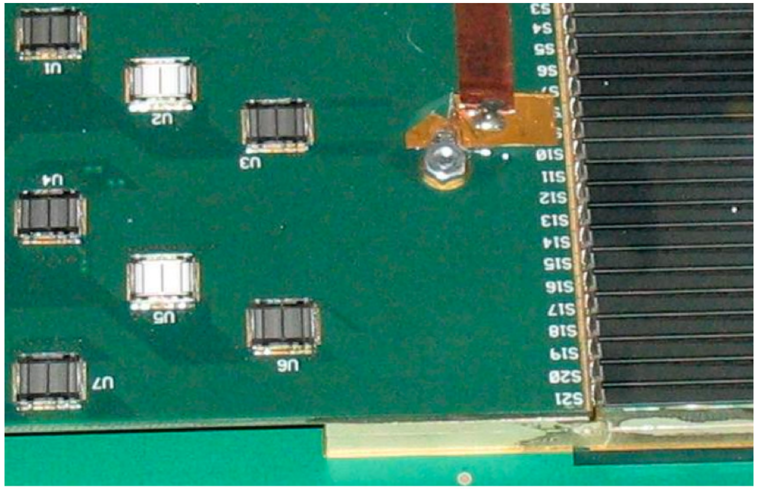
D. Menichelli et al., Nucl. Instr. and Meth. A, 583, 109 (2007).

441 Si *n+p* diodes
50 µm epi layer growth on MCz *p*.
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.

1 Module Prototype

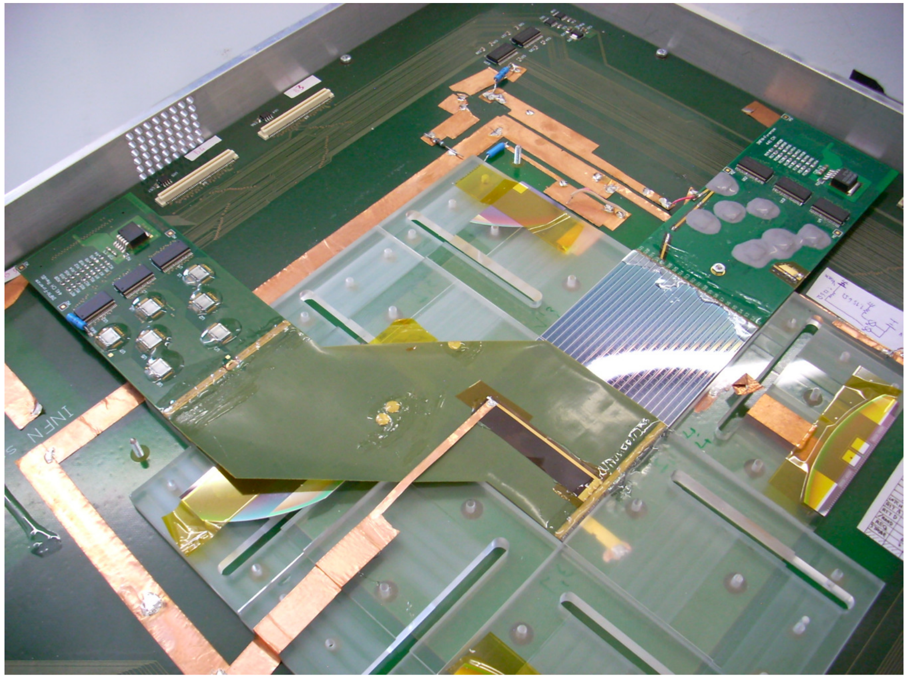


441 channels silicon module with the readout electronics based on IBA Dosimetry TERA06 chips.

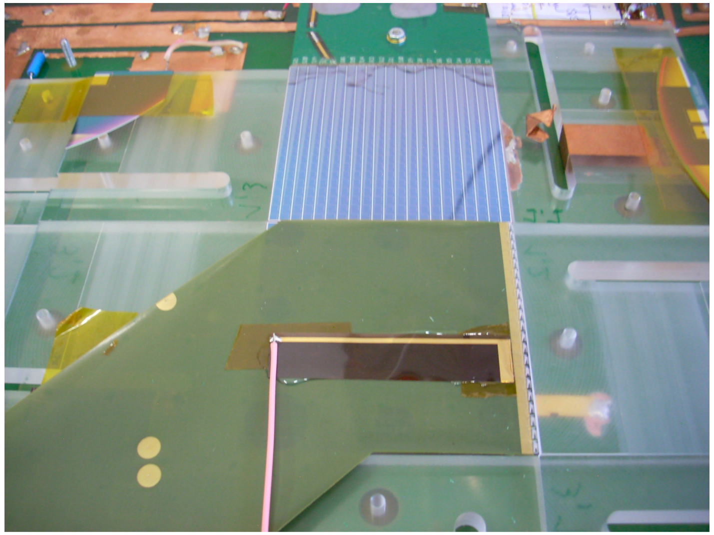


Details of the seven TERA06 die (U1-U7) and the wedge-bonding connections between the printed circuit board and the silicon module.

9 Modules Prototype under production



Two modules placed on the 3x3 mother-board covering almost 20x20cm^2 planned with a 4k channels read-out



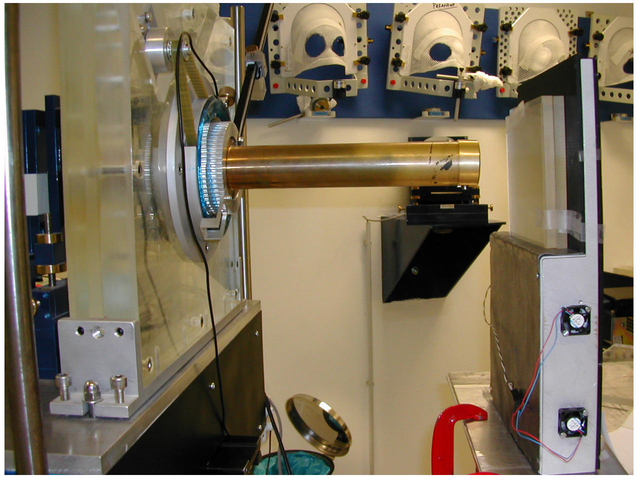
Dosimetric characterization

Test Beams:

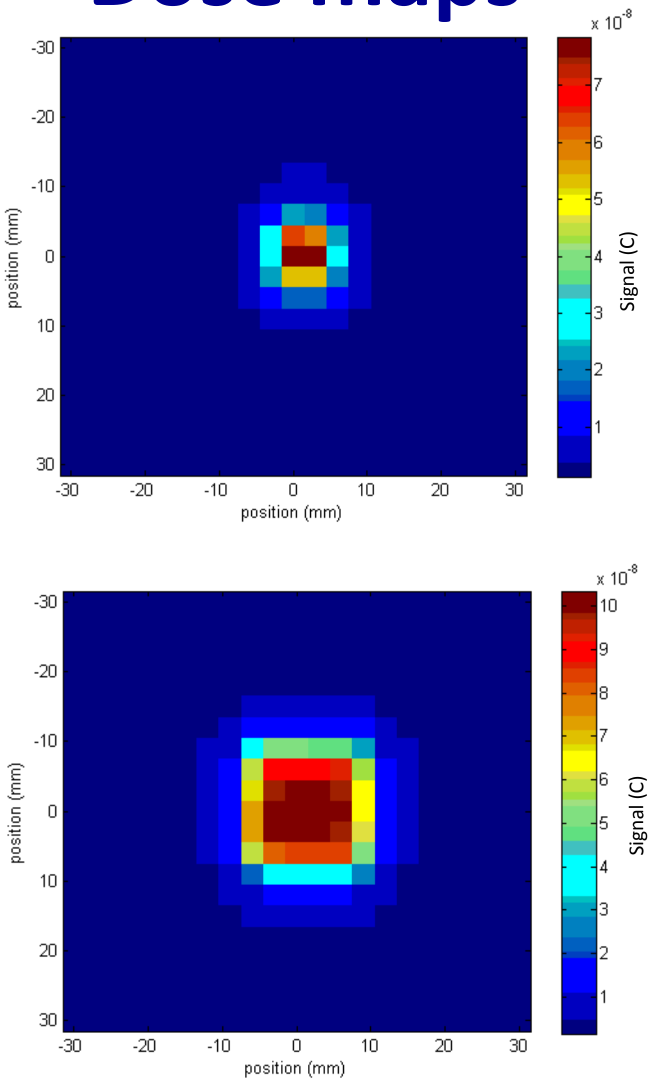
-6, 10, 25 MV photon beams from Precise/Synergy LINAC (ELEKTA) at the **Careggi University Hospital in Florence** and at **Neumarkt, IBA Dosimetry** site using a Siemens LINAC;

-^{60}Co gammas at **Lucca Hospital** (Lucca ASL2, Radiotherapy division);

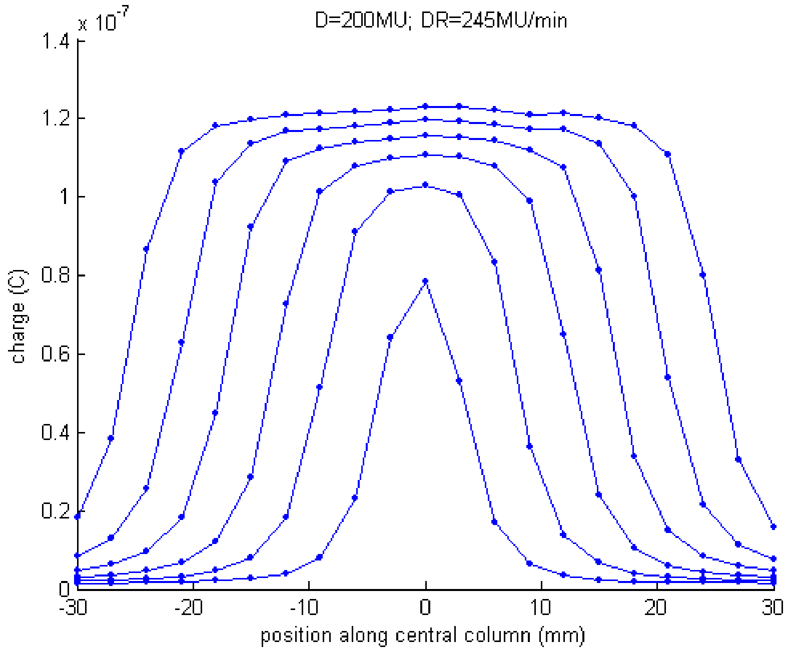
-62 MeV protons for medical applications at **INFN-LNS Catania.**



Dose maps



Profiles

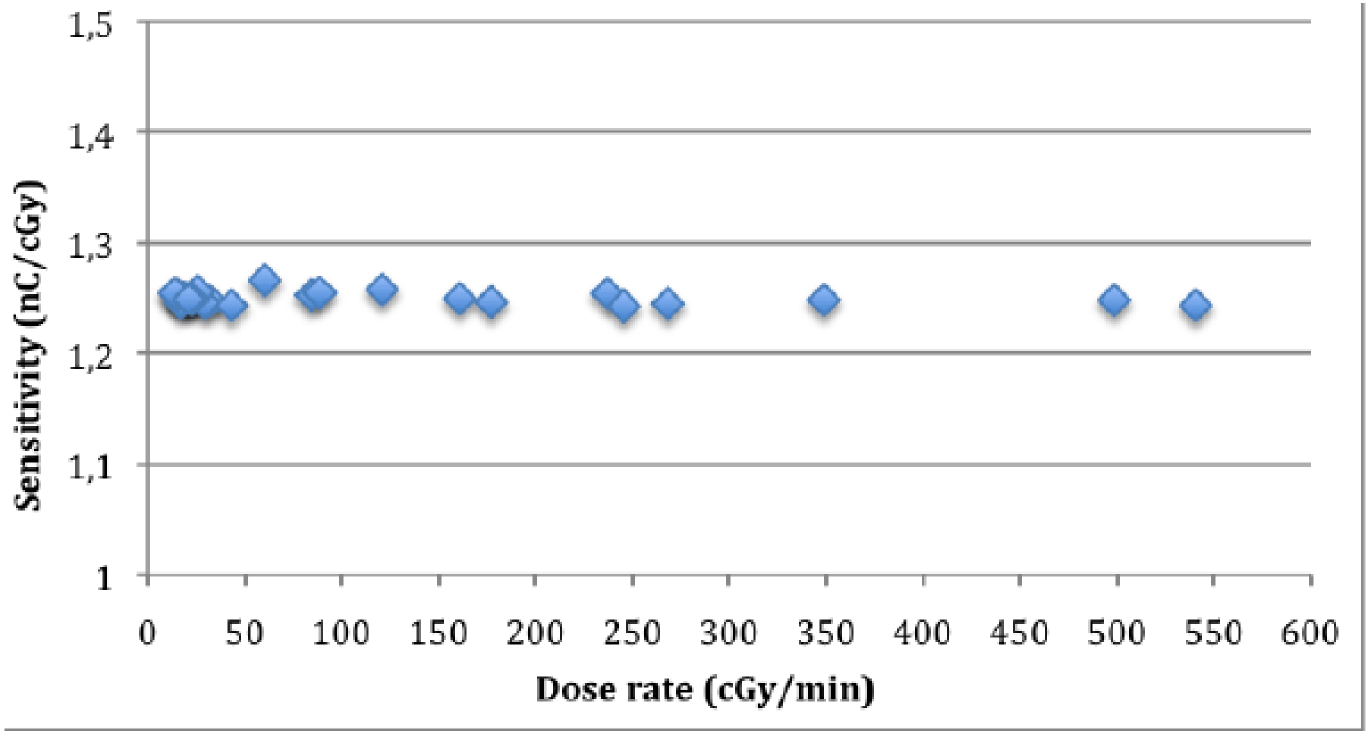


Profile along the central column for different field size

(0.8X0.8, 1.6x1.6, 2.4x2.4, 3.2x3.2, 4x4, 4.8x4.8)

6MV photon beam at Careggi Hospital

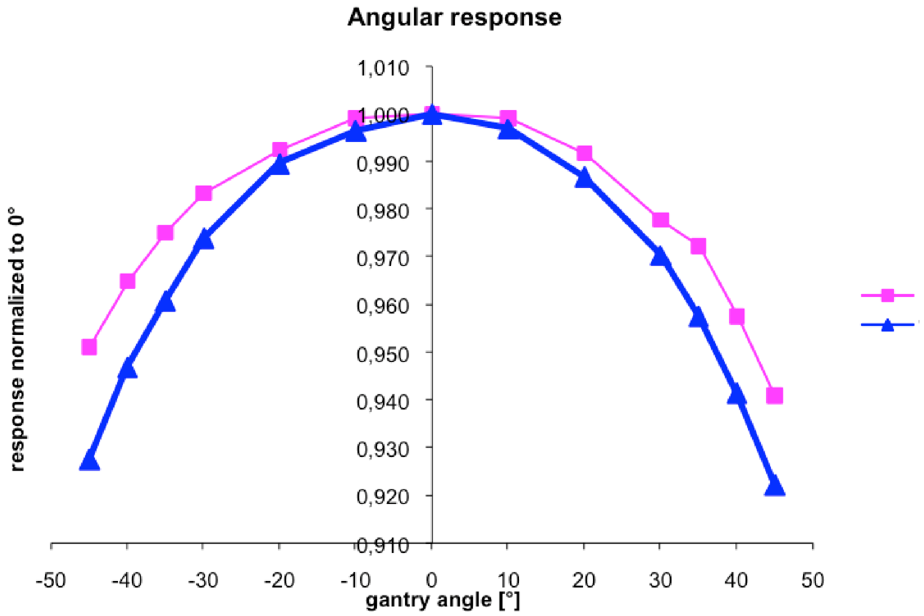
Average sensitivity as a function of the dose-rate (6MV photons and 60Co gammas). Standard deviation 0.3%

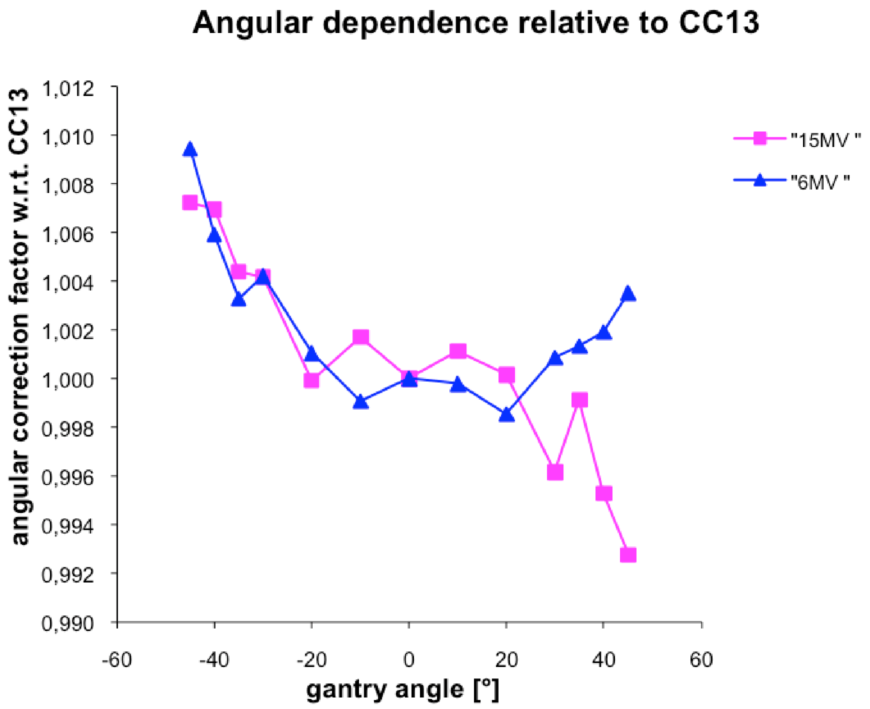


Sensitivity = 1.248 ± 0.004 nC/cGy

Much higher than commercially available devices (30nC/Gy). This encourages in further reducing the size of each sensitive element.

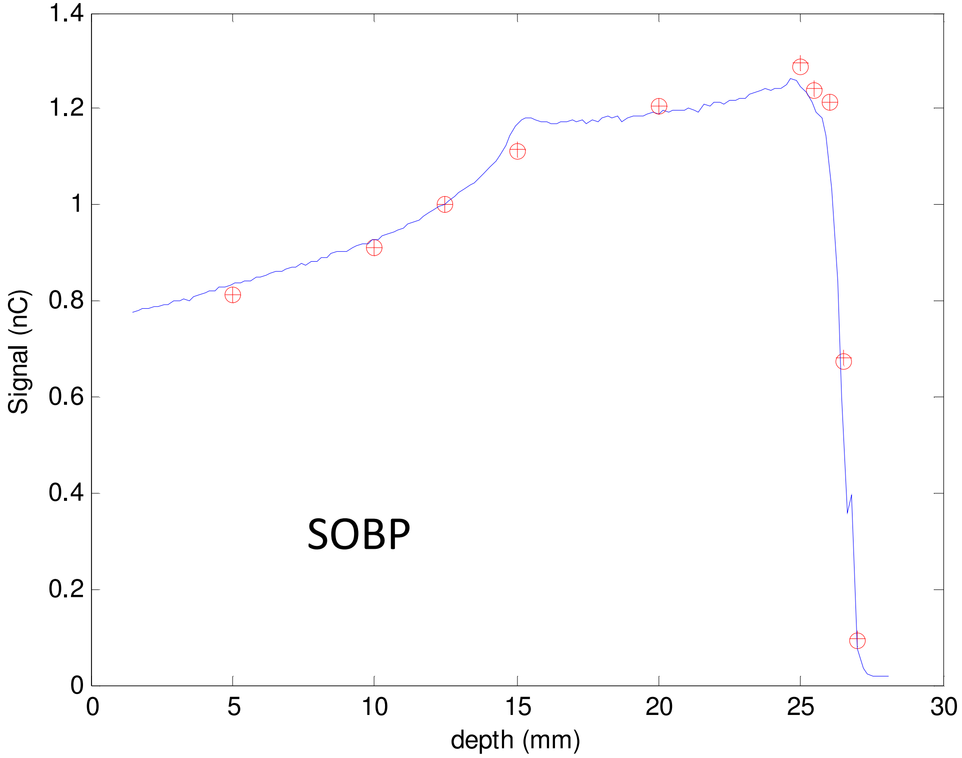
Angular dependence vs gantry angle for 6MV and 15MV photons and corrections relative to a IC chamber.





Angular dependence almost negligible up to 45°. This encourages application for dosimetric verification in rotational treatments

Application in proton beams

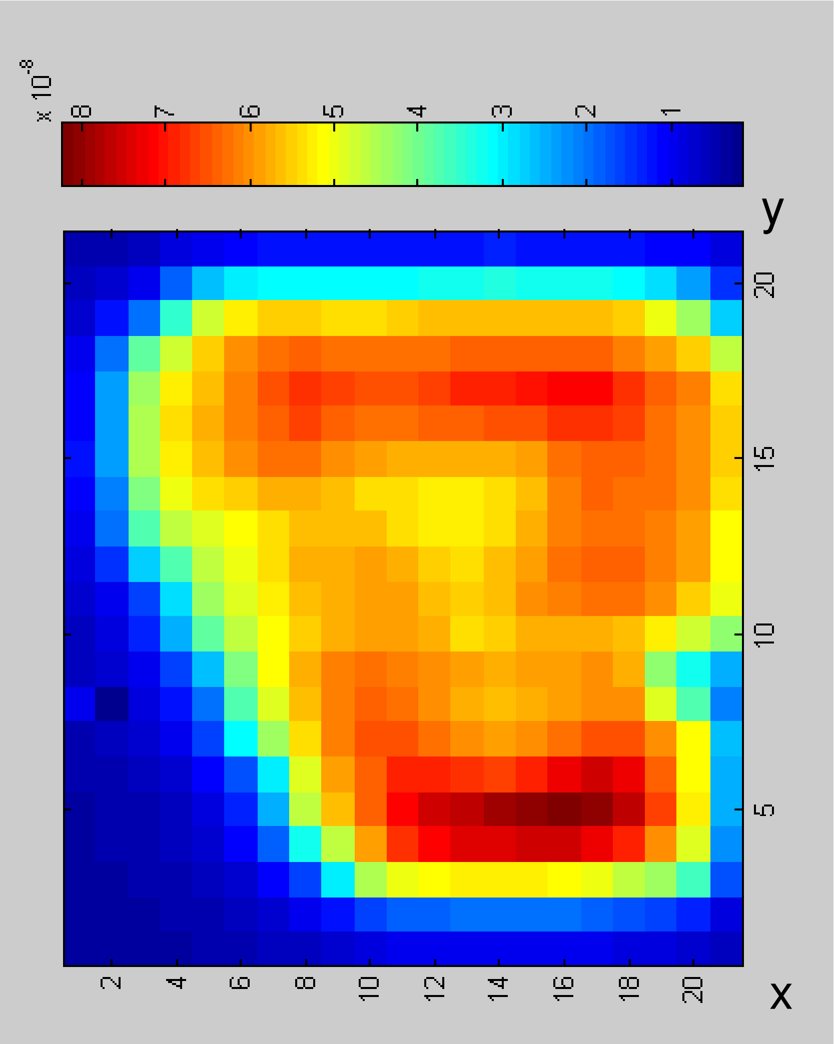


CATANA:
62 MeV proton beam
Measurements in PMMA
Signal normalized at 12.5 mm

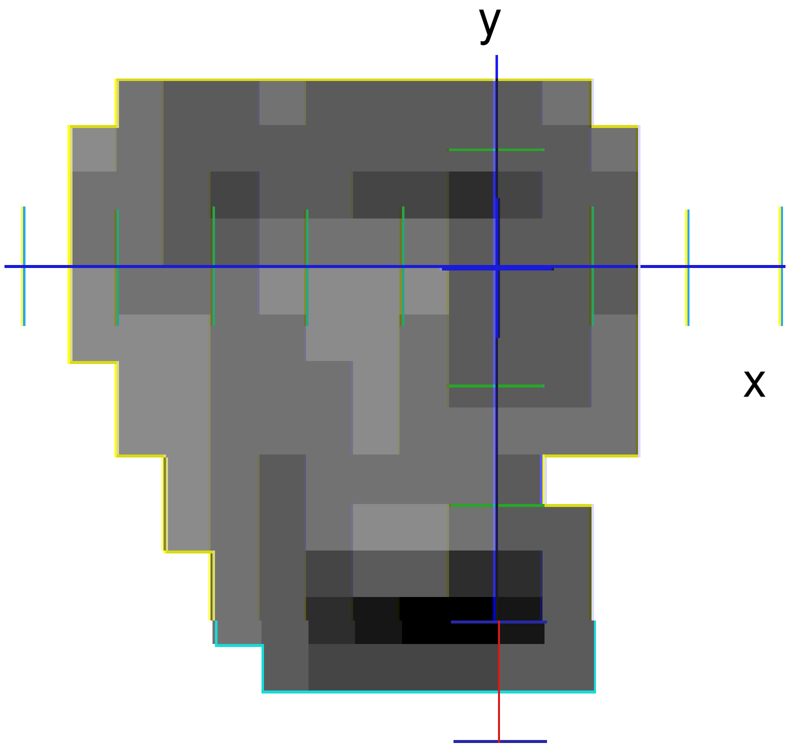
Depth-dose profile of a Spread-Out Bragg Peak obtained with the proton line CATANA at LNS – INFN Catania, as measured with the 2D p-type epitaxial Si module. Good results encourage in applying for dosimetric verification in proton treatments.

Application in an IMRT Field

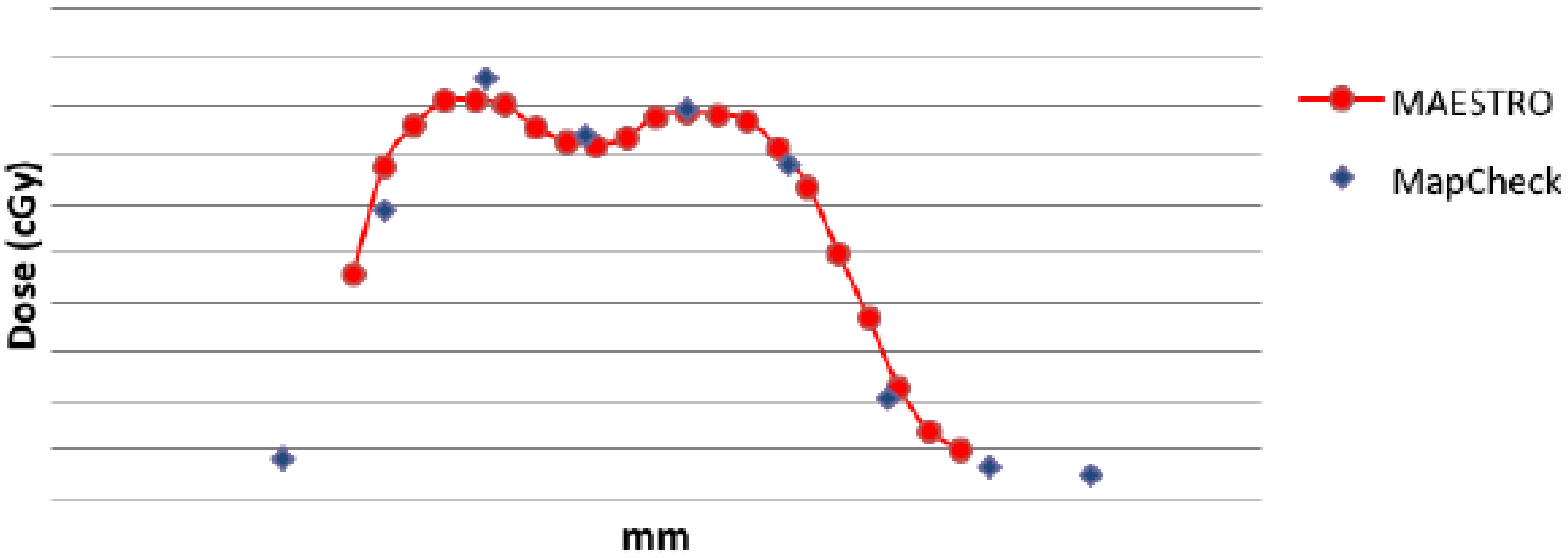
10MV photon beam at Careggi Hospital



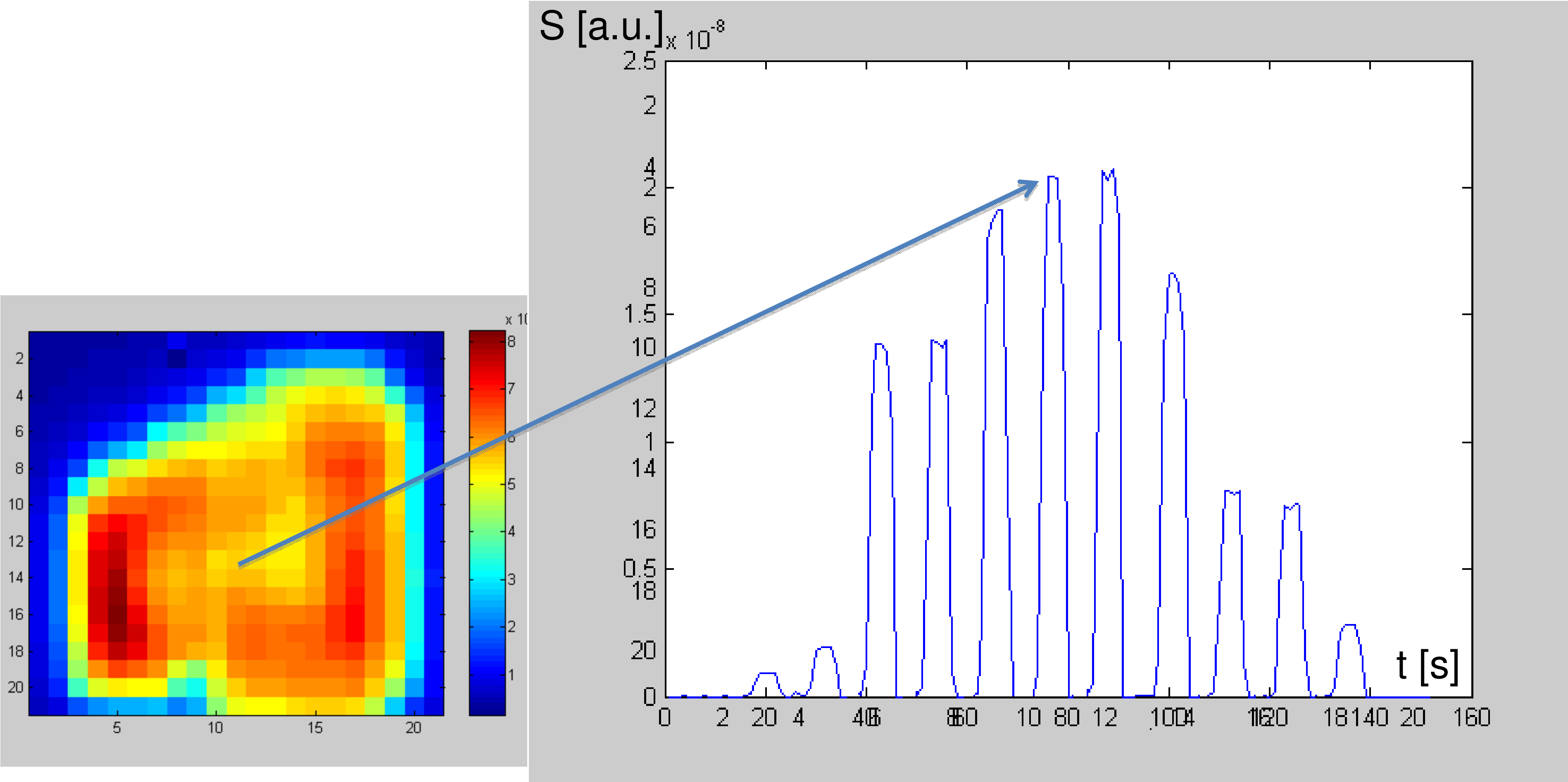
Comparison between dose map measured with the MAESTRO 2D p-type epitaxial Si module and corresponding treatment planning map



Example of a dose profile measured with the MAESTRO dosimeter as compared with the commercial system MAPCHECK. Agreement is very good, and much higher spatial resolution is possible with the MAESTRO device.



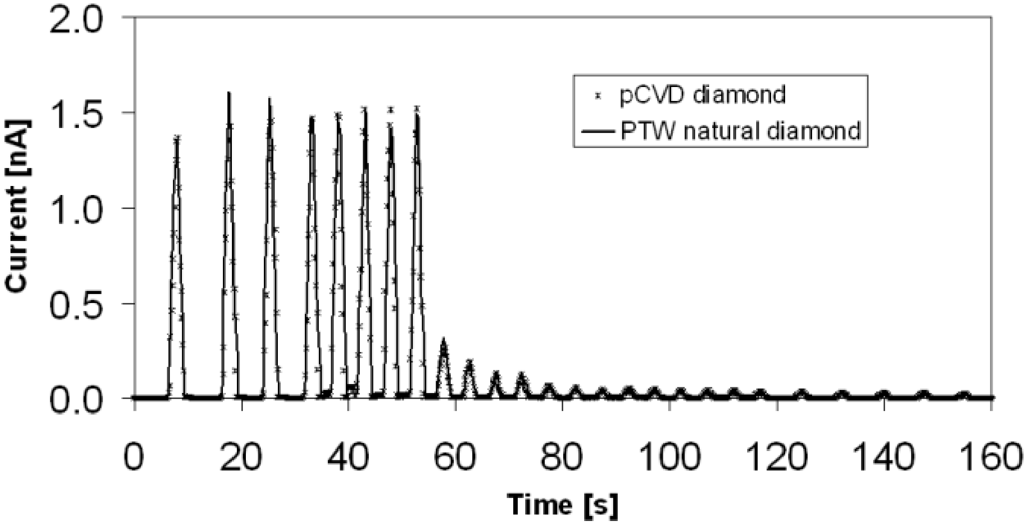
Due to its fast response each active element clearly distinguishes among the different segments of the beam irradiation structure



10MV photon beam at Careggi Hospital

Beyond Silicon: towards a large area IMRT 2D dosimeter with synthetic Diamond

Diamond is potentially the best material for dosimetry due to its almost tissue equivalence. The high crystalline quality of single crystal diamond makes this material best suited to this purpose, main disadvantage is the limited active area (typically lower than 1cm^2). Nonetheless, recent studies performed by us on high quality polycrystalline CVD diamond samples show promising results for IMRT when used in zero bias operation. This could open the way to the production of large active area 2D diamond dosimeters.



M. Bruzzi, C. De Angelis, M. Scaringella, C. Talamonti, D. Viscomi, M. Bucciolini Zero-Bias Operation of polycrystalline Chemically Vapour Deposited Diamond films for Intensity Modulated Radiation Therapy, Diamond and Related Materials, (2011)

Development and Test of a prototype system for proton imaging

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Istituto Nazionale di Fisica Nucleare

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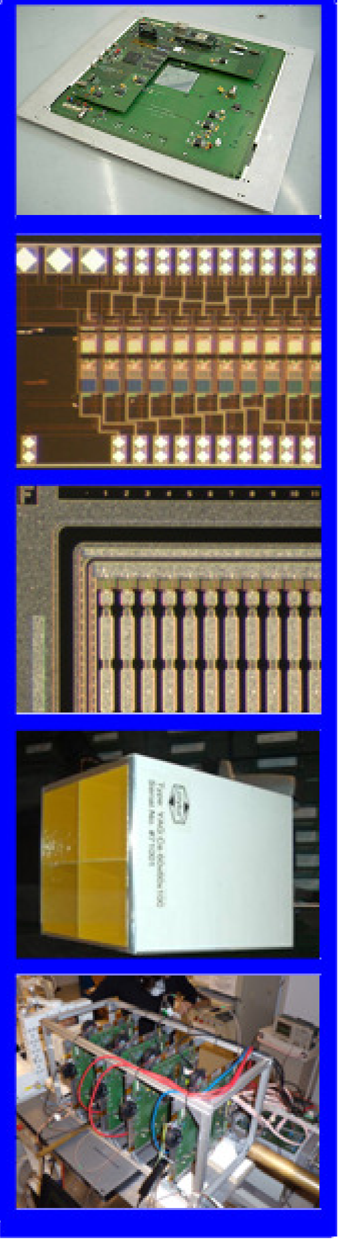
THE “PRoton IMAging PROJECT” INFN Vth Commission

proton Computed Tomography (pCT) is a medical imaging method based on the use of proton beams with kinetic energy of the order of 250 MeV. **This method would permit a direct measurement of the tissues’ stopping power distribution (presently calculated from X-rays attenuation coefficients), thus improving the accuracy of treatment planning in hadron therapy**.



PROGRAM

- Manufacture a high-performance prototype for proton radiography.
- Develop suitable imaging algorithms:
    - analysis of data;
    - MC simulations.
- Validate the pCR system with pre-clinical studies
- Conceive a configuration for a pCT system:
    - Hardware and data acquisition;
    - Reconstruction algorithms (ART, SART...).

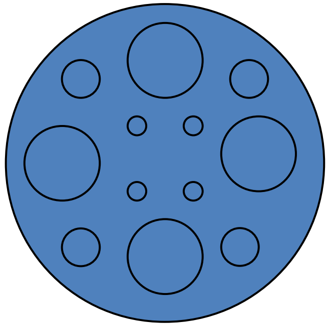
Schema of Proton Computed Radiography Device manufactured by the PRIMA(PRoton IMAging) collaboration

4 x-y TRACKER MODULES → **Entry and Exit position and direction**

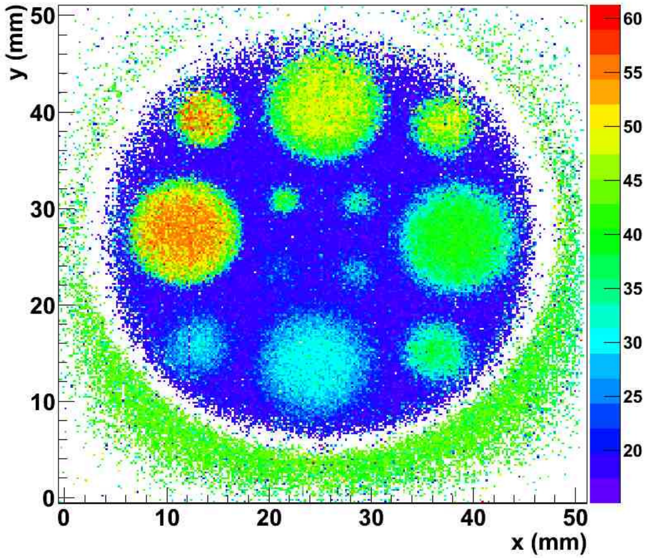
1 CALORIMETER → **Residual Energy**

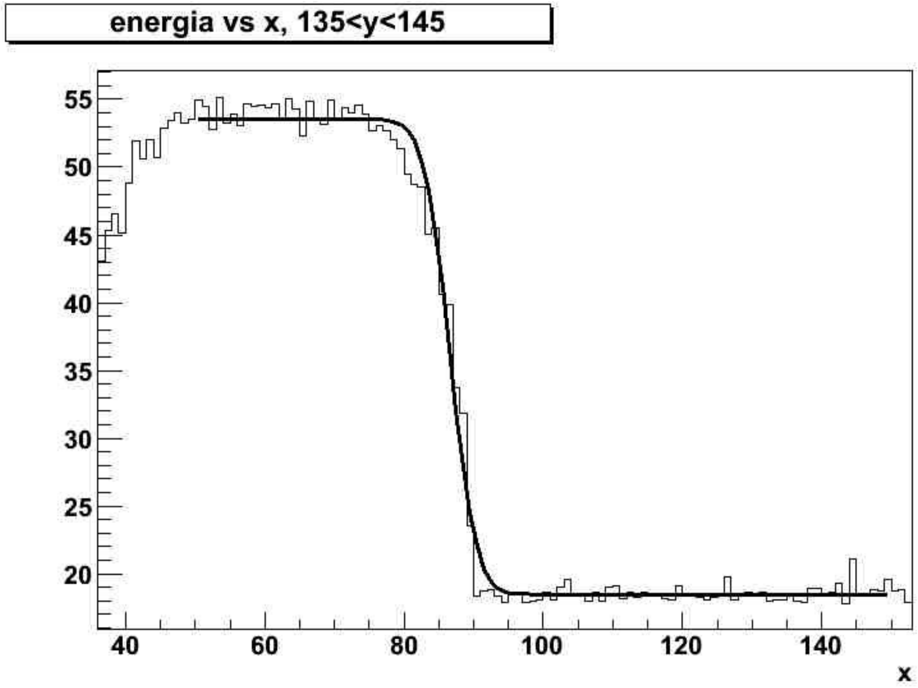
Complete pCR apparatus

Test at LNS (13May 2010)



Phantom with different density zones

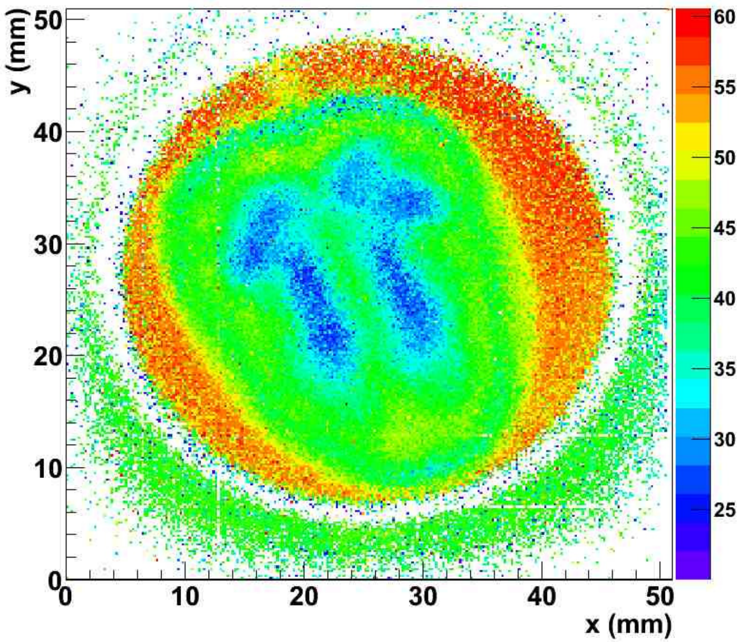


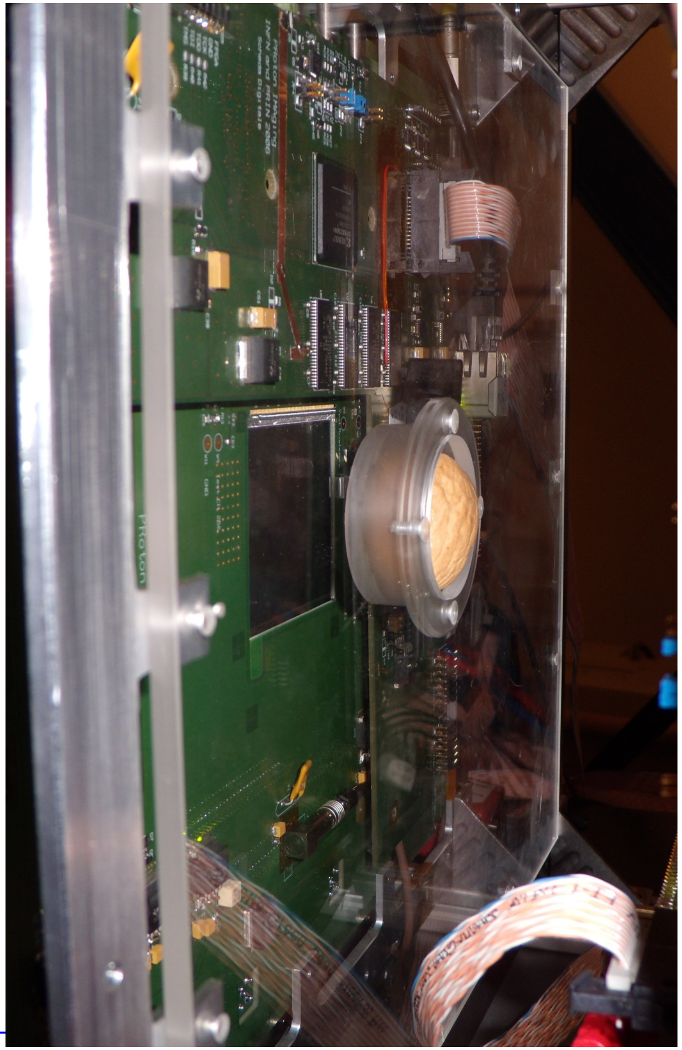


Between 55MeV and 22MeV → σ = 3strips (600µm)

Complete pCR apparatus

Test at LNS (13May 2010)

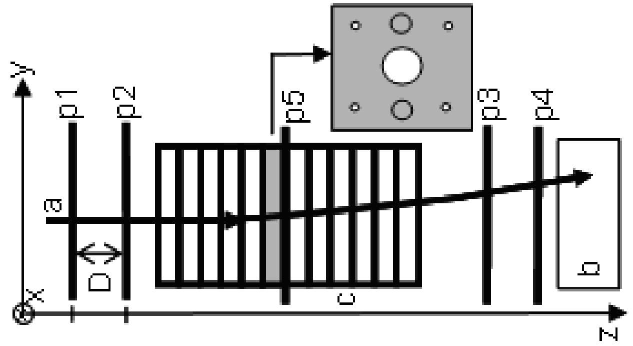


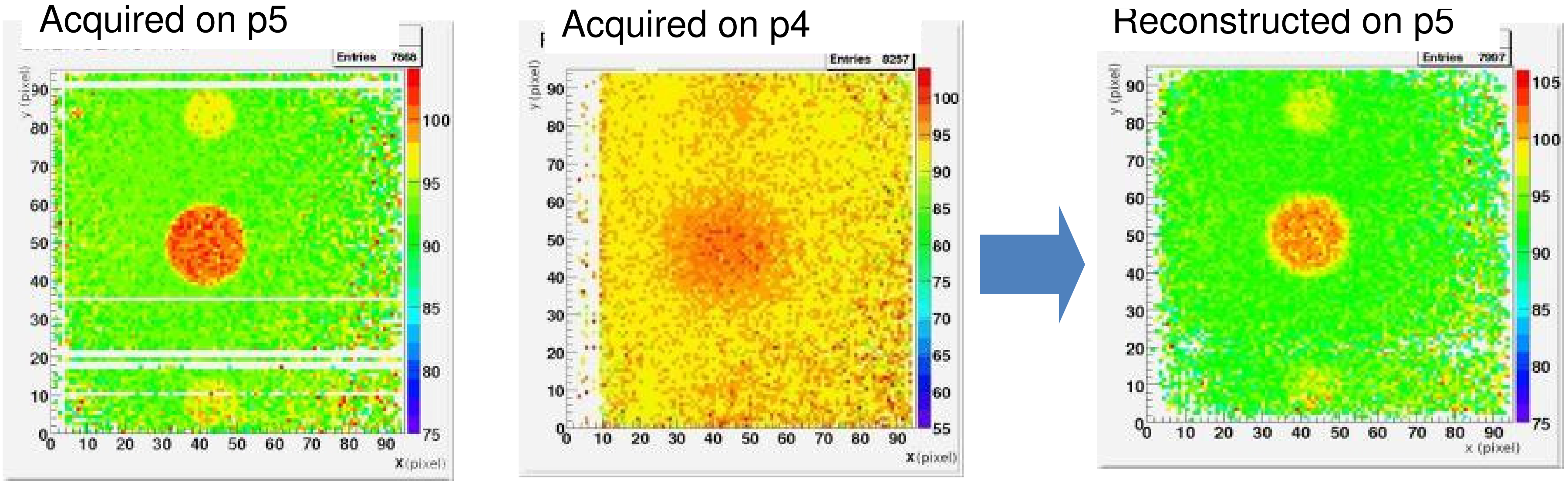


Validation of semi-analytical algorithms with pre-existing data

Data acquired at LLUMC
Proton beam 201MeV

Silicon tracker UCSC CsI(Tl) calorimeter




Acquired on p5

Acquired on p4

Reconstructed on p5

C. Talamonti et al., "Proton Radiography for clinical applications," NIM A, 612(2010)571–575

Conclusions

We developed and tested:

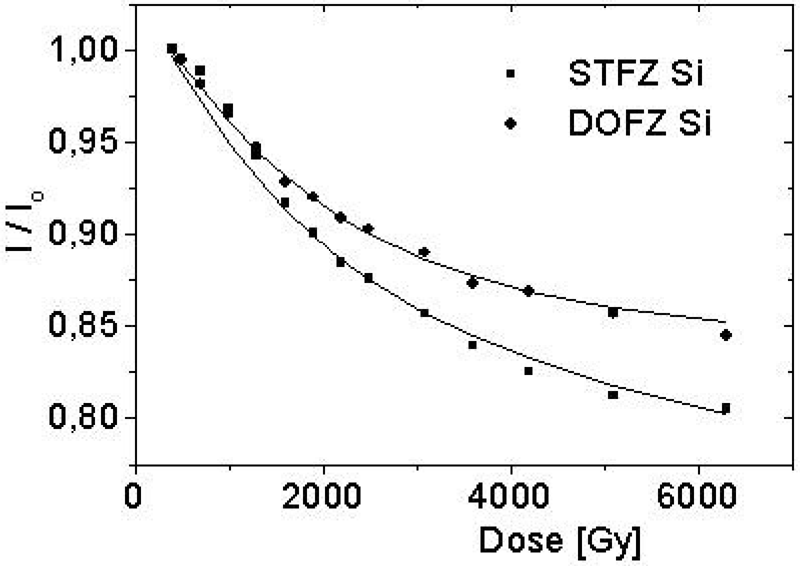
-A large area 2D bidimensional Si dosimeter system based on p-type epitaxial Si grown on Cz substrates. Applications under ^{60}Co gammas, photon, electron and proton beams as well as IMRT field for clinical applications have been investigated. Dosimeter works comparable or better than commercial devices, in particular showing higher sensitivity, and finer temporal and spatial resolutions. Extension of the system to large area polycrystalline CVD diamond to get an almost tissue equivalent device.

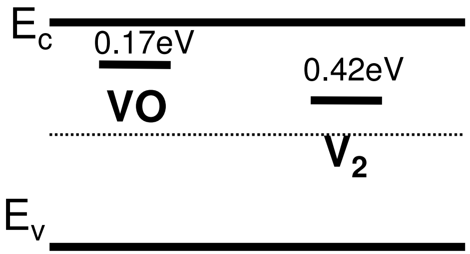
- A system based on silicon telescope made with microstrp detectors plus a calorimeter has been developed proton for Computer Tomography in collaboration with Catania INFN LNS: first tests carried out with 62MeV proton in LNS show promising results. A scale up of the system is under development.

Spares

Defect Engineering – Oxygen ?

In DOFZ (Float Zone enriched with Oxygen up to 10^{17}cm^{-3}) it is known that V_2 formation can be partially depressed in favour of the shallower V-O. With high concentration of oxygen a reduction of the radiation-induced defects generation rate could be expected



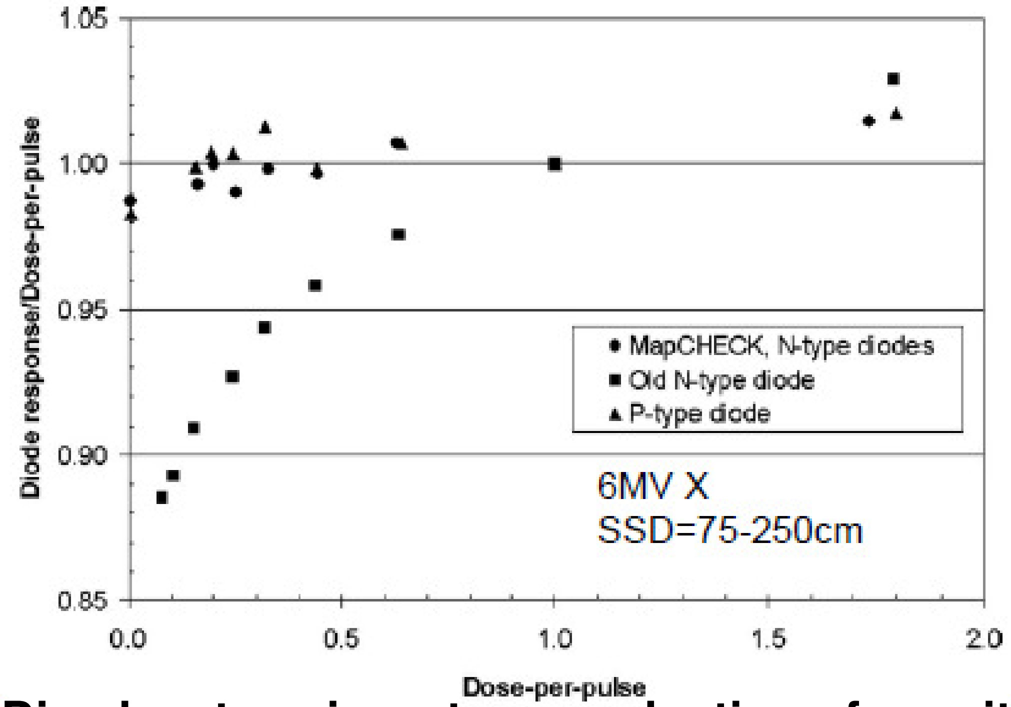


M.Casati et al., "Characterization of standard and oxygenated Float Zone Si diodes under radiotherapy beams," Nucl. Instr. and Meth.A, 552 (2005), 158-162.

Only a slight increase of radiation hardness to radiotherapic beams was found in oxygenated silicon against standard float zone silicon, so this option was abandoned.

Defect Engineering – Pt

Other radiation-hard solutions adopted later (≈2000) for dosimetry considered defect engineering. Introducing a large concentration of a midgap level will dominate the transport properties of the material and Signal will be independent of the radiation induced centers, thus independent of the accumulated dose. An example is given by Pt-Doping in n-type silicon, adopted on commercial devices.



$E_V+0.42eV$,
$\sigma_h=2.7x10^{-12}cm^2$
$\sigma_e=1.62x10^{-16}cm^2$.

After Jursinic P. A. and Nelmsb B. E., 2003, Med. Phys. 30, 870-879.

Disadvantage is a strong reduction of sensitivity of the active element.