Nuclear Physics Mid Term Plan in Italy

LNF – Session

Frascati, December 1st - 2nd 2022

Dosimetry, quality assurance and radiotherapy

Giada Petringa

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Istituto Nazionale di Fisica Nucleare
Catania, Italy

Outline

1. Flash Radiotherapy:
    a. FRIDA project
    b. Unbalance Core Dosimeter

2. Microdosimetry:
    a. Diamond detectors
    b. Gas detectors (TEPC)

3. New devices for dosimetric purposes:
    a. Silicon Carbide for dosimetric and microdosimetric applications
    b. Synthetic diamond with 3D electrodes
    c. Hydrogenated Amorphous Silicon Devices

Flash radiotherapy

Contributions

- **Alessio Sarti (spokesperson for the FRIDA collaboration)**
  Università di Roma Sapienza
  Istituto Nazionale di Fisica Nucleare – Sezione di Roma 1

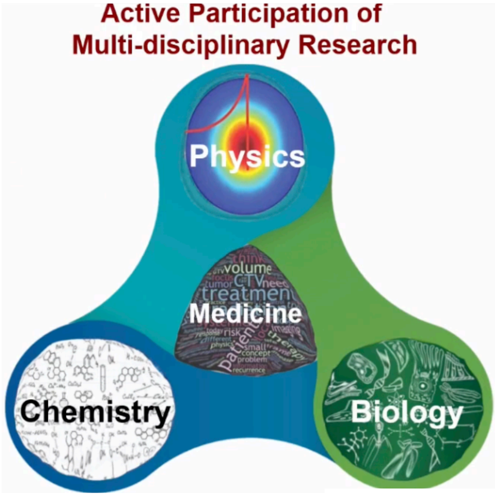
FRIDA project

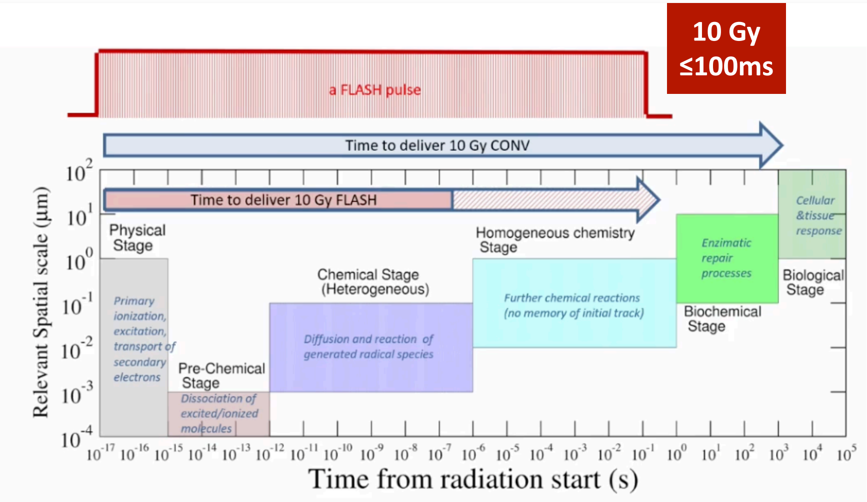
- **Roberto Bedogni (spokesperson for the LEMRAP collaboration)**
  Istituto Nazionale di Fisica Nucleare – Laboratori Nazionali di Frascati

Unbalanced core dosimeter

State of the art: FLASH particle therapy

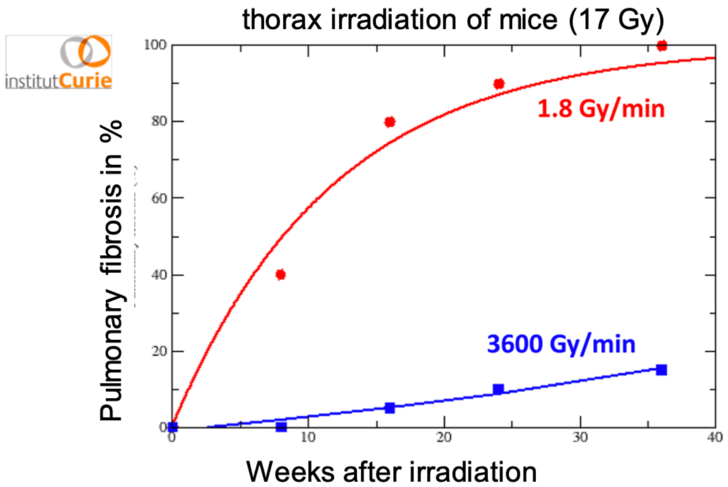
A promising new radiotherapy strategy to limit the toxicities and maintain the tumour control





Weber, Scifoni, Durante Med Phys 2021 acc.

FLASH Factors:
- Dose
- Dose Rate
- LET?
- Tissue oxygen level
- Repair kinetics
- Biological endpoint
- ???

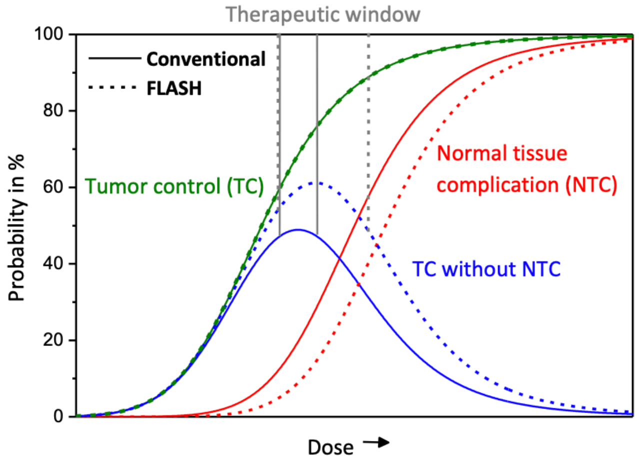


Favaudon et al., Sci Transl Med 6 (2014) 245ra93

Durante et al., Br J Radiol 91 (2018) 20170628

FLASH effect

ultra-high dose rates



FRIDA (FLASH Radiotherapy with hIgh Dose-rate particle beAms)

Goal of FRIDA is to make a step forward in all the crucial areas... Four work-packages [mechanism modelling & rad-bio experiments; beam delivery; beam monitoring; treatment planning] working in parallel, >25 FTEs, 7 INFN units with know-how in the fields and a solid international network of research centres and companies (SIT, STLab) are the resources to accomplish the research program.

	1			2			3		
	1-4	5-8	9-12	13-16	17-20	21-24	25-28	29-32	33-36
Air fluorescence									
ICB									
Silicon and Diamond									
"Free-standing membrane" SiC									
BM Research and Development									
Calorimeter									
Scintillators									
SiC Dosimeters									
Dosimeters R&D									
Beam characterization									
Intercomparisons									
Guidelines									
Prototypes commissioning									

WP1
The FLASH mechanism
E. Scifoni (modeling)
G. Forte (bio experiments)

WP2
Beam delivery
A. Mostacci (e-)
G. A. P. Cirrone (p)

WP3
Beam/dose monitoring
A. Vignati (Beam monitoring)
G. Bisogni (Dose monitoring)

WP4
Treatment planning
A. Schiavi (Dose sim/optim.)
M. Schwarz (Treatment planning)

FRIDA

Beam and dose monitoring: the main goal

Task 1 Development and test of new Beam Monitoring systems

Task 2 Development and test of new dosimetric systems

Task3 Intercomparisons, calibrations and codes of practice

	1			2			3		
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Guidelines									
Prototypes commissioning									

Faraday Cup
Calorimeter

→ Absolute dosimetry

Multi-gap ionization chamber
Air fluorescence
Diamond
Silicon Carbide
Free-standing membrane SiC
Secondary Emission Monitoring
Integrating current transformer (ICT)
Alanine
RCF

Relative dosimetry and diagnostic

Beam and dose monitoring: recent results

Centro PIsano Flash Radiotherapy

CPFR

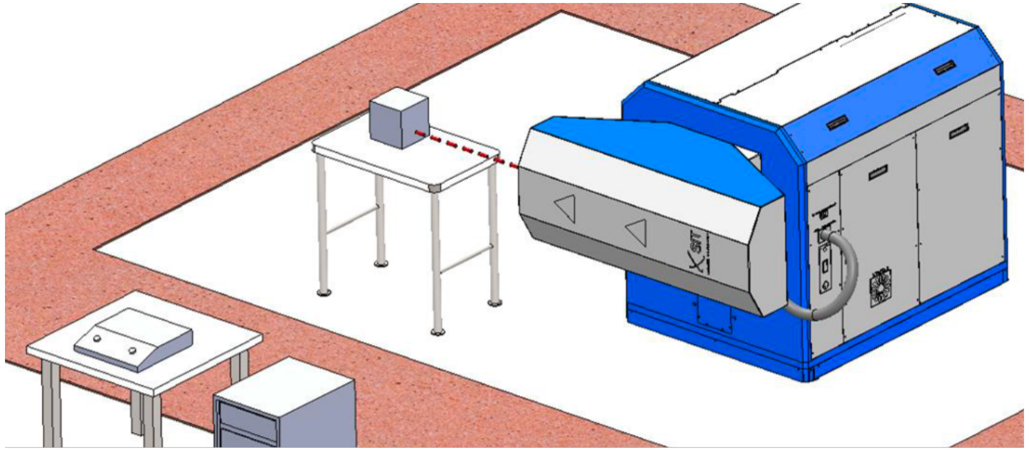
SIT ELECTRONFLASH 4000

Electrons E max = 10 MeV

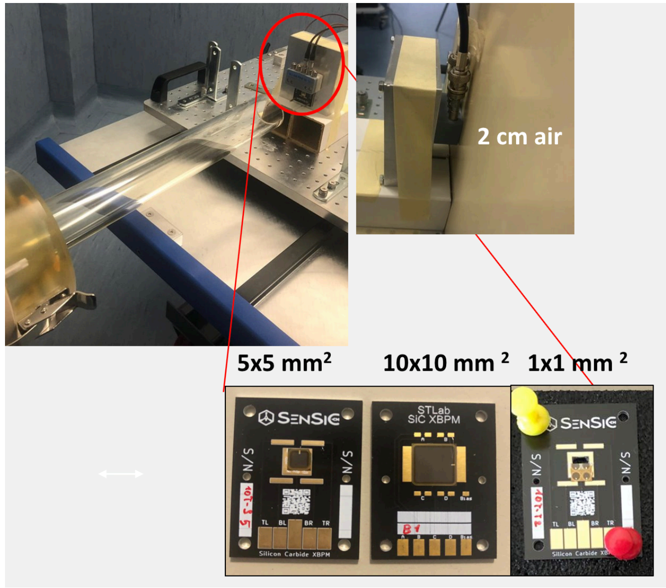
Triode e-gun

DR 0,005 Gy/s f- 10.000 Gy/s.

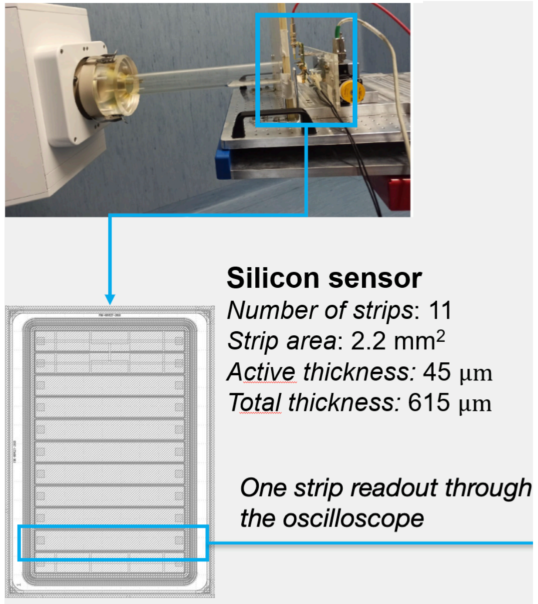
Pulse width 0,2µs -4µs;
PRF 1Hz to 350Hz (1Hz step).
1 cm – 12 cm ∅ collimators



SiC membrane



Si sensor



- Alanine: tested@CPFR
- RCF: tested@LNS and ELI
- SiC: exp.run on going
- FC & SEM: exp.run on going
- ICT: already realized

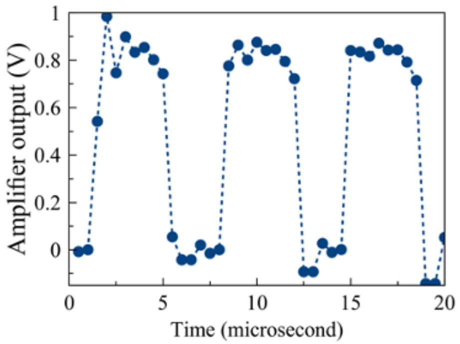
The unbalanced Core Dosimeter (UCD)

Flash radiotherapy (FRT) bases on the ‘FLASH effect’: if the therapeutic dose is delivered at ultra-high dose rates (> 50 Gy/s), lower toxicity is observed in normal tissues, with respect to conventional RT.

- UCD was funded by INFN TT (FLASHDOS 1 y project, call R4I 2022)
- Solid state device - Patented by INFN
- Conceived for the needs of the emerging FRT, but potentially applicable to generic high-dose-rate beam monitoring
- Typical requirements for an ideal FRT dosimeter
  - ✓ Waterproof and few-mm size
  - ✓ Linear up to MGy/s and resistant to radiation damage
  - ✓ Isotropic response
  - ✓ Accurately measures spatial dose distribution in radiotherapy water phantom

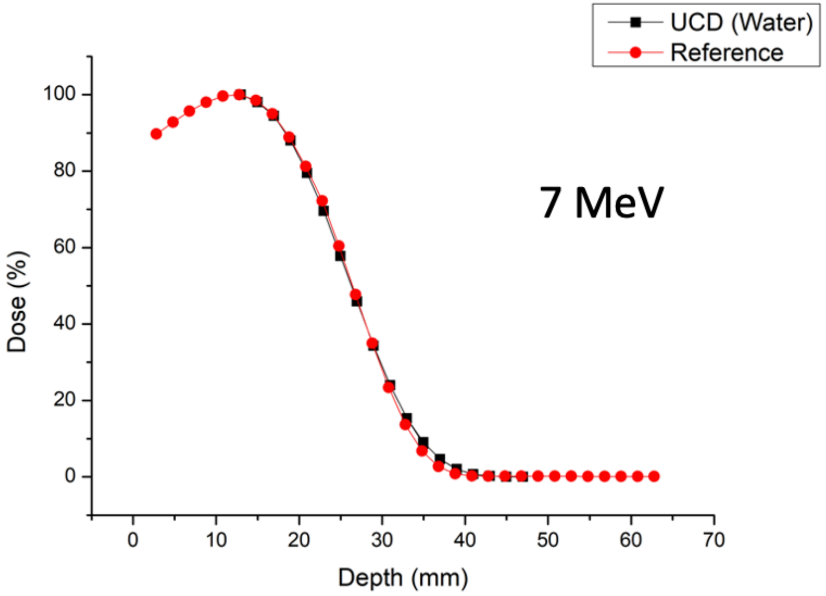
UCD Main features

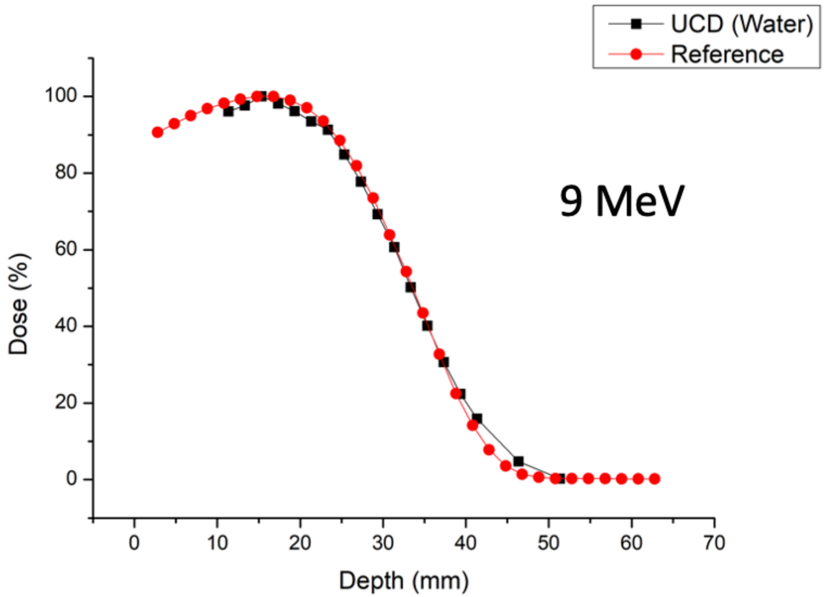
- Spherical core (2-3 mm radius, selectable)
- Intrinsically isotropic
- Waterproof
- Fades only 1% every 100 kGy
- Found linear up to 6.5 MGy/s
- Describes the pulsed time structure of the beam with time resolution hundreds ns



The unbalanced Core Dosimeter (UCD)

• UCD was tested in collaboration with *SIT - Sordina IORT Technologies S.p.A.* (Aprilia) using 7 and 9 MeV flash electron beams in water phantom
• In-phantom spatial dose distributions with UCD (3 mm radius) well compare with reference ones





Next steps:
1- Complete the UCD characterisation by minimizing the core radius
2- Seeking for an industrial partner to reach the market

Microdosimetry

Contributions

- **Valeria Conte**
- **Anna Vignati (spokesperson for MUSICA project)**
- **Anna Selva**

Istituto Nazionale di Fisica Nucleare – Laboratori Nazionali di Legnaro

Gas detectors (TEPC)

- **Claudio Verona (spokesperson for DIODE project)**
- **Gianluca Verona Rinati**

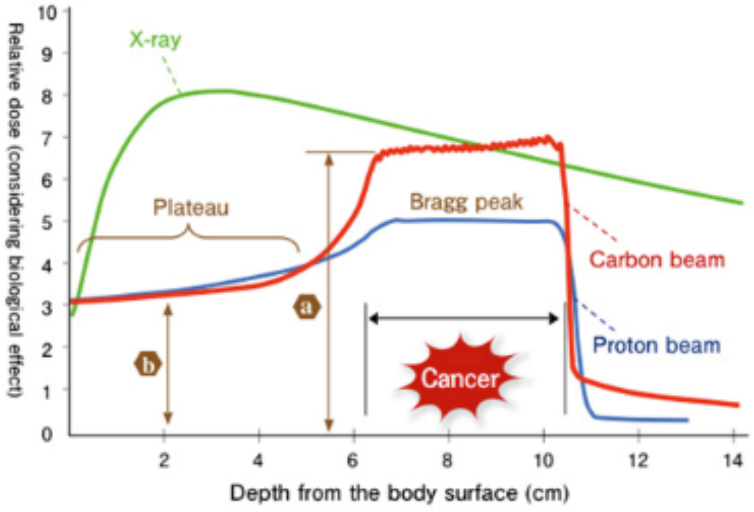
Università di Roma Tor Vergata - Dipartimento di Fisica

Instituto Nazionale di Fisica Nucleare - Sezione di Roma Tor Vergata

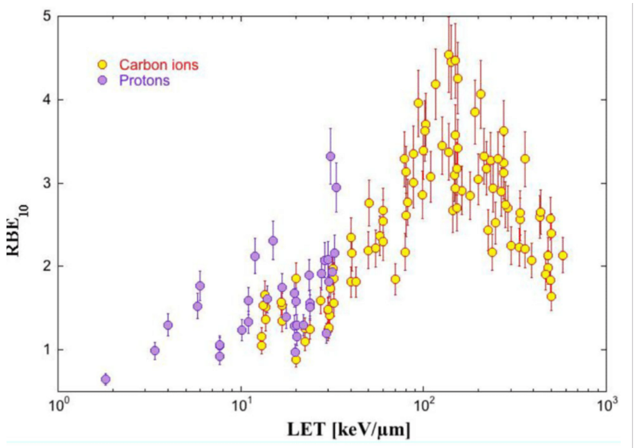
Diamond detectors

Diamond detectors for microdosimetry

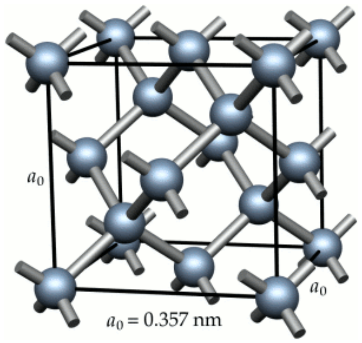
- **Hadrontherapy:** the main advantage is the ability to more precisely localize the delivered dose.
- Protons and carbon ions produce high local ionization density.
- Solid state dosimeters typically exhibit a strong energy dependence due to Linear Energy Transfer (LET) variation



The biological effectiveness (RBE) of high LET particles can be very different from that of high energy photons (RBE > 1). The TPS procedures are based on the product of the absorbed dose (dosimetry) and proper weighting factors accounting for the RBE of the radiation (microdosimetry).



The only conventional dosimetry is not enough for a comprehensive characterization of clinical radiation.

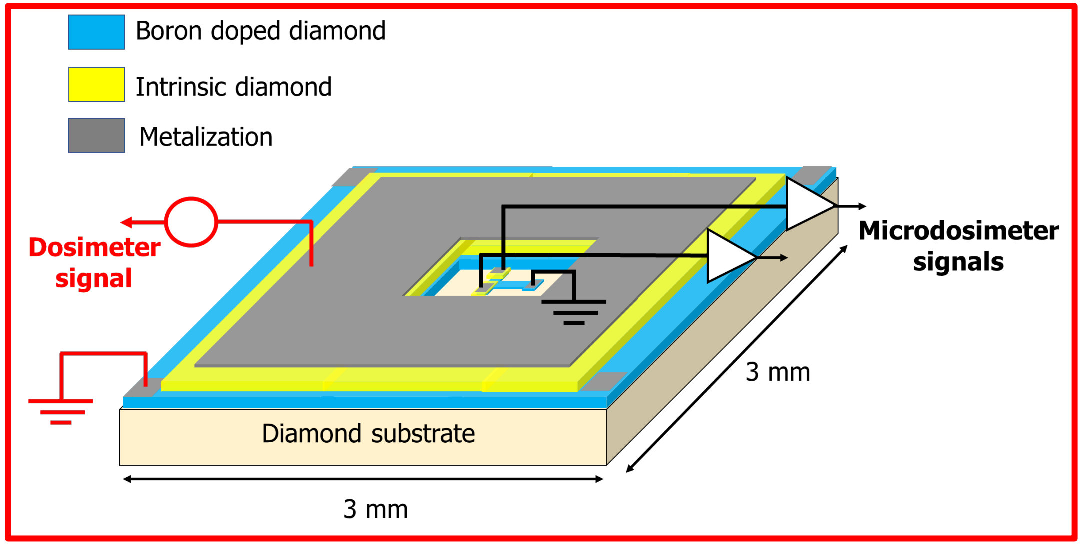


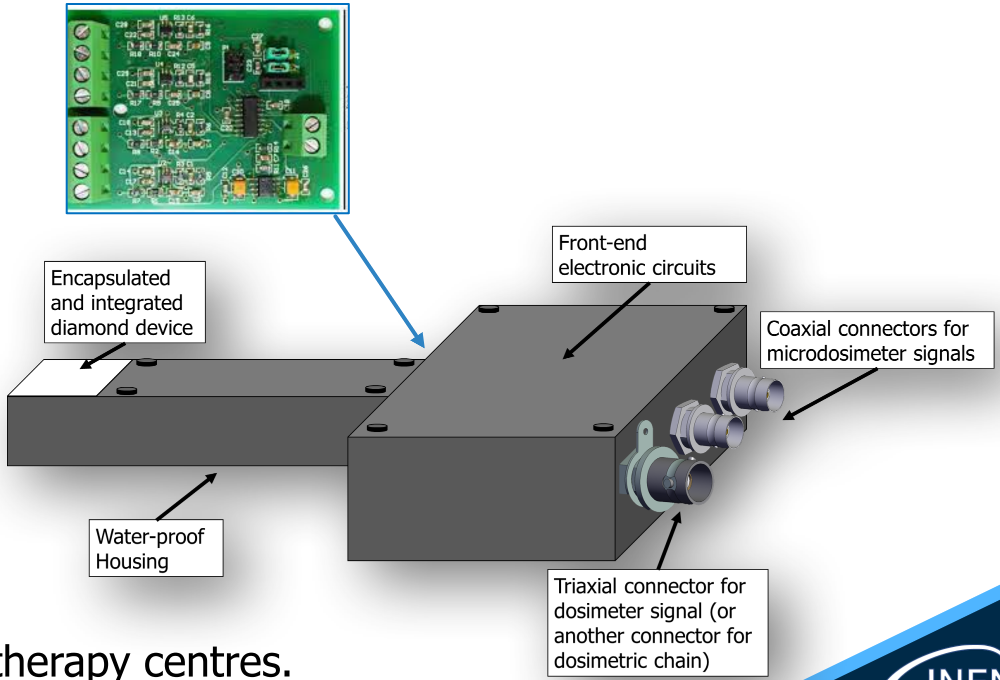
Synthetic single crystal diamond is an ideal candidate material to produce dosimetere and microdosimeters thanks to its outstanding properties:

- ✓ Small size
- ✓ Low energy dependence
- ✓ Near tissue equivalence
- ✓ near-constant ratio of stopping power with water for proton and carbon ions
- ✓ low dielectric constant
- ✓ high radiation hardness.

DIODE project
(Diamond integrated devices for Hadrontherapy)

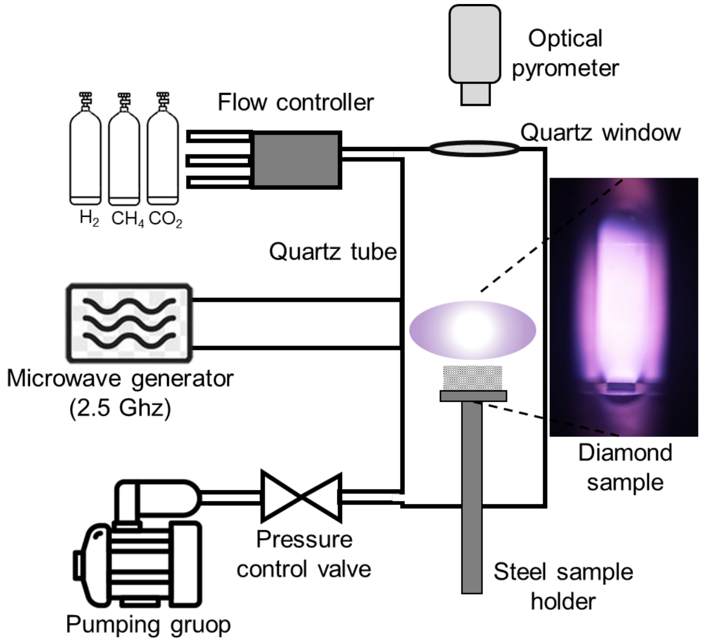
The aim of the **DIODE** project is the development and characterization of a novel detection system based on synthetic single crystal diamond able to simultaneously perform dosimetric (current integration measure) and microdosimetric (single particle energy deposition measure) characterization of clinical hadron beams.



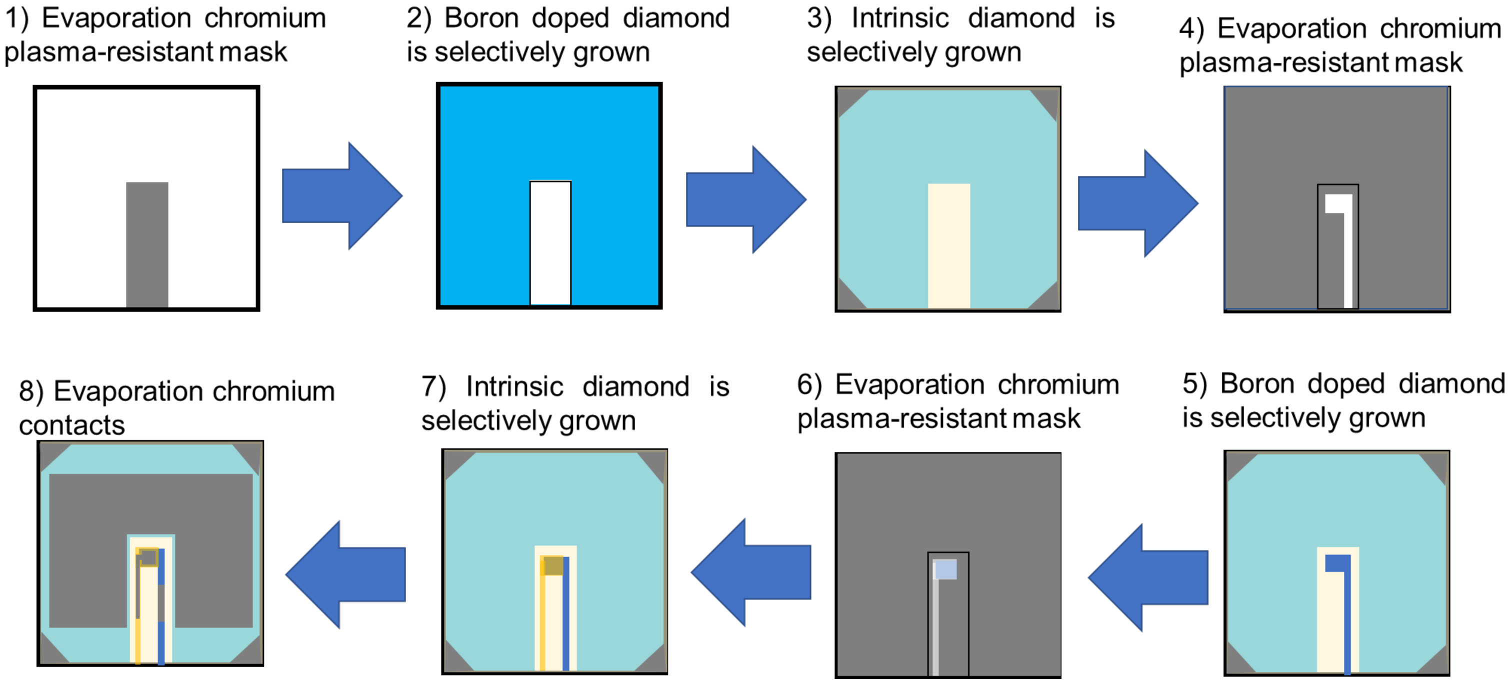


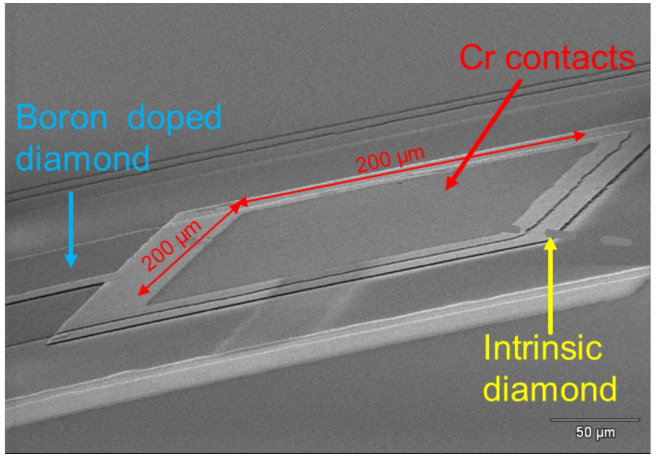
- ✓ Fast and exhaustive beam characterization and quality assurance in hadrontherapy centres.
- ✓ Reduction of the experimental uncertainties such as those associated with the detector positioning.
- ✓ Dosimetric information will be used to compensate the distortions at the lowest part of the microdosimetric spectrum due to the unavoidable electromagnetic noise.

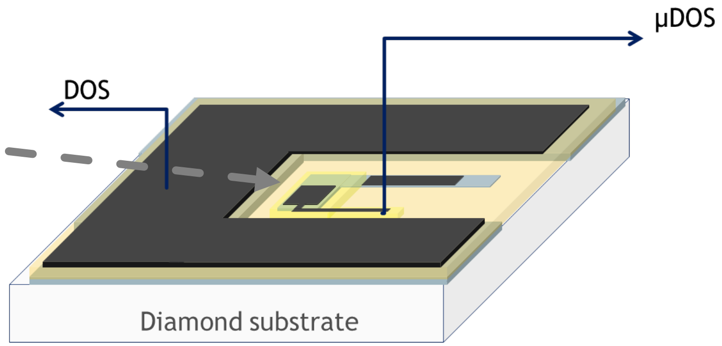
Diamond devices: Fabrication process

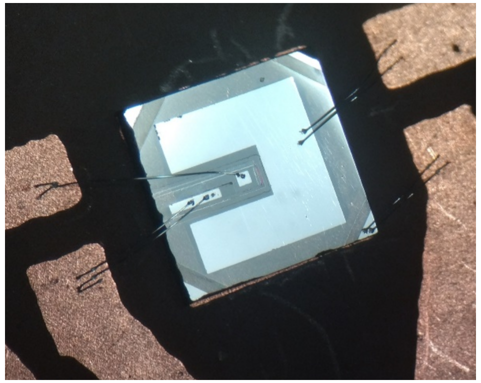


Dos-µDos fabrication process









Gas detectors for microdosimetry

Isotropic response, tissue equivalence

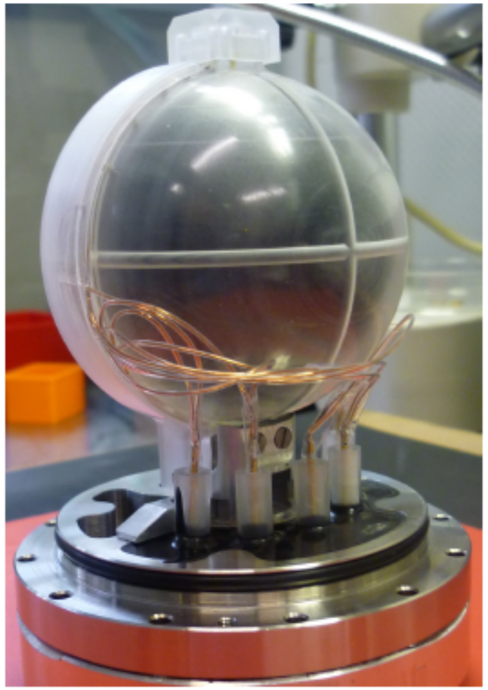
Hadron Therapy

- ➢ Miniaturization for application in hadron therapy
  - Size reduction: from 12.7 mm (smallest commercial TEPC) to 1 mm
- ➢ Engineerization
  - High reproducibility
- Limits of TEPC: sustainable beam current (10^5 particle $mm^{-2}s^{-1}$)
  - ➢ Implementation of variance-covariance techniques
- ➢ Innovative detectors for multi-site measurements (MUSICA - Young researchers grant – 5° commision INFN)

Future: implementation of microdosimetry as QA tool for hadron therapy and improved modelling of the radiation effect on cells with multi-site measurements

Gas detectors for microdosimetry

Environmental microdosimetry

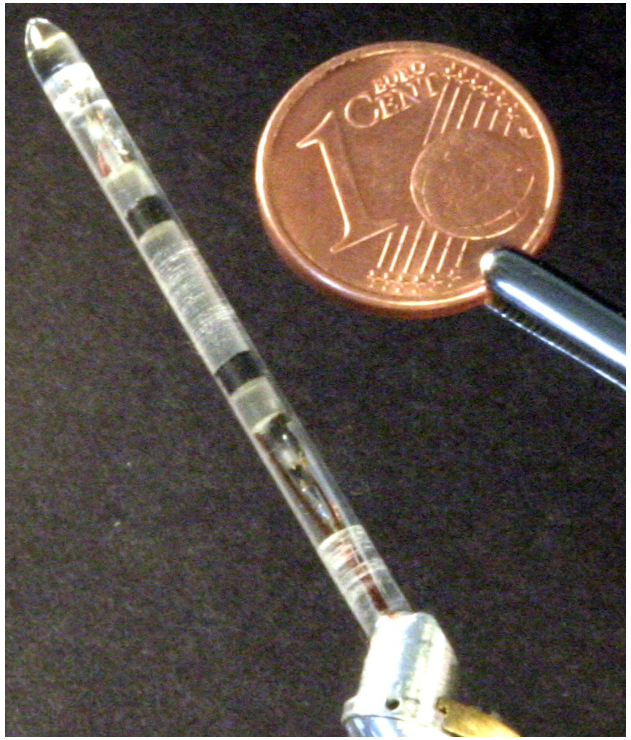


- Large expertise in development of advanced microdosimeters with segmented cathode
- Low dose area monitoring
- Radiation protection in space missions

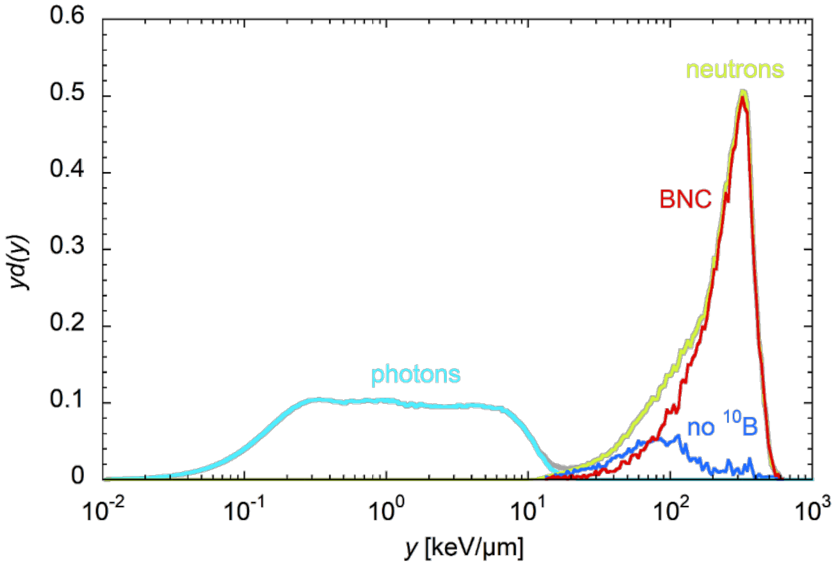
Future: development of a microdosimetric system for continuous monitoring at LNGS

Gas detectors for microdosimetry

BNCT



- TEPC with replaceable cathode walls, either boron-doped or without doping
- Identical TEPCs with different boron concentrations in the cathode walls
- Discrimination of the spectral components and dose contributions in a fast measurement (~5 minutes)



Gamma dose: 46%

Neutron dose: 54%

BNC dose: 45.4%

Other: 8.6%

Future: implementation of microdosimetry in italian new BNCT facilities (@CNAO and @Caserta – PNRR)

New devices for dosimetric purposes

Contributions

- **Leonello Servoli (spokesperson for 3D-dose and HASPIDE project)**

Istituto Nazionale di Fisica Nucleare – Sezione di Perugia

Synthetic diamond with 3D electrode
&
Hydrogenated Amorphous Silicon Devices

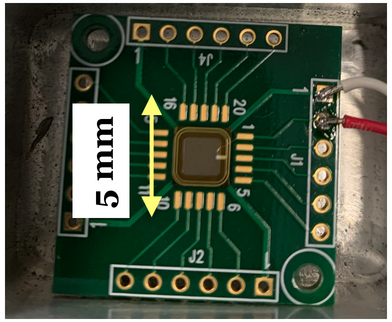
- **Giada Petringa (spokesperson for PRAGUE project)**
- **Pablo Cirrone**
- **Roberto Catalano**
- **Mariacristina Guarrera**
- **Alma Kurmanova**
- **Salvatore Tudisco**

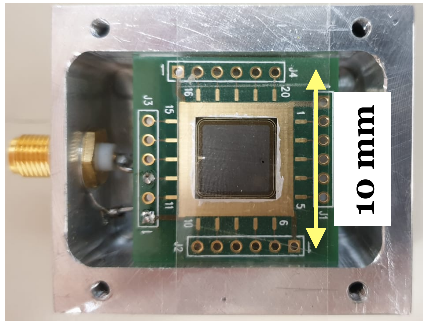
Istituto Nazionale di Fisica Nucleare – Laboratori Nazionali del Sud

Silicon Carbide for dosimetric & microdosimetric applications

Silicon Carbide detector for dosimetric and microdosimetric purposes

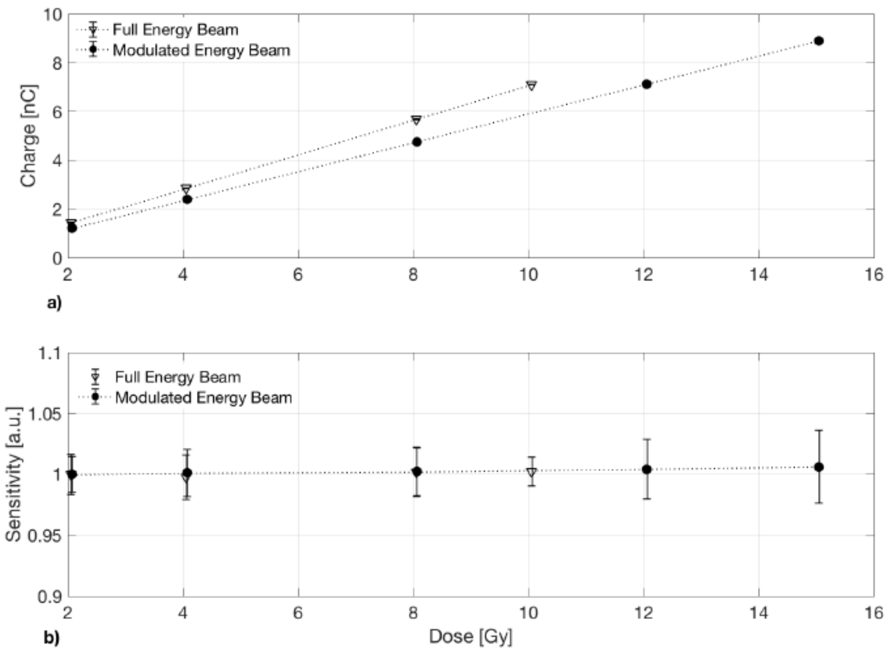
Properties	Diamond	Silicon	4H-Silicon Carbide
Energy Gap [eV]	5.45	1.12	3.26
Relative dielectric constant ε_r	5.7	11.9	9.7
Breakdown electric field (MV/cm)	10	0.2-0.3	2.2-4.0
Density (gr/cm^3)	3.52	2.33	3.21
Atomic Number Z	6	14	10
e-h pair energy (eV)	13	3.62	7.78
Saturated electron velocity (10^7 cms^{-1})	2.2	1.0	2
Hole mobility [cm^2/Vs]	1200-1600	450-600	100-115
Electron mobility [cm^2/Vs]	1800-2200	1400-1500	800-1000
Threshold displacement energy (eV)	40-50	13-20	22-35
Thermal conductivity (W/cm °C)	20	1.5	3-5
Max working temperature (°C)	1100	300	1240
Hole lifetime τ_p	10^{-9}	$2.5*10^{-3}$	$6*10^{-7}$





First characterization of a new Silicon Carbide detector for dosimetric applications

G. Petringa, G.A.P. Cirrone,[1] C. Altana, S.M. Puglia and S. Tudisco
[a] *INFN-LNS (Italian Institute for Nuclear Physics), Via S. Sofia 62, Catania, Italy*
E-mail: cirrone@lns.infn.it

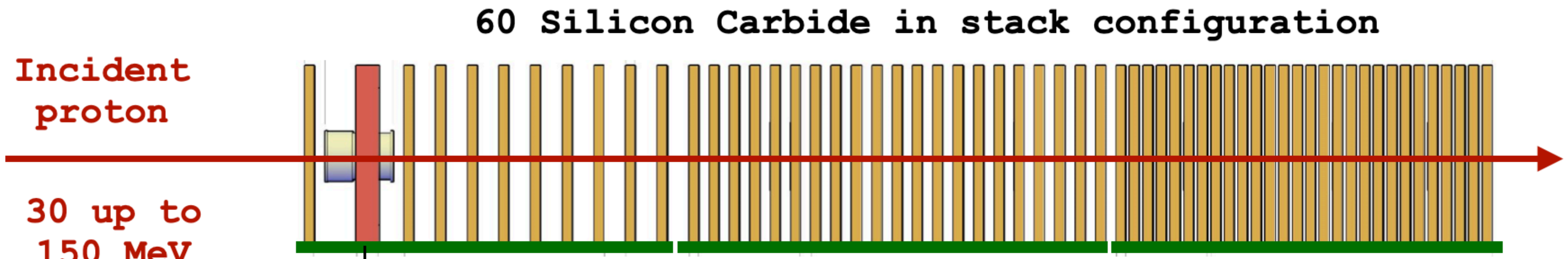


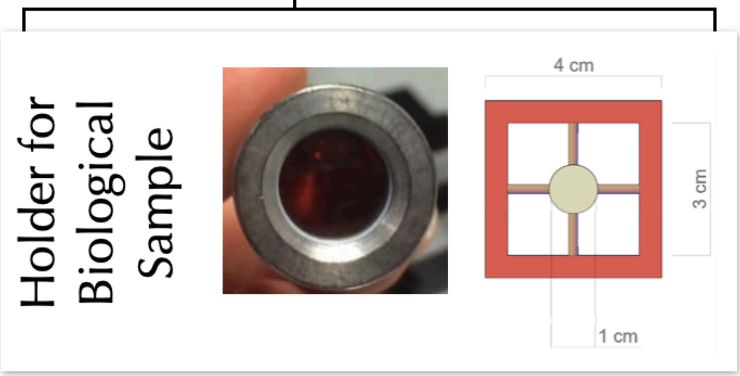
IMM

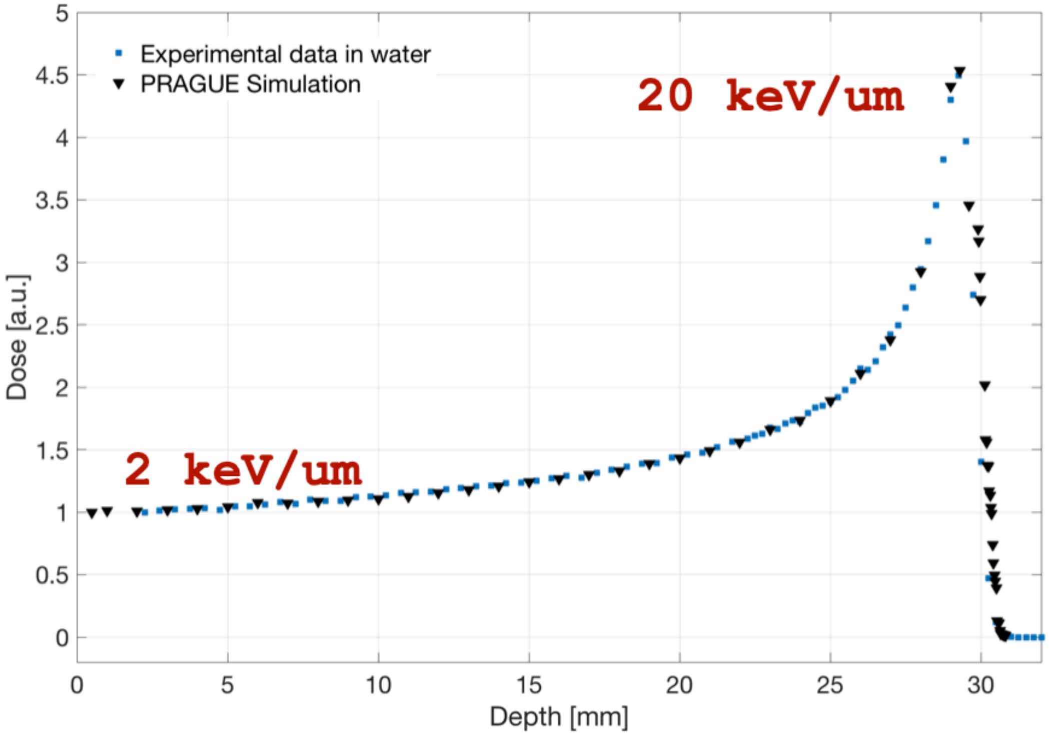
INFN LNS Istituto Nazionale di Fisica Nucleare Laboratori Nazionali del Sud

DoSiC: rivelatore dosimetrico per radiazioni ionizzanti in Carburo di Silicio" N. Rif. 102018000007139 depositato in data 12.07.2018.
"PRAGUE: rivelatore per dosimetria in carburo di silicio". N.Rif:102020000007780 depositato in data 14.05.2020

PRAGUE project
(proton range measure using Silicon Carbide)

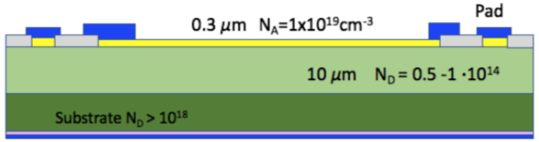


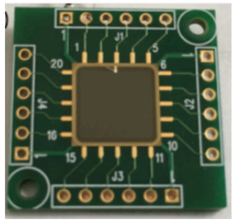




PRAGUE project
(proton range measure using Silicon Carbide)

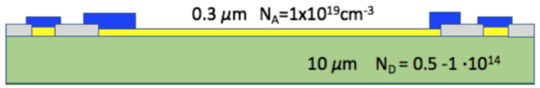
Entrance and proximal position reconstruction

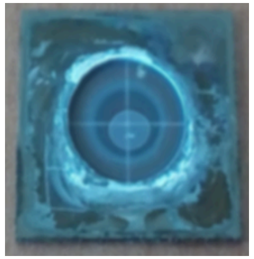




15 x 15 mm^2

Distal position reconstruction

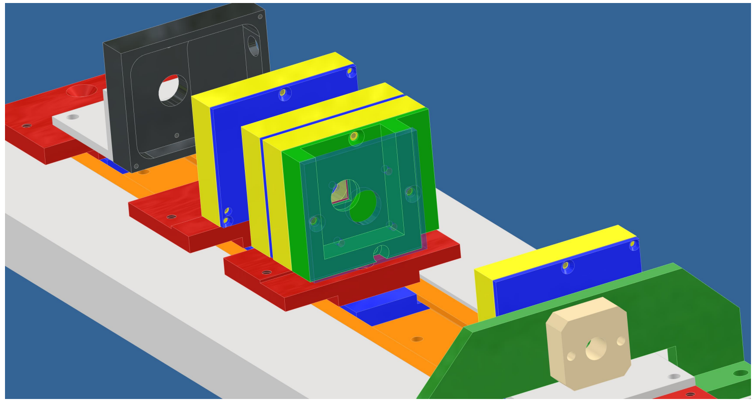


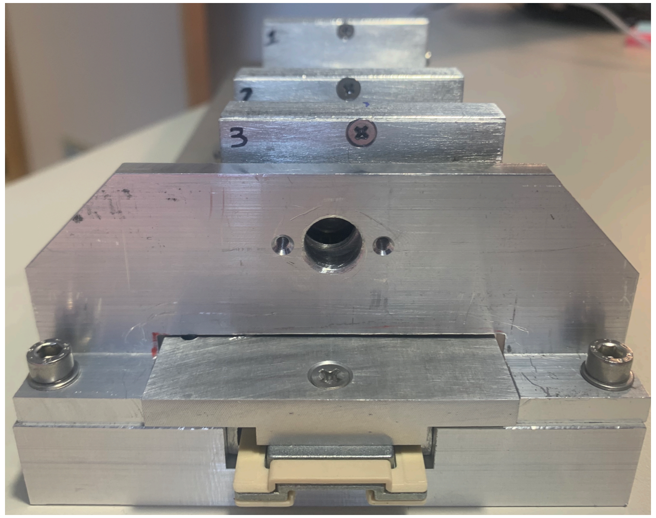


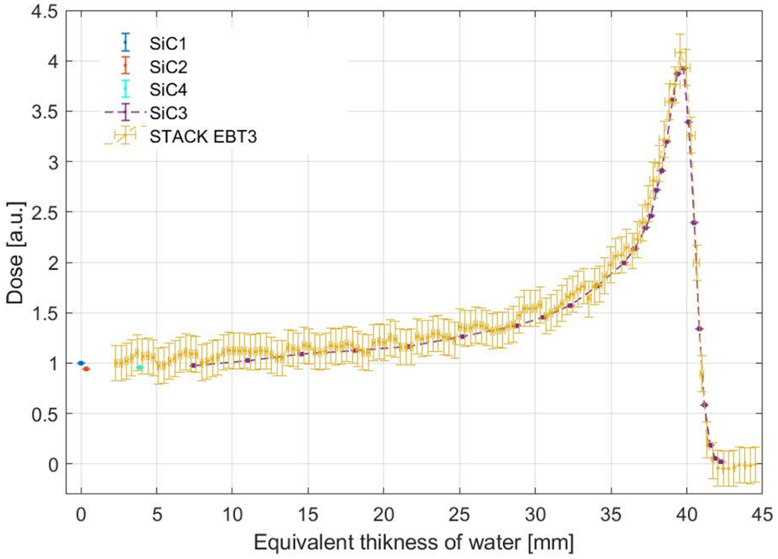
15 x 15 mm^2

The First Prototype was realized and tested @PTC of Trento (IT)
@Ústav jaderné fyziky av cr (CZ)
@INO-CNR (IT)

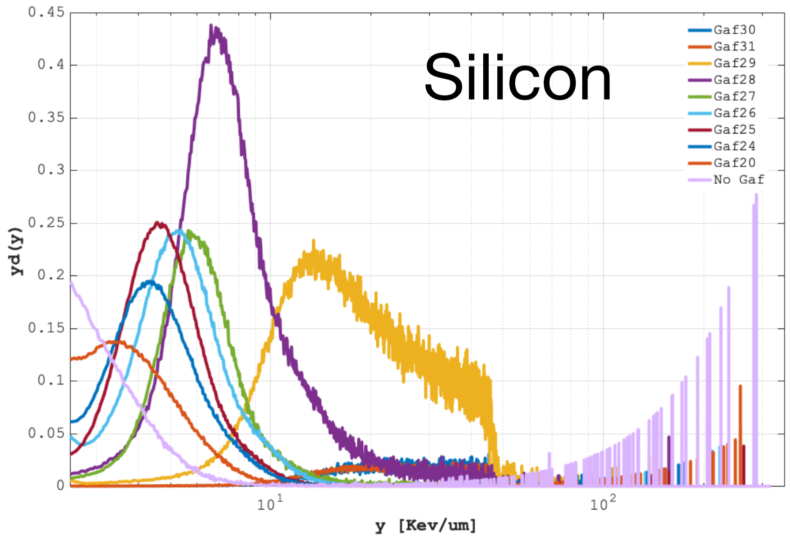
The system was entire simulated with TOPAS

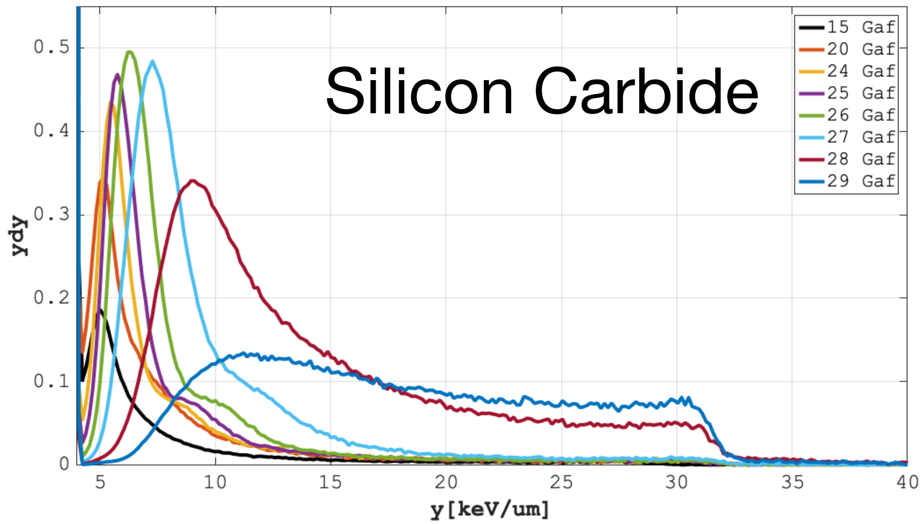






Silicon Carbide for microdosimetric applications (DoT-SiC project)

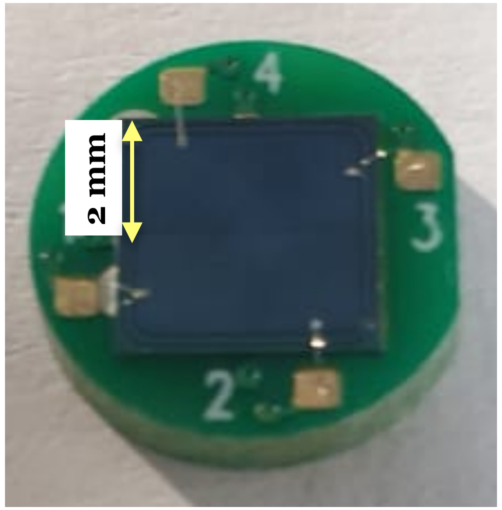




Entrance: 4keV/um
Distal: 18 keV/um

Entrance: 4keV/um
Distal: 16 keV/um

The First Prototype was tested @Ústav jaderné fyziky av cr (CZ) with 30 MeV proton beam and @APPS (Trento Protontherapy center) with 70 MeV and 150 MeV



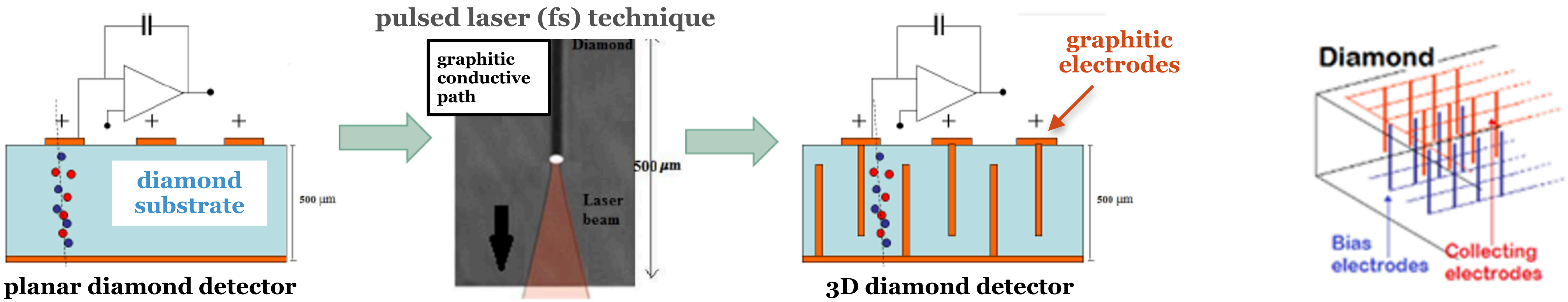
Experimental data compared with Silicon and Diamond detector

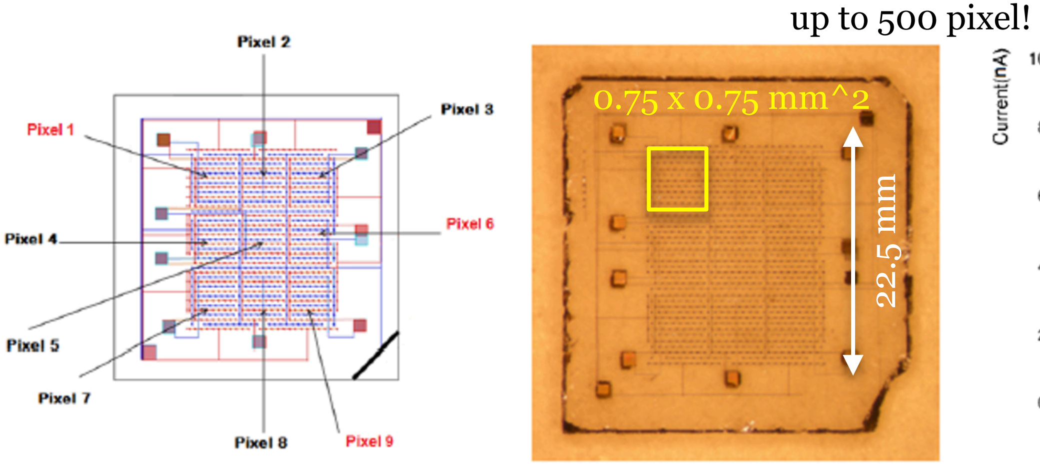
Silicon Carbide detector for dosimetric and microdosimetric purposes: next step

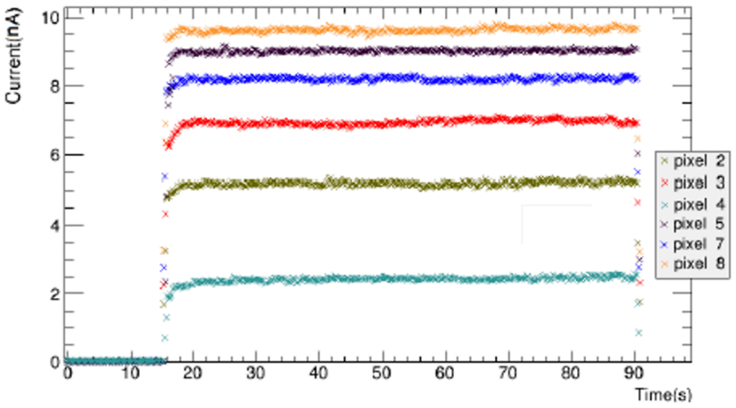
- PRAGUE: detector assembling and test with clinical and high dose rate proton beams
- PRAGUE: experimental test with 4He beam
- Microdosimeter: experimental test with 12C and 4He beam
- Microdosimeter: electronic read-out optimization

Syntetic Diamond with 3D electrodes (3D-Dose project)

Production of synthetic diamond (both scCVD and pcCVD) devices with graphitic conductive paths inside substrate and on the surface. Graphitization via focused laser pulses. Column width ~10 μm diameter.



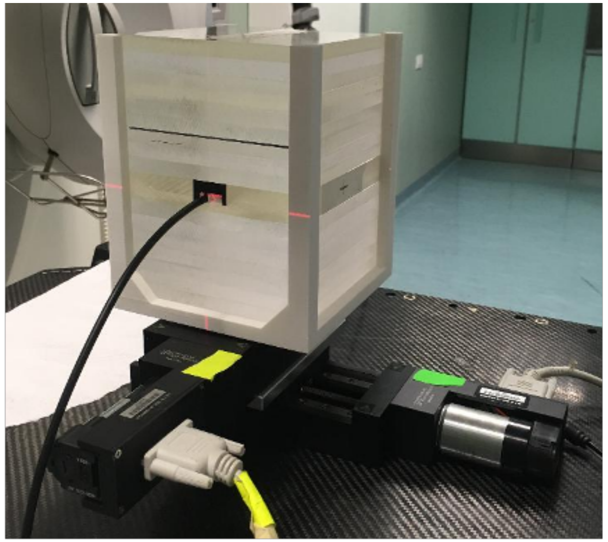




Calibration of 6 pixels on 6 MV 10x10 photon field

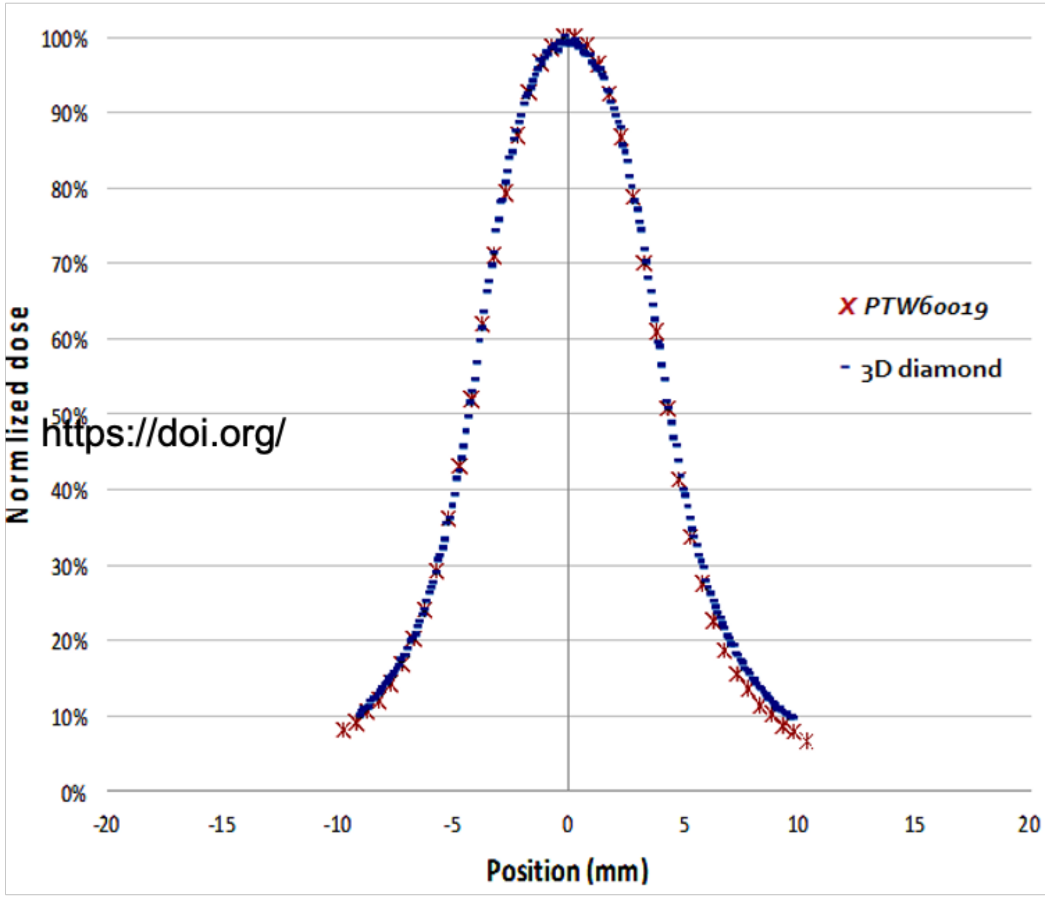
the resulting structure has an arrays of graphitic columns of 10um in diameter forming cells with a thichness of 0.5 mm for a single cell of sensitive volume of 0.004 mm^3 and a total volume of 1.1 mm^3

Small photon beam dosimetry - Firenze Hospital



Comparison between:

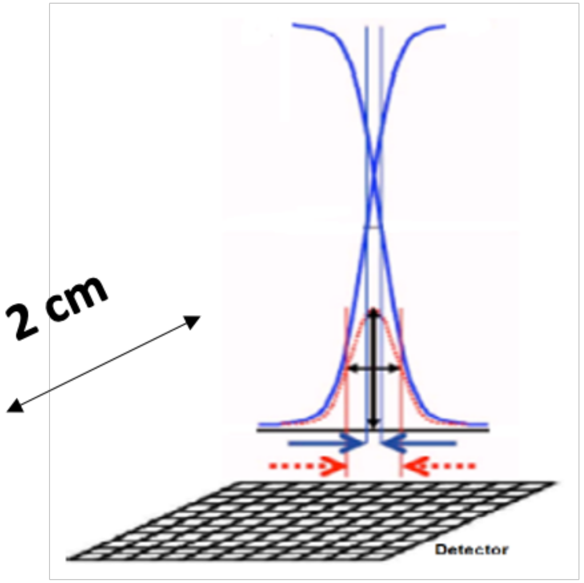
- 3D pcCVD diamond (0.5 x 0.5 mm^2)
- Diamante PTW 60019 diamond



Field size 8 mm x 8 mm

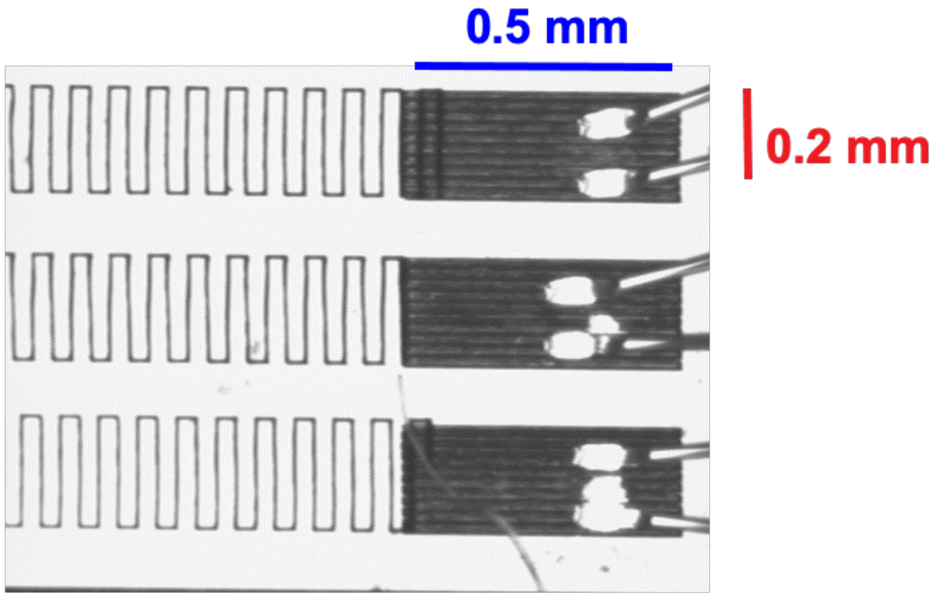
https://doi.org/10.1088/1748-0221/12/01/P01003
https://doi.org/10.1088/1748-0221/13/06/P06006
https://doi.org/10.1016/j.nima.2019.162730
https://doi.org/10.1016/j.ejmp.2022.09.006

Future work and development lines



Produce highly segmented polycrystalline diamond dosimeter to obtain spatial distribution of small fields.

Test to directly bond microwires over graphite pads to avoid the metalization step and have an all-carbon detector



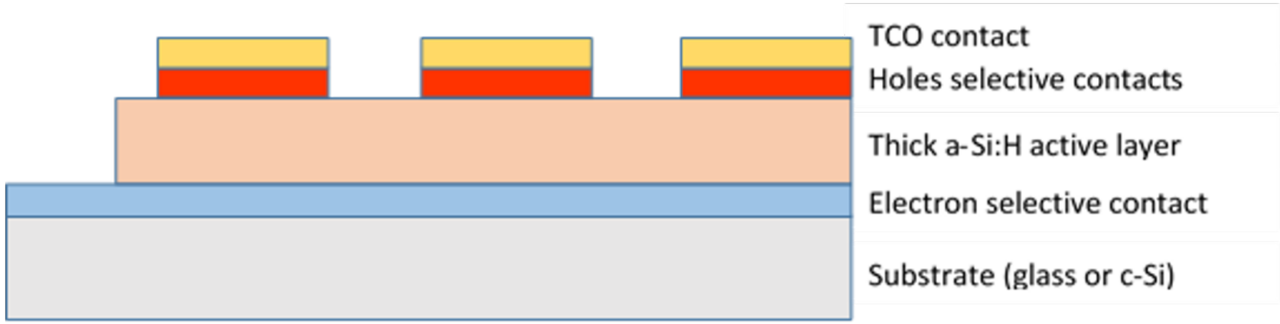
256 channels readout system

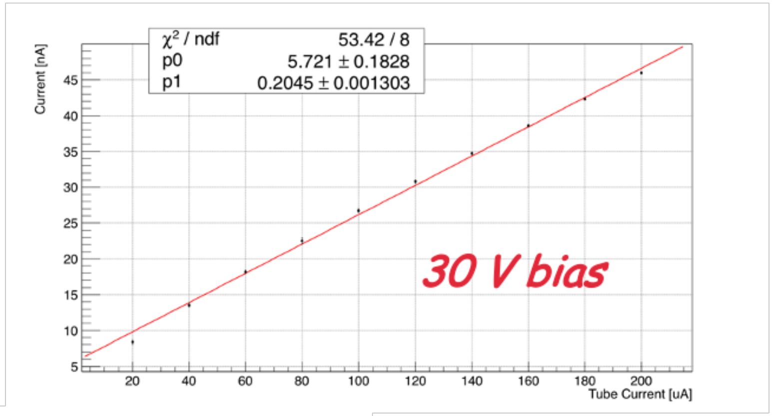
Hydrogenated Amorphous Silicon Devices

a-Si:H is a disordered semiconductor => in a-Si not all of the Si-Si bond can be saturated => H is introduced (i.e plasma enhanced CVD) ;

Production of thin a-Si:H (1- 10 μm) ionizing radiation detectors deposited over thin supports to be used for beam monitoring and dosimetry of medical LINACs and other types of accelerators.

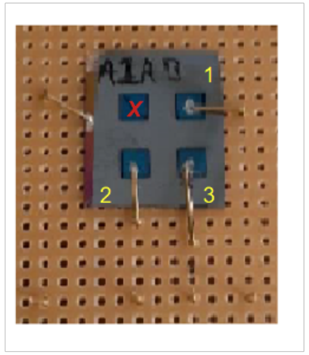
Two method to contact the device: p-i-n and Charge Selective Contacts



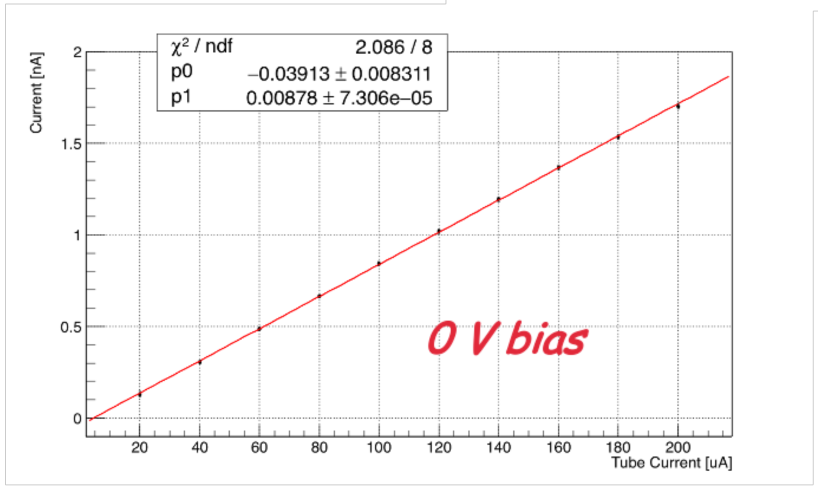


good for flux measurements but low S/N ratio

3D geometry can limit the S/N ratio



Charge Selective Contacts a-Si:H structure:
4x4 mm² area, 6.2 μm thick, CSC, 0 and 30 V bias.



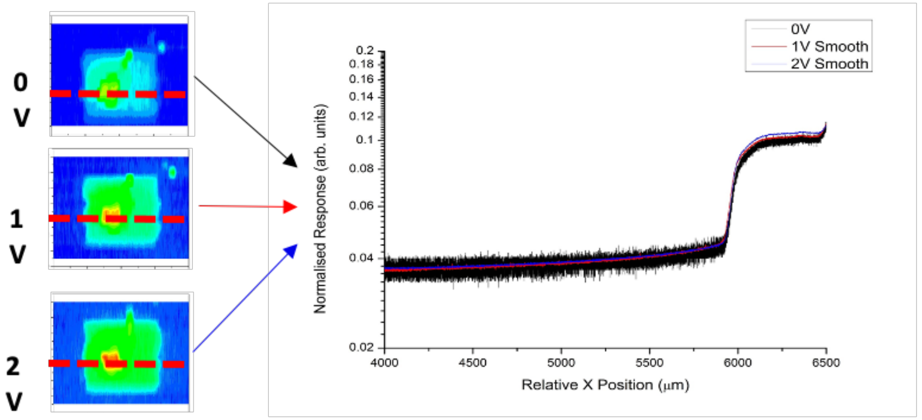
Linearity ~ 1-2%

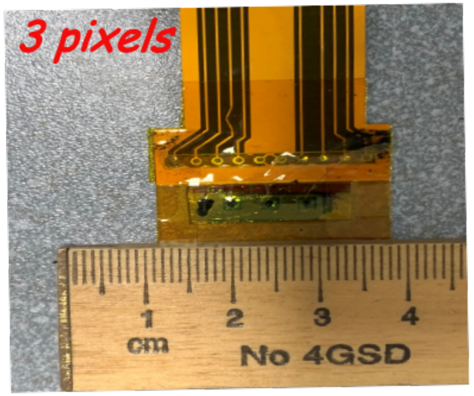
Sensitivity(0 V)/Sensitivity(30 V) ~ 23

Hydrogenated Amorphous Silicon Devices

a-Si:H devices have a well defined sensitive volume → good for dosimetry

Capability to build pixel arrays of a-Si:H devices deposited on thin kapton to be used for dosimetry with Clinical LINACs.





Surface scan of same sensors using microfocalized Synchrotron radiation at different biases.

- a-Si:H : 2.5x2.5 mm^2, 2.5 μm thick;
- Kapton substrate thickness: 25 μm
- Kapton tail: 400 μm thick,
- Kapton tail lenght: 35 cm,
- Kapton tape overlayer: 70 μm
- Number of pixels: 3 with pitch 5 mm

Hydrogenated Amorphous Silicon Devices: next step

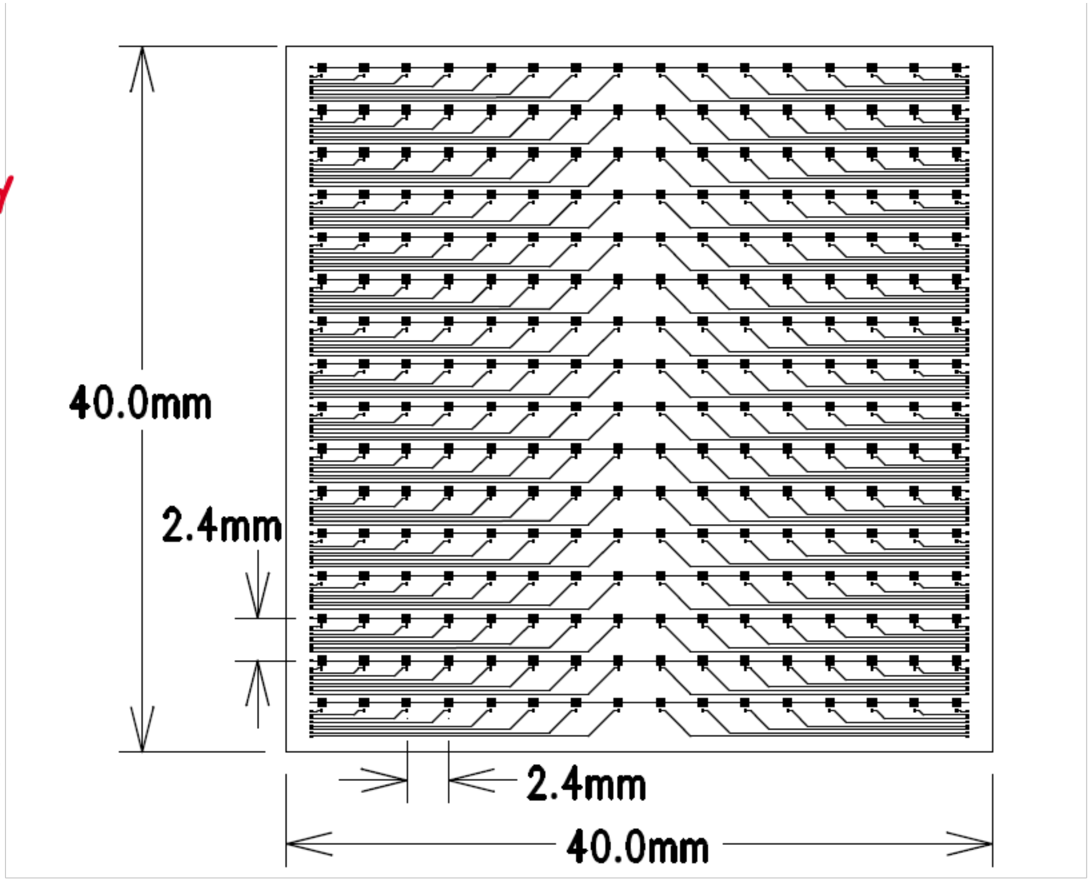
→ *optimize sensitivity wrt specific application (standard dosimetry, FLASH dosimetry, ion beam monitoring, nuclear medicine, space dosimetry or solar radiation measurement…)*

→ *define calibration procedure for single diodes, linear arrays, 2D arrays.*

→ *apply to some specific medical use cases like:*

3D Conformal Breast tangential (skin dose monitoring in steep dose gradient areas at the surface of the breast during 3D-CRT).

Skin Dosimetry in the Soft Tissue Sarcoma using Helical Tomotherapy total skin electron therapy.



Proceed toward 2D matrix of detectors to be used in transmission mode, including readout.

Thanks for your attention