Development of a tissue equivalent crew dosimeter based on 3D silicon processing

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TEC-EPS Final presentations: Space environment and radiation effects
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Outline

1. Introduction
2. Microdosimetry
3. Solid State Microdosimetry (brief-history)
4. Silicon 3D Microdosimeters
   - Idea and implementation
   - Results from early sensor generations
   - Some notable issues identified and possible solutions
   - Results from the latest sensor generation
5. 3D microdosimeters for space applications
   - Consideration on dosimetry in space
   - Sensor optimization (layout and technology)
   - Readout system and prototype design
   - Characterisation plan
6. Conclusions and Upcoming activities

SINTEF MiNaLab

(Micro- and Nanotechnology Laboratory, Oslo)

- The new laboratory opened in 2005
- Shared facility with the University of Oslo
- Two separate cleanroom floors:
  - SINTEF: 800 m^2
  - University of Oslo: 600 m^2

- SINTEF:
  - Silicon production line with annual capacity of 10.000 wafers
  - 150mm wafers

- Situated on the University of Oslo campus

- QA System apprved ISO 9001:2008

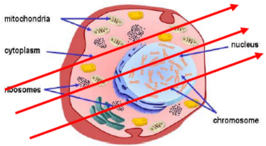
SINTEF

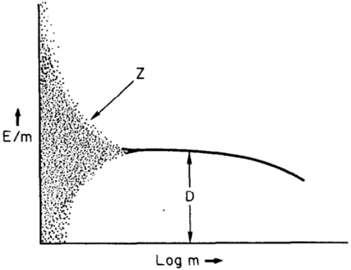
Tissue-Equivalent Crew Dosimeter Based on Novel 3D Silicon Processing

- This project is funded by ESA within the Technology Research Program (TRP)
- The initial development was funded by the Norwegian Research Council, within the NANO2021 program, initially targeting novel Particle Therapy treatments
- The work is carried out at SINTEF MiNaLab in Oslo in collaboration with the Centre for Medical Radiation Physics at the University of Wollongon, Australia.
- **Objectives:**
  1. Design silicon 3D micro dosimeter having:
     » Low-power and real-time operation
     » Operate in mixed radiation fields
     » High-radiation tolerance
     » Mimic the interaction of human tissue with radiation
  2. Develop and finalise the underlying fabrication technology
  3. Design and manufacture a prototype instrument utilising the developed sensors
  4. Characterise the prototype instrument

Introduction to Microdosimetry

- Study of the distribution of the deposited energy in a well-defined microscopic volume
- Aims at relate the type and amount of radiation to a biological effect
- The basic concept of **microdosimetry** is the ”event”, i.e. the energy deposited by a single particel (including δ-electrons) in a cell nucleus
- Microdosimetry focuses on the energy deposited at microscopic level
- The reduction of the target size, changes the deterministic deposition of energy to stochasitc
- Each radiation type has its own signature
- **The standard detector in mircodosimetry is the Tissue Equivalent Proportional Counter (TEPC)**
  - High voltage required
  - Bulky and difficult to reduce in size
  - Low spatial resolution





Fluctuations in dose with low mass/volume Kase, Kenneth R., and Walter R. Nelson. *Concepts of Radiation Dosimetry*. New York: Pergamon, 1978. Print.

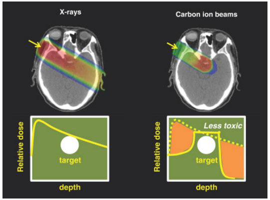
Microdosimetry and Particle Therapy

Particle therapy

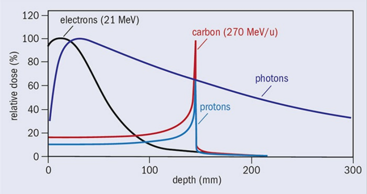
- High conformity
- Enhanced Biological effect

Bragg Peak

- Precise energy deposition
- Targeted and Accurate Treatment
- Less damage to surrounding tissues



**S. N. Ahmed, 'Physics and Engineering of Radiation Detection (2nd Edition) 2015'*



**M. Disanjh, 'The changing landscape of cancer therapy', Physics World, 07 Feb 2018*

For QA and Treatment Planning Systems

- Secondary nucelear fragments
- Secondary neutrons
- Mixed radiation fields and microscopic scale
- Conventional dosimetry is insufficient for precise RBE determination at micron scale
- **Solid-state sensors are a great candidate for the next generation of dosimeters**

Solid-state microdosimetry at CMRP

SOI planar technology

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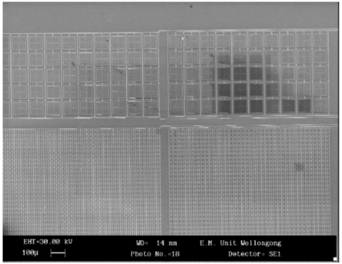
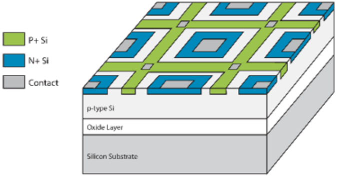
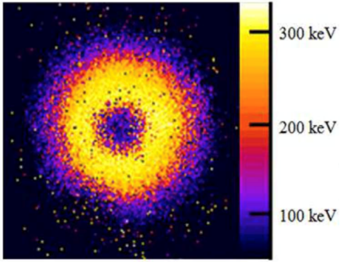
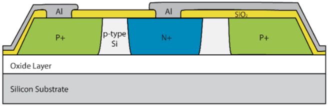


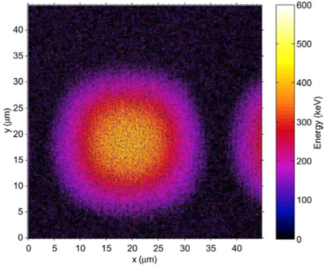


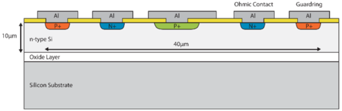
[P. D. Bradley, A. B. Rosenfeld, and M. Zaider, "Solid state microdosimetry," Nucl. Instrum. Methods Phys. Res. B, vol. 184, no. 1-2, pp. 135-137, Sep. 2001.]





[A. L. Ziebell et al., "A cylindrical silicon-on-insulator microdosimeter: charge collection characteristics," IEEE Trans. Nucl. Sci., vol. 55, no. 6, pp. 3414-3420, Dec. 2008.]





[J. Livingstone et al., "Charge collection in n-SOI planar microdosimeters," IEEE Trans. Nucl. Sci., vol. 60, no. 6, pp. 4289-4296, Dec. 2013.]

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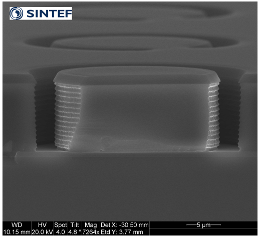
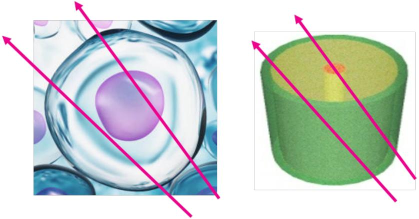
Silicon 3D Microdosimeter

- Idea proposed by CMRP in 2012
- Well-defined microscopic sensitive volumes
- Complete encapsulation of the active volume
- Minimise charge sharing between individual elements
- Can operate with close to zero power consumption
- **3D sensor technology is an ideal candidate for the future of solid-state microdosimeters**

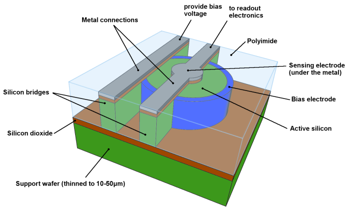




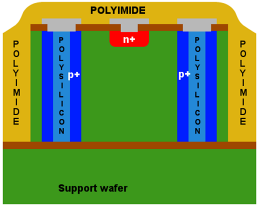
Cell like 3-dimensional detector (µm)

- **Fully encapsulated**
- **Cell size dimensional (~15 µm)**
- **No signal sharing between cells**

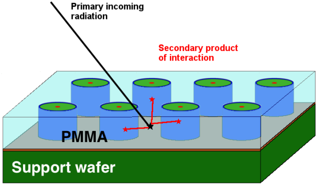
Silicon 3D Microdosimeter



Example of a single cell



Cross-section of a singel cell



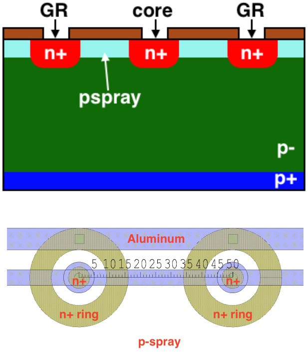
Array of cells

Full design idea based on a CMRP patent (US patent No. 8421022 B2)

- Create single sensitive volumes with 3D sensor technology
- Remove excess silicon outside the cells
- Back-fill with a Tissue-Equivalent material (e.g. Polyimide)
- Mimic interaction of radiation with human cells
- Detect both primary and secondary charged particles produce by the radiation field
- Possible to detect recoils produced by fast neutrons interaction with polyimide

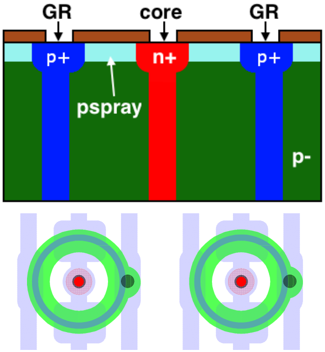
Development through the different generations (1)

Planar benchmark (2015)



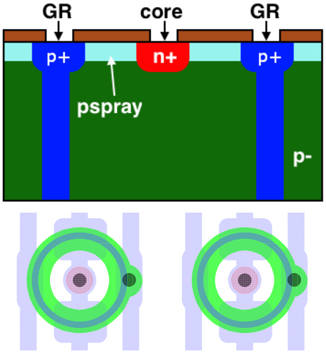
- Planar core and ring electrode
- Uniform back side bias
- P-spray

Full 3D (2016)



- 3D core electrode
- 3D cylindrical trench electrode
- P-spray (only front)

Planar n+ - 3D p+ (2016)



- Planar core electrode
- 3D cylindrical trench electrode
- P-spray (only front)

Development through the different generations (2)

Scanning with focused X-ray beams at ESRF ID21

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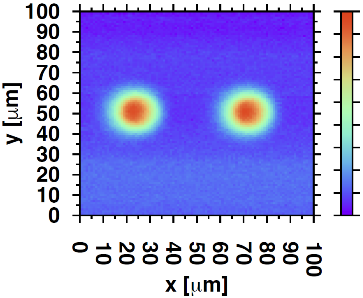
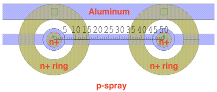
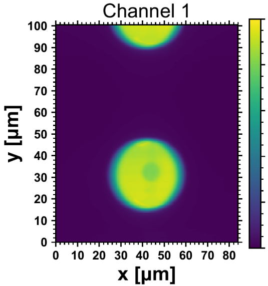
Planar benchmark (2015)

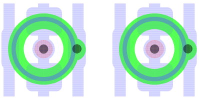




- Good response of the cells
- Considerable smearing at the edges

Planar n+ - 3D p+ (2016)





- Good response of the cells
- Much better definition

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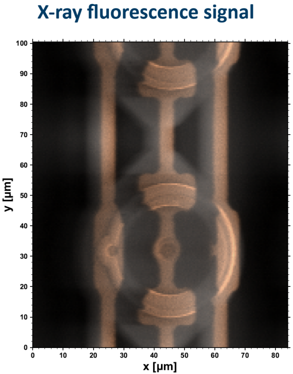
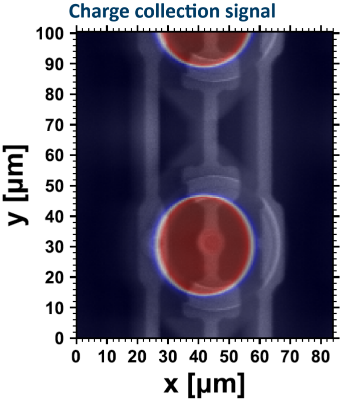
Development through the different generations (3)

Scanning with focused X-ray beams at ESRF ID21





LEFT: X-ray fluorescence detector

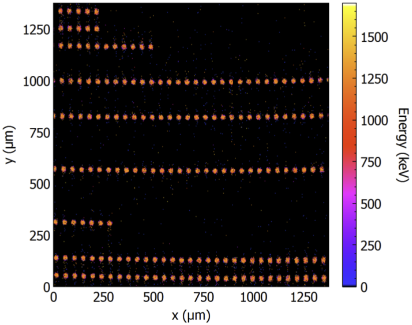
- Precise material information at each x-y scan point
- Helps in determining which areas of the sensor are active

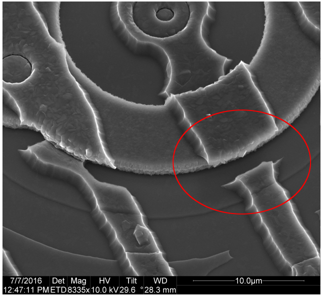
RIGHT: sensor response

- Extremely well confined charge collection
- No signal outside of the cylindrical cells
- **NOTE: small parallax distorsion due to the X-ray beam 30deg incidence angle**

Main issue identified in the early generations

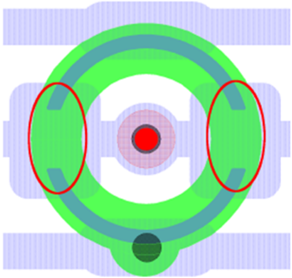
- Some devices showed a low number of working cells
- Issue identified with breaks in the metal lines
- Found to be caused by the topography of the front sensor surface

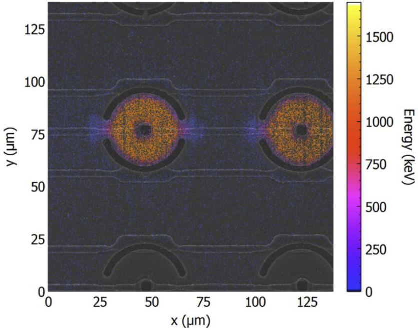




Possible solution - Attempt n.1

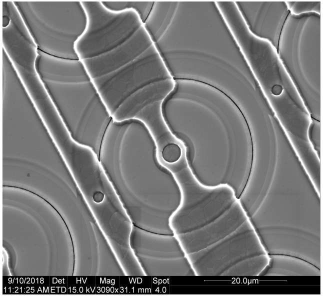
- Crossing the trench with a metal line is a possible point of failure
- Leave an opening in the trench where the surface is flat
- **NOTE:** The cell is not fully enclosed
- **PRO:** Yield problem solved!
- **CONS:** Poor definition of the sensitive volume

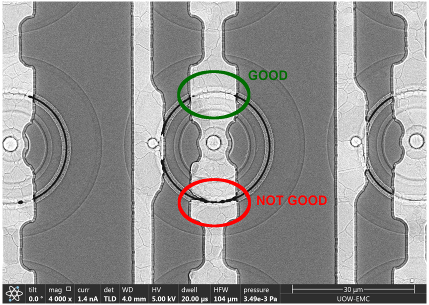




Possible solution - Attempt n.2

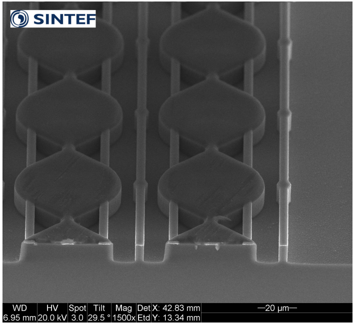
- Planarize the surface of the sensor by removing all unnecessary polysilicon
- **NOTE:** Risk of re-opening the trench after filling
- **PRO:** Good definition of the sensitive volume
- **CONS:** Yield issue improved but some very minor issues still remain

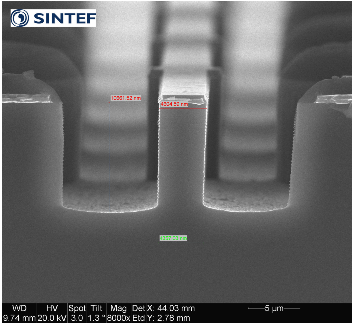


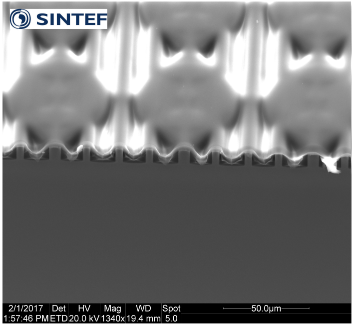


Tissue-equivalent polymer deposition

- Removal of excess silicon outside the cells (Deep Reactive Ion Etching, with photo-resist protection mask)
- Back-filling with a tissue equivalent polymer in multiple steps
- Multiple vacuum and thermal treatments to remove air bubble and set the polymer
- **Requires further optimization / Test of new materials**

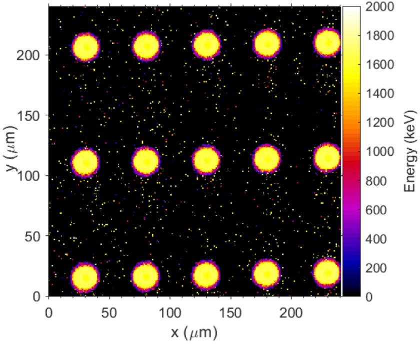


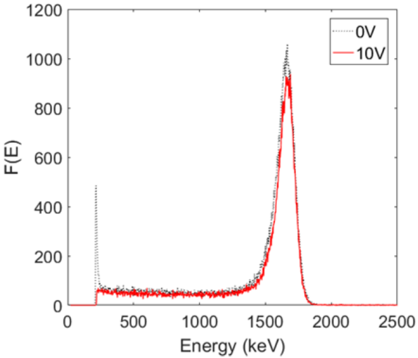




Functional measurment on latest sensor generation

ANSTO - IBIC - 5.5 MeV He^{2+} ions

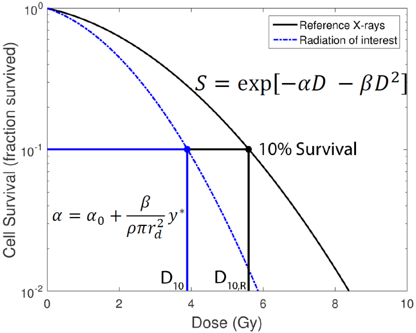


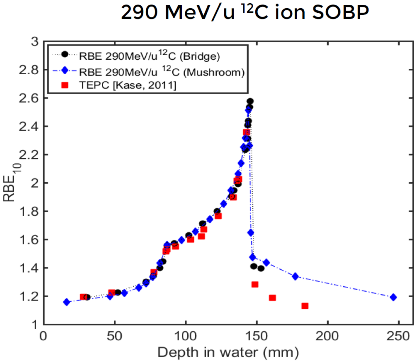


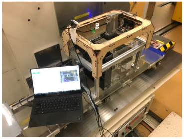
- Median map of charge collection within three rows of a 3D microdosimeter at bias of 10V
- Excellent definition of the sensitive volumes
- Charge collection in agreement with expectations
- Very little influence of bias voltage!!!

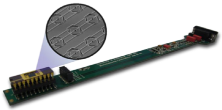
Functional measurment on latest sensor generation

Medical Beam - HIMAC, Japan - ^{12}C ions 290 MeV/u





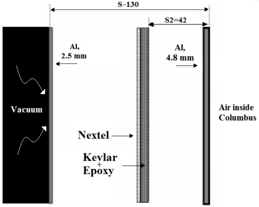




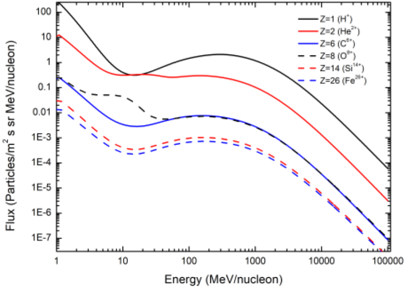
- In medical applications the quantity of interest is the RBE10 (radio biological effectiveness)
- Dose necessary to achieve 10% cell survival rate
- 3D microdosimeters match the TEPC but show higher spatial resolution

Moving toward applications in space...

Considerations on spacecraft shielding layers



Schematic layout of the Columbus debris shield configuration [R. Destefanis et al.]



Radiation models

- CREME96: model for Galactic Cosmic Rays (GCR) (p and α up to 100GeV/u)
- JPL-91: model for Solar Particle Events (SPEs) (SPE protons up to 500 MeV)
- NASA AP8/AE8: model for Van Allen Belts (p up to 400 MeV, e up to 7 MeV)

Dose Equivalent evaluation inside the ISS

Microdosimetric Spectra analysis:

- Calculation of the Dose Absorbed in Silicon (D_{Si}) and in Tissue Equivalent (D_{TE})
- Calculation of the Mean Quality Factor (Q_{mean})
- Calculation of the Dose Equivalent (H)

Analyitical calculation of the Dose rate in 1day-mission inside the ISS:

- Calculation of the daily Dose Absorbed in Tissue Equivalent (D_{TE}) and the Dose Equivalent (H)

Source 2π	Q_{mean}	D_{TE} (μGy/d)	H (μSv/d)
GCR protons	1.41	190	267
GCR alpha	1.52	39	60
SPE protons	0.73	42	31
Trapped protons	0.69	550	378

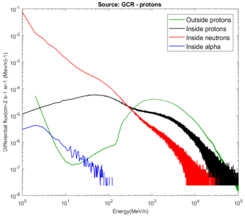
Simulation: 2x10^9 events/source

$$Q(y) = \frac{a_1}{y}[1 - e^{(-a_2 * y^2 - a_3 * y^3)}]$$

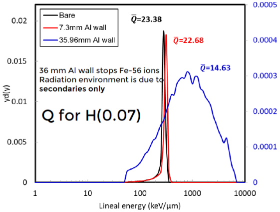
$$D_{TE} = D_{Si} * 0.58$$

$$H = D_{TE} * Q_{mean}$$

- Excellent agreement with measured Dose Equivalent with the ISS TEPC
- 3D Microdosimeters are possible choice for aviation and space radiation environments



500 MeV, Fe-56 Ions (10mm PMMA + Al):



Experimental results, S. Peracchi, et al., https://doi.org/10.1109/TNS.2019.2943597

Optimization of the single sensitive volume (1)

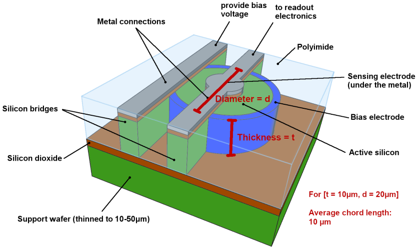
1. Radiation Hardness (sensor)

- Total fluence received from cumulative irradiations with medical beams
- No noticeable modification in sensor properties
- 3D sensor technology has been proven to operate correctly at over 10^{16} 1MeV n.eq./cm^{2}i

	Fluence (counts/cm2)		
	Primary	*Fragments*	*Total*
Carbon 290 MeV/u Wall experiment	1.80E+08	9.50E+07	2.75E+08
Si 230 MeV/u (Experiment in water)	6.89E+07	8.62E+07	1.55E+08
Si 230 MeV/u (Wall experiment)	1.26E+06	1.18E+08	1.20E+08
Si 180 MeV/u (Wall experiment)		2.04E+07	2.04E+07
Total fluence	**2.50E+08**	**3.20E+08**	**5.70E+08**

2. Aspect ratio of the single sensitive volumes

- Experimental evidence point to an optimal structure where the thickness is the same as the mean chord length
- For example: t=10μm, d=20$\mu m \Rightarrow$ mean chord length, $\bar{l} = 10\mu m$
- This is already taken into account in the new sensor layout
- Wafers with multiple thicknesses will be tested (from 2 to 50μm)



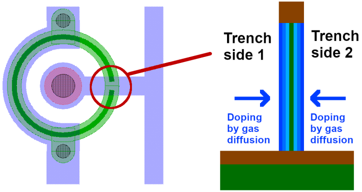
Optimization of the single sensitive volume (2)

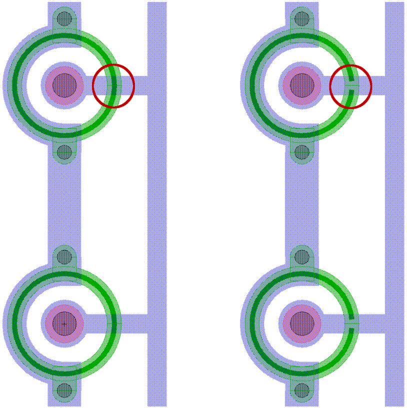
New metal connections

- Shift of the metal line for the core electrodes
- Series connection
- A single failure does not disconnect a full line

Smaller trench opening and deeper doping

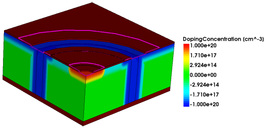
- Leave a small opening ($\sim 2\mu m$)
- Join the two sides with deep gas doping diffusion
- Creation of a ”doped” wall

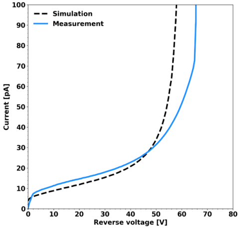




Numerical simulations

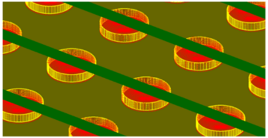
TCAD simulations

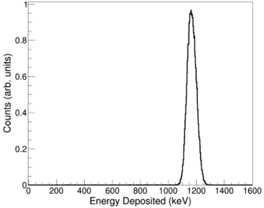




- Detailed TCAD numerical model
- Process parameters extracted from production
- Very good agreement

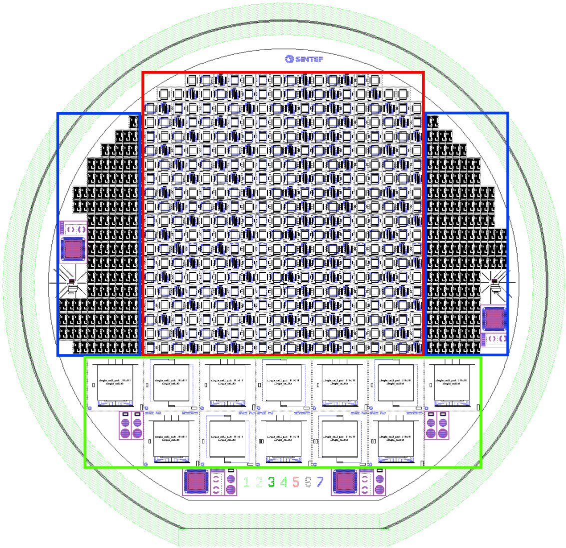
GEANT4 simulations





- Real sensor dimensions measured with SEM
- 6 MeV Helium Ions (same as ANSTO)
- Simulated energy measured 1.15MeV
- In agreement with experiments

Wafer layout and sensor options

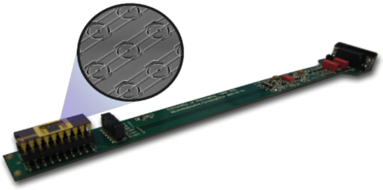


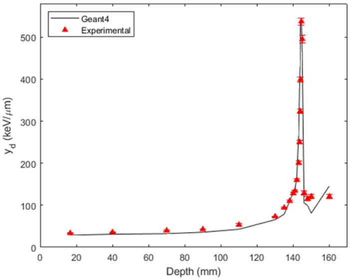
- Multiple sensor implementations
- Diodes, strips, pixels...
- A total of ∼600 sensors per wafer
- Minimum 12, maximum 48 wafers per batch
- Cost per sensor roughly 10-20€
- Production time 5-6 months

Readout electronics (1)

Simulation vs. Experiment

MicroPlus probe for medical applications

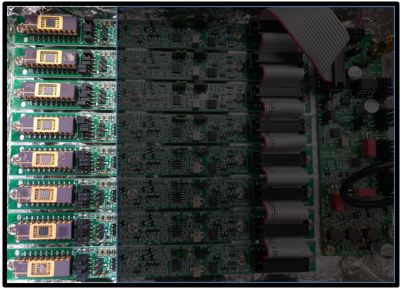




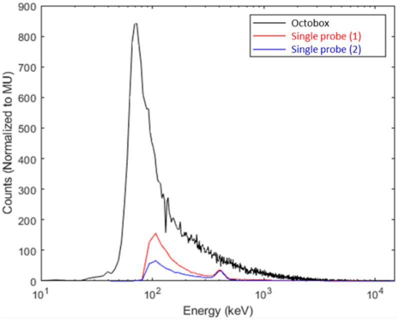
- The MicroPlus probe is designed and produced at CMRP specifically for medical applications (Ion Therapy)
- Can house one sensor of maximum size 4x4 mm^2
- Operates very good in high intensity field where the counts per second are high
- Wireless operation
- **For the type of fluxes encountered in space the sensor area must be increased, but this can lead to SNR degradation due the larger capacitance and current...**

Readout electronics (2)

"Octobox"



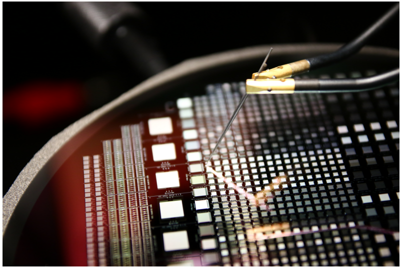
Count comparison with MicroPlus



- The Octobox is designed and produced at CMRP specifically for space applications
- Allows to increase the total sensing area without going to strip or pixel detectors that require "power hungry" ASICS
- Can house 8 sensors in parrallel (total size 1.28 cm^2)
- Automatic detection of channel over threshold and full parallel operation
- Wireless operation
- **Considerable increase in counting rate with no SNR degradation**

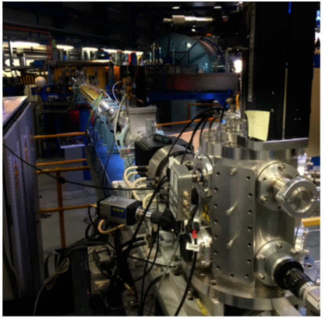
Characterisation plan

Electrical parametric testing



- Verification of fabrication quality with standard test structures
- Current/Capacitance tests on 3D microdosimeters at wafer level
- Automatic probestation for full characterisation and rapid yield estimation

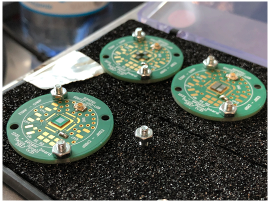
Radiation testing

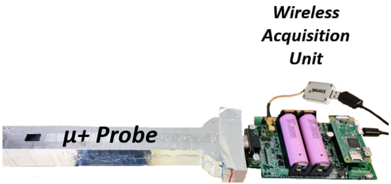


- CMRP will be in charge of radiation testing
- Several beam time slots available during the year
- ANSTO, Australia; HIMAC, Japan; Pavia/Catania, Italy...
- Planning for additional beam time at ESRF ID21 for detailed functional scans

Conclusions and Upcoming activities

- The 3D microdosimeter sensor technology at SINTEF is now mature
- Results from previous sensors generations are well understood and very promising
- Ready to order the photo masks and start the fabrication on the next technology iteration
- Tests on previous sensor generations are continuing with focus on space radiation
- The new readout electronics is being characterised and further improved
- Complete fabrication expected by the summer 2020
- Full prototype characterisation summer/autumn 2020
- Currently investigating possible collaborations with other groups to produce a flight ready instrument



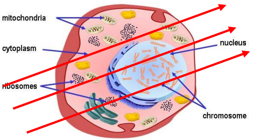


SINTEF

Technology for a better society

BACKUP SLIDES

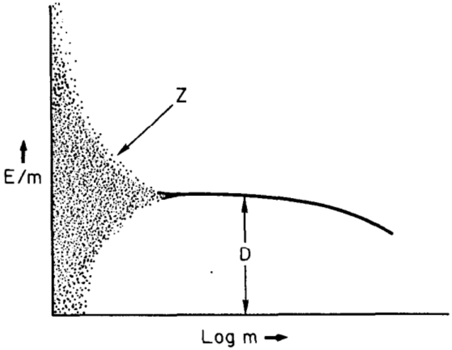
Introduction to Microdosimetry



- Study of the distribution of deposited energy in well-defined microscopic volumes
- Aims to relate the type and amount of radiation to a biological effect
- The **basic concept of microdosimetry** is the event , i.e. energy deposited by a single particle (including δ-electrons) in a cell nucleus volume -site
- Fundamental quantity lineal energy:

$y = \frac{\epsilon_1}{\bar{l}}$ with distribution $f(y)$

$$y_D = \frac{\int_0^\infty y^2 f(y) dy}{\int_0^\infty y f(y) dy}$$



Fluctuations in dose with low mass/volume Kase, Kenneth R., and Walter R. Nelson. *Concepts of Radiation Dosimetry*. New York: Pergamon, 1978. Print.

Energy per unit mass vs mass for *constant* dose D.

Reducing of the target is changing deterministic deposition of energy to stochastic. Each radiation type has own signature.

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Radiobiological Effectiveness (RBE)

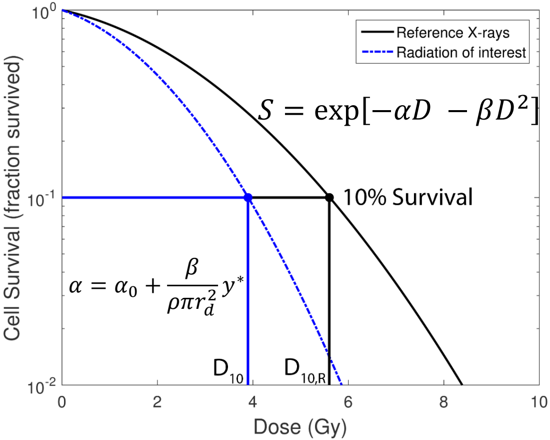
- **Relative biological Effectiveness (RBE):**

$$RBE_{10} = Dose\ that\ gives\ 10\%\ cell\ survival\Big|^{X-rays}_{Radiation}$$
$$= \frac{D_{10,R}}{D_{10}}$$
$$= \frac{2\beta D_{10,R}}{\sqrt{\alpha^2 - 4\beta\ln(0.1)} - \alpha}$$

where α and β are cell- and radiation-specific characteristics

- **Biological Dose takes into account the differing RBE of radiation at each point in the body:**

$$D_{Biological} = RBE_{10} \times D_{Physical}$$



Example Cell survival curves demonstrating the meaning of RBE_{10}

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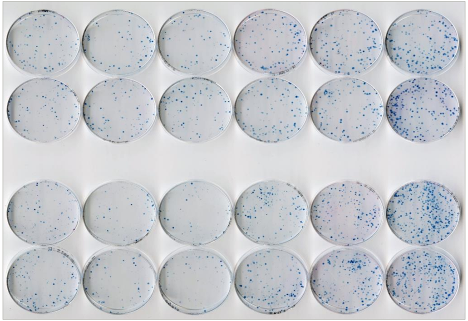
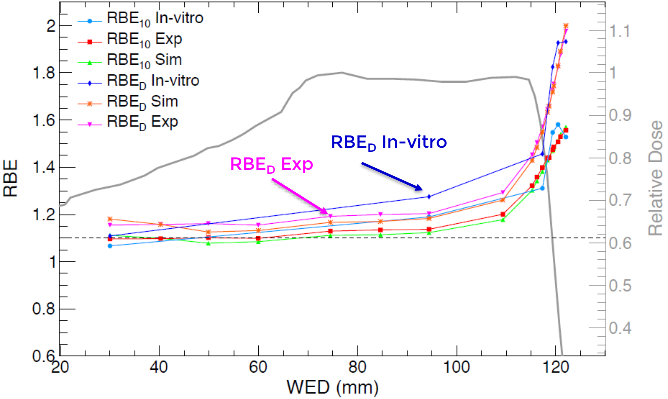
Comparison of RBE obtained with Si microdosimeter and cells
130 MeV SOBP protons, passive scattering (in-field measurement)



Petri-dishes representing colony survival in CHO-K1 cells at 6 positions (from left to right: 18.98%, 39.76%, 57.18%, 83.44%, 101.10% and 74.88% of along the Bragg curve, exposed to doses of 4 Gy (2 top rows) and 8 Gy (2 bottom rows). *Courtesy of Charlot Vandevoorde et. al.*



RBE values calculated from in-vitro CHO cell survival curves and calculated using the modifed MKM with CHO fit parameters and lineal energies.

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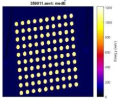
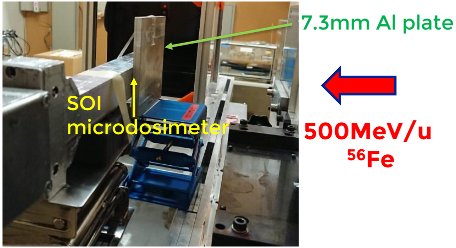
E Debrot, L Tran, L Chartier et. Al. "SOI microdosimetry and modified MKM for evaluation of relative biological effectiveness for a passive proton therapy radiation field", ***Physics Medicine and Biology, 2018***

Ions Fe-56 , energy 500MeV/u

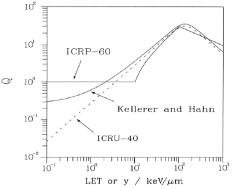
Aims: Modelling of radiation environment inside of the Columbus module
Effect of the THIN and THICK Aluminium wall (7.3 mm and 36 mm.)
0.07 mm and 10mm PMMA slab in front of MicroPlus
Mushroom 10um | 2x2mm^2 | 18um diameter | 50um pitch

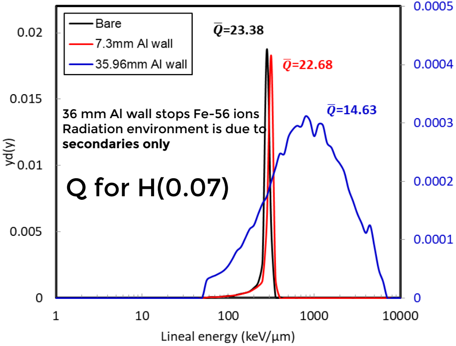


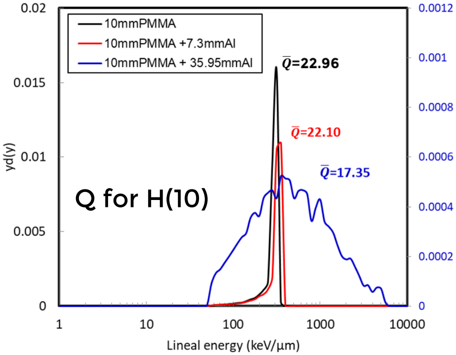


Average quality factor:

$$\bar{Q} = \int_0^\infty Q(y)d(y)dy$$







❑ **European Space Agency (ESA)** grant for project: *“Tissue-Equivalent Crew Dosimeter Based on Novel 3D Si processing”* **2018-2020** €300K (CMRP **U.S. Patent No. 8421022)**