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.
PT center under operation

40,000 patients

22 PT centers

40,000 patients

22 PT centers
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 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 cm² diodes Pitch 1.0 cm
- 1024 cylindrical ionization chambers
  - 24 x 24 cm² Pitch 7.5mm
- 729 ionization chambers
  - 27x27 cm² Pitch 10 mm

RD07 International Conference on Large Scale Applications and Radian hardness of Semiconductor detectors
Florence, June 27-29 2007
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

<p>| | |</p>
<table>
<thead>
<tr>
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</table>
| 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% |
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 \(\sim 3.6 \text{ eV/pair}\) \(\Rightarrow\) small active volume \(\Rightarrow\) high spatial resolution;
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.

\[ S \propto L = \sqrt{D \tau}, \quad D \text{ diffusion coefficient}, \quad \tau \text{ minority carrier lifetime}: \]
\[ \frac{1}{\tau} = \frac{1}{\tau_0} + K D \]


Standard Si dosimeters

- Pre-irradiation up to 10kGy
- Frequent Calibration
Choice of Si material and pixel geometry
- Irradiation of test samples with $^{60}$Co and 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 $X=10$ mm) and it is almost constant up to 10 kGy (within 1.8%).
Design and production of silicon modules

441 Si $n^+p$ diodes, 50 mm epi layer on p MCz.
Active area: 6.29x6.29 cm$^2$.
Segmentation: 21x21 pixel (2x2 mm$^2$, 3 mm pitch).
Overmetal strips to 441 pads along one single side.
Diffused guardring structure at 20 mm 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 cm².
System complexity: ~4k channels
441ch TERA-based prototype
<table>
<thead>
<tr>
<th>Device</th>
<th>State</th>
<th>Completed /to be completed by:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon Module (15 6x6 samples from IRST)</td>
<td>☑ Designed, manufactured and tested</td>
<td>Aug. 2005</td>
</tr>
<tr>
<td>441 ch prototype with discrete electronics</td>
<td>☑ Assembled and tested</td>
<td>March 2006</td>
</tr>
<tr>
<td>ASIC choice and testing</td>
<td>☑ Done</td>
<td>June 2006</td>
</tr>
<tr>
<td>441 ch prototype with integrated electronics</td>
<td>Design</td>
<td>Sept. 2006</td>
</tr>
<tr>
<td>Part manufacturing</td>
<td>☑ Done</td>
<td>Jan. 2007</td>
</tr>
<tr>
<td>Assembling</td>
<td>☑ Done</td>
<td>May 2007</td>
</tr>
<tr>
<td>Debug</td>
<td>O In progress</td>
<td>May 2007</td>
</tr>
<tr>
<td>Beam test</td>
<td>X To be done</td>
<td>Sept. 2007</td>
</tr>
<tr>
<td>Full detector 4k ch</td>
<td>Design</td>
<td>during 2008</td>
</tr>
<tr>
<td>Part manufacturing</td>
<td>OX In progress, in part</td>
<td></td>
</tr>
<tr>
<td>Assembling</td>
<td>X To be done</td>
<td></td>
</tr>
<tr>
<td>Debug</td>
<td>X To be done</td>
<td></td>
</tr>
<tr>
<td>Beam Test</td>
<td>X To be done</td>
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</table>
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 \textit{repeatability} < 0.5\%, \textit{reproducibility} < 1\%, \textit{deviation from linearity} < 1\%, \textit{dose rate dependence} < 1\%.

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 \(\gg T=205\) ms). They are summed off line \((Q)\).

The signal is expressed in C, assuming the integration on a conventional capacity of \(1 \text{nF}\).

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

\[
q_{ni} \equiv 1 \text{nF} \times V_{ni}
\]

\[
Q_{nj} = \sum_{i} q_{ni}
\]
Field size 20 mm diameter
Repeatability

- The repeatability improves with the SNR.

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

<table>
<thead>
<tr>
<th>Dose rate (Gy/min)</th>
<th>Repeatability</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma$ (%)</td>
<td>$N_{0.5}$ (%)</td>
</tr>
<tr>
<td>0.18 V=0,01</td>
<td>0.8</td>
</tr>
<tr>
<td>2.5 V=0,06-0,07</td>
<td>0.2</td>
</tr>
<tr>
<td>6.8 V=0,18</td>
<td>0.2</td>
</tr>
<tr>
<td>14 V=0,4</td>
<td>0.5</td>
</tr>
</tbody>
</table>

MAESTRO requirement: $\sigma\% < 0.5\%$

$N_{0.5}$ is the percentage of pixels with $\sigma(\%) < 0.5\%$. 
Linearity

<table>
<thead>
<tr>
<th>Nominal dose rate (Gy/min)</th>
<th>$&lt;d_n&gt;$ (%)</th>
<th>$N_1$ (%)</th>
<th>$&lt;a_n&gt;$ (nC/cGy)</th>
<th>$&lt;\delta a_n&gt;$ (nC/cGy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>1</td>
<td>65</td>
<td>0.723</td>
<td>0.002</td>
</tr>
<tr>
<td>2.5</td>
<td>1</td>
<td>57</td>
<td>0.895</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Range 20-5000 cGy

MAESTRO requirement: $d<1$ %

Dose rate 14 Gy/min

Dose rate 2.5 Gy/min
Output factors (protons)

![Graph showing output factors for different collimator diameters]

- Markus
- scanditronix diode
- GAF
- TLD
- MAESTRO

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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 datum agrees with the results of experiments performed on single diodes of the same materials.

Considering the results obtained with the single diode, we expect that the sensitivity does not decrease any more with the accumulated dose.

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 data with the electron curve and this datum 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

mar. '07

may '07

dark current (nA)
dose (Gy)
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 higher LET.
• Next step is to characterize the new prototype with a discret electronics
• We are also planning to performe study of radiation damage with proton beam on the single diode