IRPT (Innovation in Radio- and Particle-Therapy)

proton Computed Tomography (PRIMA-RDH-IRPT)

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Polycrystalline CVD Diamond 2D Dosimeter (DIAPIX-RDH-IRPT)

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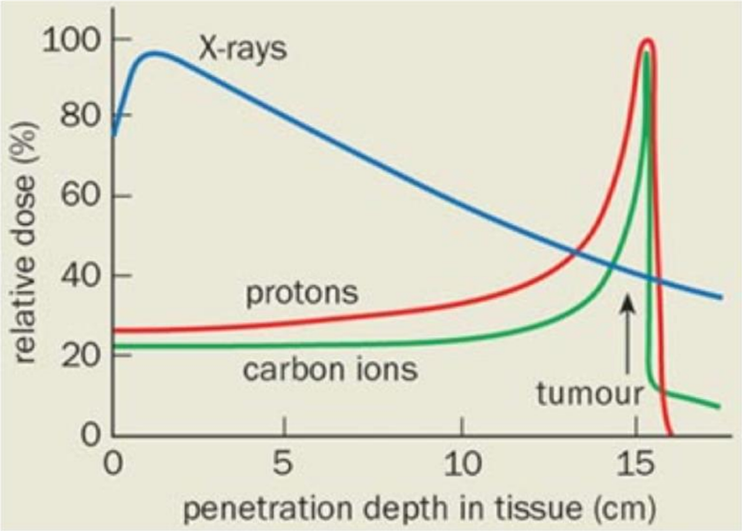
C. d. S. INFN Firenze, 01/07/16

The proton Computed Tomography - principle

Proton Radiotherapy → first proposed by R.R. Wilson in 1946 "Radiological Use of Fast Protons", Radiology, 47:487-491 (1946)



Advantage :

Highly conformational dose distribution

i) lower dose to healthy tissues in front of it;

ii) healthy tissues beyond tumor not damaged;

Inaccuracies: Treatment planning presently performed by X-CT → expected errors typically of a few millimeters

B. Schaffner and E. Pedroni Phys. Med. Biol. **43 (1998) 1579–1592**

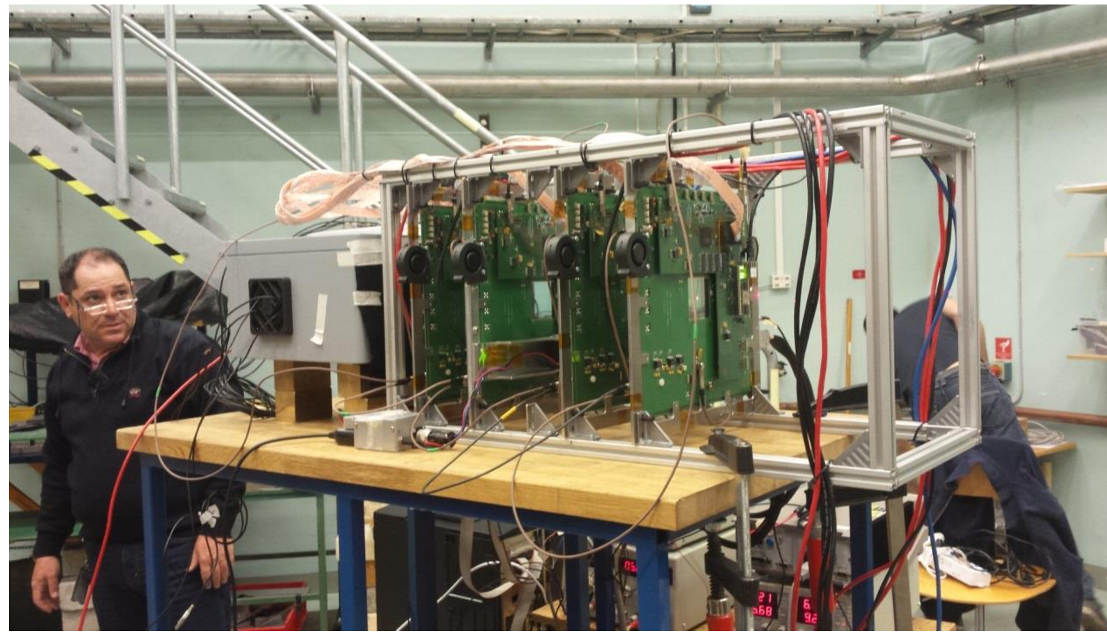
pCT

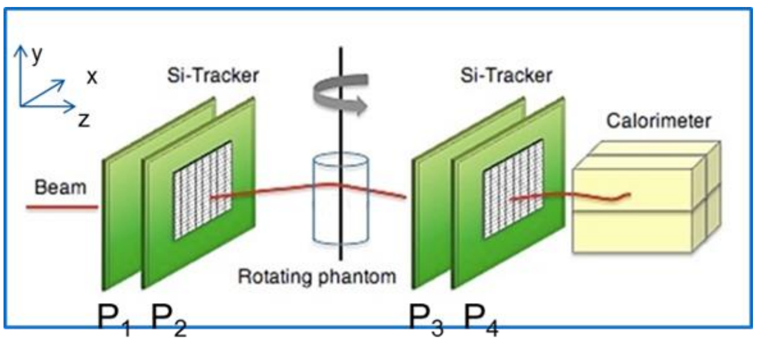
- ✓ Direct measure of the stopping power maps
- ✓ Precision improvement when positioning and treatment are made in one go

small area pCT apparatus

First test at INFN-LNS (60 MeV):
May 2011

High energy test (180 MeV) at TSL-Uppsala:
June 2015



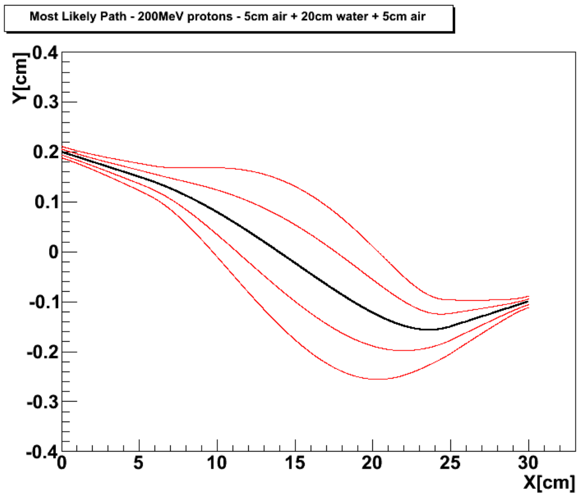


5x5 cm^2 active area

Four x-y silicon microstrip based tracking planes → Proton entry and exit positions and directions

Yag:Ce calorimeter → Proton residual energy

Reconstruction (Firenze)



- Calculation of Most Like Path starting from D.C. Williams Phys. Med. Biol. **49** (2004) and R.W. Shulte *at al.* Med. Phys. **35 (11)** (2008)

- Stopping power integral

$$-\int_{E_{\text{in}}}^{E_{\text{out}}} \left[\frac{S}{\rho}(\mathrm{H_2O})\right]_{E}^{E_0} dE = \int_{\text{path}} S(x,y,E_0)\,dl$$

Wang, Med.Phys. 37(8), 2010: 4138

- Subdivision of the image in N pixels

$$p_i = -\int_{E_{\text{in}}}^{E_{\text{out}}} \left[\frac{S}{\rho}(\mathrm{H_2O})\right]_{E}^{E_0} dE = \sum_{j=1}^{N} w_{ij} S_j(E_0)$$

- Solution with Algebraic Recursive Tecnhique (ART)

$$S^{k+1} = S^k + \lambda_k \sum_{i\in Ak} \{(p_i - \langle w^i, S^k \rangle)\, w^i\} / \|w^i\|^2$$

Gordon, R; Bender, R; Herman, GT J. Theor. Biol. (1970) **29** (3): 471–81.

Tomographic images

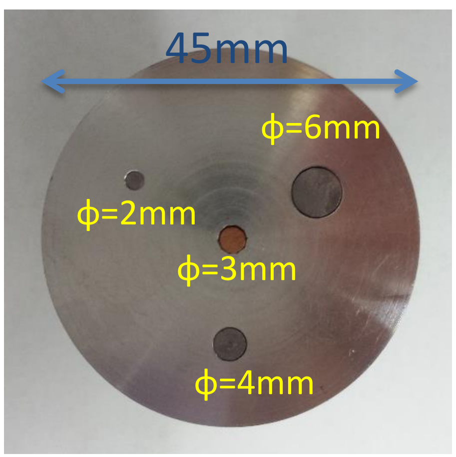
Data sets:

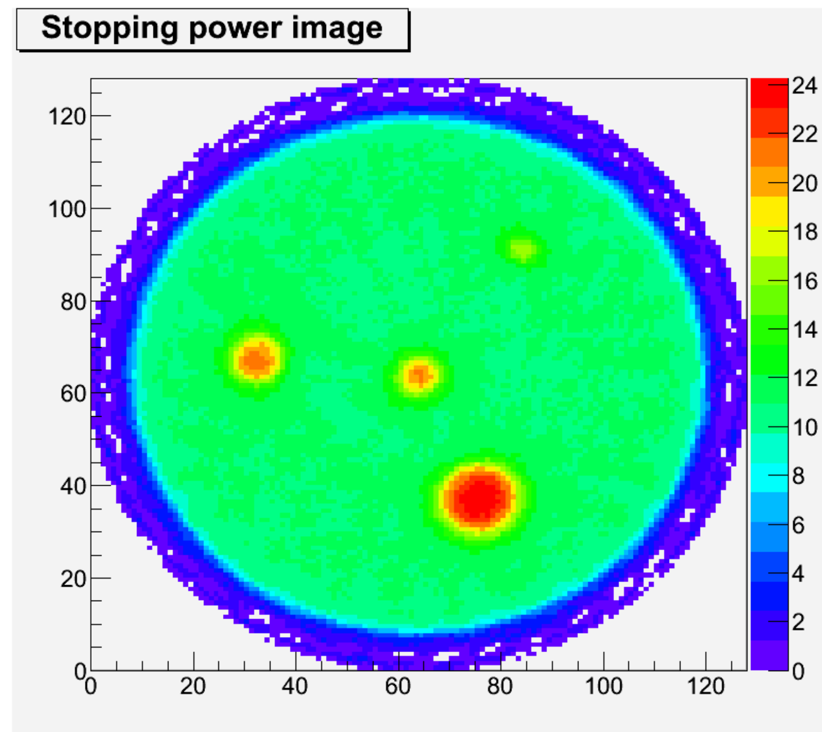
Calorimeter calibration: 10^6 events at 78, 121, 160 MeV (no phantom)

Tracker alignment: $3*10^6$ events at 173 MeV (no phantom)

40 angles (0^o-351°): $1.5*10^6$ events per angle

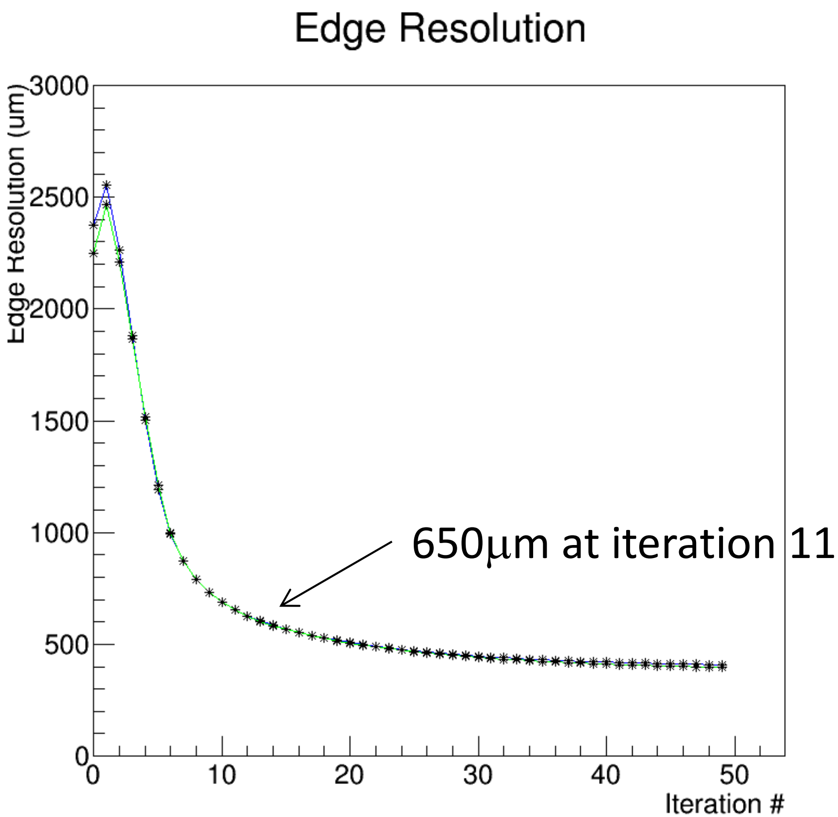
phantom

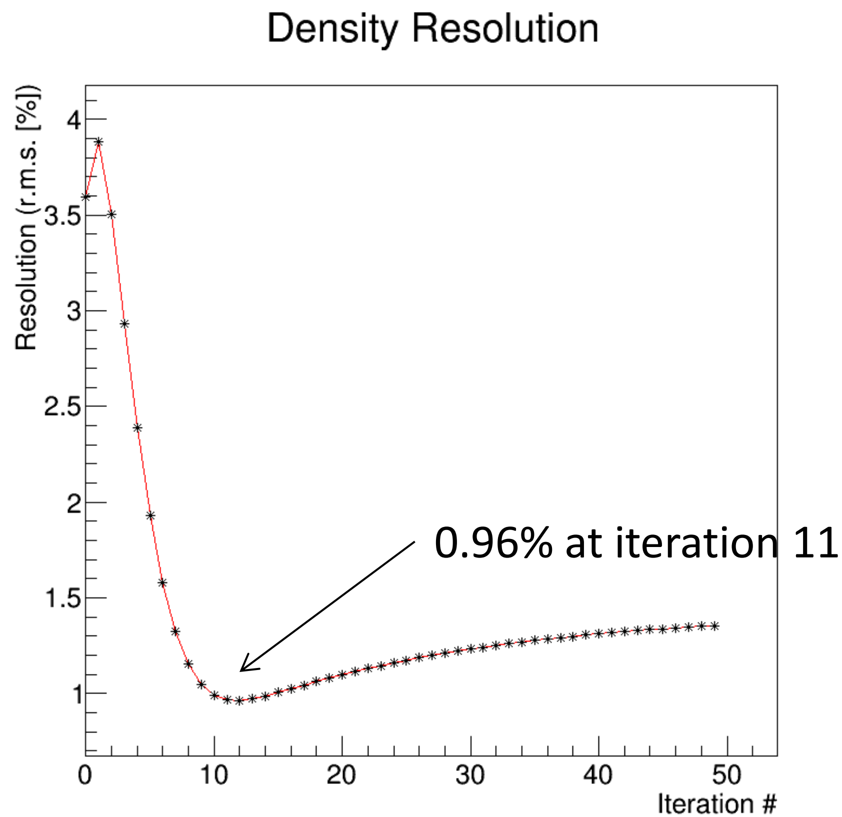




Implementation on GPU (NVIDIA Titan X) to accelerate elaboration

Resolutions

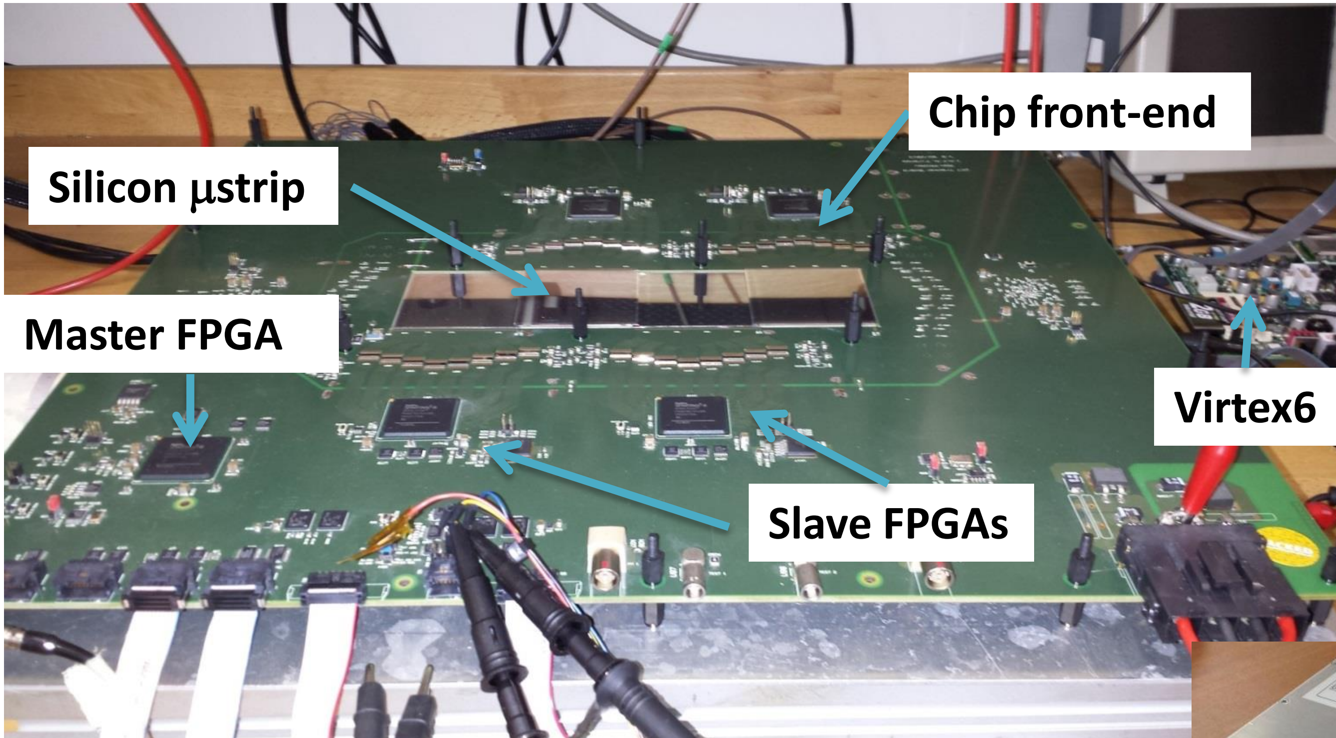




The edge resolution has been obtained fitting the edge of the tomography with an error function and quoting the sigma

The density resolution is the r.m.s. of the pixel stopping power distribution taken in a uniform fiducial region of the phantom

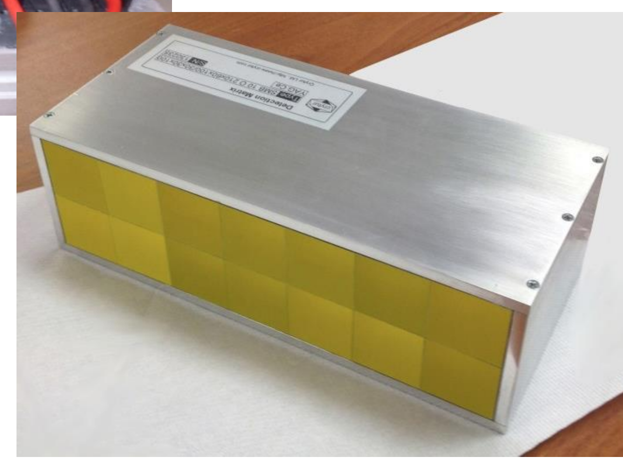
Large area Prototype



Tracker plane (Firenze)

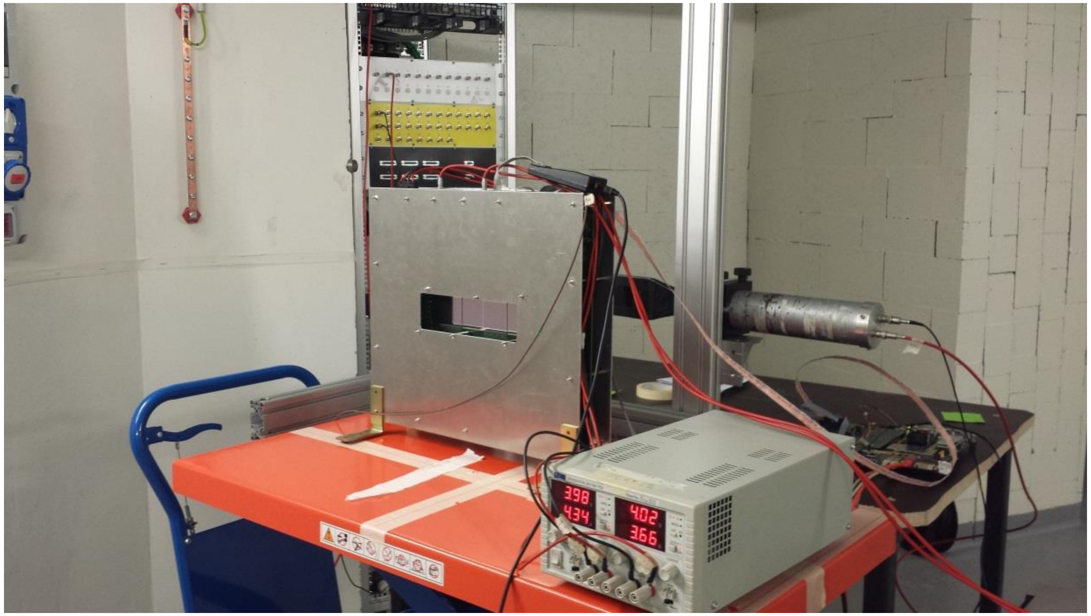
20x5 cm^2

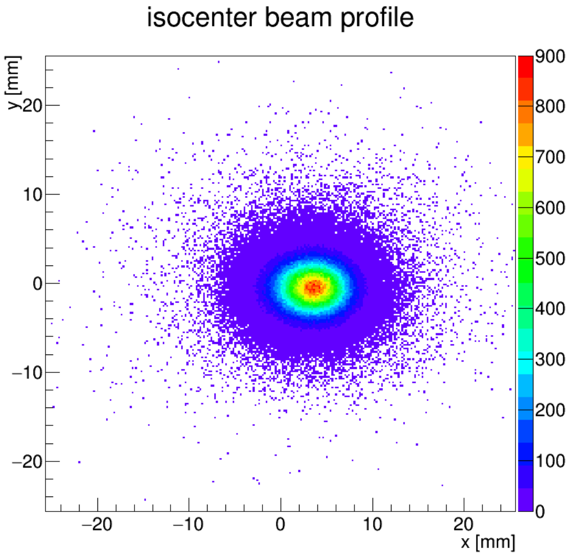
Calorimeter (Catania - Sassari)



2x7 YAG:Ce Crystals Array
Size: 3x3x10cm^3

Test-beam in Centro di Protonterapia – Trento (up to 220 MeV protons), April 2016





Instantaneous proton rate down to 400 Hz (50% duty cycle)

Future plans

- Analysis
  - 3D reconstruction, algebraic algorithm evolution, reconstruction parameters optimization
- Extended view pCT system
  - Assembly of the 4 more final tracker planes by September 2016
  - Data taking with the full system during second half of 2016

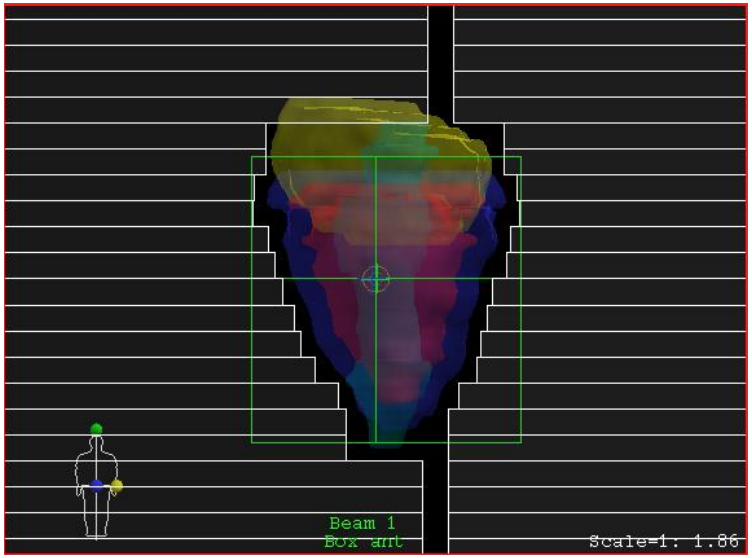
DIAPIX-RDH: Motivations

Modern radiotherapy techniques : dose-delivery conformal to tumors to spare healthy tissues

- ✓ **Intensity Modulated RadioTherapy – IMRT**
- ✓ **Volumetric Modulated Arc Theraphy - VMAT**

→ high spatial gradients, strong variations in space and time of dose rate and energy spectrum.

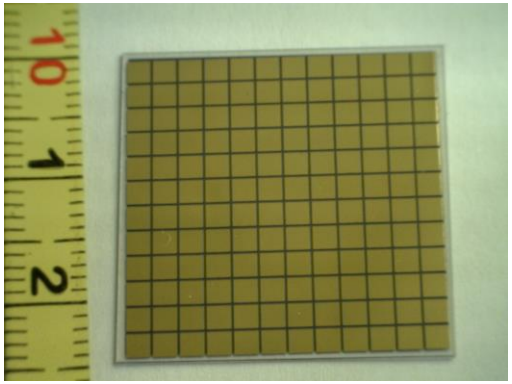
Requirement: Tissue equivalent bidimensional dosimeter for pre-treatment verifications



Multi Leaf Collimator (MLC) mounted on the linear accelerator head

- Material

- Up to three polycrystalline diamond films $2.5x2.5 cm^2$ active area each, 300μm thick;
- Premium Detector Grade Element Six, UK



- Contacts

• Schottky Barriers produced @ University of Florence as;
•12 x 12 matrix, pixel size: $1.8x1.8 mm^2$ → 288 pixels in total

- Read Out Electronics

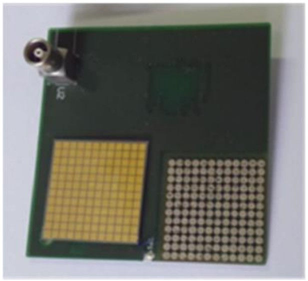
•four 64 channels 20 bit current-input analog to digital converter chips able of measuring currents from fAs to mAs; 160μs-1s integration time (50ms)
•custom printed circuit board;
•semi-rigid silver-silicone pin-contacts produced by us connecting each pixel of the 144 matrix connecting vias on PCB .

-Measurements

•Low voltage to get fast and reproducible signals;
•Device can be moved in x-y directions to cover a wider radiation field area.

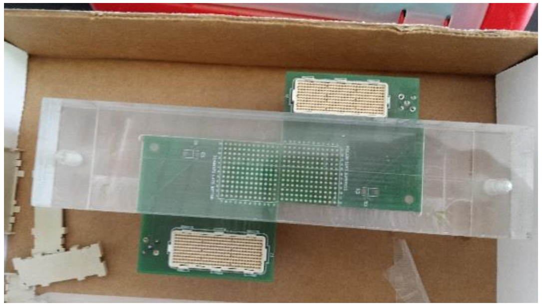
Experimental Setup

LINAC X 6MV @ Azienda Ospedaliera Careggi Firenze

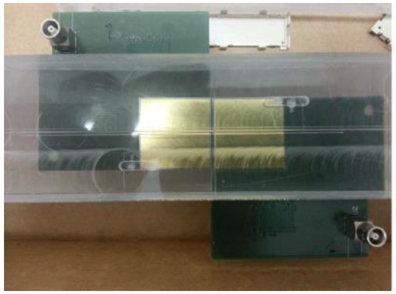


1 pCVD on PCB

Connecting pins

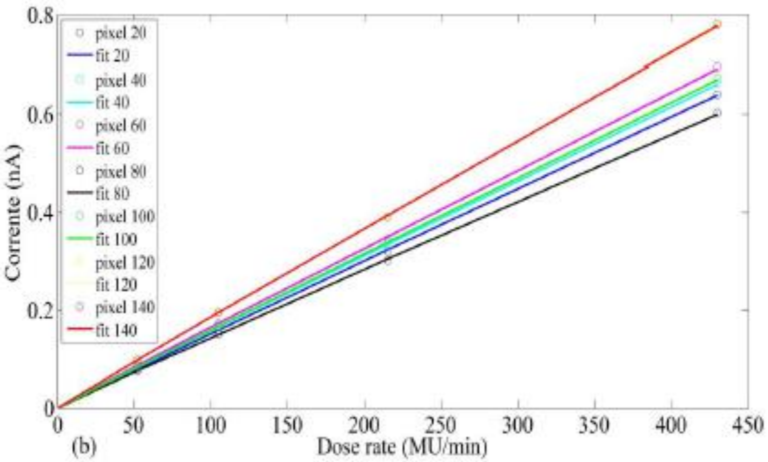


2 pCVD in PMMA /front



/rear

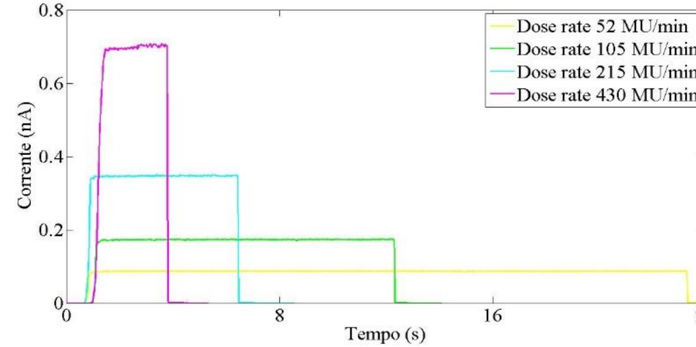
Dose rate dependency



$$I = I_{dark} + R D_r^{\Delta} \qquad (I_{dark} = 10^{-13} A)$$

$\Delta = 0.9832 \pm 0.0015$

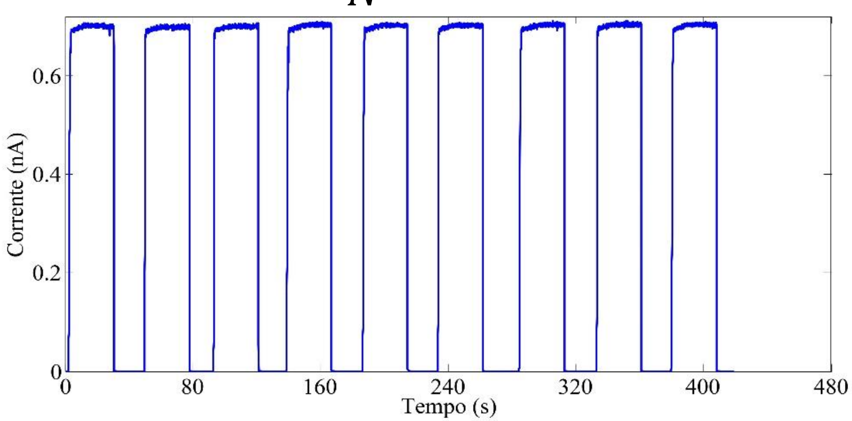
Rise and fall times



Dose rate (MU/min)	Tempo di salita (s)	σ_{salita} (s)	Tempo di discesa (s)	$\sigma_{discesa}$ (s)
52	0.56	0.01	0.1200	0.0008
105	0.44	0.02	0.1200	0.0004
215	0.400	0.01	0.0800	0.0003
430	0.56	0.01	0.0400	0.0074

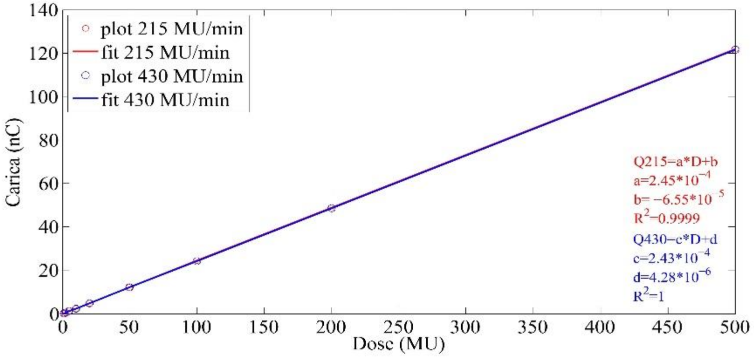
Signal repeatability

$$I_{mean} = \frac{\sum_{i=1}^{N} I_i}{N}$$



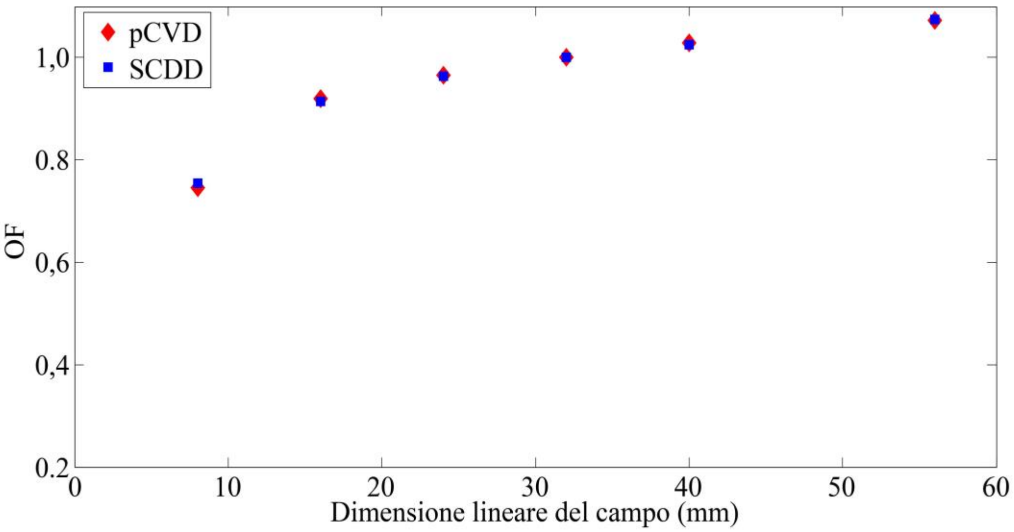
Dose rate (MU/min)	σ_n(%)	$N_{0.3}$(%)
107	0.2223	97.9
215	0.0633	99.3
430	0.2623	91.7

Linearity and sensitivity



- S= 24.022 ± 0.270 nC/Gy a 430 MU/min
- S= 24.022 ± 0.273 nC/Gy a 215 MU/min

Output factors



Field size (mm)	pCVD	SCDD	Deviation (%)
8	0.7466	0.755	1.11
16	0.9201	0.915	0.56
24	0.9658	0.963	0.29
32	1	1	0
40	1.0280	1.025	0.29
56	1.0730	1.075	0.19

Future plans

- Tests and data analysis with the 2 diamond system with IMRT/VMAT beams
- Development of the PCB electronic readout for 3 diamonds (7.5x2.5cm^2)
- Tests with the 3 diamond system

Publications & Thesis

Papers:

- M. Bruzzi, C. Civinini, M. Scaringella, D. Bonanno, M. Brianzi, M. Carpinelli, G.A.P. Cirrone, G. Cuttone, D. Lo Presti, G. Maccioni, S. Pallotta, N. Randazzo, F. Romano, V. Sipala, C. Talamonti, E. Vanzi, "Proton computed tomography images with algebraic reconstruction", Nuclear Instruments & Methods in Physics Research A (2016), http://dx.doi.org/10.1016/j. nima.2016.05.056
- C. Talamonti*, A. Baldi, M. Scaringella, E. Pace, A. Pasquini, L. Livi, S. Pallotta, M. Zani, M. Bruzzi, "Characterization of a bidimensional polycrystalline CVD diamond dosimeter with photon beams" Physica Medica , 32, Supplement 1, February 2016, Pages 65-66 http://dx.doi.org/10.1016/j.ejmp.2016.01.225
- C. Talamonti, A. Bartoli, I. Cupparo, A. Baldi , M. Scaringella, S. Pallotta, M. Bruzzi,
  Atti del Workshop: „ Tecniche speciali e avanzate di dosimetria e radioprotezione" 24 giugno 2016
  Codice ISBN 9788894124514

Conferences:

- M. Bruzzi, M. Scaringella, A. Pasquini, E. Pace, A. Baldi, C. Talamonti, "Extraction of VMAT 2D maps of dose with a large-area monolithic bidimensional dosimeter made with polycrystalline CVD diamond", International Conference on Diamond and Carbon Materials, Bad Homburg, Germany, 8 September 2015 (Oral presentation)
- C. Talamonti*, A. Baldi, M. Scaringella, M. Zani, A. Pasquini, E. Pace, L. Livi, S. Pallotta,, M. Bruzzi "Large area 2D polycrystalline CVD diamond dosimeter under intensity modulated beams" ESTRO 35- 29April-3 May 2016 Turin, Italy (Poster)

Thesis:

- "Sviluppo firmware e software di un rivelatore bidimensionale per radioterapia", A. Pasquini, tesi magistrale in Ingegneria Elettronica (Relatori: Proff. M. Bruzzi, P. Tortoli, Ing. M. Scaringella)
- " Caratterizzazione dosimetrica di un rivelatore bidimensionale a diamante policristallino", I. Cupparo, tesi triennale in Fisica (relatore: Prof.ssa C. Talamonti)