3D sensors for microdosimetry with ions

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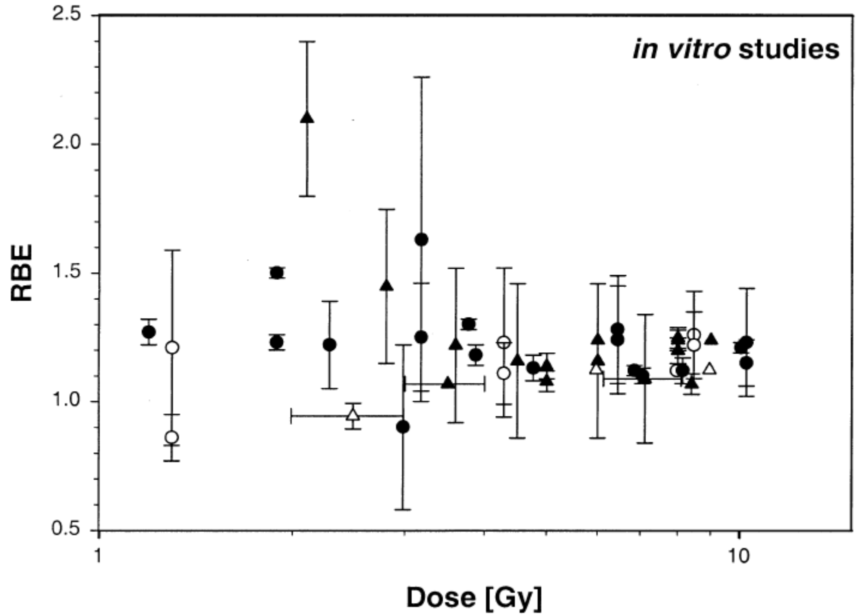
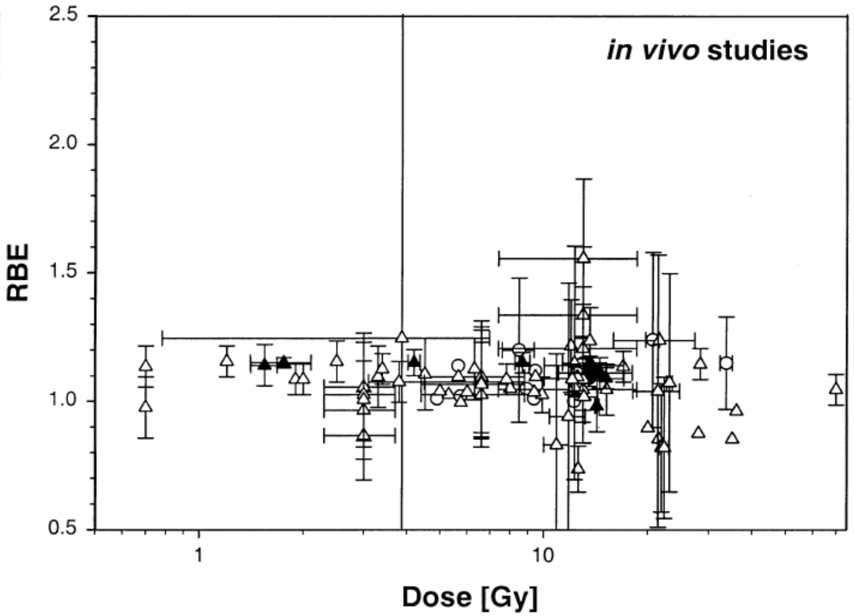
Relative Biological Effectiveness (RBE) is not constant!





Paganetti et al., Int. J. RadiationOncology Biol. Phys. Vol.53, N2, pp407-421,2002

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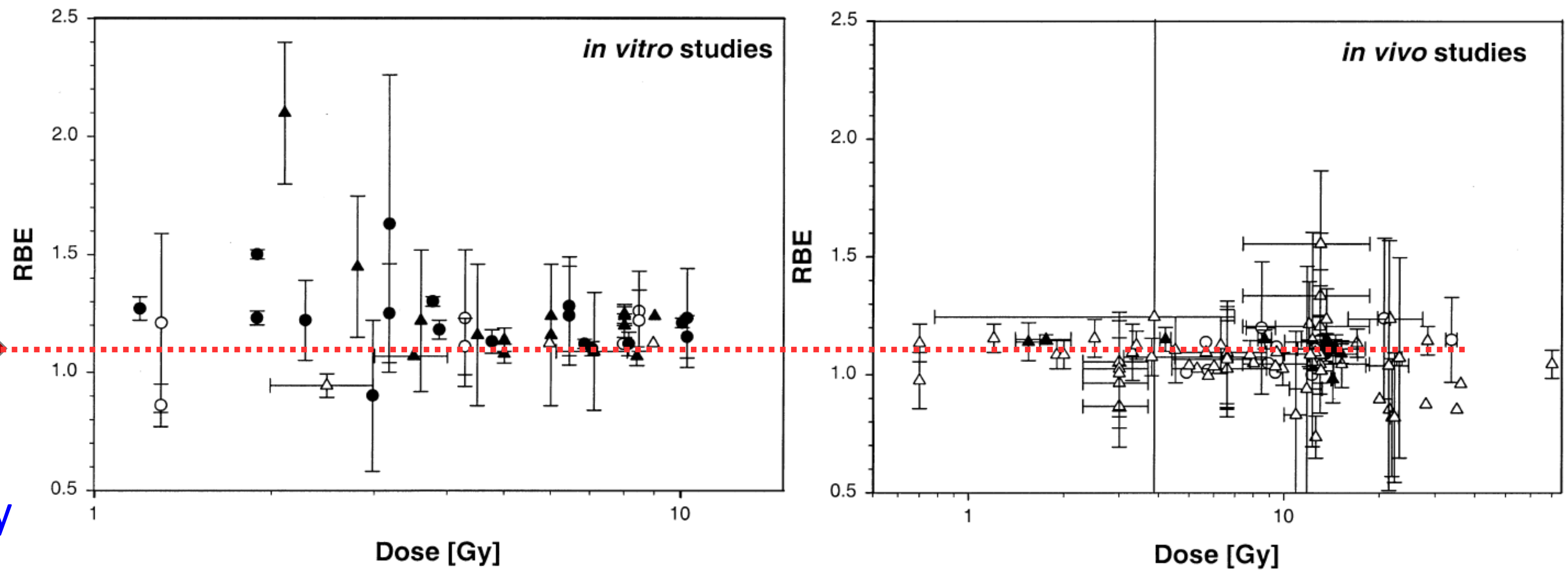


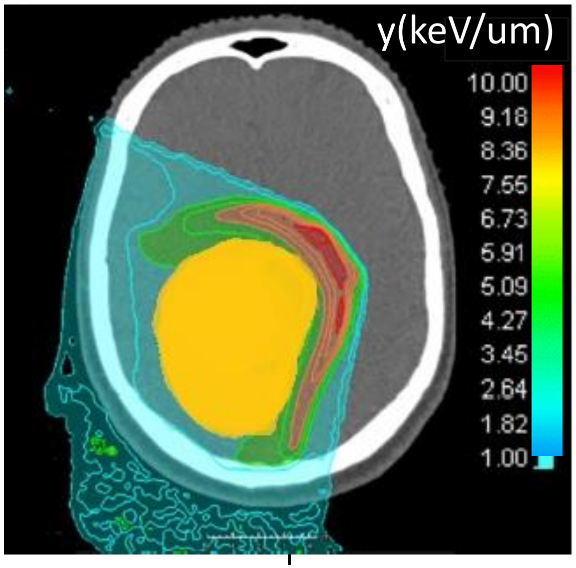
1.1

proton therapy

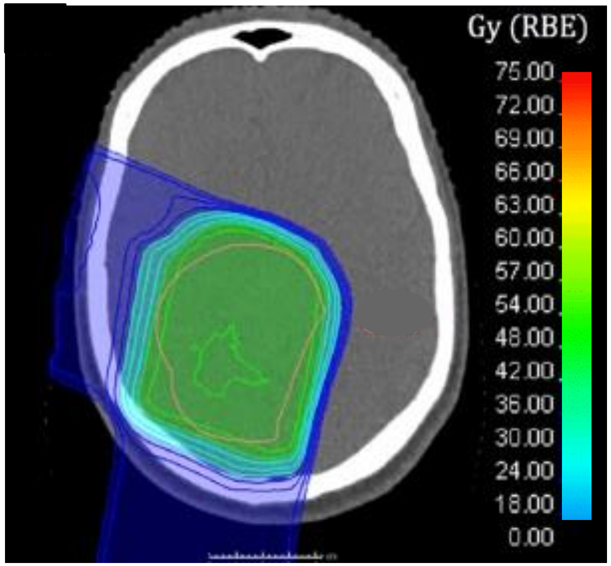
In current clinical practice it is assumed that proton beams are **10%** more efficient than clinical photon beams for cell-killing

MKM, LEM

Physics → Biological effectiveness (RBE)



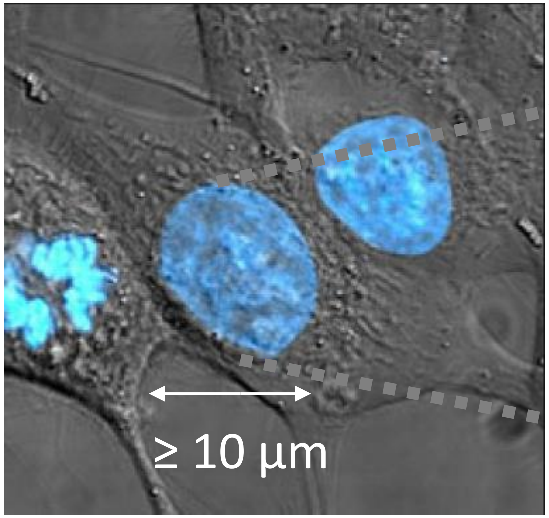
$$D_{Biol} = D_{Phys} \times RBE$$

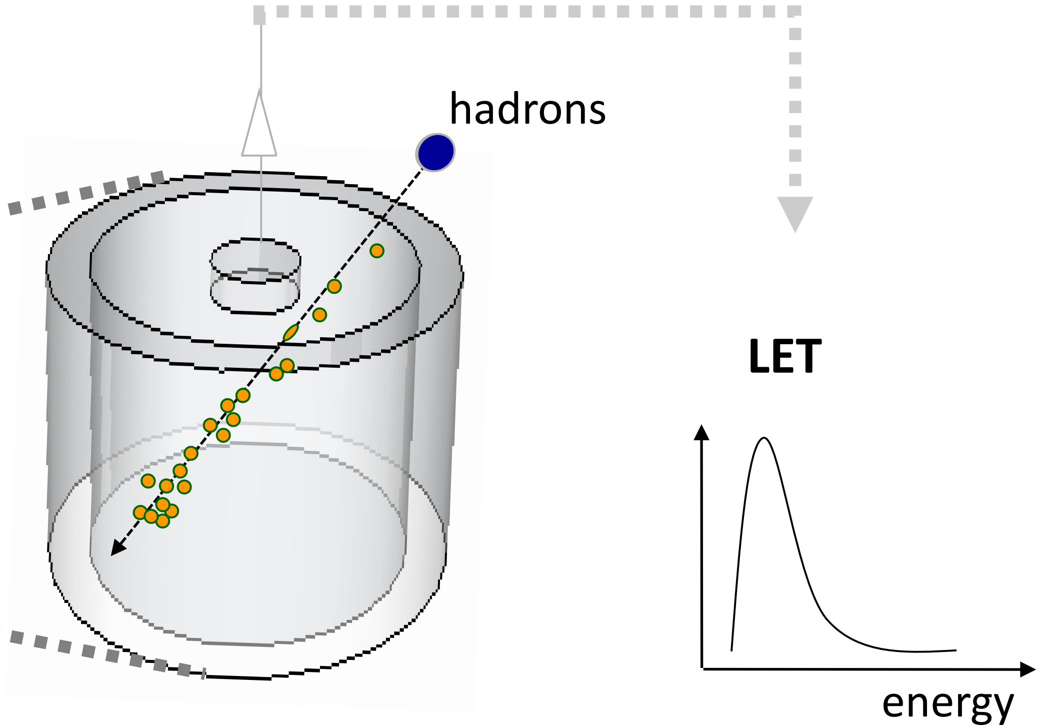


Quantify LET

Optimize patient treatment preserving healthy tissues

Idea: to create radiation 3D-microdetectors as cellular nucleus

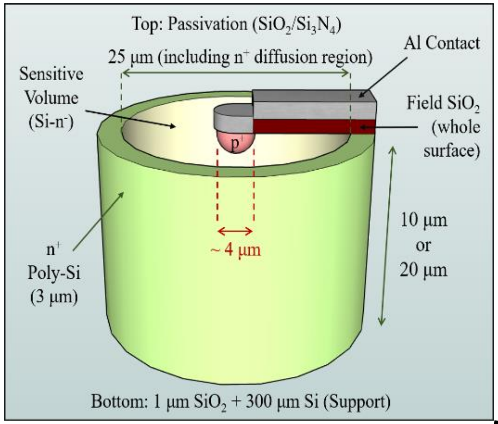


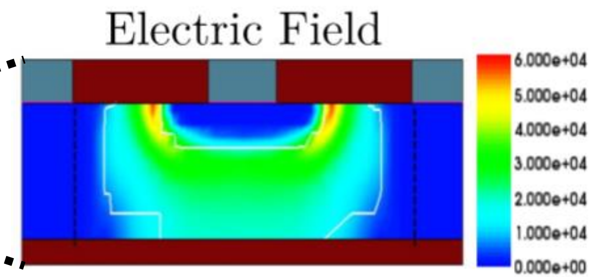


DNA is inside **cellular nucleus**
→ where we need to know **LET**

novel 3D-cylindrical silicon diode:
well-defined micro-volume

Novel 3D-cylindrical silicon microdetectors

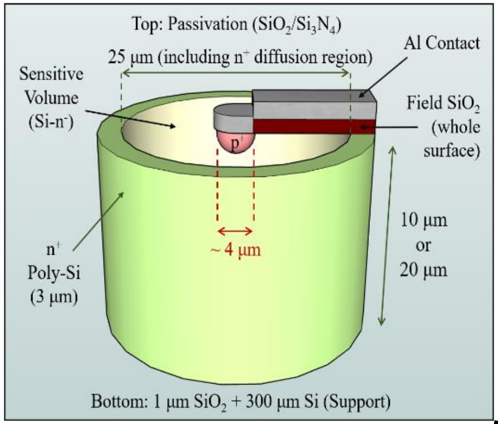


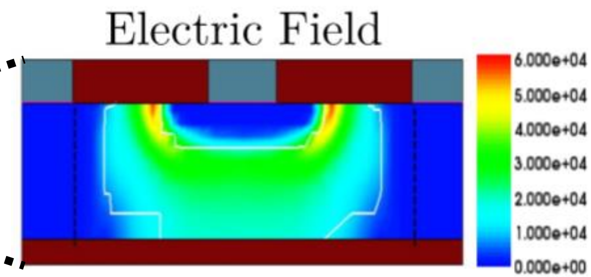


C. Guardiola et al.,
Brevet ref: PCT/ES2015/070056

Diameters: 9, 10, 15, 20, 25 µm
Thickness: 5, 10, 20 µm

Novel 3D-cylindrical silicon microdetectors





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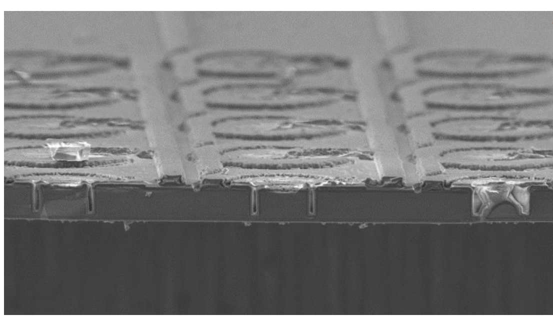
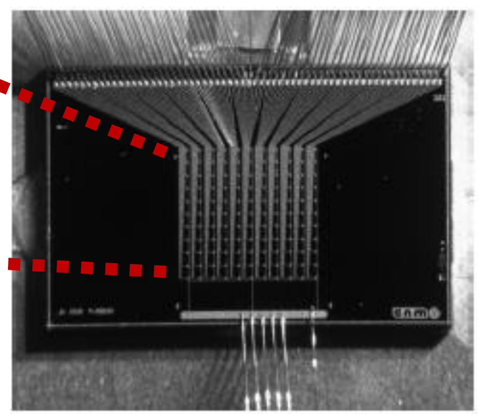
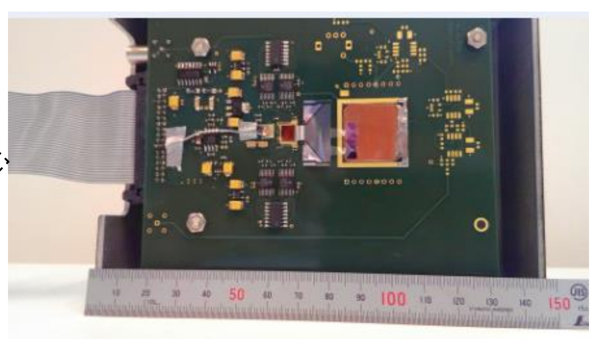


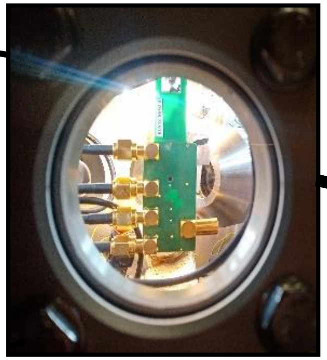




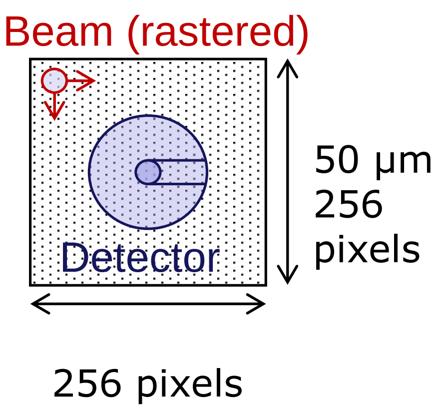
Pitch: 25, 50, 100, 200 µm

Charge Collection Efficiency (CCE)

Studied with **ion beam induced charge (IBIC)** technique

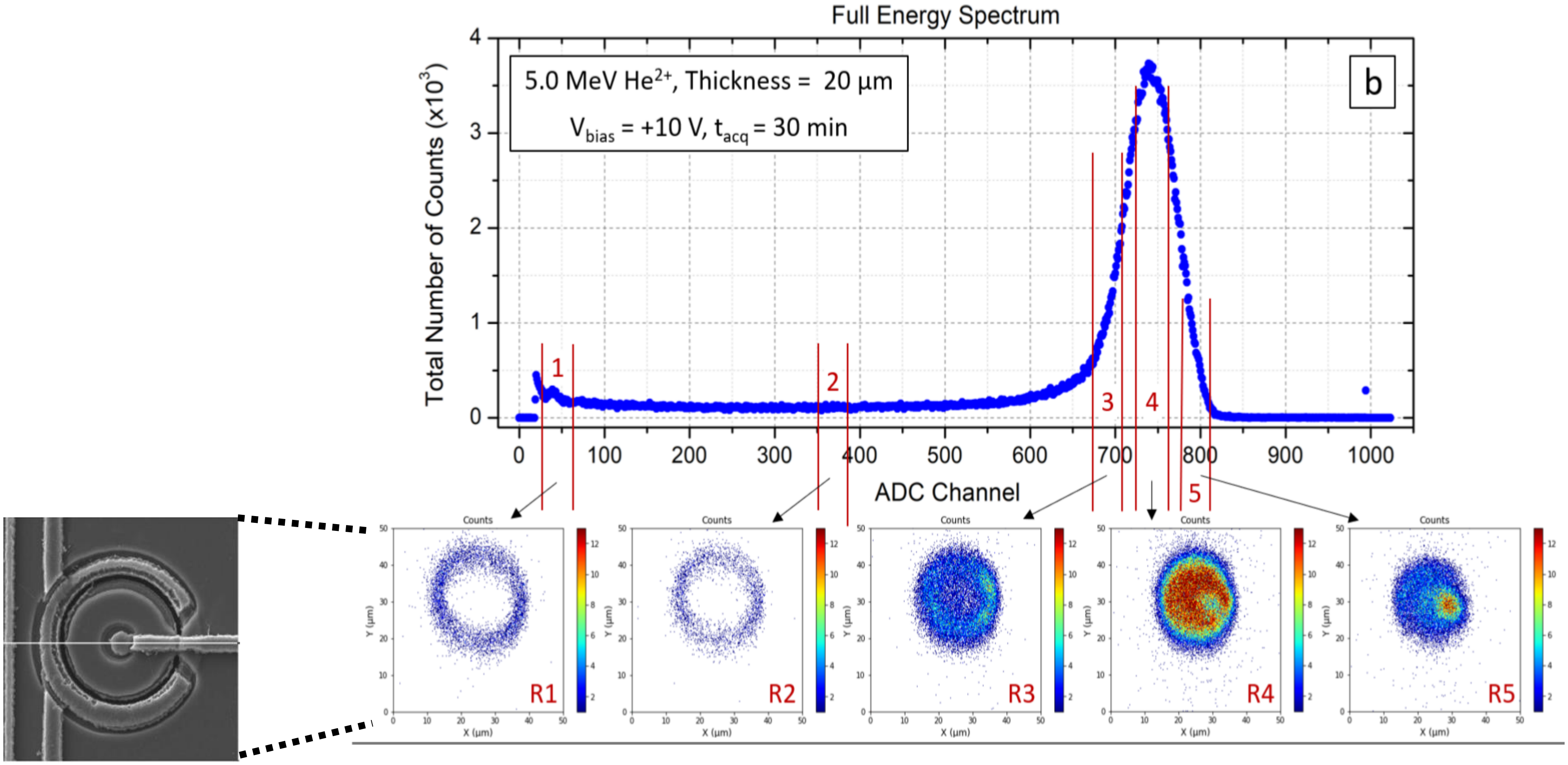


Centro Nacional de Aceleradores (CNA, Seville)



- 5 MeV alpha microbeam(3 µm × 3 µm)
- $4 \cdot 10^{7}\ s^{-1}cm^{-2}$

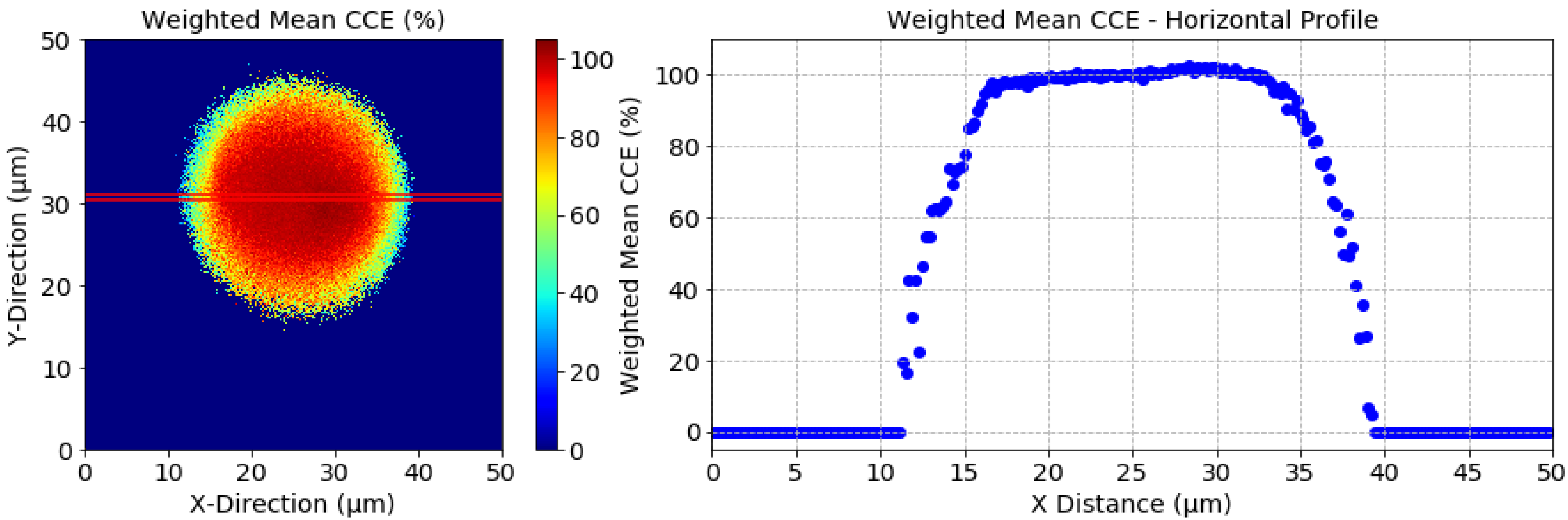
CCE has effect on the evaluation of the imparted energy



Near the edge the CCE may be lower
(lower electric field, some carriers diffuse outside detector)

Bachiller-Perea D. et al., IEEE Transactions on Instrumentation & Measurement, Vol.70, 2021

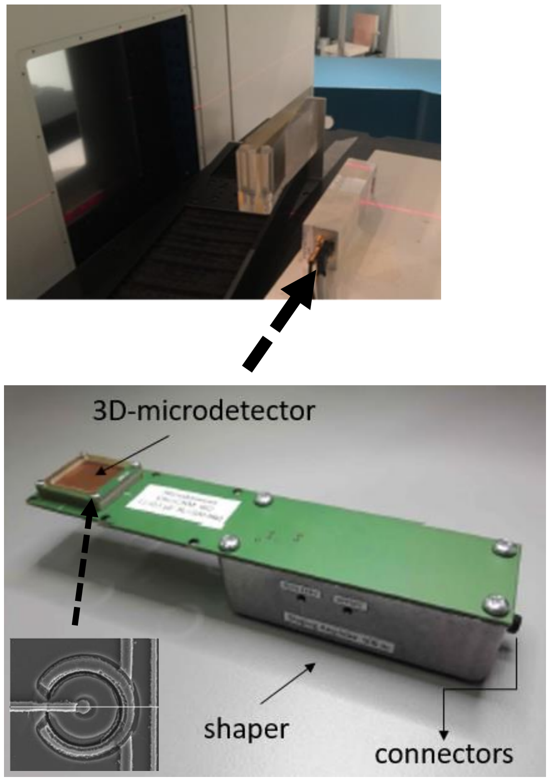
CCE has a radial dependence



CCE decreases slowly from 100 % to 90 % as a function of the radial distance until r ≈10.75 µm, and then it drastically falls to our detection limit (3.5 %) near the detector edge (< 1.5 µm)

Bachiller-Perea D. et al., IEEE Transactions on Instrumentation & Measurement, Vol.70, 2021

RBE evaluation at therapeutic fluence rate ($5 \cdot 10^7$ $s^{-1}cm^{-2}$) in carbon therapy (CNAO, Italy) @ 115.23 AMeV ^{12}C



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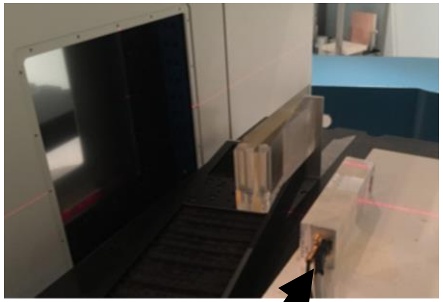

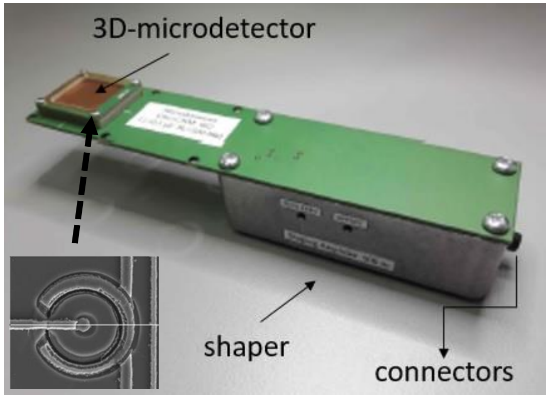

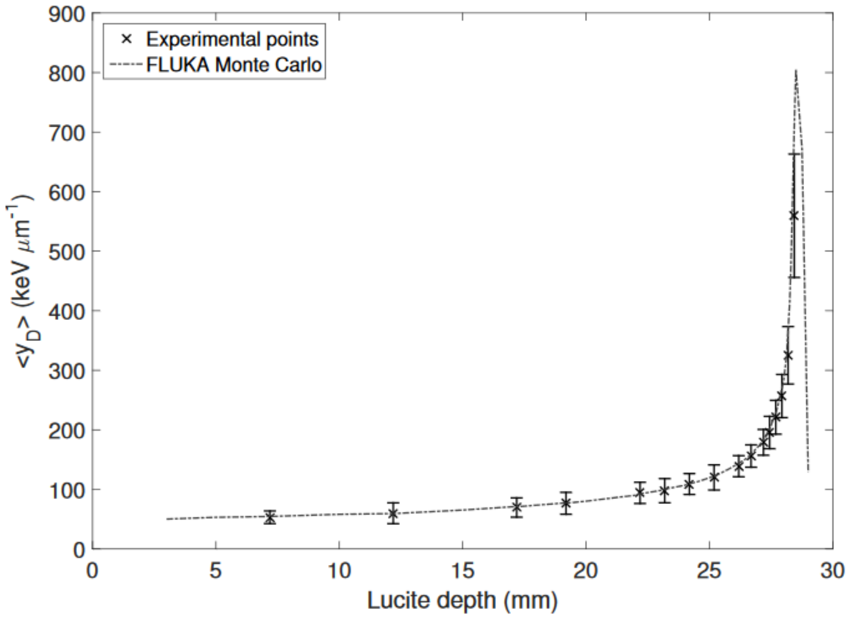

Prieto-Pena J. et al. IEEE Transactions on Nuclear Science, Vol 66, Issue 7, July 2019

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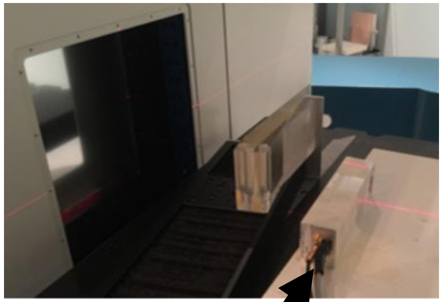
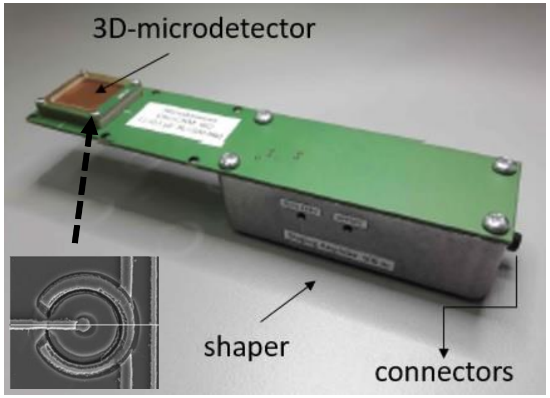
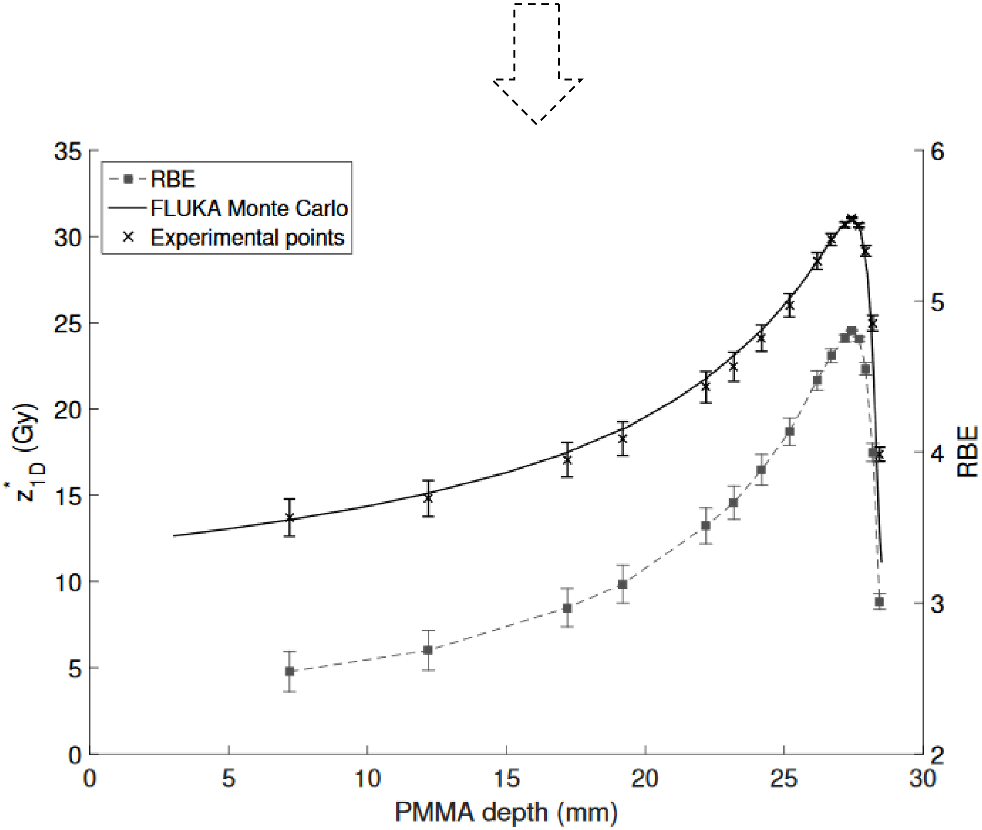
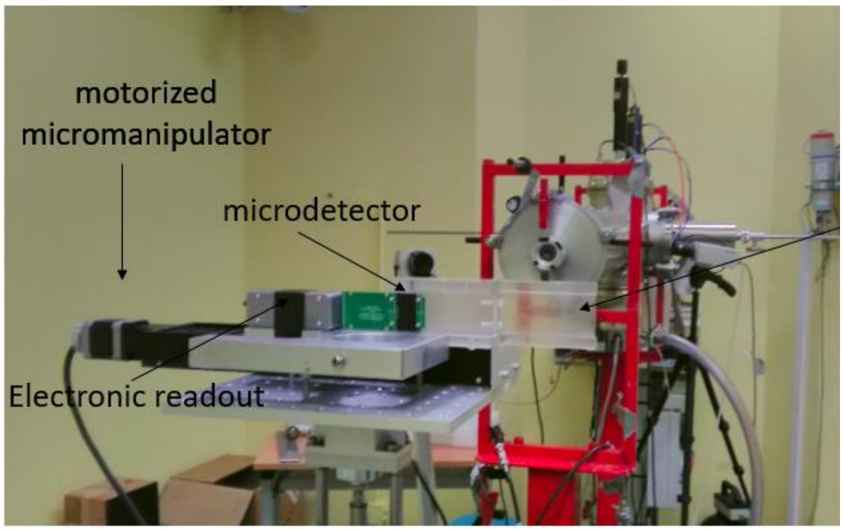


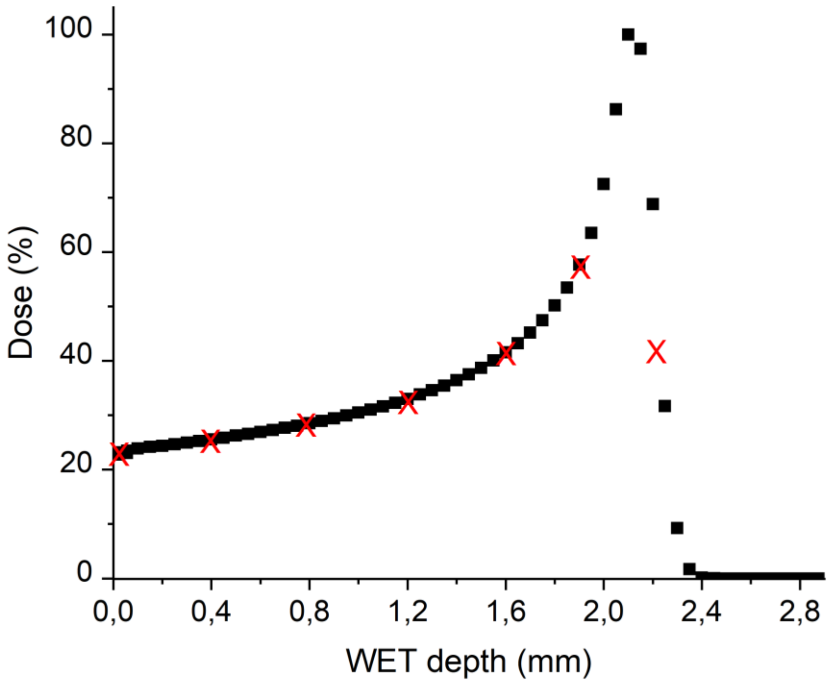




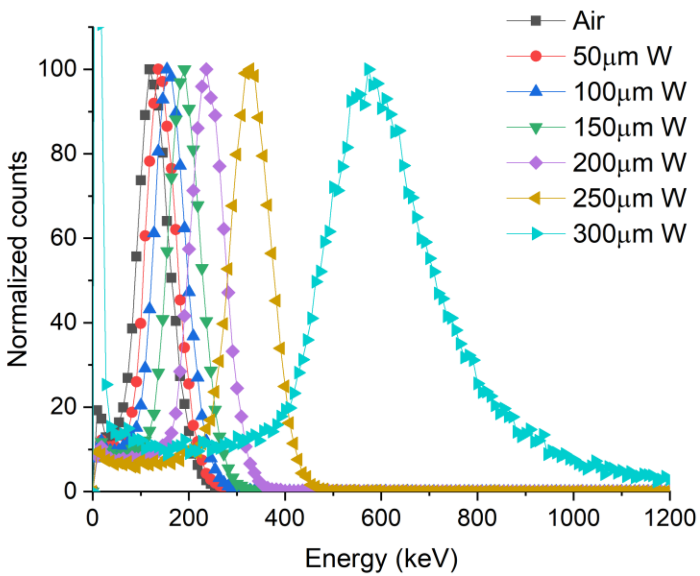
Prieto-Pena J. et al. IEEE Transactions on Nuclear Science, Vol 66, Issue 7, July 2019

- 18 MeV proton beamline at National Accelerator Centre (CNA, Spain)
- Clinical-equivalent fluence rate ($3\cdot10^7\ s^{-1}cm^{-2}$)

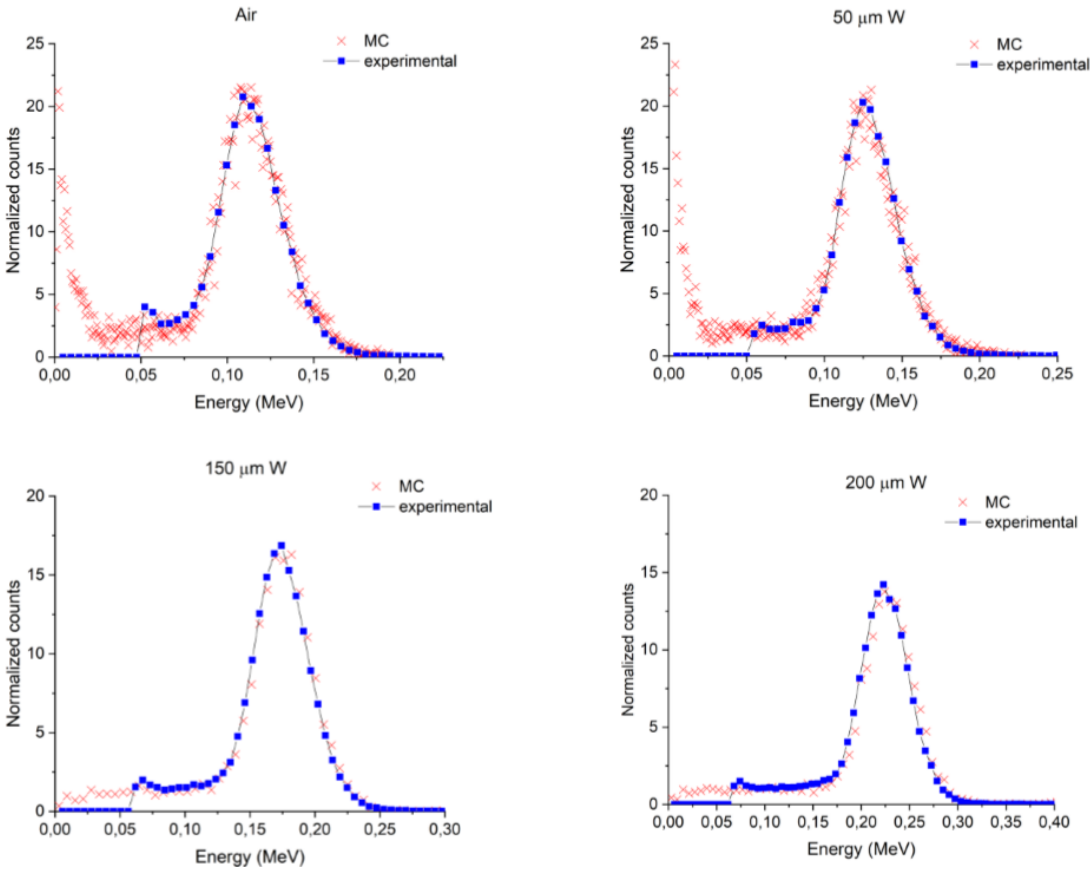




Pulse height spectra measured

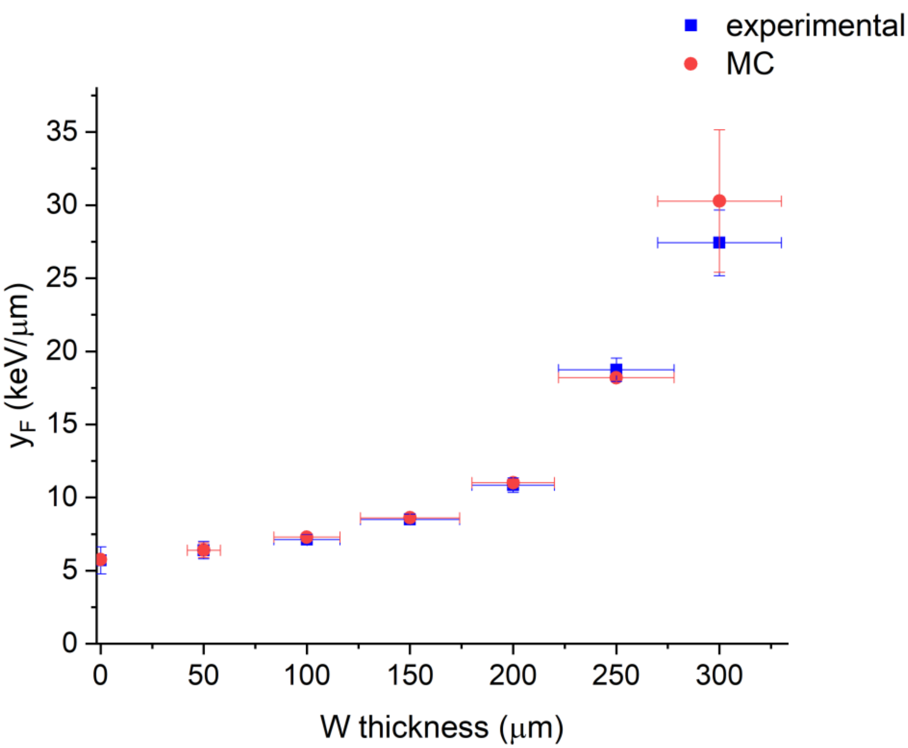


Experimental vs Simulated spectra

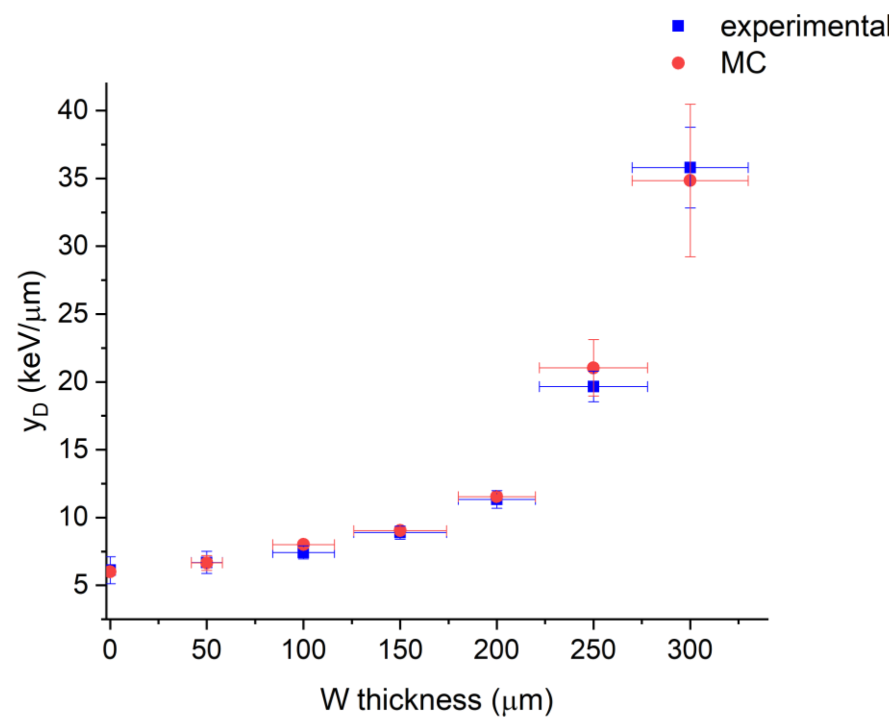


Guardiola C. et al Phys. Med. Biol. 66 (2021) 114001

y_F experimental and simulated



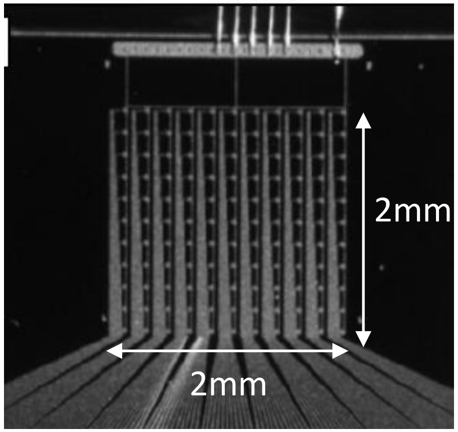
y_D experimental and simulated



Demonstrated feasibility with one 3D-cylindrical microdetector in clinical scenario

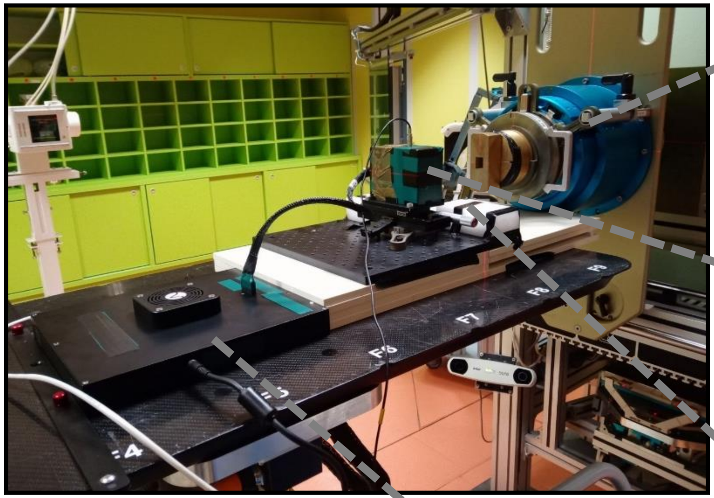
Guardiola C. et al Phys. Med. Biol. 66 (2021) 114001

LET maps in 2D?



121 independent microdetectors

Institut Curie-Center of Proton therapy d'Orsay (ICPO)

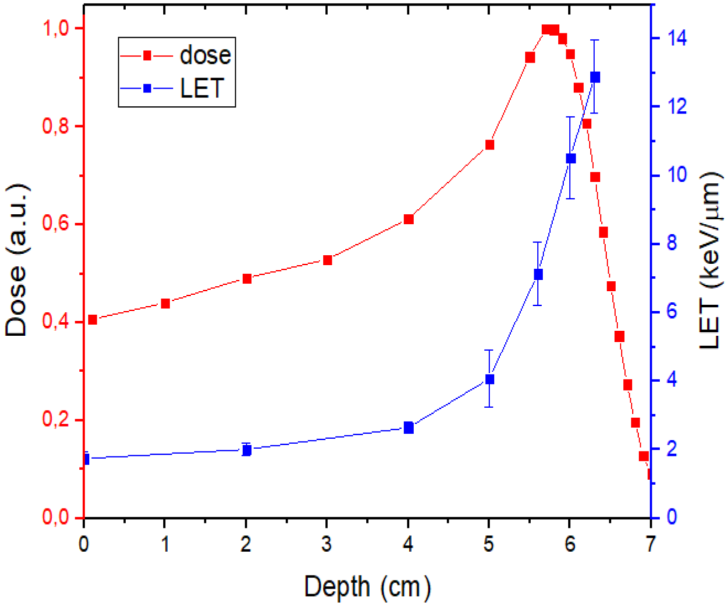


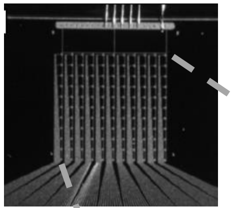
Double-scattering delivering mode @ 89 MeV protons

Microdetector array @ 5V

Solid-water (SW) equivalent

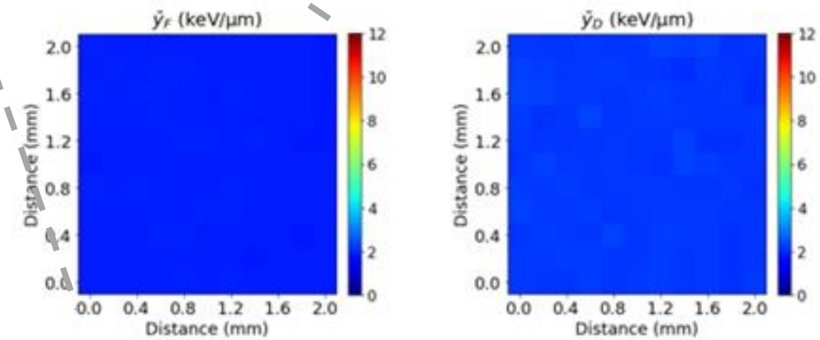
Mother board (DAQ)





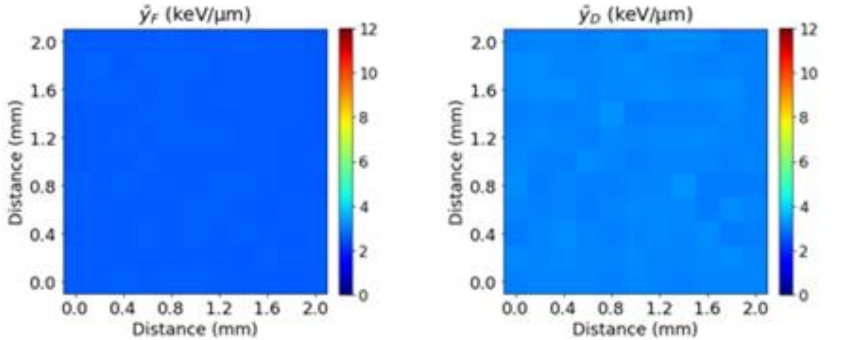
First LET 2D-maps in clinical conditions

0 cm



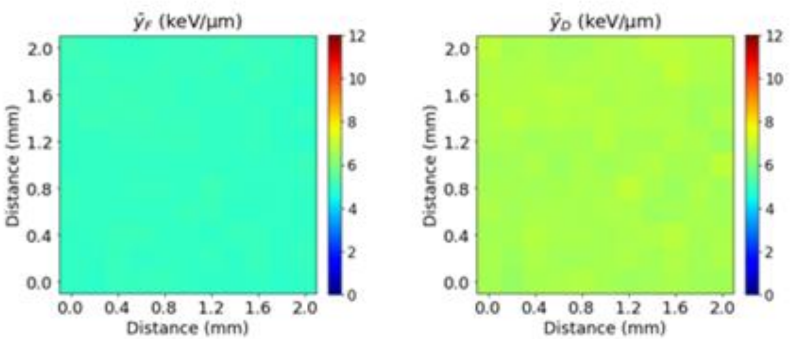
$(1.858 \pm 0.019)\mathrm{keV \cdot \mu m^{-1}}$ $(2.17 \pm 0.05)\mathrm{keV \cdot \mu m^{-1}}$

4.0 cm



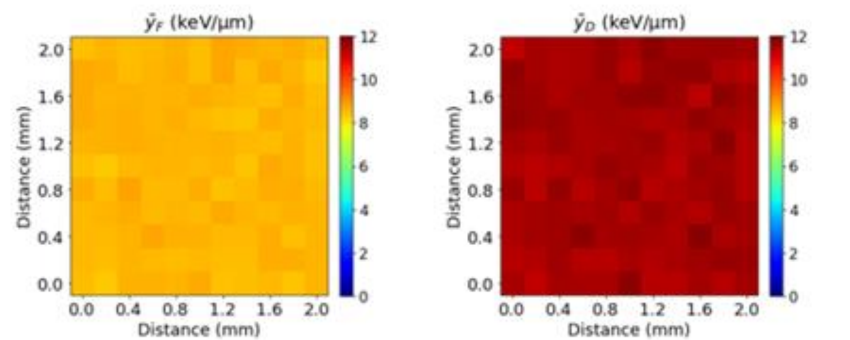
$(2.61 \pm 0.03)\mathrm{keV \cdot \mu m^{-1}}$ $(3.08 \pm 0.06)\mathrm{keV \cdot \mu m^{-1}}$

5.6 cm



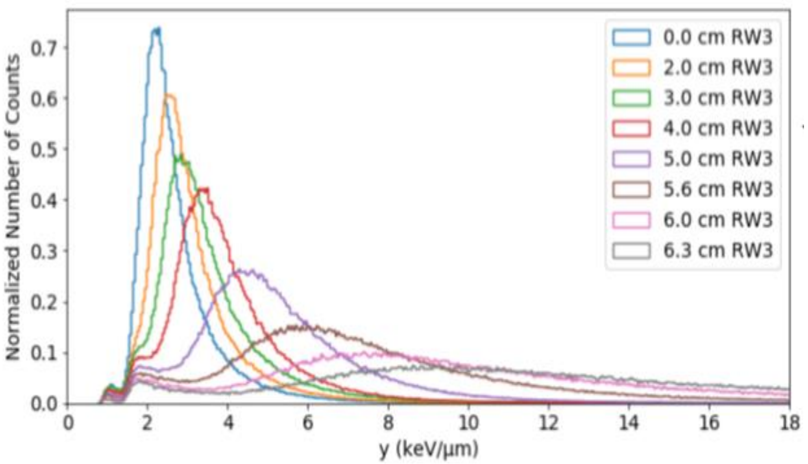
$(4.97 \pm 0.05)\ \mathrm{keV \cdot \mu m^{-1}}$ $(6.69 \pm 0.11)\mathrm{keV \cdot \mu m^{-1}}$

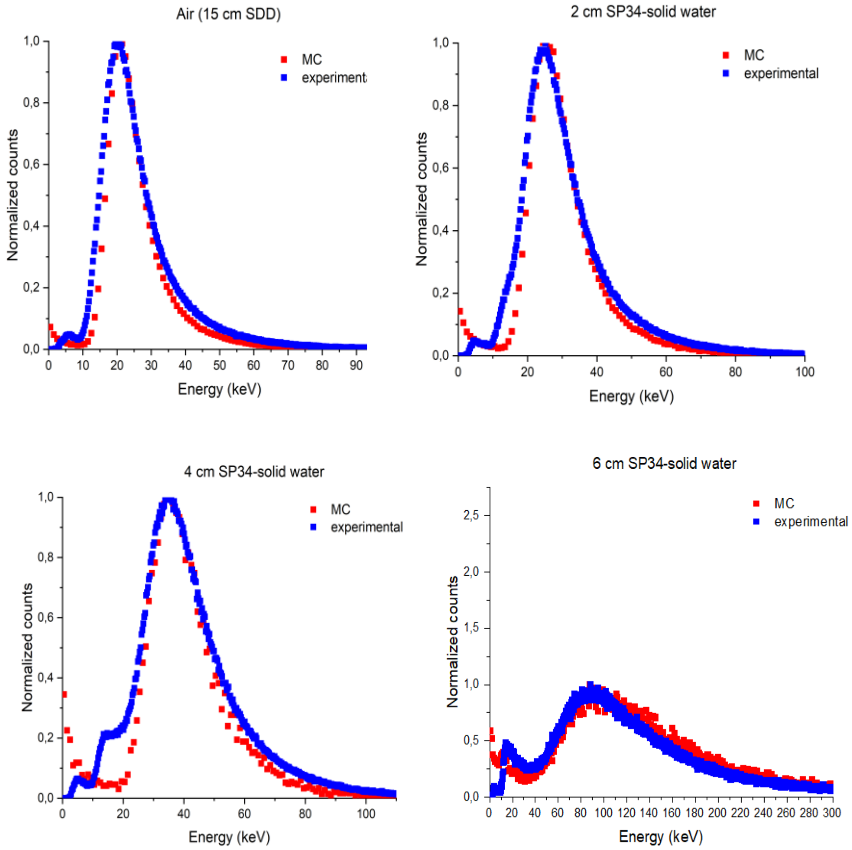
6.3 cm



$(8.6 \pm 0.1)\ \mathrm{keV \cdot \mu m^{-1}}$ $(11.60 \pm 0.13)\mathrm{keV \cdot \mu m^{-1}}$

Normalized number events vs Lineal energy (y)

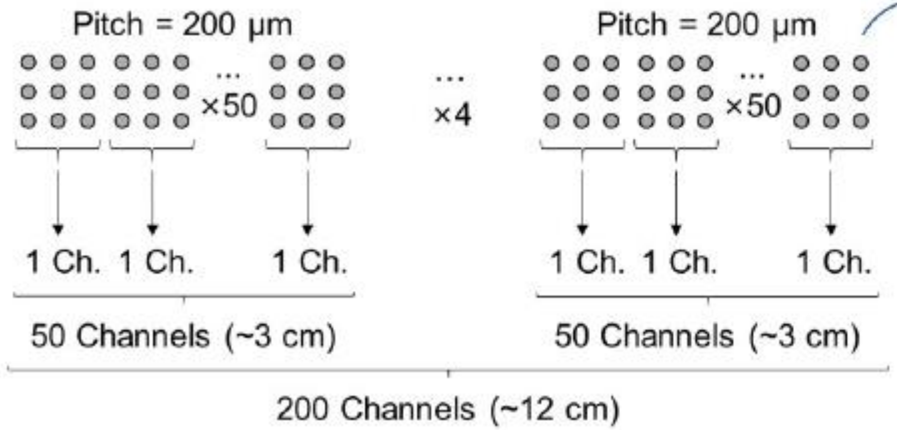


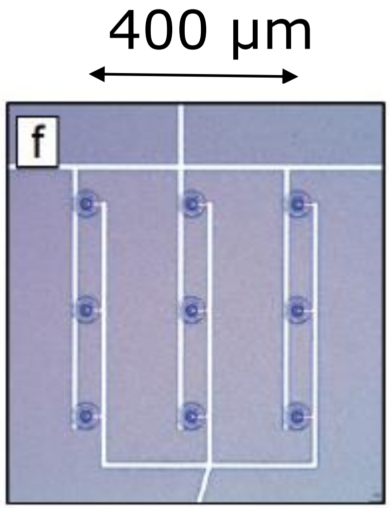


Guardiola C. et al, under review in Physics and Imaging in Radiation Oncology *(2021)*

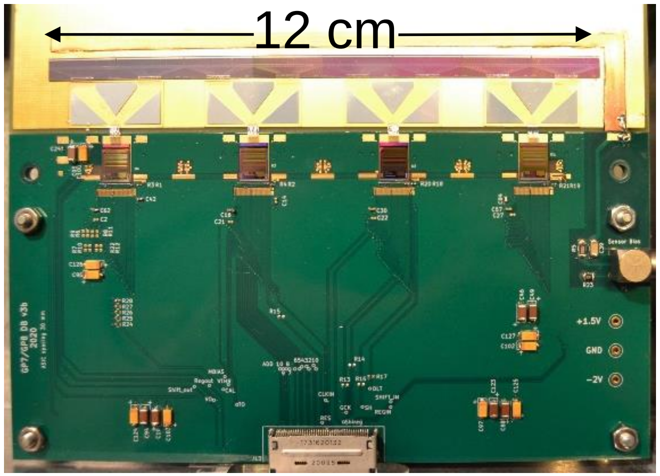
Covering larger sensitive surfaces (cms)

New layouts



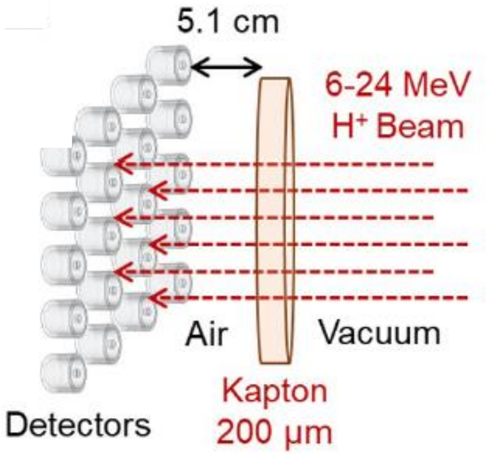


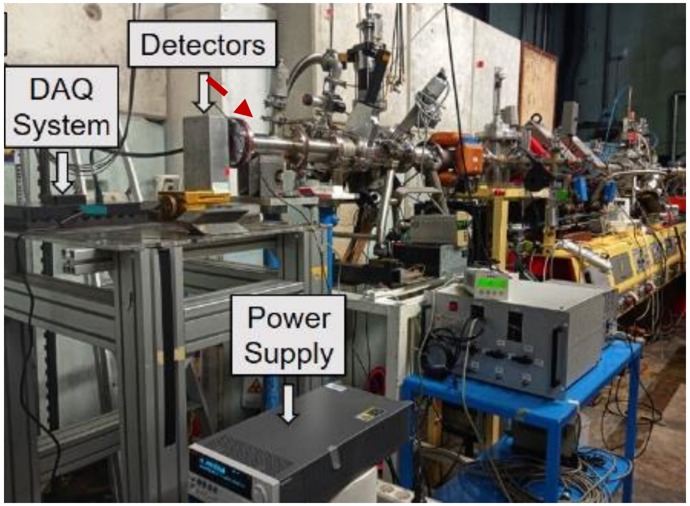
3 x 3 arrays



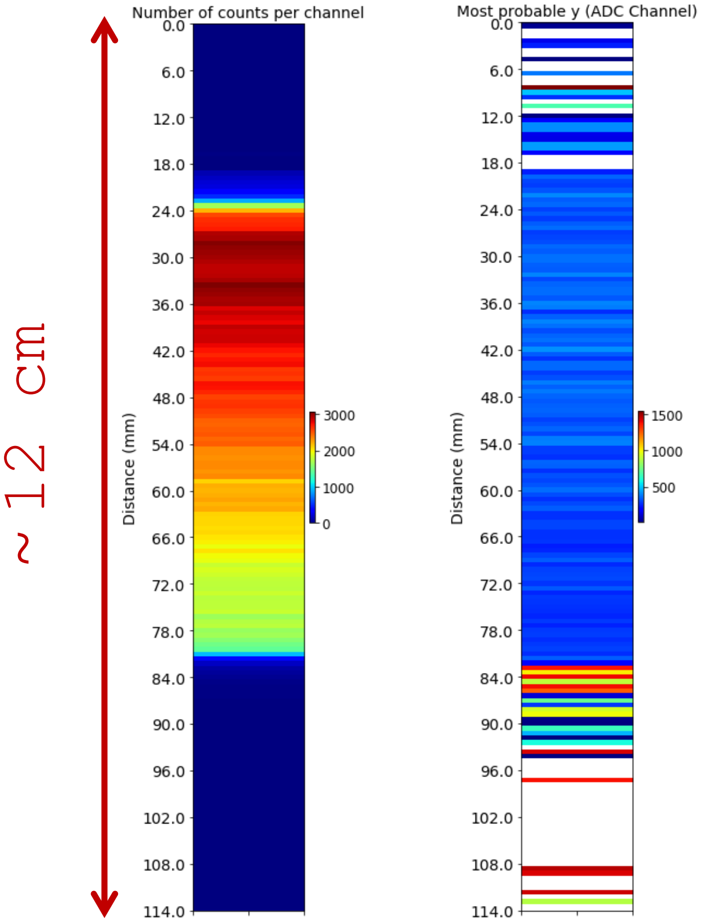
Covering larger sensitive surfaces (cms)

Energy Calibration



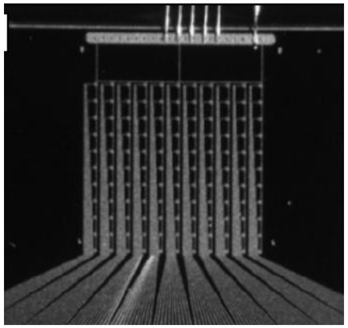


@ 16 MeV Protons

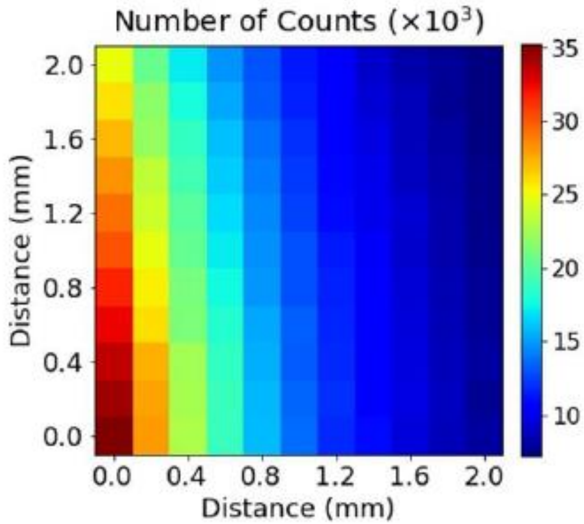


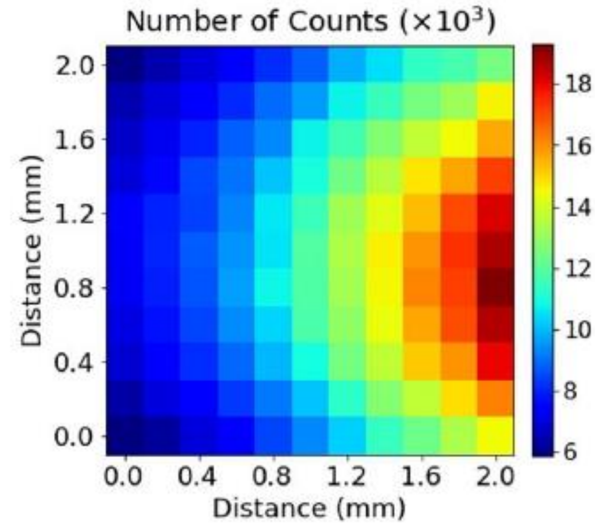
Beam intensity characterization

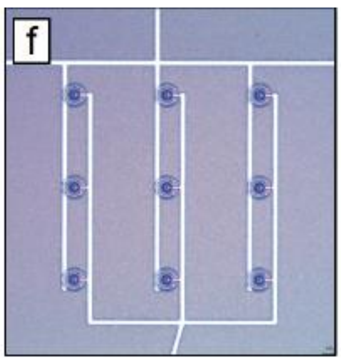
6 MeV **18 MeV**



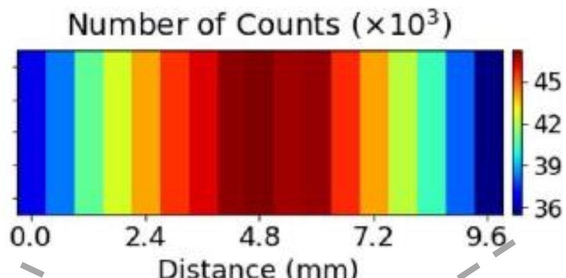
Pixel Type

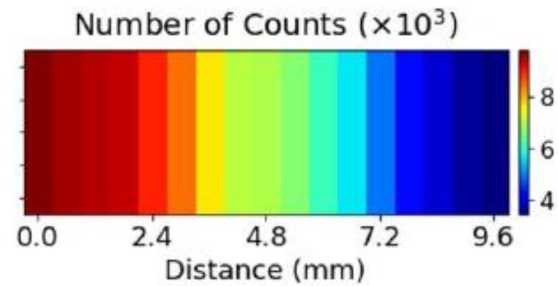






Pad Type





x200 channels

12cm

Bachiller-Perea D.. et al, submitted Scientific Reports

Conclusions

- First 3D-cylindrical microdosimeter
- Microdosimetry measurements at proton & carbon beamlines with clinical fluence rates
- Very good agreement with simulations

Ongoing

- Tests in proton therapy centers
- 4nd generation of arrays to cover larger surfaces
- GUI for data analysis

Thanks for your attention!

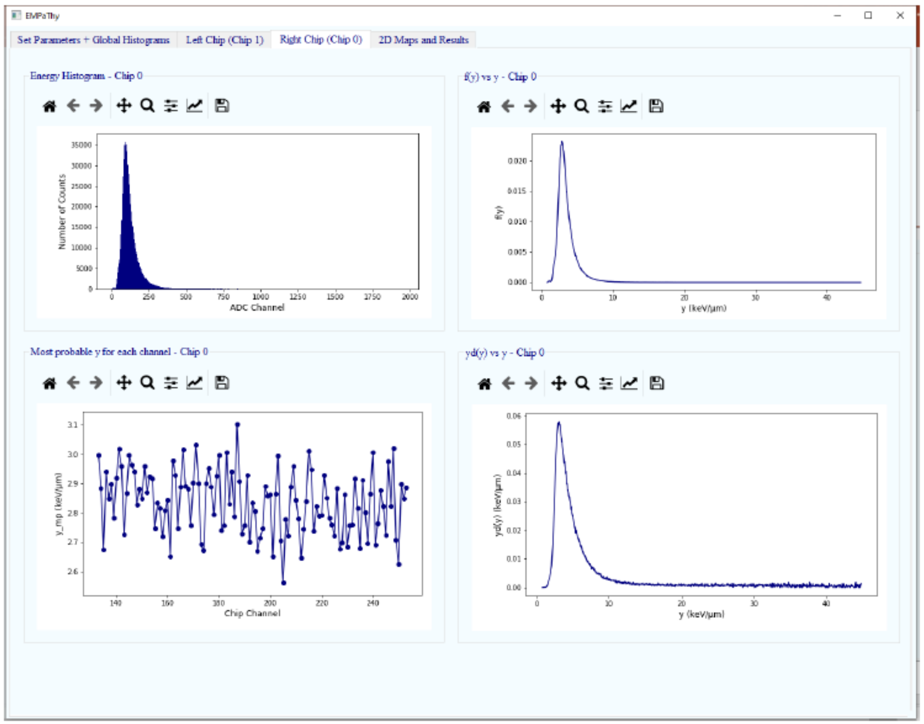
Acknowledgments

- Marie Sklodowska-Curie grant
- CNRS-Momentum fellow
- AIDA2020-CERN proof-of-concept, under European Union’s Horizon 2020 Research and Innovation programme (No. 654168)

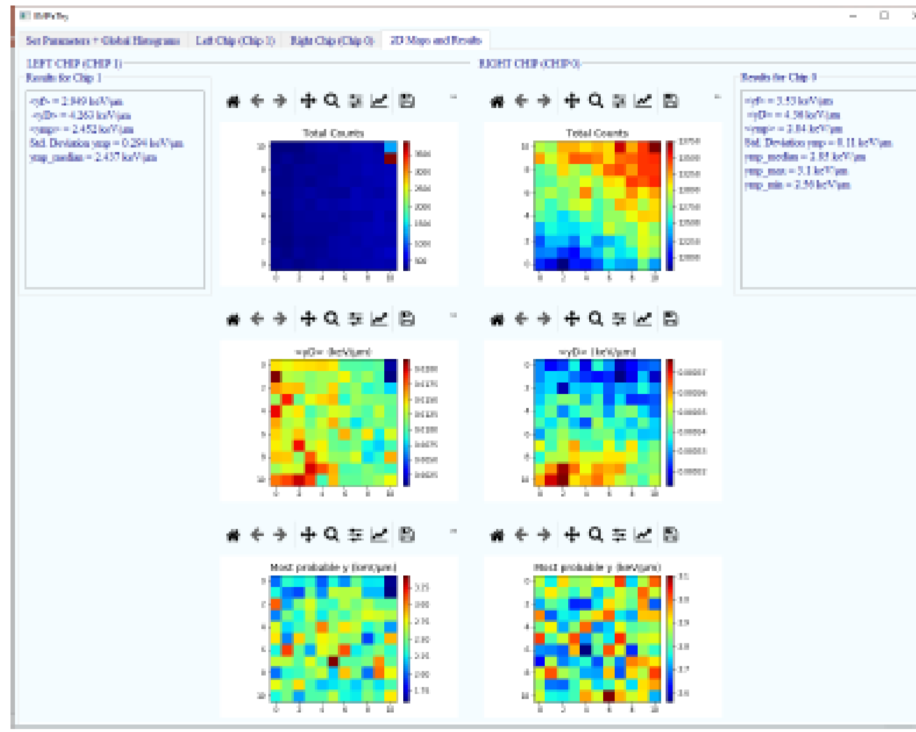
BACKUP SLIDES

In-house Python code for GUI for in-situ fast data analysis

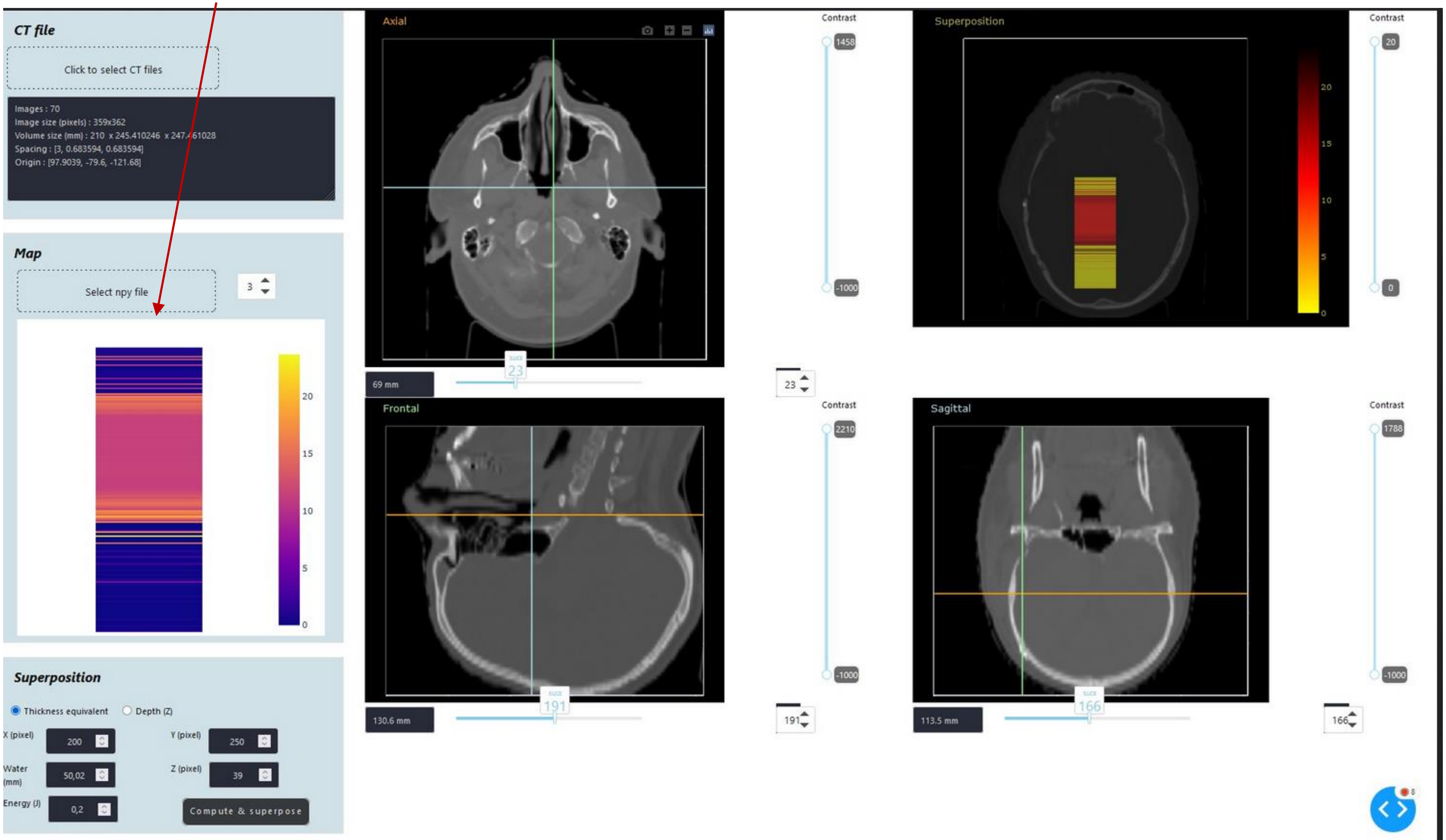
Energy spectra



LET maps



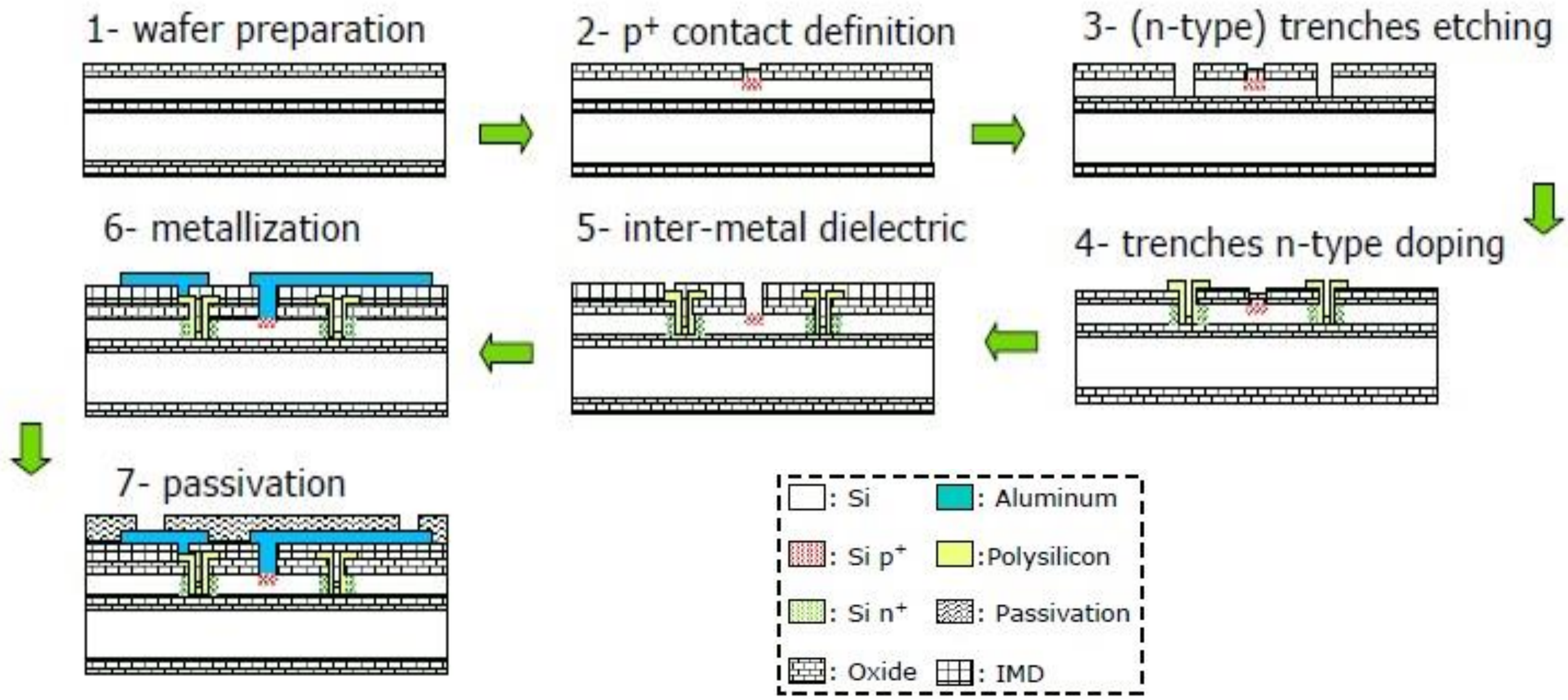
2D LET maps in Silicon → 2D LET maps in CT



Ongoing: conversion of 2D LET maps in silicon to patient conversion with AI algorithms

Microfabrication process

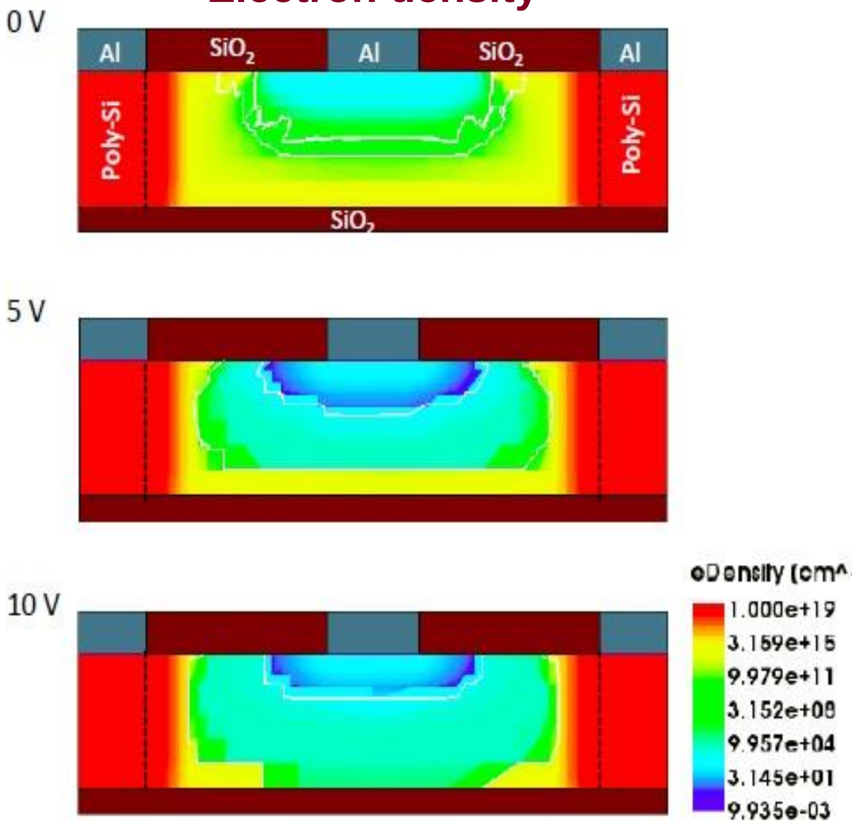
- silicon-on-insulator (SOI) wafers, N-type active silicon (5, 10, 20 µm thickness)
- 7 mask levels
- 122 microfabrication steps



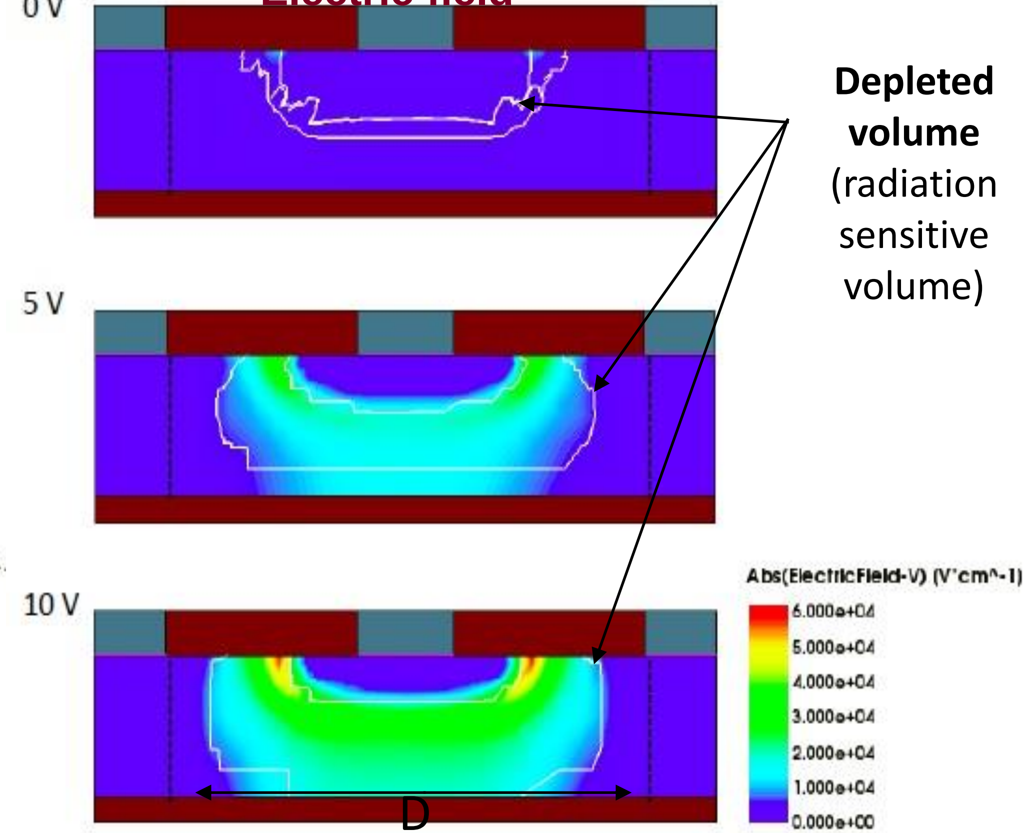
Electrical simulation: Synopsis TCAD Sentaurus code

- p+ & n+ doping profiles are approximated as Gaussian decays ($10^{19}cm^{-3}$, 0,3 µm sigma)
- 1,7µm SiO_2 top and 1µm back-sides (uniform positive 10^{11} cm^{-2} for non-irradiated SiO_2)
- Silicon resistivity 5 kΩcm

Electron density



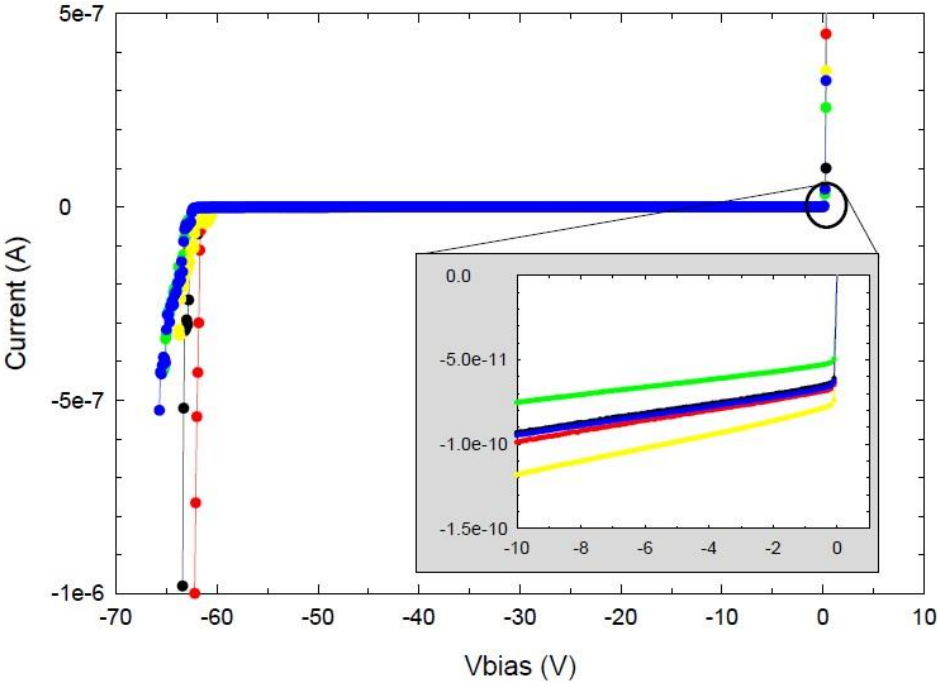
Electric field

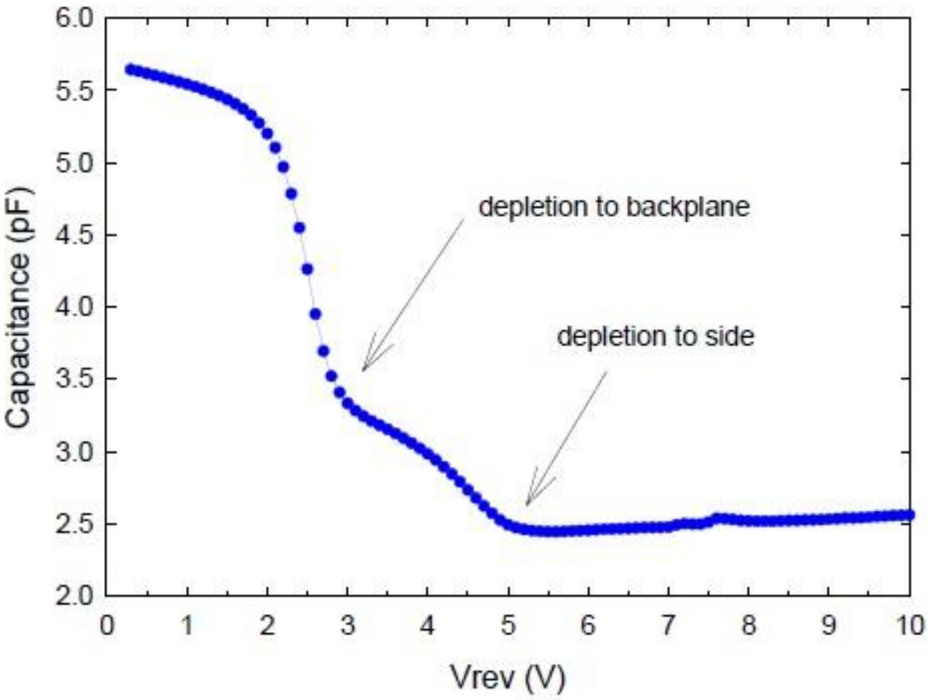


Current-voltage curve

Capacitance-voltage curve

(few representative values)





-Good diode characteristics
-Breakdown voltages higher than 60V
-Reverse currents <100 pA @ 5V

Depleted volume reaching:
-the backplane at 3V
-lateral n-contact at 5V