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AdvaNced Technologies for Human-centEred Medicine

Geant4 Monte Carlo simulations for medical physics applications and novel radiotherapy techniques

Giuliana Milluzzo

Istituto Nazionale di Fisica Nucleare Sezione di Catania

INFN CATANIA
Istituto Nazionale di Fisica Nucleare
Sezione di Catania

Computing@CSN5: applications and innovations at INFN
Bari, 14-16 Ottobre 2024

giuliana.milluzzo@ct.infn.it

GEANT4
A SIMULATION TOOLKIT

A bit of history…

In **1949**: First paper on the Monte Carlo methods. ("**The Monte Carlo Method**, Metropolis and Ulam)

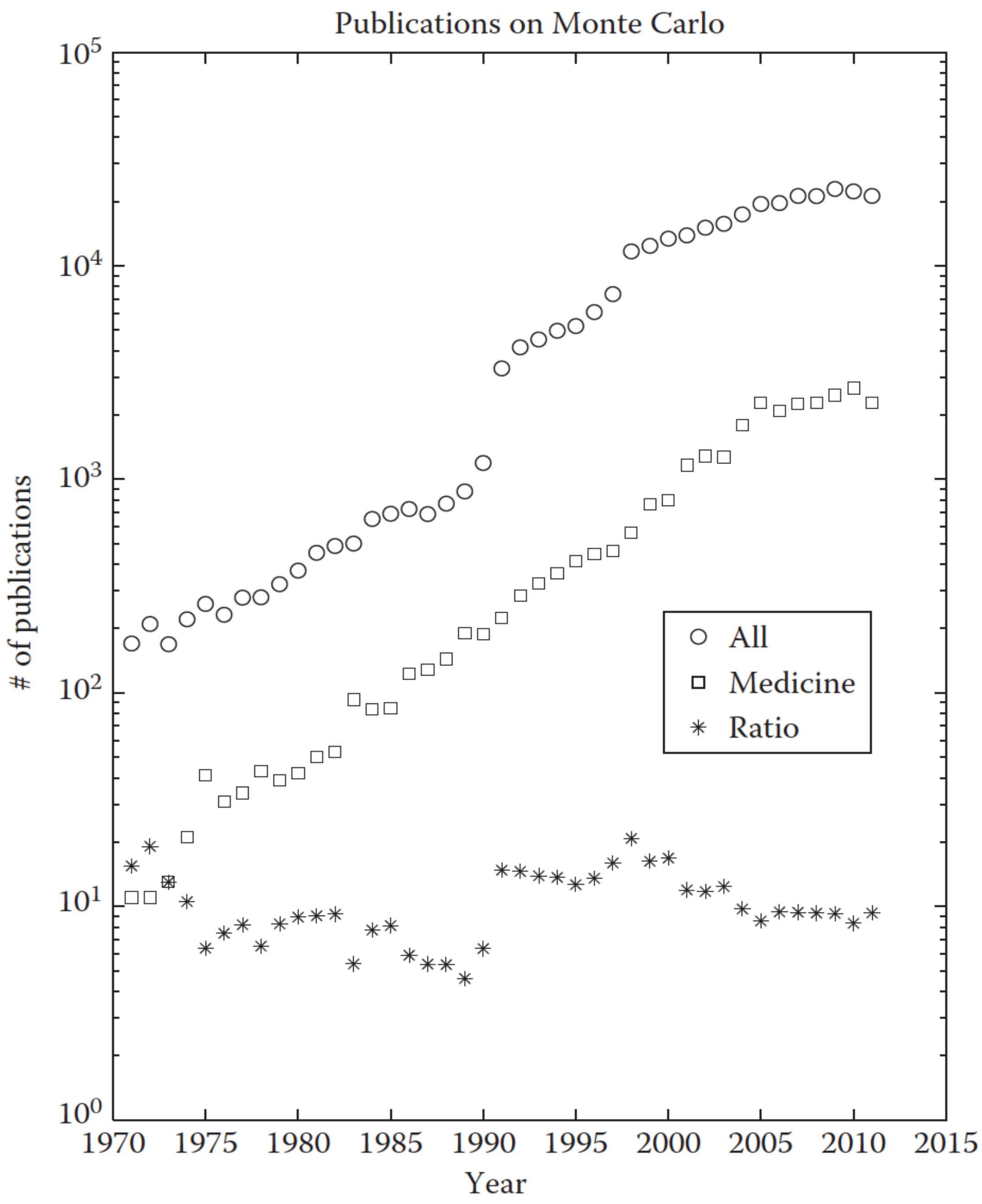
1950-52: *First papers employing the Monte Carlo method using electron transport for Medical Physics*, by Robert R. Wilson

1954: The **Symposium on Monte Carlo Methods** with 70 attendees, many of whom would be recognized as "founding fathers" by Monte Carlo practitioners in the radiological sciences.

1958-60: first use of an electronic digital computer in simulating high-energy cascades by **Monte Carlo methods for Medical Physics** reported by Butcher and Messel (independently by Varfolomeev and Svetlolobov).

Publications using Monte Carlo methods rapidly increased

10% of them related to medical applications



Monte Carlo simulations for medical physics applications

Predicting physical quantities of interest in medical physics

Dose, energy, fluence distributions, beam spot size for radiotherapy, diagnostics, TPS

Computing physical/biological quantities difficult to measure

LET, RBE, microdosimetric spectra

Choose a reliable tool for the simulation of these processes

Validation of physical models and continuous benchmarking with experimental data

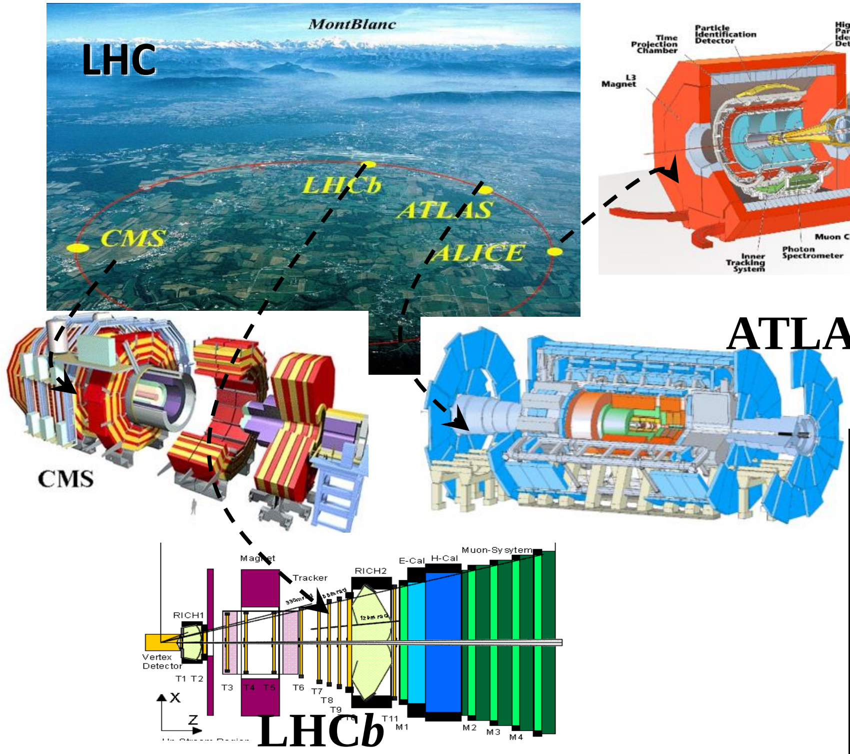
Modelling, design of new devices, beamlines in conventional-RT and for innovative radiotherapy modalities

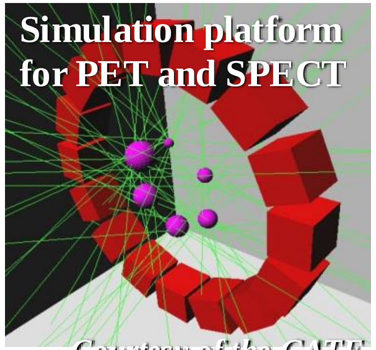
GEANT4
A SIMULATION TOOLKIT

The Geant4 Monte Carlo toolkit

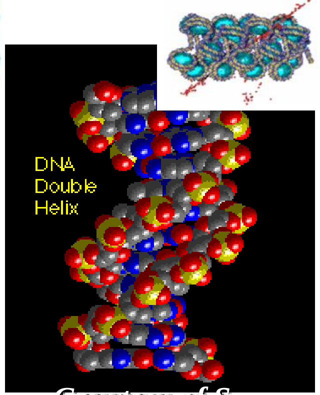
GEANT4 A SIMULATION TOOLKIT → ***Geometry and Tracking***

1974: First version of the code released at CERN for high energy particles
1983: Geant3 written in Fortran language
1998: Geant4 written in C++ object oriented language was released for the simulation of large scale HEP experiments at CERN (Geneva)



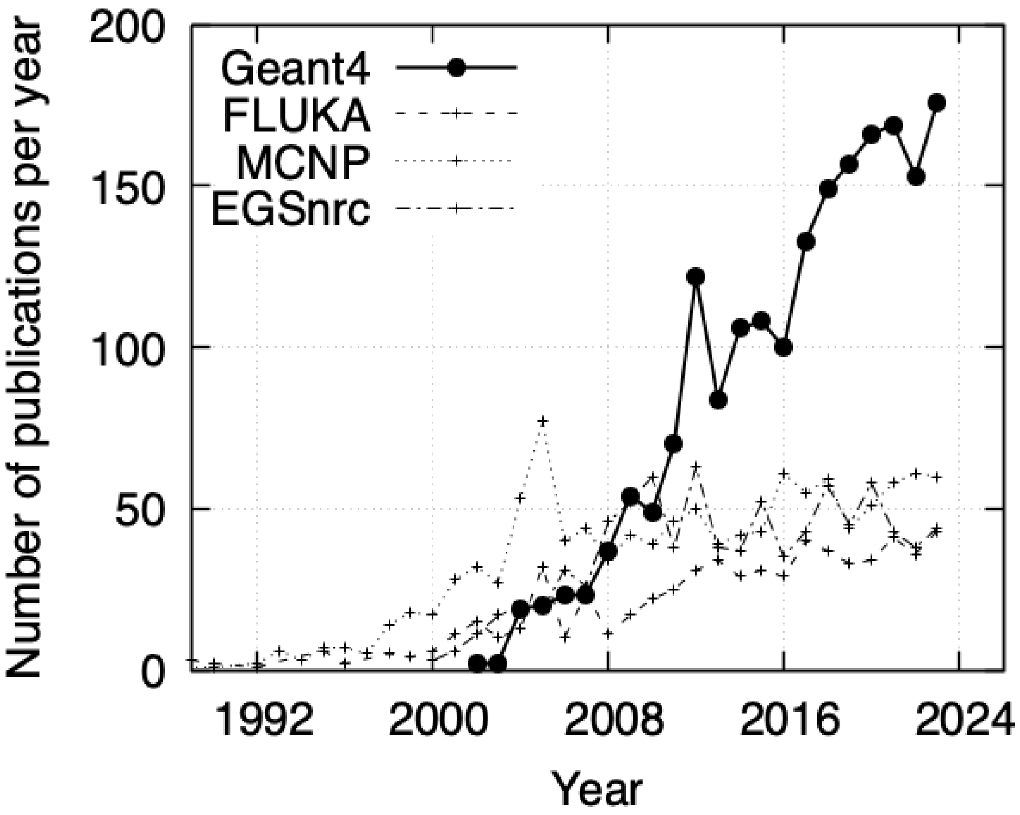


Courtesy of the GATE Collaboration



Courtesy of S. Incerti, Bordeaux

Geant4 Medical applications

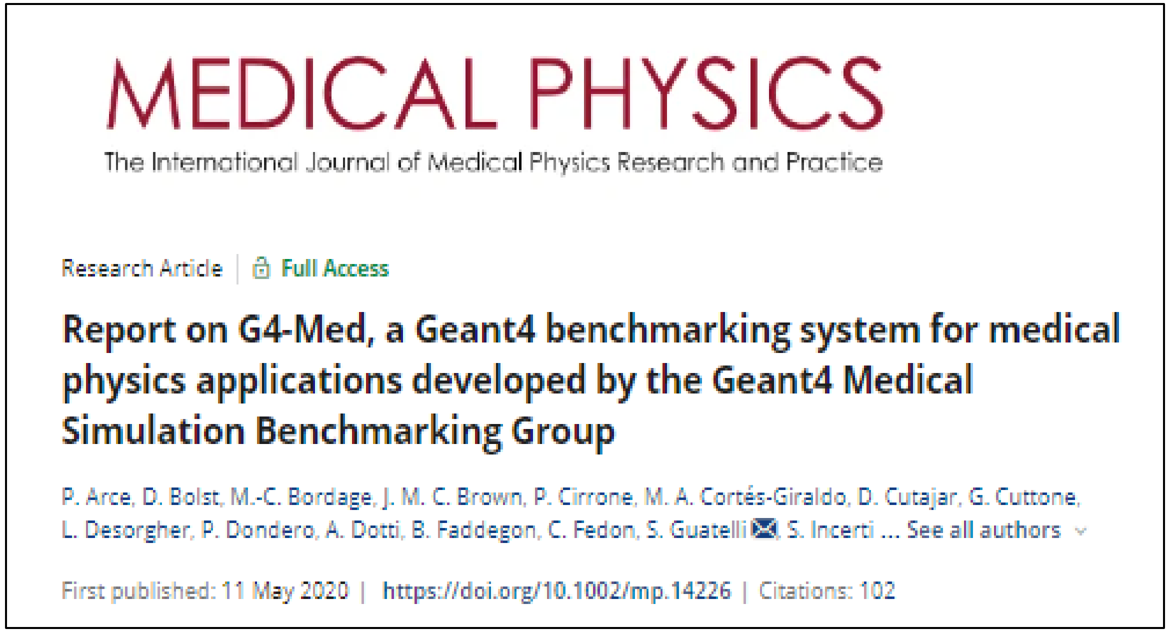


The Geant4 Medical Simulation Benchmarking Group (G4MED)

https://twiki.cern.ch/twiki/bin/view/Geant4/G4MSBG

P Arce[1], J Archer[2], L Arsini[3], D Bolst[2], J M C Brown[4], B Caccia[5], A Chacon[6], P Cirrone[7], M A Cortés-Giraldo[8], D Cutajar[2], G Cuttone[7], P Dondero[9], A Dotti[10], B Faddegon[11], S Fattori[7], C Fedon[12], S Guatelli[2,*], A Haga[13], S Incerti[14], V Ivanchenko[15], D Konstantinov[16], I Kyriakou[17], A Le[2], Z Li[14], M Maire[18], A Malaroda[19], C Mancini-Terracciano[3], A Mantero[9], C Michelet[14], G. Milluzzo[20], F Nicolanti[3], M Novak[21], C Omachi[22], L Pandola[7], J. H. Pensavalle[23], A Perales[24], Y Perrot[25], G Petringa[7], S Pozzi[5], J M Quesada[8], J Ramos-Méndez[11], F Romano[20], A B Rosenfeld[2], M Safavi-Naeini[6], D Sakata[26], L G Sarmiento[27], T Sasaki[28], Y Sato[13], A Sciuto[7], I Sechopoulos[29,30], E C Simpson[31], R. Stanzani[9], A. Tomal[32], T Toshito[22], N H Tran[14], C. White[2], D H Wright[10]. *INFN

- Created in 2014.
- **Coordination Team since 2018:**
  - **Coordinator: Susanna Guatelli (Univ. Wollongong, Australia)**
  - **Deputy-coordinator: Pedro Arce (CIEMAT, Spain)**
- 57 researchers; 32 institutions from 12 different countries.


MEDICAL PHYSICS
The International Journal of Medical Physics Research and Practice

Research Article | Full Access

Report on G4-Med, a Geant4 benchmarking system for medical physics applications developed by the Geant4 Medical Simulation Benchmarking Group

P. Arce, D. Bolst, M.-C. Bordage, J. M. C. Brown, P. Cirrone, M. A. Cortés-Giraldo, D. Cutajar, G. Cuttone, L. Desorgher, P. Dondero, A. Dotti, B. Faddegon, C. Fedon, S. Guatelli, S. Incerti ... See all authors

First published: 11 May 2020 | https://doi.org/10.1002/mp.14226 | Citations: 102

+ Second paper under review in Medical Physics

Courtesy of S. Guatelli

G4-Med tests

Electromagnetic physics tests

- **Brachytherapy** (Ir-192 and I-125)
- Electron **FLASH radiotherapy**
- MV X-ray **radiotherapy test**
- Photon attenuation coeff
- Electron electronic stopping power
- Electron backscattering
- 13 MeV electron forward scattering
- **Bremsstrahlung** from thick targets
- Fano cavity

Geant4-DNA tests

- Low dose energy electron Dose Point Kernels
- Microdosimetry
- Chemistry

Hadronic nuclear cross section tests

- Nucleus-nucleus hadronic inelastic scattering cross sections
- **62 MeV/u ^{12}C fragmentation**
- Charge-changing cross sections for 300 MeV/u ^{12}C ions

Electromagnetic + hadronic physics tests

- **62 MeV proton** beam test (cell survival modelling and averaged LET track)
- In-vivo PET for carbon ion therapy
- 67.5 MeV proton Bragg curves in water
- Light Ion Bragg Peak curves
- Neutron yield of 113 MeV and 256 MeV protons and 290 MeV/u carbon ions
- **Fragmentation test** of a 400 MeV/u ^{12}C ion beam in water

Goals:

Provide physics list recommendations

Monitor physics capability of Geant4 through the different version of the code

Electromagnetic physics models

Opt3, **Opt4**, Livermore, Penelope, SS

Hadronic physics models

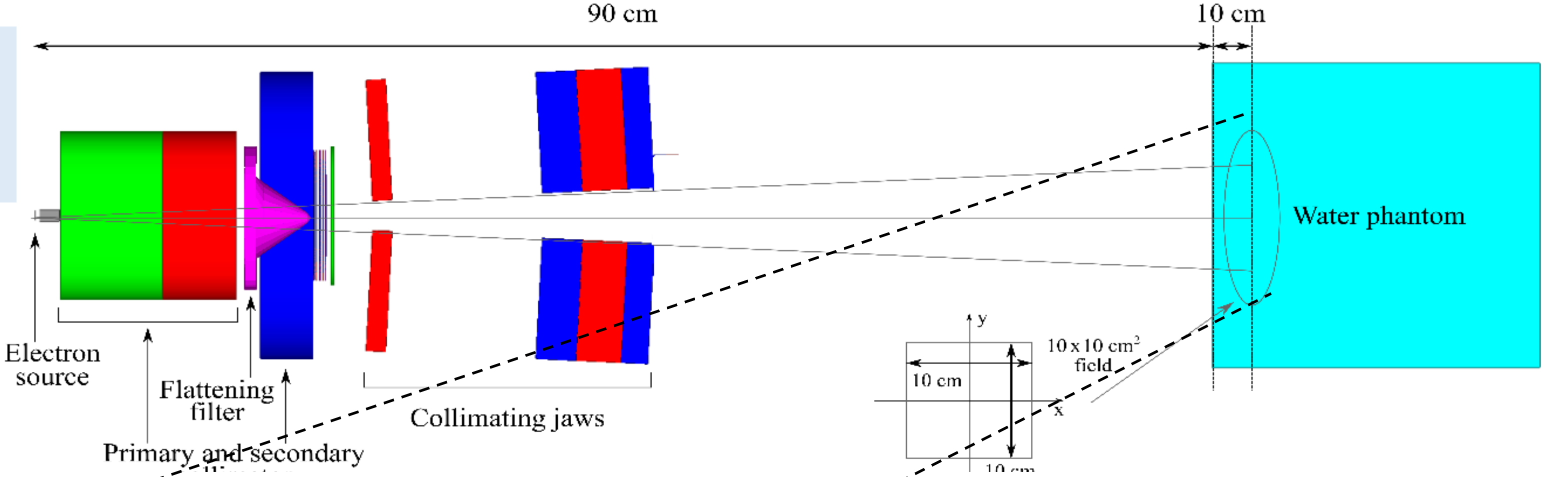
The **Binary Cascade Model** (BIC), Quantum Molecular Dynamics (QMD), Liege Intranuclear Cascade (INCL)

Conventional radiotherapy

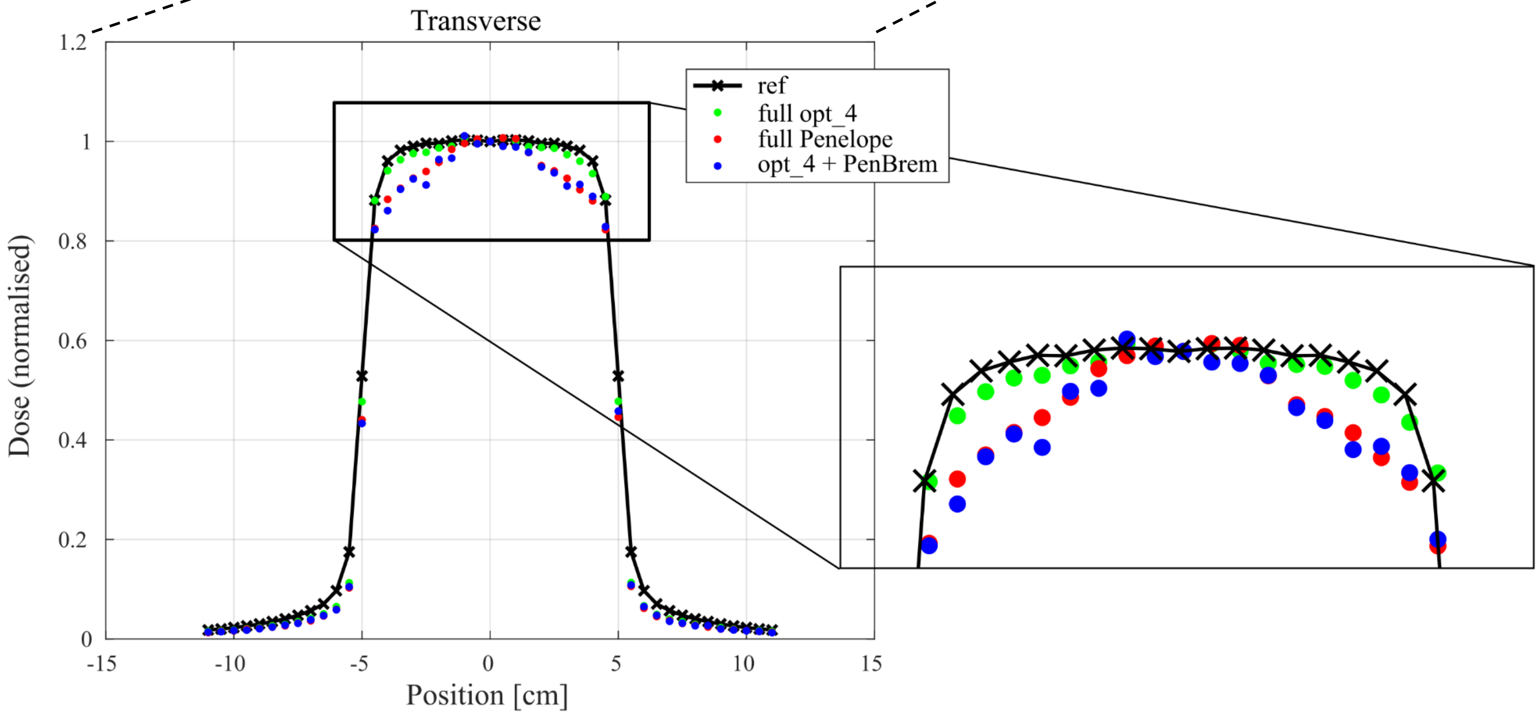
The MV X–ray radiotherapy test

By B. Caccia and S. Pozzi (Istituto Superiore di Sanita', Rome, Italy), and C. Mancini-Terracciano (La Sapienza, Rome, INFN-RM1, Italy)

- Geant4 advanced example **medical_linac**
- Model of a GE Saturne 43 linear accelerator (EURADOS Report Caccia et al, 2020-05)



- The Geant4 Penelope Bremsstrahlung process seems to have problems
- This is now under investigation



Courtesy of S. Guatelli

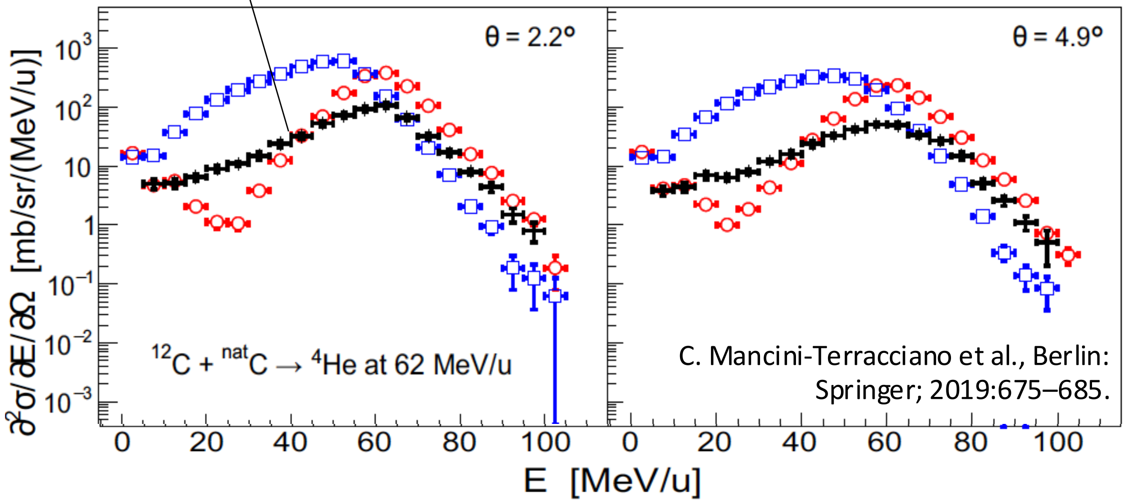
Proton and hadrontherapy

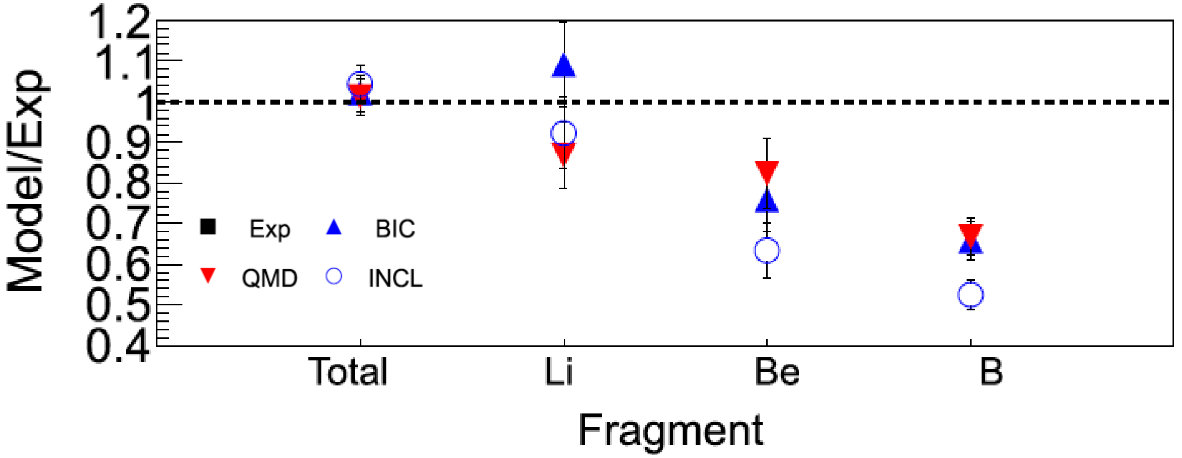
^{12}C fragmentation tests

C. Mancini-Terracciano (Uni-Ro, INFN-RM1), S.Guatelli (CMRP), D. Bolst, C. Omachi, T. Toshito (Nagoya PTC), T. Sasaki (KEK)

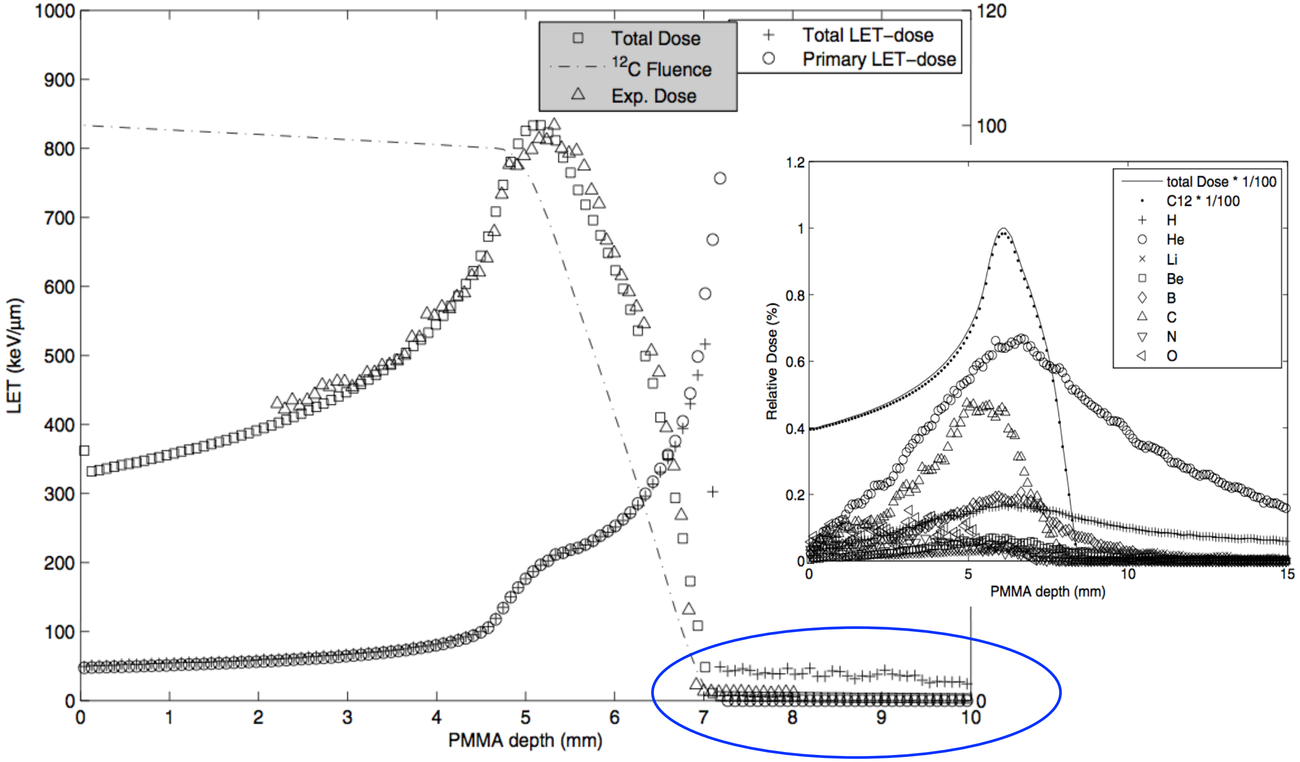
FRAGG & FRATT experiment@ INFN-LNS
De Napoli *et al*. PMB **59** (2014)

Alpha particle spectra





ARCE et al., Med Phys, 48 (1), 2021



Romano *et al*. PMB **59** (2014)

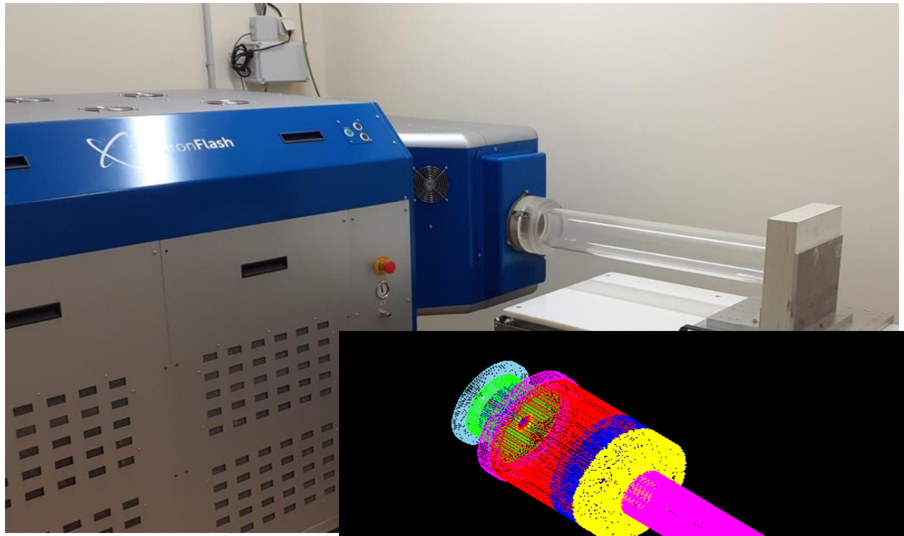
Increased biological effects respect to the predictions

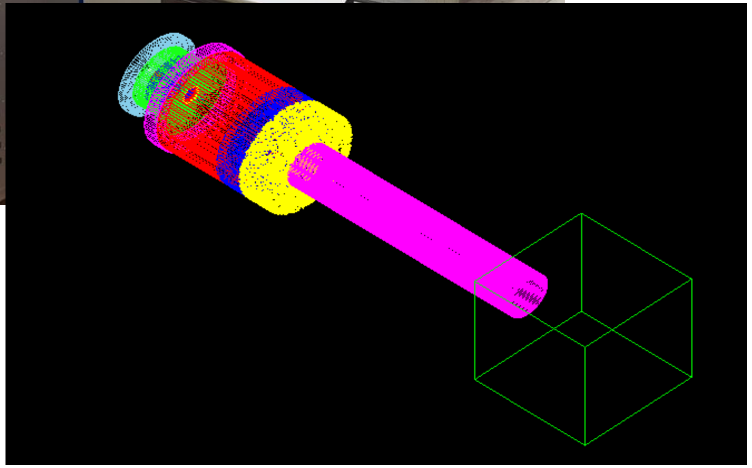
FLASH radiotherapy

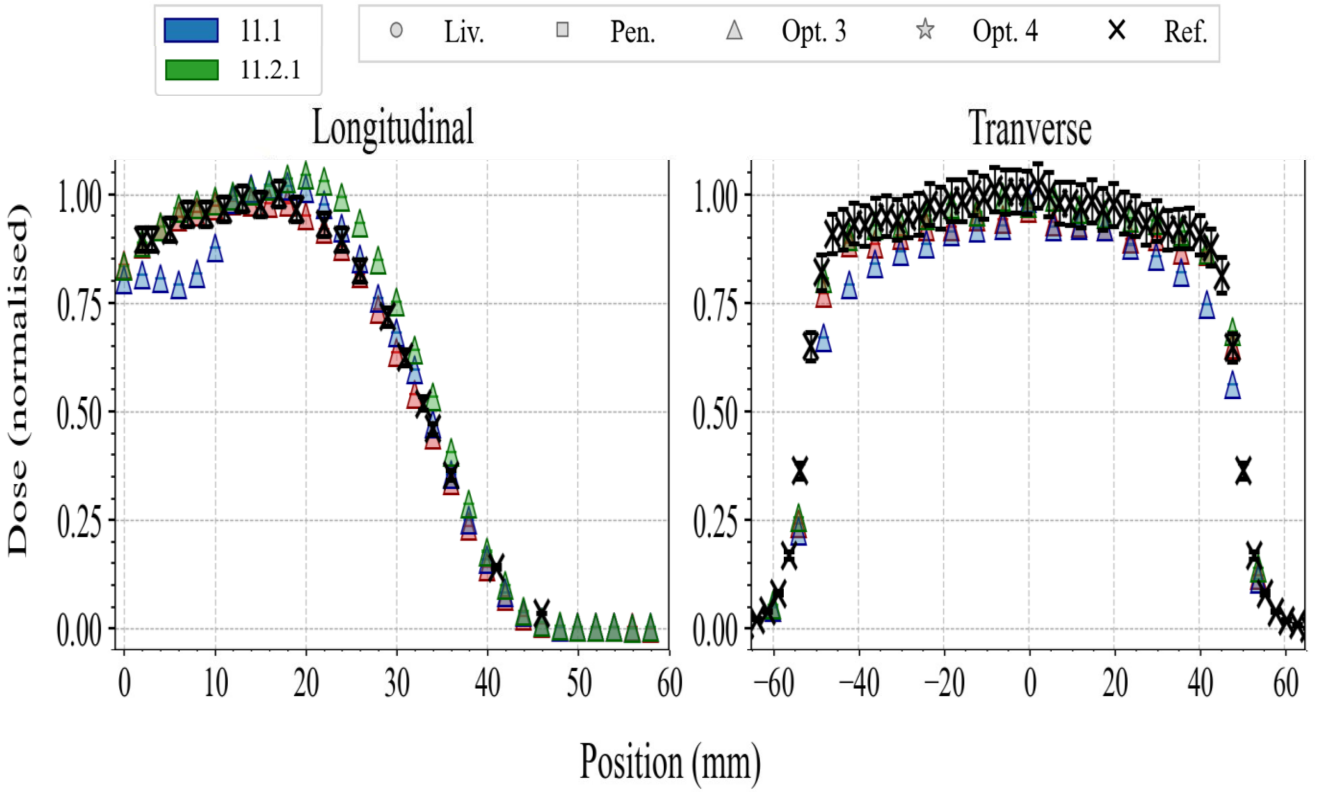
Electron FLASH radiotherapy test

G. Milluzzo & F. Romano (INFN Catania), and J. H Pensavalle (Azienda Ospedaliero Universitaria Pisa)

Triode Electron Gun Equipped **ElectronFlash** Linac, manufactured by Sordina Iort Technologies S.p.A installed at the **CPFR (Centro Pisano Flash Radiotherapy)** in Pisa, Italy







eFLASH_radiotherapy impact within the national projects

FRIDA
CSN5

INFN GEANT
CSN5

MIRO Minibeam Radiotherapy
CSN5

DREAM
CNTT

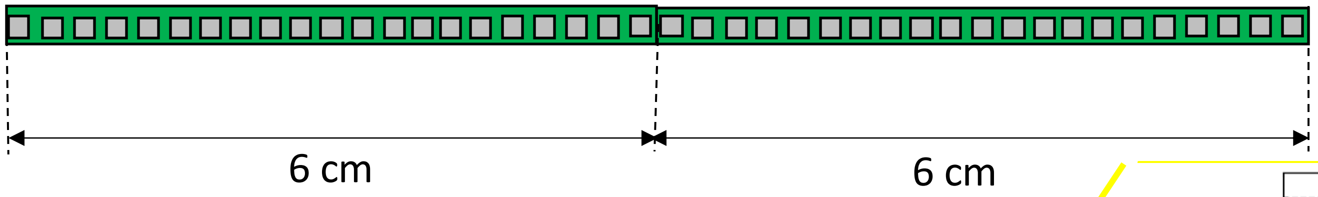
Anthem
Spoke4 (WP3)

ICSC Centro Nazionale di Ricerca in HPC, Big Data and Quantum Computing
Spoke8 (WP2)

Silicon carbide array **D**etecto**R** for dose profil**E** me**A**sure**M**ents at FLASH regimes

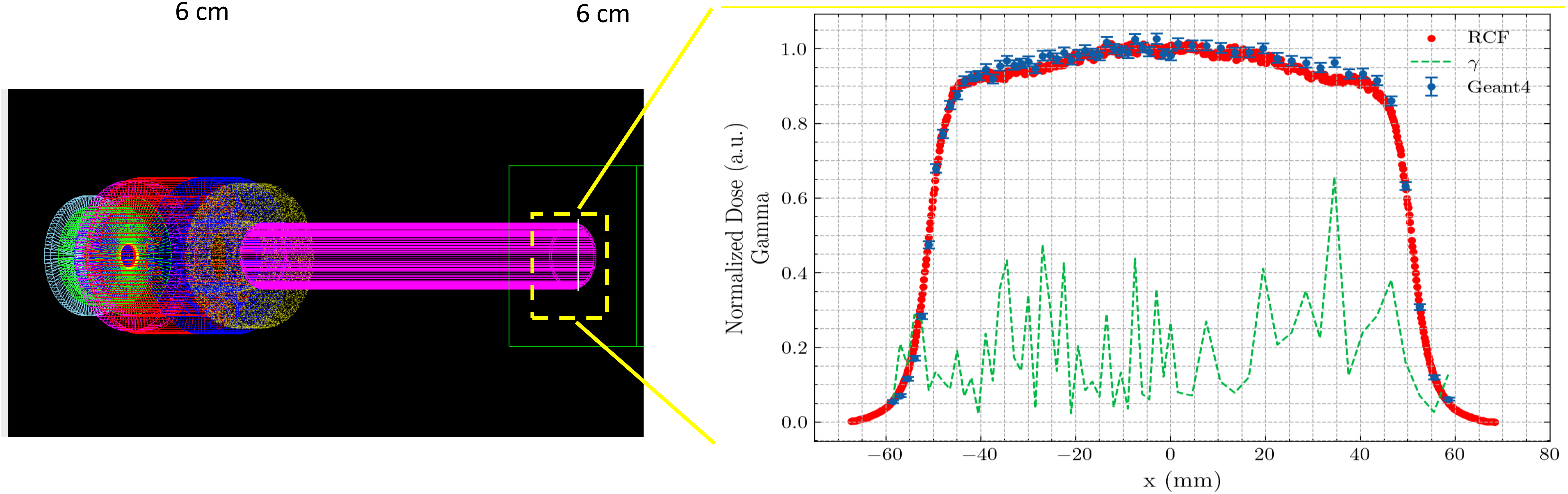
DREAM

1. Reducing the total amount of delivered dose
2. Keeping a high spatial resolution
3. Minimize the cost and the complexity → number of detectors



FLASH RADIOTHERAPY

Dose per pulse: **1-20 Gy**
Instantaneous Dose Rate: > 40 Gy/s
Irradiation Time: <200 ms



Applications in minibeam radiotherapy

Conventional-RT

Minibeam-RT (MBRT)

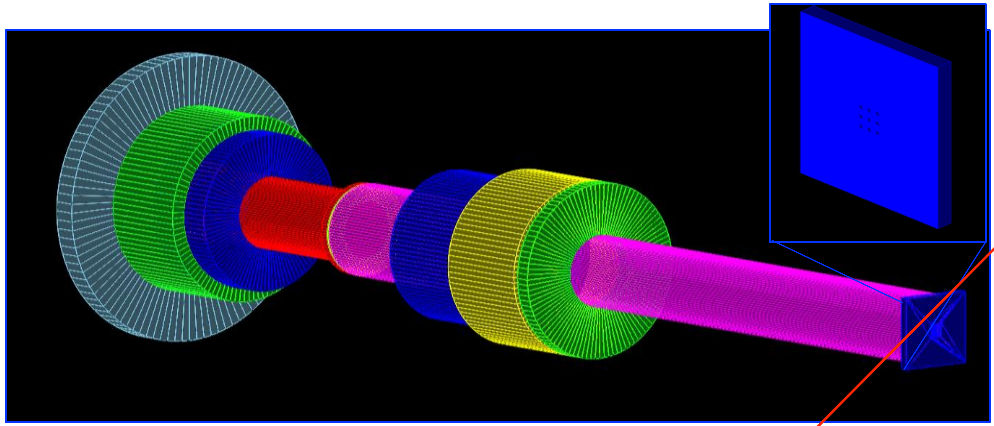
MIRO
Minibeam Radiotherapy

PI: F. Di Martino (INFN-PI)
F. Romano (INFN-CT)

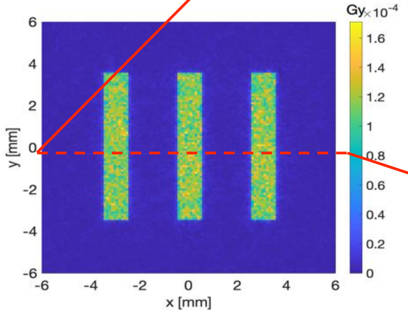
Minibeam facilities

- **Electron** minibeams @ CPFR & INFN-TO & INFN-CT
- **Proton** minibeam @ Trento Protontherapy Centre

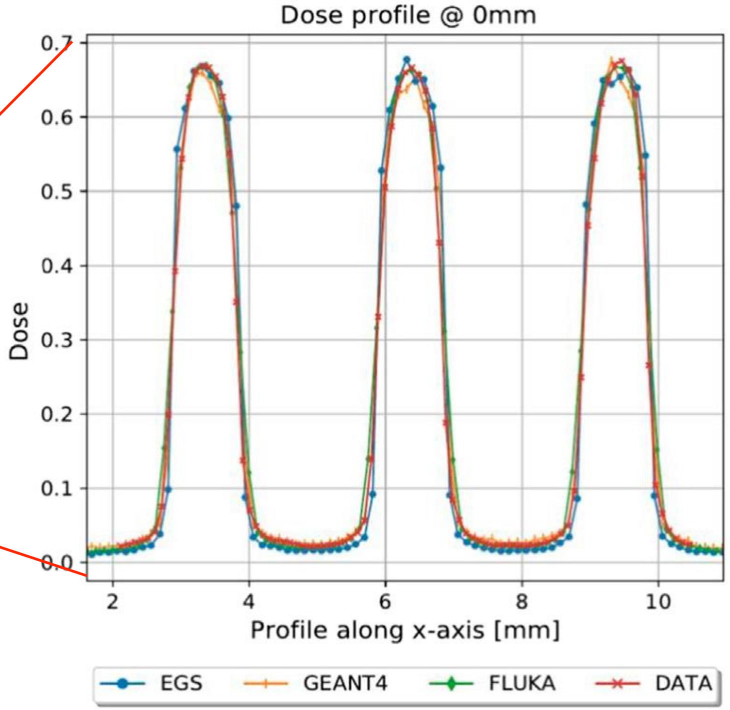
Minibeam collimator design for the ElectronFLASH linac in Pisa



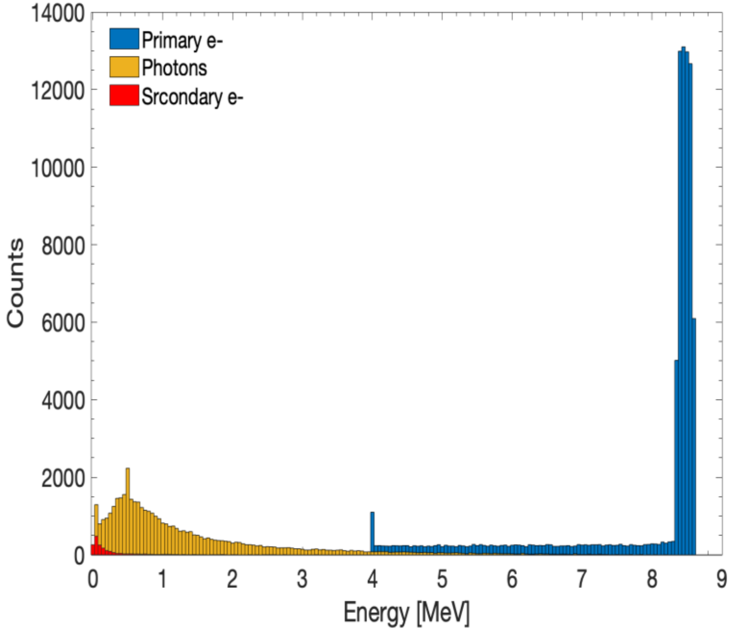
Real tungsten collimators



J. Pensavalle et al.,Frontiers Physics 2023



Simulations of secondary particles contamination



Evaluation of microdosimetric parameters

Microdosimetry: *measurement of the statistical fluctuations of energy deposition in site size (cellular and sub-cellular scale)* → biological effects as the result of energy deposition in sensitive *sites* or *targets* of specific size.

The *lineal energy*, y, is the quotient of ε_s by $\bar{l}$, where ε_s is the energy imparted to the matter in a given volume by a single energy-deposition event, and $\bar{l}$ is the mean chord length of that volume, thus

$$y = \frac{\varepsilon_s}{\bar{l}}.$$

Unit: J m^{-1}

Measurement of microdosimetric spectra

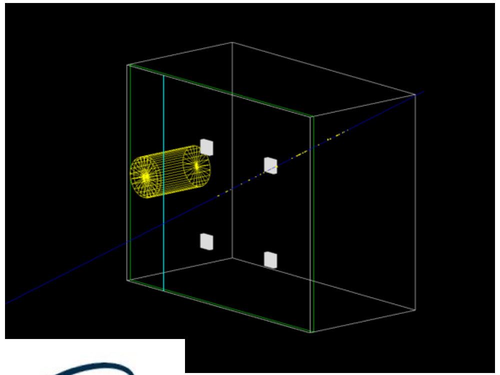
TEPC-based detectors
Solid state detectors

Colautti P et al., Front. Phys. 8:550458.

V. Conte et al., Phys. Med. Biol. 65 (2020) 245018

Monte Carlo track structure and condensed history codes

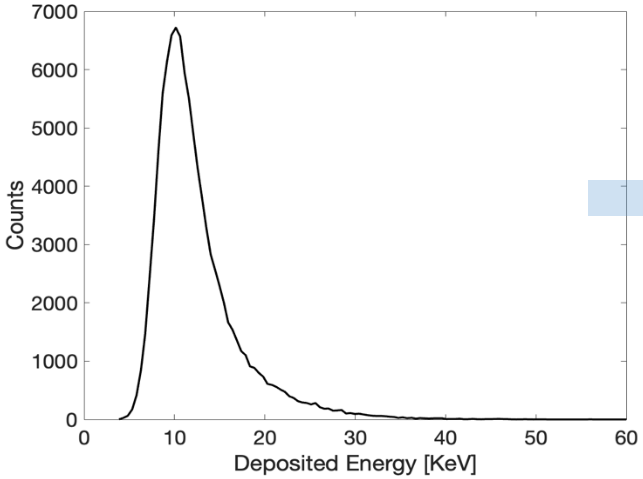
exp_microdosimetry Geant4 advanced example



Microdosimeters

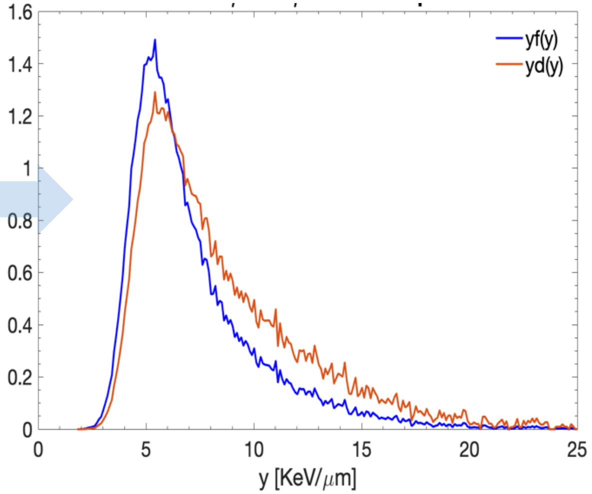
- Semplified diamond microdosimeter
- The microdiamond detector (TorVergata)
- Bridge silicon microdosimeters
- Diamond telescope
- **SiC microdosimeter**
- **Mini TEPC**

20 MeV protons,
SiC 100x100 um^2/2 um



Microdosimetric Kinetic Model (MKM)

$$S(D) = \exp - \left(\alpha_0 + \frac{\beta}{\rho\, \pi\, r_d^2}\, \bar{y}_D \right) D + \beta D^2$$

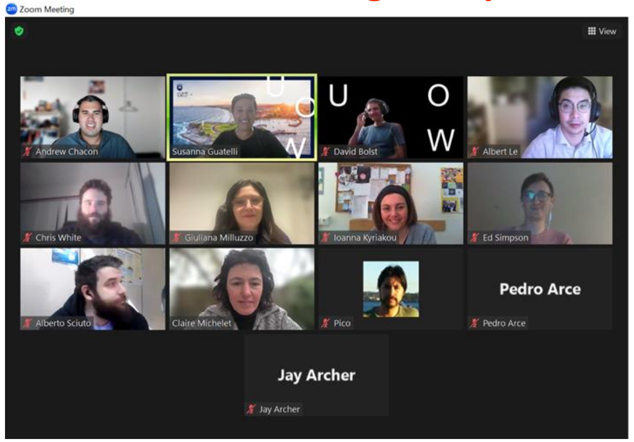


Conclusions and remarks

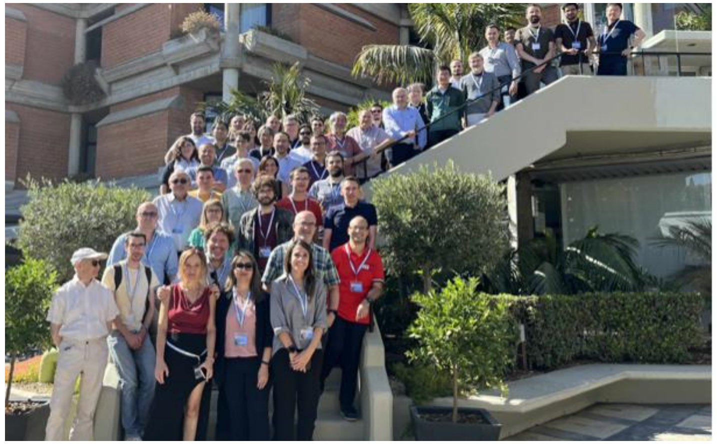
- **Geant4** is an open source toolkit maintained by the international collaboration continuously validated against experimental data
- The **G4-Med** project born to benchmark the physical models in the domain of medical physics application, has proved:
  - To monitor how changes in the Geant4 physics component translate in physical quantities of interest;
  - To supports significantly the development of the Geant4 physics component.
- **Geant4 applications** and simulations are actively used in **INFN** and **PNRR** projects

Acknowledgements

The Geant4 Medical Simulation Benchmarking Group



Geant4 International collaboration



INFN-CT Research group

Francesco Romano, Giuliana Milluzzo, Chinonso Okpuwe, Gabriele Trovato, Said Ahmed

CPFR

F. Di Martino, J. Pensavalle, L. Masturzo

MIRO Minibeam Radiotherapy

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Thank you for your attention