Development of dosimeters based on polycrystalline diamond

Mara Bruzzi[a,b], M. Bucciolini[a], C. Talamonti[a,b], M. Zani[a,b] M.Scaringella[b], E.Pace[a,b], A. de Sio[b]

[a]INFN Firenze, Italy
[b]Università di Firenze, Italy

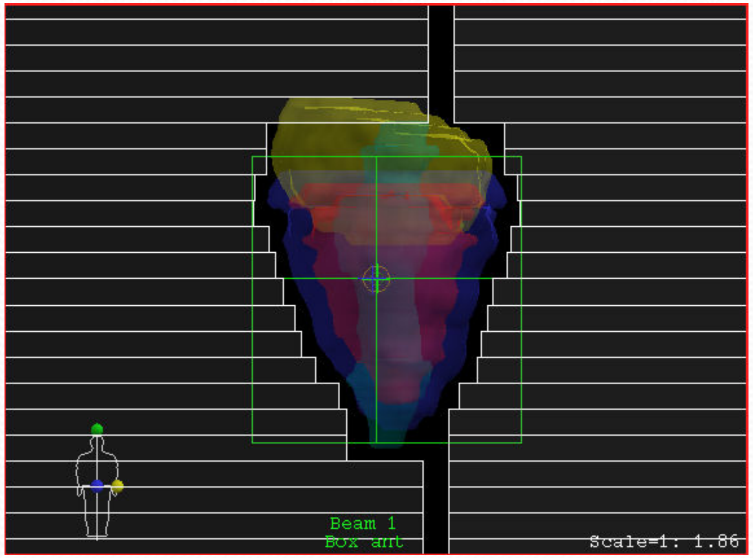
Motivation

- in Italy, almost **2 milions** during their life got a tumour diagnosis;
- Mortality by tumours in Italy represents almost **30%** of the total annual decess, survival after 5 years from diagnosis it's increasing, now about **47%** (as average in Europe).
- Treatment protocols for neoplastic pathologies requires radiotherapy in **70%** of the whole cases.

UNIVERSITÀ DEGLI STUDI FIRENZE

Radiotherapy Machines

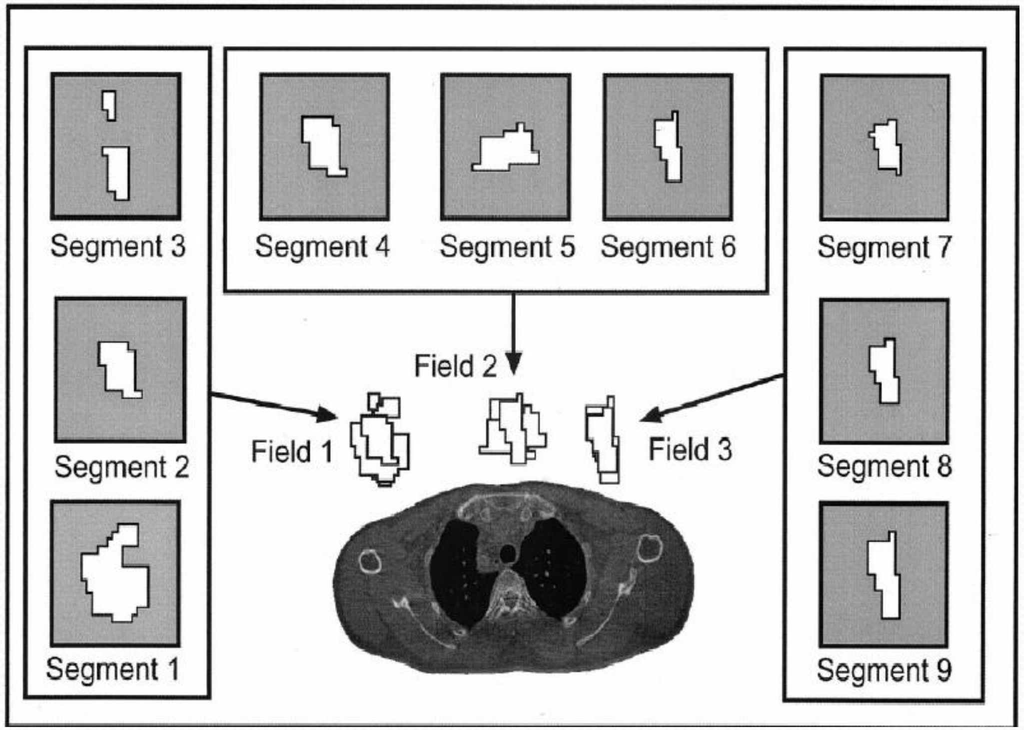
Modern radiotherapy techniques (Intensity Modulated RadioTherapy -IMRT, hadrontherapy, stereotactic treatments..) dose delivering conformal to tumors require high spatial gradients as well as variations in space and time of the dose rate and of the beam energy spectrum.

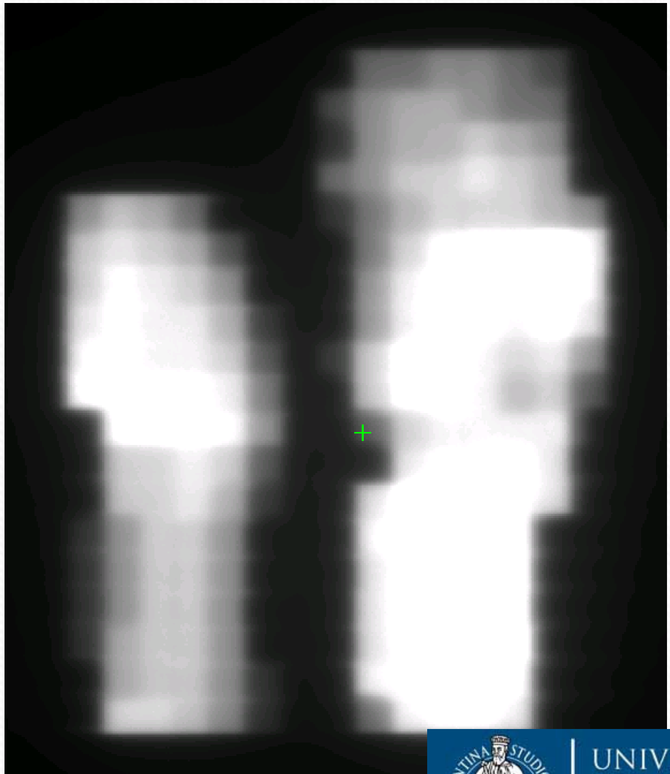


Modulation is obtained thanks to a Multi Leaf Collimator (MLC) mounted on the linear accelerator.

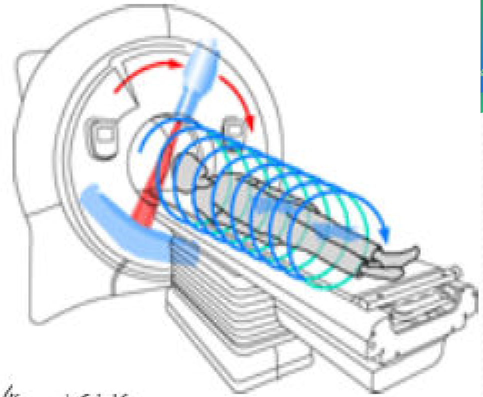
IMRT: Step and shoot modality

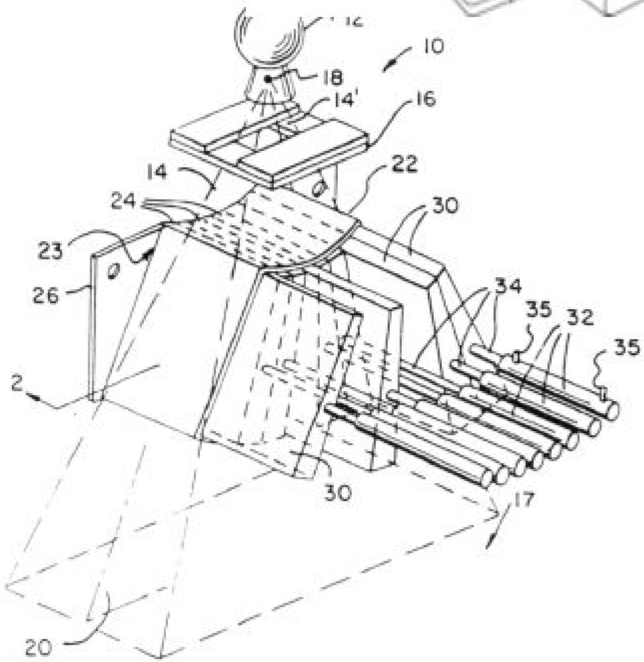
Non-uniform fluence distribution obtained by a sequence of static irradiations (segments) characterized by a different MLC configuration.
Beam switched off during the MLC rearrangement.





Tomotherapy



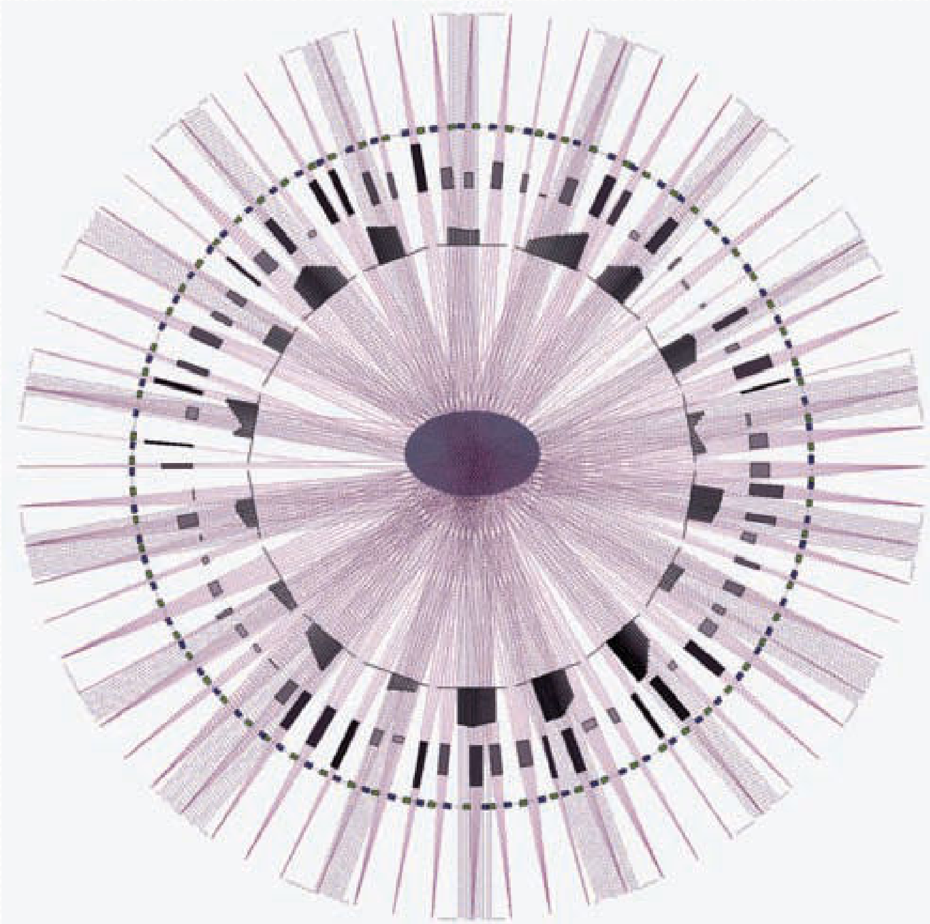


Intensity modulated radiotherapy (IMRT) : during helical delivery, couch travels at a constant velocity through a continuously rotating gantry, while multileaf collimator (MLC) leaves open and close on a subsecond timescale.

Tomotherapy also employs megavoltage CT imaging.

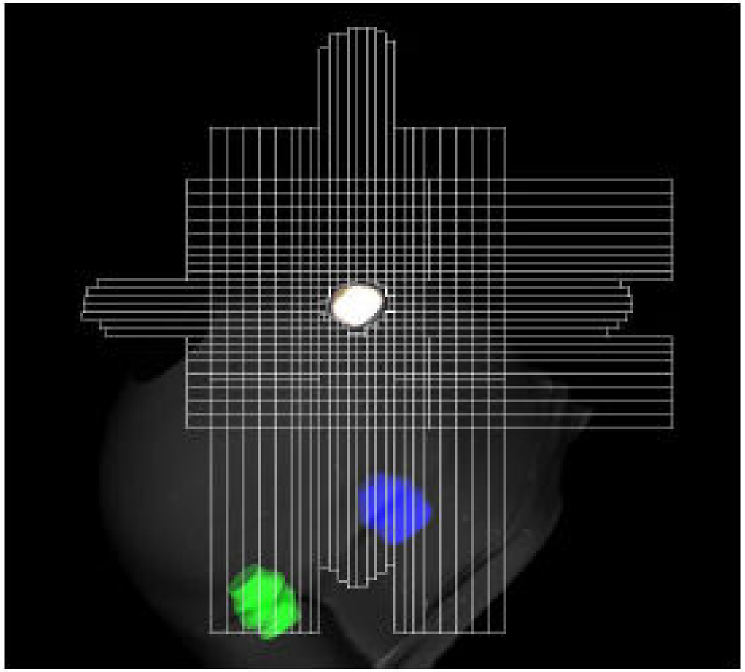
Volumetric-modulated arc therapy (VMAT) delivers radiation by rotating the gantry of a linac through one or more arcs with radiation continuously on.

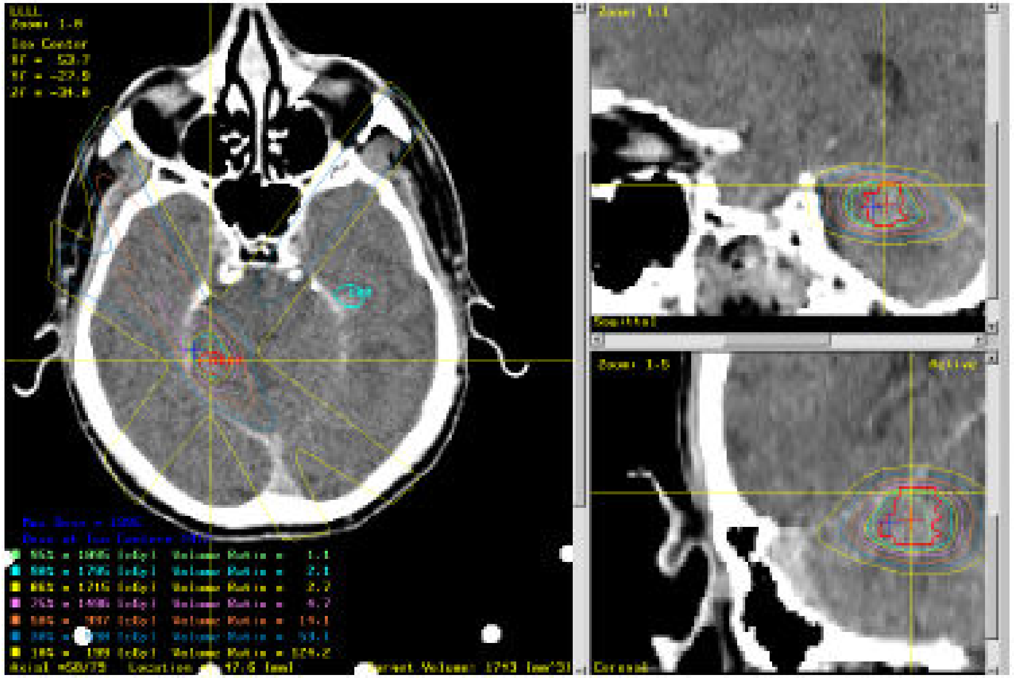
Divergent ray paths, leaf positions and segment weighting
at each gantry angle.
Reconstructed parallel rays and associated intensity-modulated beam are shown for every 4th angle.



Stereotactic Radiotherapy

Small tumors treatment, especially brain, tumors typically 3 cm or less in diameter. It requires a precisely focused, high-dose radiation beam. Real time, high resolution, multi-dimensional measurements of absorbed dose distributions required.





Gamma Knife Perfexion

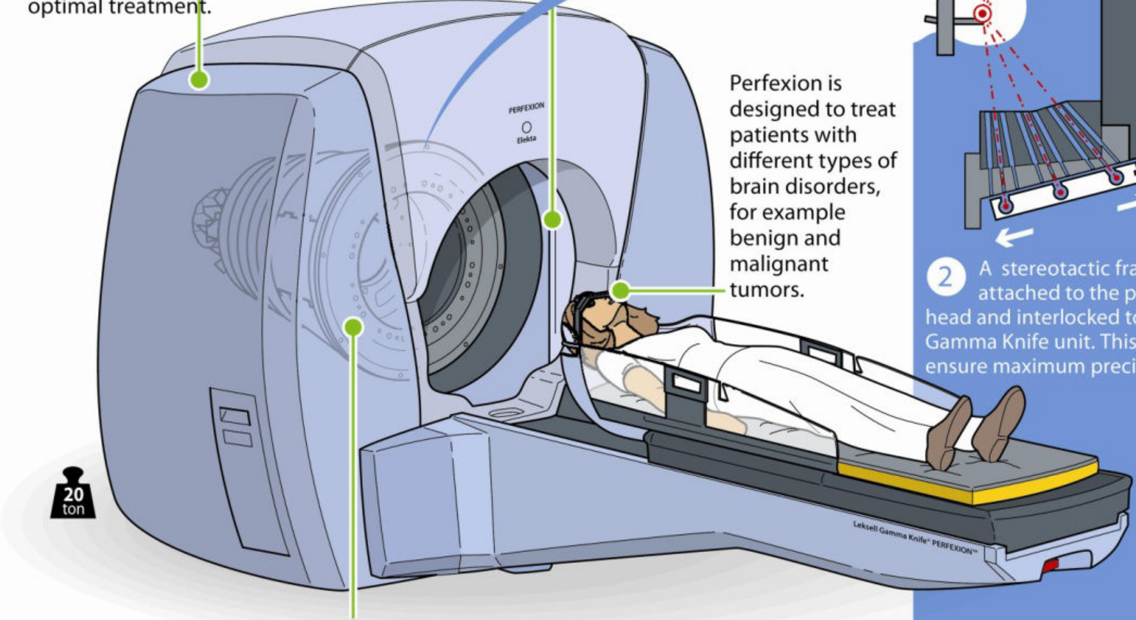
Leksell Gamma Knife Perfexion

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.

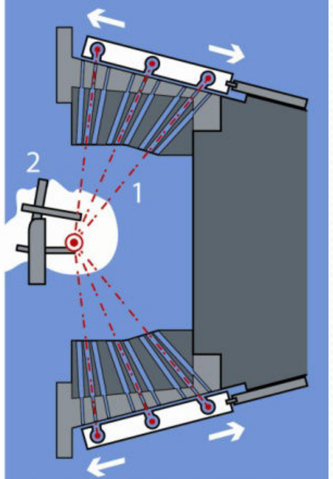
Perfexion is designed to treat patients with different types of brain disorders, for example benign and malignant tumors.



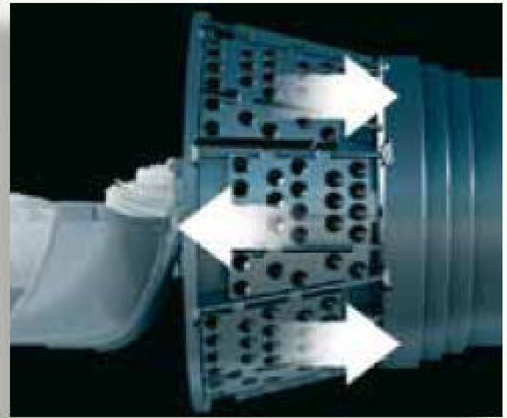
Leksell Gamma Knife Perfexion is fully automated. The radiation unit is housed inside of the machine itself. The radiation beams are shaped exactly around the tumor. Several tumors can be treated in one session.

Radiation unit

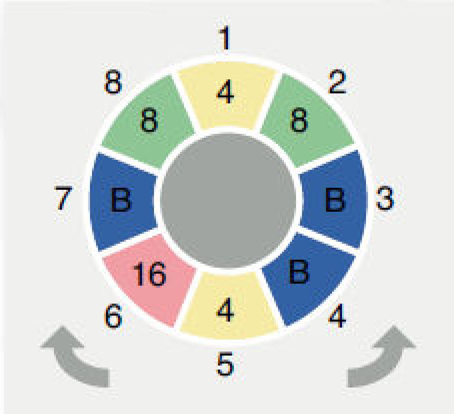
1. Ionizing gamma radiation is emitted from 192 cobalt-60 sources whose beams converge on a precise selected area of the brain. The accuracy is about 0.5 mm. There is minimal effect on the surrounding healthy tissue.



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 d...
treatment of comple...
Composite Shots and...

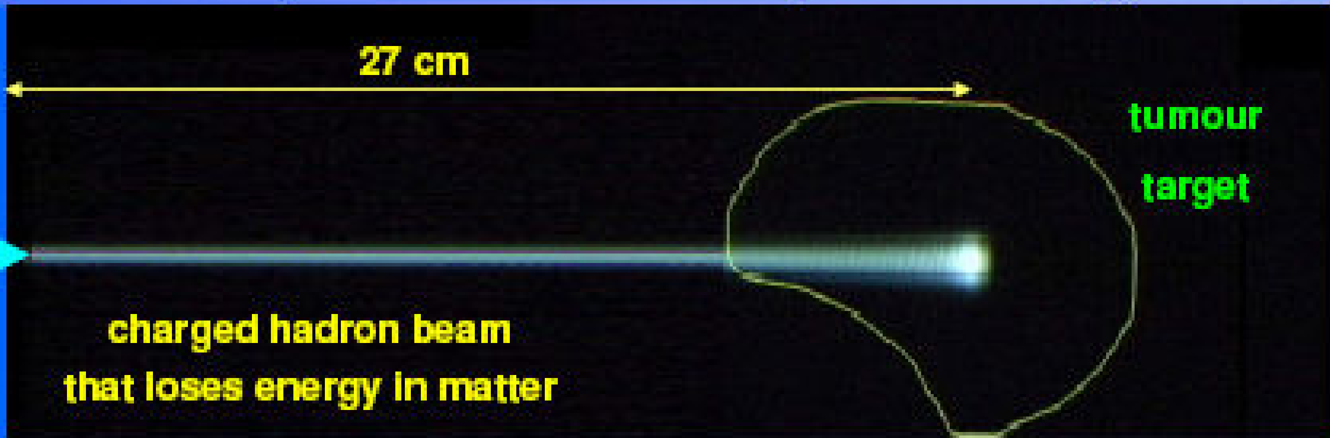
UNIVERSITÀ DEGLI STUDI FIRENZE

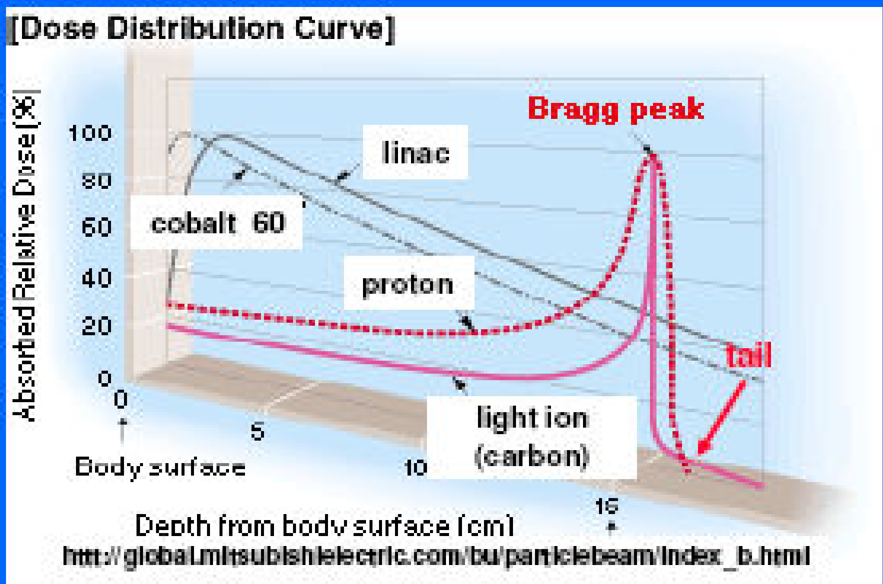

Targeting System
Cyber Knife
Sistema
Synchrony™
LINAC
Robotic Delivery
System

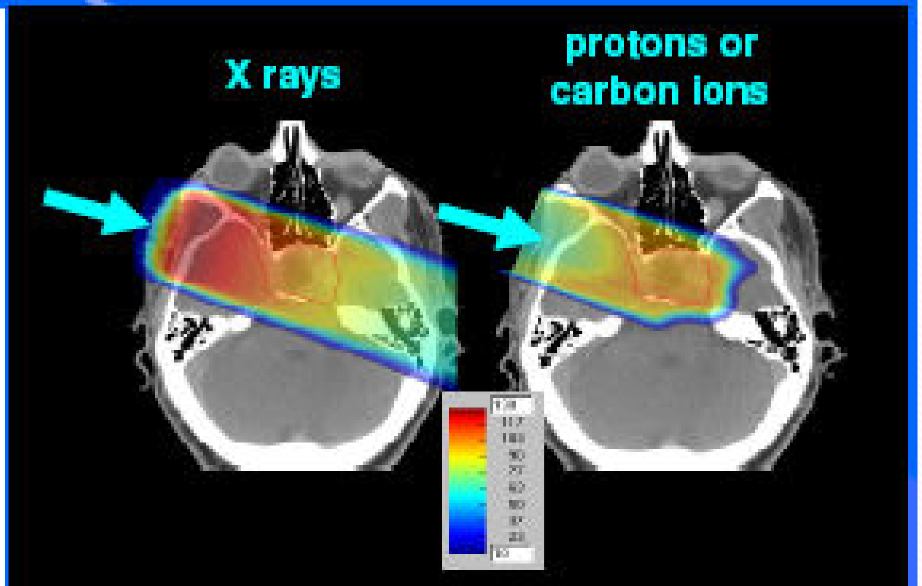
Basic facts: protons and ions spare healthy tissues

200 MeV - 1 nA
protons

4800 MeV – 0.1 nA
carbon ions
which can also control
radioresistant
tumours







Hadrontherapy in Italy

CNAO

National Centre for Oncological Hadrontherapy

Pavia, Italy

Catana beam line LNS-INFN Catania, Italy

Trento - under development

UNIVERSITÀ DEGLI STUDI FIRENZE

Matrix Dosimeters

Dose measurements must face non-uniform beam fluences and large dose rate ranges.

Best solution is a matrix detector

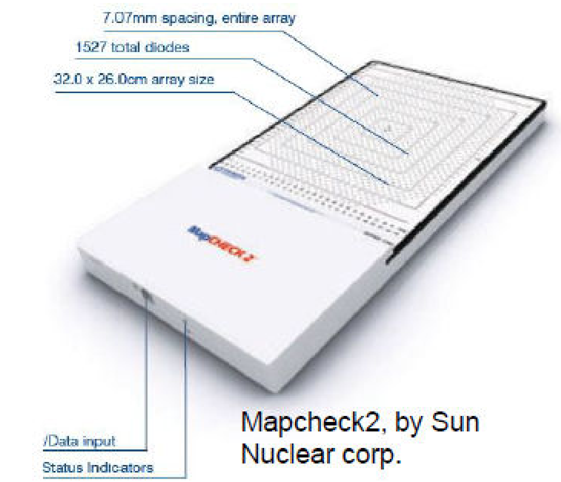
- •High sensitivity,
- •High spatial resolution,
- •Fast dynamics and
- •Stable response
- •Active area comparable with radiation field (up to 20x20cm^2)

Arrays of single diodes in Si already commercially available for 1D and 2D measurements, but granurality is limited.

MAPCHECK

445 Si diodes in a 22x22 cm^2 matrix

- **active area 0.8 mm x 0.8 mm**
- **Inner field10 cm x 10 cm: 1cm pitch**
  External field : 2 pitch cm



Mapcheck2, by Sun Nuclear corp.

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

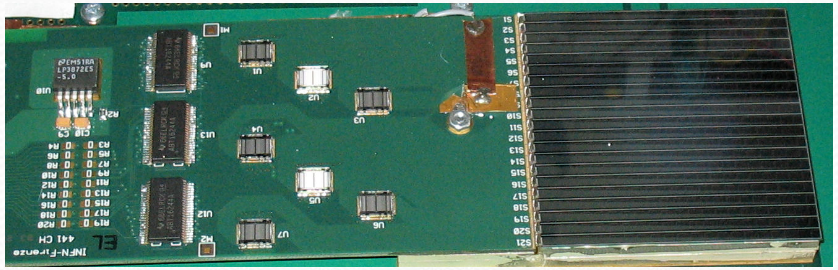
IBA dosimetry LDA99.

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

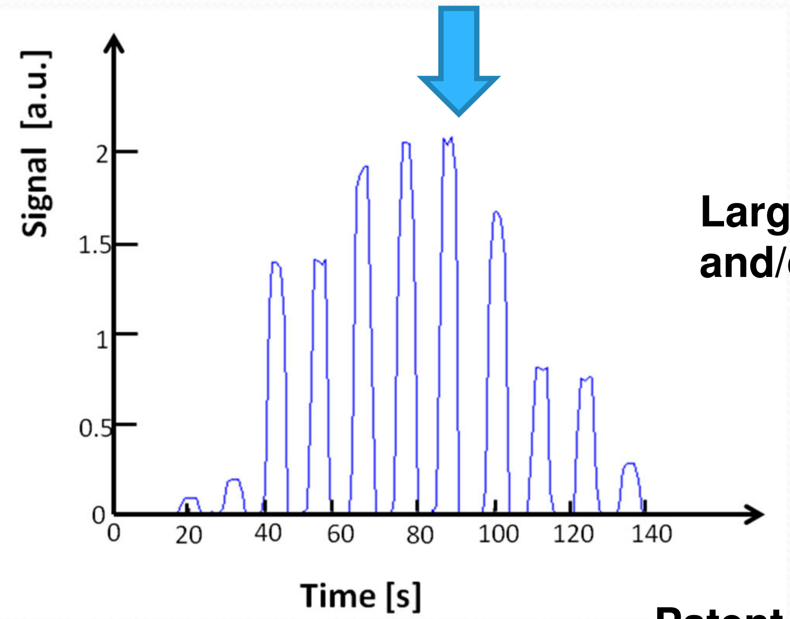
UNIVERSITÀ DEGLI STUDI FIRENZE

Si bidimensional dosimeter

Florence group designed and manufactured a high performance cost-effective device based on epitaxial p-type silicon (radiation-hard, no dependence on the accumulated dose), designed to get a high resolution matrix of macropixels (2x2mm^2). Module:6.3x6.3cm2, 441ch. MAESTRO EU Integrated project



Measured time structure of dose segments



Large area IMRT covered by mosaic composition and/or shifting modules along x-y axes.

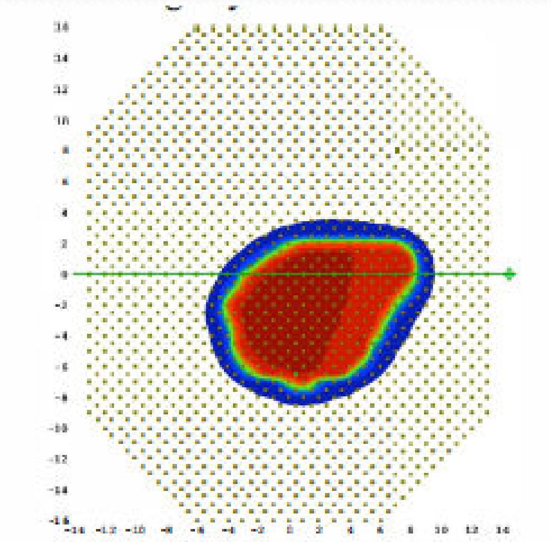
C.Talamonti et al. 2011 Nucl. Instr. Meth A, vol. 658, p. 84-89.

M. Bruzzi et al. 2012 IEEE Nuclear Science Symposium and Medical Imaging Conference Record (NSS/MIC) N14-187 1316-1319

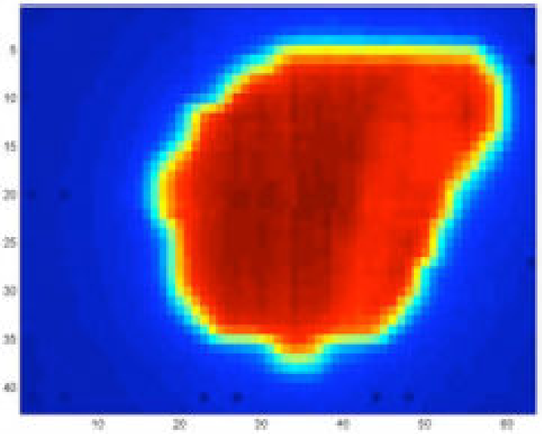
Patent : US2010176302 (A1) – 2010-07-15

Dose map corresponding to an IMRT field for prostate cancer

as calculalated by treatment planning system (dots evidence MAPCHECK Si diodes positions).



As measured by our 2D silicon dosimeter.



M. Bruzzi et al. 2012 IEEE Nuclear Science Symposium and Medical Imaging Conference Record (NSS/MIC) N14-187 1316-1319

Patent : US2010176302 (A1) – 2010-07-15

Beyond Silicon: Diamond Dosimeters

- **it is almost water equivalent**

☺ it doesn't perturb the radiation field → small fields
the energy is absorbed as in the water → no correction factors

- **high radiation hardness** → long term stability
- high density → high sensitivity → small dimensions
- non toxic

Natural diamond

- **very high production costs, difficult to select stones with proper dosimetric response** ♠

Polycrystalline CVD diamond

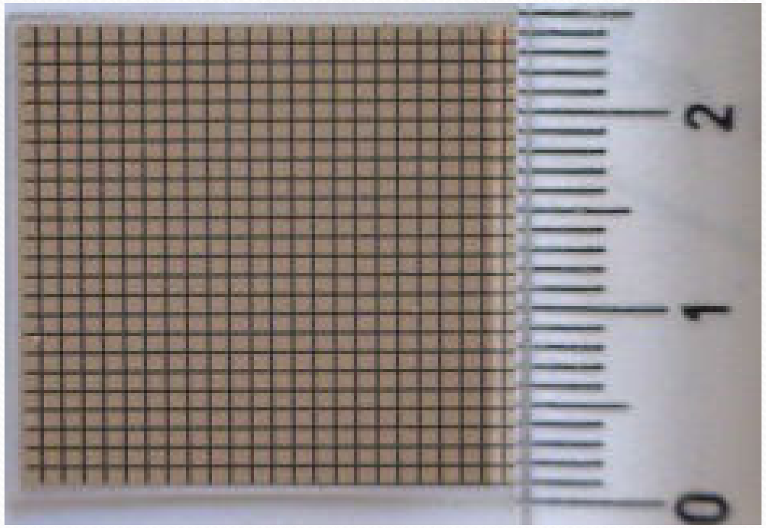
☺ **ability to produce large area wafers of 3-5"**

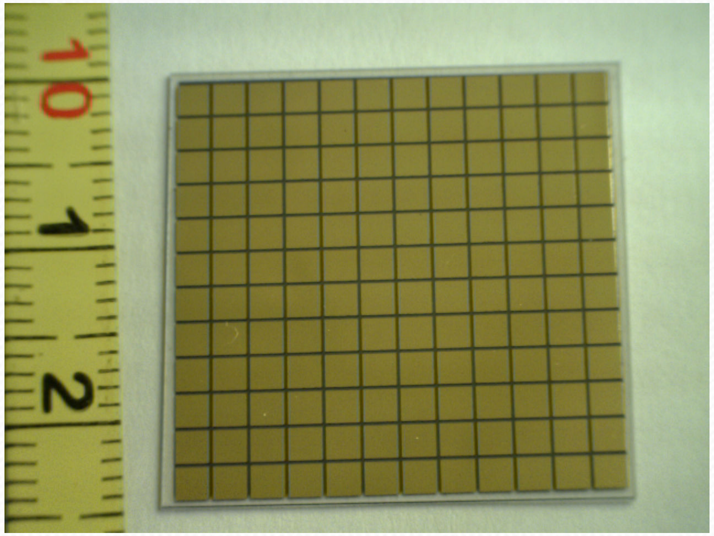
Single crystal CVD (Chemically Vapour Deposited) diamond

- **grown on HPHT diamond, not available in large areas** ♠

pCVD diamond bidimensional dosimeter

We designed and manufactured 24x24 and 12x12 matrixes of Cr/Au contacts (2x2mm^2 pixel) on Premium Detector Grade (Diamond Detectors Ltd) polycrystalline diamond, area 2.5cmx2.5cm, W = 300μm.





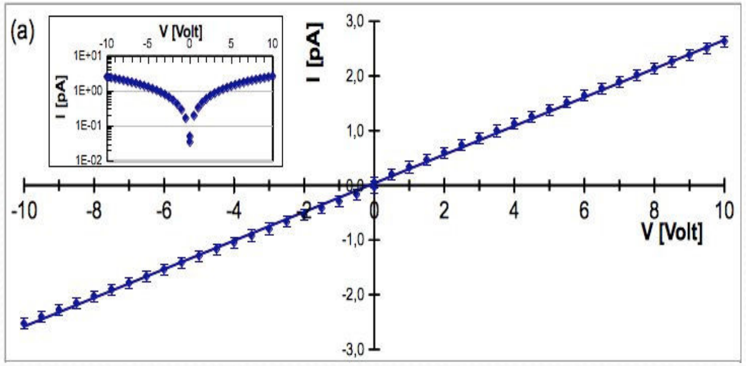
Developed under WP2 DIAPIX Experiment INFN CSN5

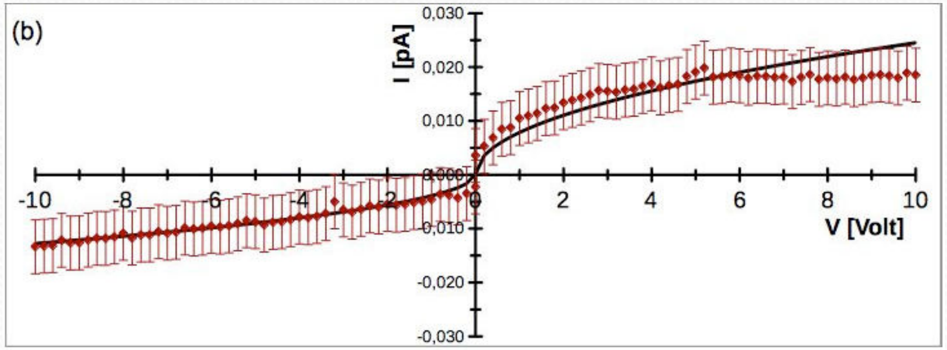
dark I-V on pCVD diamond matrix

I-V in dark (air)

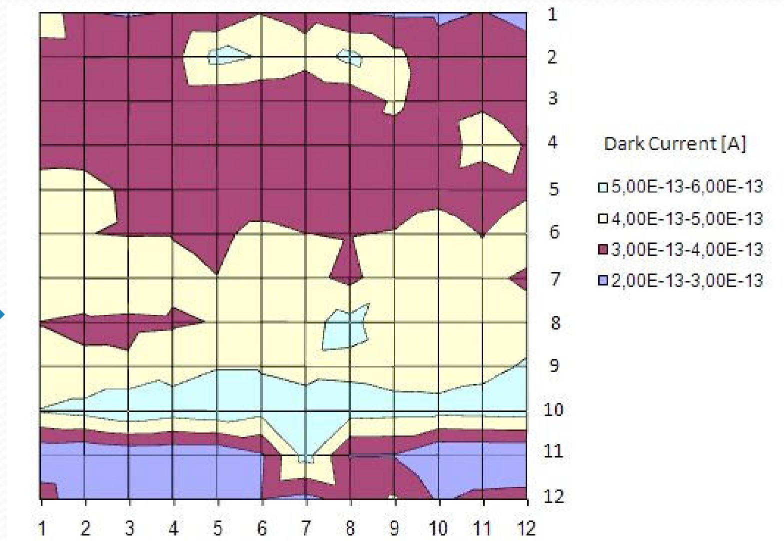
I-V in dark (vacuum)

$I \leq 2x10^{-14}$ A $-10V \leq V_{app} \leq 10V$



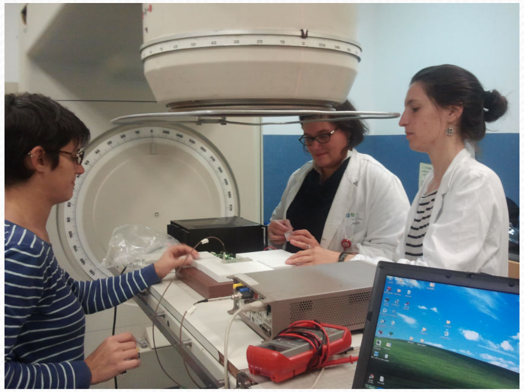


Current map in dark (air)



M. Zani et al. NIMA 730, 1st Dec. 2013

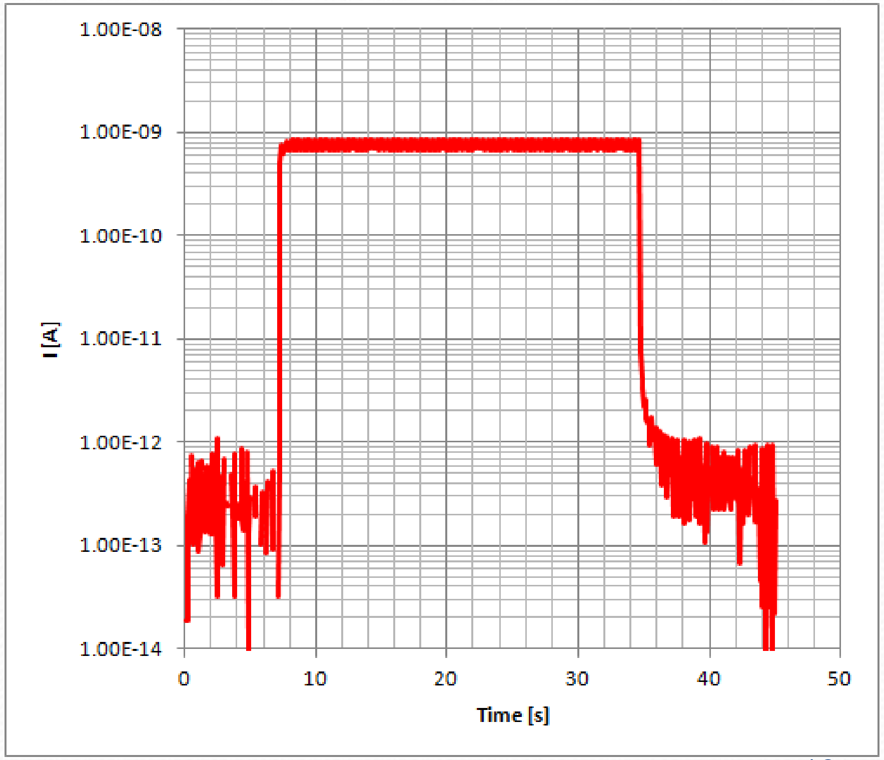
First results with the pCVD diamond matrix



FE: 64-channel, current input, 20-bit analog-to-digital (A/D) converter.
-160μs-1s integration time.
-High precision current measured from fraction of pAs to μA
- 3x6 =18 pixels connected and measured

Current response of one pixel in a 10cmx10cm conventional 10MV X beam .
D = 200MU, Dr = 400Mu/min. V_{app} = 1V. Uniformity of examined pixels : 5.6%.

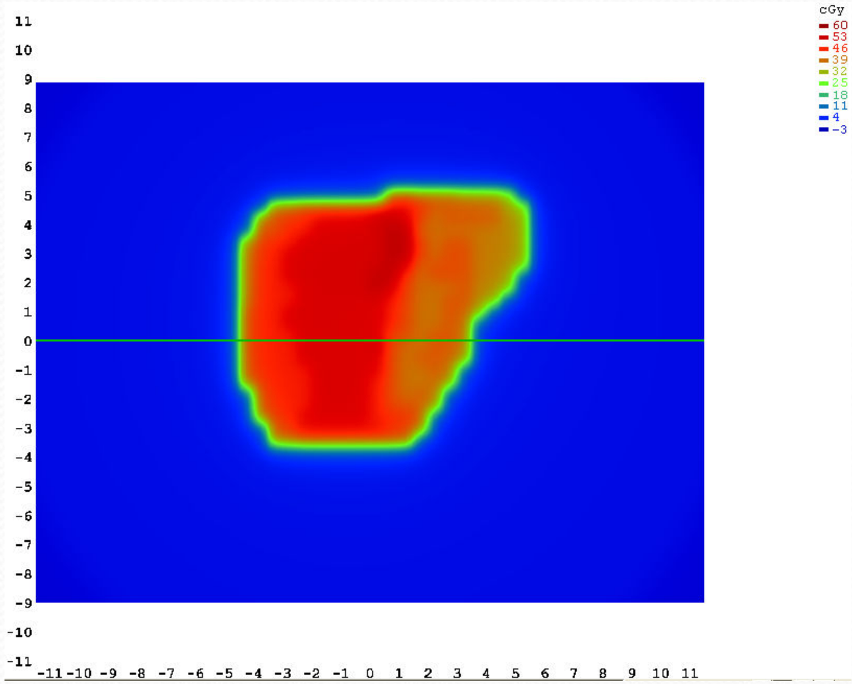
M. Bruzzi Radiation Dosimetry in the Medical Field
IEEE/NSS/MIC – Seoul Oct 27 2013



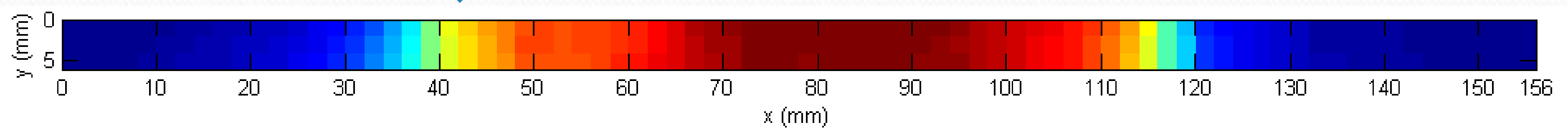
First results of pCVD diamond matrix under IMRT beam

10 MV photon beam for prostate treatment in step-and-shoot modality.

TPS

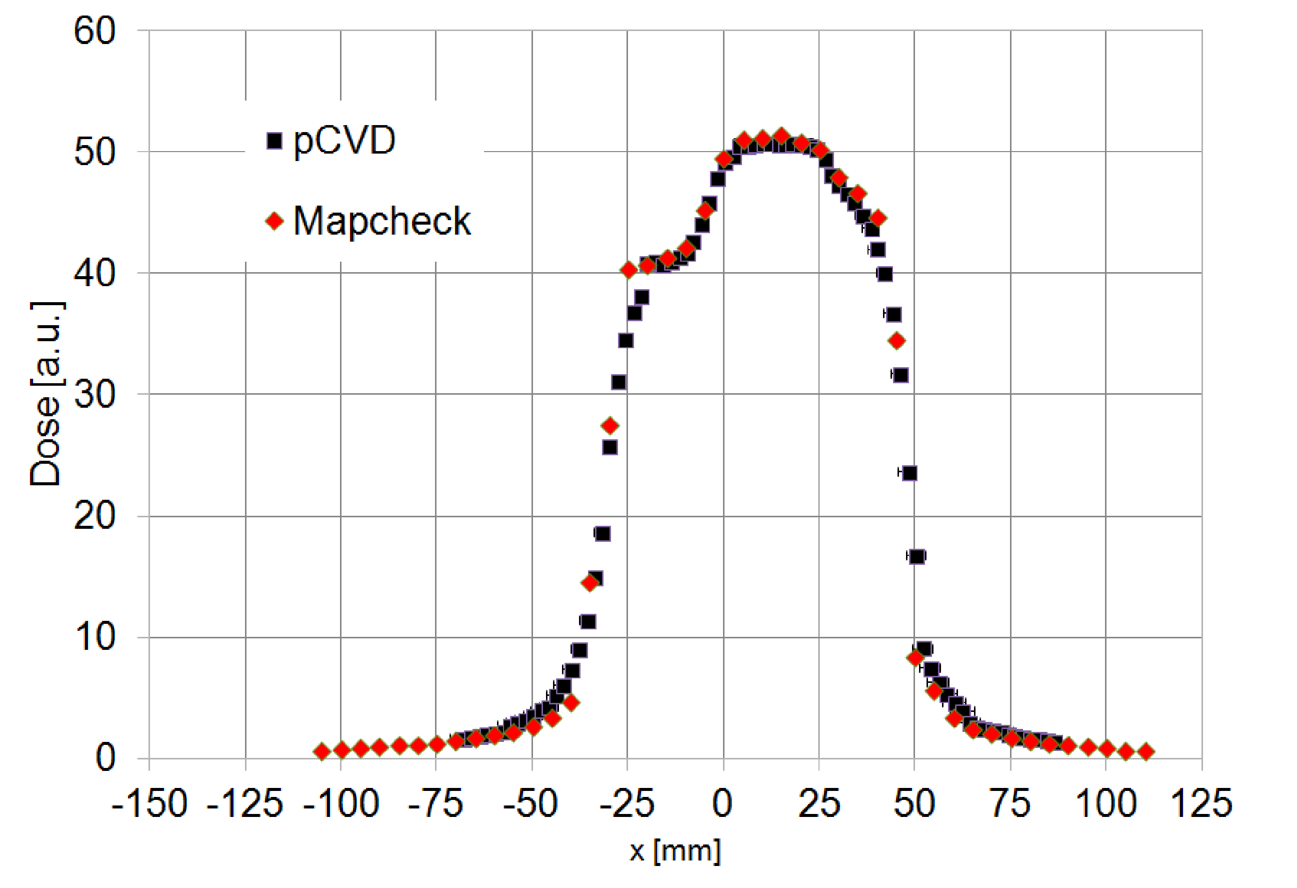


Profile (6mmx15.6cm) measured by the pCVD diamond moving along x the pCVD matrix (3y 6x pixels)



M. Bruzzi et al. , Radiation Dosimetry in the Medical Field workshop IEEE/NSS/MIC – Seoul Oct 27 2013

Comparison of profiles obtained with pCVD diamond and Mapcheck Si



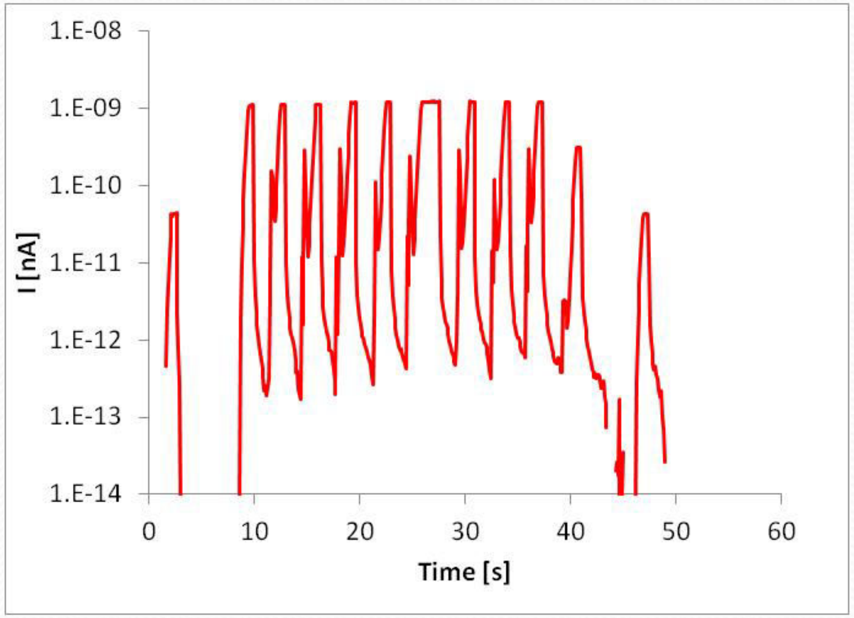
M. Bruzzi et al. , Dosimetry in the Medical Field workshop IEEE/NSS/MIC – Seoul Oct 27 2013

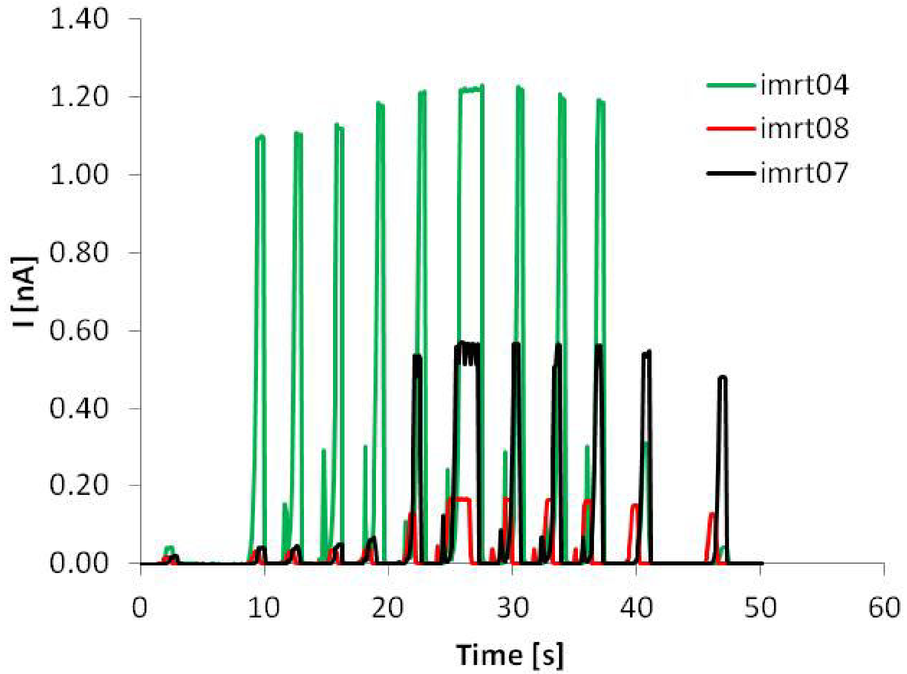
- Good agreement, higher spatial resolution

Time structure of the pCVD diamond signal along profile

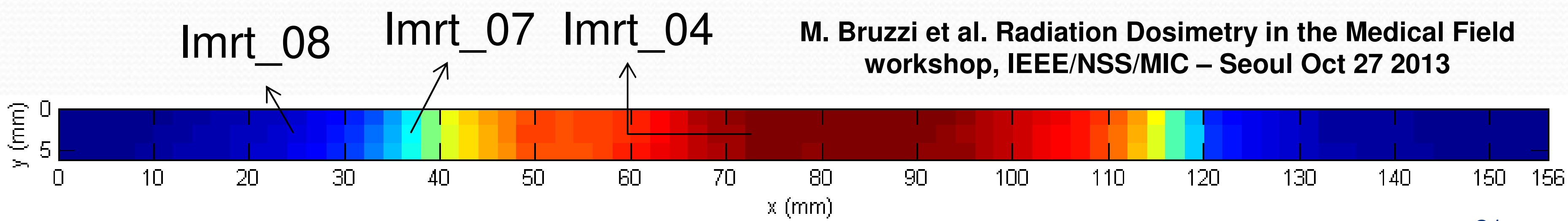
- Fast dynamics;
- high SNR;
- no persistent current effects.

Time structure of the 12 IMRT segments as measured by the pCVD diamond in 3 different positions of the IMRT map.



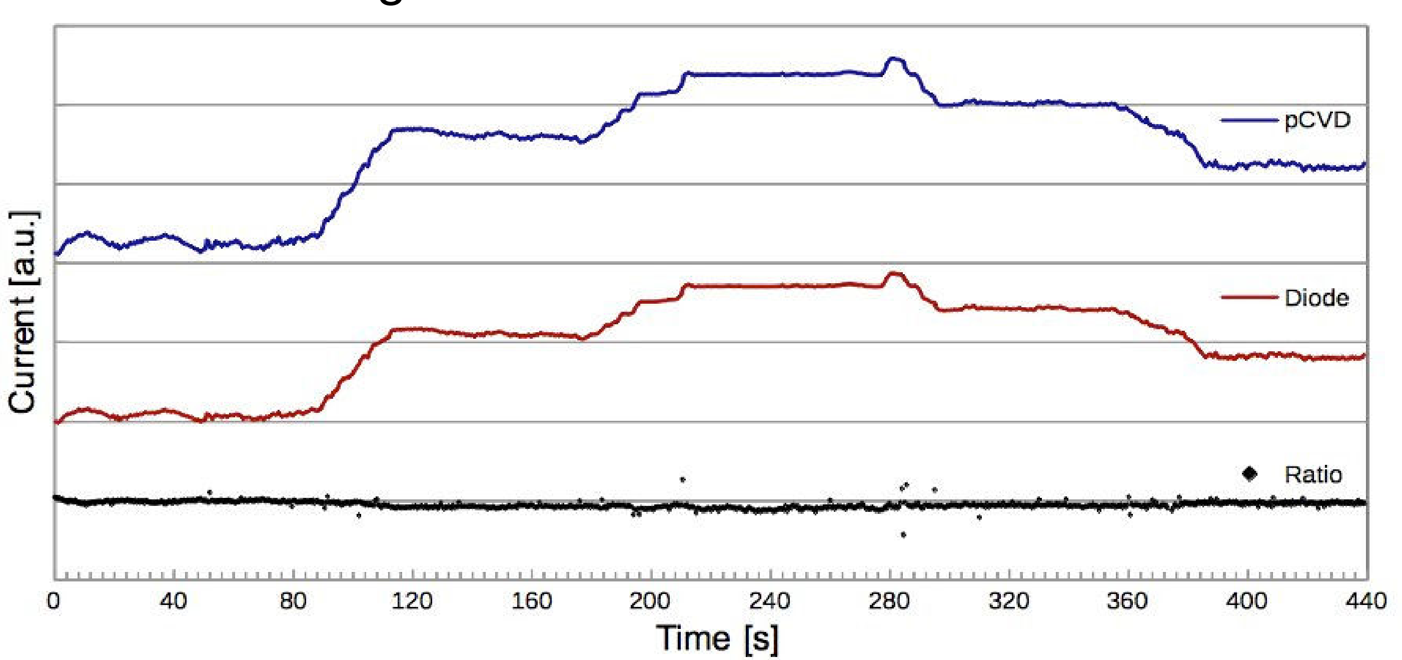


M. Bruzzi et al. Radiation Dosimetry in the Medical Field workshop, IEEE/NSS/MIC – Seoul Oct 27 2013



Tests of pCVD diamond under proton beam 1

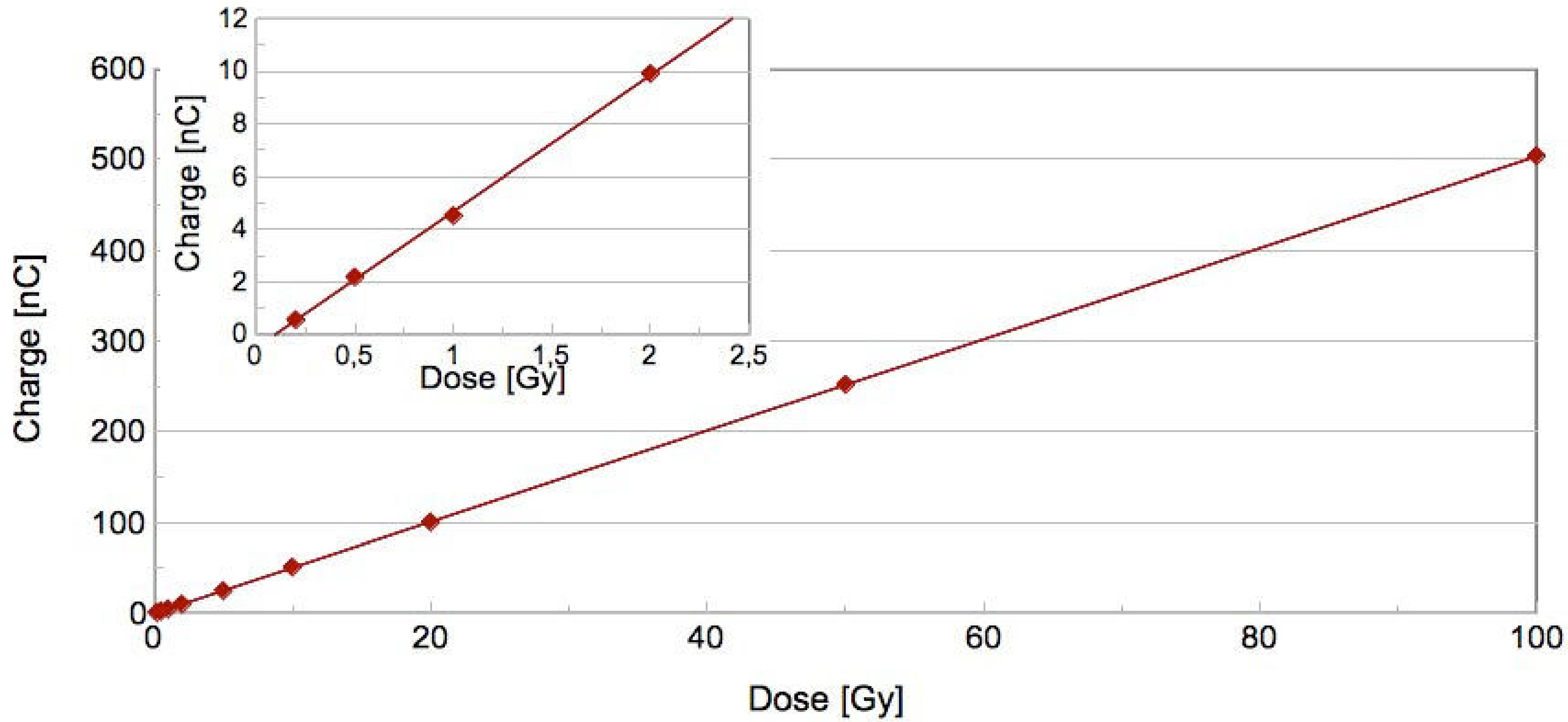
- Irradiation with Catana ILNS-INFN 62 MeV proton beam.
- Proton fluence rate in real-time (four different dose rates) compared with signal collected by one pad of pCVD sample.
- Ratio between two signals in black.



M. Zani et al. NIMA 730, 1st Dec. 2013

Tests of pCVD diamond under proton beam 2

Irradiation with Catana ILNS-INFN 62 MeV proton beam.
Linearity test of collected charge vs dose.
Inset: low dose range (10cGy -2Gy).



M. Zani et al. NIMA 730, 1st Dec. 2013

Conclusions

- Advanced radiotherapy systems need large-area matrix detectors for precise dose measurements in real-time;

-A large-area 2D-bidimensional Si dosimeter system based on p-type epitaxial Si has been developed and tested proved to be quite rad-hard, with higher sensitivity and spatial resolution than commercial devices;

- pCVD diamond suitable for dosimetric pre-treatment verification analysis in IMRT and proton beams, allowing for the development of large area monolithic devices with effective costs;

-First measurement with a matrix of pixels on pCVD diamond gave promising results on a profile of 15.6cm of a IMRT prostate beam, a systematic analysis is in progress;

-Measurements in proton beam promising, more investigation in future.