Applications of diamond devices in large area conformal radiotherapy and space experiments

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INFN Sezione di Firenze and University of Florence, Italy

Florence INFN group on dosimetry development Projects and Collaborations

INFN

- **IDDD (Italian Diamond Detector and Dosimeter)** **1996-1999**
- **CANDIDO (we CAN do a DIamond DOsimeters)** **1999-2002**
- **CONRAD (CONformal RADiotherapy)** **2003-2005**
- **DIAPIX (diamond pixel detectors development)** **2011-2013**

Collaborations within Europe

RD42 **1996-**

MAESTRO (Methods and Advanced Equipment for Simulation and Treatment in Radiotherapy) European Integrated Project - framework VI **2005-2009**

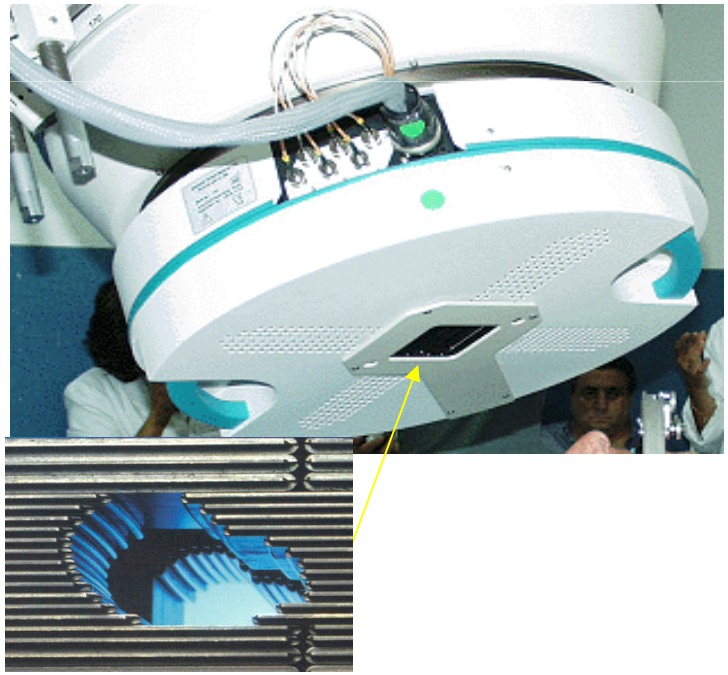
INFN DIAPIX Project WP2 Mara Bruzzi , Marta Bucciolini, Antonio de Sio, Riccardo Mori, Emanuele Pace, Monica Scaringella, Cinzia Talamonti, Lorenzo Tozzetti, Margherita Zani

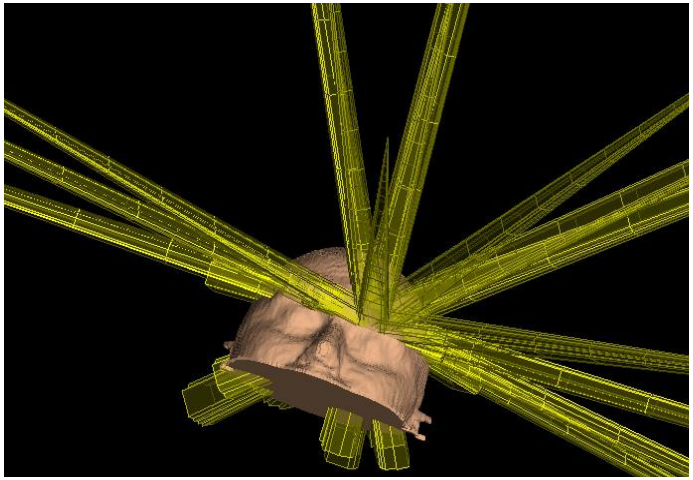
Objective

Production and IMRT characterisation of a first prototype of large area bidimensional polycrystalline diamond produced by Chemical Vapor Deposition.

Clinical Radiotherapy : Motivation

Modern Radiotherapy techniques frequently usenon standard radiation fields produced by small segments , intenstity modulated in non electronic equilibrium conditions, where detector perturbation can be very important.

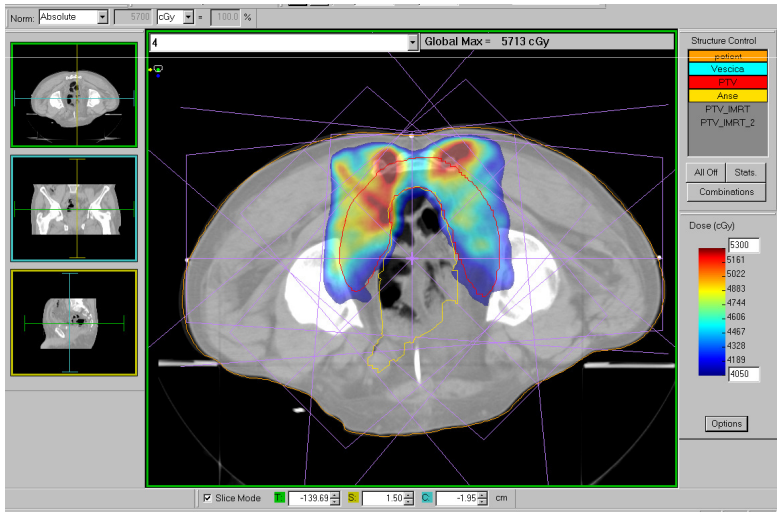




Why new 2D detectors in radiotherapy

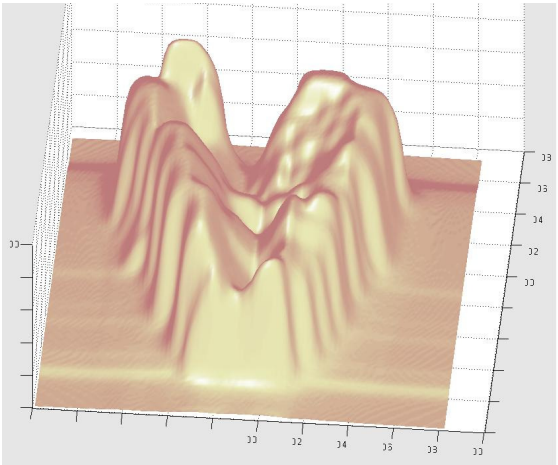
Main problems of conformal radiotherapy as Intensity Modulated RadioTherapy (IMRT), stereotactic beams, proton therapy beam due to:

- **High dose gradients;**
- **High variations of dose rate in space and time;**
- **Variation of the energy spectrum of the beam in space and time**



Body axial section

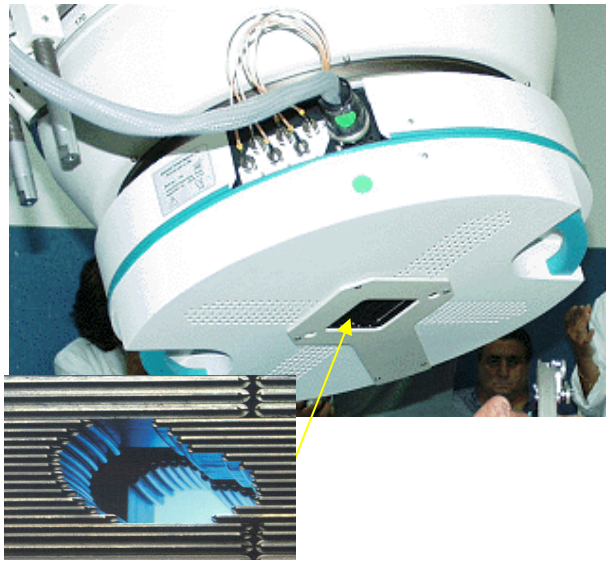
GTV = gross target volume
CTV = clinical target volume = gTV + margini
PTV planning target volume = cTV + margini



TPS IMRT for prosthate cancer

Available Radiotherapy facilites in Florence

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



Tomotherapy

Cyberknife

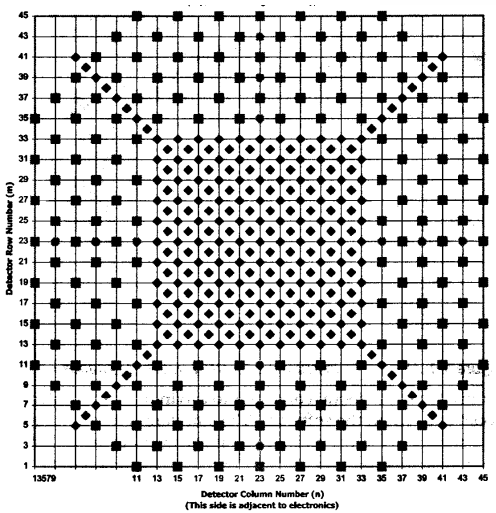
Gammaknife

University Hospital or Santa Chiara Hospital - Florence

Commercial Devices for IMRT pre-treatment dosimetric verification

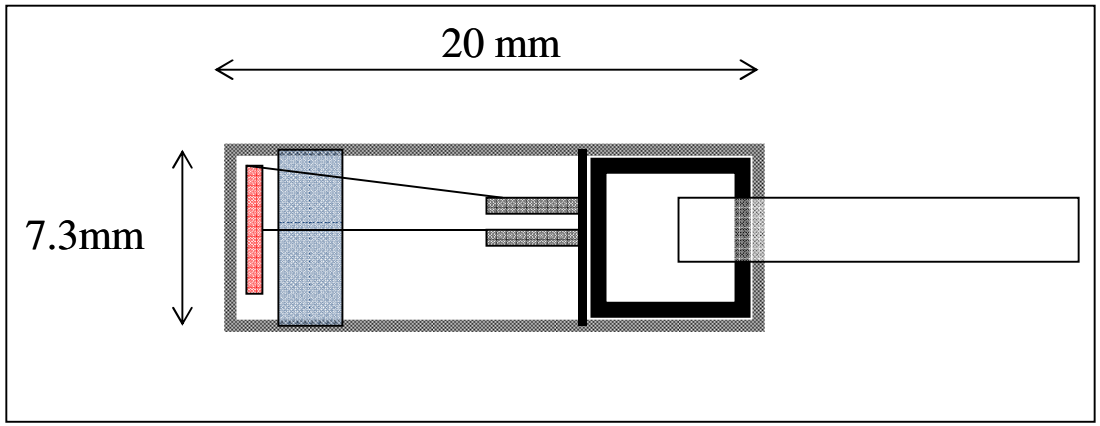
MapCHECK (Sun Nuclear Corp.) planar matrix of Si diodes

- **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



PTW natural diamond single point device

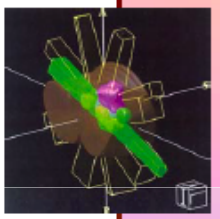
- active area: 4.3/4.5 mm^2
- active volume: 1.3/1.4 mm^3
- Thickness 0.30/0.31 mm
- Operating bias:100 V



PREVIOUS COLLABORATIONS ON DEVELOPMENT OF 2D RADIOTHERAPY DOSIMETERS: MAESTRO EU VI FRAMEWORK INTEGRATED PROJECT

MAESTRO : four main objectives

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



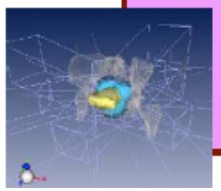
- Conformational Intensity Modulation Radiotherapy (IMRT)
- Intensity Modulation Proton Therapy (IMPT)
- Equipments for real time patient positioning and organ tracking
- Equipments to assess and control doses in vivo

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

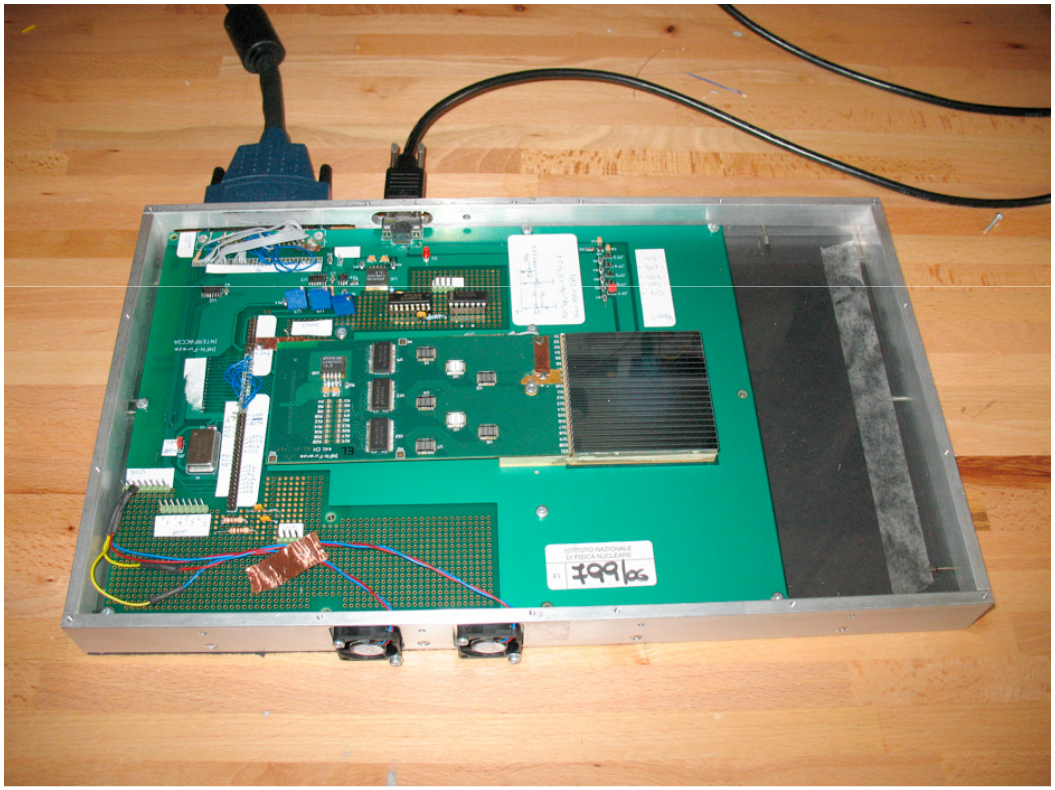


- Design and point-out new protocols for doses delivering
- Make available new procedures adapted to real time treatment control

WP3.3 Univ. Florence Team Leader M. Bruzzi

Development of a Rad-Hard Si bidimensional dosimeter for IMRT

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



Objective: to develop a device adequate for 2D pre-treatment in phantom dose verifications in conformal radiotherapy.

D. Menichelli et al., Nucl. Instr. Meth, 2007, vol. 583, 109-113.

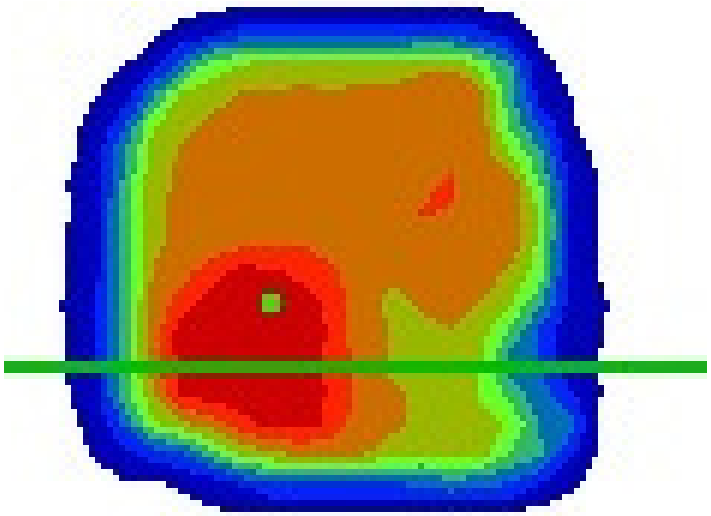
C.Talamonti et al. Nucl. Instr. Meth A, vol. 658, p. 84-89 (2011).

Patented by University of Florence, M. Bruzzi, M. Bucciolini, D. Menichelli, C. Talamonti *(FI2006A000166)*

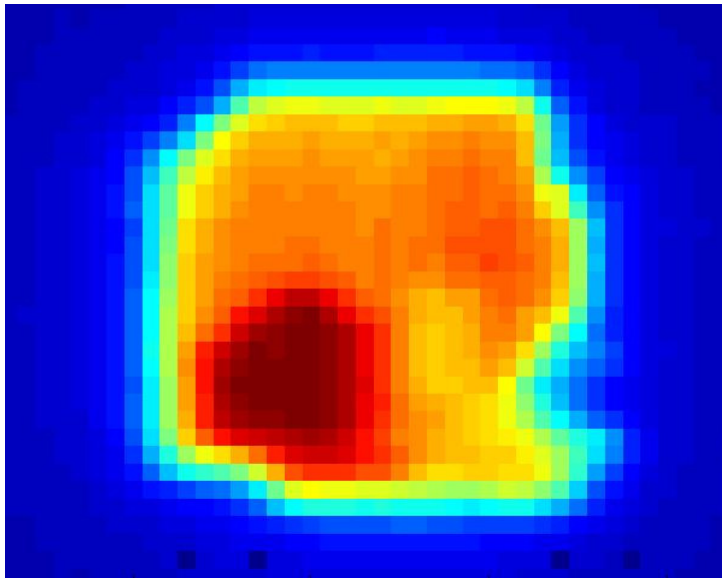
first large area 2D map of dose

Map of dose (head) in 19x12 cm^2 IMRT field shows very good agreement with TPS

TPS



Our 2D Si device



M. Bruzzi et al., IEEE NSS MIC Symposium Conference Record, 2012.
C. Talamonti et al. Presented at RESMDD12, October 2012, submitted to NIMA A.

♠ **BUT … Silicon no water equivalent**

Advantages of Diamond for clinical radiotherapy

- diamond 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 density → high sensitivity → small dimensions
- non toxic
- Diamond has a reputation for being radiation hard.

♠ BUT… in diamond, radiation induced defects play a crucial role, as in silicon. High defect density give rise to priming effects, polarization and in general instability of the signal.

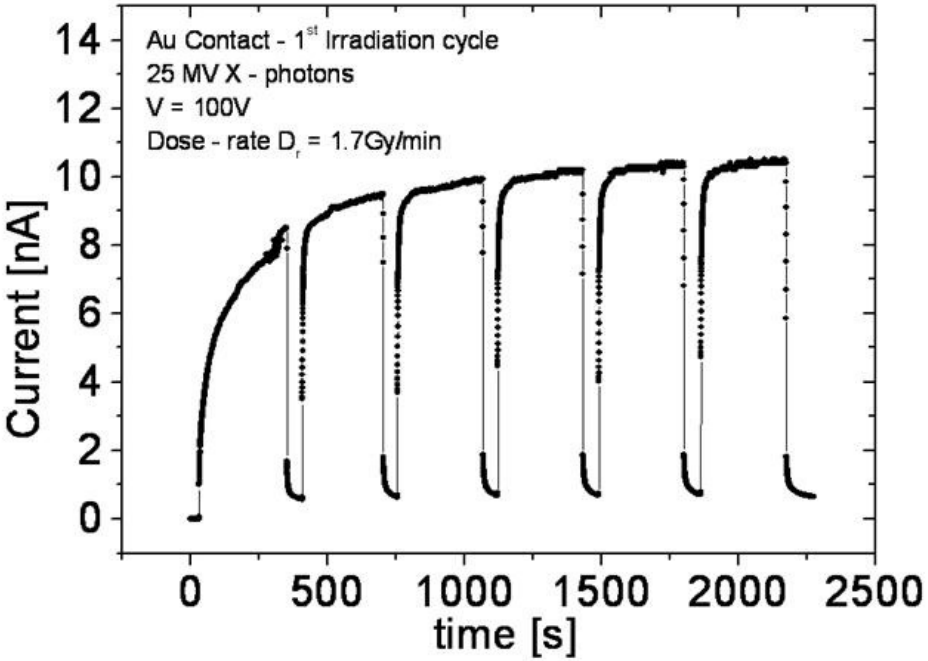
Strategies must be assessed.

→ work with single crystal diamond BUT small area, high prices

OUR WORK → polycrystalline diamond for keeping large area devices at reasonable costs BUT develop specific strategies to minimize unwanted effects from defects

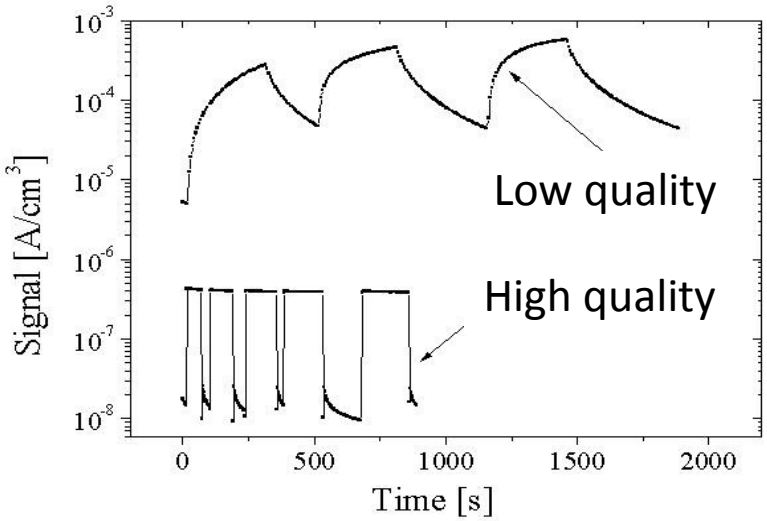
Previous knowledge on defects affecting dosimetric properties

Priming due to defect passivation



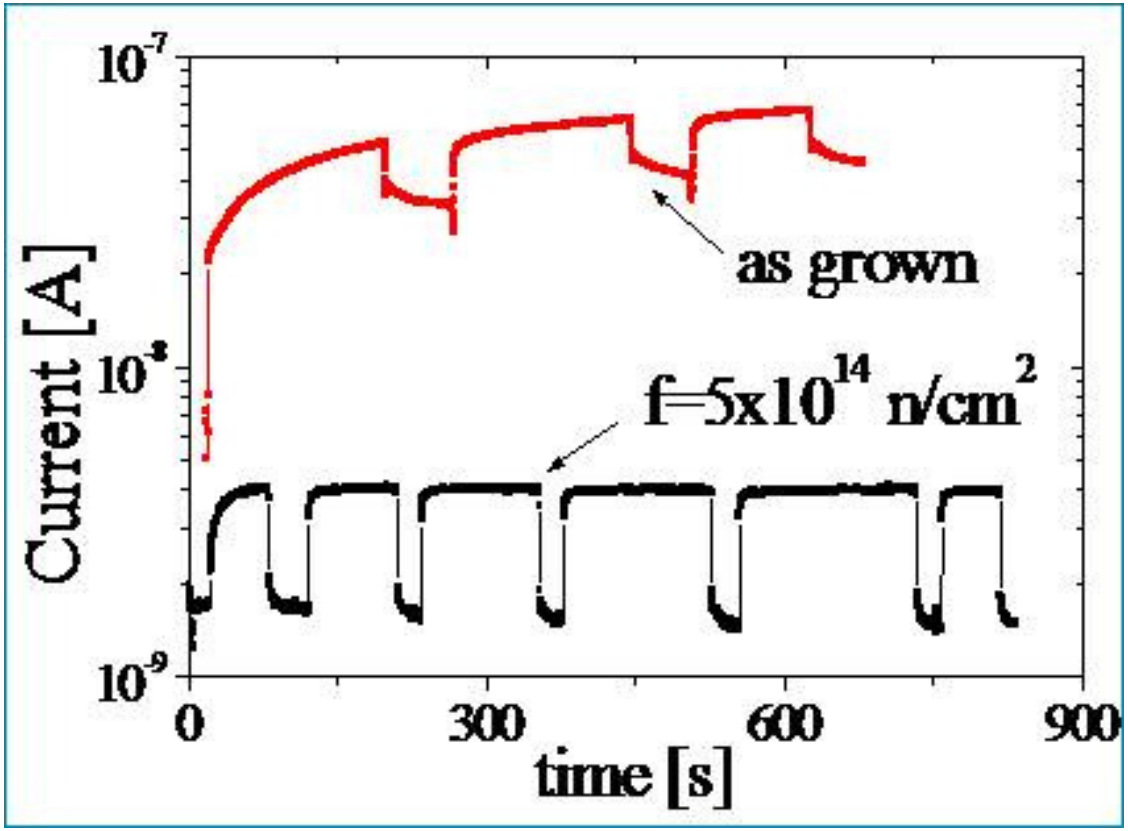
Current response of the unirradiated sample (Au contact) showing the priming effect during the first 6 successive irradiations.

Morphologic quality influences sensitivity, dynamics and reproducibility



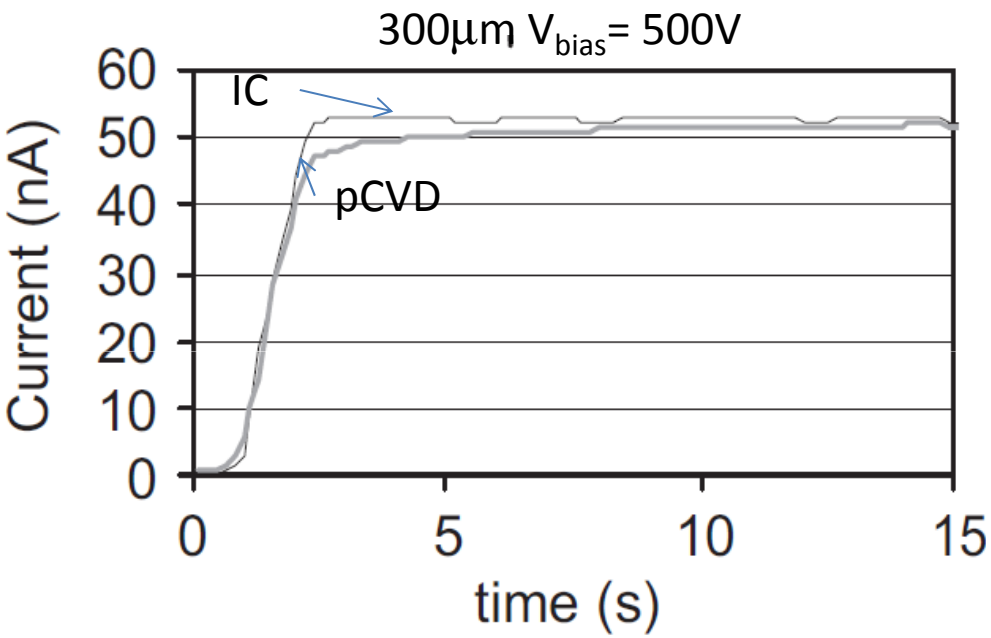
pCVD diamond CVD under a Co^{60} γ- (0.2Gy/min)

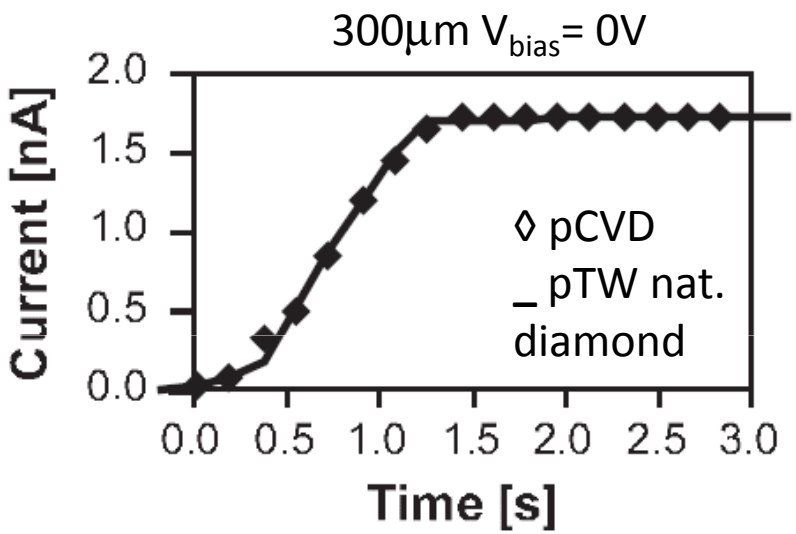
Effect of neutron irradiation on native electrically active defects in pCVD Diamond: **decrease of TSC peaks due to deactivation of high temperature defects** **(see talk of R. Mori).** Defect Removal brings to better dynamics after neutron irradiation, good for conventional radiotherapy



M. Bruzzi et al., Appl. Phys. Lett, (2002)

BUT .. pCVD in conventional operation (E = 1V/μm) has still too slow dynamics for IMRT application .
Our solution: reduce to null / small bias to decrease polarization effects (Schottky contacts) . Signal reduced but faster dynamics!



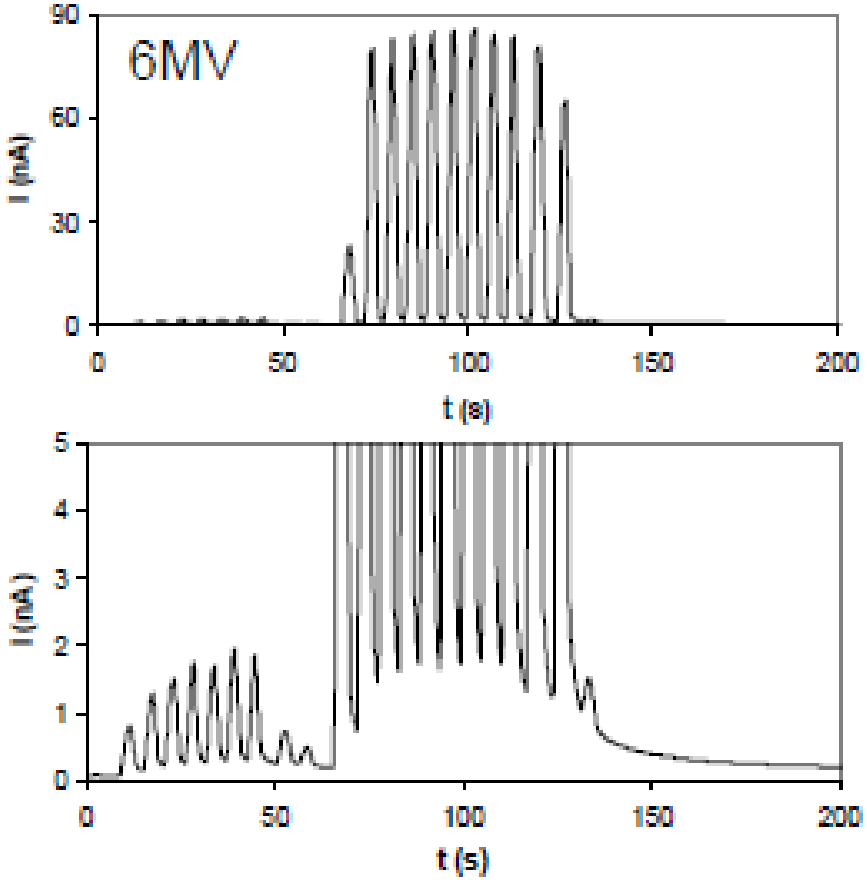


C. De Angelis et al., Present limitations of CVD diamond detectors for IMRT applications NIMA 2007, A 583 (2007) 195–203.

M. Bruzzi et al., Zero-bias operation of polycrystalline chemically vapour deposited diamond films for Intensity Modulated Radiation Therapy, Diamond & Related Materials 20 (2011) 84–92

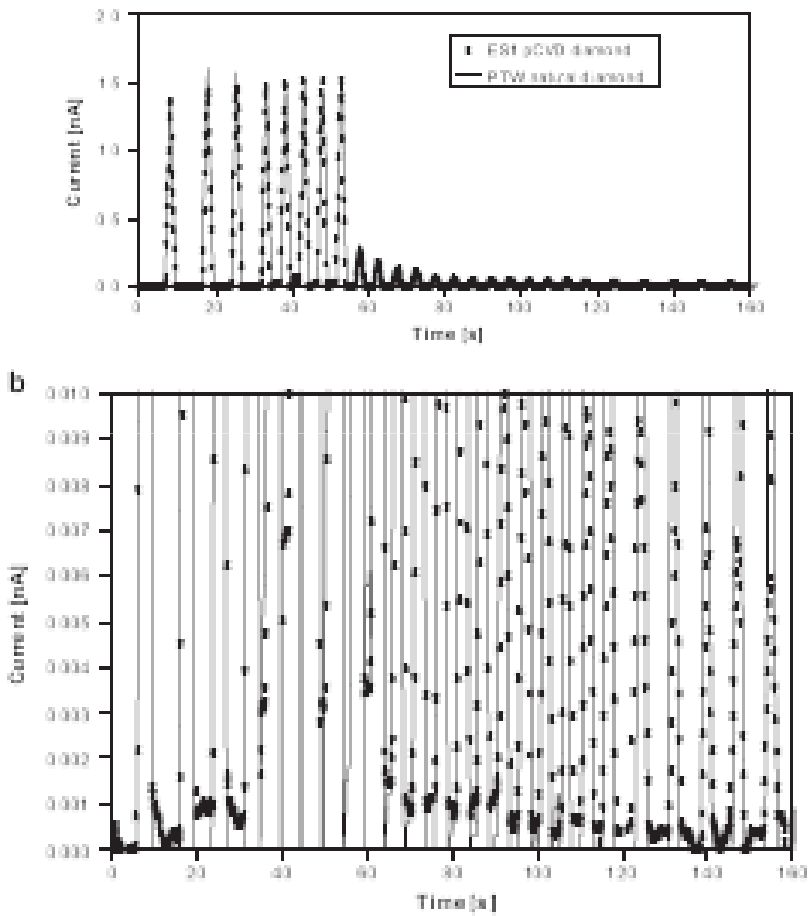
Much faster dosimeter when in null bias → more precise dose measurement

pCVD diamond – 300µm V_{bias}= 500V



C. De Angelis et al. NIMA 2007, A 583 (2007) 195–203.

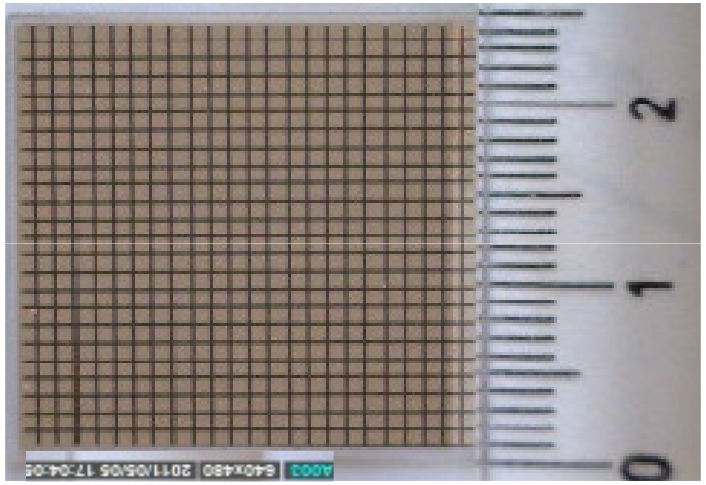
pCVD diamond – 300µm V_{bias}= 0V



M. Bruzzi et al., Diamond & Related Materials 20 (2011) 84–92

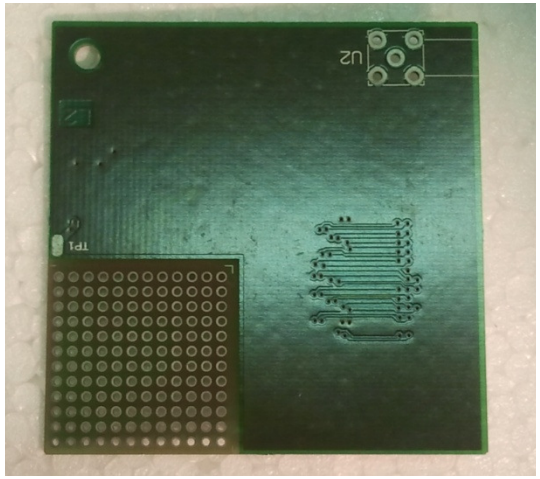
First large area 2D dosimeter prototypes with synthetic Diamond

Premium Detector Grade (Diamond Detectors Ltd) polycrystalline diamond, area 2.5cmx2.5cm, thickness = 300μm. 2D matrix of pixels produced in Florence, XUV lab with Cr/Au evaporation.



24x24 matrix,
pixel area 0.8x0.8mm^2

M. Bruzzi et al. JINST 2012



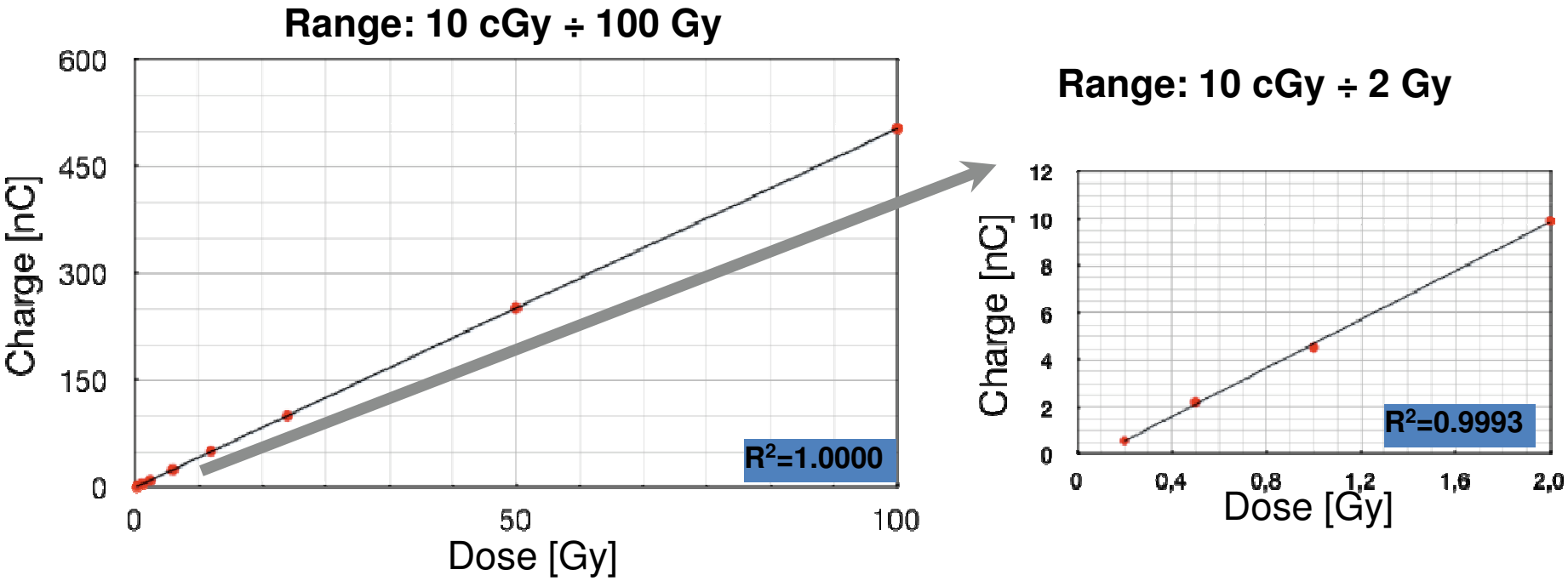
DIAPIX custom- made PCB to connect matrix

M. Zani et al. RESMDD12, October 2012 submitted to NIM A

Modular device made of a mosaic of up to four 2D pCVD diamond dosimeters in view to cover an area up to 5x5cm^2.

CHARACTERIZATION UNDER PROTON BEAMS:

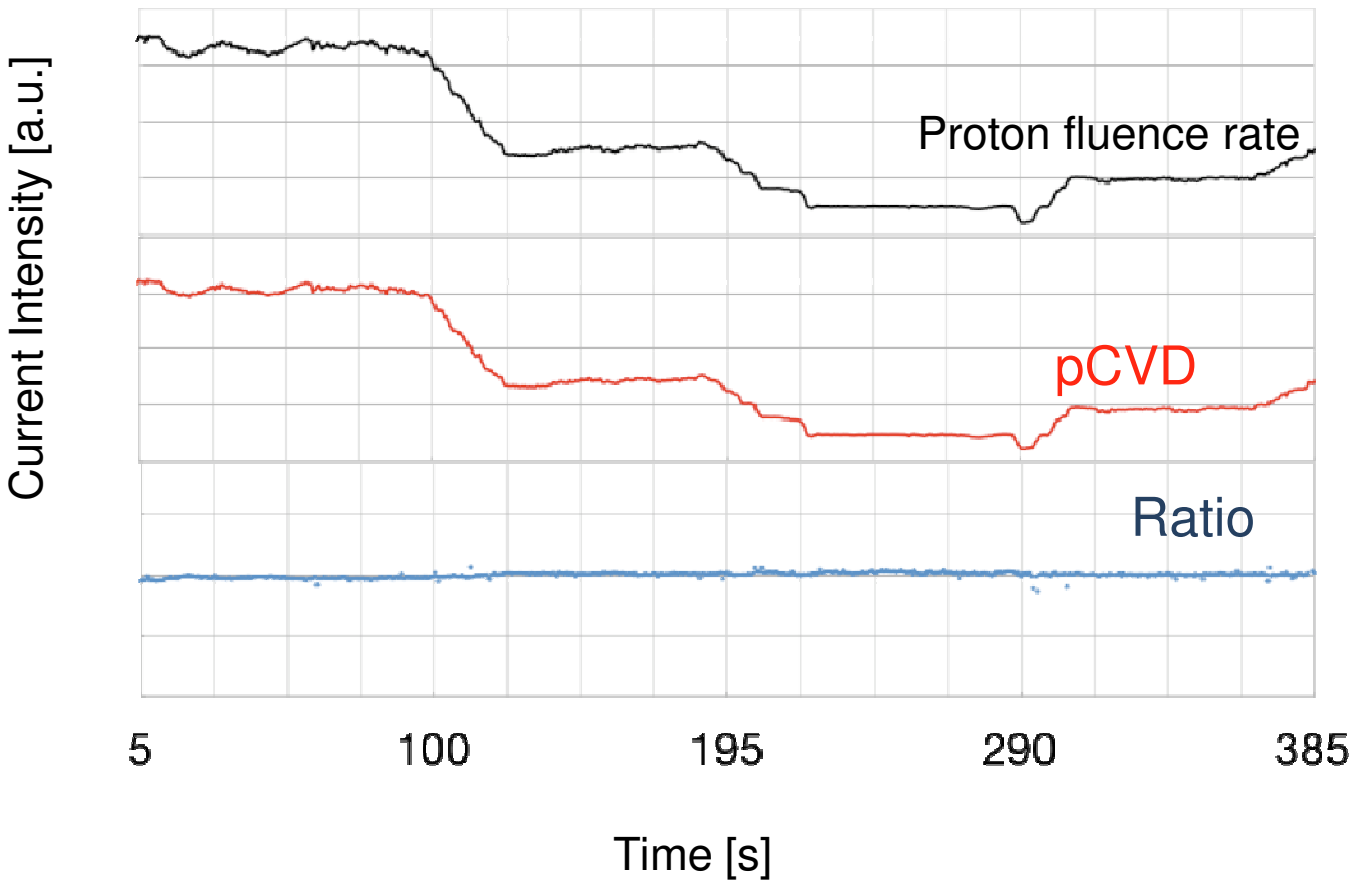
A chacterization of the detector under a clinical proton beam (62 MeV) has been performed at Laboratoni Nazionali del Sud (LNS), Catania. Very good linearity of the response of each pad with dose, even at very low doses.



M. Zani et al. RESMDD12 , submitted to NIM A

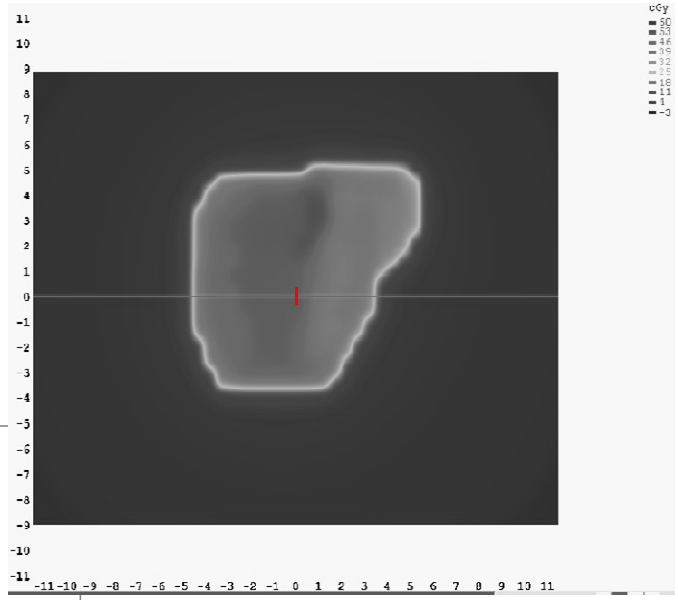
62MeV proton beam: Dose Rate dependence

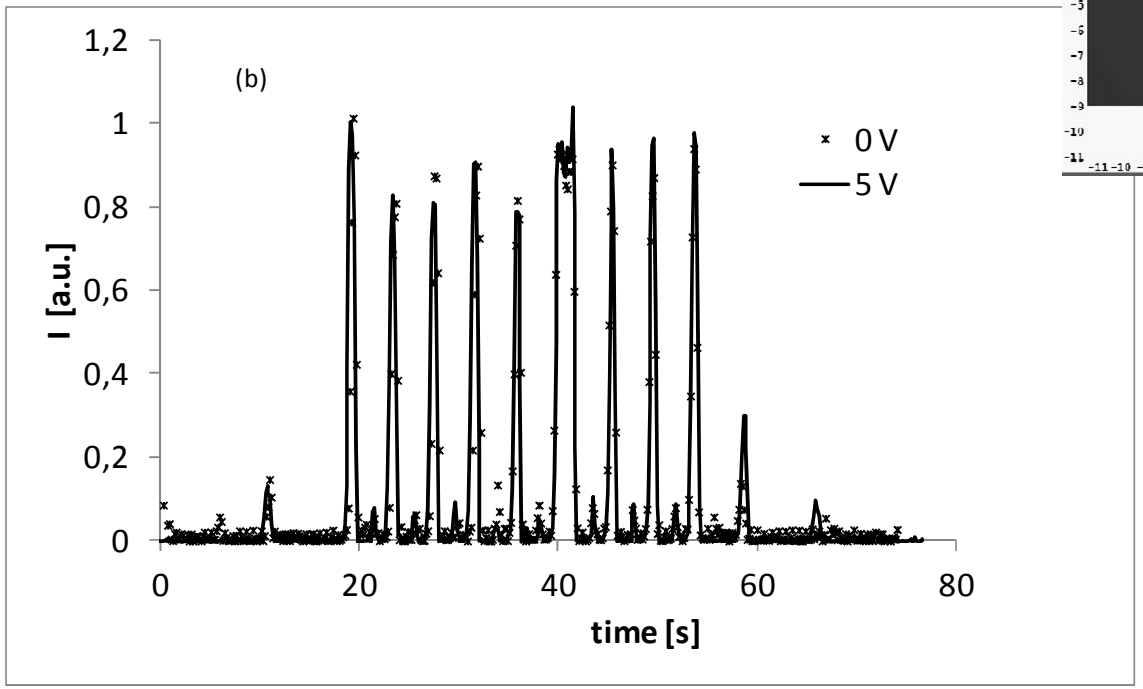
The proton fluence rate has been measured with a reference diode; four different dose rates were investigated. Very good response in real-time operation.



M. Zani et al., presented at RESMDD12 , submitted to NIM A

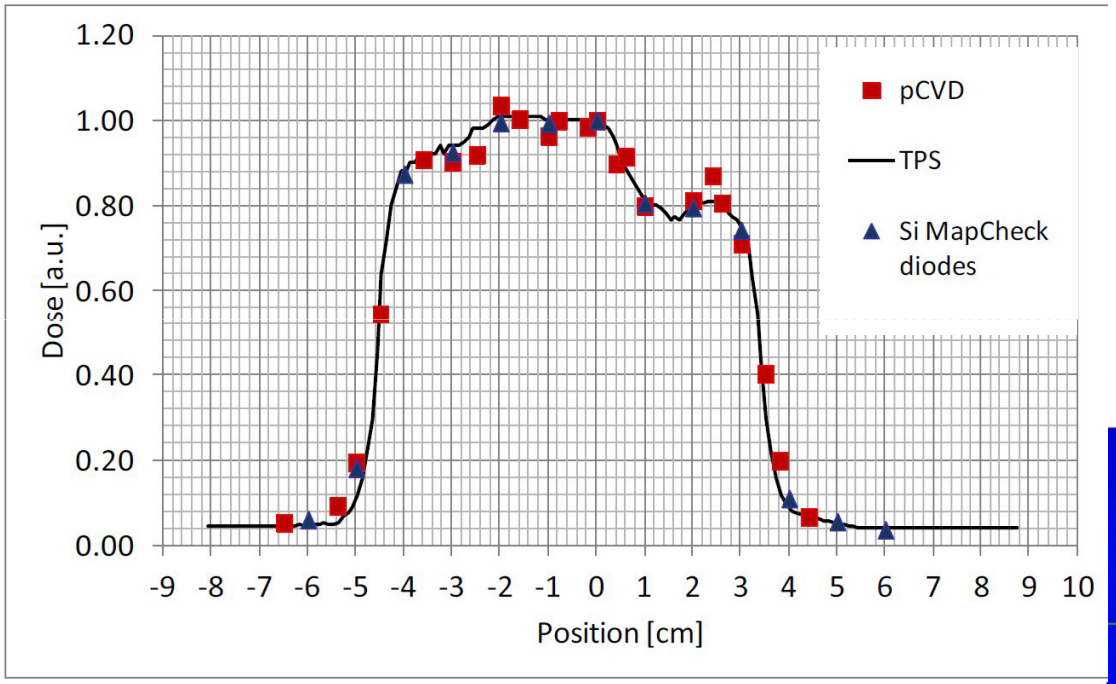
With applied null to small voltages pCVD diamond proved to follow delivery of dose deposited in several segments during an IMRT allowing for a precise dose evaluation in high conformal fields. Possibility of real-time measurements.

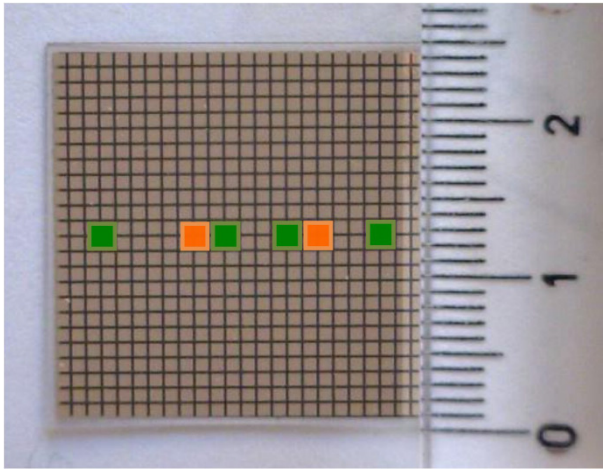


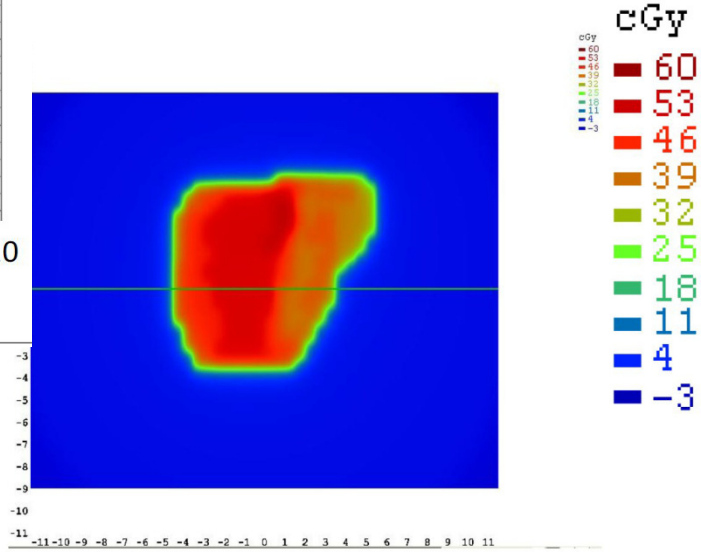


Talamonti et al. Polycrystalline CVD diamond for conformal RT, proceedings of Science, 2012

First profile of large area IMRT field by means of a pCVD diamond with pixel matrix







M. Bruzzi et al., IMRT field profiling by high-quality polycrystalline CVD diamond, 2012 JINST 7 P08003

Diamond dosimeters
Applications to radiobiology and space environments

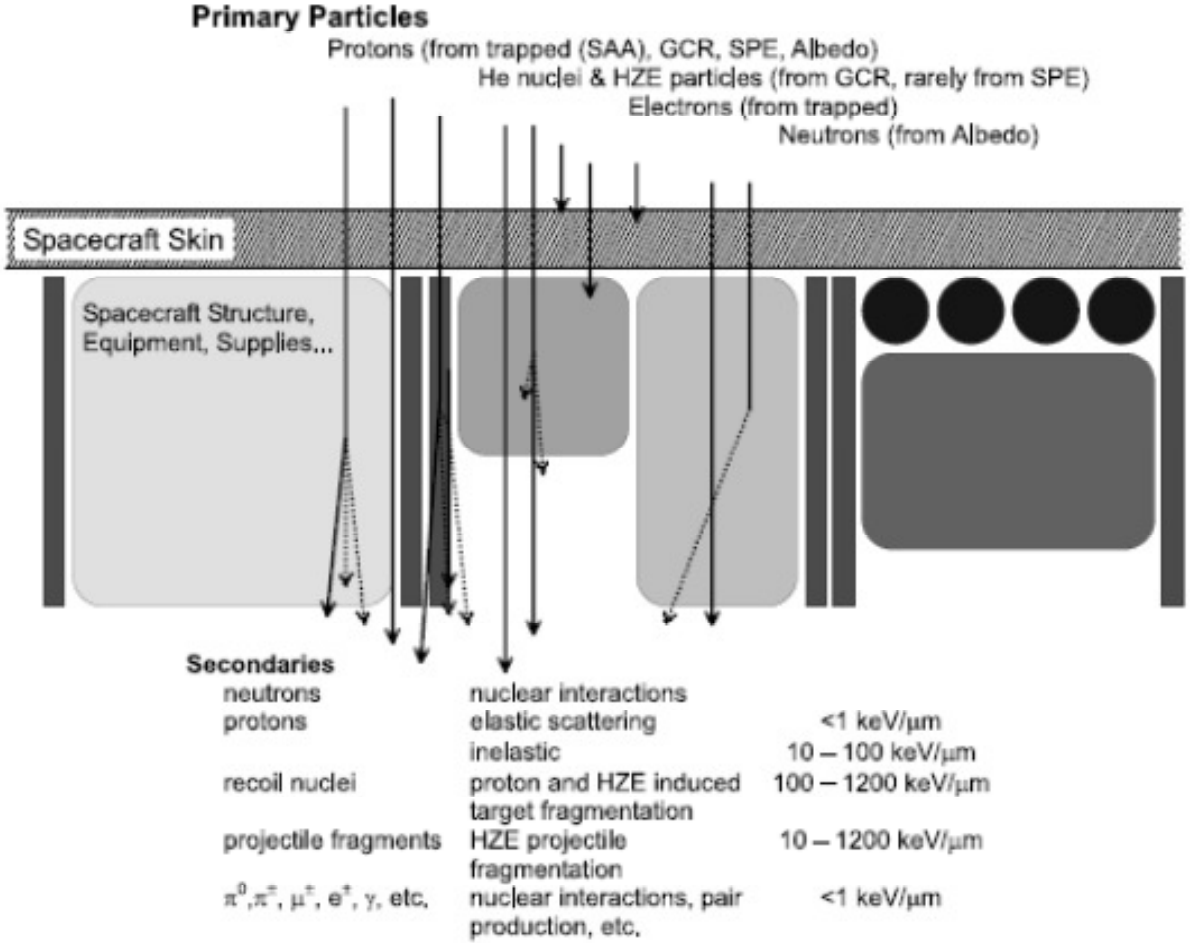
E. Pace, M. Casarosa, E. Gallori, A. De Sio, L. Tozzetti, S. Branciamore, M. Bruzzi, M.Bucciolini , M. Scaringella

University of Florence, Italy

Introduction

Human exploration and studies on the origin of life requires understanding of the global effects of radiation environments on biological materials.

high energy high-Z particle and neutron irradiation in space are the most dangerous for space missions.



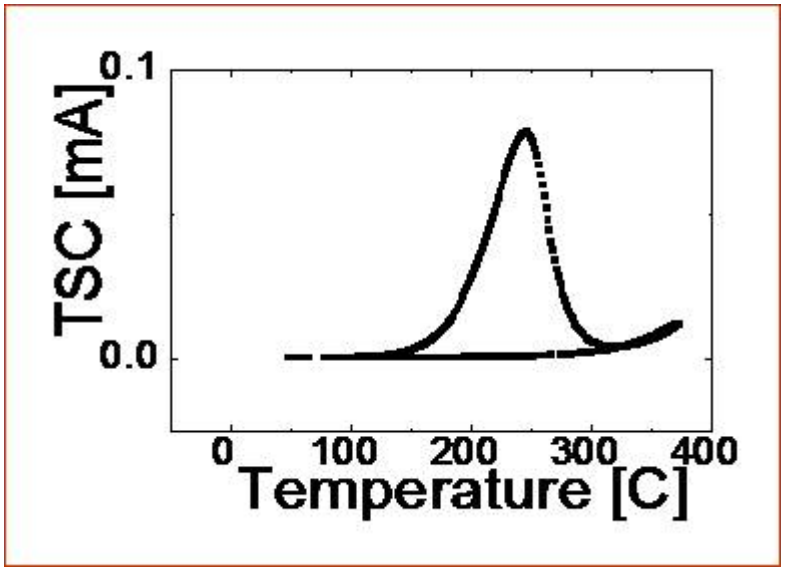
Space Shuttle

Average ~ 0.1 mGy/day

Diamond can act as passive as well active dosimeter

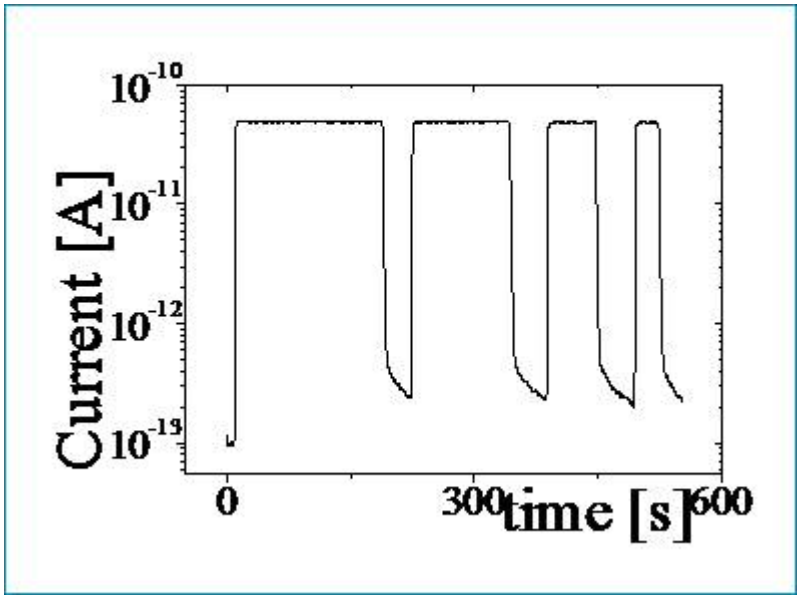
Off-line

Thermoluminescence (TL) or
Thermally Stimulated Current (TSC)
measured after irradiation



On-line

Current response measured
during irradiation



Passive dosimeters option: no electronics, very compact, lightweight

Early 2007: proposal to the Italian Space Agency → DIASPACE

- **First attempt to assess diamond dosimeters in a LEO space mission**
- **Development and use of dosimeters based on synthetic diamond**
- **Viable solution to the key issue of human crew safety in space missions and in future Moon and Mars bases**
- **Opportunity: the GENESIS-LIFE mission on board of the FOTON M3 satellite**

GENESIS-LIFE Italian mission

- The dosimeters have been tested during the GENESIS-LIFE space
- mission on board the Russian FOTON M3 orbited 12 days at about
- 300 Km.
- 8 Italian experiments located inside two BIOKON, a standard space qualified aluminum box
- Technological assessment of several dosimeters in space

our aim: **Study of offline diamond based dosimeters for space applications**

GENESIS-LIFE Italian mission

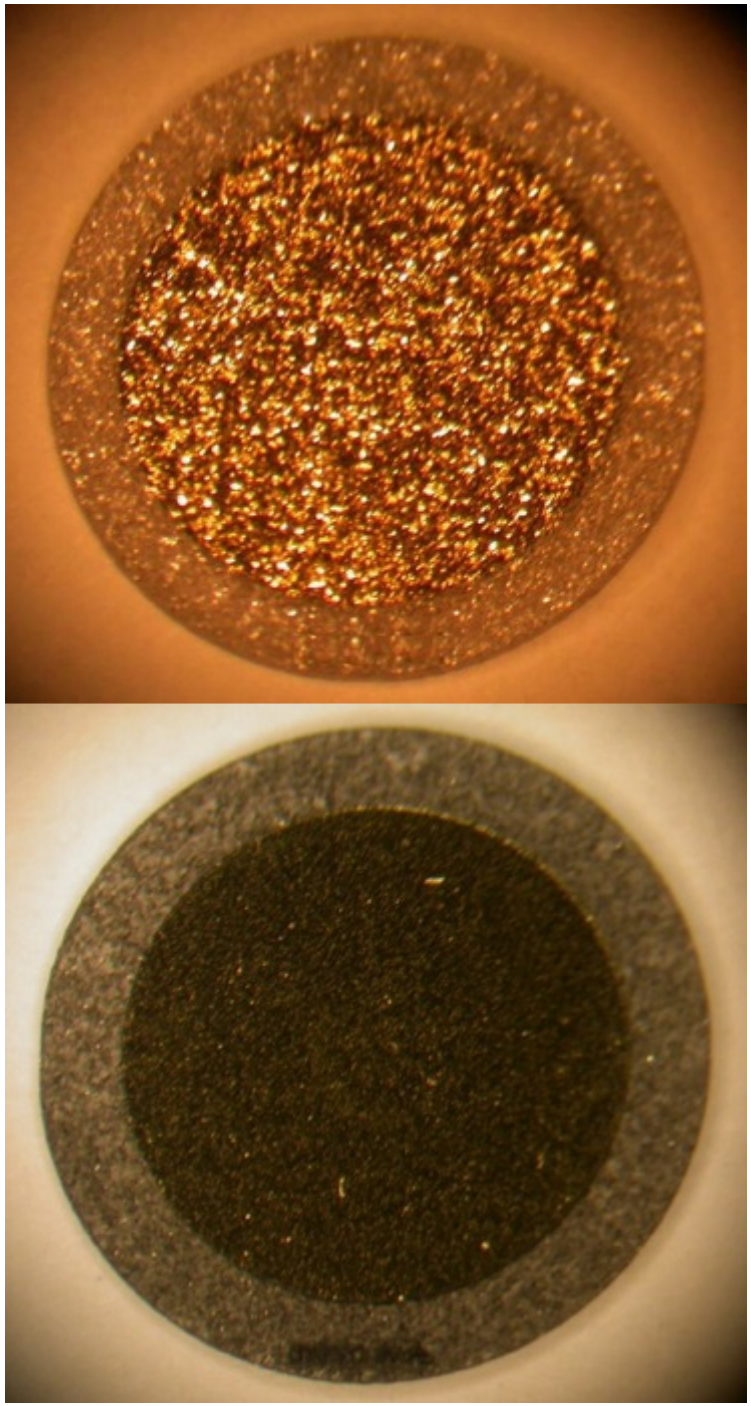
Dosimeters

3 CVD polycrystalline films (IAF)

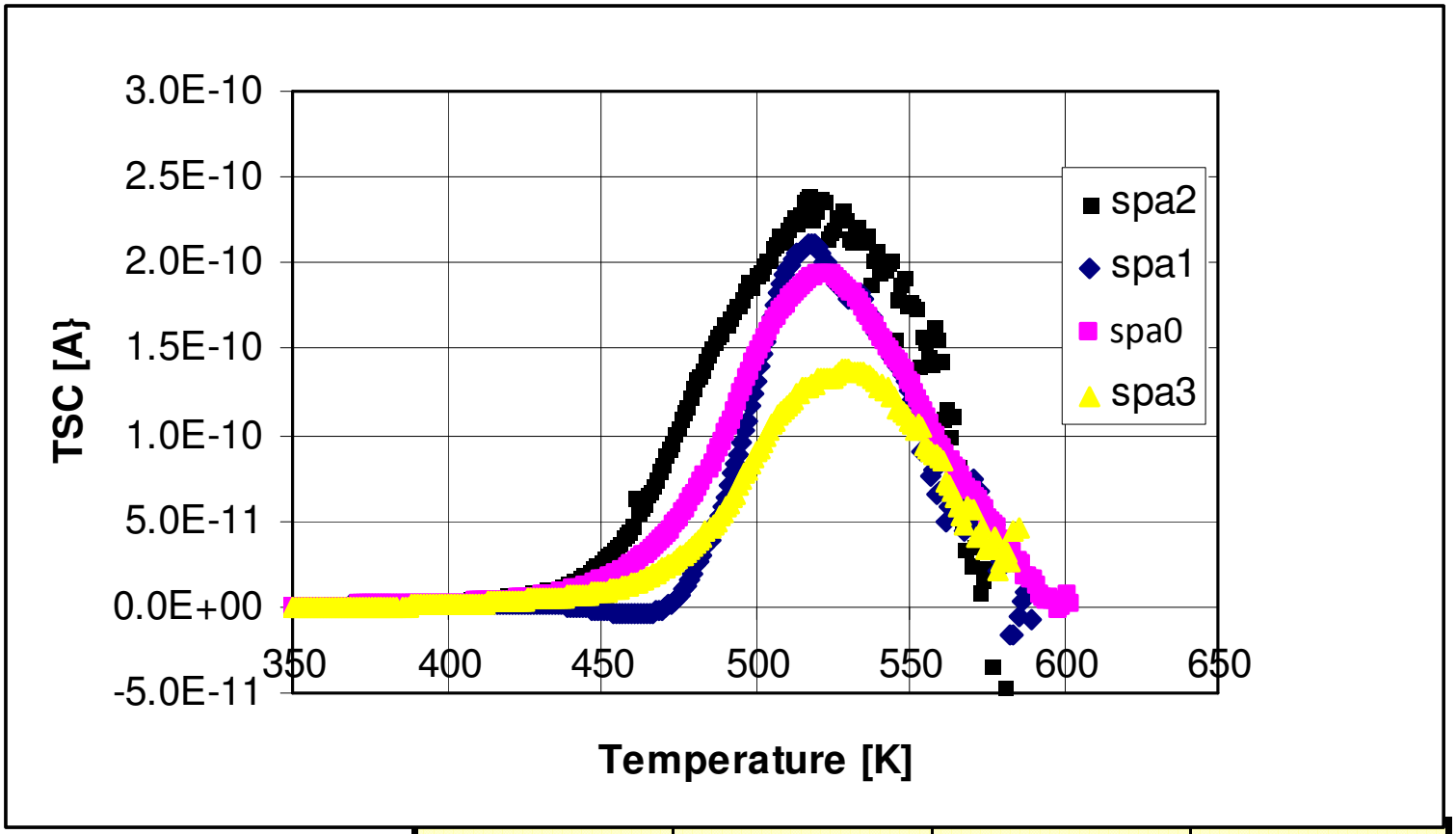
- 8 mm diameter
- 350 μm thick (from a 400 μm thick sample)
- 7 mm Cr/Au contacts

1 CVD polycrystalline film (commercial)

- 5x5 mm^2
- 300 μm thick
- 3 mm Cr/Au contacts



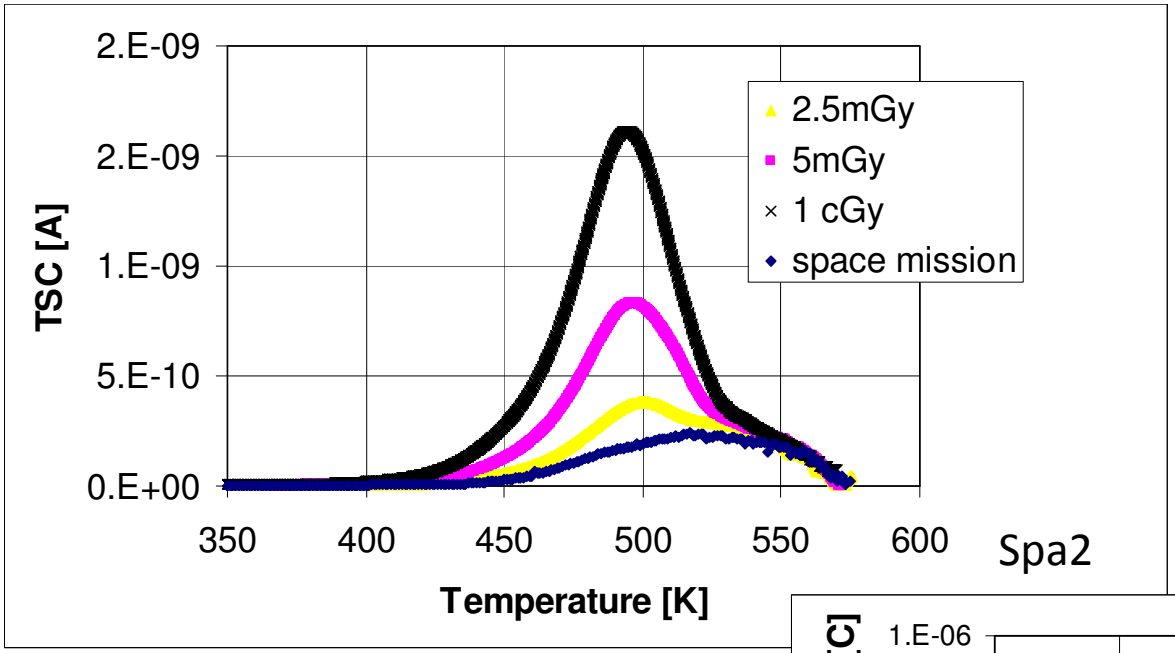
Post-flight meas



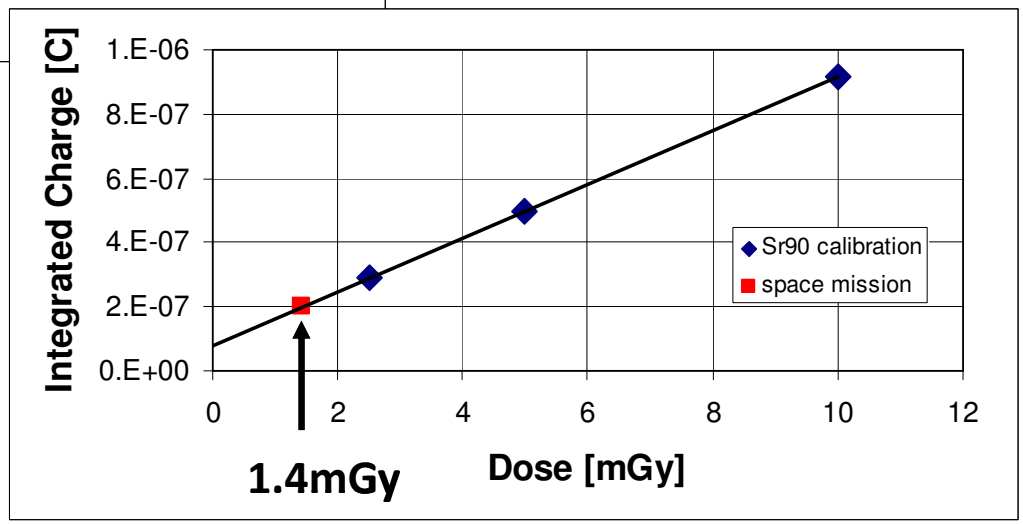
	spa0	spa1	spa2	spa3
Integrated charge [C]	1.6E-7	1.3E-7	2.0E-7	1.1E-7

A. De Sio et al. Diamond-based off-line dosimeters for environmental control in space flights, NIM A 612, Issue 3, 11 January 2010, Pages 583-587

Comparison between post-mission peak and β irradiation peaks



Dose evaluation



A. De Sio et al., NIM A 612, Issue 3, 11 January 2010, Pages 583-587

BIOKIS

Multiexperimental facility

7 experiments in the area of cellular biology, effects of radiation and radioprotection, ageing, germination and plant growth.

- BioS-SPORE
- PHOTO-EVOLUTION
- HiDOSE: Heavy Ions DOSimetry Experiment
- TARDIKISS: Tardigrades in Space
- **3DISS: DNA on Diamond Dosimeters onboard ISS**
- nDOSE: neutrons DOSimetry Experiment
- Arabidops-ISS

3DISS
Targets

To measure the radiation dose by using an innovative device based on a tissue equivalent substrate.

To measure the total radiation damage induced by the radiation environment on genetic material.

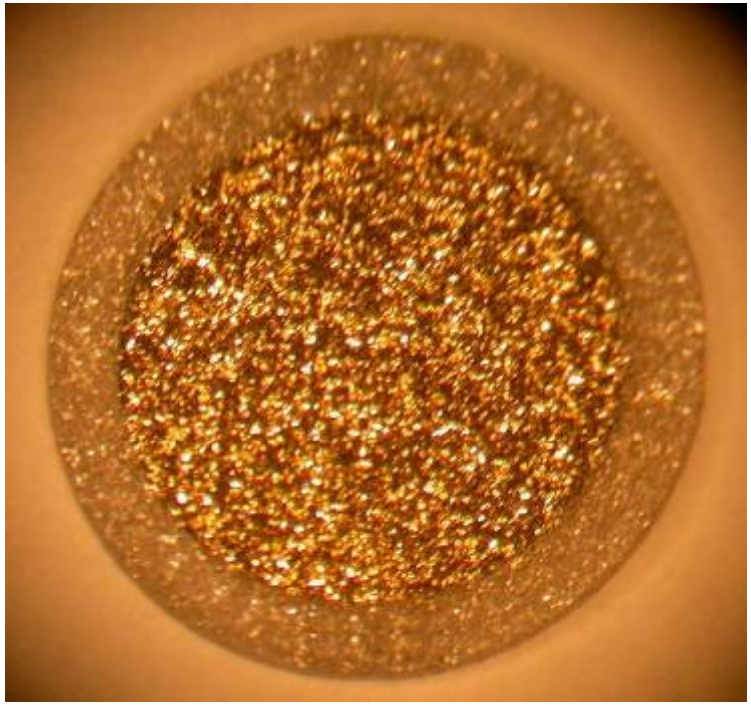
To correlate the 3DISS results with the radiation environment measured by other experiments.

To correlate dosimetric measurement with type and amount of the total radiation damage.

3DISS
Nucleic acids

- Simultaneous local measurement of radiation dose and damage on biological materials.
- The biological material will be removed by the dosimetric device before reading out dose information, in order to avoid degradation of the genetic material due to the thermal cycles. Irradiated NA will be stored in sealed protective containers to be later analysed to correlate the suffered damage.

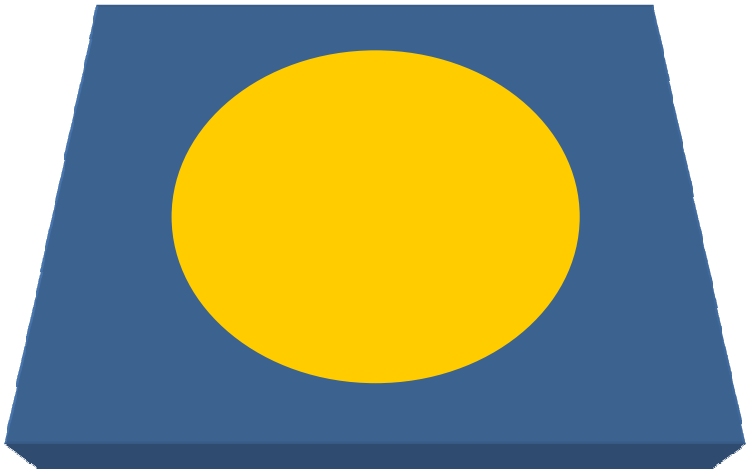
3DISS
Experiment



3 diamond dosimeters

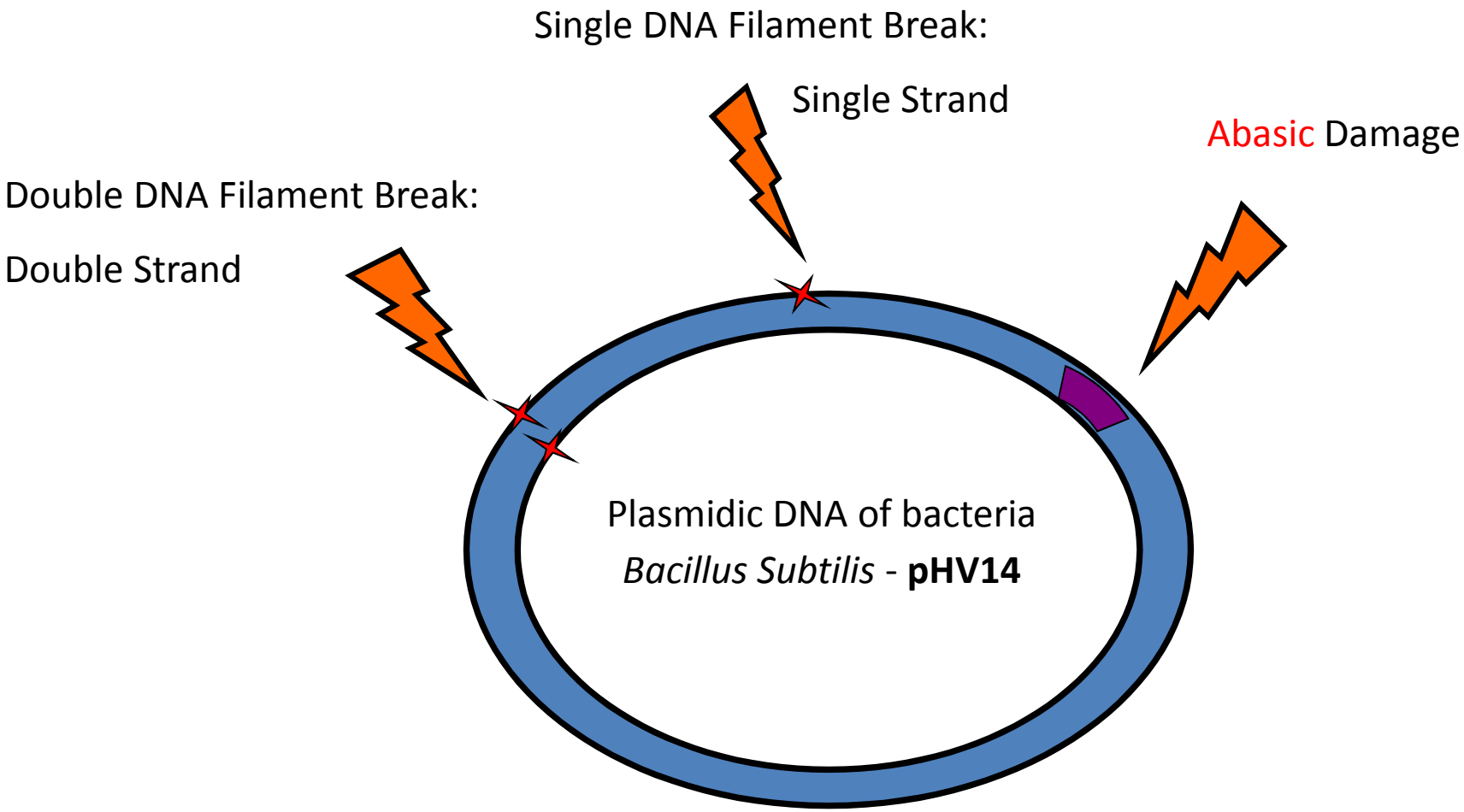
17 NA samples

4 dosimeters + NA



Analysis

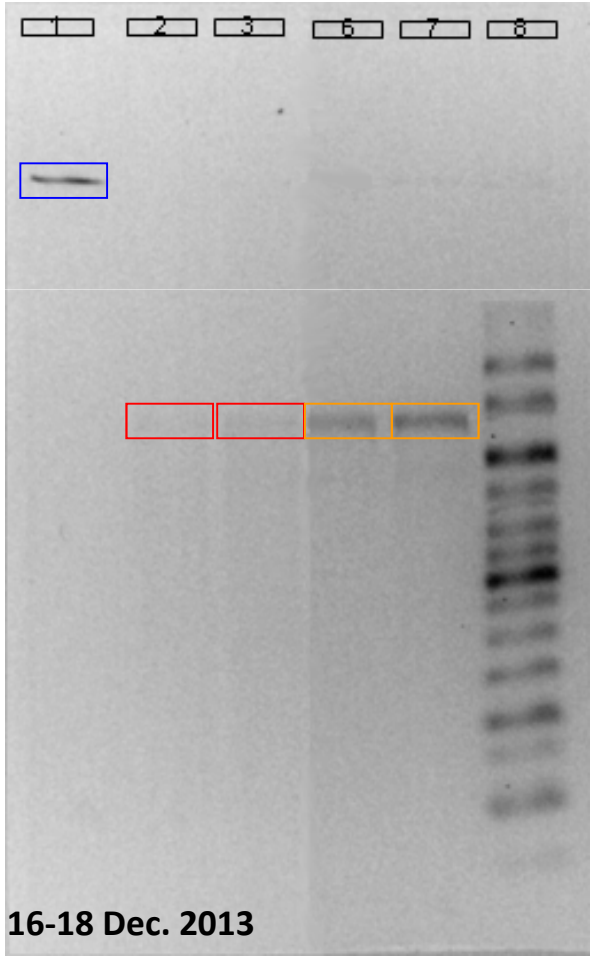
DNA damage types



Analysis
Single strand break

Measured total dose 5.2 mGy

1. **On Ground DNA pHV14 not denatured**
2. **DNA pHV14 on Diamond substrate denatured**
3. **DNA pHV14 on Diamond substrate denatured**
6. **On Ground Control DNA pHV14 denatured**
7. **On Ground Control DNA pHV14 denatured**
8. **Ladder denatured**

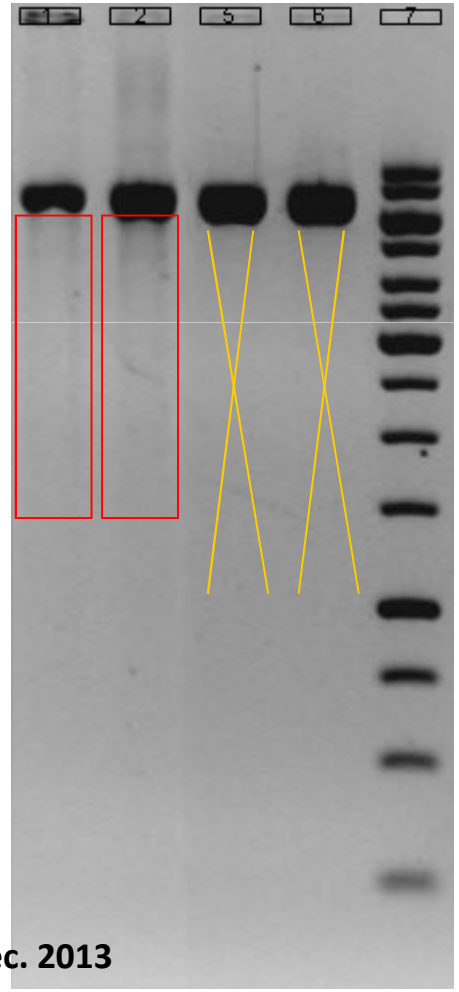


Lower intensity of the band corresponding to the intact strand in the exposed DNA with respect to the control

EVIDENCE OF SINGLE STRAND BREAK DURING THE FLIGHT

Analysis
Double strand break

Measured total dose 5.2 mGy



1. **DNA pHV14 Flight on Diamond substrate**
2. **DNA pHV14 Flight on Diamond substrate**
5. **On Ground Control DNA pHV14**
6. **On Ground Control DNA pHV14**
7. **Ladder**

EVIDENCE OF DOUBLE STRAND BREAKES DURING THE FLIGHT

Conclusions

1) Diamond offer the opportunity to build dosimeters almost with no energy dependence with respect to water, so it is ideal for radiotherapy issues;
2) At the moment, only dosimeters based on natural diamond are commercially available for clinical use but as small single point devices;
3) Development of performant devices has been up to now technologically difficult and expensive; availability of a reliable, reproducible and not too expensive technology would determine a huge expansion of diamond in radiotherapy;
4) Single crystal CVD dosimeters works very well but for large-area applications as in IMRT pCVD material is best choice;
5) Operation with null/small bias allows improves stability and speed of response getting pCVD applicable also in IMRT fields;
6) First 2D pixel matrix prototypes on pCVD diamond have been produced by us and characterised under IMRT beams with very promising results.
7) Diamond can be used in real-time as well as in off-line modality. This latter application has been applied by us in recent space missions with promising results.