4He dose- and track- averaged Linear Energy Transfer: Monte Carlo algorithms and experimental verification

G. Petringa, S. Agosteo, D. Bortot, V. Conte, G. Cuttone, A. Di Fini, S. Fattori, D. Mazzucconi, L. Pandola, I. Petrovic, A. Rosenfeld, A. Ristic-Fira, U. Weber and G.A.P. Cirrone

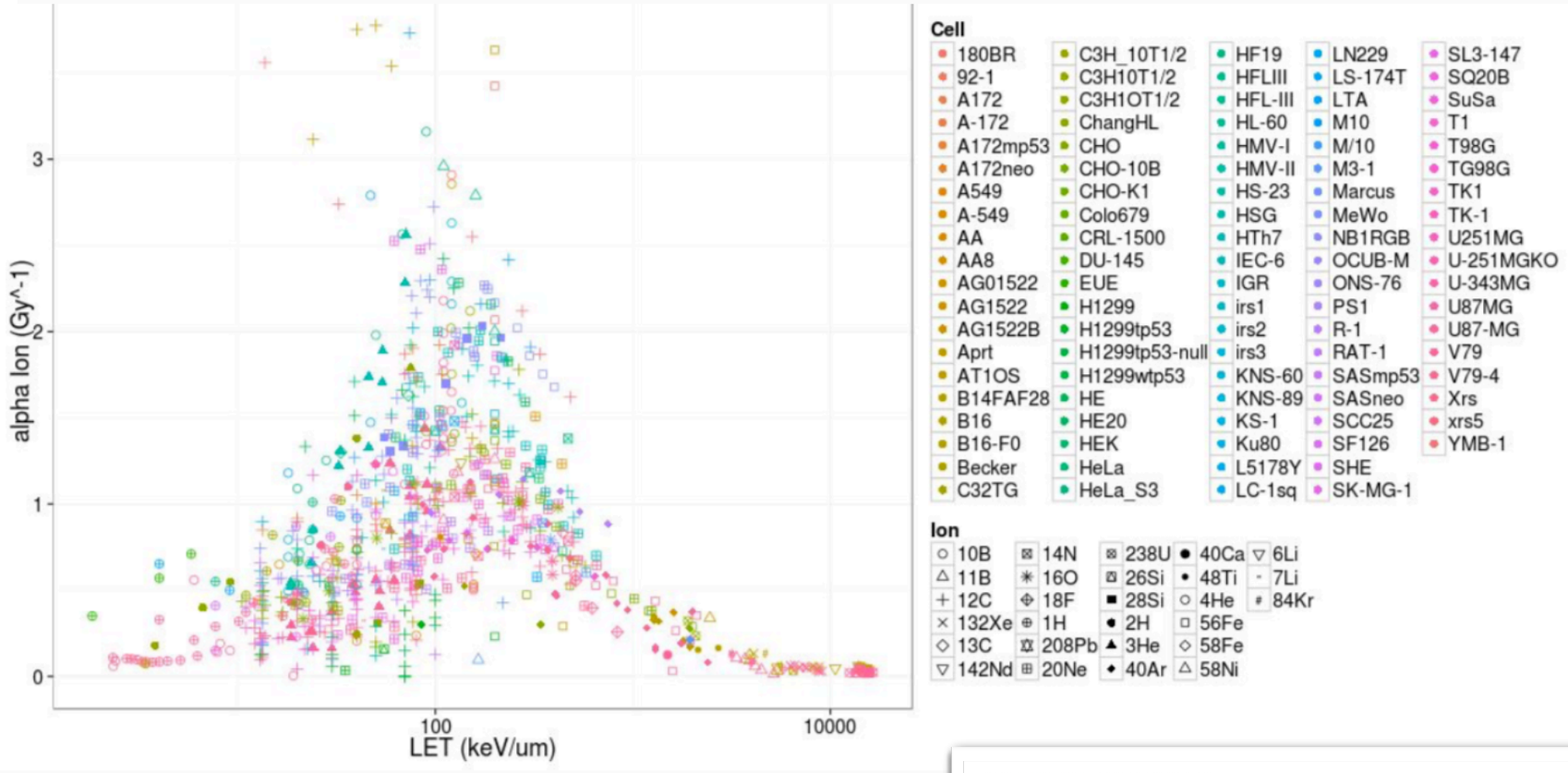
Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali del Sud (Italy)

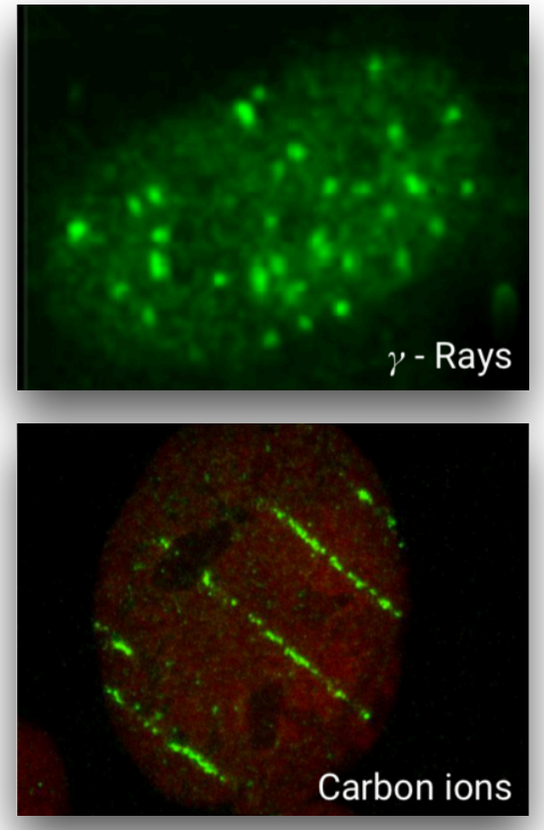
Outline

- Linear Energy Transfer: a new approach
- Validation study with 4He beams
- Pristine and Modulated Bragg peak with ridge and ripple filters
- Secondary particles contribution
- Biological damage estimation
- Next steps

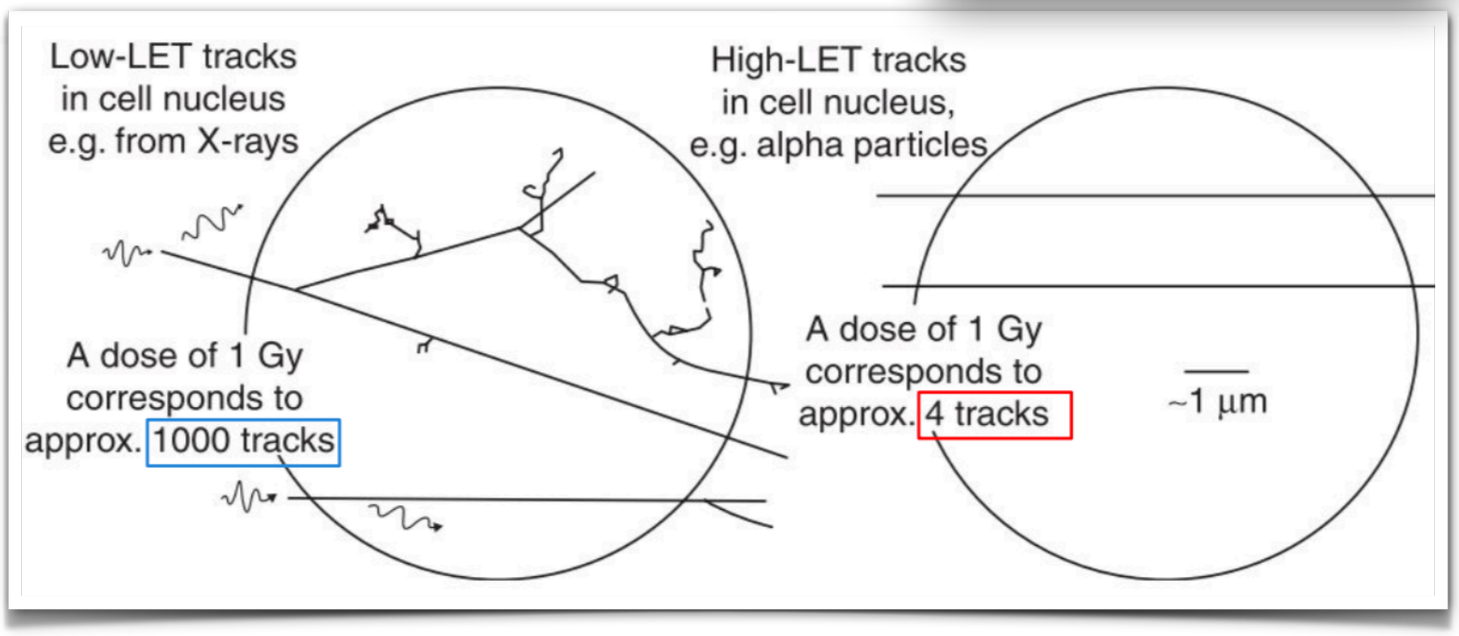
Linear Energy Transfer

Friedrich, T., Scholz, U., Elsässer, T., Durante, M., & Scholz, M. (2012). *Journal of Radiation Research*.





The biological damage is strictly related to the radiation quality



Linear Energy Transfer: a new approach

ICRU Report n.16

$$\bar{L}_D = \frac{\int_0^\infty L^2 \cdot f(L)dL}{\int_0^\infty L \cdot f(L)dL} \qquad \bar{L}_D^{Total} = \frac{\sum_{j=1}^N \int_0^\infty L_j^2 \cdot f_j(L)dL}{\int_0^\infty L_j \cdot f_j(L)dL}$$

$$\bar{L}_T = \frac{\int_0^\infty L \cdot f(L)dL}{\int_0^\infty f(L)dL} \qquad \bar{L}_T^{Total} = \frac{\sum_{j=1}^N \int_0^\infty L_j \cdot f_j(L)dL}{\int_0^\infty f_j(L)dL}$$

Our Algorithms

$$\bar{L}_d = \frac{\sum_{i=1}^N L_i \varepsilon_i}{\sum_{i=1}^N \varepsilon_i} \qquad \bar{L}_T = \frac{\sum_{i=1}^N L_i l_i}{\sum_{i=1}^N l_i}$$

$$\bar{L}_d^{Total} = \frac{\sum_{j=1}^n \left[\sum_{i=1}^N L_i \varepsilon_i\right]_j}{\sum_{j=1}^n \left[\sum_{i=1}^N \varepsilon_i\right]_j} \qquad \bar{L}_T^{Total} = \frac{\sum_{j=1}^n \left[\sum_{i=1}^N L_i l_i\right]_j}{\sum_{j=1}^n \left[\sum_{i=1}^N l_i\right]_j}.$$

Physics in Medicine & Biology

PAPER

Monte Carlo implementation of new algorithms for the evaluation of averaged-dose and -track linear energy transfers in 62 MeV clinical proton beams

G Petringa[1], L Pandola[1], S Agosteo[2,3], R Catalano[1], P Colautti[4], V Conte[4], G Cuttone[1], K Fan[5], Z Mei[5], A Rosenfeld[6] + Show full author list

Published 30 November 2020 • © 2020 Institute of Physics and Engineering in Medicine

Physics in Medicine & Biology, Volume 65, Number 23

Citation G Petringa *et al* 2020 *Phys. Med. Biol.* **65** 235043

Linear Energy Transfer: a new approach

5

Physics in Medicine & Biology

PAPER

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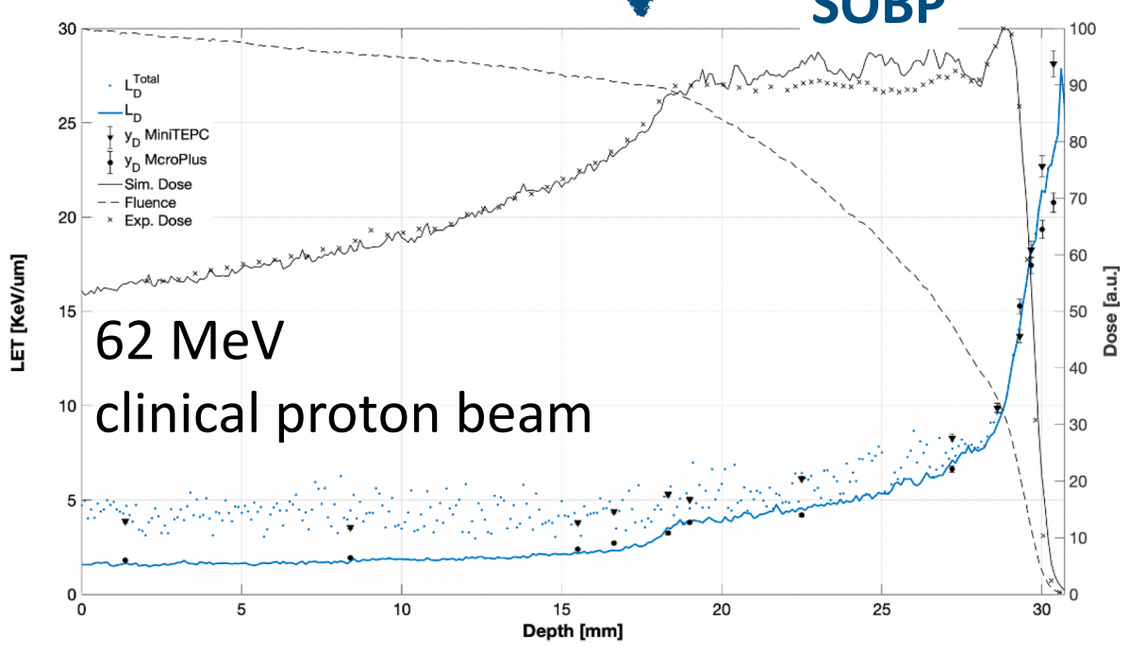
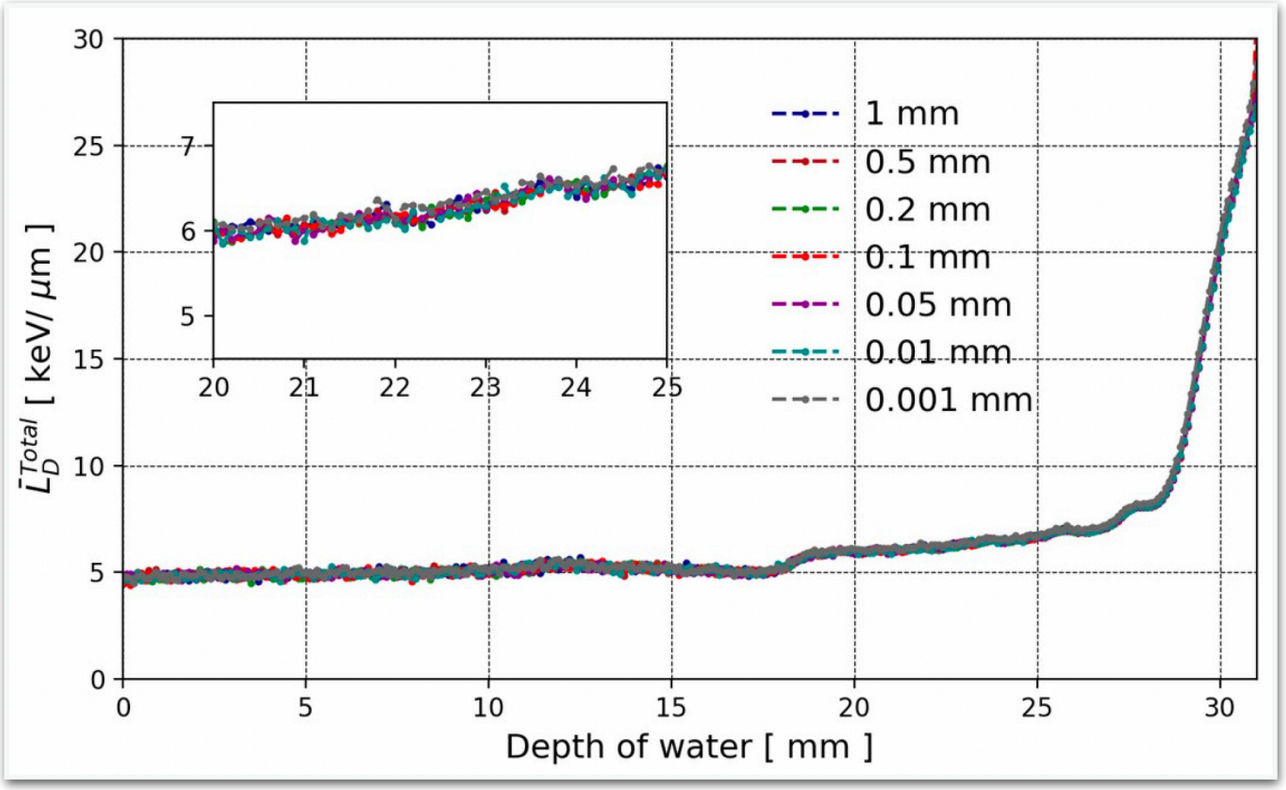
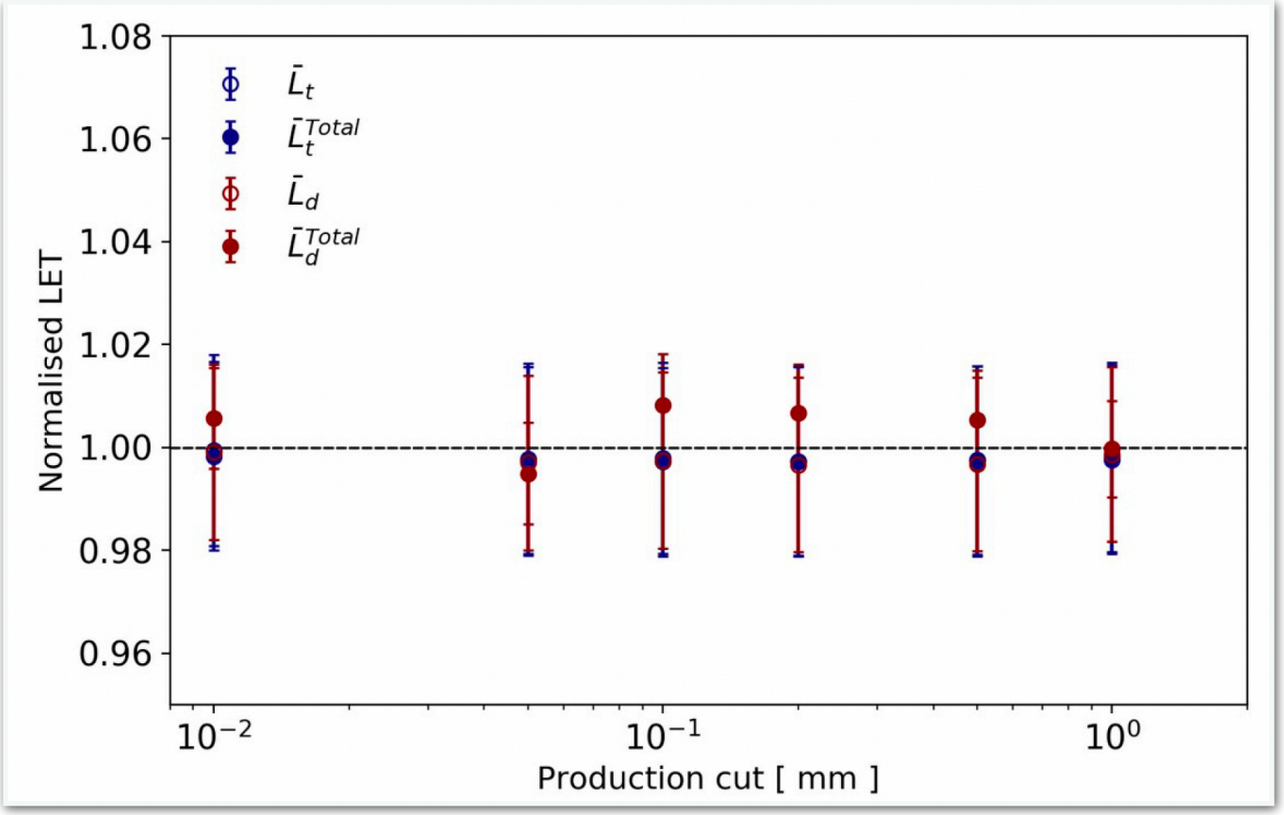
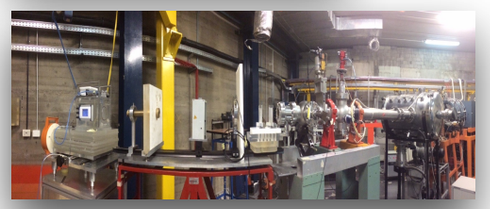
SOBP







Hadrontherapy: a Geant4 advanced Example



Geometry:
- Passive ProtonBeam Line
- Passive CarbonBeam Line
- Laser DrivenBeamLine
- TrentoPassiveProtonBeamLine

Physics Lists:
- HADRONTHERAPY_1
- HADRONTHERAPY_2
- new Physics for proton enhancement

Hadrontherapy

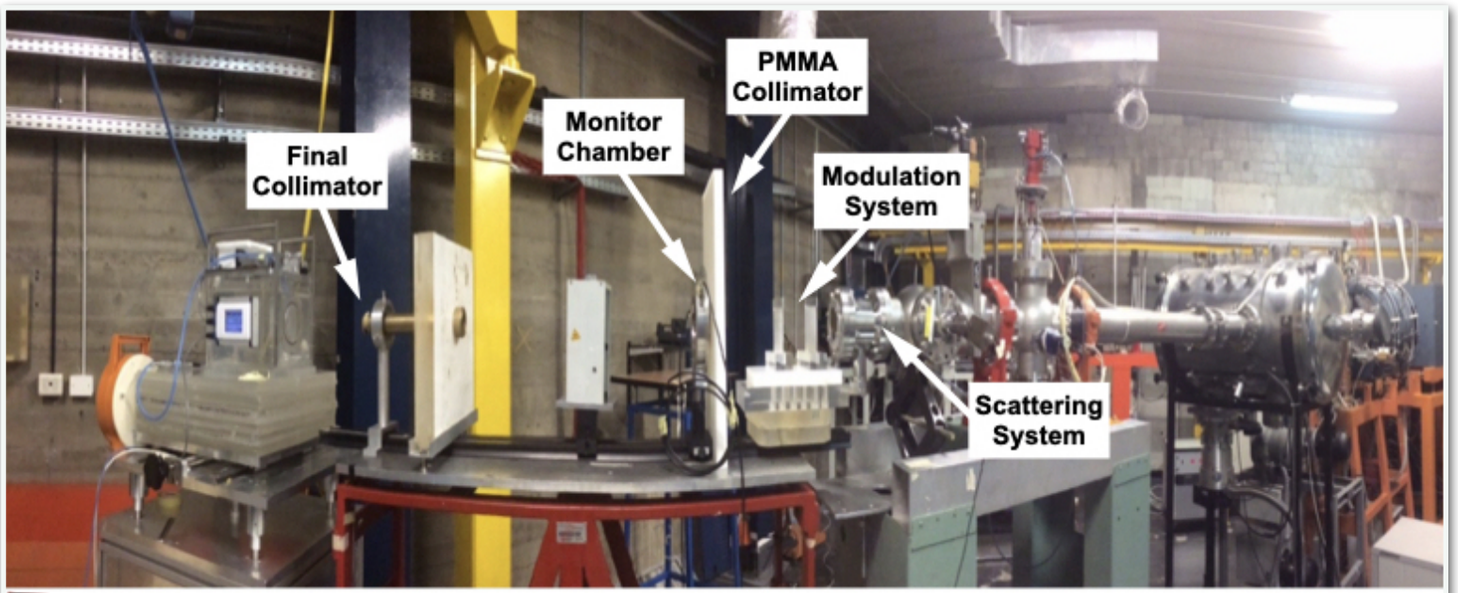
A G4 advanced Example dedicated to radiobiological studies

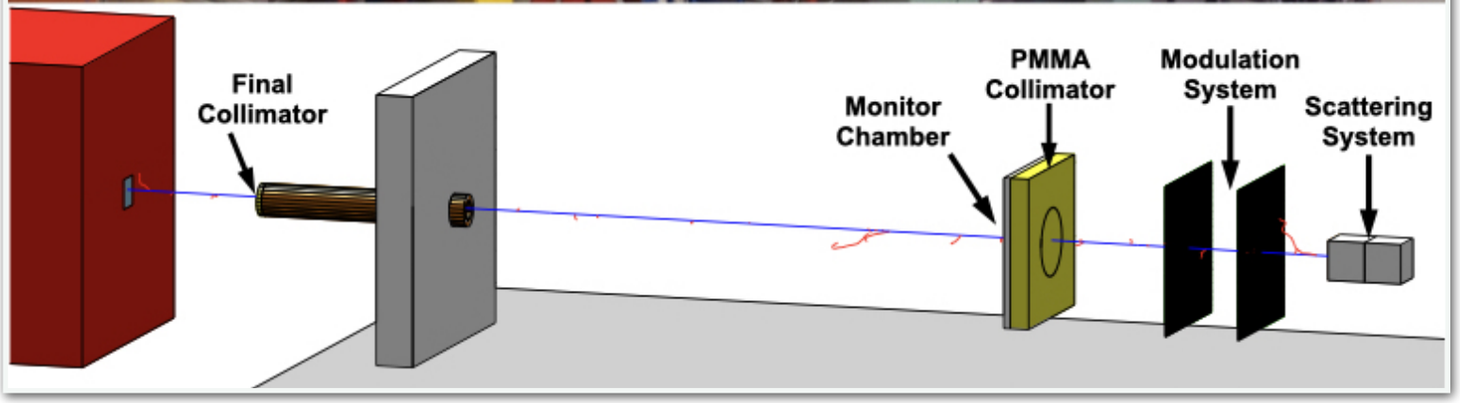
Calculation of radiobiological quantities:
- Dose
- **LET-dose**
- **LET-track**
- RBE

Primary Event Generator:
- Standard GPS definition
- External Source

G Petringa, PhD - giada.petringa@lns.infn.it

A validation study with 4He beams





Experimental run @LNS-INFN
- 4He beam - 62 AMeV

- **Configuration A**: Pristine peak with the MicroPlus probe;
- **Configuration B**: Modulated peak (with ridge filter) with MicroPlus probe;
- **Configuration C**: Modulated peak (with ripple filter) with nano-TEPC.

Physics in Medicine & Biology

PAPER

^{4}He dose- and track-averaged linear energy transfer: Monte Carlo algorithms and experimental verification

S Fattori[1], G Petringa[1,2], S Agosteo[3,4], D Bortot[3,4], V Conte[5], G Cuttone[1], A Di Fini[6], F Farokhi[1,7], D Mazzucconi[3,4], L Pandola[1], I Petrović[8], A Ristić-Fira[8], A Rosenfeld[9], U Weber[10] and G A P Cirrone[1,11] – Hide full author list

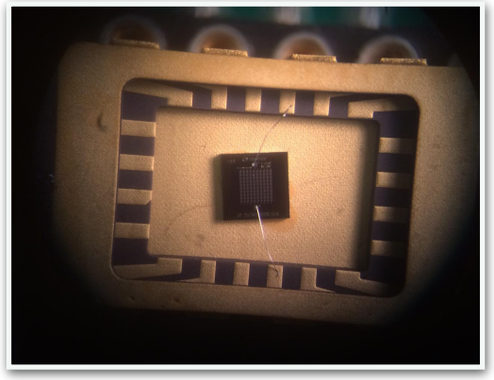
Published 5 August 2022 • © 2022 Institute of Physics and Engineering in Medicine
Physics in Medicine & Biology, Volume 67, Number 16
Citation S Fattori *et al* 2022 *Phys. Med. Biol.* **67** 165003

Adopted microdosimetric detectors

mean-chord-length: 306 ± 1nm

nano-TEPC (LNL & MI - INFN)

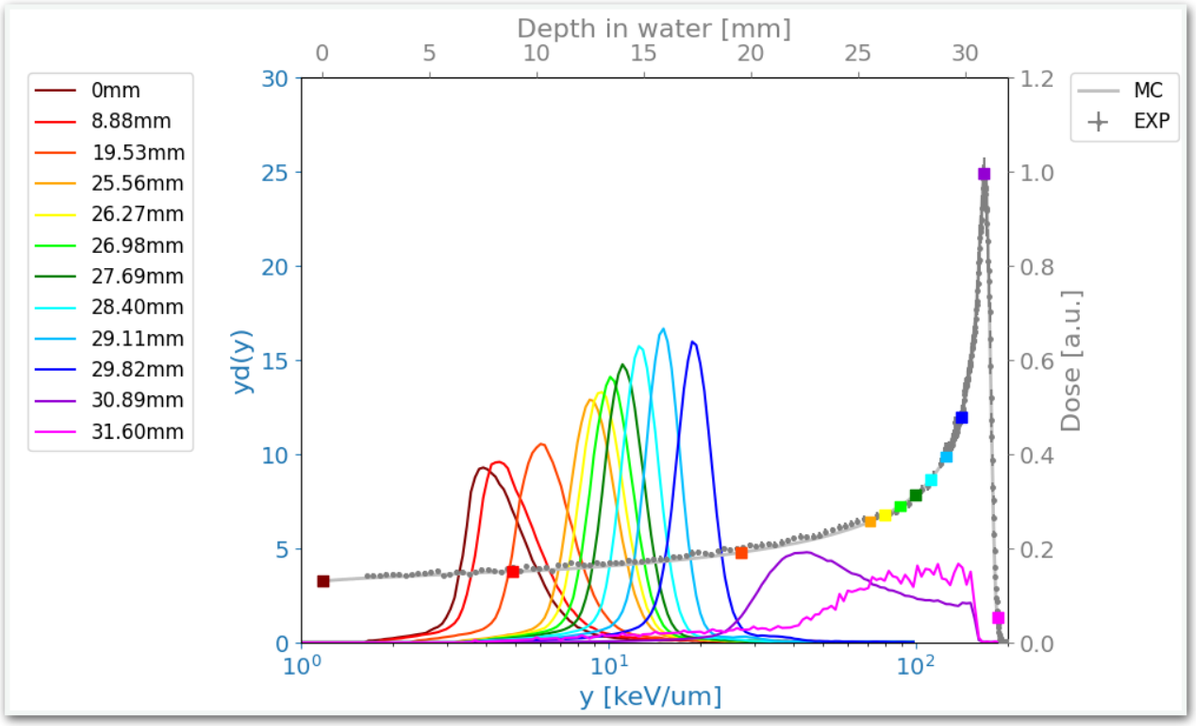
mean-chord-length: 17 ± 0.5 um

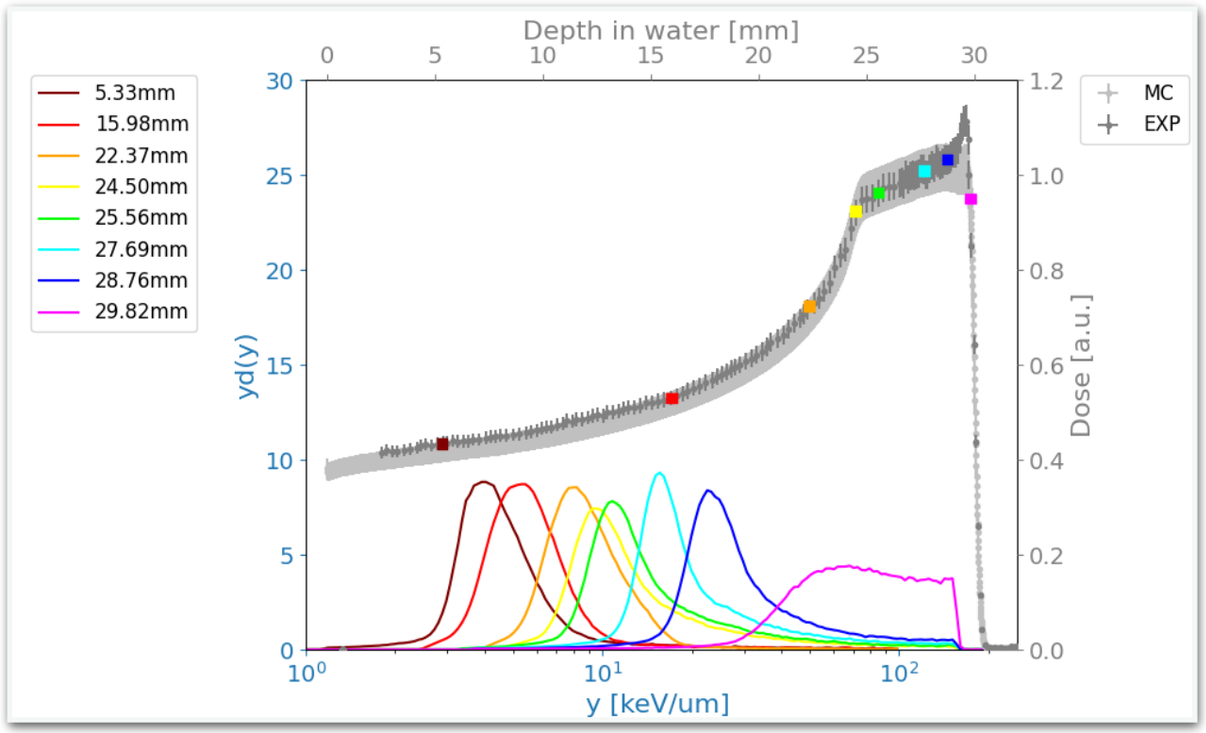


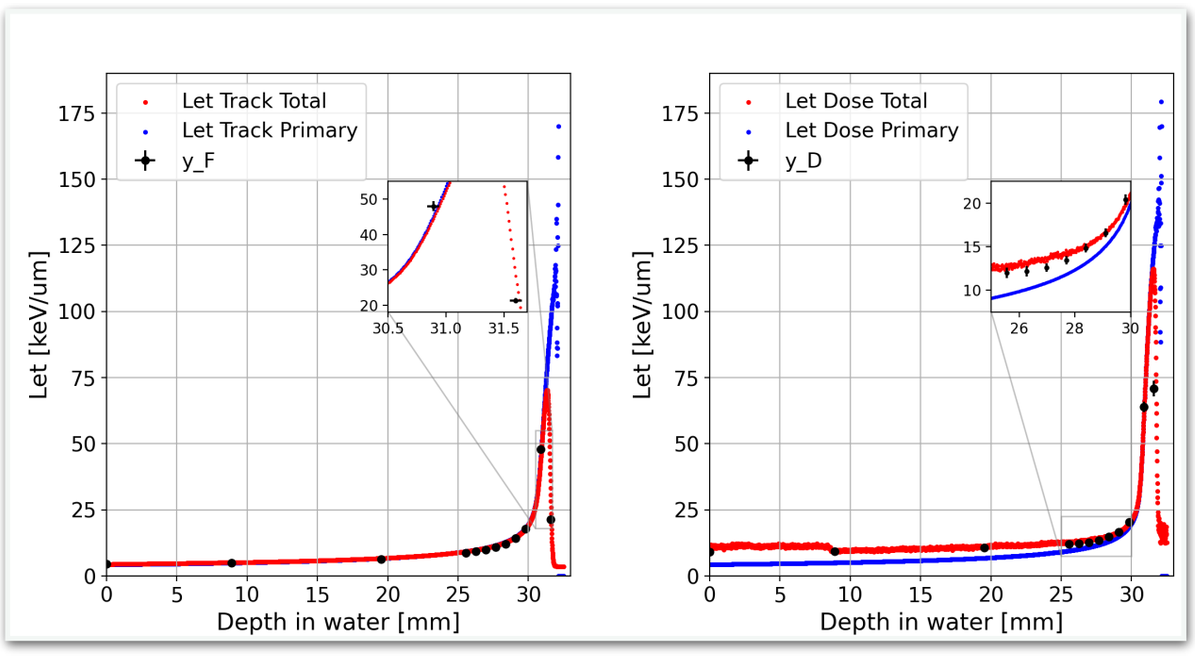
Microplus probe (UOW & LNS-INFN)

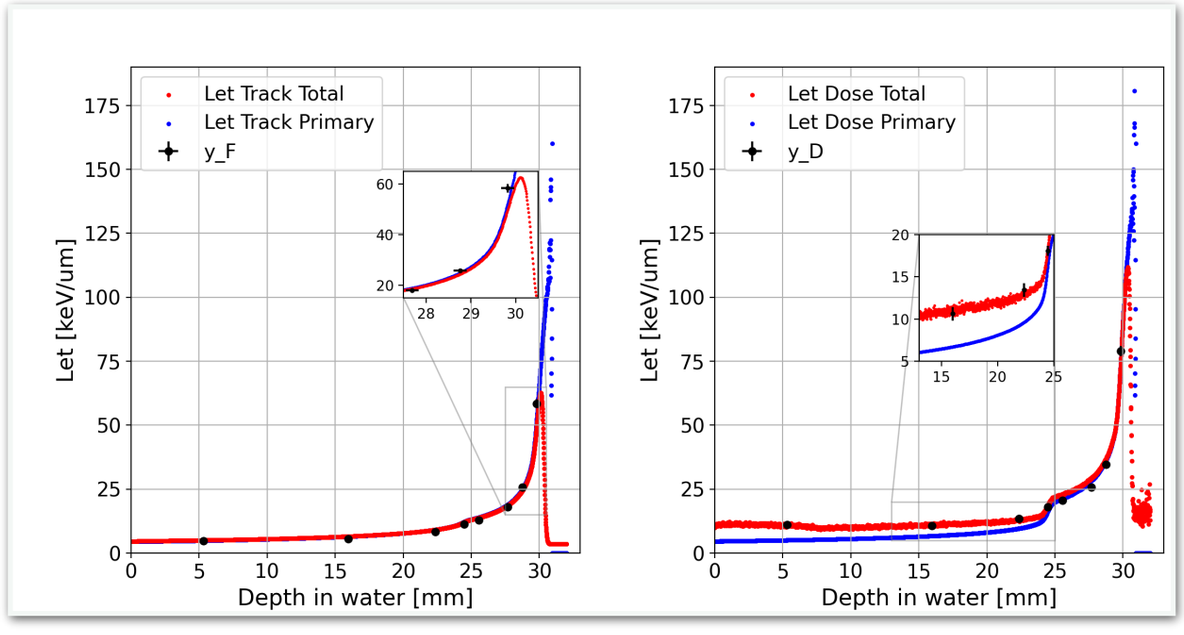
Pristine and Modulated Bragg peak with ridge filter

8 Microplus probe



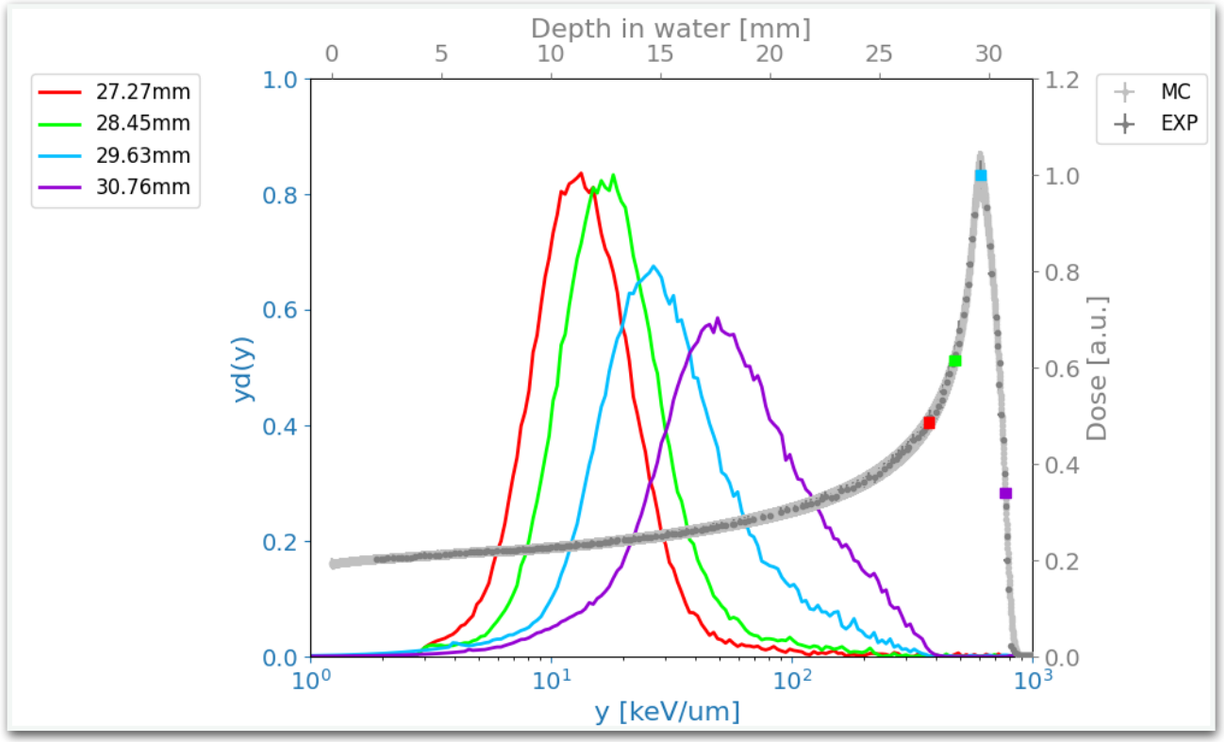


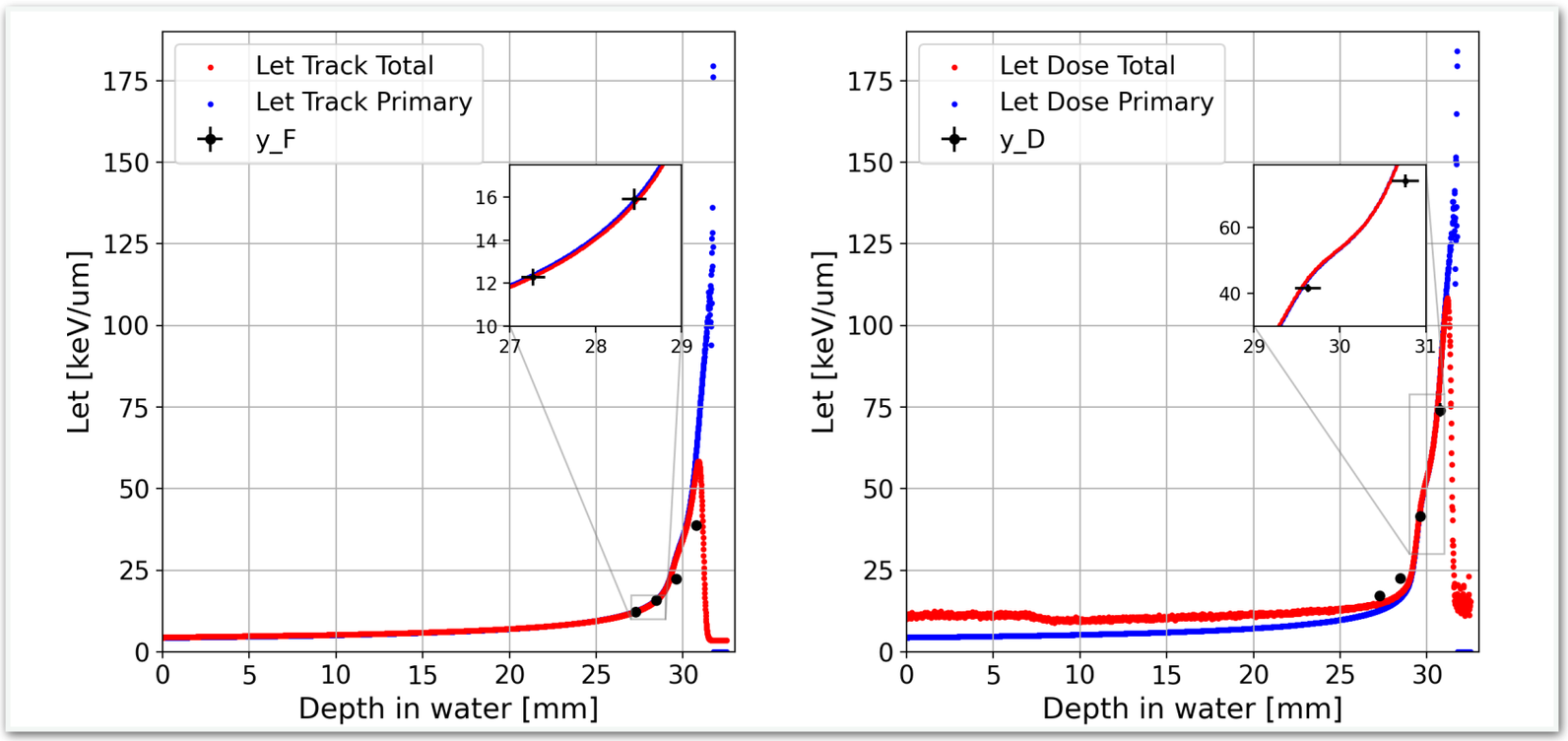




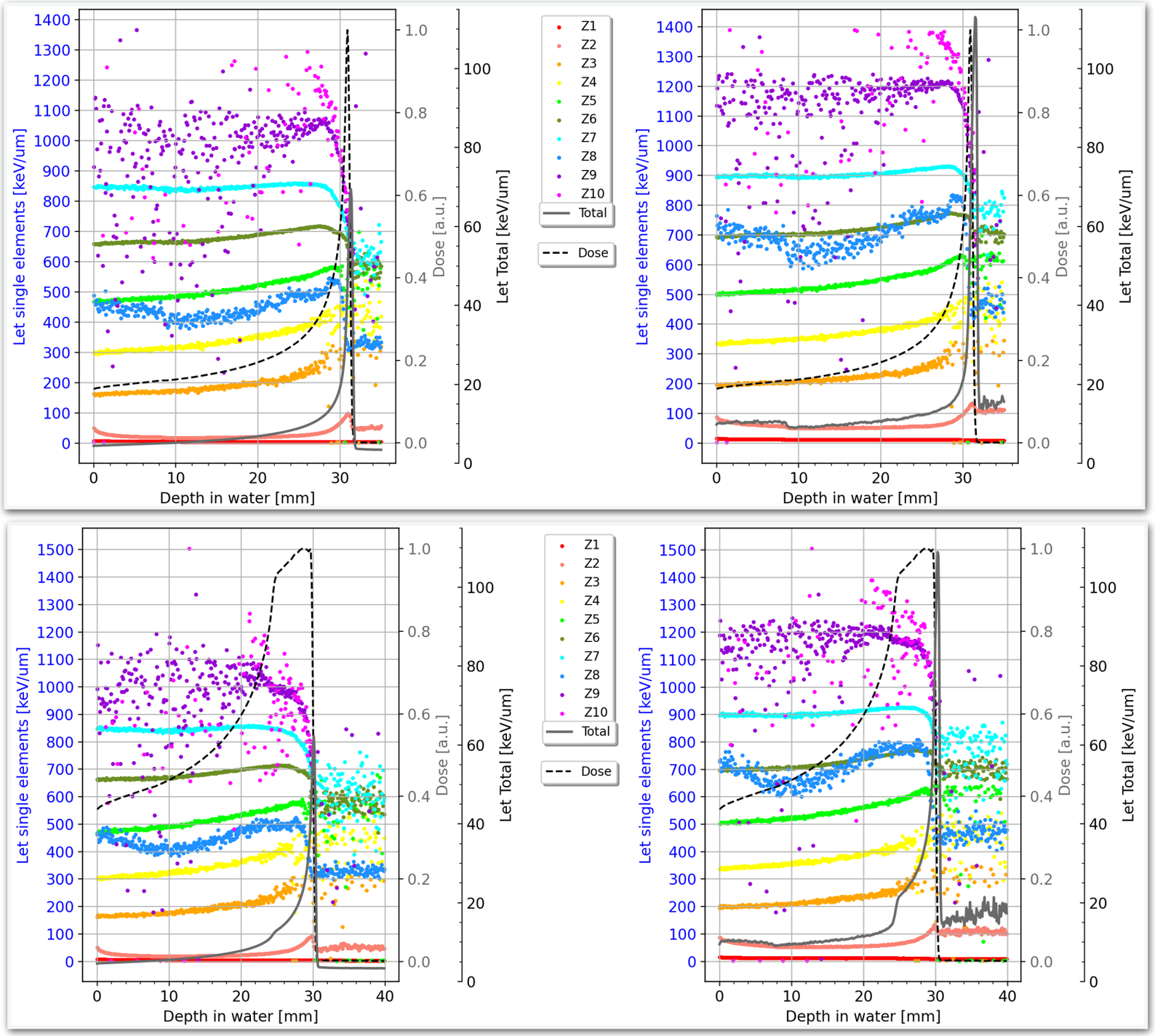
Modulated Bragg peak with ripple filter

nano-TEPC





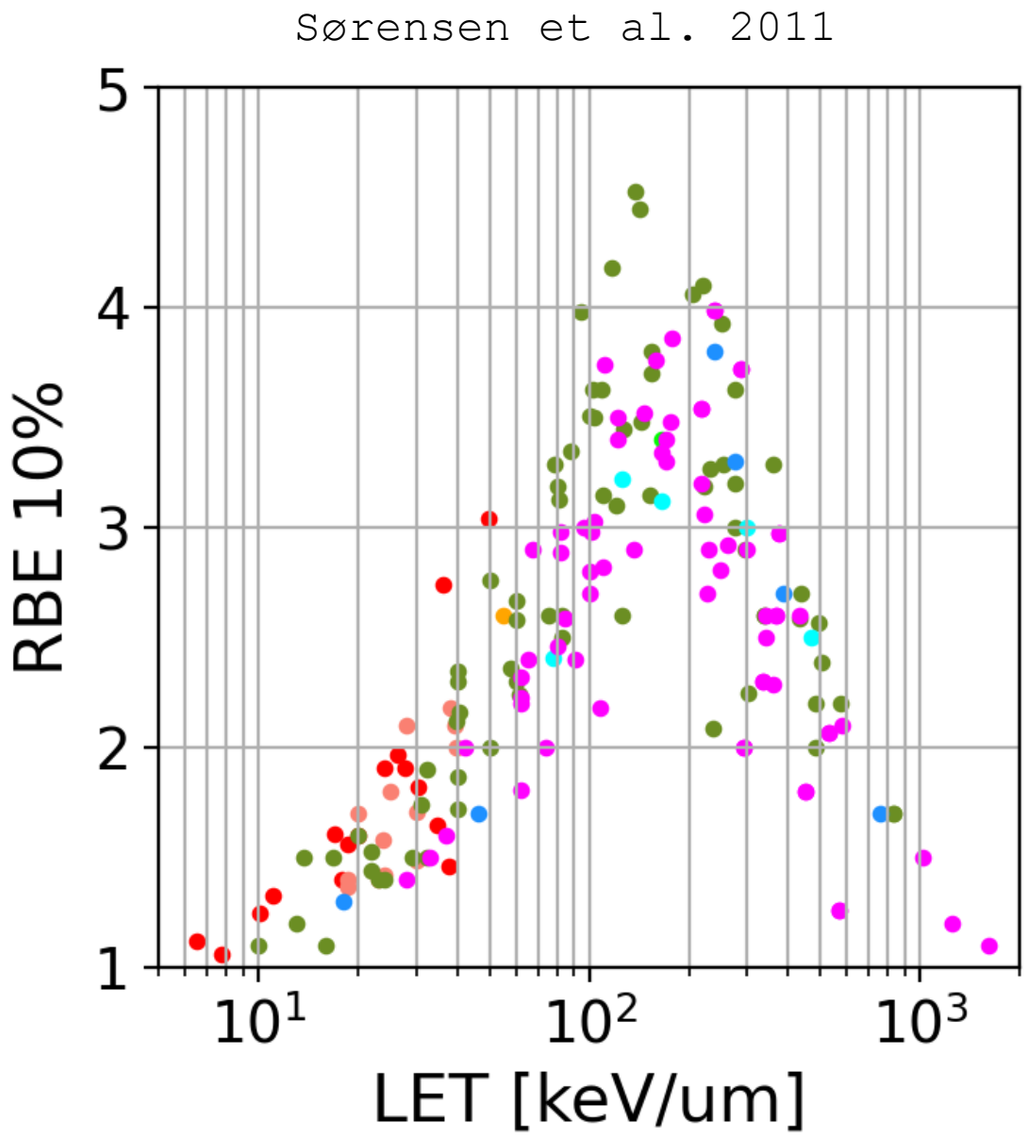
Secondary particles contribution estimation



Electromagnetic interaction:
G4EmStandardPhysics option4

Elastic and inelastic hadronic processes:
G4HadronElasticPhysicsHP;
G4IonElasticPhysics,
G4HadronPhysicsQGSP BIC AllHP
G4IonPhysicsPHP models

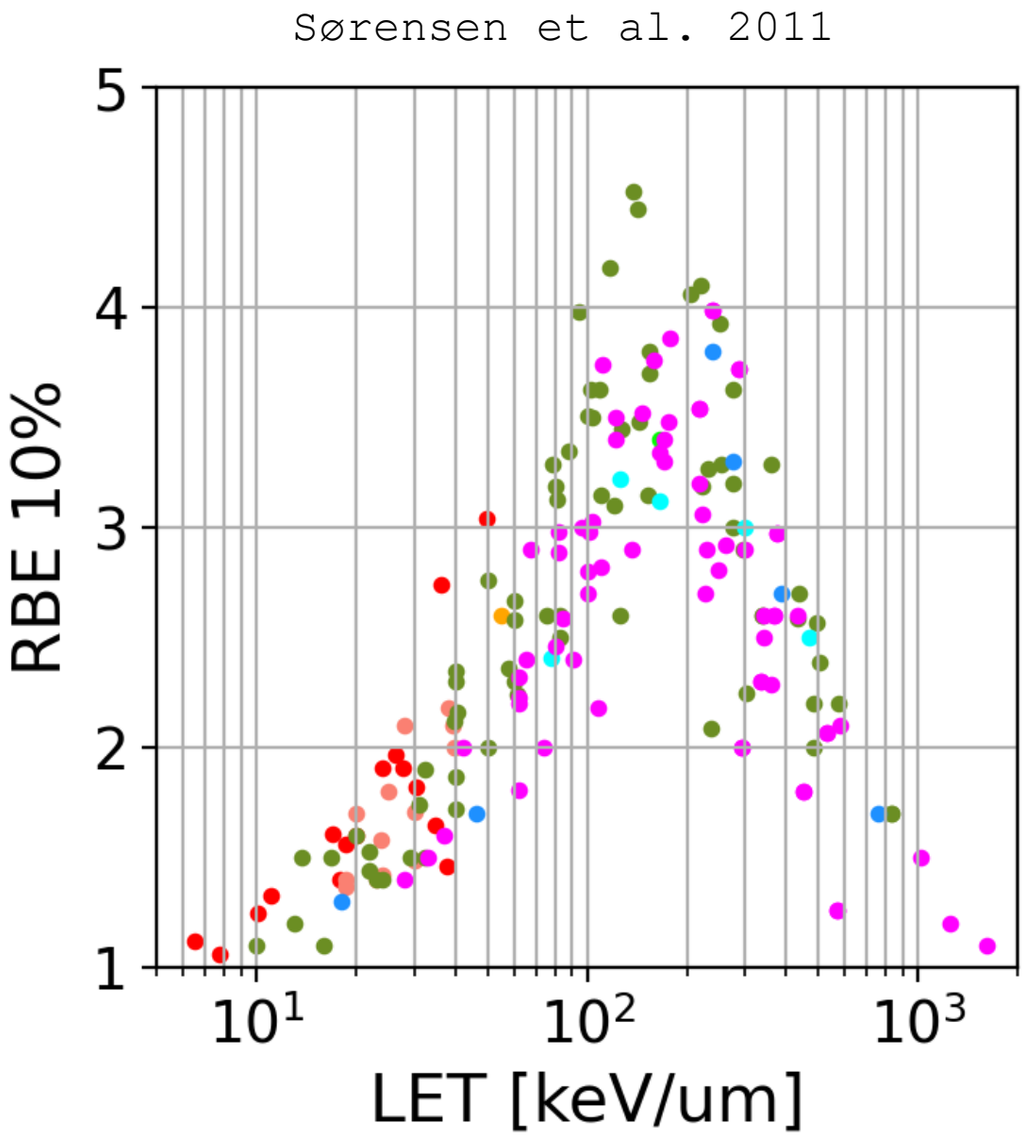
Biological damage



- $RBE_{4.0}$ (RBE $>$ 4.0): LET in the range 100 - 200 keV/μm
- $RBE_{3.5}$ (RBE $>$ 3.5): LET in the range 100 - 300 keV/μm
- $RBE_{3.0}$ (RBE $>$ 3.0): LET in the range 75 - 300 keV/μm
- $RBE_{2.5}$ (RBE $>$ 2.5): LET in the range 50 - 500 keV/μm
- $RBE_{2.0}$ (RBE $>$ 2.0): LET in the range 25 - 600 keV/μm

RBE Level	LET	Z Value of Fragments	
		Entrance	Distal
4.0	Dose	3	2
3.5	Dose	3	2, 3 (configuration B and C)
3.0	Dose	3	2, 3 (configuration B and C)
2.5	Dose	2, 3, 4	2, 3, 4, 8
	Track	3, 4, 5, 8	2, 3, 4, 8
2.0	Dose	2, 3, 4, 5	2, 3, 4, 8

Biological damage



=> we can conclude that ions with very high LET (1000- 1500 keV/ m), which can be stoppers in sensitive volumes, do not produce essential change in a final RBE determination with depth, in 4He therapy

- $RBE_{4.0}$ (RBE $>$ 4.0): LET in the range 100 - 200 keV/μm
- $RBE_{3.5}$ (RBE $>$ 3.5): LET in the range 100 - 300 keV/μm
- $RBE_{3.0}$ (RBE $>$ 3.0): LET in the range 75 - 300 keV/μm
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RBE Level	LET	Z Value of Fragments	
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	Track	3, 4, 5, 8	2, 3, 4, 8
2.0	Dose	2, 3, 4, 5	2, 3, 4, 8

Lithium and secondary Helium

Z= 9 and Z=10, besides having a subdominant relative fluence, do not participate in any of the RBE levels defined

Next steps

Validation with12C and 16O beams

- two experimental campaigns were already performed @LNS-INFN adopting Microplus probe detector;
- a collaboration with the Vinca Institute (Belgrade) is currently on going to correlate the LET (experimental and simulated) with the observed radiobiological damage in biological samples;
- the LET calculation and secondary estimation of 16O is ongoing;
- a new microdosimeter based on the Silicon Carbide techonology will be developed @LNS (preliminary experimental test with proton beams with energies between 30 to 150 MeV was already performed)

Thanks for listening

Left to right:
Roberto Catalano, Davide Passarello, Pablo Cirrone, Emilio Zappalà, Nino Amato, Luciano Pandola, Giuliana Milluzzo, Michele Costa, Mariacristina Guarrera, Serena Fattori, Antonio Russo, Beatrice Cagni, Alma Kurmanova, Carmen Altana,Andrea Matamoros, Giuliana Navarra, Salvo Tudisco, Giacomo Cuttone, Giada Petringa, Gustavo Messina
INFN-LNS Medical Physics Group - Catania, April 30, 2021

Different approaches for the same quantity

LET Dose

Cortes M.G. et al. Phys.Med.Bio. 60 (2015)

$$\bar{L}_D = \frac{\left(\sum_{i=1}^{N} \varepsilon_i\right)^2}{\sum_{i=1}^{N} l_i} \qquad \bar{L}_D = \frac{\sum_{i=1}^{N} L_i \varepsilon_i}{\sum_{i=1}^{N} \varepsilon_i}$$

Romano F. et al. Phys.Med.Bio. 59 (2014)

$$\bar{L}_D = \frac{\sum_{i=1}^{N} \frac{\varepsilon_i^2}{l_i}}{\sum_{i=1}^{N} \varepsilon_i} \qquad \bar{L}_D^{Total} = \frac{\sum_{j=1}^{n} \left[\sum_{i=1}^{N} \frac{\varepsilon_i^2}{l_i}\right]_j}{\sum_{j=1}^{n} \left[\sum_{i=1}^{N} \varepsilon_i\right]_j}$$

LET Track

Guan F. et al. Medical Physics (2015)

$$\bar{L}_T = \frac{\sum_{i=1}^{N} \left(\frac{\varepsilon_i}{l_i}\right) l_i}{\sum_{i=1}^{N} l_i} = \frac{\sum_{i=1}^{N} \varepsilon_i}{\sum_{i=1}^{N} l_i}$$

Linear Energy Transfer: a new approach

The total electronic stopping powers Li were extracted at each particle step i, using the method **ComputeElectronicDEDX**() belonging to the Geant4 **G4EmCalculator class.** This function, in fact, retrives Li from the electronic stopping power tables built at the beginning of the simulation, once the particle type, kinetic energy and material are provided.

Our Algorithms

$$\bar{L}_d = \frac{\sum_{i=1}^{N} L_i \varepsilon_i}{\sum_{i=1}^{N} \varepsilon_i}$$

$$\bar{L}_d^{Total} = \frac{\sum_{j=1}^{n} [\sum_{i=1}^{N} L_i \varepsilon_i]_j}{\sum_{j=1}^{n} [\sum_{i=1}^{N} \varepsilon_i]_j}$$

$$\bar{L}_T = \frac{\sum_{i=1}^{N} L_i l_i}{\sum_{i=1}^{N} l_i}$$

$$\bar{L}_T^{Total} = \frac{\sum_{j=1}^{n} [\sum_{i=1}^{N} L_i l_i]_j}{\sum_{j=1}^{n} [\sum_{i=1}^{N} l_i]_j}.$$