Applied Physics Research @ TIFPA-INFN

G. Battistoni

TIFPA Trento Institute for Fundamental Physics and Applications

INFN Istituto Nazionale di Fisica Nucleare

What is TIFPA

TIFPA (Trento **I**nsititute for **F**undamental **P**hysics and **A**pplications**)** is an INFN **collaborative center for translational physical research**
Partners are INFN, UNITN, FBK, and APSS. Founded in 2013.

Scientific excellence
Synergism
Infrastructures
Technological transfer

Both Fundamental and Applied research are present

Research areas @ TIFPA

High Energy Physics

Astroparticle Physics in Space Missions

Nuclear Physics

Gravitational Waves both space and ground based

Anti-matter Physics

Interdisciplinary and technological research

Biophysics

Experimental and Theroretical activitity on almost all of these items

Applied and Interdisciplinary Physics Research

- Sensor development
- Detector development
- Technology for Space Missions and Gravitational Wave research
- Medical Physics
- Radiation Physics and Nuclear Physics Applied to Medicine
- Space radioprotection
- Quantum Technologies

Nuclear Fragmentation Measurements
proton/ion beam Treatment planning
New radiotherapy modalities: FLASH therapy
Radiobiological modeling
Radiation induced toxicities modeling
New ion beams characterization
Micro/Nanodosimetry
Monte Carlo Radiation Transport and Track structure
Radiation Chemistry
Bioeffect based detectors
Radiosensitization

Experimental room @ APSS ProtonTherapy - Trento

PAC submission
Open to users

www.tifpa.infn.it/sc-init/med-tech/p-beam-research/

Two beam lines

Energy range at beam exit: 70 – 225 MeV

54 exp from 2016, by local /external groups

Biology Line

Tommasino et al. Phys Med 2019

Physics Line

Tommasino et al. NIMA 2017

Beam Production:

- Isochronous Cyclotron IBA Proteus 235
- Energy Range: 70-225 MeV
- Beam Current: up to 320 nA
- Typical Efficiency: ≈55%

Target experiments:

- Radiation Biophysics
- Radiobiology
- Space Research
- Detector Development

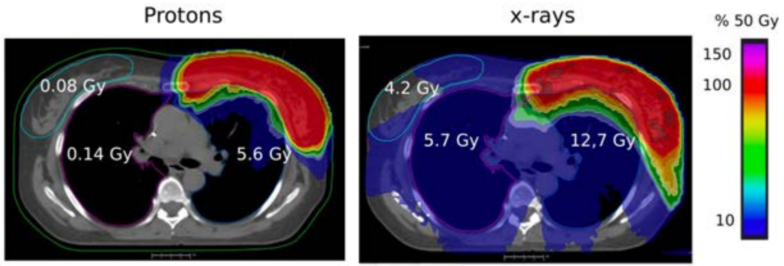
X-Ray and Bio-lab @ TIFPA

X-ray 195 kV shielded irradiator

System for small animal anaesthetization.
Optical microscope
Laminar flow biological hood
Centrifugator
Incubator
Distribution pipe-lines for CO_2 and N_2

Secondary Cancer risk modeling: particles vs X-rays

Dosimetric studies : strong reduction of Excess Relative Risk (EAR) in **p** vs **X** –rays plans according to different models



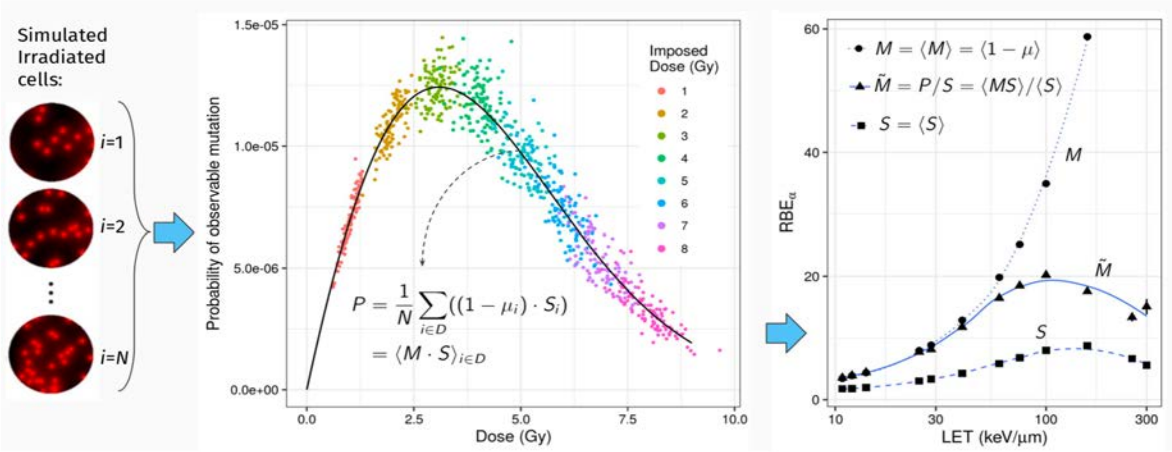
EAR(cases/10000 persons/year:	VMAT			PT		
	Linear	**Lin-exp**	**Lin-plat**	**Linear**	**Lin-exp**	**Lin-plat**
Ipsilateral Lung	131±17	40±3	37±3	63±5	20±3	18±2
Contralateral Lung	55±8	35±3	30±2	2±2	1±1	1±1
Contralateral Breast	44±6	35±4	31±3	0±0	0±0	0±0

Cartechini et al. *Radiot. Oncol.2020*

- Biophysical modeling:

New **MKM** based model for **Mutation Induction RBE** (RBE_M) of particles versus X-rays in analogy to the standard RBE for clonogenic survival (RBE_S)

Attili et al. *PTCOG 2021, in prep for Rad. Res.2021.*



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FONDAZIONE BRUNO KESSLER

Azienda Provinciale per i Servizi Sanitari

Generalized Equivalent Uniform Dose (gEUD) and Normal Tissue Complication Probability (NTCP)

volume effect parameter (organ specific)

$$gEUD[Gy] = \left(\sum_{i=1}^{N} v_i D_i^a\right)^{\frac{1}{a}} = \begin{cases} D_{min} & a \to -\infty \\ D_{mean} & a = 1 \\ D_{max} & a \to +\infty \end{cases}$$

bins of DVH

- $a = 1$: **Large volume effect**
- $a \to +\infty$: **Small volume effect**

Lyman–Kutcher–Burman (LKB) model (1989):

$$NTCP(u) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{u} e^{-t^2/2} dt$$

Important **index** for **ranking treatment plans (clinical acceptability)**

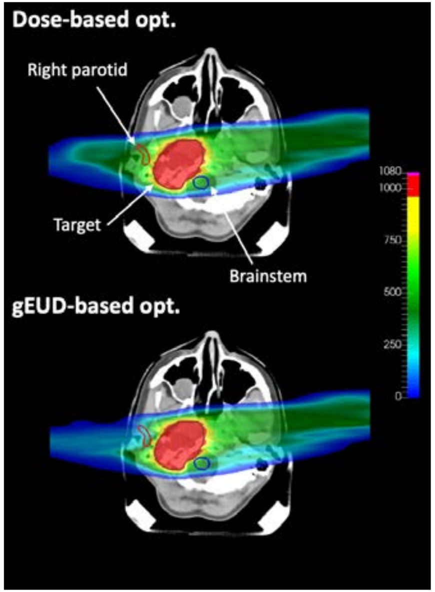
$$u = \frac{gEUD - TD_{50}}{m \cdot TD_{50}}$$

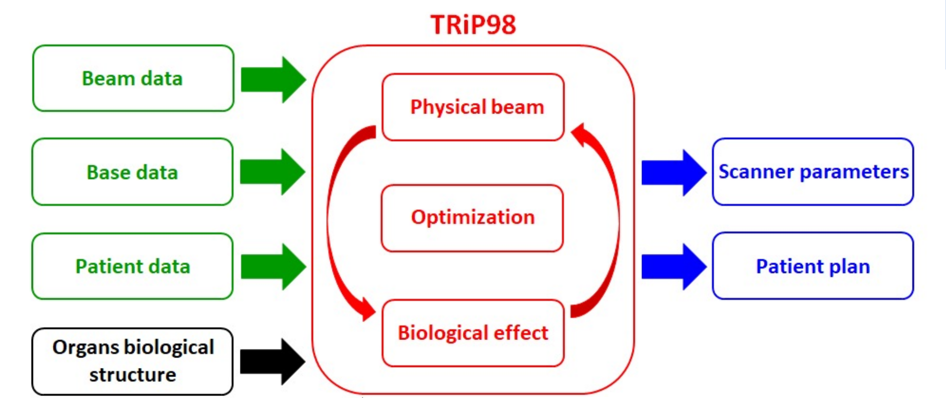
TD_{50}: whole organ dose for NTCP = 50%

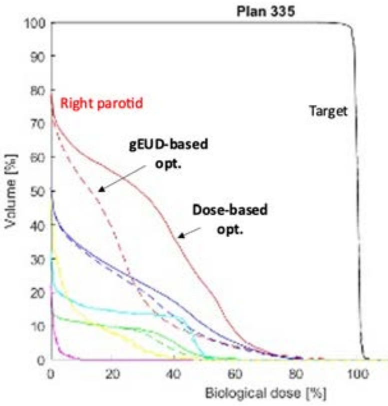
m: curve slope at TD_{50}

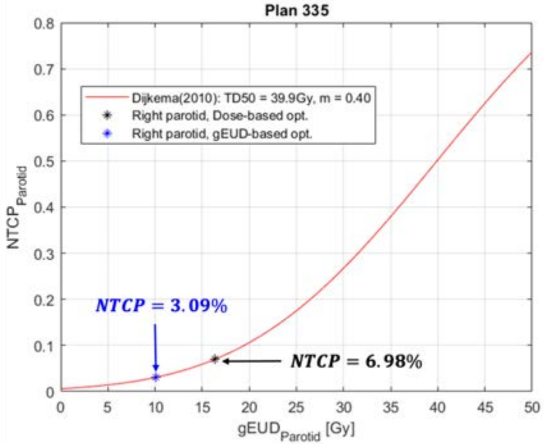
NTCP based optimization

Including **Volume effects** in inverse planning:
Beyond Dose based optimization
First implemenation of gEUD based optimization in Treatment planning for partcle beams





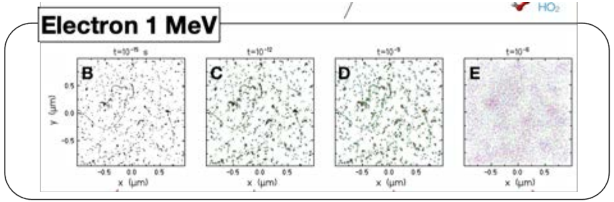




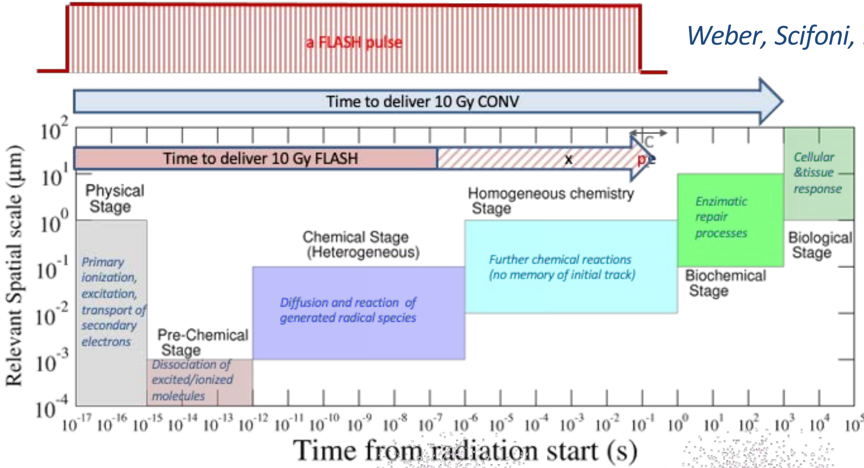
Battestini et al. in preparation for ***Frontiers in Oncology, - see M. Battestini 'sTalk.***

Unraveling the FLASH radiotherapy

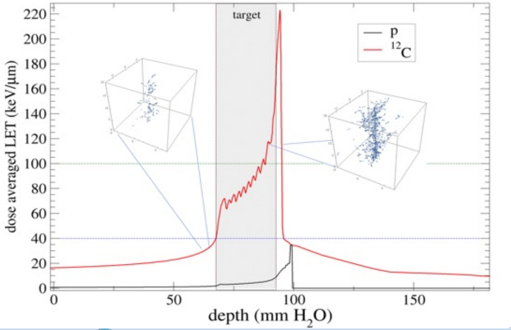
- Multiscale Mechanistic studies for understanding the FLASH effect and its feasibility with different radiation type / irradiation conditions

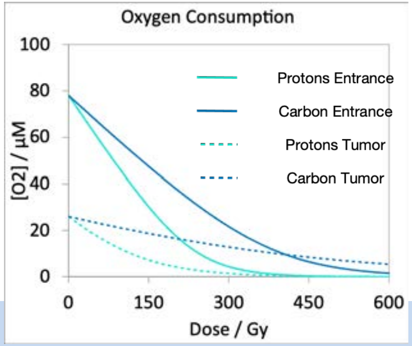


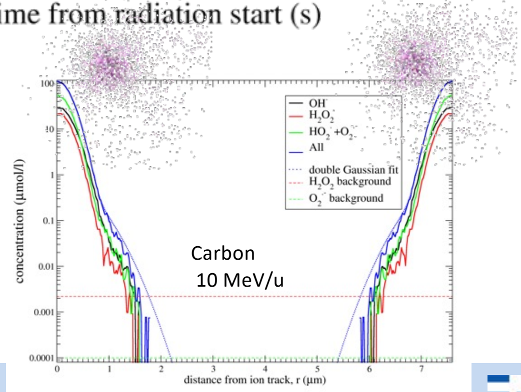
Boscolo et al. Radiother Oncol 2021



Weber, Scifoni, Durante Med Phys 2021







Scifoni et al. talk@PTCOG 2021
In prep. for Phys Med Biol

Microdosimetry as a bridge between physics and biology: The MICROBE-IT project

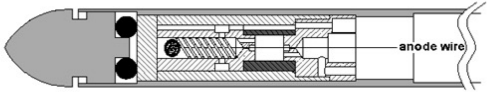
Microdosimetric spectra [physics] → **Data** → Radiation field quality and dose [physics] → **Data + Model** → RBE [biology]

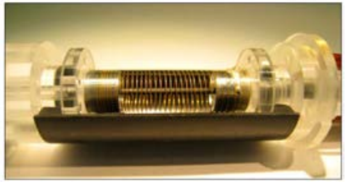
C. La Tessa

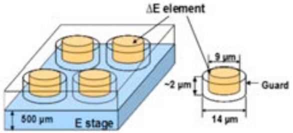
MICROdosimetry-based Biological Effectiveness assessment in Ion Therapy

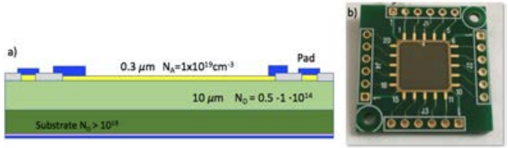
A) Characterization of Radiation Field using 6 different detectors:

- Miniature and nano-dosimetric tissue-equivalent proportional counters (**mini- and nano-TEPC**): gas-based detectors.
- **Silicon telescope**: ΔE (microdosimeter) and an E stage (particle identification).
- **Micro Plus probe**: silicon detector
- Silicon carbide (**SiC**): semiconductor based
- **HDM** (hybrid detector for microdosimetry): 2-stage microdosimeter composed of a TEPC followed by Low Gain Avalanche Detectors (LGADs).









B) Development of a stochastic microdosimetry-based kinetic model (GSM²) for RBE to improve treatment planning accuracy and effectiveness, as well as to decrease toxicity in the normal tissue.

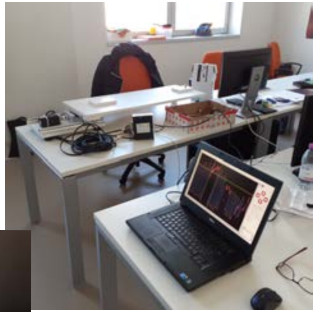
4D phantom for dose measurement of moving targets in hadrontherapy

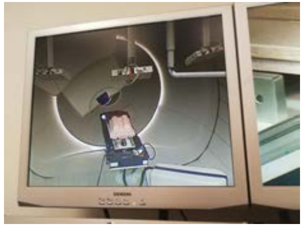
project cofunded by CARITRO

B. Di Ruzza et al

Dose sensor located on a movable plane that will reproduce the x(t), y(t) and z(t) patient breath movement simulated or real (stored using an infrared camera).

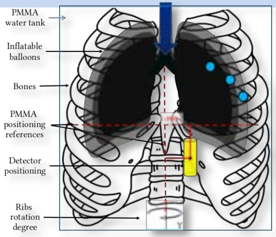
2D (time+X) phantom prototype: delivered and tested in the Trento APSS Gantry on January 2020





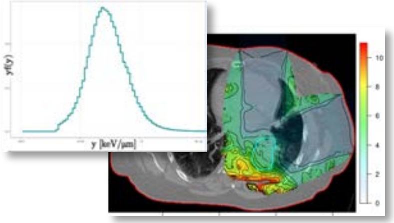
4D LETytBE

A 4D Phantom for radiation quality (LET, *y*) characterization in ion beam therapy

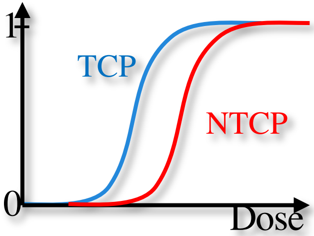


01 4D phantom with respiratory stop-motion and adjustable geometry for translational research

Elettra V.Bellinzona



02 Innovative radiation quality on-line measurement in respiratory motion condition
1. high resolution LET measurement
2. microdosimetric measurement

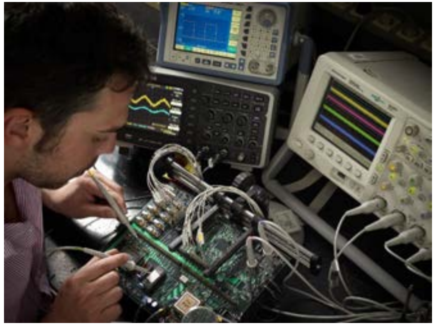


03 . RBE and NTCP/TCP model to account for biological effects and tumor control

Università di Trento
TIFPA Trento Institute for Fundamental Physics and Applications
INFN Istituto Nazionale di Fisica Nucleare Sezione di Roma Tre
Azienda Provinciale per i Servizi Sanitari Provincia Autonoma di Trento

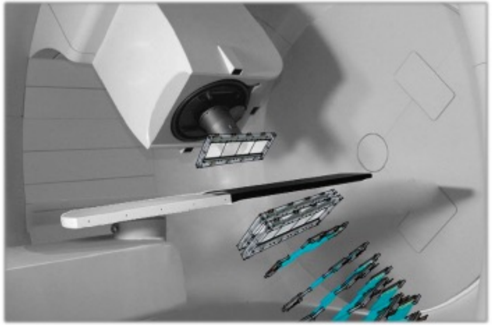
SENSOR Development

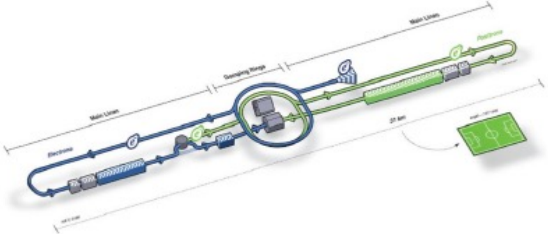
Beyond its own cleanroom, TIFPA can take advantage from FBK facilities (cleanrooms and characterization labs)

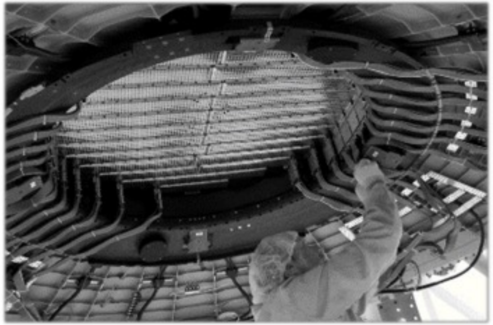


ARCADIA: CMOS Fully Depleted MAPS at INFN

- Design and fabrication platform for large-area Fully-Depleted CMOS sensors, targeting **space**, **medical** and future **HEP** infrastructures (thin sensors) and **X-ray** detectors (thicker sensors)
- **INFN CSNV call project** involving the sections of Bologna, Milano, Padova, Pavia, Perugia, TIFPA and Torino







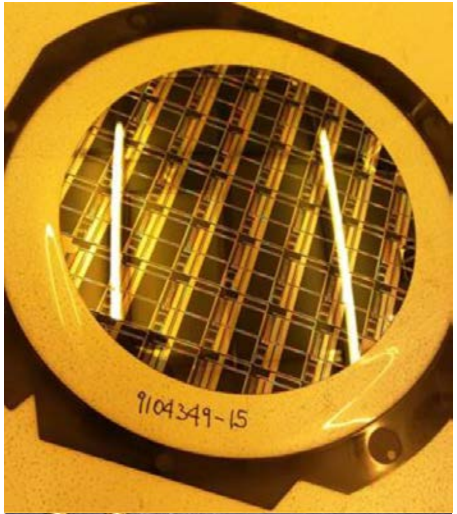
Medical
- Low power (≤ 40 mW/cm^2)
- Medium rate ≈ 10 MHz – 100 MHz/cm^2
- Ultra low material budget (low energy)
- Very large area (≥ 16 cm^2)
- 3-side buttable design
- Low to medium rad-tolerance ≈ 10 kGy

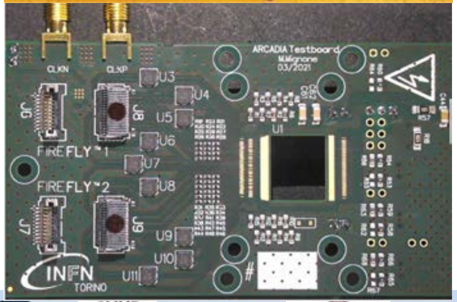
e^+e^-
- Low power (≤ 40 mW/cm^2)
- Medium rate ≈ 10 MHz – 100 MHz / cm^2
- Very low material budget
- Large area (≥ 6 cm^2)
- 3-side buttable design
- Low to medium rad-tolerance ≈ 10 kGy

Space
- Ultra low power (≤ 10 mW/cm^2)
- Very low rate ≈ kHz/cm^2
- Low material budget
- Large area (≥ 6 cm^2)
- 3-side buttable
- Low rad-tolerance ≈ 1 kGy

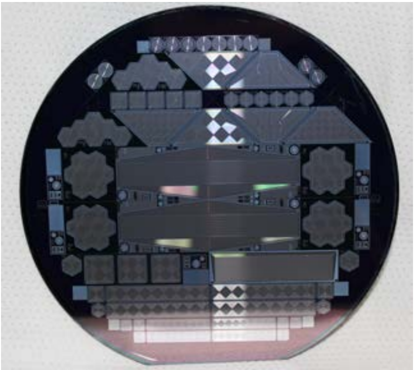
ARCADIA project: current status

- **Process** developed in collaboration between INFN and LFoundry: Italian patent granted, **international patent** pending
- First run, **12 wafers** delivered in May 2021:
  - 3 values of fully depleted active thickness: **50µm – 100µm – 200µm**
  - **Main demonstrator with 512 x 512 pixels** (25µm pitch)
  - **Test devices** for pixel sensors, integrated strips and small pixel arrays
- Current status of test:
  - Sensors: full depletion verified on test structures
  - Operation of digital readout circuitry verified
  - Analog front-end under test
- **Second design** completed in July 2021, **third design** foreseen in 2022
- Expanding **network:** synergy with other collaborations/institutions (PSI, ALICE, RD-FCC, AIDAinnova …)

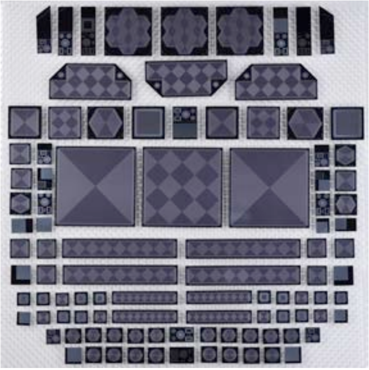




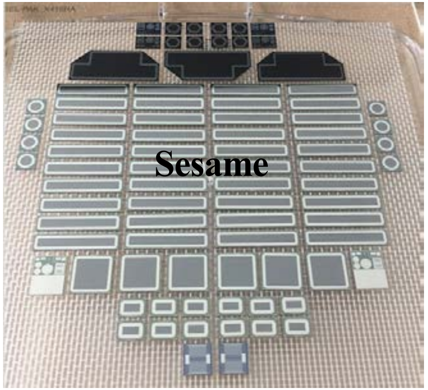
ReDSoX, XRO
Silicon Drift Detector



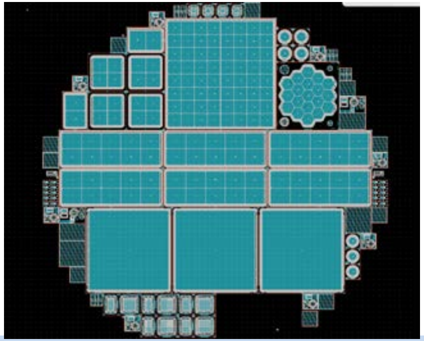
RedSox2
2015



Redsox3
2016



Sesame
2018

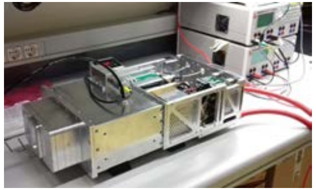


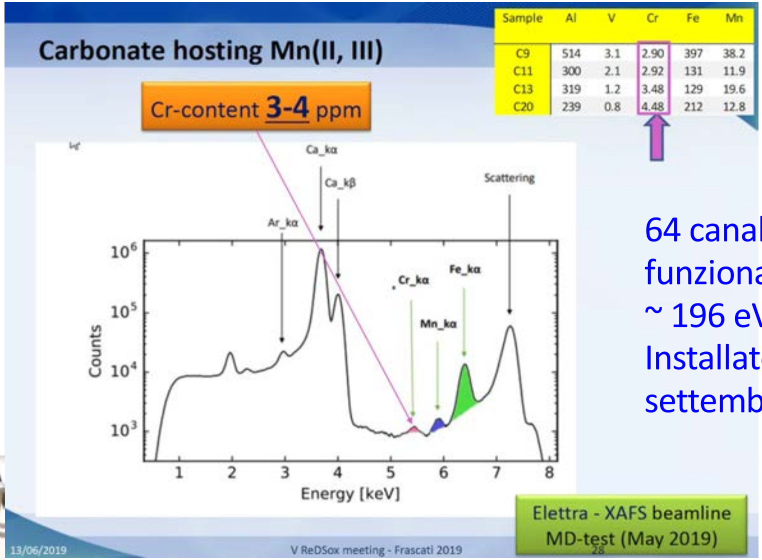
Redsox4
2019

- Test e caratterizzazione eletrica di varie lotti di Silicon Drift Sensors
- Ispezione ottica dei sensori
- Classificazione dei difetti e Studio di resa
- Definizione dei parametri di processo e del materiale attraverso la caratterizzazione delle strutture di test
- Partecipazione al design

Application for Synchrotron Light Experiments

- Sesame





Sample	Al	V	Cr	Fe	Mn
C9	514	3.1	2.90	397	38.2
C11	300	2.1	2.92	131	11.9
C13	319	1.2	3.48	129	19.6
C20	239	0.8	4.48	212	12.8

64 canali perfettamente funzionanti!
~ 196 eV FWHM Fe
Installato in Giordania in settembre 2019

Applications for astroparticle and space

- eXTP (enhanced X-ray Timing and Polarimetry)

Study of matter under extreme conditions of gravity, density and magnetism. For the first time: simultaneous, high-throughput spectral, timing and polarimetry observations.

640 SDD LAD 7x12 cm, 24 SDD WFM 6x7 cm

LAD = Large Area Detector WFM = Wide Field Monitor

- Hermes

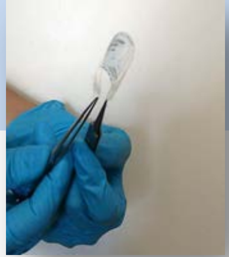
dedicated to the realization of a a cluster of nano-satellites for gamma astrophysics

- Flares

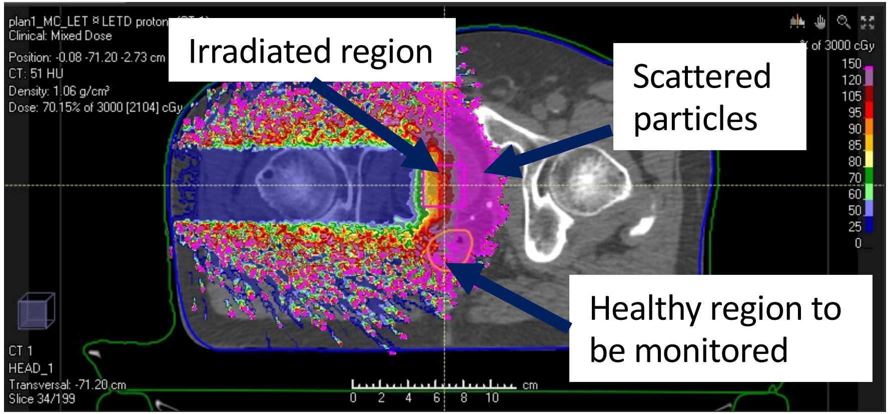
Applicazione di SDD come photodetector per il cristallo scintillante CdWO4 per i studi di "rare nuclear decays, such as the possible neutrinoless double beta decay".

Example of Detector Development

FIRE:
Flexible organing Ionizing Radiation dEtectors



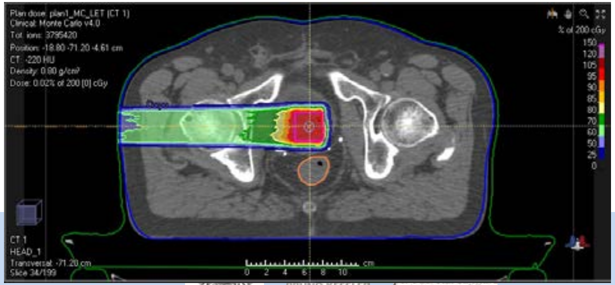
Collaboration Unibo – TIFPA – LNL-UniPD – Roma3-CNR – UniNA+CNR



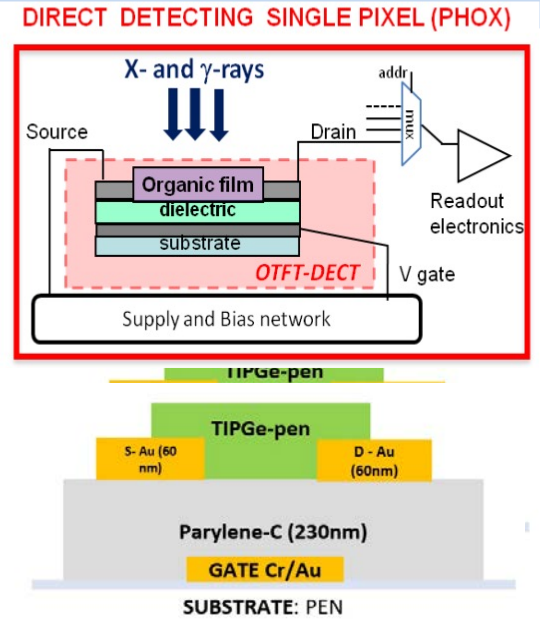
Flexible organic detectors for real time dose monitoring.

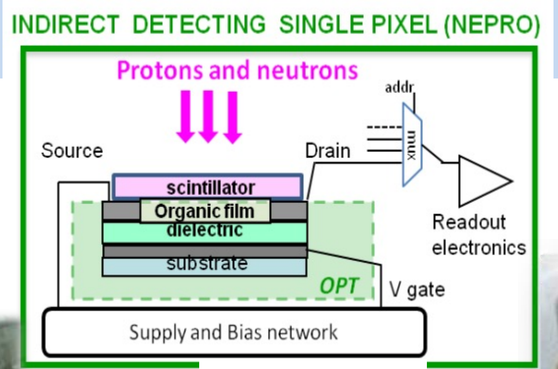
Monitoring of the dose released on healthy tissues during radiotherapy.

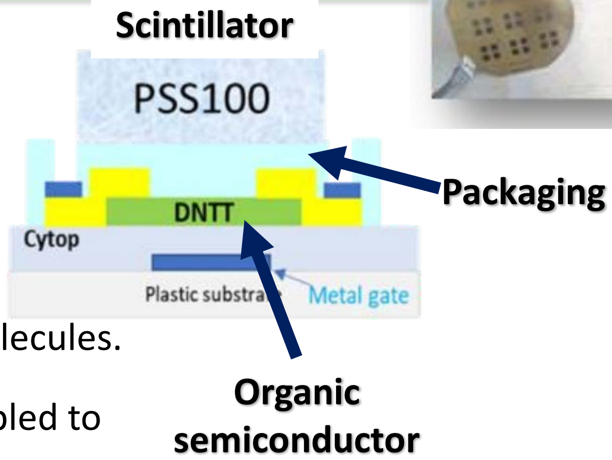
Organic detectors: low cost, low voltage, no clean rooms…

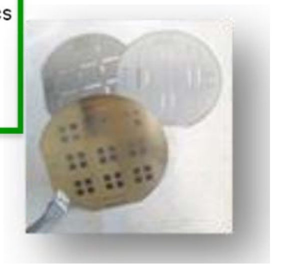


Detector Structure





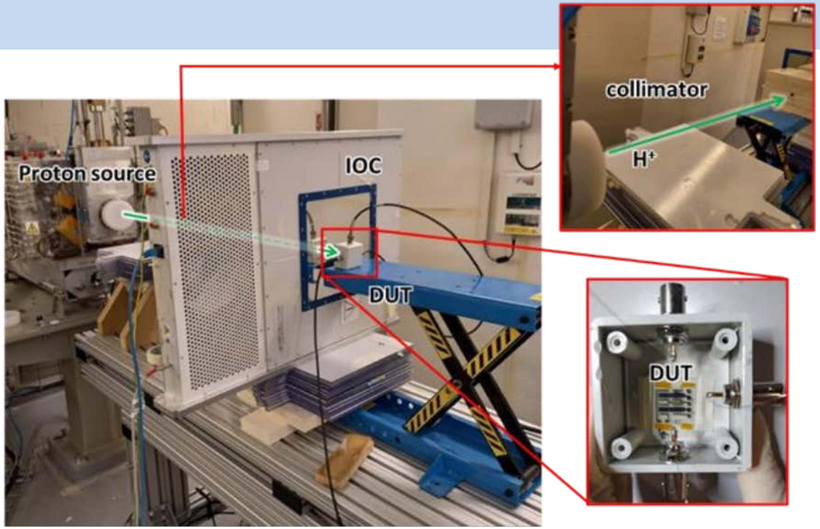


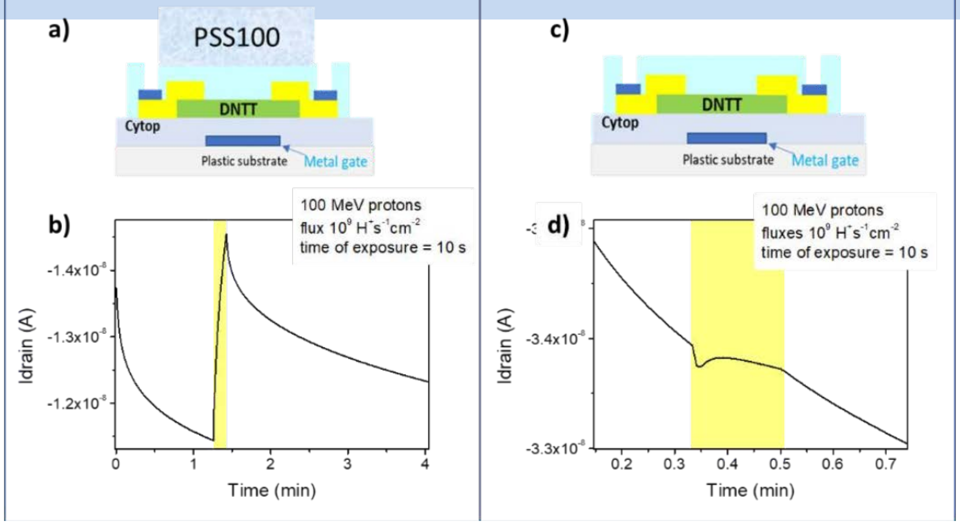


Direct detectors mainly for photons based on crystals of metalorganic molecules.

Indirect detectors for ions based on flexible polysiloxane scintillators coupled to organic photodetectors.

The case of Indirect Detectors





- Preliminary tests on indirect sensors were performed at the APSS proton facility.
- Polysiloxane scintillators were couplet to organic photodetectors.
- The detector exhibits a fast response.
- More complete systematics are planned for the full response characterization.

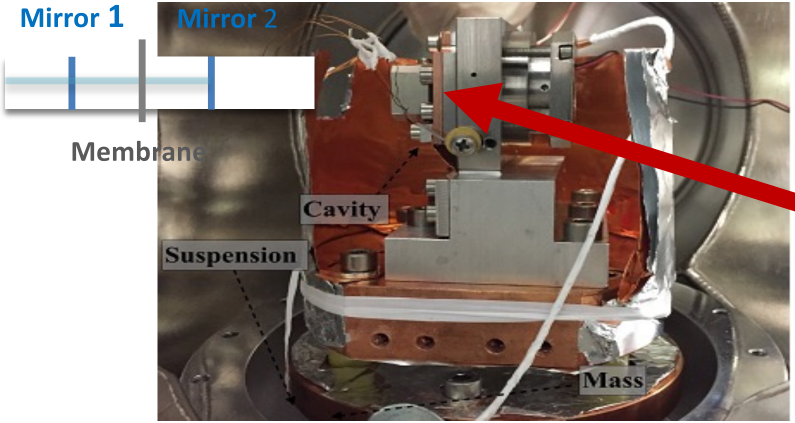
Developments in Quantum Technologies

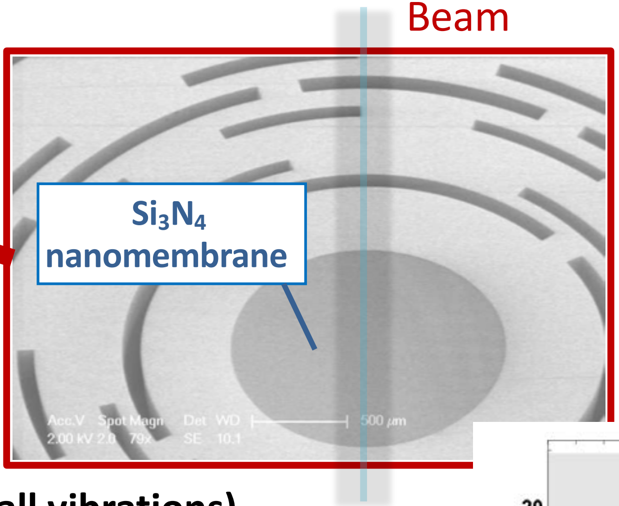
Q@TN is a joint laboratory of University of Trento, Bruno Kessler Foundation, and INFN, aimed at coordinating their on-going activities and to start new ones in the field of Quantum Science and Technologies

- Quantum computing
- Single photon detectors
- RF technology
- Photonic integrated circuits
- Ultracold atoms
- .....

https://quantumtrento.eu/

Silicon Nitride nanomembrane sensors embedded in a Fabry-Perot cavity (Membrane-In-the-Middle)



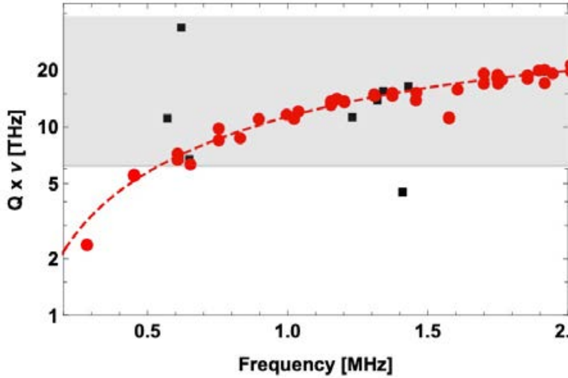


Sensitive to **radiation pressure (small vibrations)** because of low coupling with the thermal bath.

mass of 10-100 ng mechanically resonating at frequencies in the range **0.2-3 MHz** with a mechanical **quality factor in excess of 10^7.**

Q-factor x frequency is related to the number of coherent oscillations

Room temperature Quantum Optomechanical region



E. Serra, M. Bonaldi,…

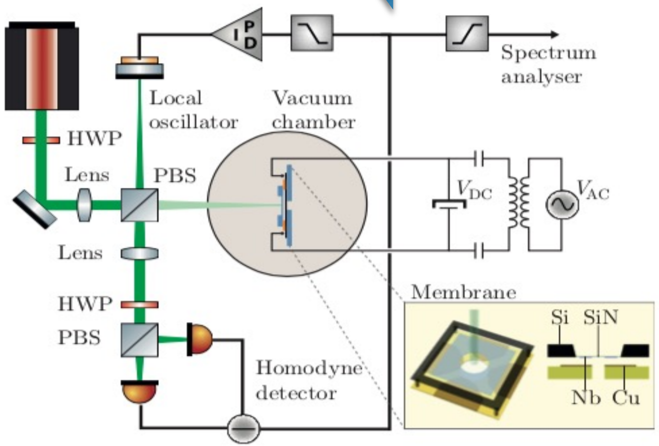
Journal of Applied Physics **130**, 064503 (2021); https://doi.org/10.1063/5.0055954

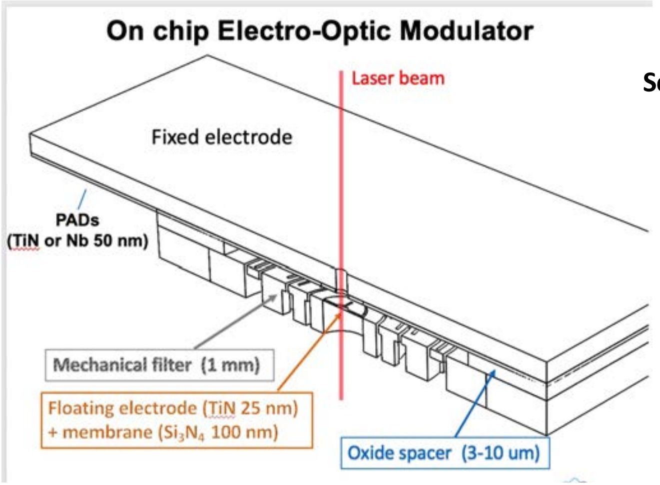
Functionalization by TiN films for RF/Optical transduction

Toward RF/Optical transduction of weak signals exploiting the electro-optomechanical interaction.

Related experiment INFN-THEEOM_RD

OPTICAL DOMAIN ← **RF DOMAIN**



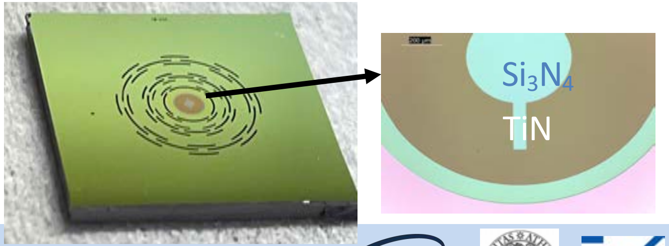


Scientific/technological collaboration in related EU projects:

QUANTERA

QuaSeRT

Functionalized Si_3N_4 nanomembranes can be seen as **ultra-sensitive force detector embedded in a quantum-limited** measurement set-up. This configuration opens new prospective in exploiting the Quantum Technologies for bio-sensing at the Nanoscale with Scanning Force Microscopy, Photo-Acoustic-Detection, as well as 3D imaging of nano-objects at the atomic scale with NanoMRI.



INFN Istituto Nazionale di Fisica Nucleare

FONDAZIONE BRUNO KESSLER

Azienda Provinciale per i Servizi Sanitari

Per maggiori dettagli:

TIFPA Activity Reports

http://www.tifpa.infn.it/contacts/downloads/

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