2D monolithic silicon dosimeter: Florence experience

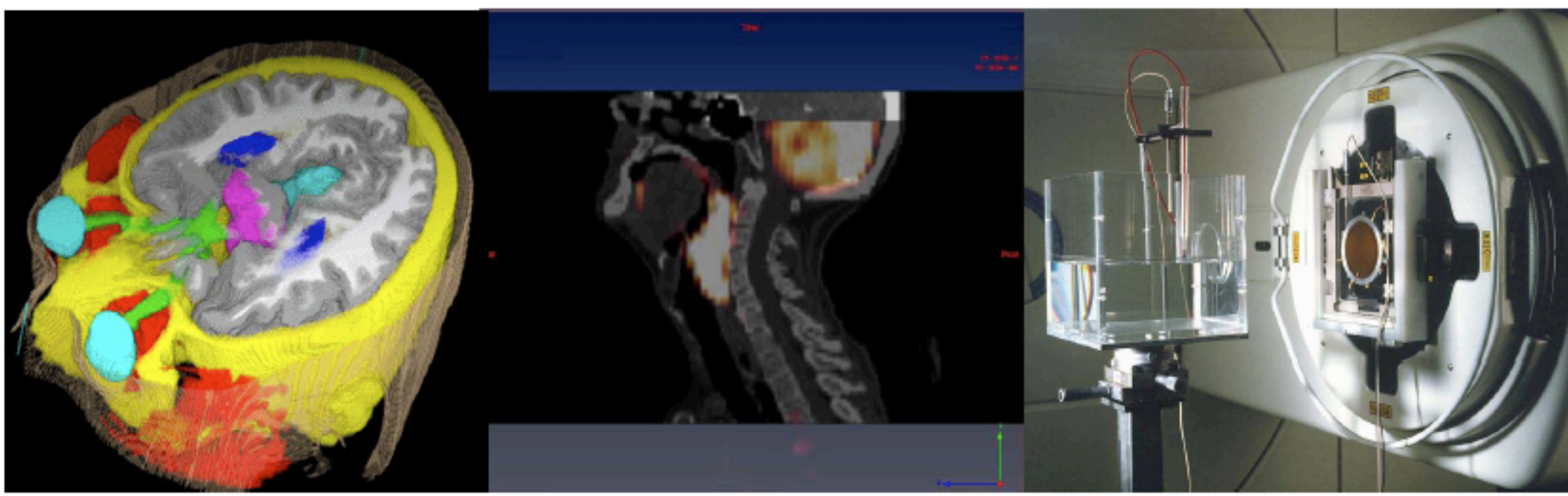
Cinzia Talamonti
University of Florence

IX Seminar on Software for Nuclear, Subnuclear and Applied Physics.
Technology Transfer Workshop.
Alghero, 28 May -01 June 2012

Outline

- Maestro project
- Introduction on radiotherapy
- The detector
- Conclusions and considerations

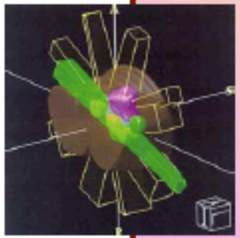
Methods and Advanced Equipment for Simulation and Treatment in Radio Oncology



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

MAESTRO : four main objectives

1. To design, develop and validate new equipments for an accurate conformational Radiotherapy.

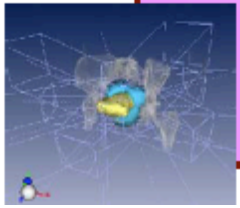


- Conformational Intensity Modulation Radiotherapy (IMRT)
- Intensity Modulation Proton Therapy (IMPT)
- Equipments for real time patient positioning and organ tracking
- Equipments to assess and control doses in vivo

2. To provide supports and research training
   - Training of clinicians to use new MAESTRO tools
   - Share the new knowledge between clinics

3. To disseminate knowledge towards manufacturers

4. To increase the use of MAESTRO tools in oncology centres



- Design and point-out new protocols for doses delivering
- Make available new procedures adapted to real time treatment control

MAESTRO Consortium

25 partners from 9 European countries

Manufacturers

IBA
Dosisoft
Eldim
NRG
SCX

5

Research

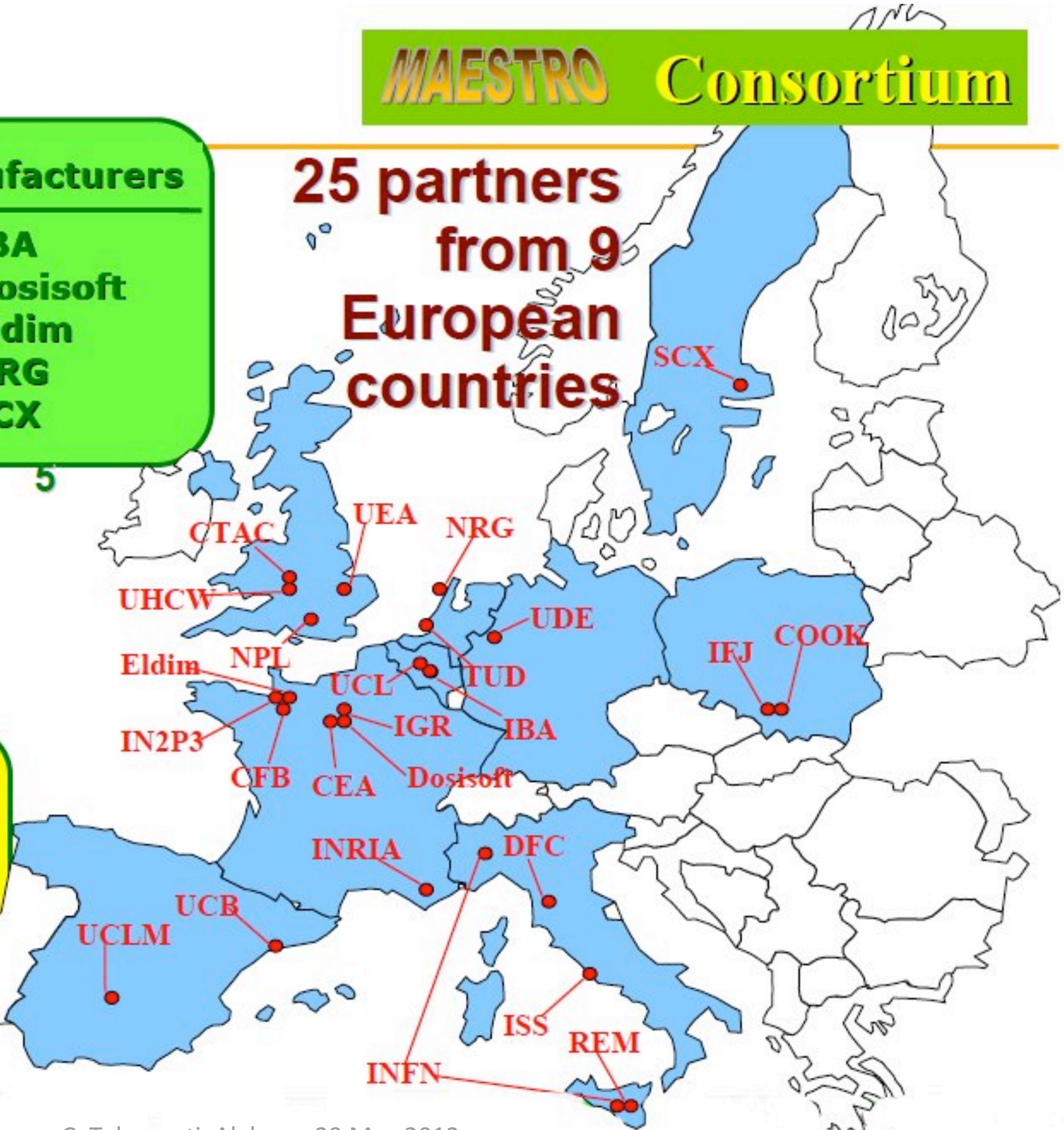
CEA, INFN, NPL
IFJ, IN2P3, ISS
Delft, Coventry
UBC, UEA, UCLM
INRIA

12

Clinics

IGR	UDE
CFB	DFC
REM	COOK
UHCW	UCL

8



Structure of *MAESTRO*

6 Work-packages:

Techniques 3, Medical 1, Training / dissemination 1, Management 1

- Automatic Patient Positioning
- Moving phantom
- Real Time Organ Tracking
- PBS for IMPT

1

- Multi modality imaging
- Monte Carlo dose calculation software

2

- Sensors and
- 2/3D imagers for Dose evaluation in radiotherapy

3

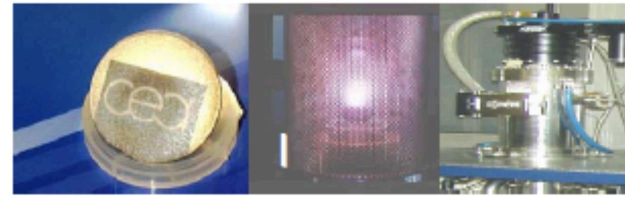
Management
6

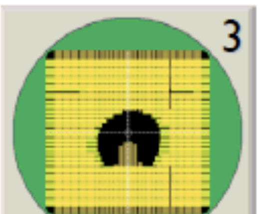
- Quality Assurance and Protocols for clinical validation
- Patient radiation protection

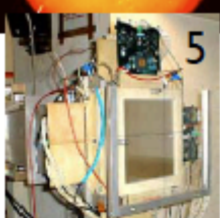
4

Training and demonstration workshops for fully developed products in *MAESTRO*
5

3 - Dosimetric Tools

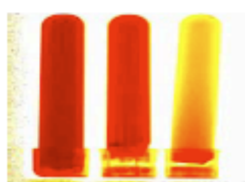




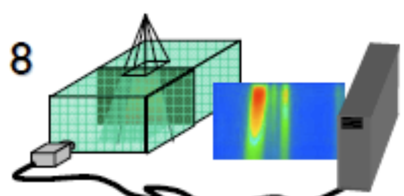


1. Diamond Dosimeter : ionisation chamber (CEA, IFJ, INFN)
   Thermoluminescence (CEA, IFJ)
2. 16 ways remote OSL dosimeters using optical fibres (CEA)
3. 2D wide surface Si plan imagers (DFC, INFN)
4. 2D dose imager : Gas Electron Multiplier (U-DELFT)
5. Pixelized ionization chamber for IMPT and IMRT (SCX, INFN)
6. TL wide surface Dose imager (IFJ)
7. 3D Fricke gel polymer dosimetry (ISS)
8. 3D Plastic scintillator dosimetry (IN2P3, ELDIM)

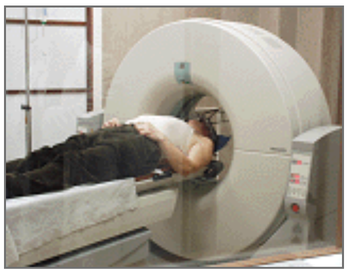
7



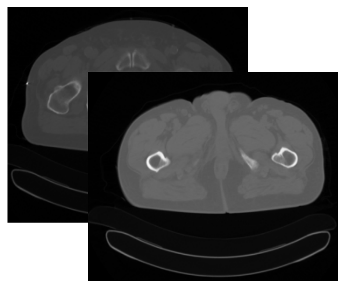
8



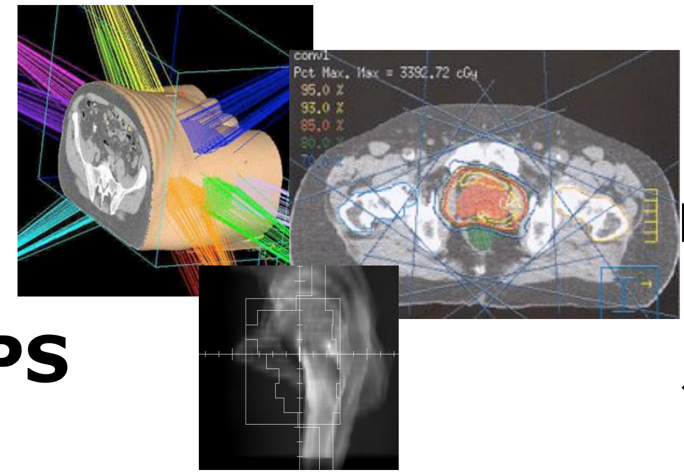
Radiotherapy treatment flow-chart



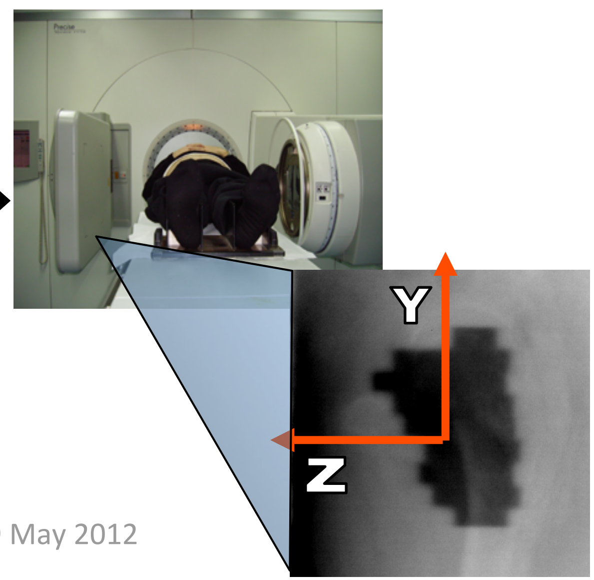
=

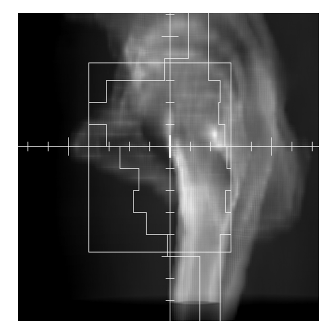


TPS

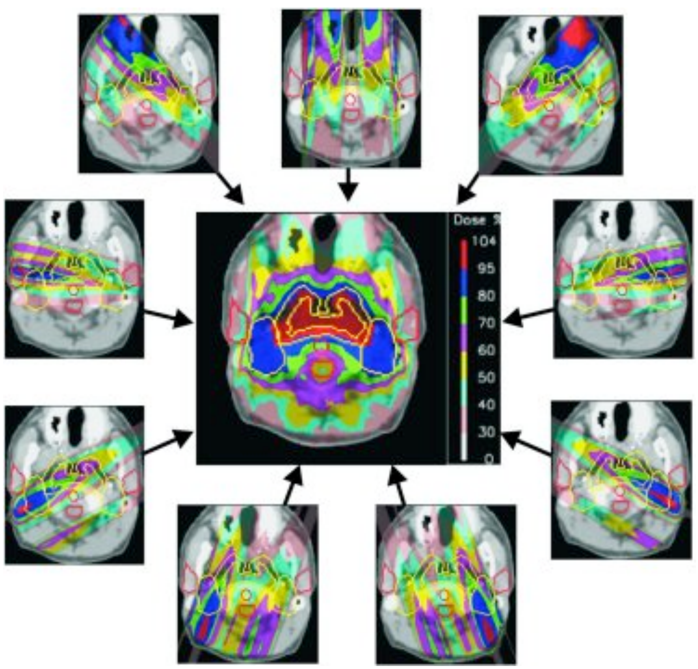


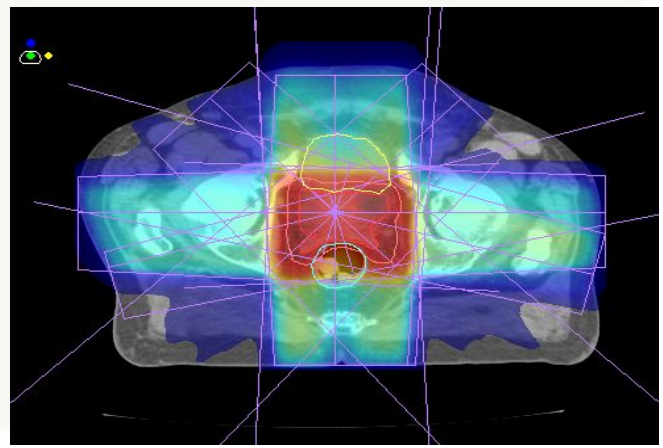
Isocenter detection

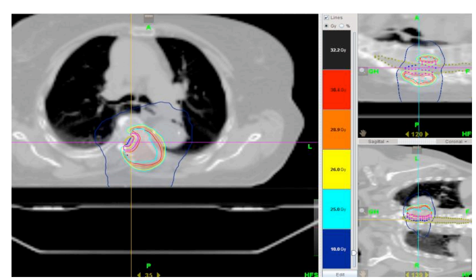


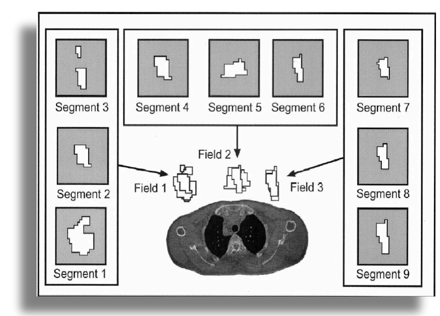


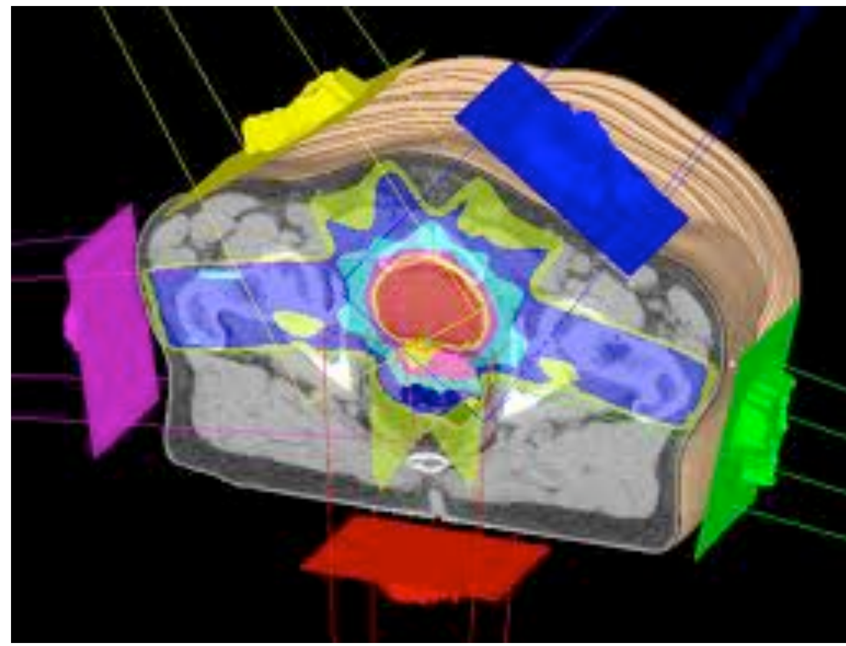
Clinical dosimetry in radiotherapy is well known matter but high conformal radiotherapy modalities (IMRT, Stereotactic treatments with photons and protons, IMPT) pose problems due to the **small radiation fields** with **high dose gradients**, to the **variation in space and time of the dose rate** and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



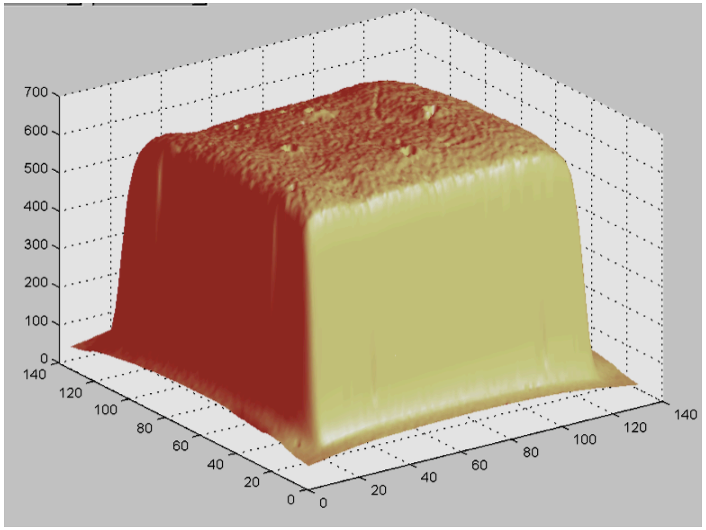


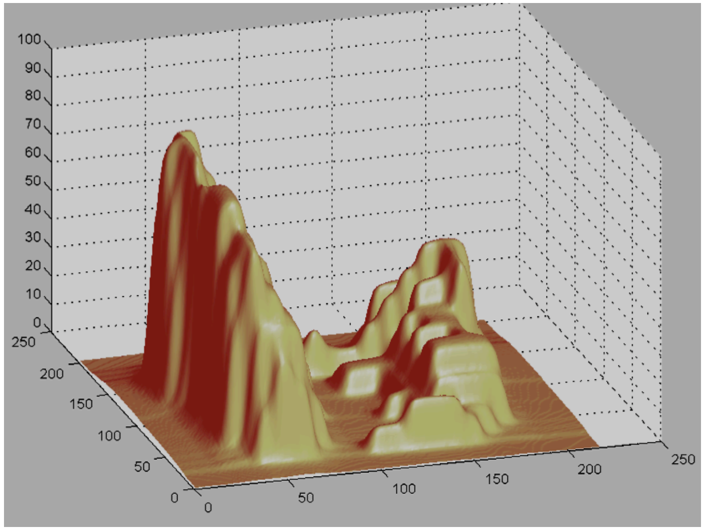






IMRT: Intensity Modulated Radiation Therapy

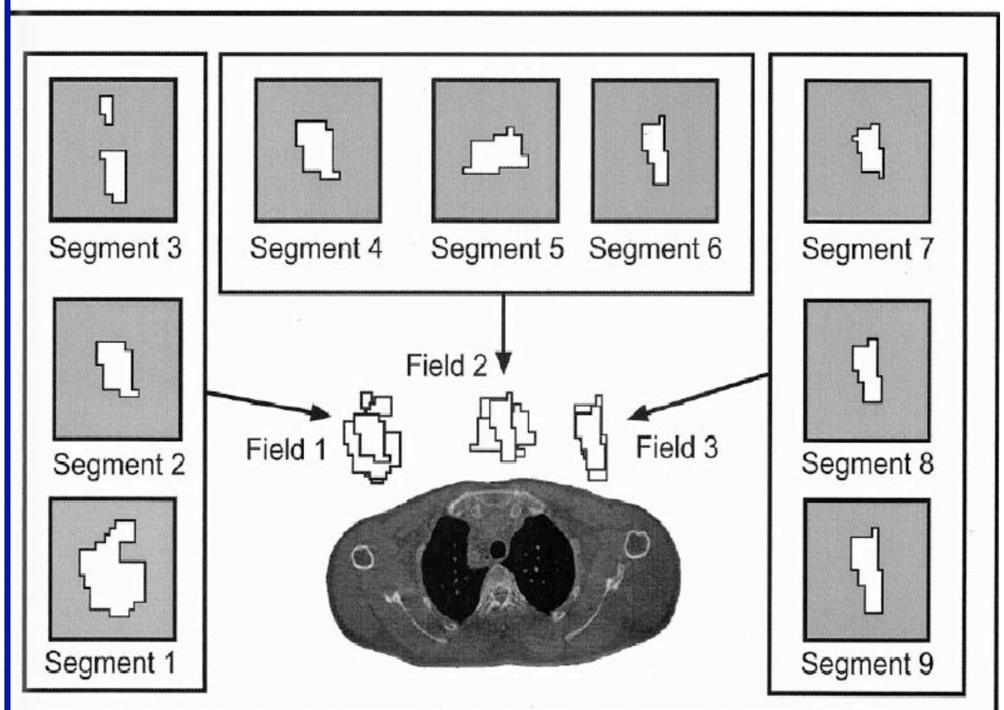


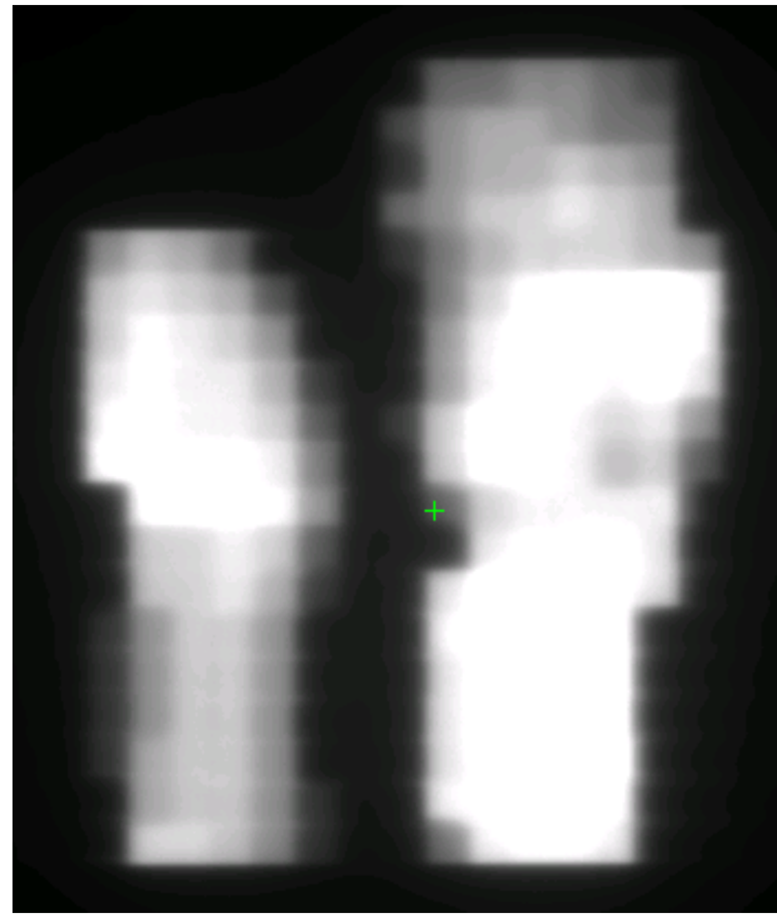


Standard field

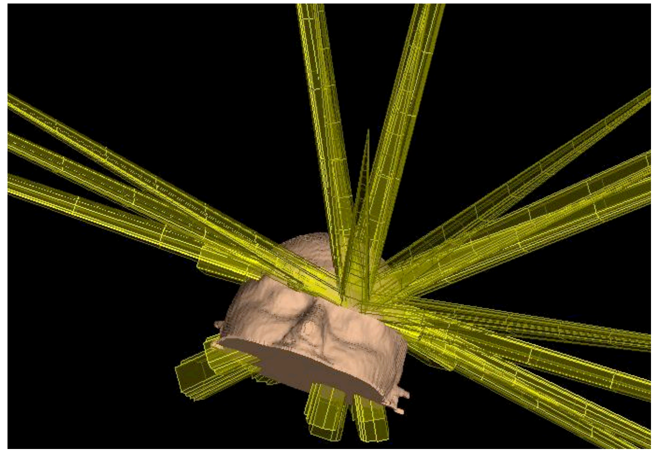
Intensity modulated field

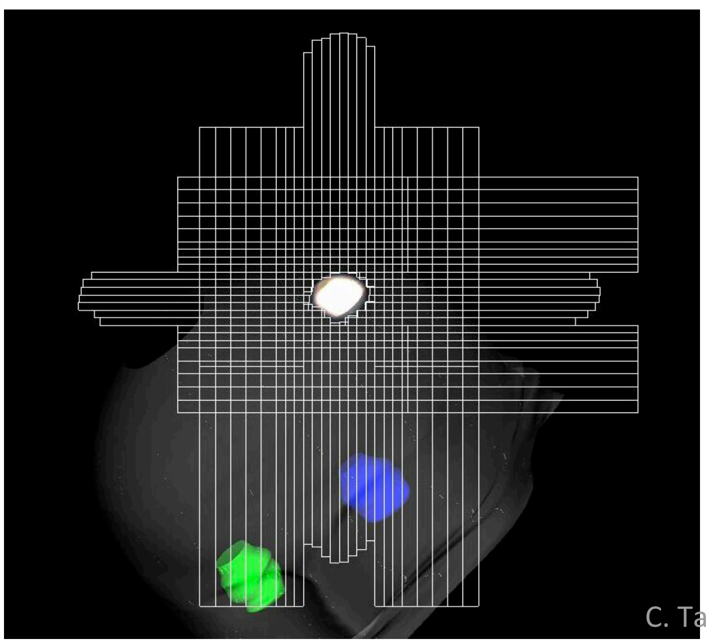
IMRT: Intensity Modulated Radiation Therapy

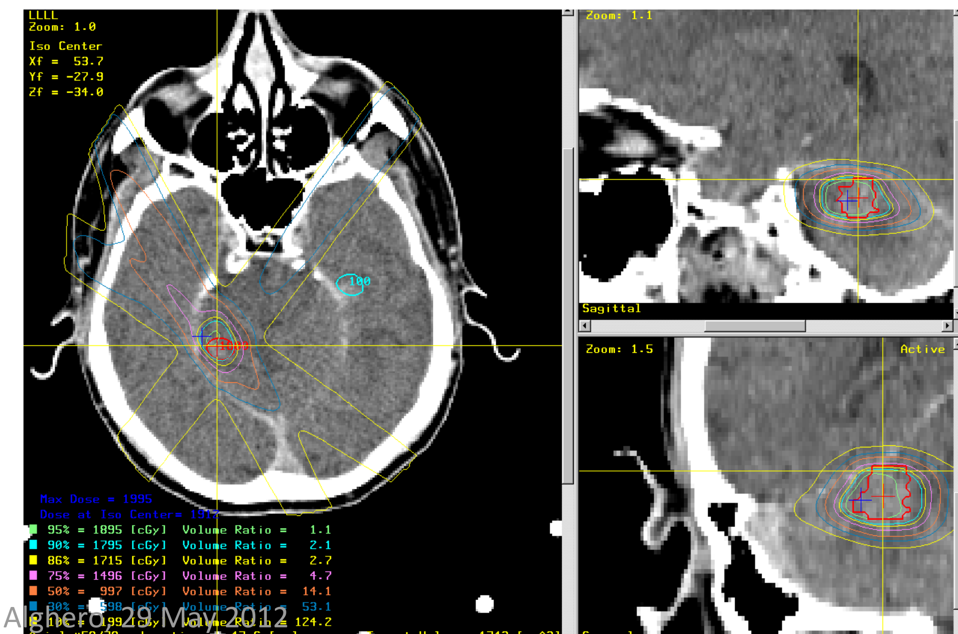




Stereotactic treatment







Gamma Knife Perfexion

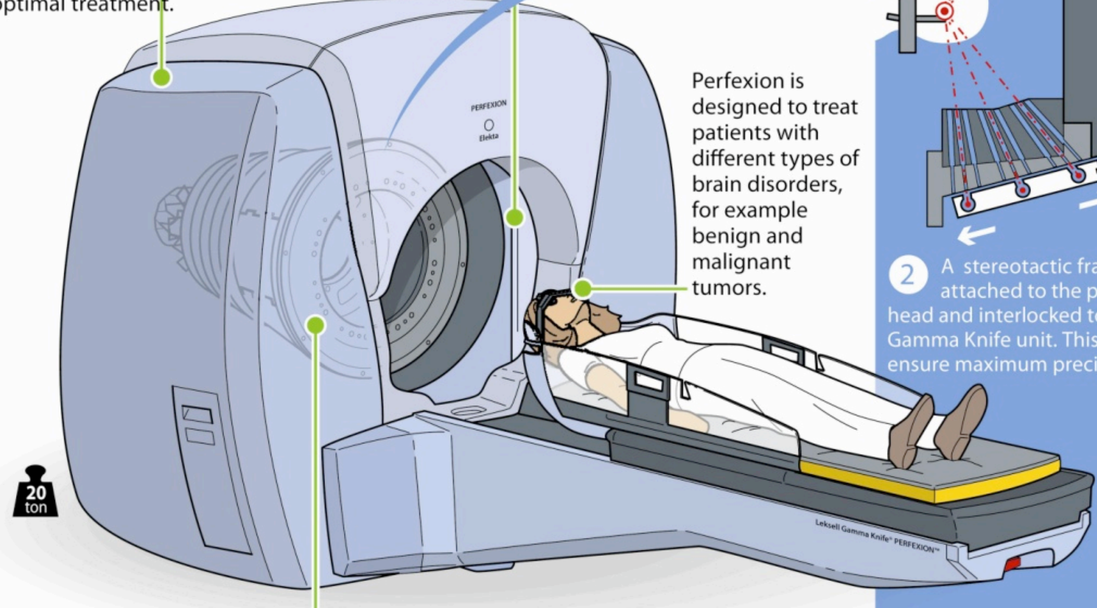
Leksell Gamma Knife Perfexion

Treats brain disorders with a high dose of radiation delivered with surgical precision.

The patient can communicate via video camera and an intercom at all times. The treatment time varies between 20 minutes and several hours depending on the complexity of the treatment.

With the treatment planning software, Leksell GammaPlan, the shape and amount of radiation is decided to give an optimal treatment.

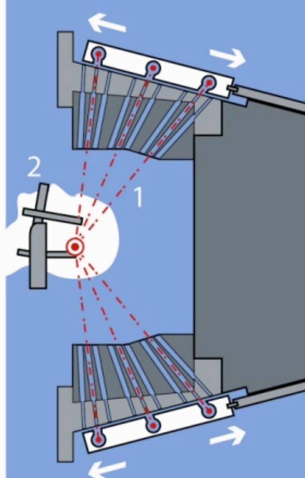
Perfexion is designed to treat patients with different types of brain disorders, for example benign and malignant tumors.



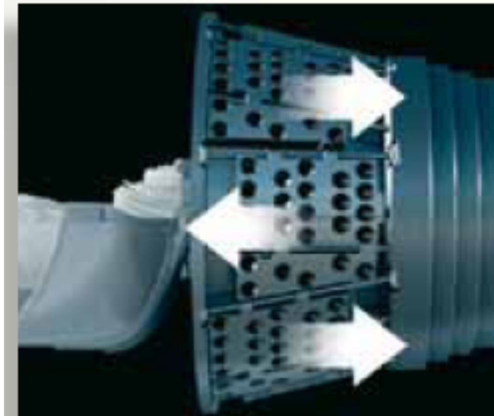
Leksell Gamma Knife Perfexion is fully automated. The radiation unit is housed inside of the machine itself. The radiation beams are shaped exactly around the tumor. Several tumors can be treated in one session.

Radiation unit

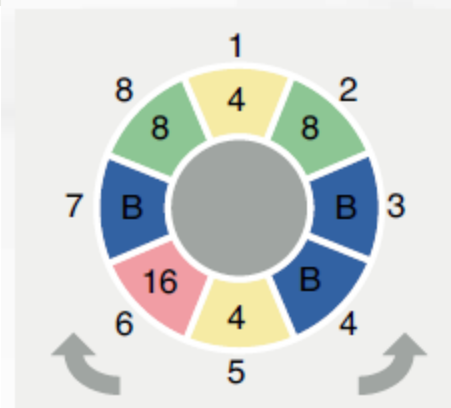
1 Ionizing gamma radiation is emitted from 192 cobalt-60 sources whose beams converge on a precise selected area of the brain. The accuracy is about 0.5 mm. There is minimal effect on the surrounding healthy tissue.



2 A stereotactic frame is attached to the patients head and interlocked to the Gamma Knife unit. This to ensure maximum precision.



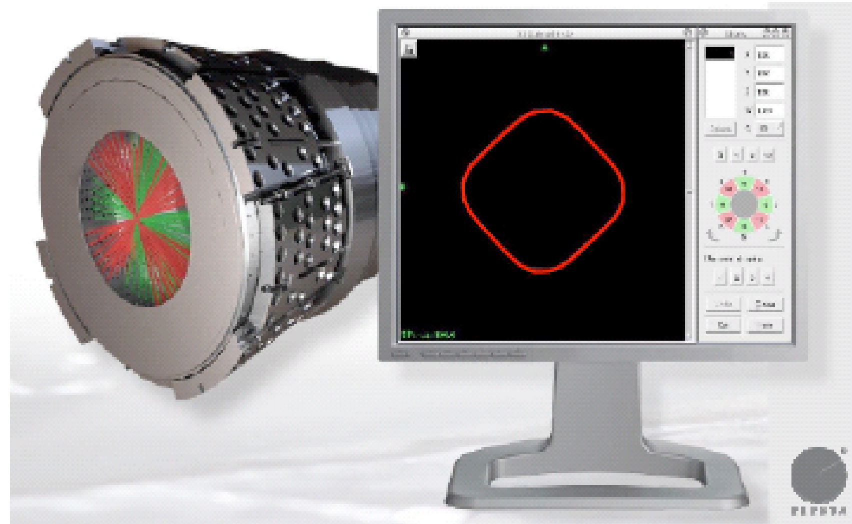
The collimator system consists of 192 cobalt 60 sources, divided into 8 sectors that can be individually positioned to any of 4 states: 4 mm, 8 mm, 16 mm or off. During treatment, these sources are positioned via the sector mechanism to generate the desired radiation beam, and enable treatment of highly complex structures.

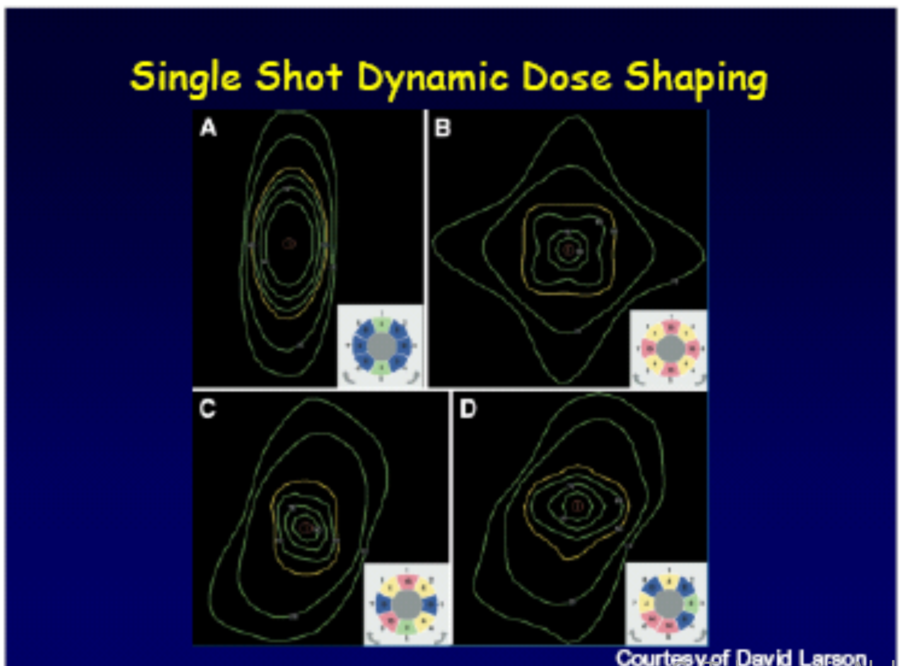


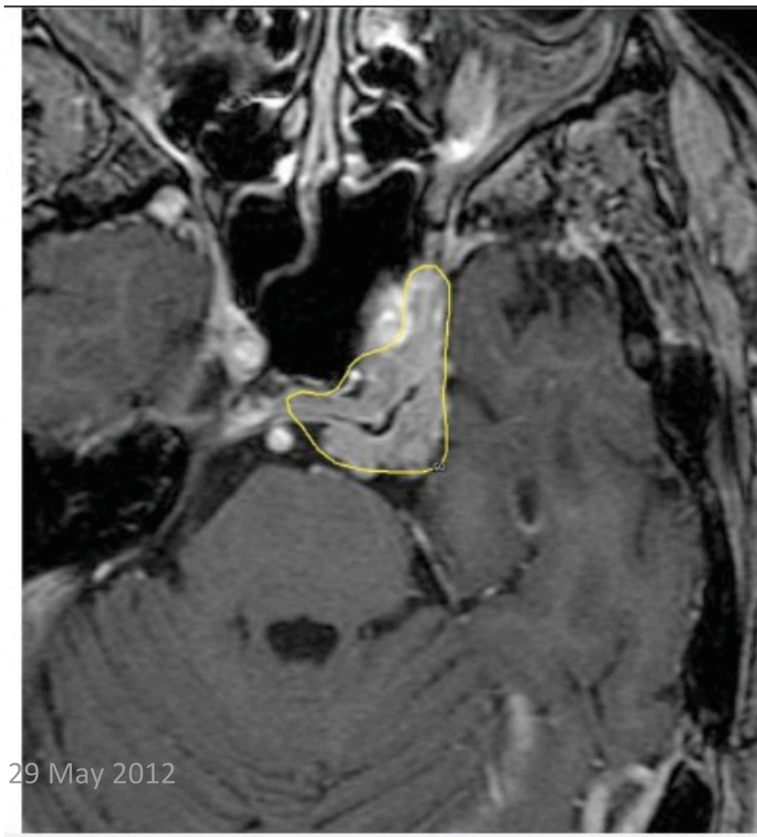
The new collimator design enables swift treatment of complex structures, i.e. through Composite Shots and Dynamic Shaping.

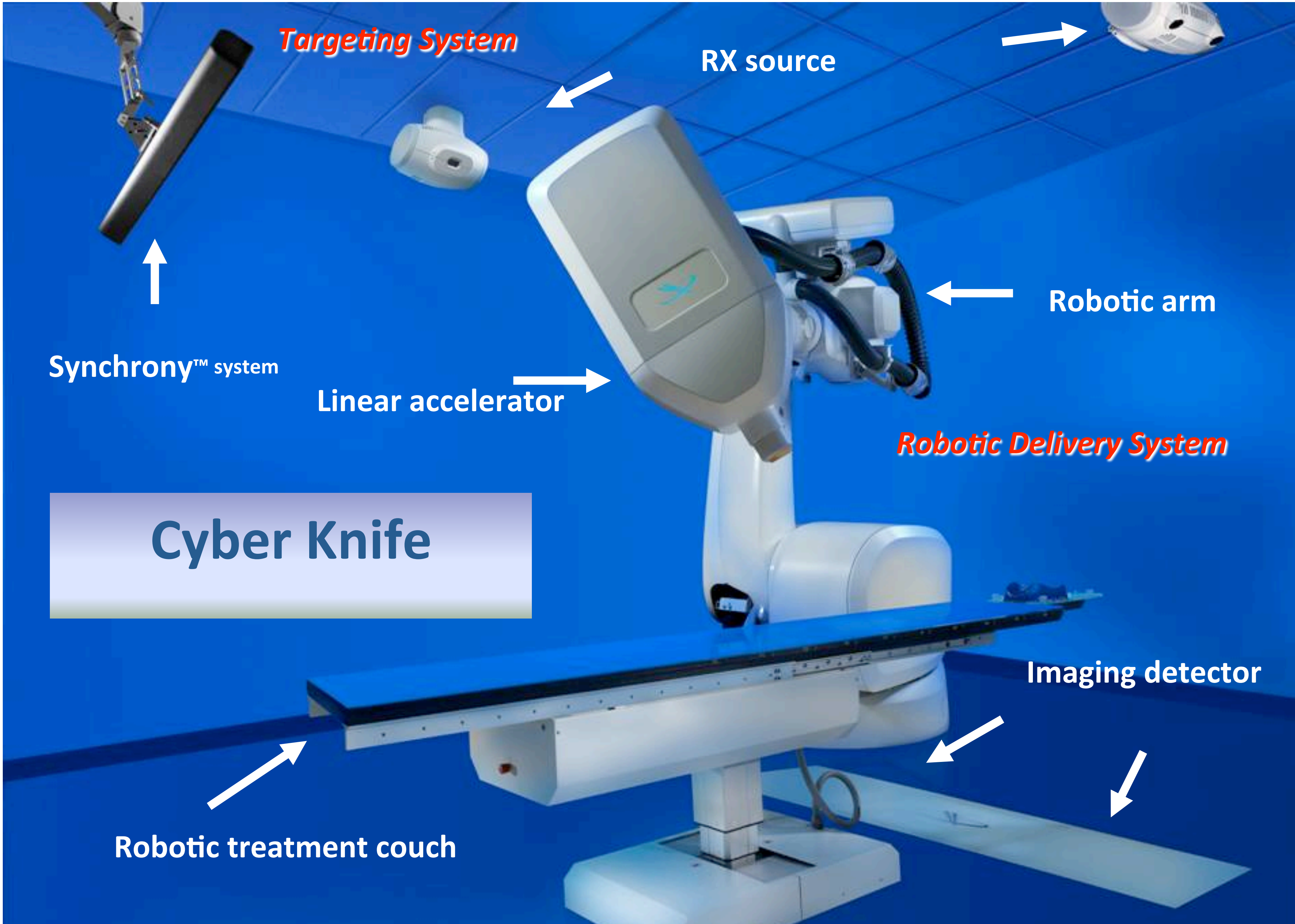
Collimator system 16-16-16-16-16-16-16-16

Collimator system 8-16-8-16-8-16-8-16



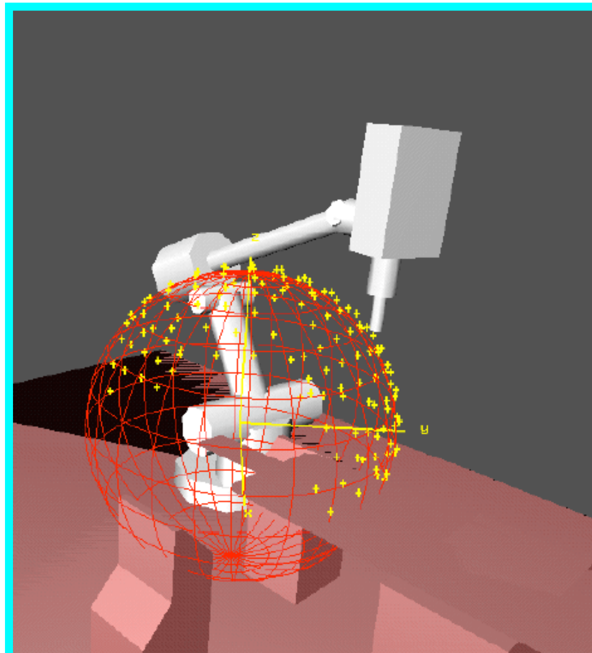


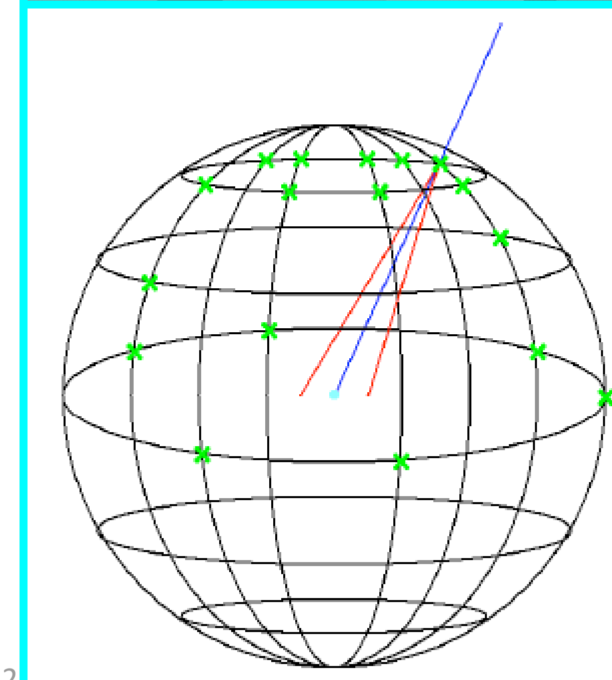



Targeting System
RX source
Robotic arm
Synchrony™ system
Linear accelerator
Robotic Delivery System
Cyber Knife
Imaging detector
Robotic treatment couch

Cyber Knife

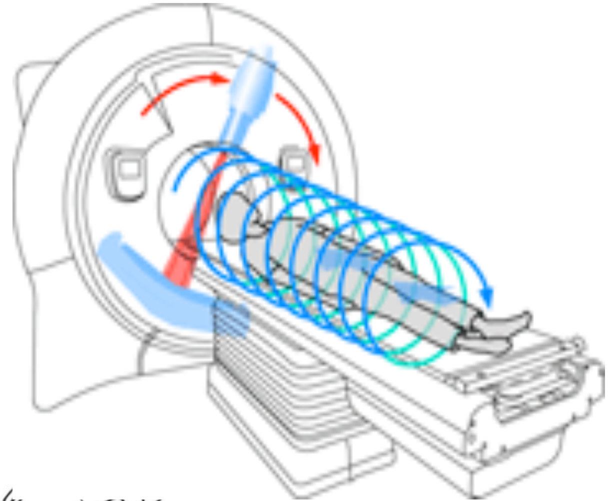
- 6 degrees of freedom
- 120 nodes
- 12 direction for each node
- 1440 orientations
- Position repeatability: < ± 0.12 mm

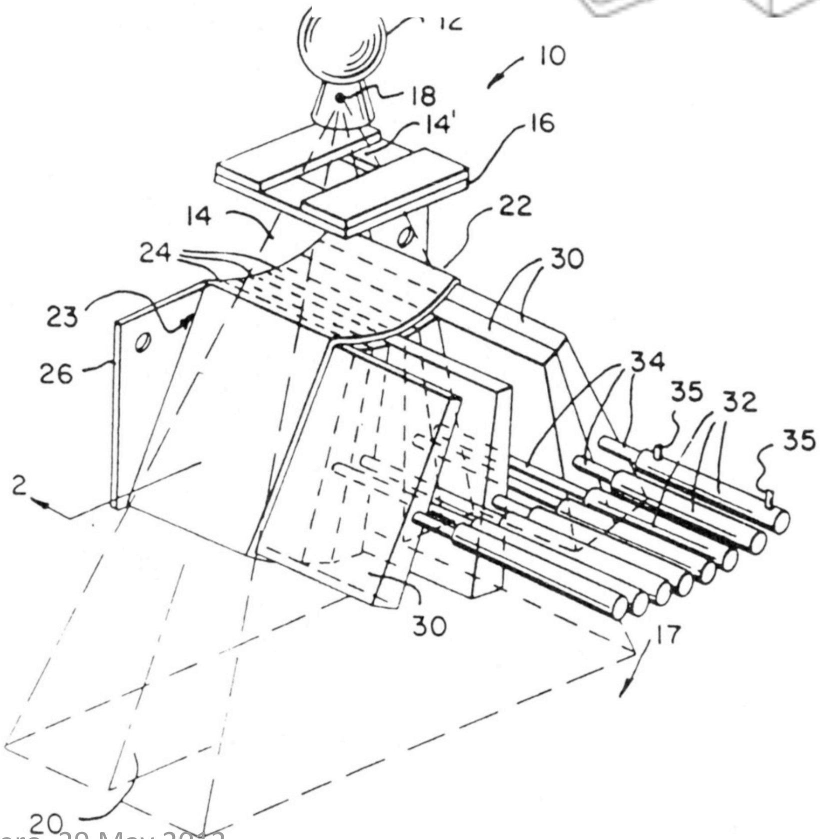




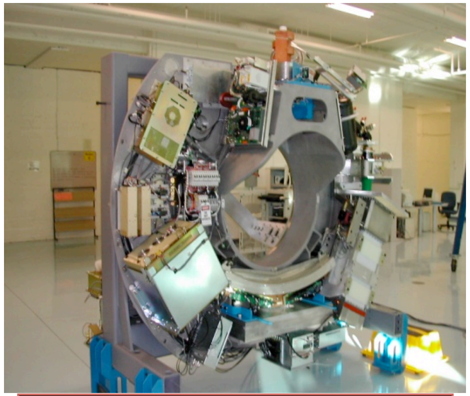
- few nodes and orientations are used for a treatment
- ~ 80 – 250 beams

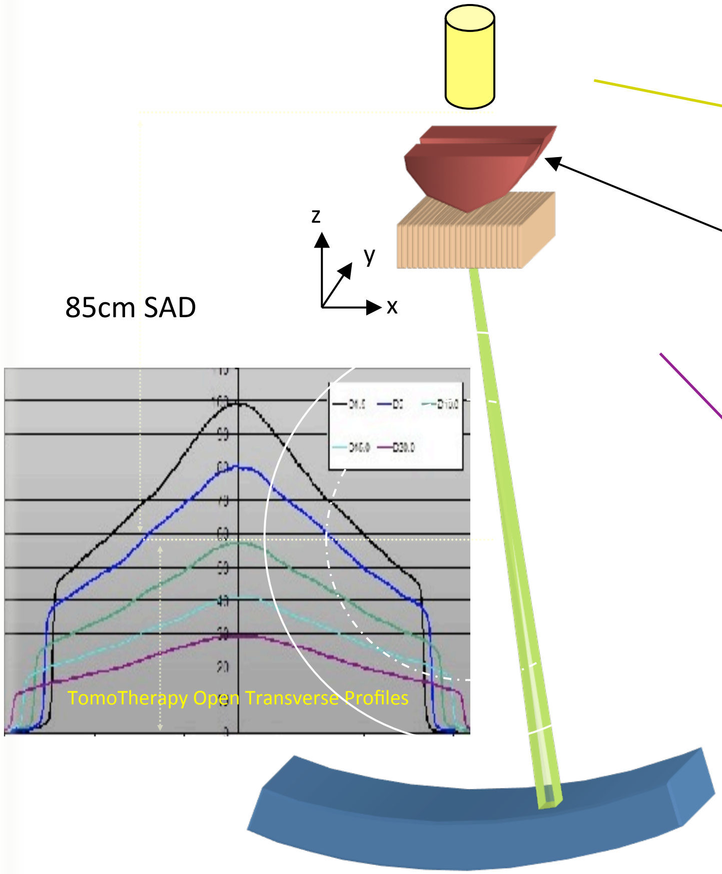
Tomotherapy





Elicodal tomotherapy Hi ART





(900MU/min)

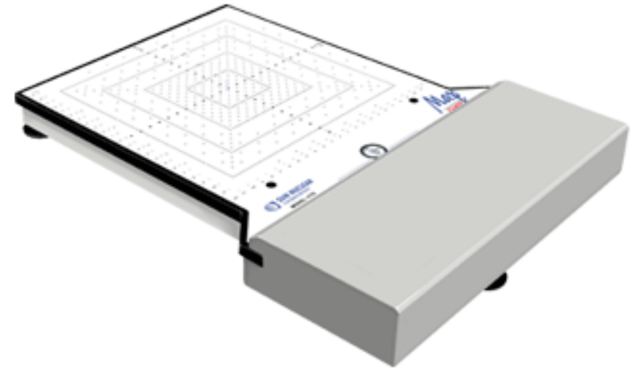
JAWS Longitudinal coll.
$40x5cm^2$ (fan beam)
Field width: 1, 2.5, 5 cm

MLC Coll.
64 leafs (6.25 mm wide, 10 cm thick)

Imaging detectors– MV CT
(738 ionization chambers)

State of the art: 2D Dosimeters

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.

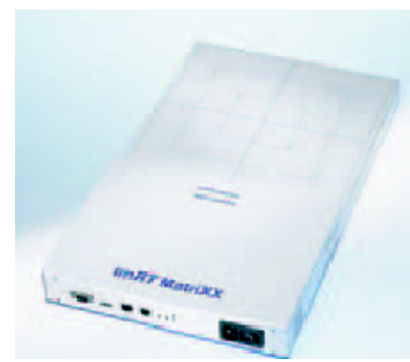


445 silicon diodes

22X22 cm^2 diodes Pitch 1.0 cm

729 ionization chambers

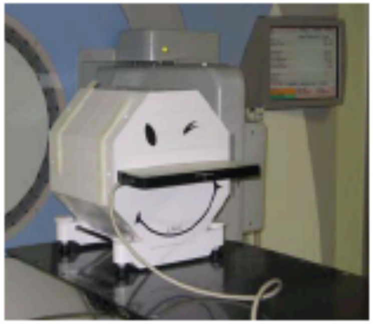
27x27 cm^2 Pitch 10 mm

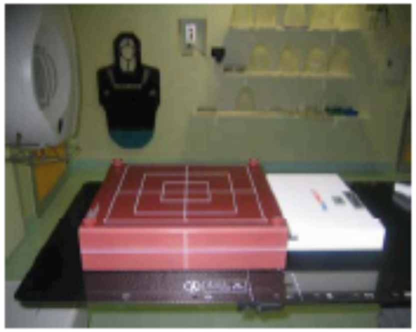


1024 cylindrical ionization chambers

24 x 24 cm^2 Pitch 7.5mm

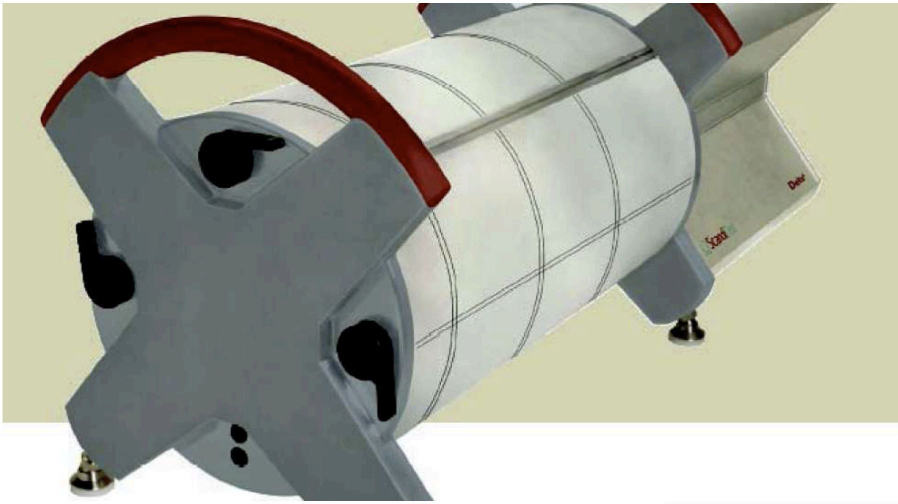
2D +1 commercial silicon detectors

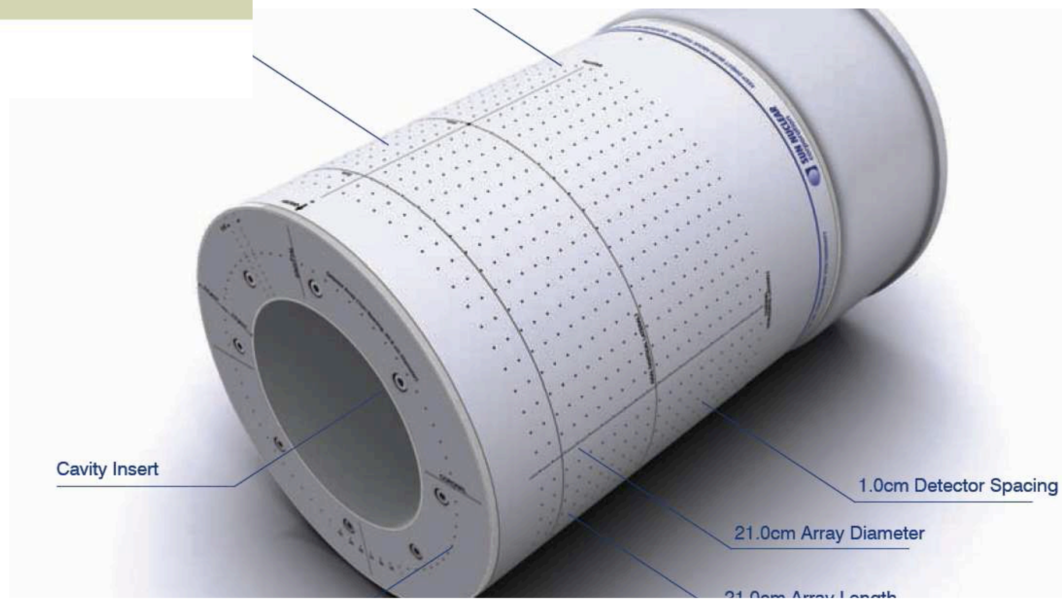




IBA Matrixx evolution + MULTICube	PTW Seven29 + Octavius	SunNuclear MapCheck2 +MapPHAN

3D silicon detectors





Goal

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.

For photon IMRT treatments this is possible thanks to a TPS option that permits to export the actual intensity map into the QA phantom. In this procedure the TPS can change, if it is more convenient, the gantry angle and the number of the delivered monitor units.

Requirements

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, high dynamic range** and **radiation hardness**.

Maestro requirements

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)	**10) Background signal** Requirement: < 0.1% of radiation induced signal
3) Spatial resolution: granularity Requirement: 1-2 mm (photons)	**11) Energy dependence** Requirement: < 1% photons in 4–25 MV 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%

Paul Jursinic: 2D arrays of electron dosimeters

Device name	I' MRT MatriXX	MapCHECK	2D-Array
Manufacturer	Scanditronix / Wellhofer	Sun Nuclear	PTW-Freiburg
Device type	Pixel-segmented ion chamber	2D arrays of diodes	2D arrays of ion chambers
Largest field size	24 cm x 24 cm	22 cm x 22 cm	26 cm x 26 cm or 27 cm x 27 cm
Detector separation	7.6 mm	7.1 mm and 14.1 mm	1.6 cm or 1.0 cm
Detector size	4.5 mm diameter	0.8 mm x 0.8 mm	5 mm x 5 mm
Number of detectors	1020	445	256 or 729
Sampling period	≥ 0.02 s	Not applicable	0.4 s
Measures	Dose and dose rate	Dose	Dose and dose rate

Paul Jursinic: 2D arrays of electron dosimeters

Device name	I' MRT MatriXX	MapCHECK	2D-Array
Device type	Pixel-segmented ion chamber	2D arrays of diodes	2D arrays of ion chambers
Inter-detector calibration	Software guided routine	Software guided routine	Provided by manufacturer
Linearity with dose	0.1 to 10 Gy	0.01 to 3.5 Gy	0.02 to 5 Gy
Dose-per-pulse dependence	Not available	< 2% over 330-fold change	Not tested
Linearity with dose rate	0.74 to 6.12 Gy/min 1% change	0.5 to 6 Gy/min 2% change	0.5 to 8 Gy/min % change not given
Output versus field size	5 x5 to 12 x 12 same as water	3 x3 to 25 x 25 same as water	2 x2 to 27 x 27 same as water
Detector stability	1 σ = ±1.3 % over 7 months	1 σ = ± 0.2 % over 9 months -1.5% per kGy	1 σ = ±1.3 % over 4 months

Granularity

The issue of detector size and detector separation is often discussed between the medical physicists working in IMRT field.

The problem of sampling has been examined in the paper of J. F. Demsey et al. "A Fourier analysis of the dose grid resolution required for accurate IMRT fluence map optimization" Med. Phys., 32(2): 380-388 (2005).

The authors show that a 2.5 mm grid resolution is sufficient to avoid errors larger than 1%.

Objective

Development of a suitable device for dosimetric verification of radiotherapic fields, where good resolution, high sensitivity to the absorbed dose and high response velocity are needed.

FIRST STEP:

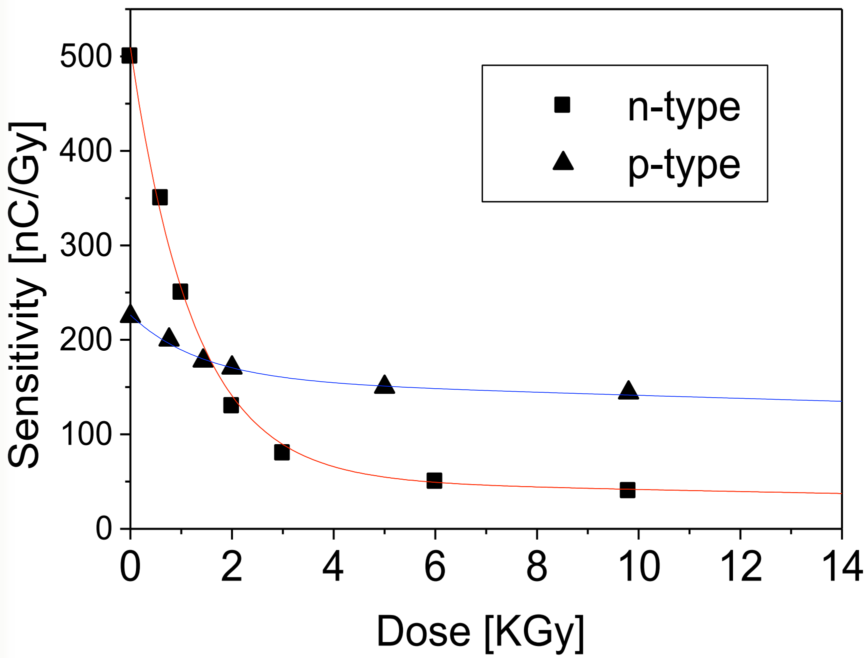
The evaluation of the best device geometry and material for the bidimensional dosimeter has been carried out: to reduce sensitivity degradation with accumulated dose

a. Material Choice

b. Geometry Choice

Material Choice

- Commercial single-pad Si dosimeters suffer of a strong dependence of the sensitivity on the accumulated dose. This issue is of concern in clinical radiotherapy applications. A significant improvement of long term stability of the dosimetric response has been achieved by us.



G.Rikner et al.Phys. Med. Biol. 28, 1983, 1261-1267

Standard Si dosimeters

➡ Pre-irradiation up to 10kGy

➡ Frequent Calibration needed

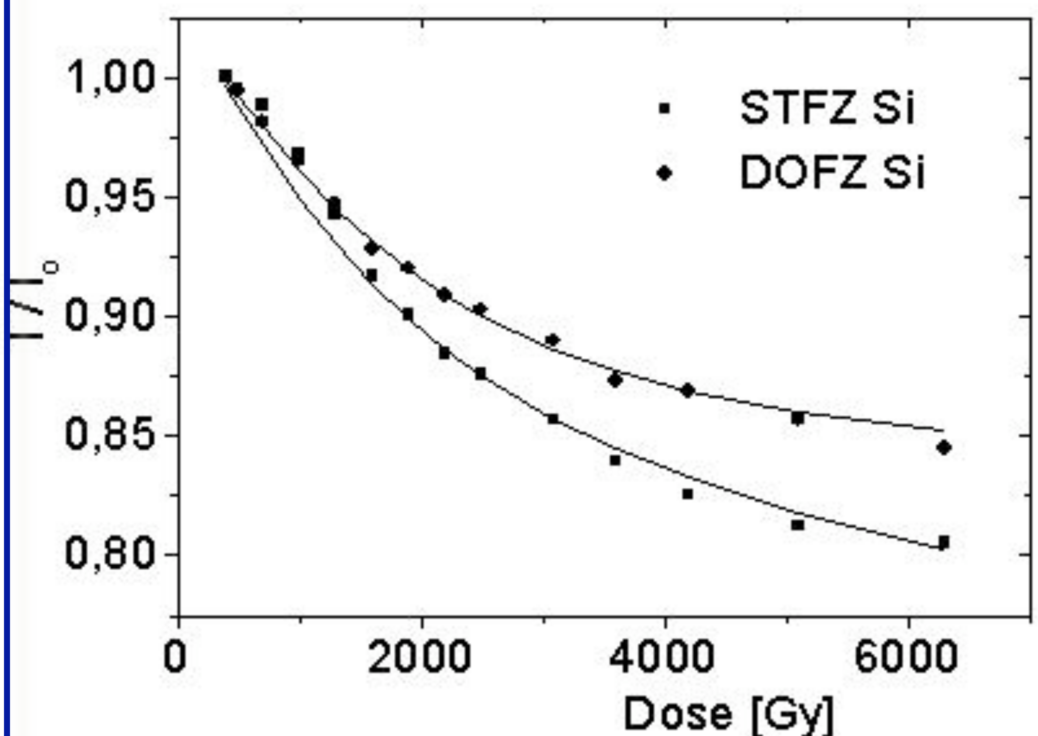
S α L = $\sqrt{(D\,\tau)}$, D diffusion coefficient , τ minority carrier lifetime:

$$1/\tau = 1/\tau_0 + K\ \phi$$

ϕ accumulated dose, with τ_0 minority carrier lifetime at zero dose.

Defect Engineering with O_i

High resistivity standard and oxygenated Float Zone Si p^+n junctions have been measured using a ^{60}Co radiotherapy beam after an accumulated dose up to 6kGy from a ^{137}Cs γ-source.



In DOFZ (Float Zone enriched with Oxygen up to $10^{17}cm^{-3}$) is characterized by a higher radiation hardness than standard FZ

Improved radiation hardness of DOFZ Si

Decrease in sensitivity with the accumulated dose due to the generation of a dominant trap acting as lifetime killer.

$1/\tau - 1/\tau_0 = \sigma\, v_{th}\, N_t$, $\quad N_t = a\ \phi$; $\ a$ = trap generation rate

σ capture cross section ; v_{th} carrier thermal velocity. N_t trap concentration.

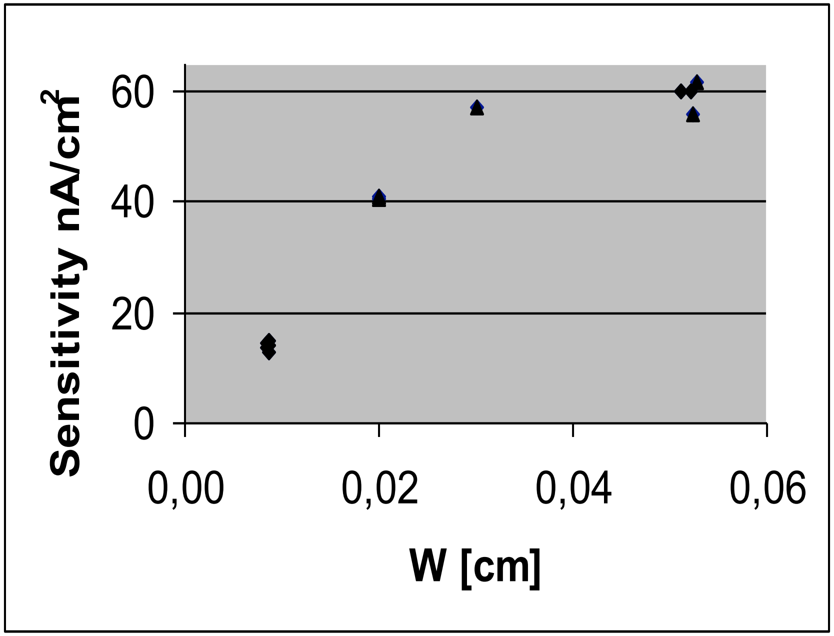
$a_{DOFZ} < a_{SFZ} \Rightarrow$ increased radiation hardness of the device to radiotherapic beams.

Response of different Si materials and thicknesses to MV beams

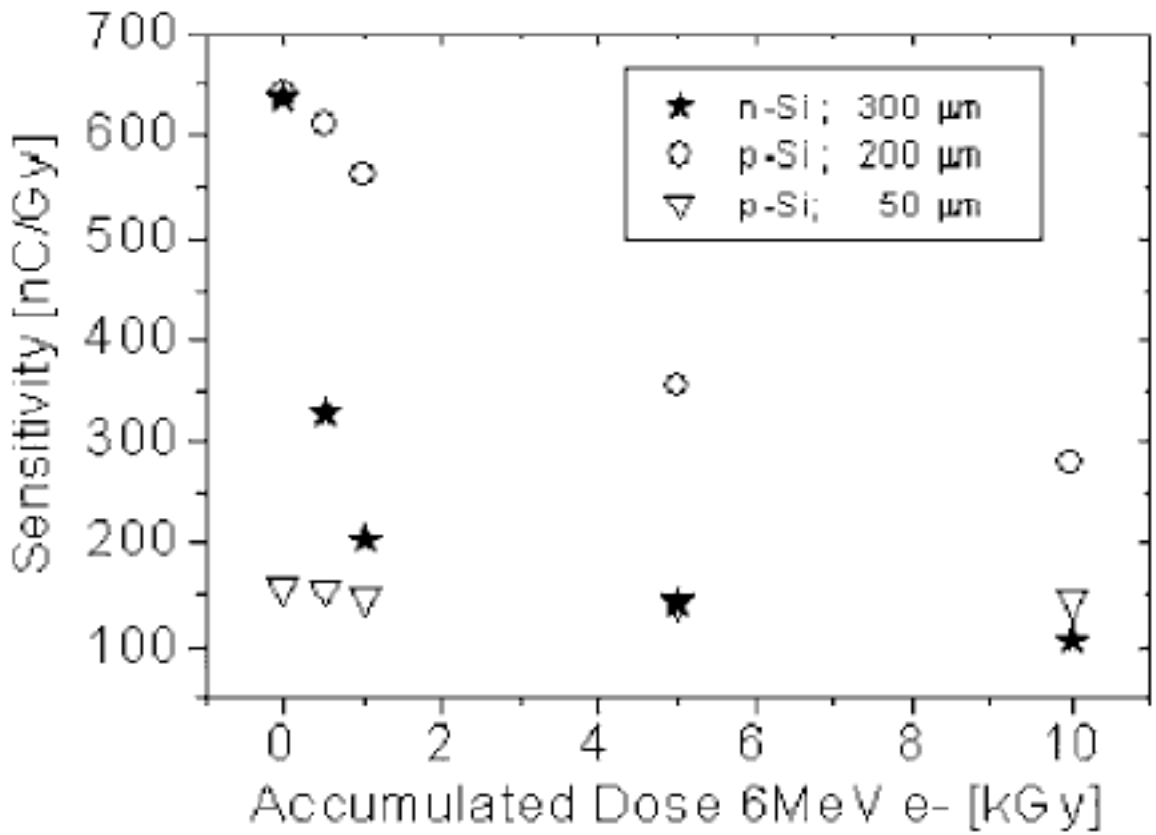
We have studied Si diodes produced from wafers of different material and thickness, resistivity, conductivity type: Standard Float Zone (SFZ), Magnetic Czochralski (MCZ), Diffused Oxygenated Float Zone (DOFZ), epitaxial grown on Czochralski substrate Si (EPI).

diode	A(mm^2)	W(μm)	type	Material
W08_14_p200	12,7	200	p	FZ
W08_12_p200	12,7	200	p	FZ
FZp500_n5	12,7	525	p	FZ
FZp500_n7	12,7	525	p	FZ
EPI_A	12,7	50	n	EPI
EPI_A	12,7	50	n	EPI
EPI_B	12,7	50	n	EPI
Q2_n50	1,9	50	n	FZ
Q1_n300	3,24	300	n	FZ
Q2_n300	1,9	300	n	FZ
MCZ380_n300	12,7	300	n	MCZ
MCZ381_p300	12,7	300	p	MCZ

Sensitivity vs. thickness

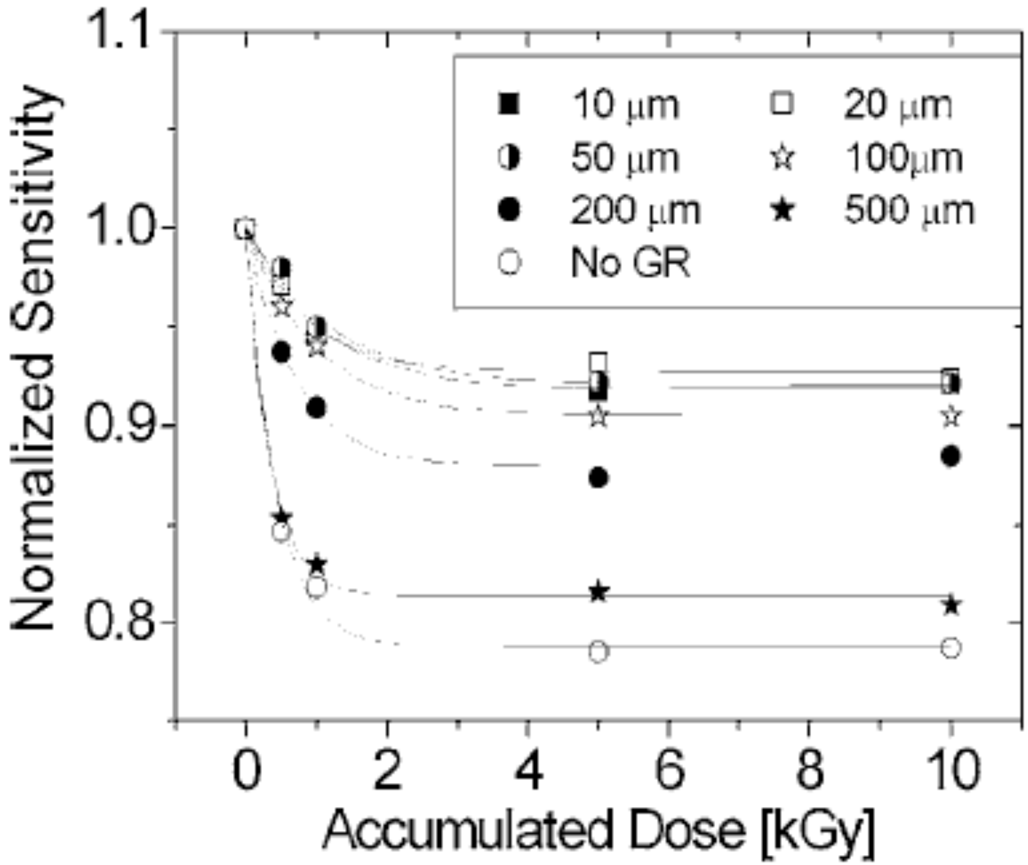


Choice of the thickness



Max diffusion length at zero dose is 200µm
The sensitivity of the epitaxial device is almost constant within 1.8% up to 10 kGy

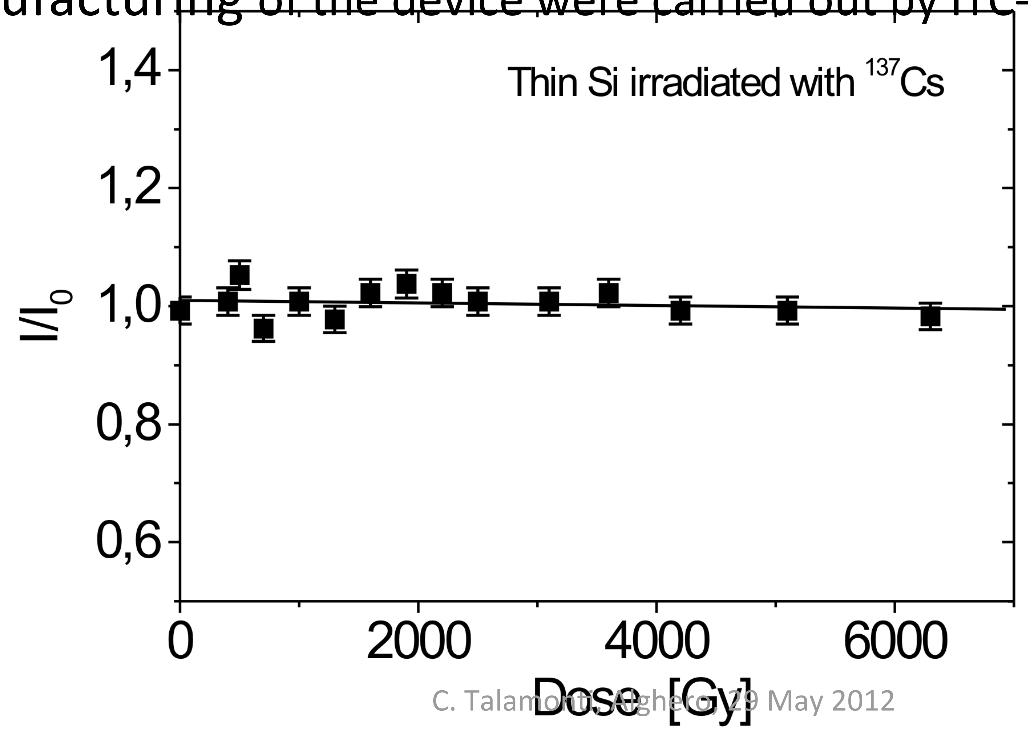
Guard ring



Normalized Sensitivity
1.1
1.0
0.9
0.8
10 μm
20 μm
50 μm
100μm
200 μm
500 μm
No GR
0
2
4
6
8
10
Accumulated Dose [kGy]

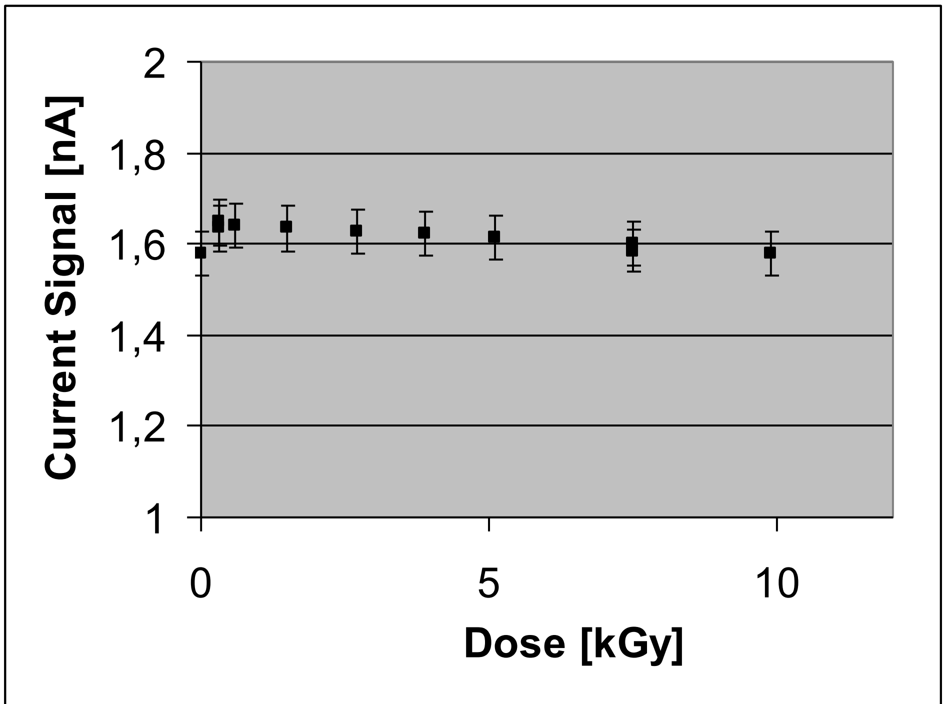
Geometry Choice

- Adding opportune grounded guard rings and using thinned substrates, we achieved signal stability up to a dose of 6kGy of gammas from a ^{137}Cs source.
- 4” p-type MCz wafer
- Epitaxial layers with 50nm thickness were grown by ITME Warsaw Poland
- Manufacturing of the device were carried out by ITC-IRST Trento (now FBK)



Best Compromise: Material/Geometry

Epitaxial Si is naturally enriched with O_i and thickness can be easily controlled during growth. Signal stability within 1.7% has been achieved with EPI diodes irradiated up to 10kGy of γs from ^{137}Cs and tested with the ^{60}Co beam.



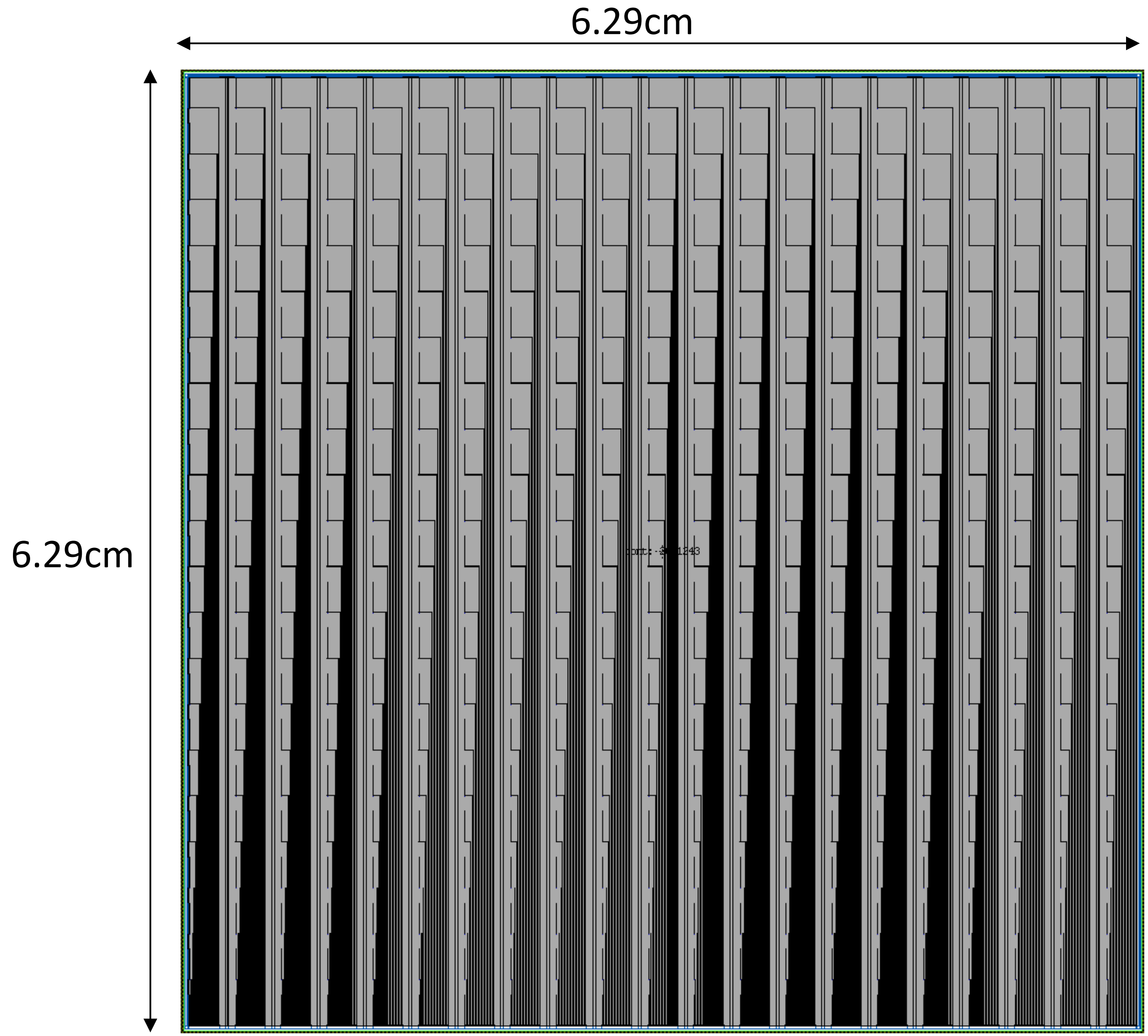
High quality crystalline epitaxial Si of 50μm thickness is now commercially available on large scale at very low costs

Development of the 2D Si Matrix

- Best compromise between bidimensional resolution and electronic read-out efficiency has been achieved by means of a modular device composed by squared matrixes of macropixel sensors. The best geometry of the pixel cell has been determined by investigation of the sensitivity and radiation hardness of single pad diodes with different thickness and active area.

- We have experimentally studied different guard-ring solutions to confine the lateral extension of each macropixel cell. Best solution is the manufacture of a guard-ring net surrounding each pixel and connected to ground.

DFC Module of 2D Si Dosimeter Designed for MAESTRO by IRST-Trento

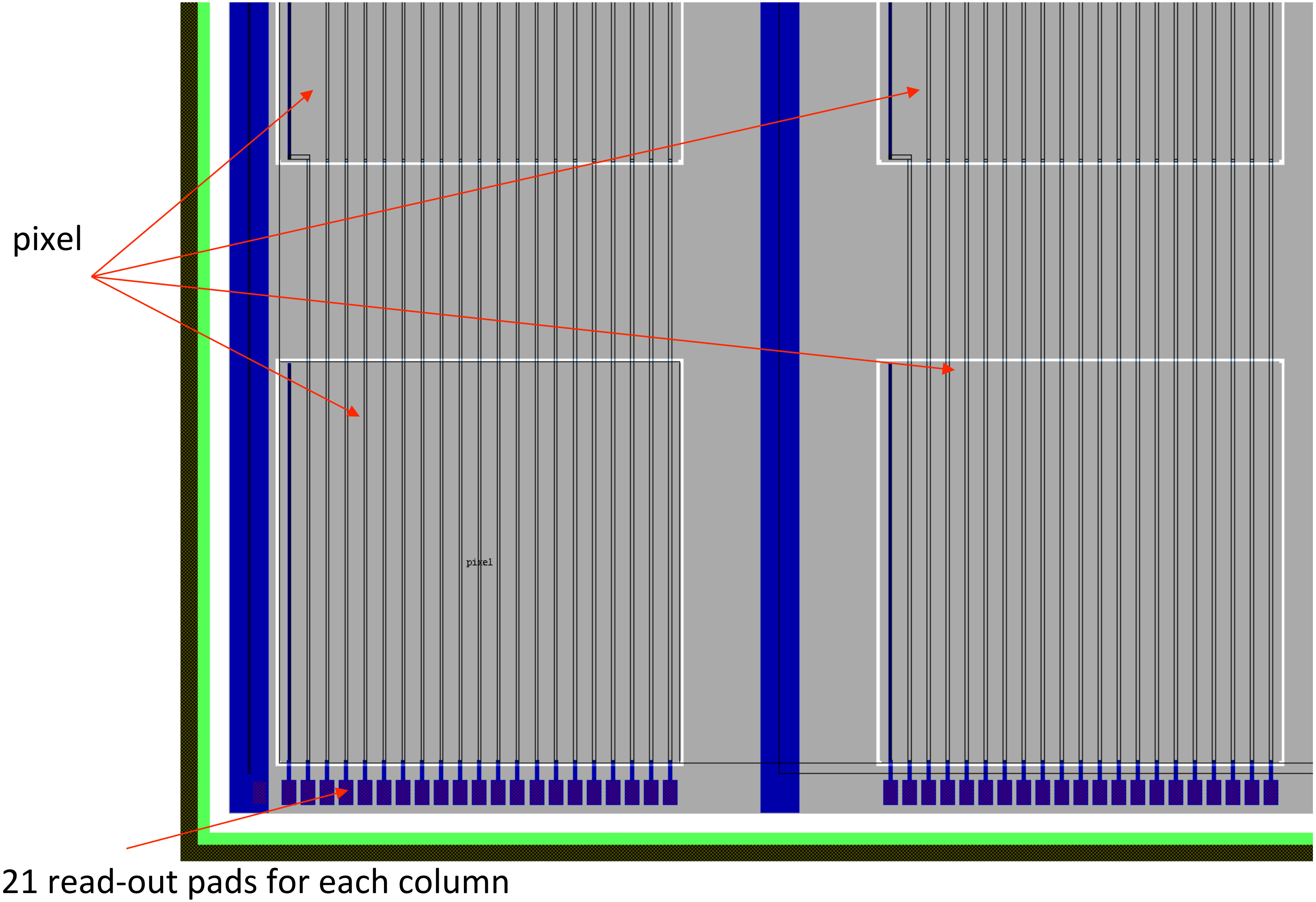


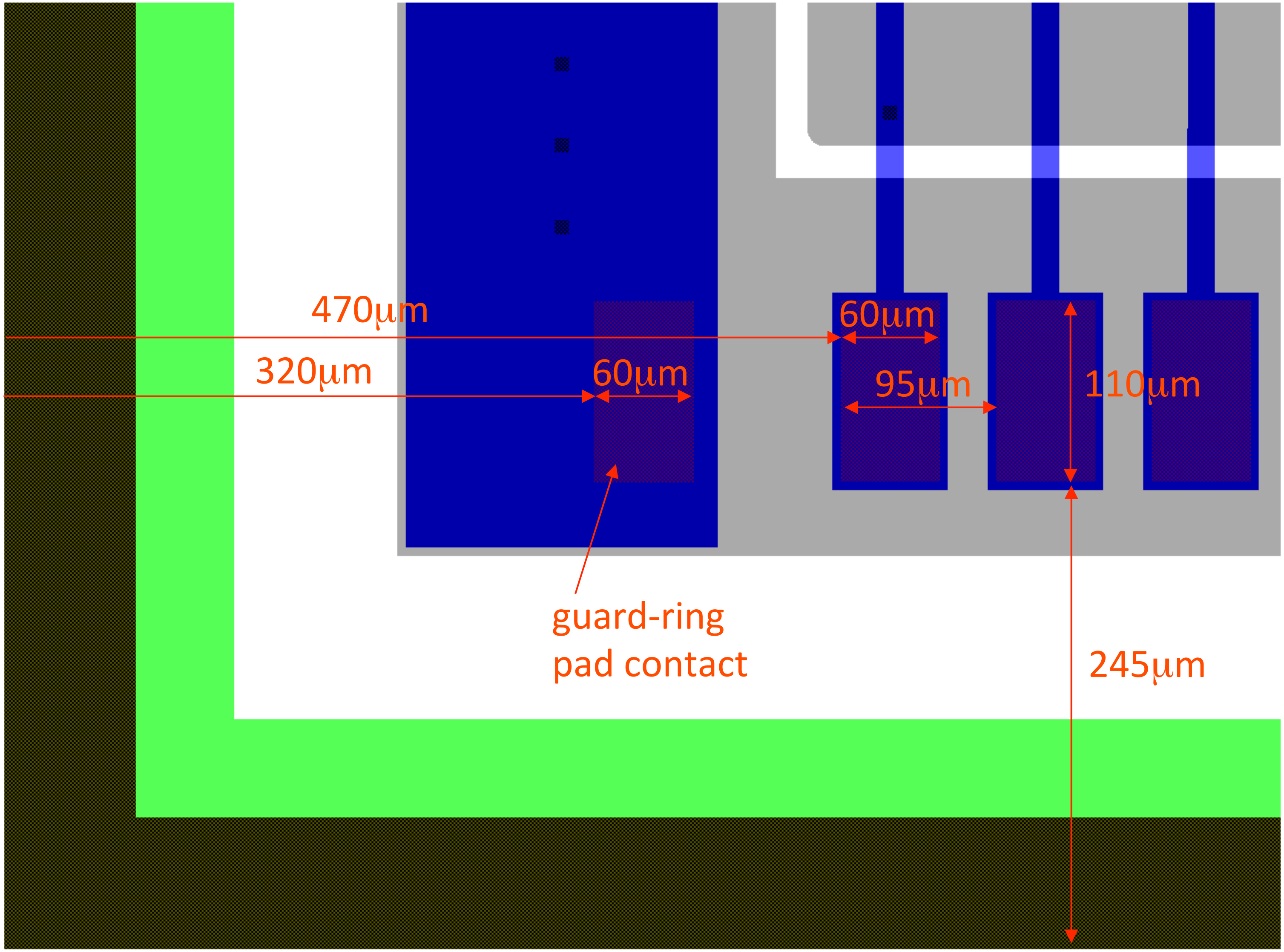
21x21pixel

Pixel: 2x2mm
Pitch: 3mm

Bottom corner

Blue=metal; grey=n implant; green=p implant;
Black=scribe line; violet=passivation opening




470μm
60μm
320μm
60μm
95μm
110μm
guard-ring
pad contact
245μm

Summary: Material choice

Attractiveness 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.
d) Radiation hardness

Summary: Material Problems solution

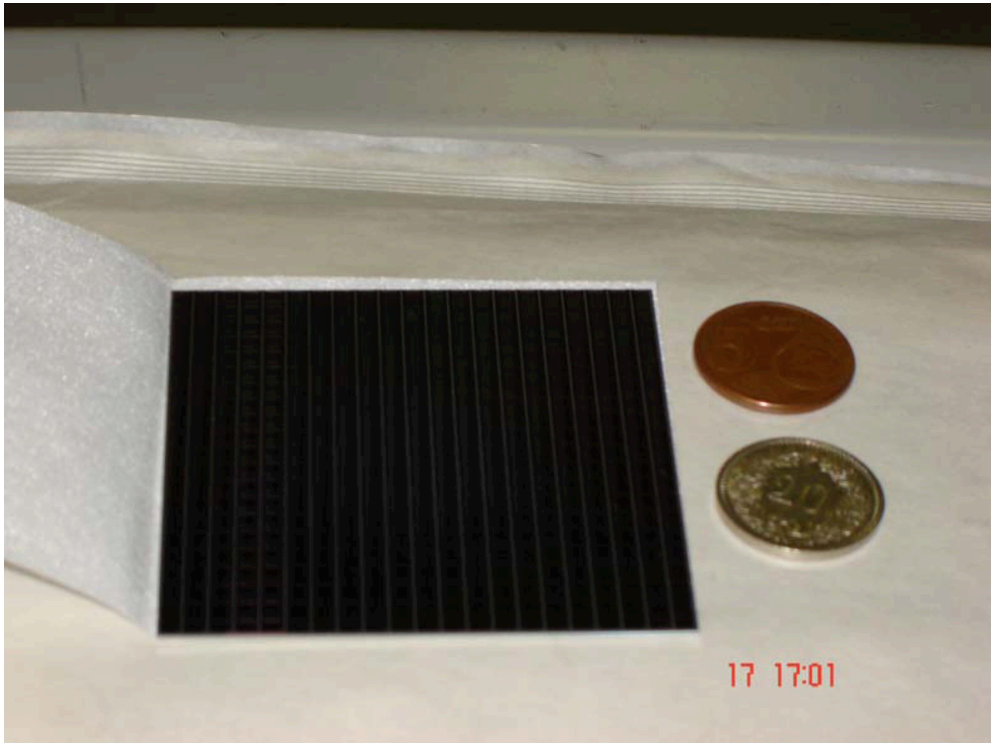
Commercial single-pad Si dosimeters: dependence of sensitivity on dose.

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.

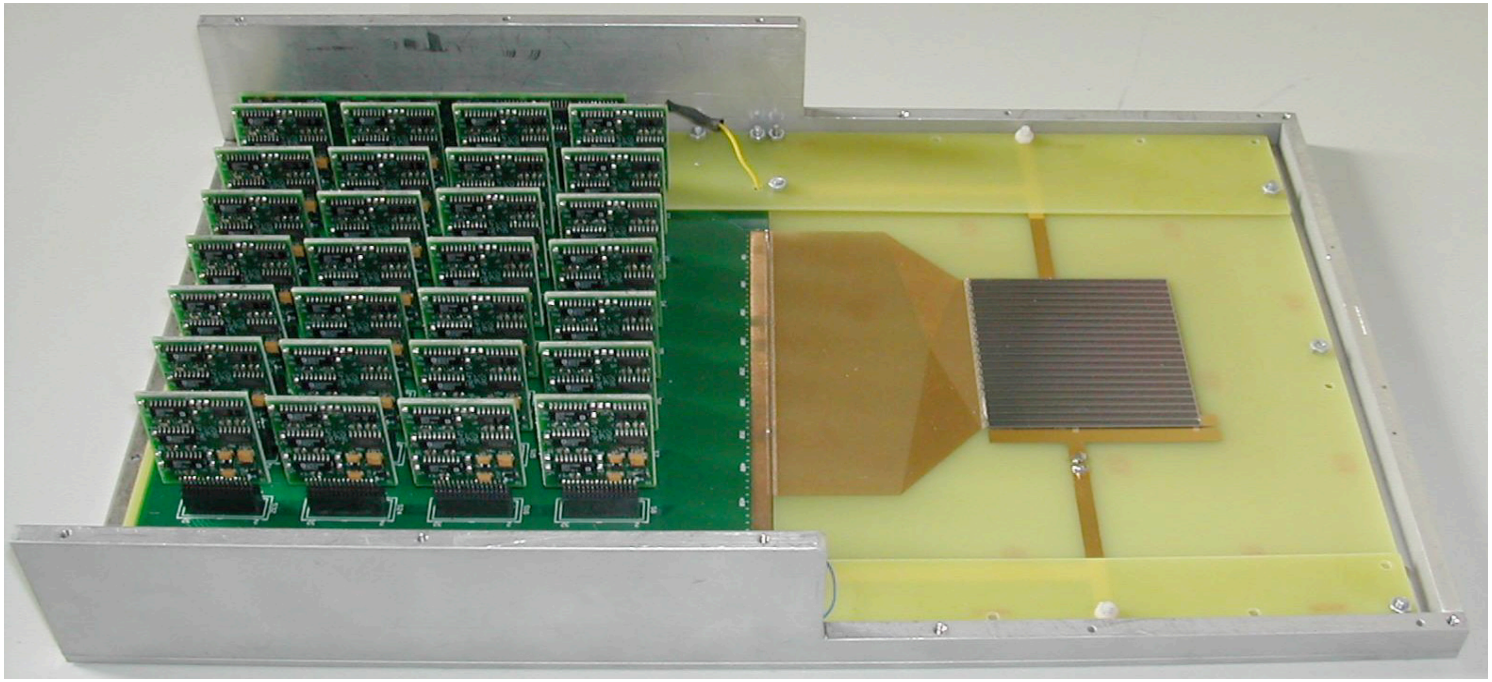
Detector



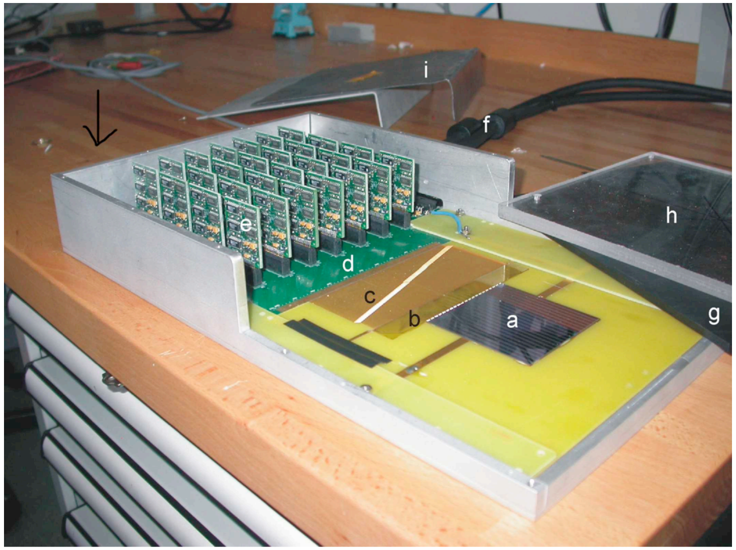
Test under probe station:
average zero-bias current : i_0=13±7 pA
Temperature coeff.: di_0/dT=4 pA/°C.
Cross-talk capacitance: $C_c \approx 2$ pF

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**.

Detector



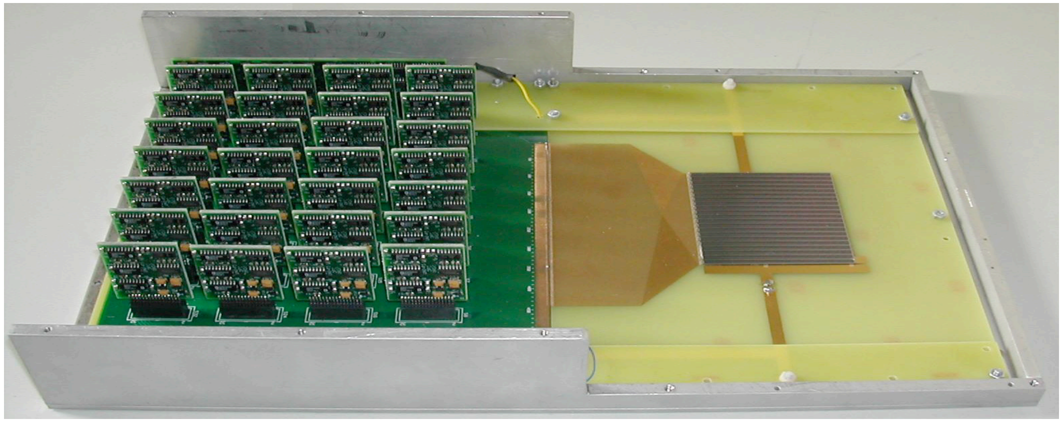
- 2006 Italian patent N FI2006A000166
- PCT/IB2007/001850 **International patent** WO2008/004091



I Prototype (2006)

Version of the 441ch detector with discrete electronics, in which the silicon module outputs are routed to a standard PCB by using a pitch adapter (b).

Upgraded I Prototype (2006)



Improved version of the 441ch detector with discrete electronics, in which the Si module outputs are connected directly to a the high-density PCB on which the silicon module is sitting.

Specifications:

a) Spatial resolution:

~1 mm granularity

b) Active area:

at least 20x20 cm^2

c) Low Background signal:

< 0.1% of signal

(zero bias operation needed)

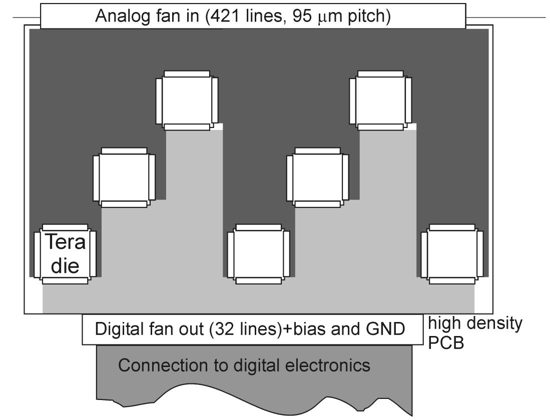
Response speed and signal strength are of no concern

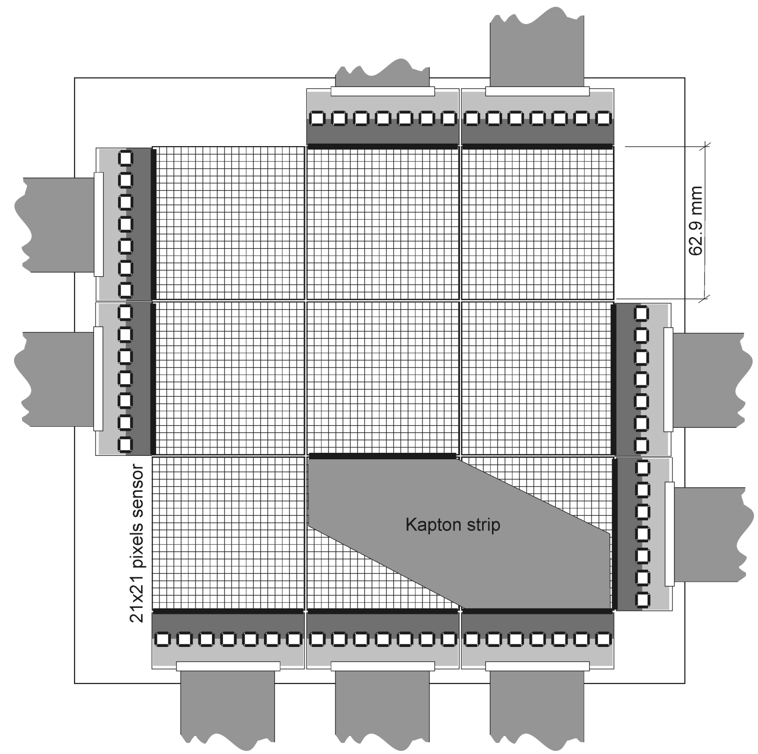
9-modules design:

A single module cut from each wafer.

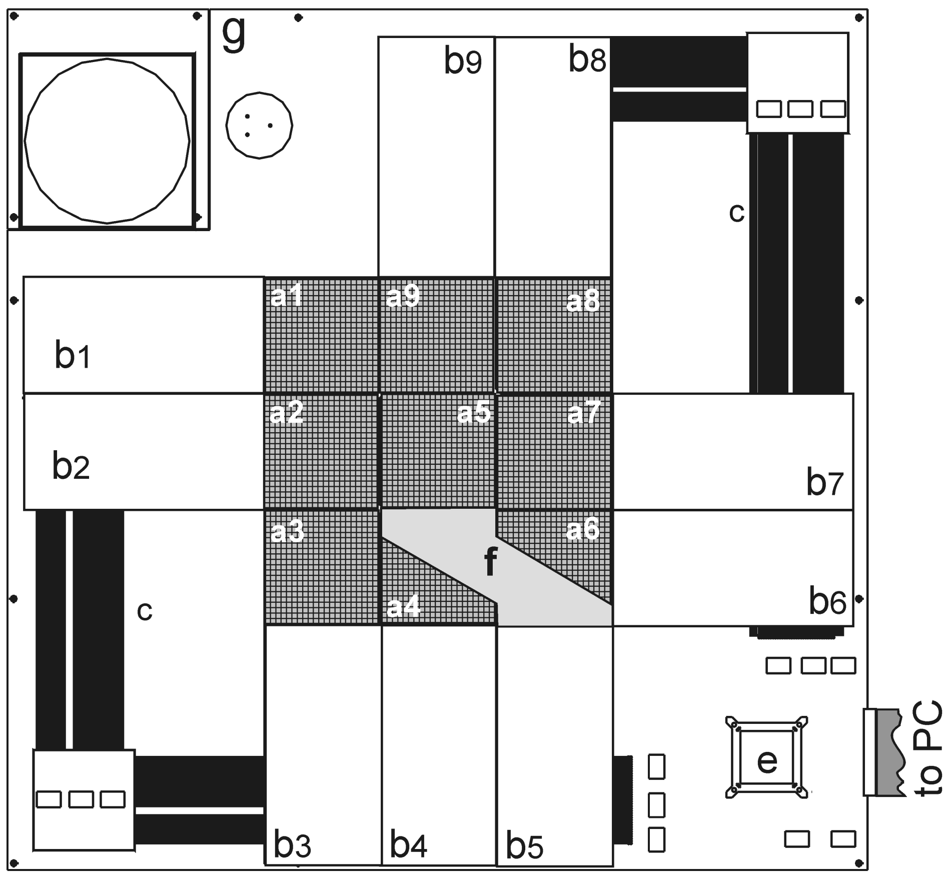
Nine modules will be used to cover an area of about 20×20 cm^2.

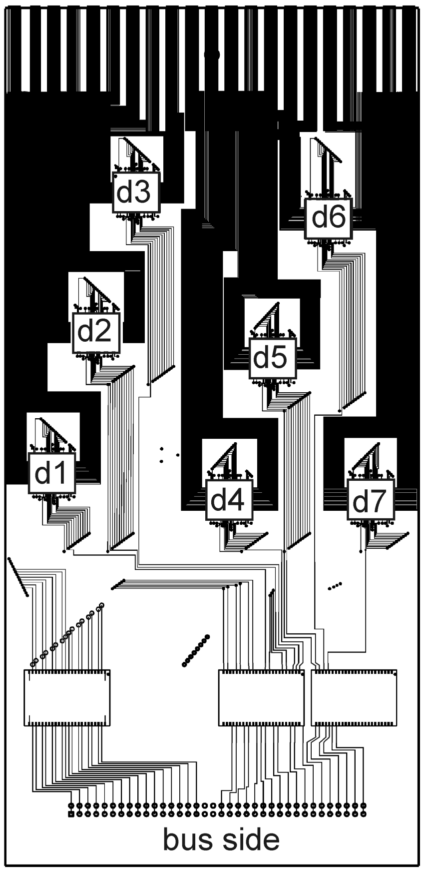
System complexity: ~4k channels





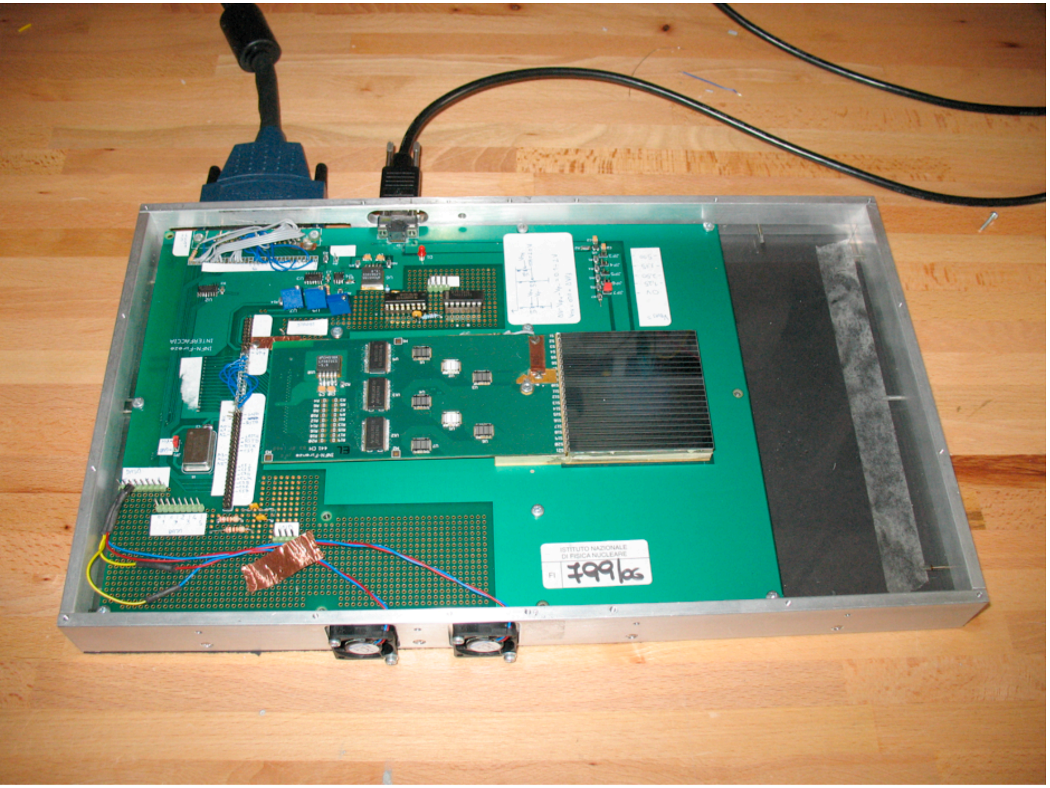
Design of TERA-based 4k ch system



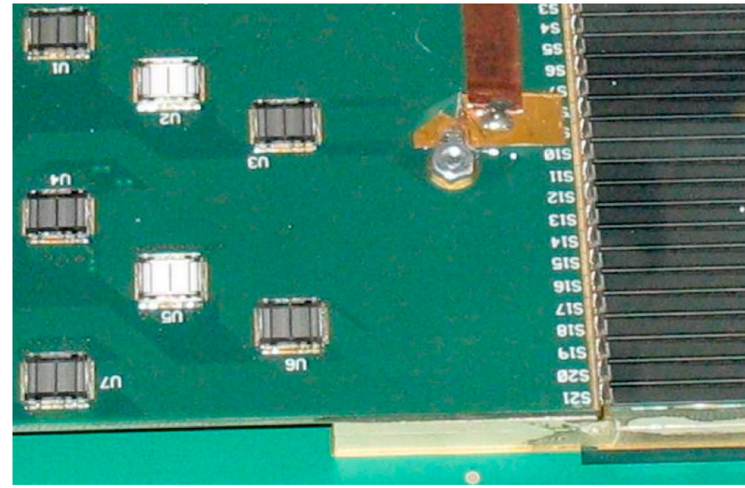


Each module: 7 TERA06 dies bonded on a high density 100 μm pitch PCB

II Prototype (2007)

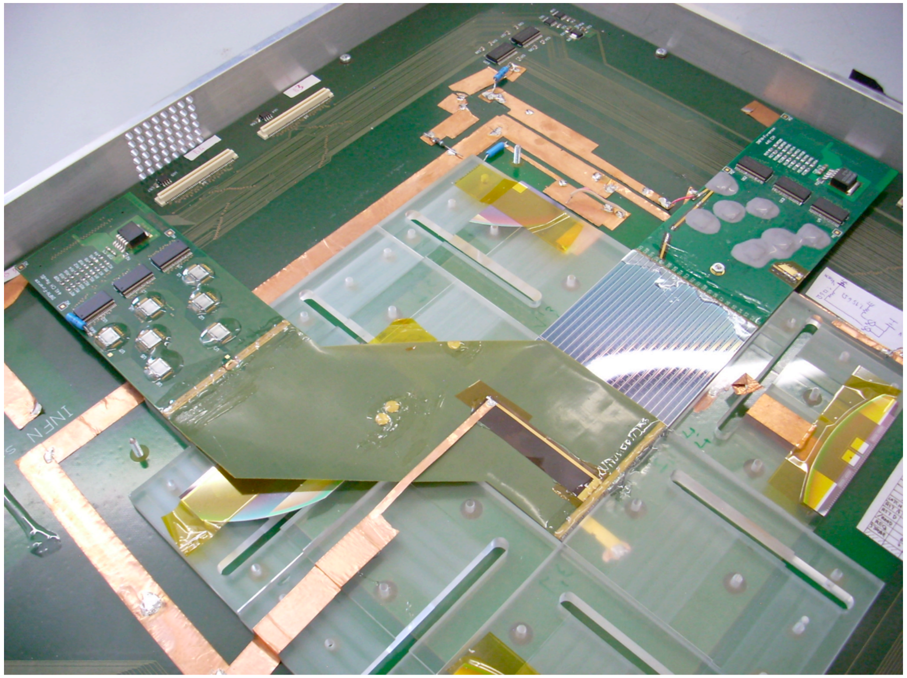


441 channels silicon module with the readout electronics based on TERA06 chips.

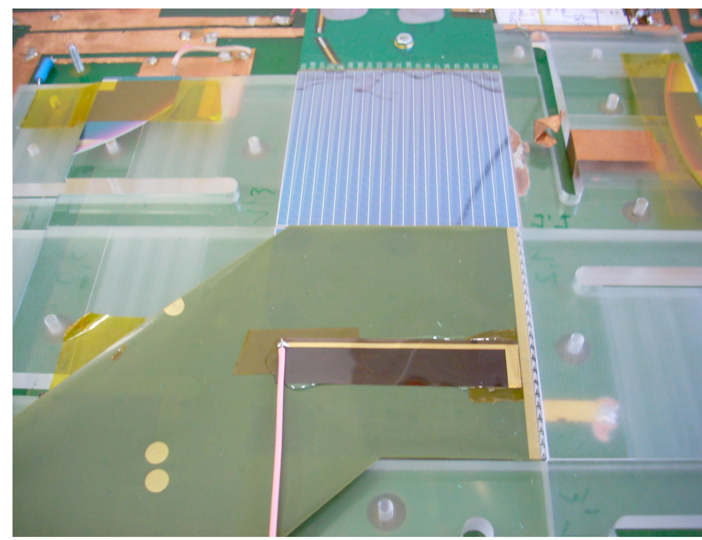


Details of the seven TERA06 die (U1-U7) and the wedge-bonding connections between the printed circuit board and the silicon module.

III Prototype (2008/2009)



4kch detector with two silicon modules out of nine

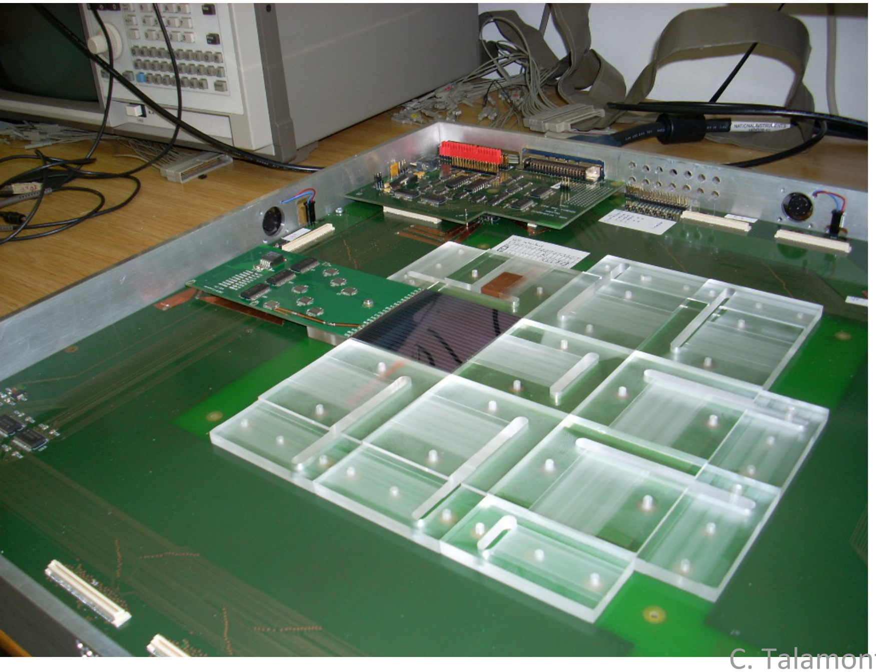


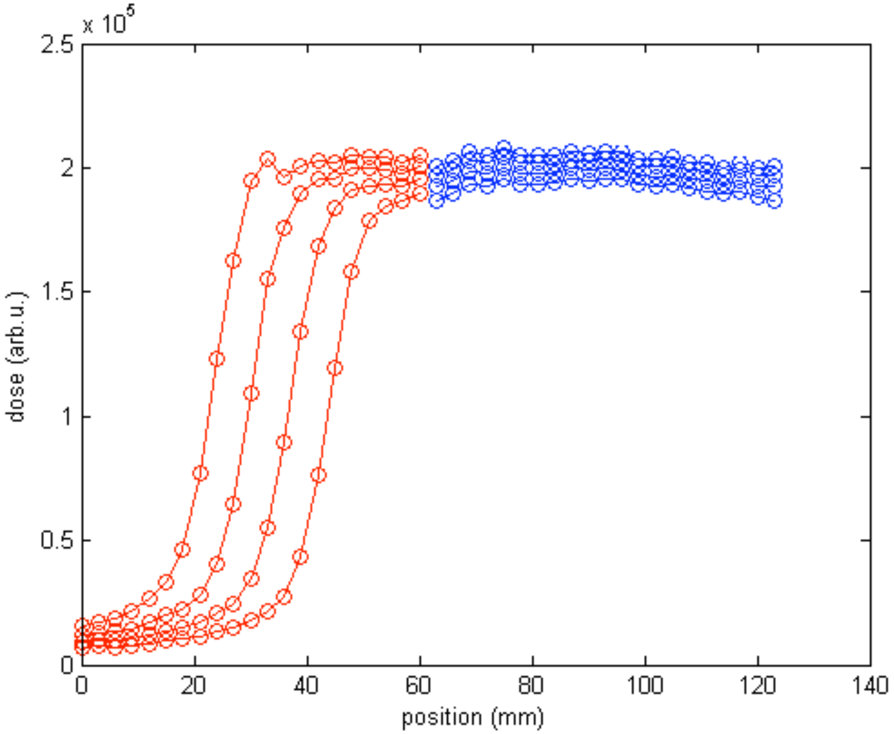
Details of connection between the kapton flexible circuit (pale green) and central silicon module. The central module is almost completely covered by the foil, but its position can be argued from that of the silicon module in the upper side of the image.

Just 25 TERA06 dies out of the 70 requested were available at IBA since they have packaged ones which do not fit our design.

7 were used to assemble the prototype II and 14 to readout the sensors included in the prototype III.

Our choice fell on the central sensor of the matrix, since it will give us the chance to get acquainted with the use of flexible printed circuits, which are likely to be required in future devices.



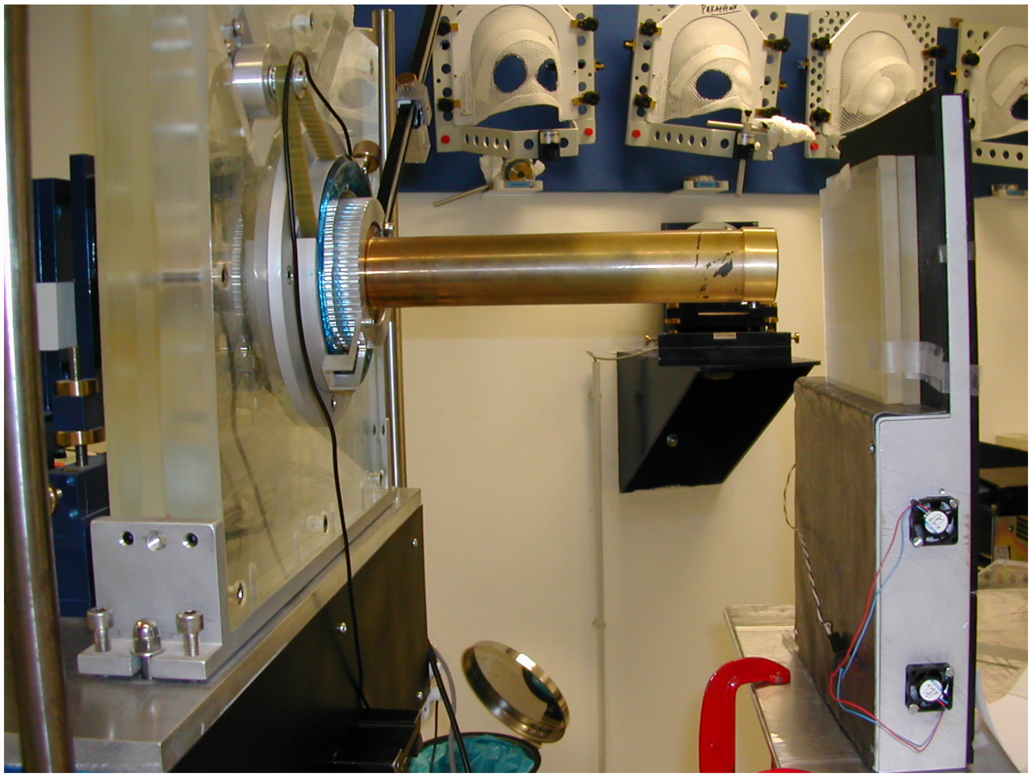


Photon Dosimetric characterization

All the MAESTRO prototypes were irradiated with 6, 10, 25 MV photon beams from Precise/Synergy LINAC (ELEKTA) at the **Careggi University Hospital in Florence**.

The III MAESTRO prototype was irradiated also at **Lucca Hospital** (Lucca ASL2, Radiotherapy division) using a ^{60}Co unit and at **Neumarkt at IBA** site using a Siemens LINAC.

Proton Dosimetric characterization:

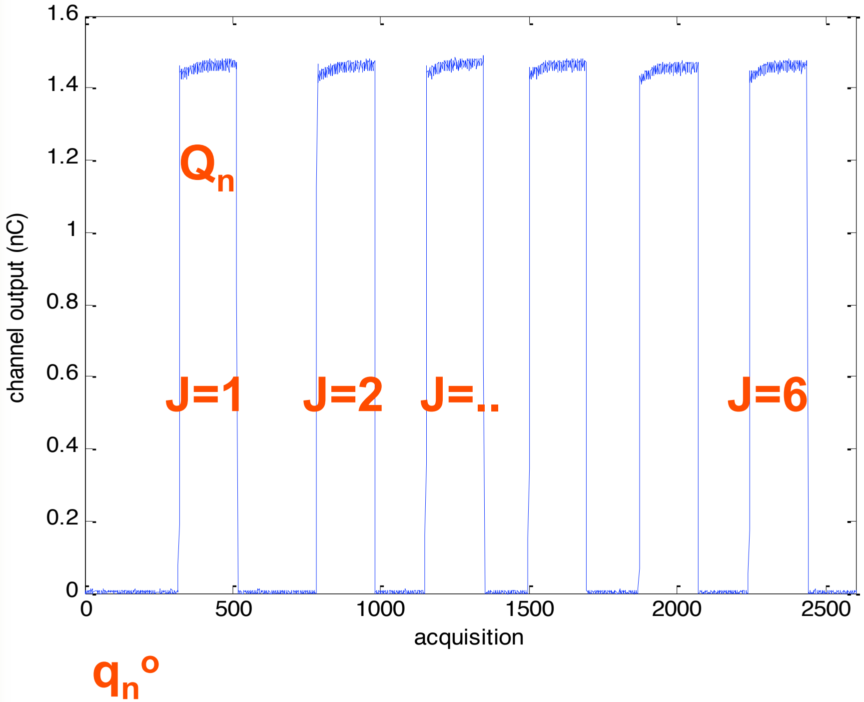


MAESTRO II Prototype was irradiated with 62 MeV protons for medical applications at INFN-LNS Catania

Results

- Repeatability
- Reproducibility
- Linearity
- Dose rate dependance
- Energy dependance
- IMRT and stereotactic beams verification

Repeatability



signal as a function of the acquisition time

D=220 cGy

$$Q_{nj} = \sum_i (q_{ni} - q_n^o)$$

dark

noise → $\sigma_n^0 = \sigma(q_n^o),$

$$\sigma_n = \sigma(Q_{nj})$$

$$\sigma\%_n = \frac{\sigma(Q_{nj})}{\langle Q_{nj} \rangle}$$

Repeatability → $< \sigma\%_n >$

<σ> (%) is the relative standard deviation of the output to different irradiations, averaged on all pixels.

Repeatability

Nominal dose rate (MU/min)	Repeatability	
	<σ> (%)	$N_{0.5}$ (%)
50	0.5	78
100	0.4	81
200	0.2	90
400	0.2	94

<σ> (%) is the relative standard deviation of the output to different irradiations, averaged on all pixels.

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

Reproducibility

Nominal dose rate (MU/min)	Reproducibility	
	σ (%)	N_1 (%)
50	1.0	87
100	1.0	89
200	0.4	97
400	0.5	97

The beam uniformity is better than 1%, a 10x 10 cm^2 field was mapped using a water phatom

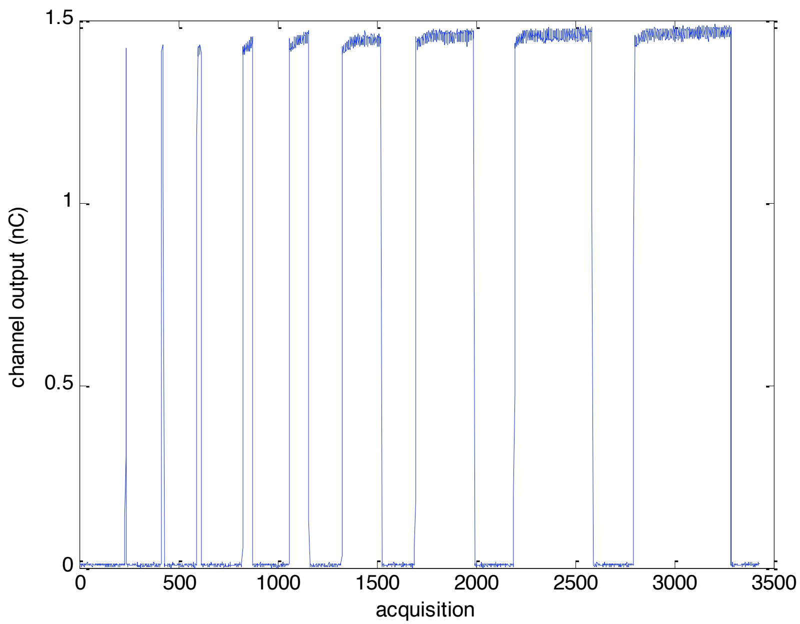
$$u_n = \frac{Q_{n1}}{\langle Q_{n1} \rangle_n} ; Q'_{nj} = \frac{Q_{nj}}{u_n}$$

$$\sigma\% = \frac{\sigma(Q'_{nj})}{\langle Q'_{nj} \rangle}$$

σ(%) is the relative standard deviation of all the pixels' output after correction.

N_1 is the percentage of pixels with reproducibility better than 1%.

Response vs. dose

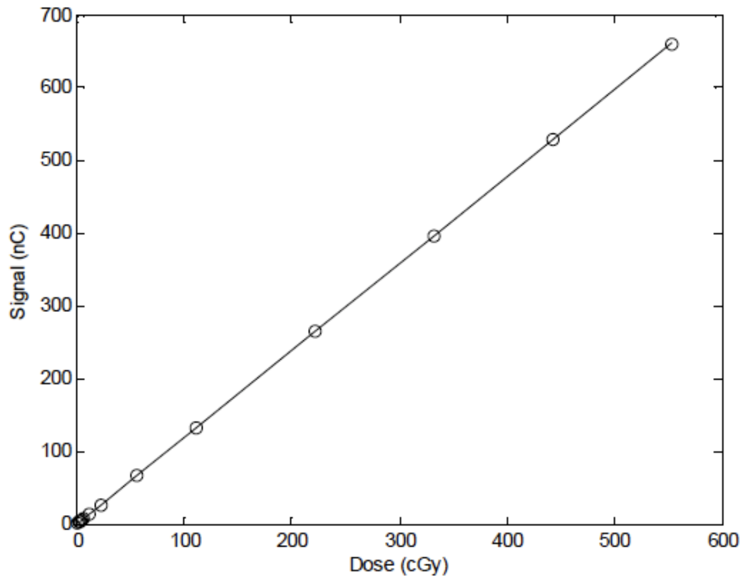


LInearity has been verified in calibration set up (5 cm depth, 10 cm x 10 cm field, at the isocentre plane).

It is necessary to study the detector linearity at very low doses down to a few cGy.

A reference beam monitor has been used to account for accelerator instabilities, in particular at low monitor units.

Response vs. dose



signal of the central pixel as a function of dose in the range 1-550 cGy, dose rate 200 Mu/min

For each channel n:

a) At different dose value (D) the signal is measuread $Q'_n = Q'_n(D)$

b) Minimum χ^2 fit
$Q_n = a_n D_j + b_n$; the sensitivity is a_n (nC/cGy).

c) Using the residual analysis is possible to evalute the deviation from linearity.

$d_n = (Q'_n - Q_n)/Q'_n$

Linearity

6MV RX
10 cm X 10 cm
SAD 100 cm

Linearity in the range 5-550 cGy

Nominal Dose rate (MU/min)	$\langle d_n \rangle_n$	$\langle a_n \rangle_n$ (nC/cGy)	$\langle \delta a_n \rangle_n$ (nC/cGy)
50	0.02	1.189	0.004
100	0.01	1.191	0.002
200	0.01	1.191	0.002
400	0.01	1.196	0.002

Linearity in the range 1-550 cGy

Nominal dose rate (MU/min)	$\langle d_n \rangle_n$	$\langle a_n \rangle_n$ (nC/cGy)	$\langle \delta a_n \rangle_n$ (nC/cGy)
50	0.07	1.190	0.004
100	0.02	1.193	0.002
200	0.06	1.193	0.002
400	0.05	1.195	0.002

6 MV Measurements

Beam calibration

In water, by Farmer ionization chamber, with a $10 \times 10\ cm^2$ field, following IAEA 398 protocol.
Depth = 5 cm, SSD=95 cm. 1MU=0.907cGy

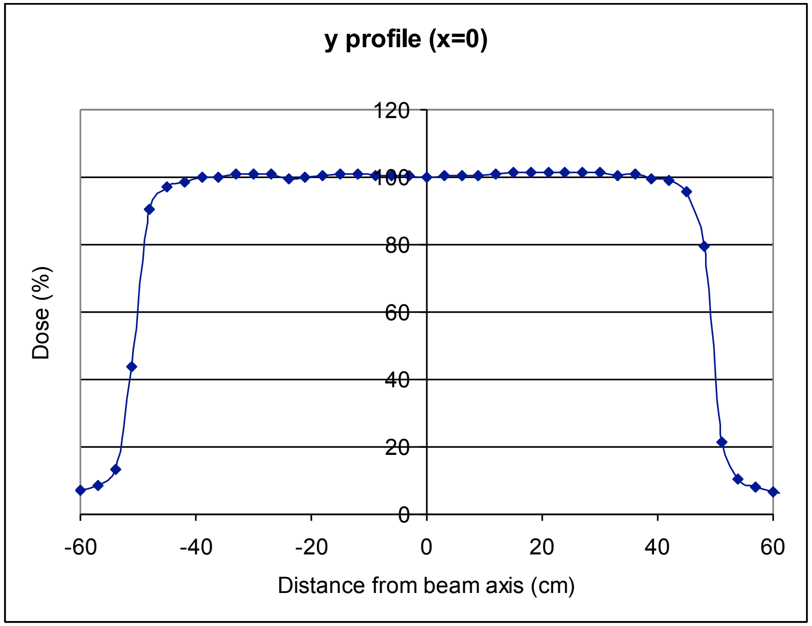
The device is placed in the bunker, around 1 hour before the irradiation, in order to reach a stable temperature.

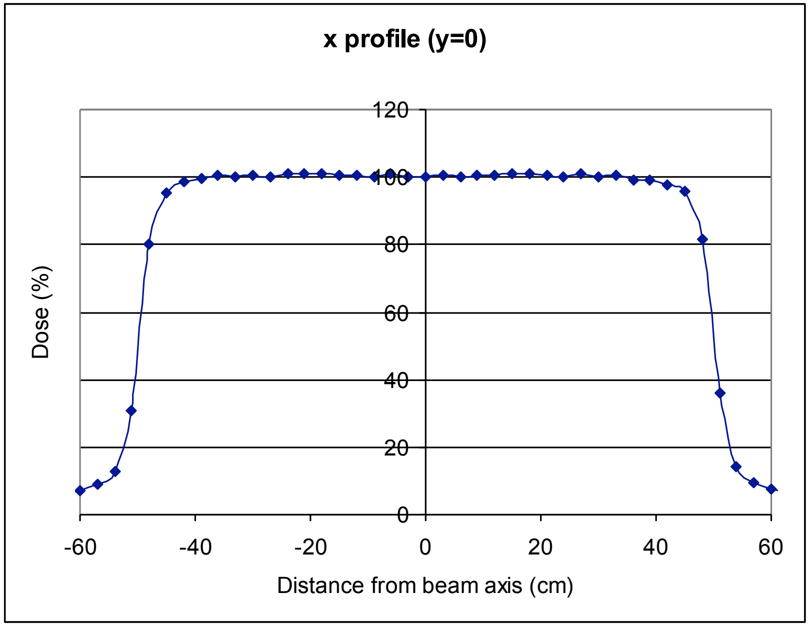
The field was mapped in water phantom in order to assess the beam homogeneity. Scanning step in both transverse directions = 3mm.

Beam homogeneity

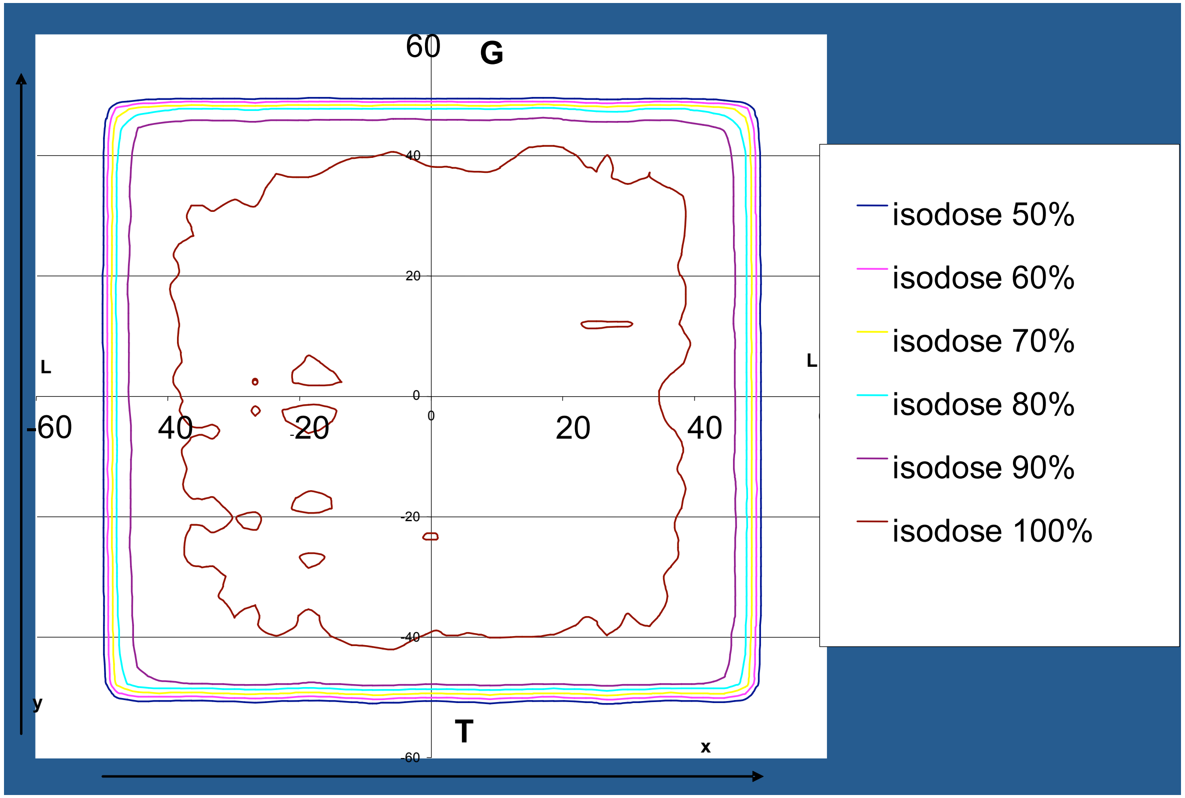
- 6 MV
- 10 cm x 10 cm
- d = 5 cm
- SSD = 95 cm
- scanning step = 3 mm in both directions

- RFA 300 water phantom





LINAC Precise (Elekta)



- Standard deviation in the region corresponding to the sensor area (6.3 cm x 6.3 cm) = 0.4 %
- Maximum deviation in the region corresponding to the sensor area (6.3 cm x 6.3 cm) = 2.4 %

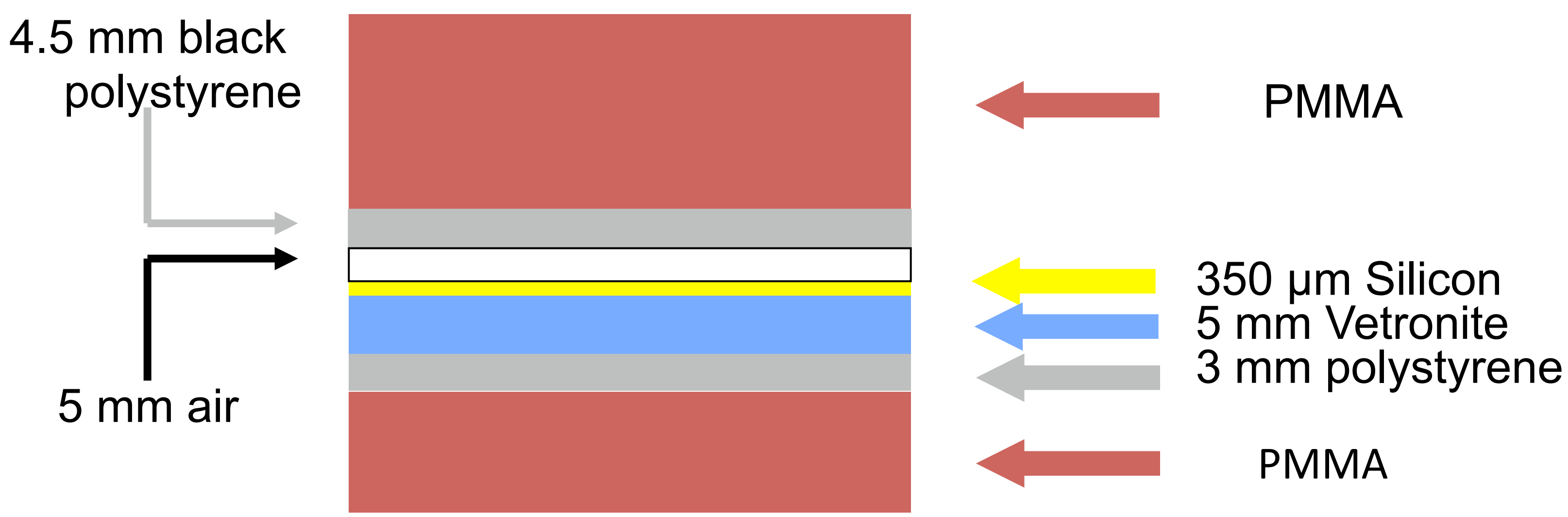
6 MV photon beam

10 cm x 10 cm field

the field was considered flat when the software correction was applied in order to correct for the lack of response uniformity between the different matrix elements

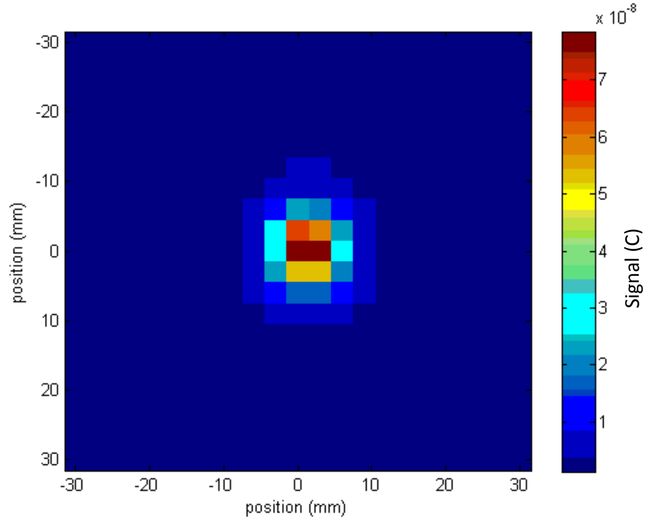
Sensor arrangement

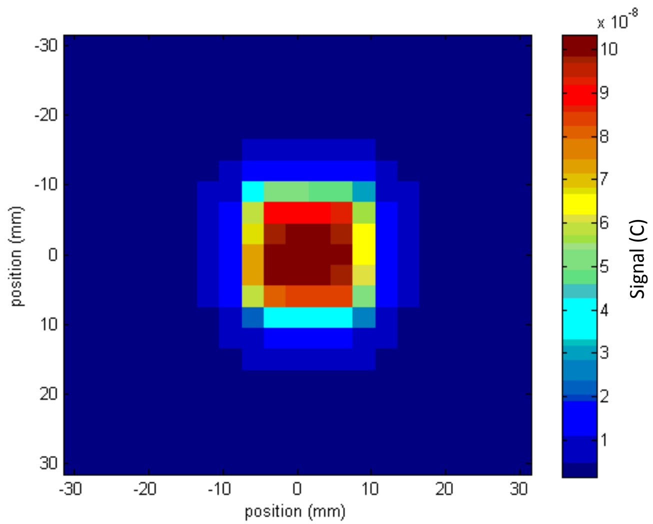
Apart the 350 μm Si, all the other materials are almost water equivalent

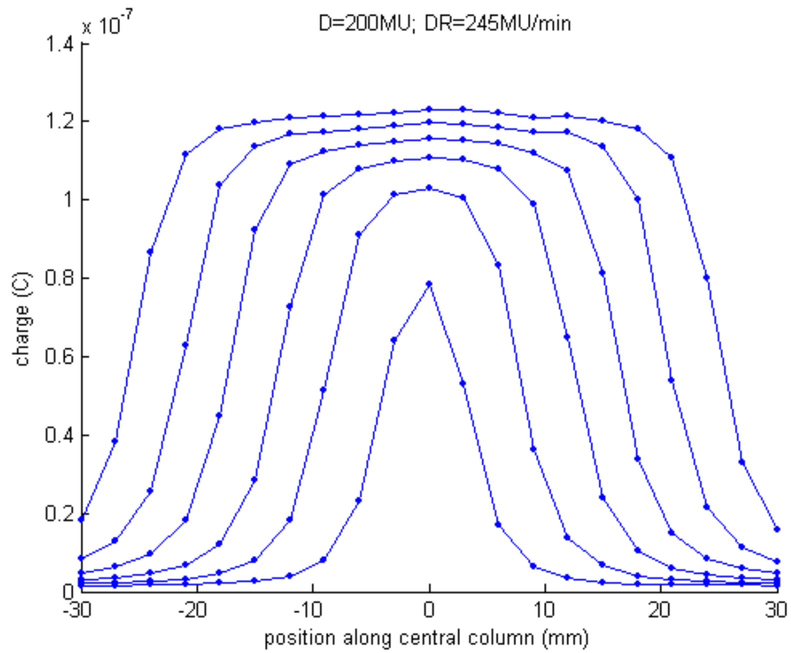


Dose maps

Profiles







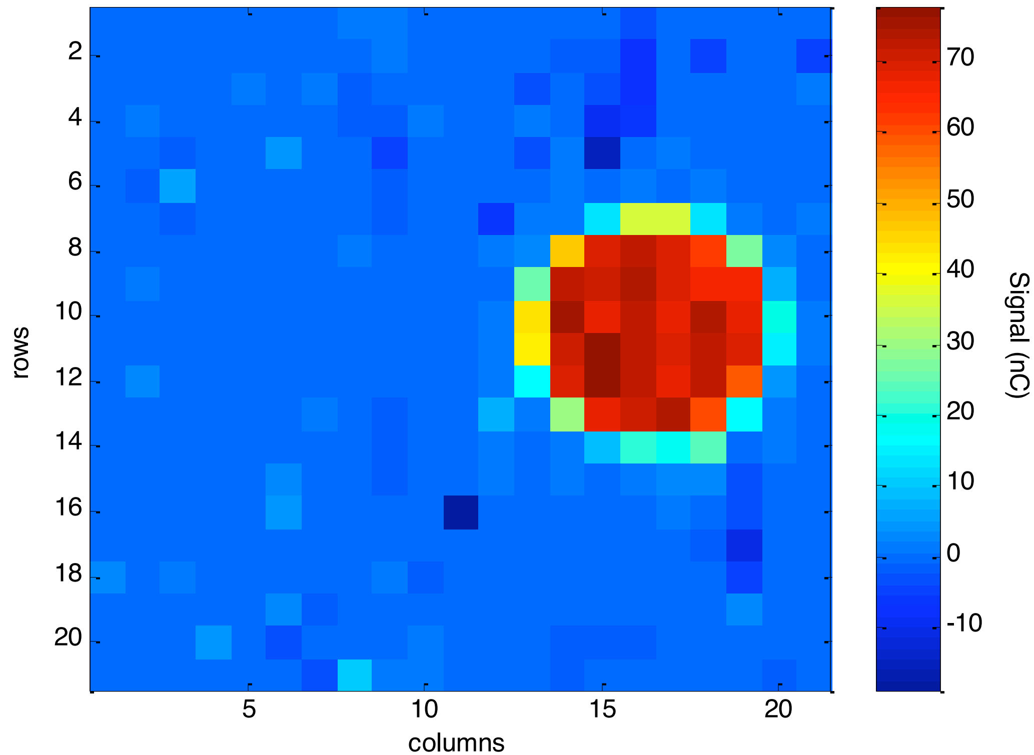
Profile along the central column for different field size

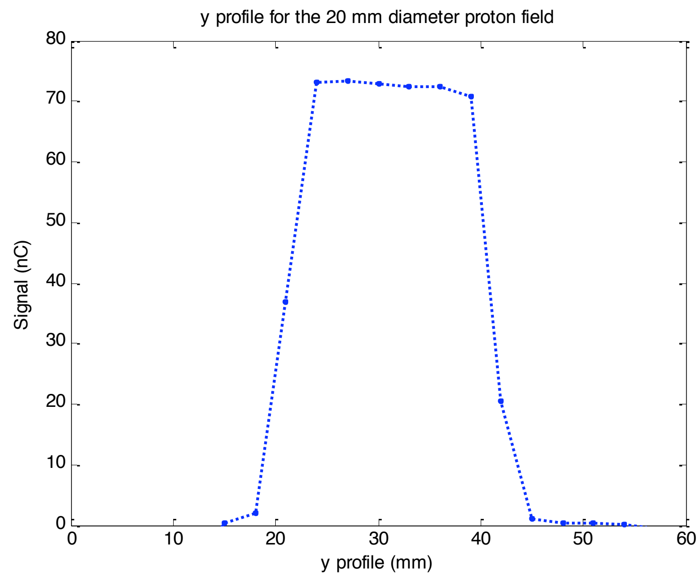
(0.8X0.8, 1.6x1.6, 2.4x2.4, 3.2x3.2, 4x4, 4.8x4.8 cm^2)

6MV photon beam at Careggi Hospital

Dose map

Profile





Field size 20 mm diameter

62 MeV proton beam at LNS Catania

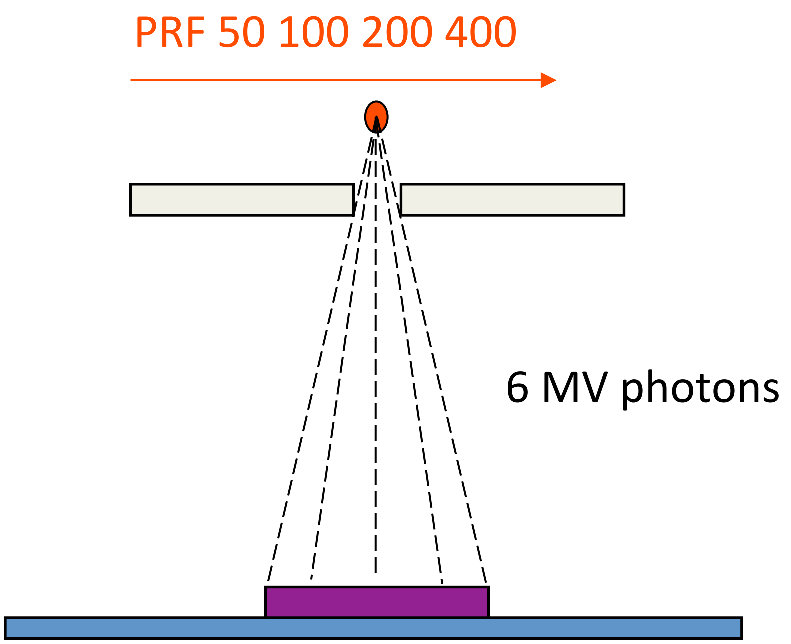
Dose rate dependence (photons)

Dose-rate values have been determined with an ionization chamber in the same position of the detector center.
Two different experiments have been performed:

A) 1 Gy is delivered at a depth of 5 cm water equivalent, detector at the isocentre plane, with different MU/min (50-400 MU/min). 200 MU/min value is the reference.

Dose rate in the range
43.2 cG/min– 348.8 cGy/min

PRF =
Pulse Repetition Frequency



Dose rate dependence (photons)

B) 1 Gy is delivered at a depth of 5 cm water equivalent, 200 MU/min, with different SSDs (Source Surface Distance):

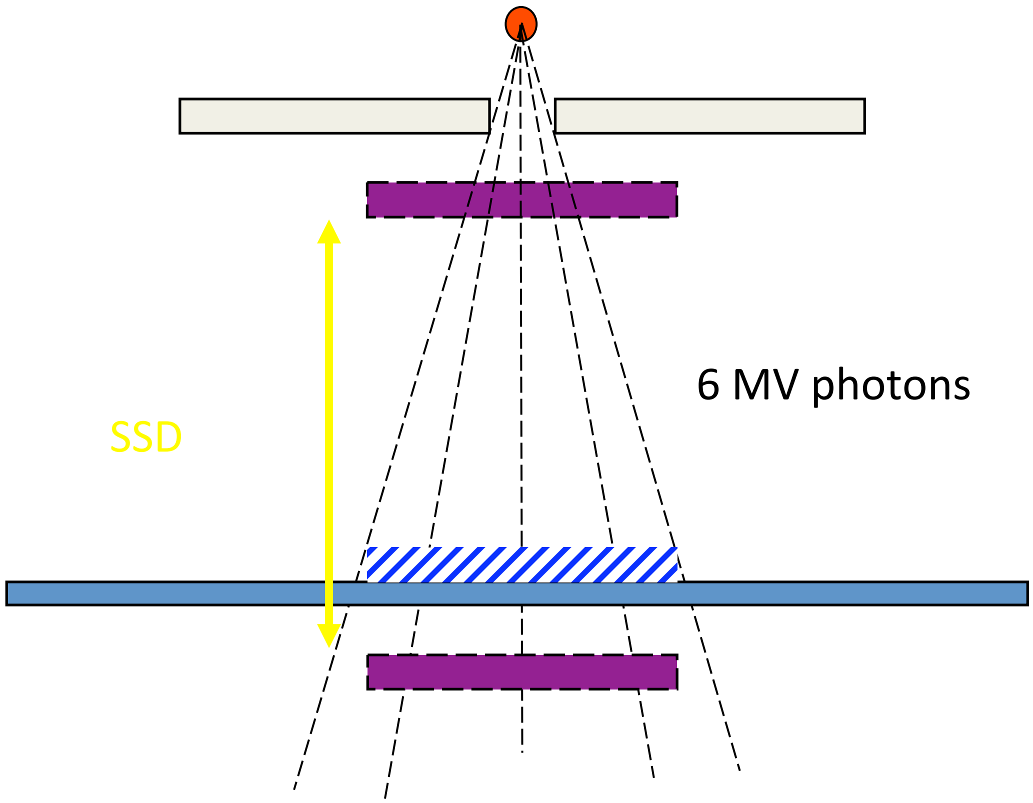
Dose rate in the range

84.4 cGy/min - 245.5 cGy/min

Changing both SSD and PRF

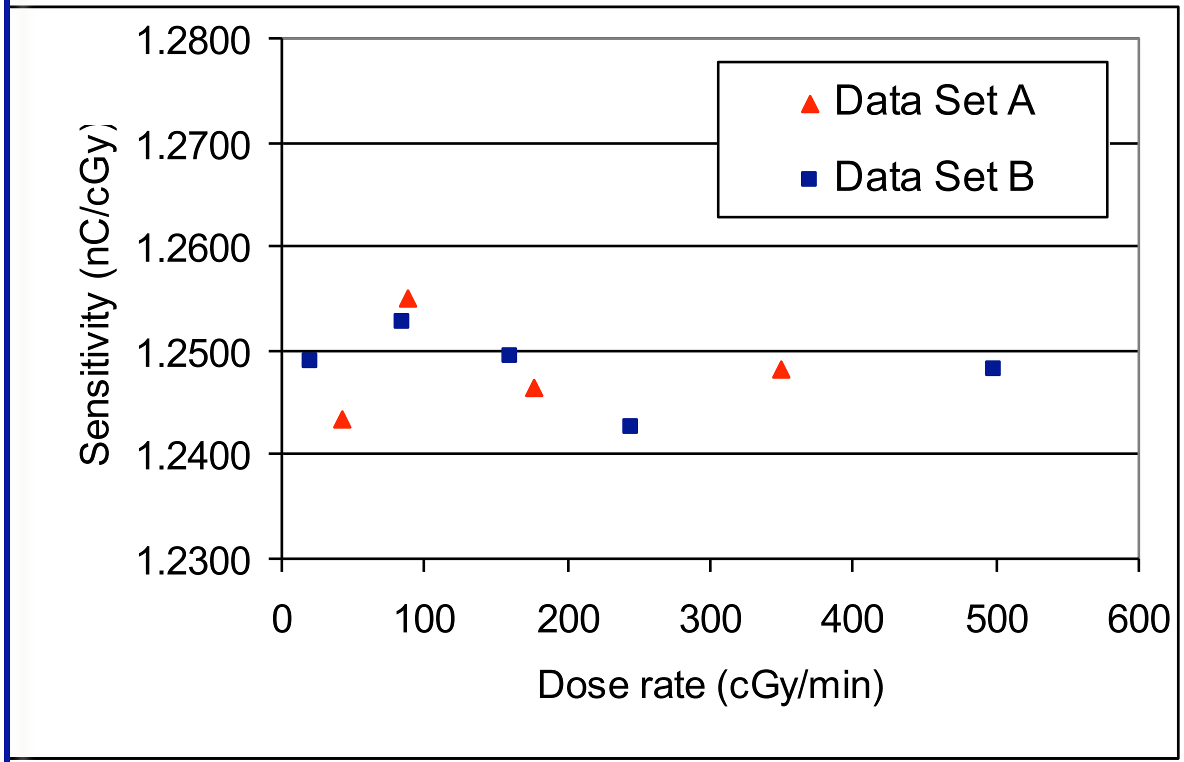
the dose rate varies in the range

21.1 - 498.5 cGy/min



Dose rate dependence (photons)

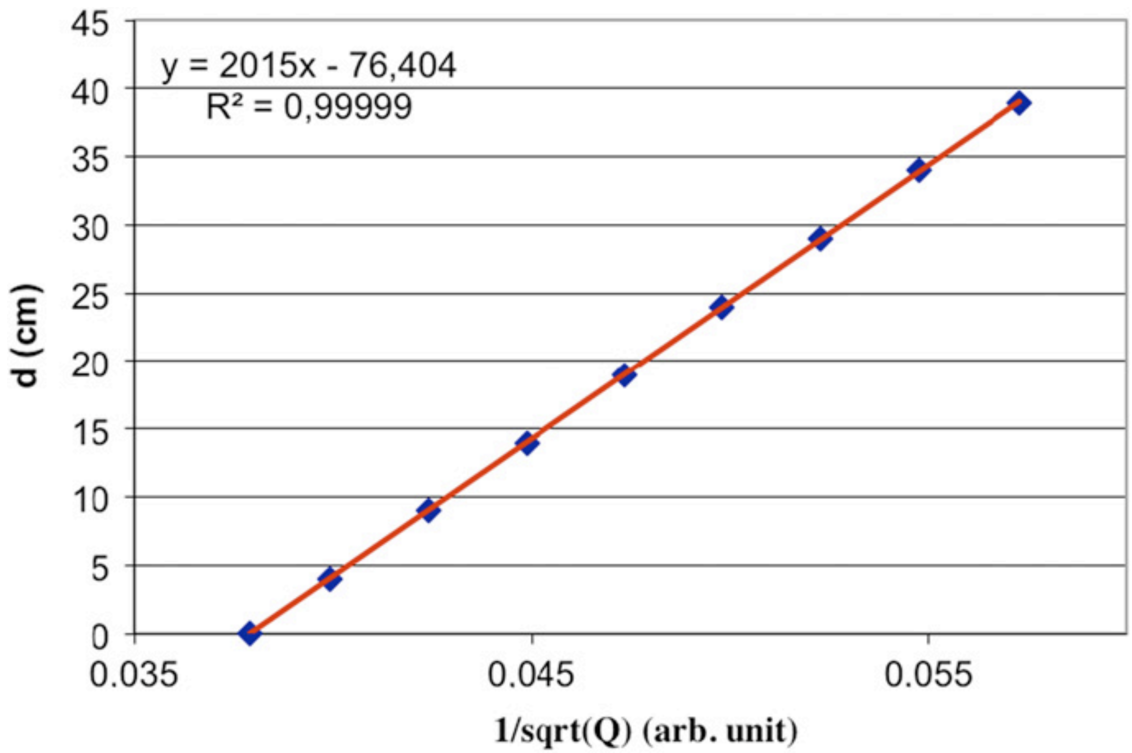
6MV photon beam at Careggi Hospital



The dose rate has been changed varying both the pulse repetition frequency (data set A) and both PRF and SSD, i.e. the dose per pulse (data set B).

Mean sensitivity = 1.248 nC/cGy ± 0.3% (1σ)

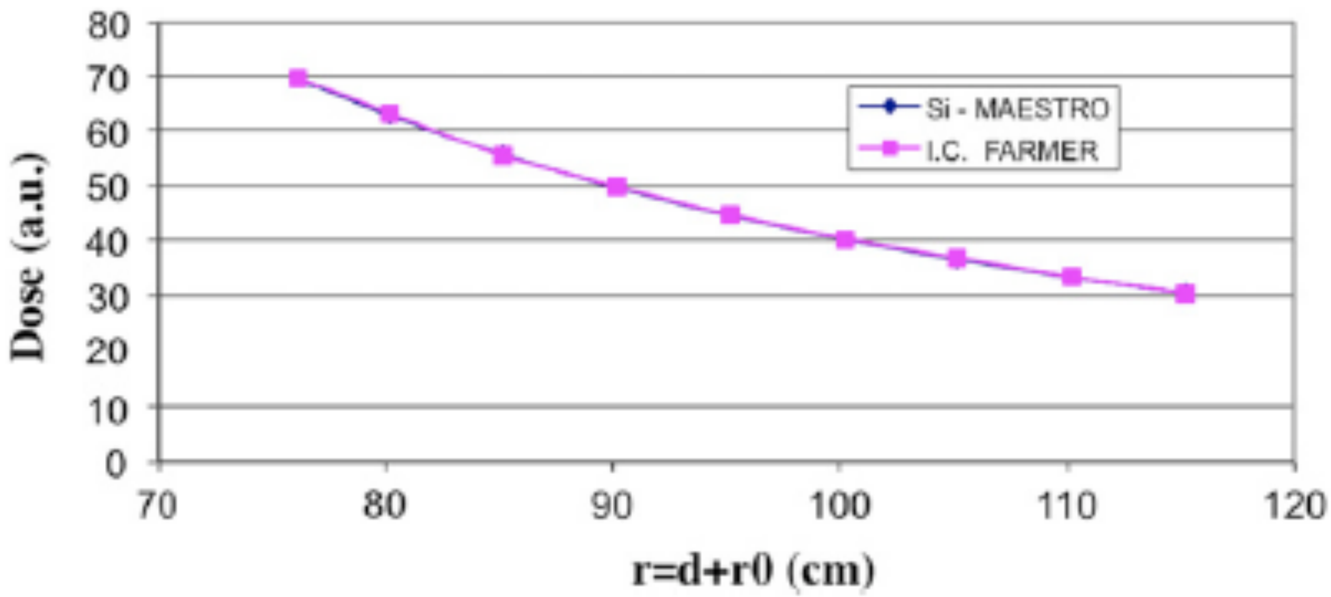
Dose rate dependence (photons)



${}^{60}Co$ source beam at Lucca Hospital

Measured charge follow pretty well the 1/r $d = k/\sqrt{Q} - r_0$ where r=d + r_0 , r_0 is the initial offset and d the relative measurement distance

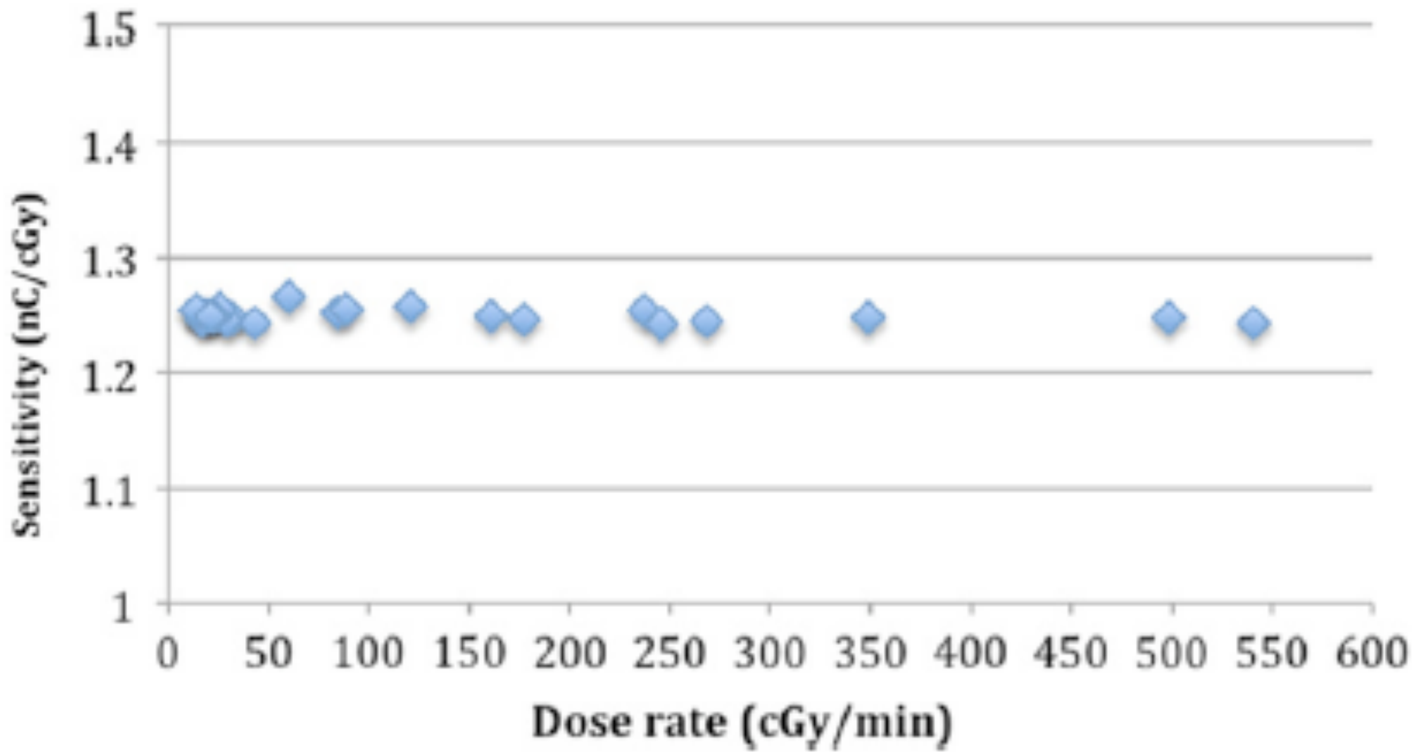
Dose rate dependence (photons)



^{60}Co source beam at Lucca Hospital

Comparison of relative dose measured with the Si dosimeter and a Farmer ionization chamber, difference between the two readings is less than 0.5% in the explored range.

Dose rate dependence (photons)



Measurements at low dose rate performed with Co^{60} are merged with the previus one. Results clear indicates no dependence of the detector sensitivity on the dose rate for the explored range.

Energy dependence

Three different controls have been performed:

A) variation of the calibration factor with the beam nominal energy

B) variation of the response with depth of measurement (same beam nominal energy)

C) variation of the response with beam size (same beam nominal energy)

B-C: same primary component, different scattered component

Energy dependence

A)

$$\frac{Sensitivity(10MV)}{Sensitivity(6MV)} = 0.993$$

$$\frac{Sensitivity(25MV)}{Sensitivity(6MV)} = 0.951$$

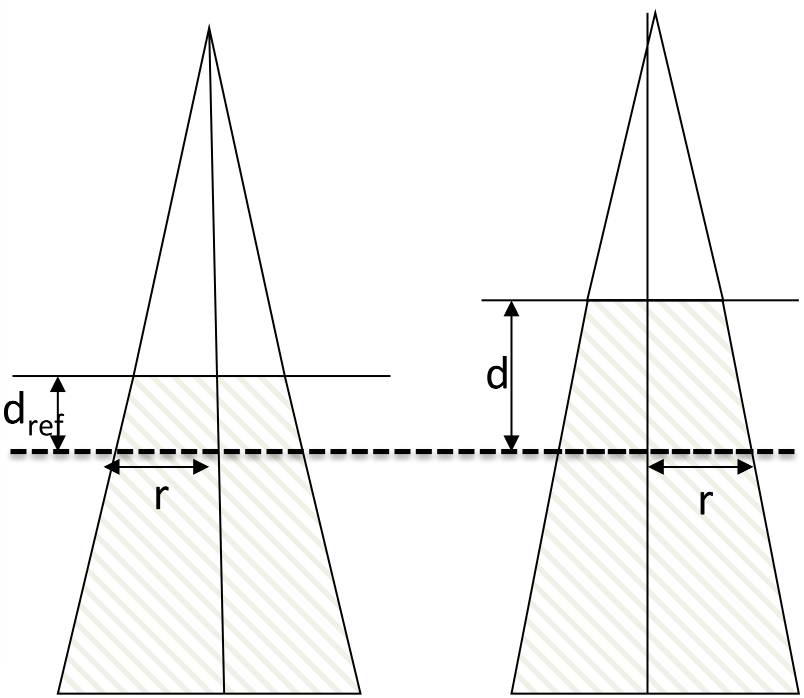
A slight energy dependence has be found and it was expected as Silicon is not water equivalent.
This only implies that the calibration factor has to be changed when a different quality beam is used.

Ionization chamber is energy dependent too!

Energy dependence

B)

For the same beam quality, detector centered at the isocentre, the TPR(d,5) have been measured and compared with ionization chamber.

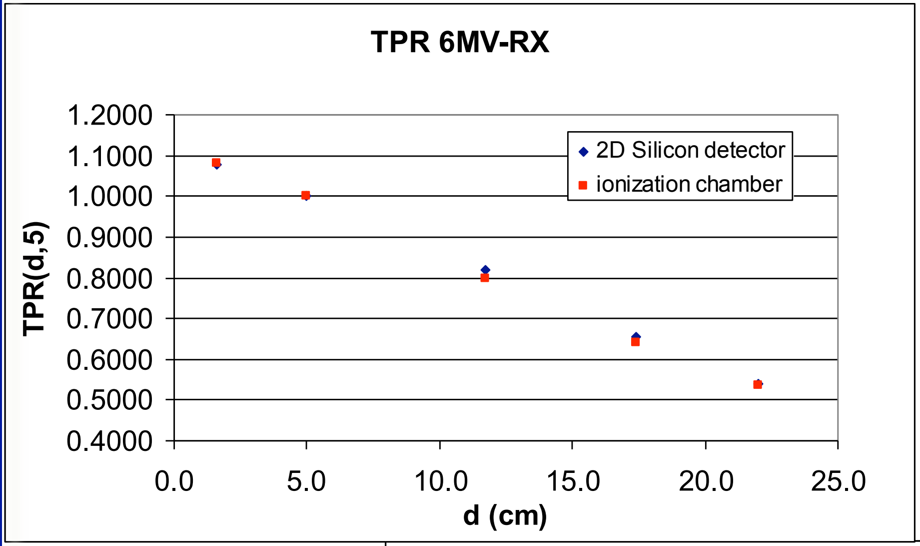


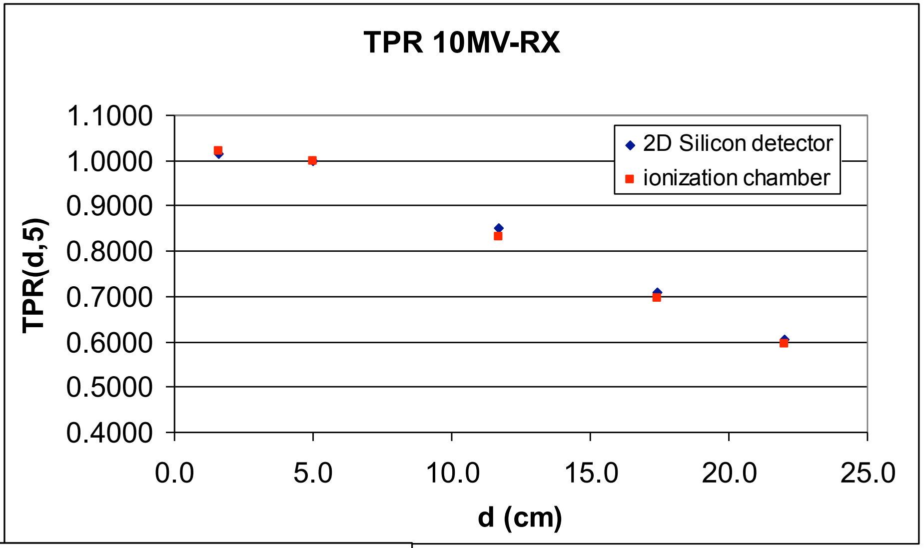
Tissue-Phantom Ratio (TPR)

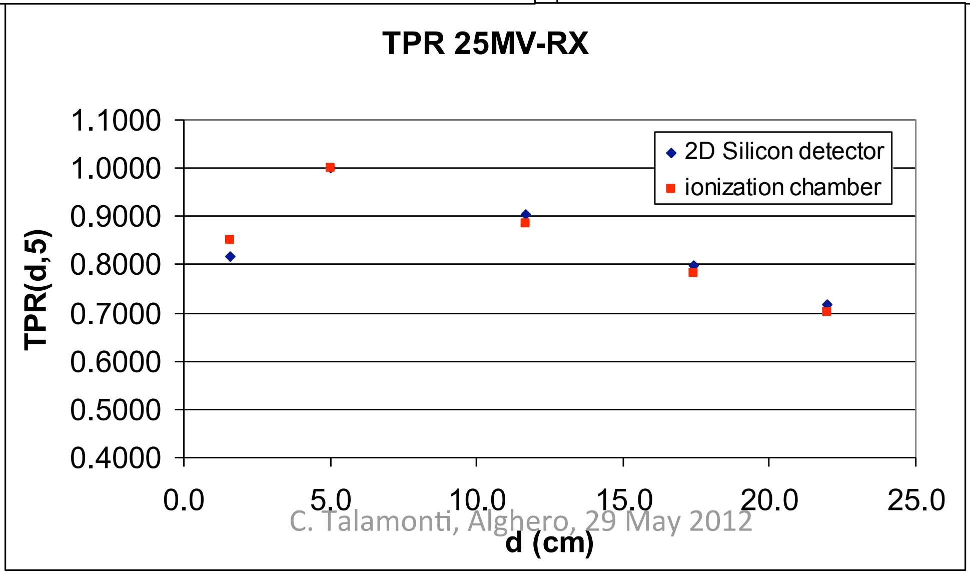
$$\mathbf{TPR = D(d)/D(d_{ref})}$$

Energy dependence

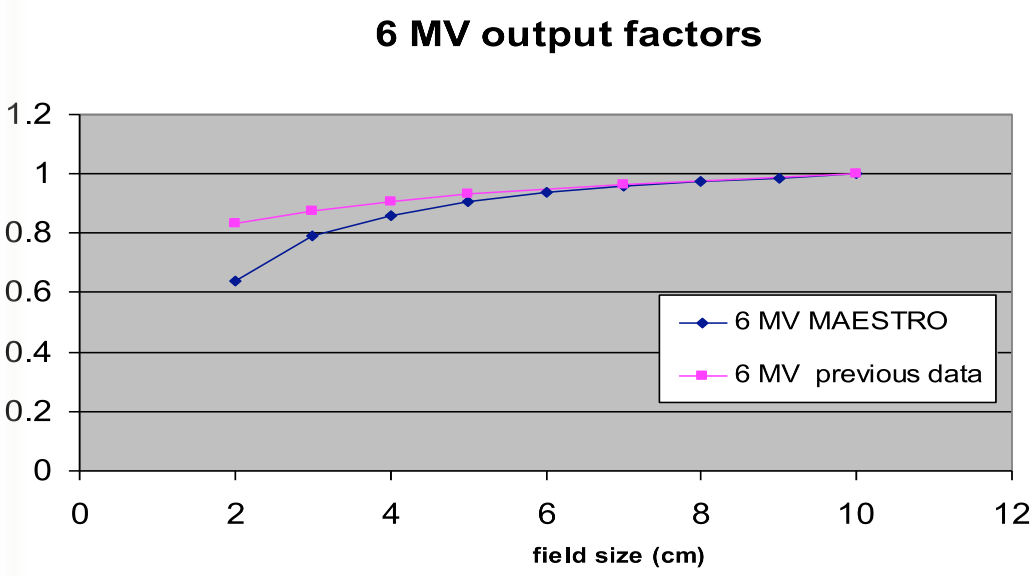
B) TPR



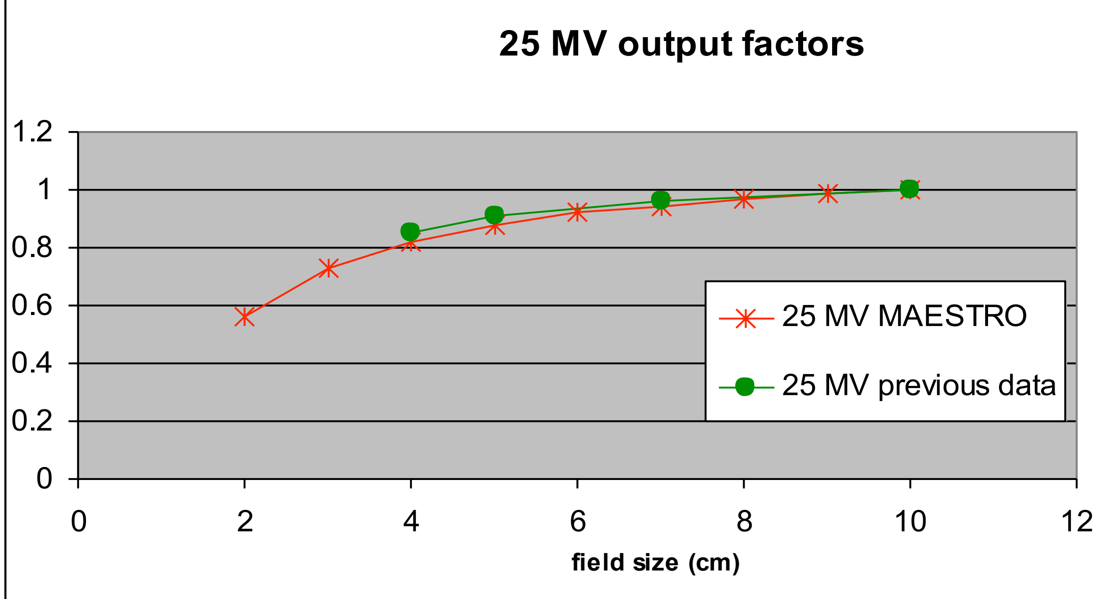




Output factors (photons)



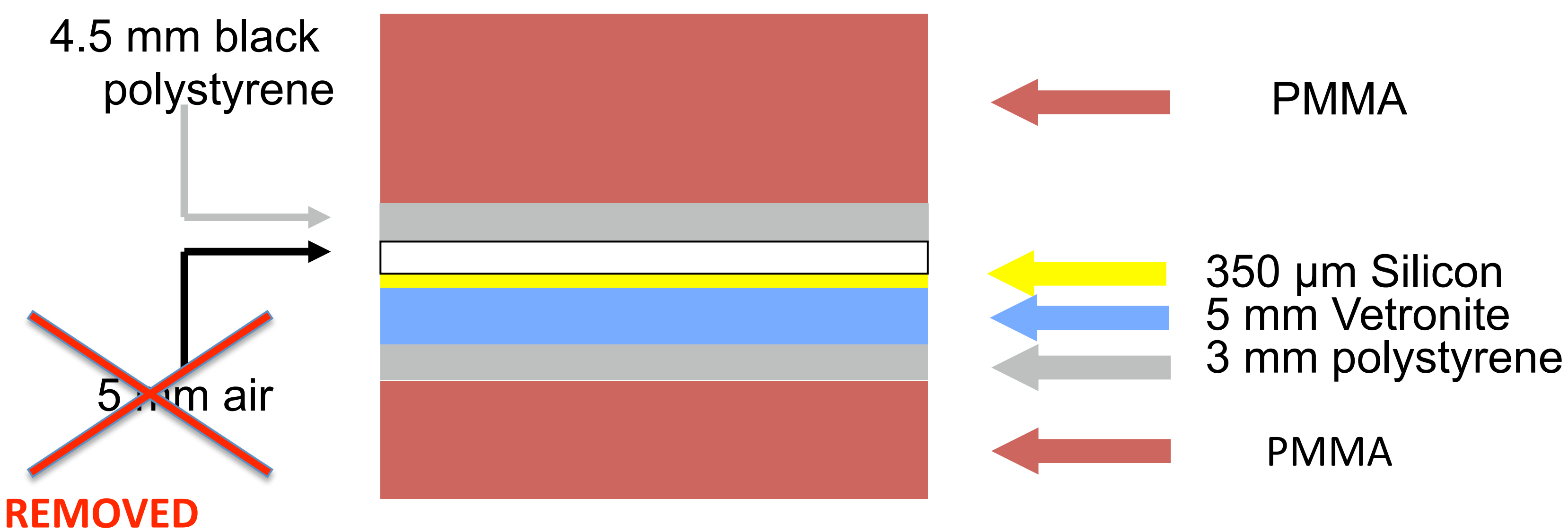
C) OUTPUT FACTORS



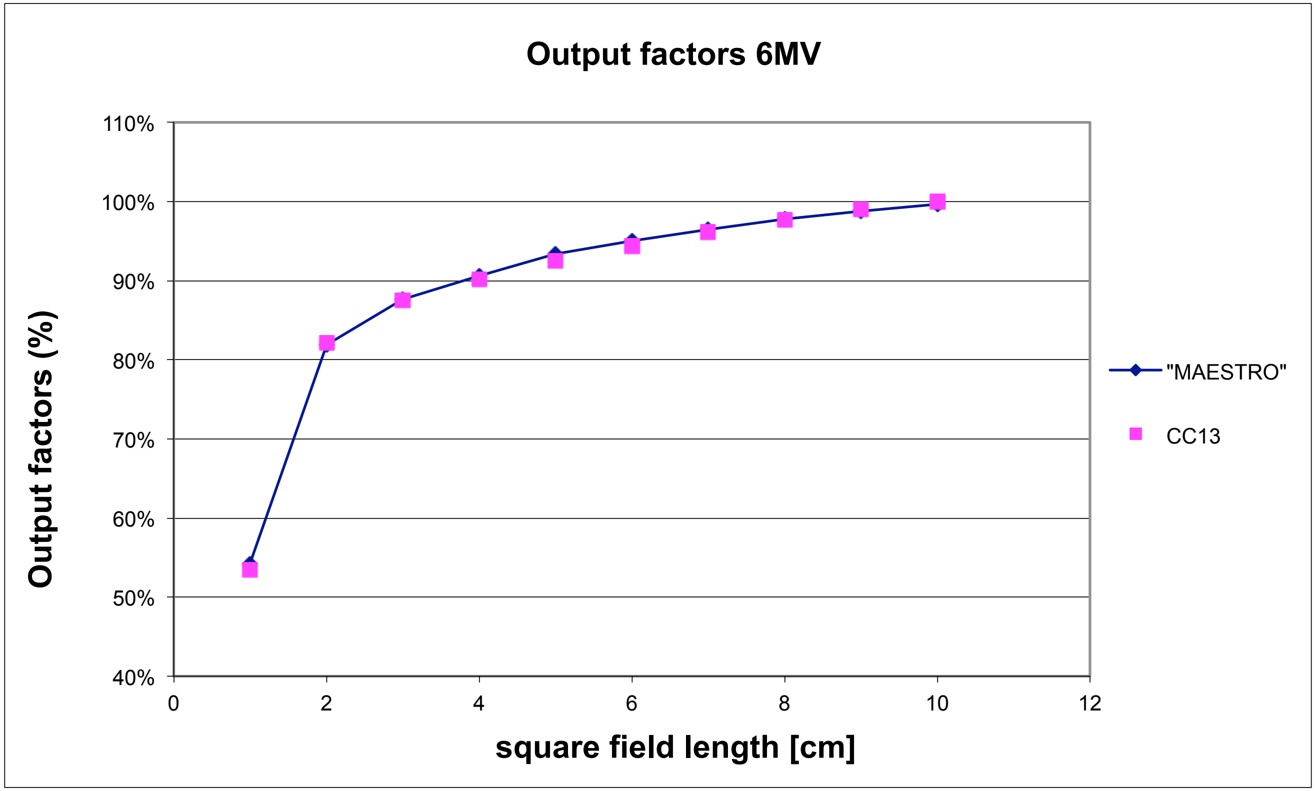
OF= D(fz)/D(fz=5cm)

Sensor arrangement

Apart the 350 µm Si, all the other materials are almost water equivalent



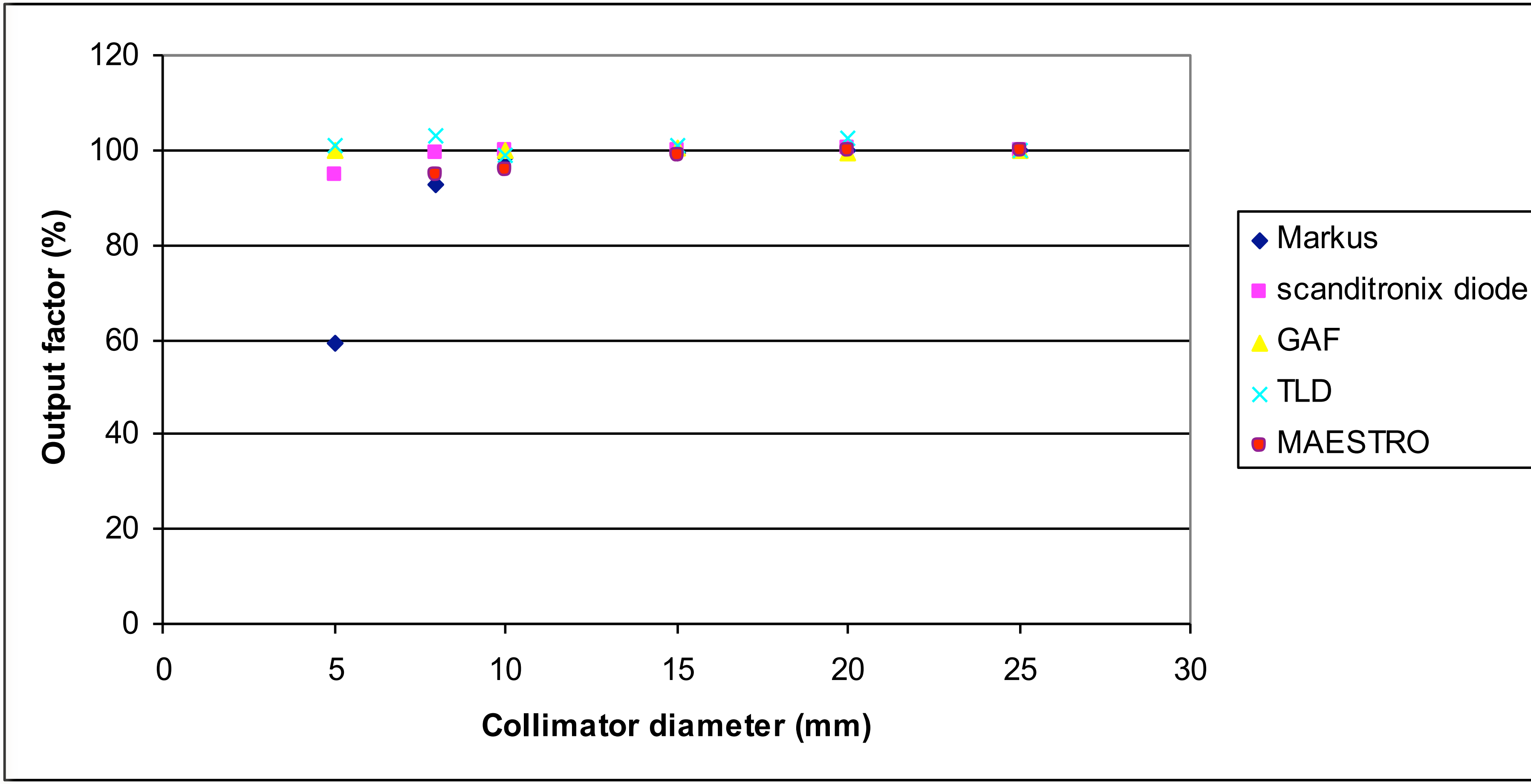
Output factors (photons)



Measurement performed at IBA site

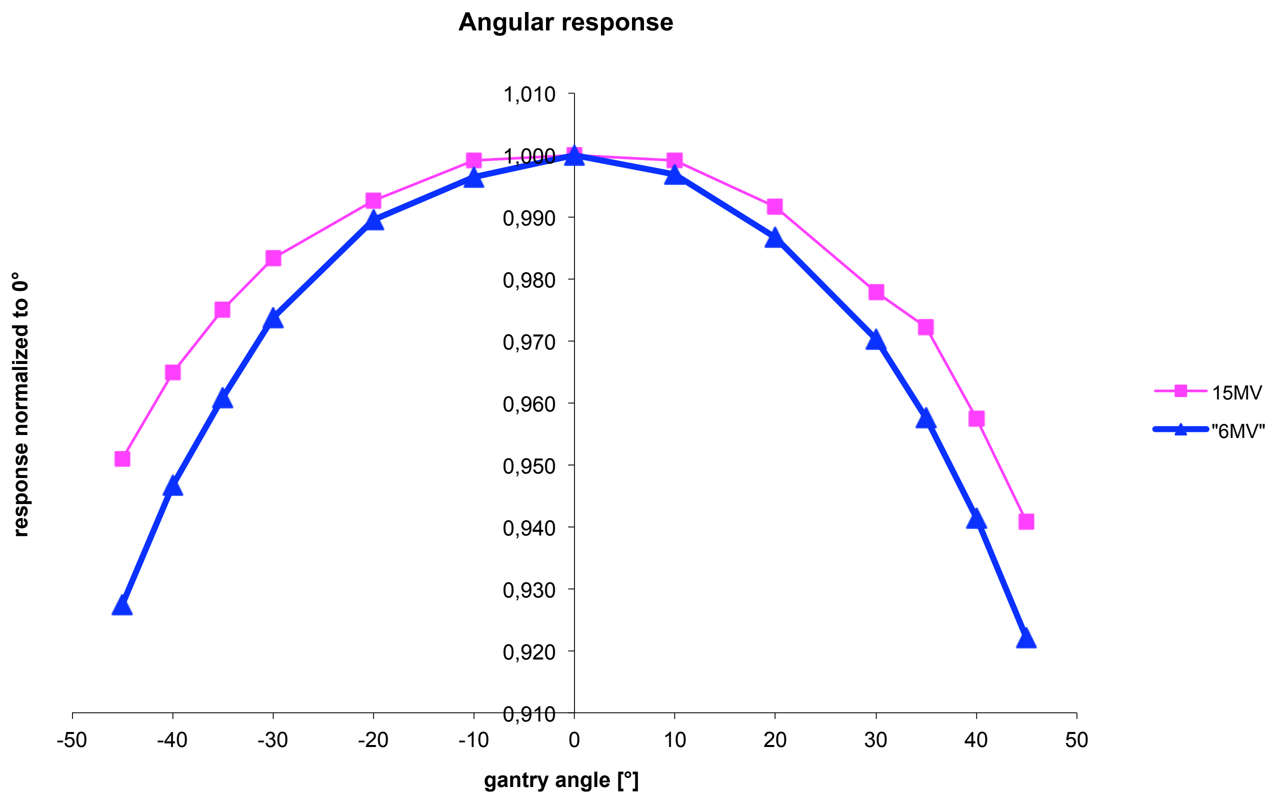
Max deviation 1.5% at the smallest field size.
This good results have been obtained resolving packing problems

Output factors (protons)



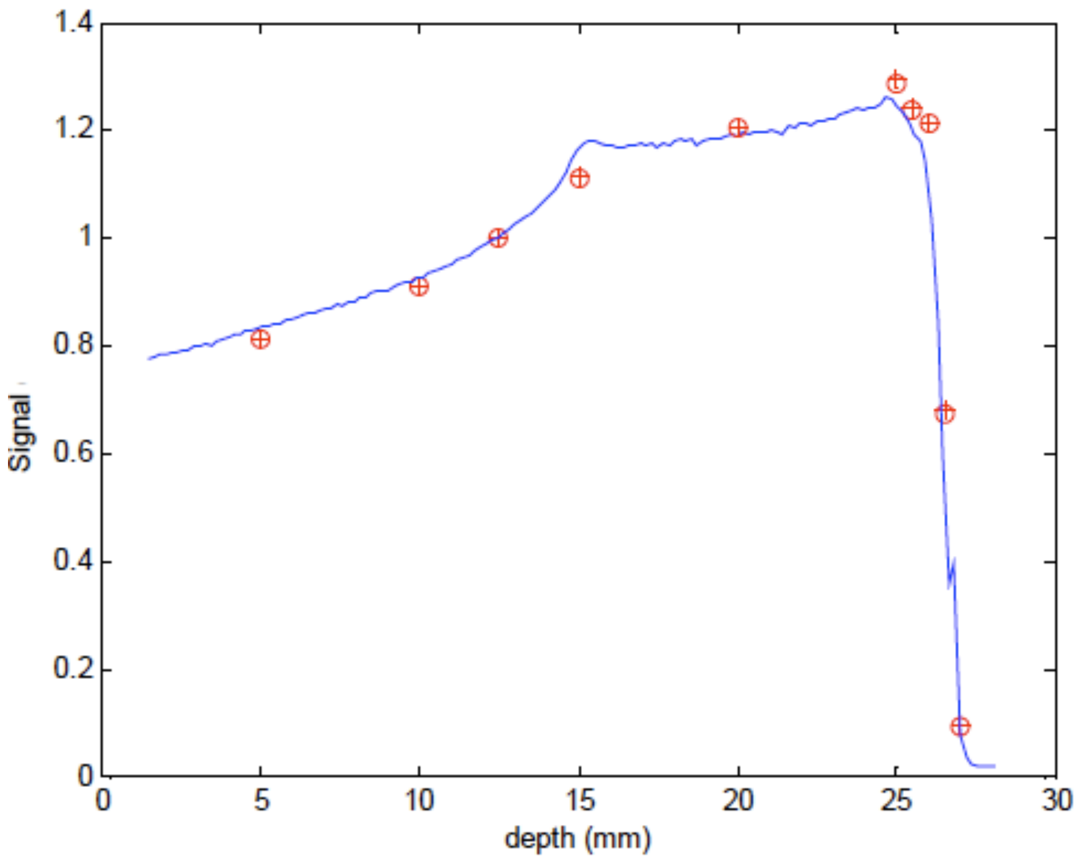
Measurement performed at Catania

Angular dependence



Measurement performed at IBA site

Depth dose measurements (protons)



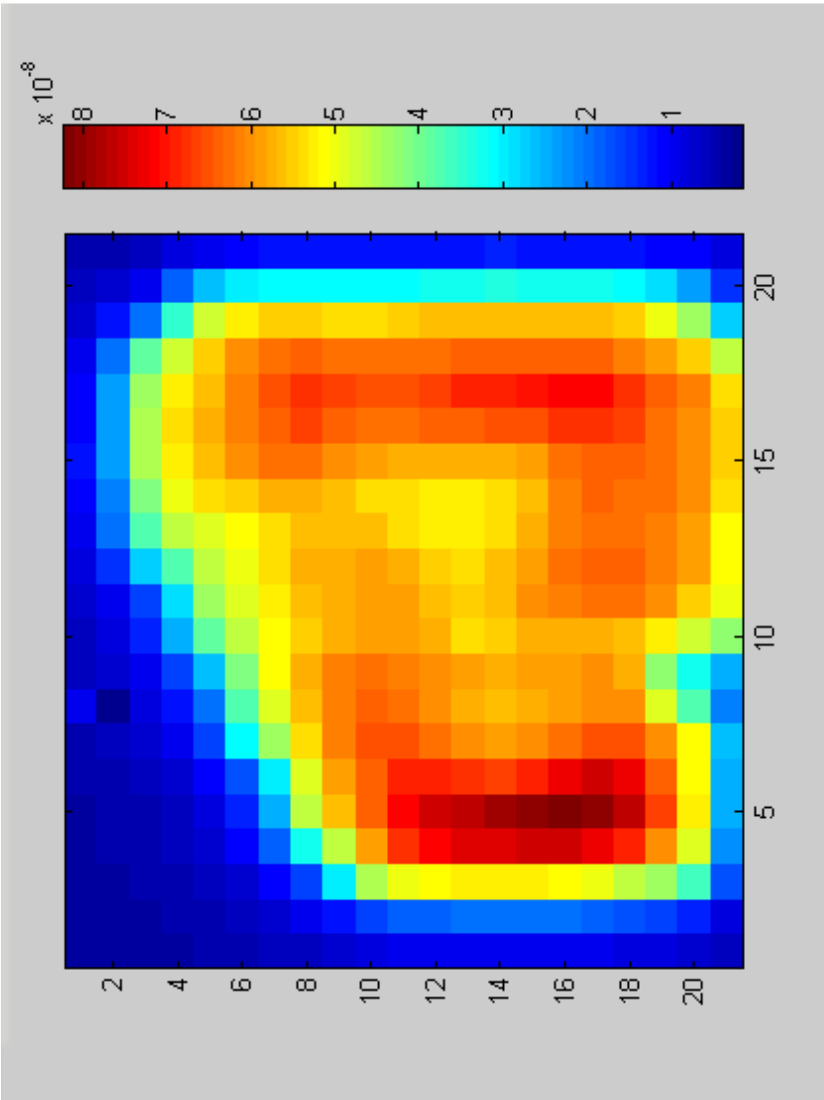
Spread Out Bragg Peak

CATANA:
62 MeV proton beam

Measurements in PMMA

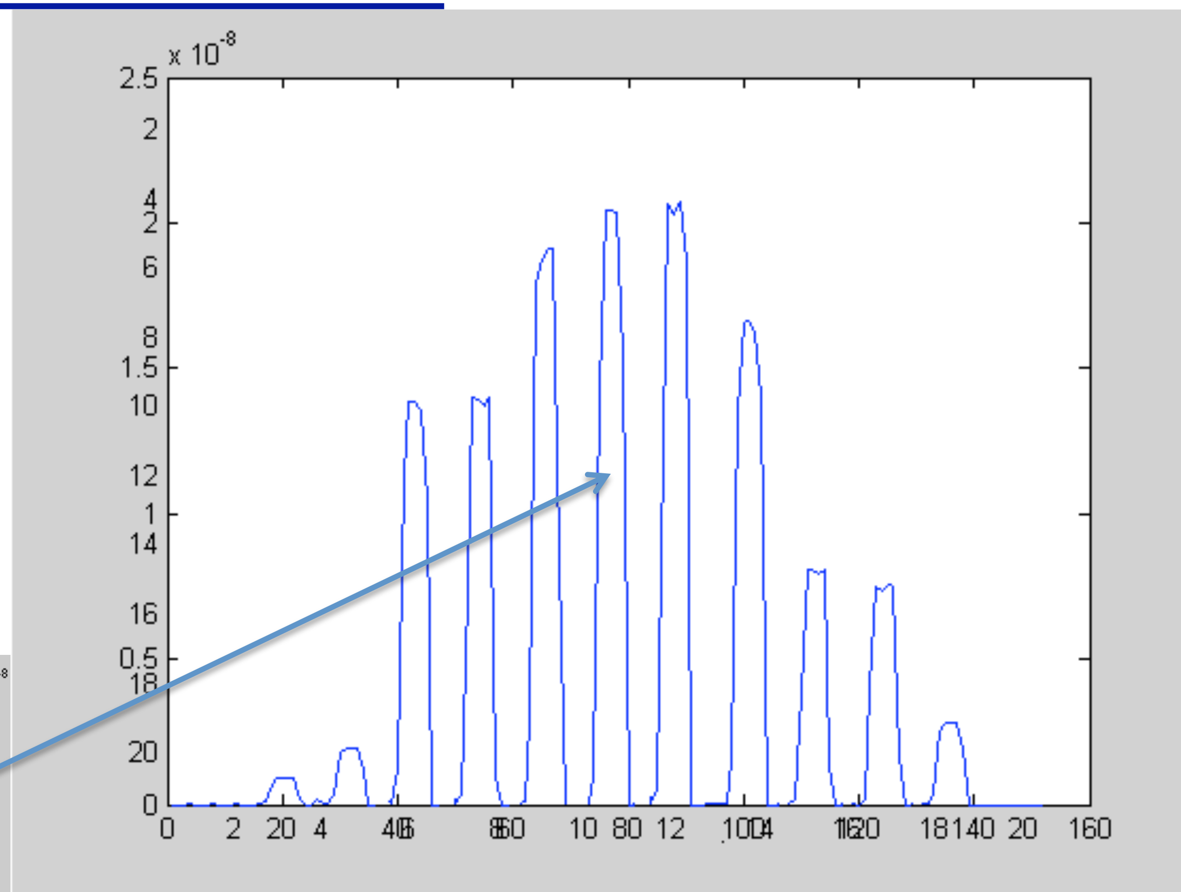
Signal normalized at 12.5 mm

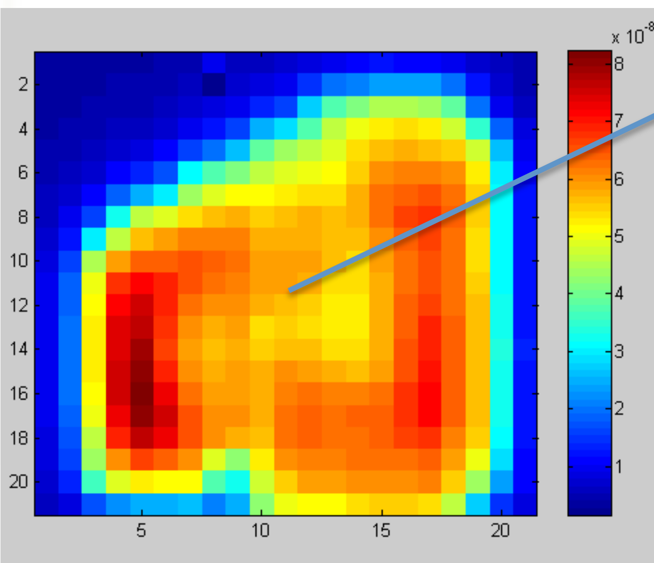
IMRT Field



10MV photon beam at Careggi Hospital

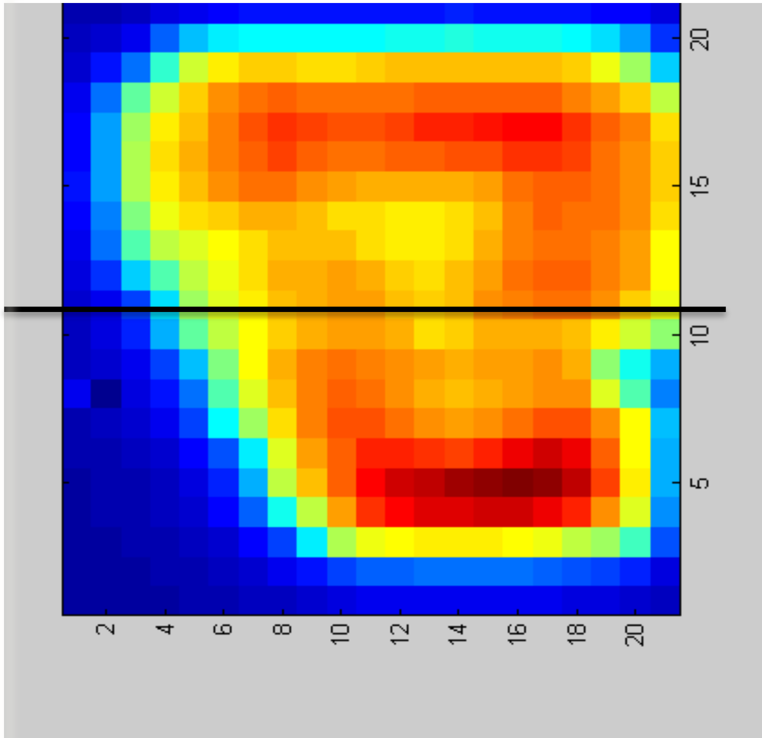
IMRT Field

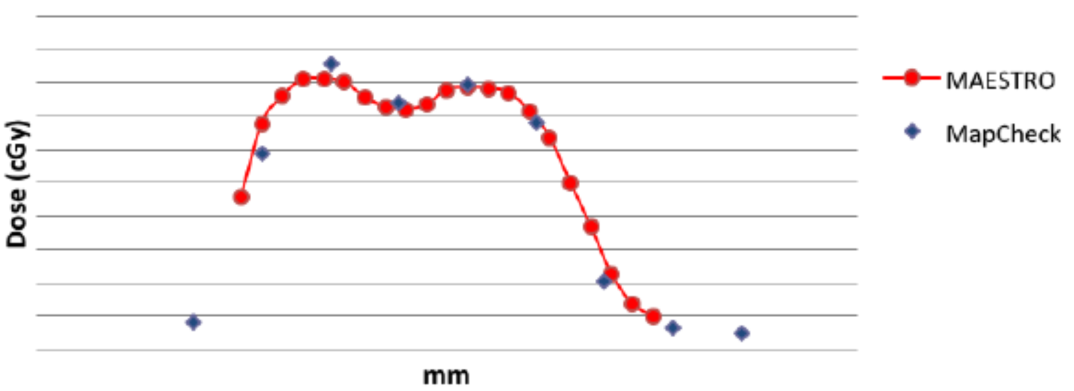




10MV photon beam at Careggi Hospital

IMRT Field





10MV photon beam

Conclusions

- In framework of European project MAESTRO we developed a 2D silicon device for pre-treatment dose verification which at present cover a region of 12,58 x 6,29 cm^2 .
- **International patent application No**. PCT/IB2007/001850 **International patent** WO2008/004091
- The new electronic of the MAESTRO dosimeter has been funded under Prima project by INFN
- We have just received by IBA the TERA 6 die chips so we are assembling the full detector to cover a region 19 x 19 cm^2

- IBA expressed an active interest towards the development of the 2D-MAESTRO dosimeter for clinical radiotherapy and suggested the accomplishment of a research program to develop monolithic pixel silicon dosimetry for other radiotherapy applications.
- IBA is going to sign a license agreement to acquire an exclusive license for the technology in order to develop and commercialize licensed products

- Even if this detector was developed some years ago, it still has up to date and we have many ideas to upgrade it to 2D+1 in order to work in a modern radiotherapy.

Florence Group

- Prof. Marta Bucciolini
- Prof. Mara Bruzzi
- Dr. Monica Scaringella
- Dr. Cinzia Talamonti
- And moved to IBA---→ Dr. David Menichelli

Pubblications

- Bidimensional silicon dosimeter: Development and characterization
  [597649] - 1a - Articolo su rivista ISI - 2011 C.Talamonti; M.Bruzzi; L.Marrazzo; D.Menichelli; M.Scaringella; M.Bucciolini NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH. SECTION A, ACCELERATORS, SPECTROMETERS, DETECTORS AND ASSOCIATED EQUIPMENT
- 2D Dosimeter Based on Monolithic Silicon Sensors for Beam Verification in Conformal Radiotherapy [397638] - 4a - Articolo in atti di congresso - 2009 Talamonti C , Bruzzi M , Bucciolini M , Marrazzo L , Menichelli D , Brianzi M , Tesi M , Cirrone GAP , Cuttone G, LoJacono P , La Rosa A
  Dresda, Germania
- Dosimetric characterization with 62 MeV protons of a silicon segmented detector for 2D dose verifications in radiotherapy [318245] - 1a - Articolo su rivista ISI - 2008 C. Talamonti, M. Bucciolini, L. Marrazzo, D. Menichelli, M. Bruzzi, G. Cirrone, G. Cuttone, P. LoJacono NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH. SECTION A, ACCELERATORS, SPECTROMETERS, DETECTORS AND ASSOCIATED EQUIPMENT
- C. Talamonti, M.Bucciolini, L. Marrazzo, D. Menichelli, M. Bruzzi, "Development of silicon segmented detector for 2D dose measurements" proceedings of the ESTRO 25 Germany, Leipzig October 8-12, 2006 Radiotherapy and Oncology vol 81 S462 2006.
- M. Bruzzi, M. Bucciolini, M. Casati, D. Menichelli, C. Talamonti, C. Piemonte, B. G. Svensson: "Epitaxial silicon devices for dosimetry applications", Applied Physics Letters 2007, 90.
- Design and development of a silicon segmented detector for 2D dose measurements in radiotherapy [200287] - 1a - Articolo su rivista ISI - 2007 D. MENICHELLI, M. BRUZZI, M. BUCCIOLINI, C. TALAMONTI, M. CASATI, L. MARRAZZO, M. TESI, C. PIEMONTE, A. POZZA, N. ZORZI, M. BRIANZI, A. DE SIO. NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH. SECTION A, ACCELERATORS, SPECTROMETERS, DETECTORS AND ASSOCIATED EQUIPMENT
- Preliminary dosimetric characterization of a silicon segmented detector for 2D dose verifications in radiotherapy [200286] - 1a - Articolo su rivista ISI - 2007 C. TALAMONTI, M. BRUZZI, M. BUCCIOLINI, L. MARRAZZO, D. MENICHELLI NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH. SECTION A, ACCELERATORS, SPECTROMETERS, DETECTORS AND ASSOCIATED EQUIPMENT –
- Development of a silicon segmented detector for 2D dose measurements [397744] - 4a - Articolo in atti di congresso - 2006 Talamonti C, Bruzzi M, Bucciolini M, Casati M, Marrazzo L , Menichelli D RADIOTHERAPY AND ONCOLOGY Leipzig, GERMANY