Simulations in Radiation Therapy

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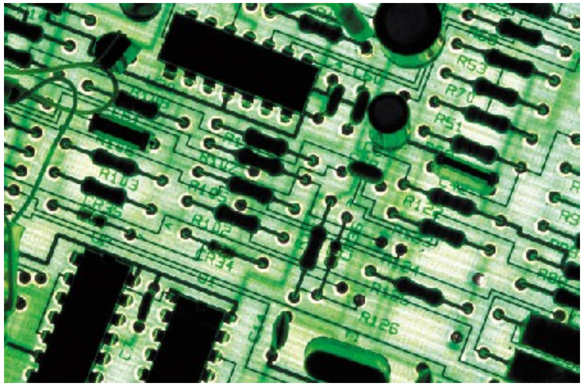
LYON ET RHÔNE-ALPES

Numerical simulations and random processes treat cancer



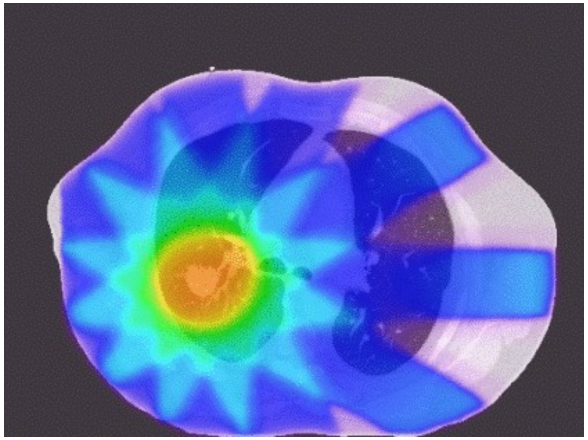
Cancer

Cancer
11 millions new/year worldwide
1st mortality cause in France

Principal treatment modalities
Surgery, chemotherapy, radiation therapy

Radiation Therapy – cancer treatment

- About 2/3 of all patients
- Treatment in fractions, i.e. 64 Gy in 32 fractions of 2Gy
- Tradeoff: dose to tumor / dose to healthy tissue
- Security margins



Radiation therapy

Advanced technology

Linac

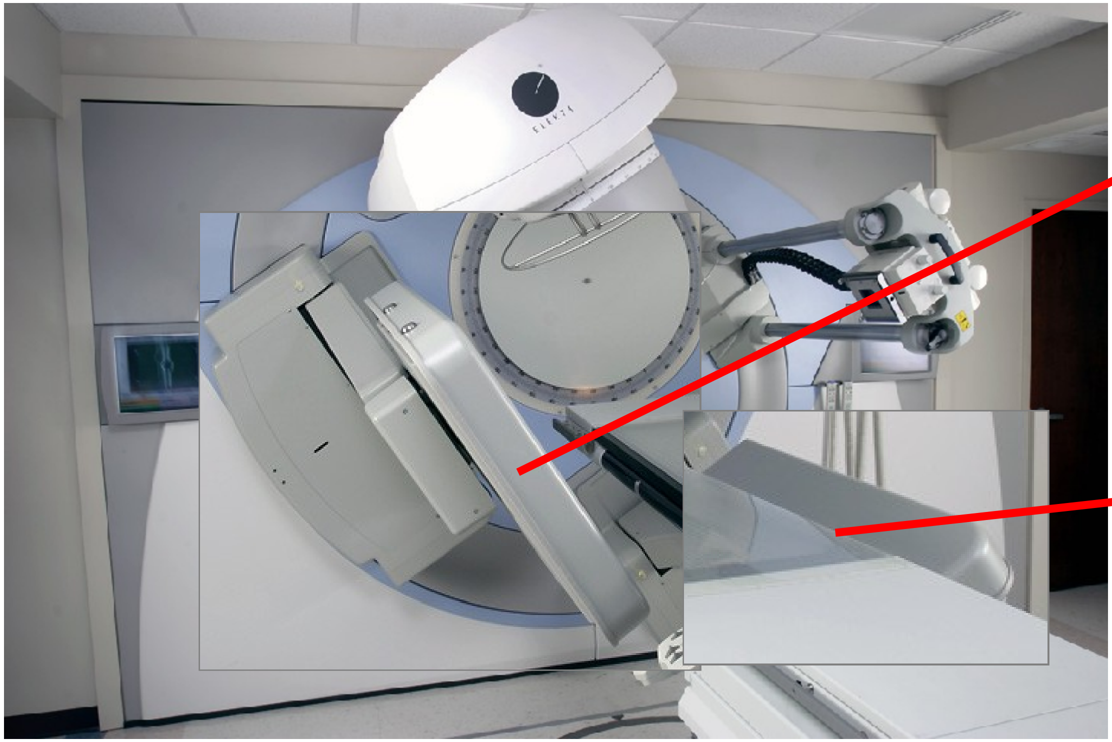
Tomotherapy

CyberKnife

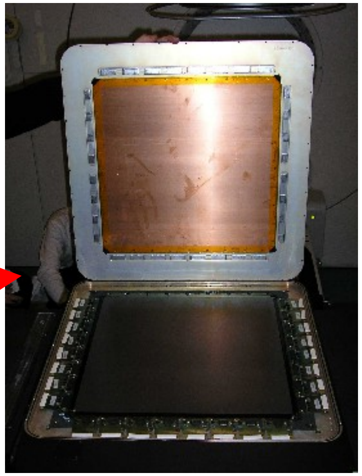
Hadrontherapy

IGRT

Image guided Radiation Therapy



On board CBCT

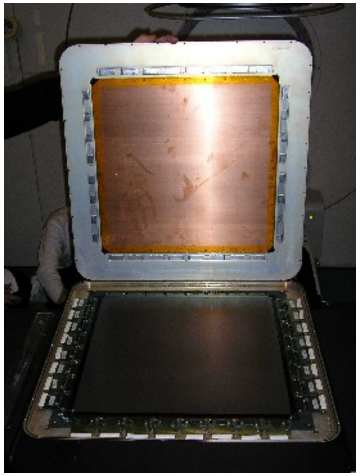


Portal imaging

Imaging devices

Optical system

CT



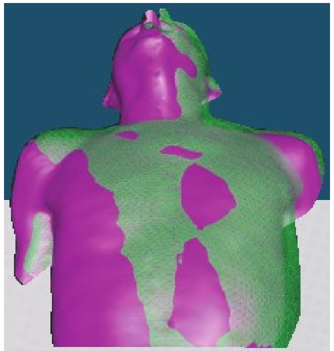
CBCT

PET-CT

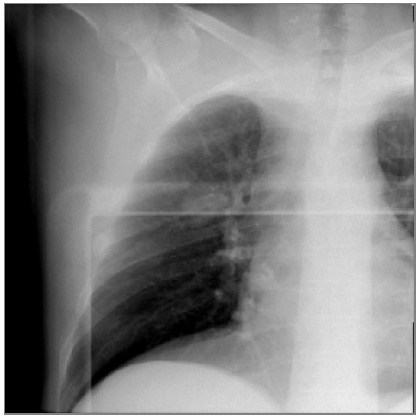
Portal

Imaging devices

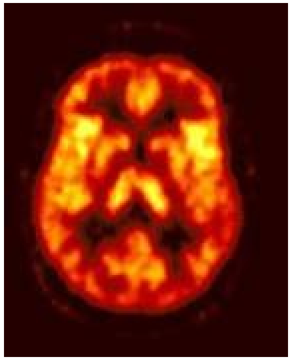
Optical system



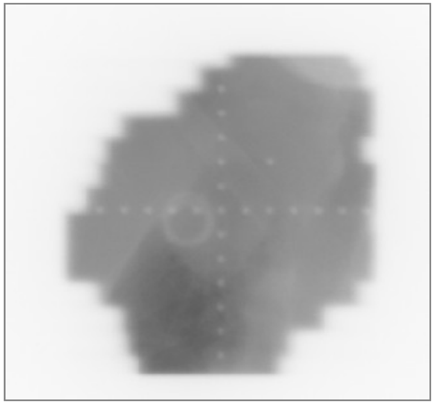
CT



CBCT



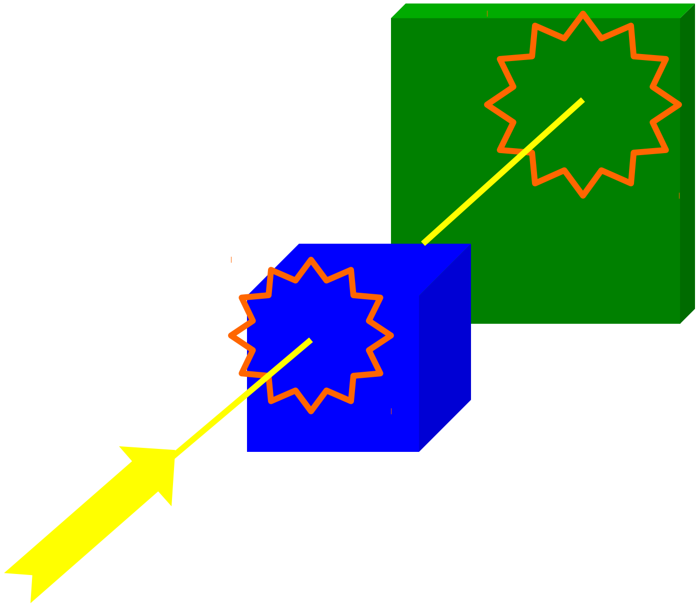
PET-CT



Portal

Medical Physics

- Imaging & Therapy
- Beam – Target - Detector



- Interaction between particles and matter = physical processes
- Absorbed energy = dose
- (Also biological for the "effect")

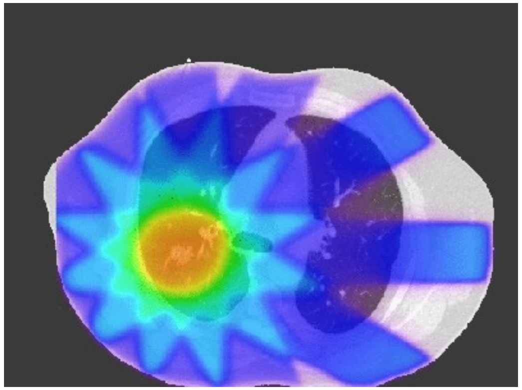
Plan

- Introduction
- **Example: dose computation in protontherapy**
- Prompt-gamma imaging device
- Conclusion

Numerical simulations in RT

- Predict absorbed dose
- Optimise treatment plan (100% of treatment)

Calcul de dose



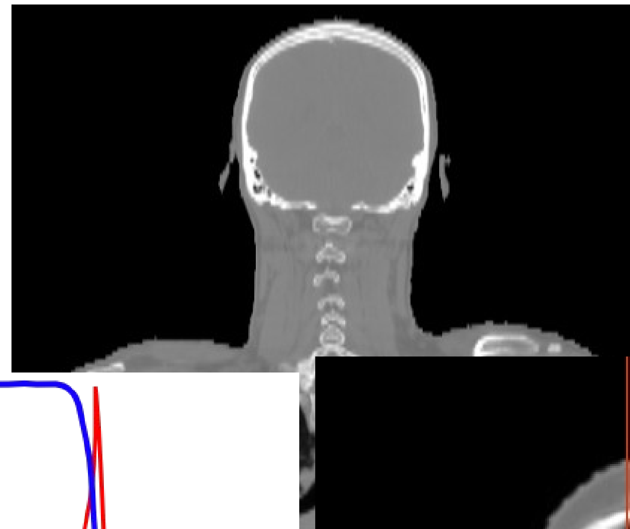
$$-\frac{dE}{dX} = 4\pi N \frac{e^4 Z_{eff}^2}{m_e c^2 \beta^2} Z_T \left[ln\left(\frac{2 m_e \beta^2}{I(1-\beta^2)}\right) - \beta^2\right]$$

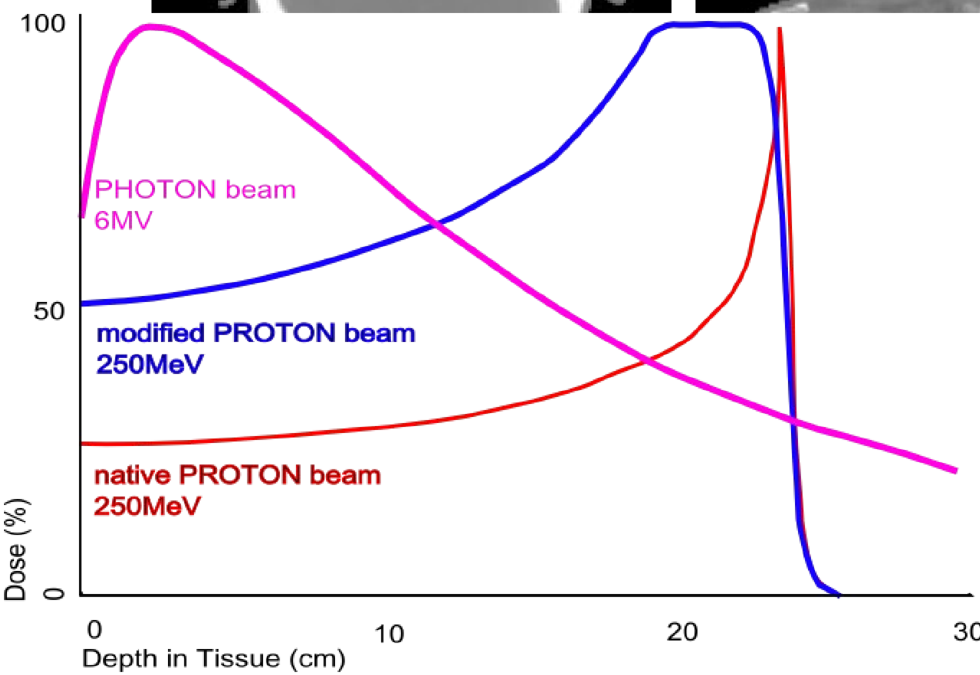
How ?

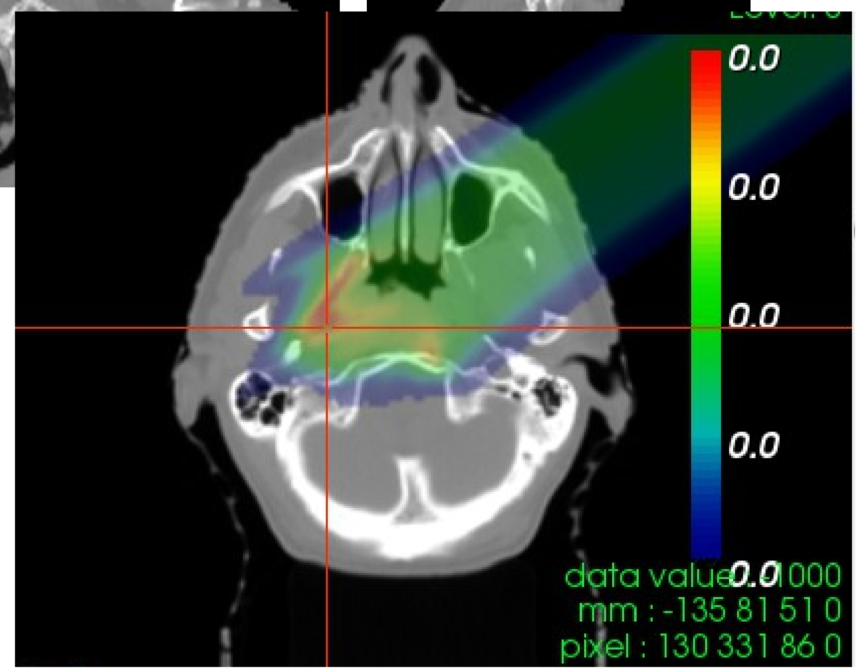
- Several methods:
  - Analytical : fast
  - Monte-Carlo : “gold-standard”

- Monte-Carlo particles tracking
  - Interaction with matter
  - Track particles by particles
  - Probability of interaction (cross-section) : stochastic resolution

Example: proton dose

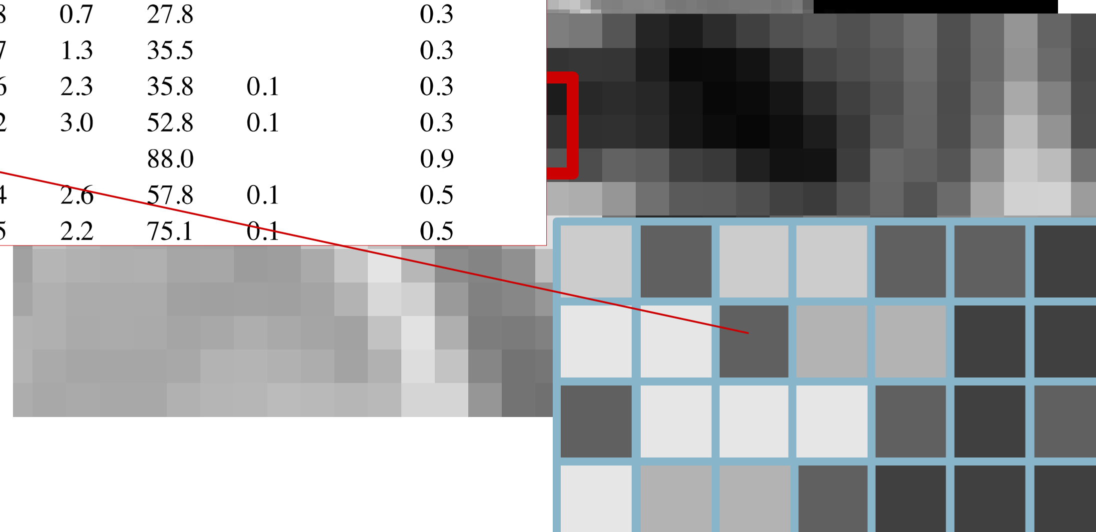





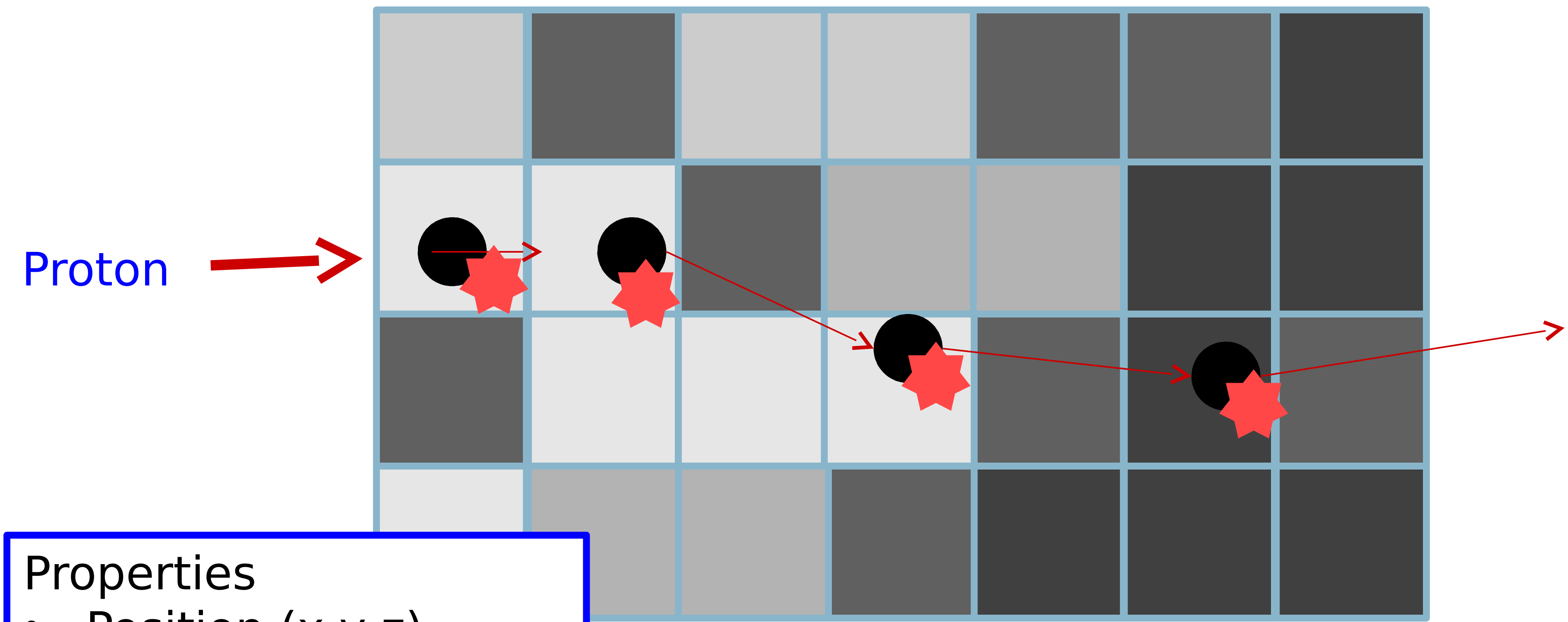


Stoichiometric calibration

Soft tissue	H	ρ (g cm^{-3})	w_i (pp) H	C	N	O	P	Ca	Others
Lung, blood-filled	−741	0.26	10.3	10.5	3.1	74.9	0.2		1.0
Adipose tissue 3	−98	0.93	11.6	68.1	0.2	19.8			0.3
Adipose tissue 2	−77	0.95	11.4	59.8	0.7	27.8			0.3
Adipose tissue 1	−55	0.97	11.2	51.7	1.3	35.5			0.3
Mammary gland 1	−37	0.99	10.9	50.6	2.3	35.8	0.1		0.3
Mammary gland 2	−1	1.02	10.6	33.2	3.0	52.8	0.1		0.3
Brain, cerebrospinal fluid	13	1.01	11.1			88.0			0.9
Adrenal gland	14	1.03	10.6	28.4	2.6	57.8	0.1		0.5
Small intestine (wall)	23	1.03	10.6	11.5	2.2	75.1	0.1		0.5



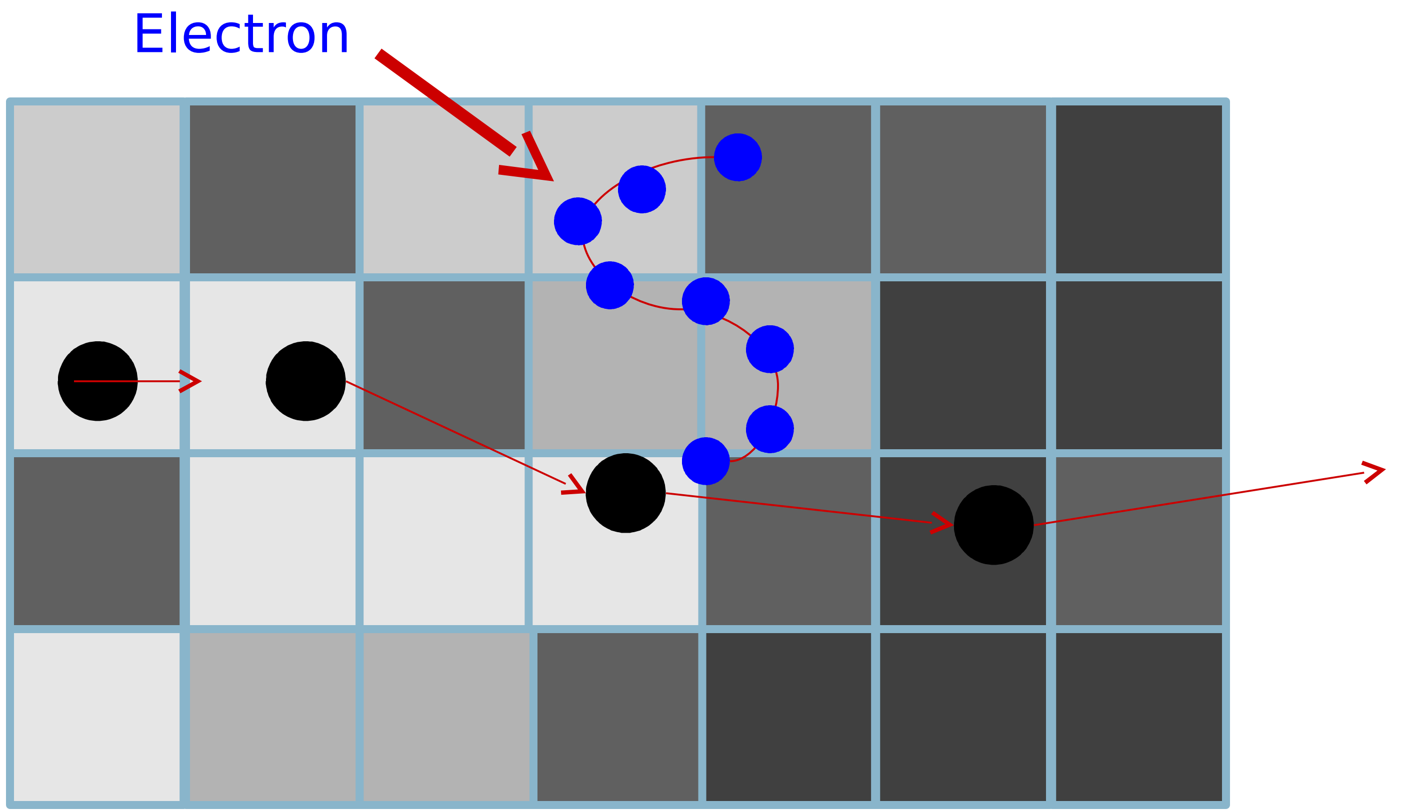
Tracking



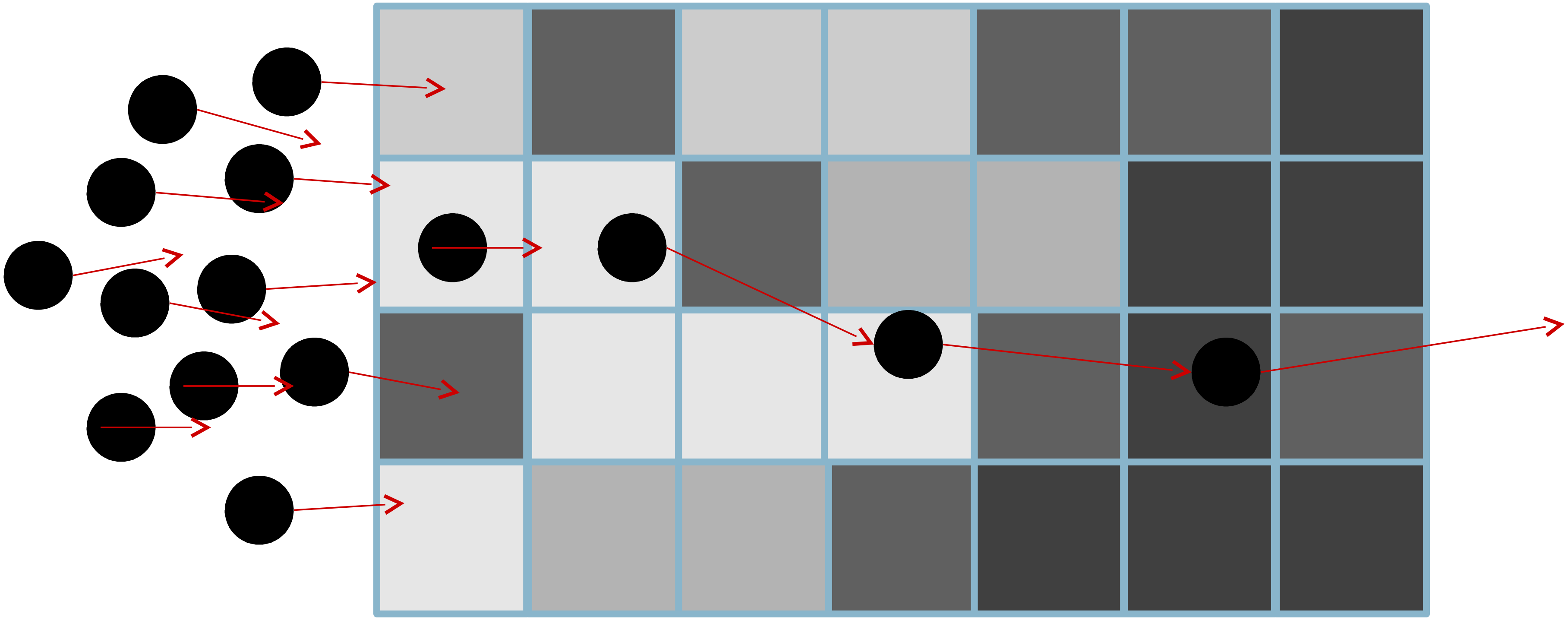
Properties
- Position (x,y,z)
- Direction (dx, dy, dz)
- Energy changed
- Energy absorbed

Absorbed energy
Dose : Energy/mass

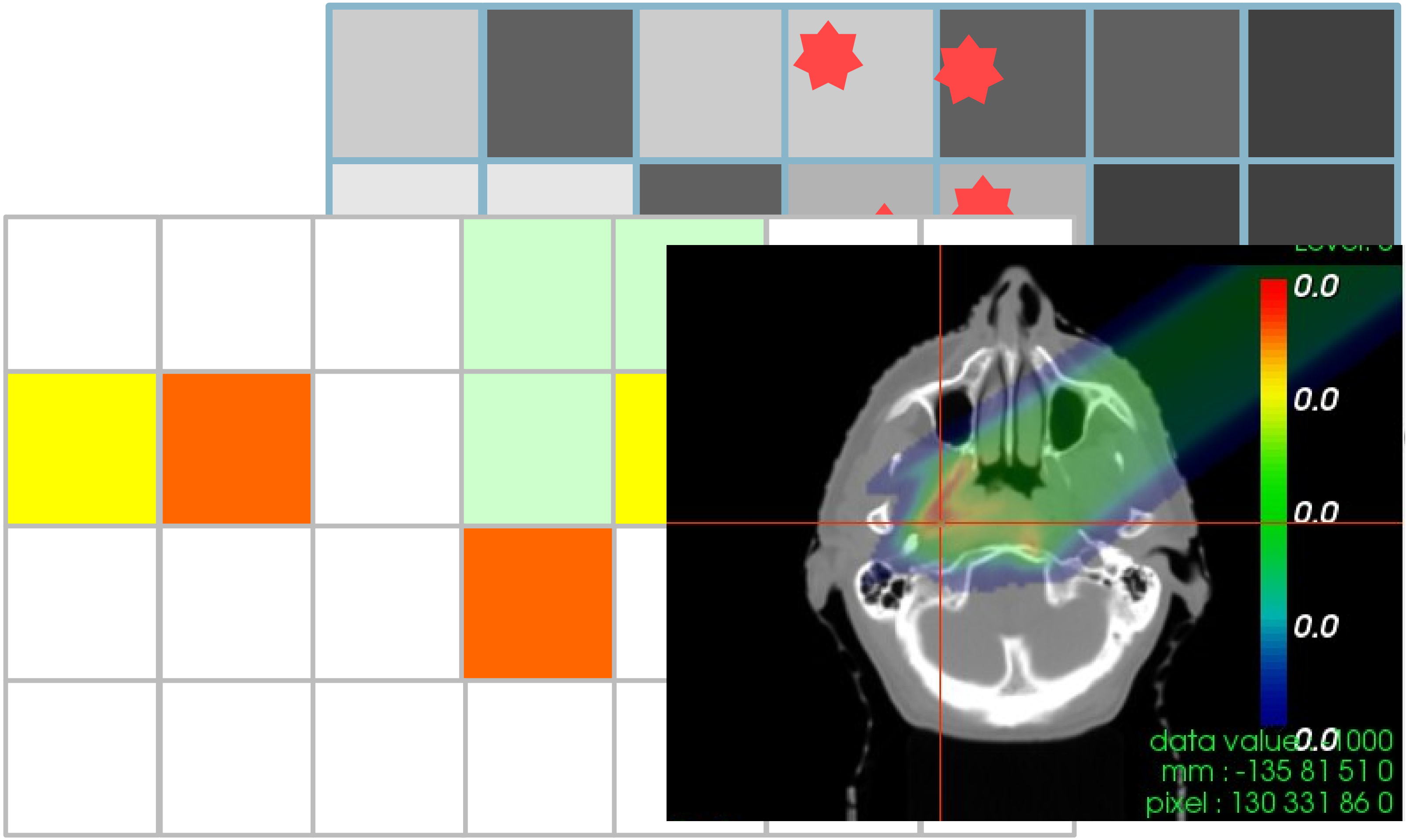
Tacking secondary particles



Primary particles



Result : 3D dose distribution



Particles tracking

- Millions (billions !) of primaries proton
- Tracking:
  - Path composed of several steps
  - Interaction at each steps (physical / geometrical)
  - Change in properties (energy, position, direction)
  - Absorbed dose
  - Other particles emissions (electron etc), also tracked
  - Electro-magnetic and nuclear interactions
- Until convergence
- Notion of “statistical uncertainties”

Numerical simulations

- Complex situations
  - Anatomical variability (toward personalized medicine)
  - Numerous “beams” condition (photon, hadron)
  - Imaging / treatment

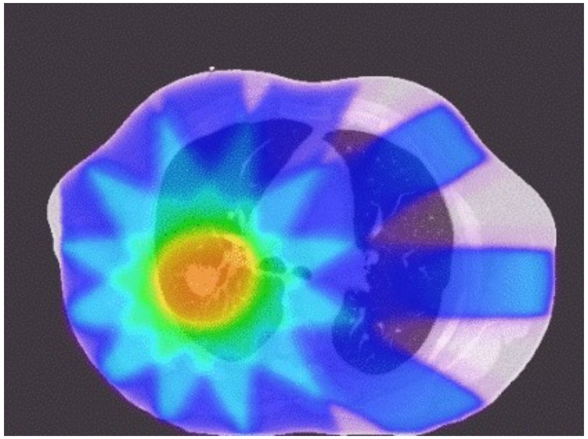
- Numerical modelling (in-silico)
  - Scene (geometrical components): machine, patient
  - Physics : beam, particles, interactions
  - Observable

Timing considerations

- Particles interactions with matter, one by one (one “history”)
- Long computation time
- (more or less) easily parallelisable
- Broad range : few minutes to several days/months.

- In practice
  - Workstation ~10 jobs (threads)
  - Cluster labo ~50 jobs
  - Computing center IN2P3 ~150 jobs
  - EGI grid ~300 jobs

Examples



Examples

Examples

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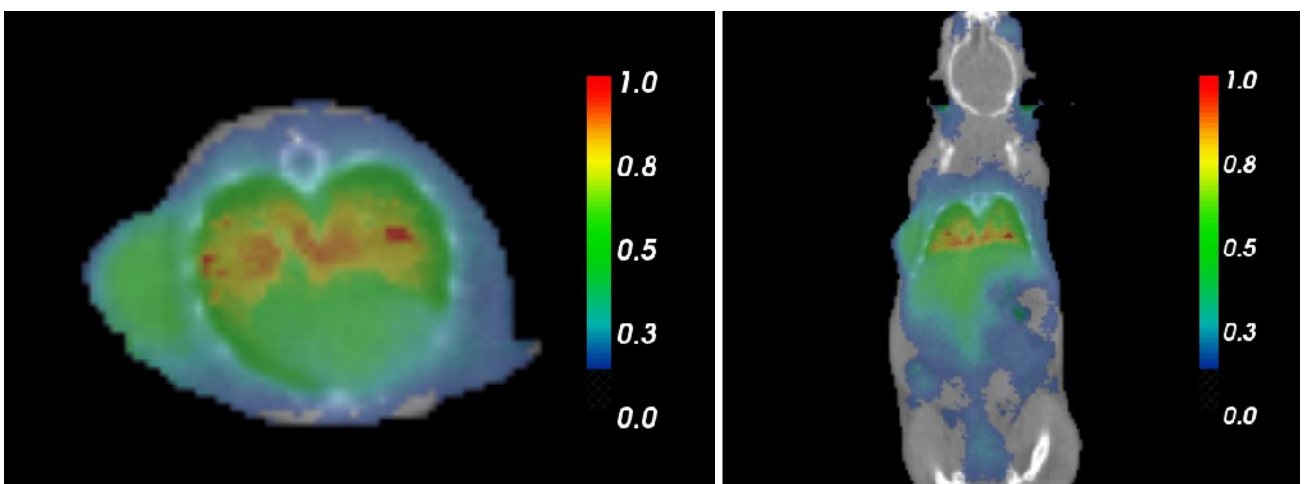


Code

- Open source Geant4 toolkit
  - Developed by an international collaboration
  - Managed at CERN
  - Nuclear physics
- Open source GATE platform
  - Developed by an international collaboration
  - Focus on Medical Physics (dose & imaging)
- Others toolkit : MCNPX, EGSNRC, Fluka etc

- C++ classes
- Development cycle : design, run, analyze …

Plan

- Introduction
- Example: dose computation in protontherapy
- **Prompt-gamma imaging device**
- Conclusion

Dose monitoring via prompt-gamma

- In protontherapy, online dose monitoring is currently being investigated with devices exploiting prompt-gamma
  - [Stichelbaut 2003] [Min 2006] [Testa 2008] [Polf 2009] [Moteabbed 2011] and others …

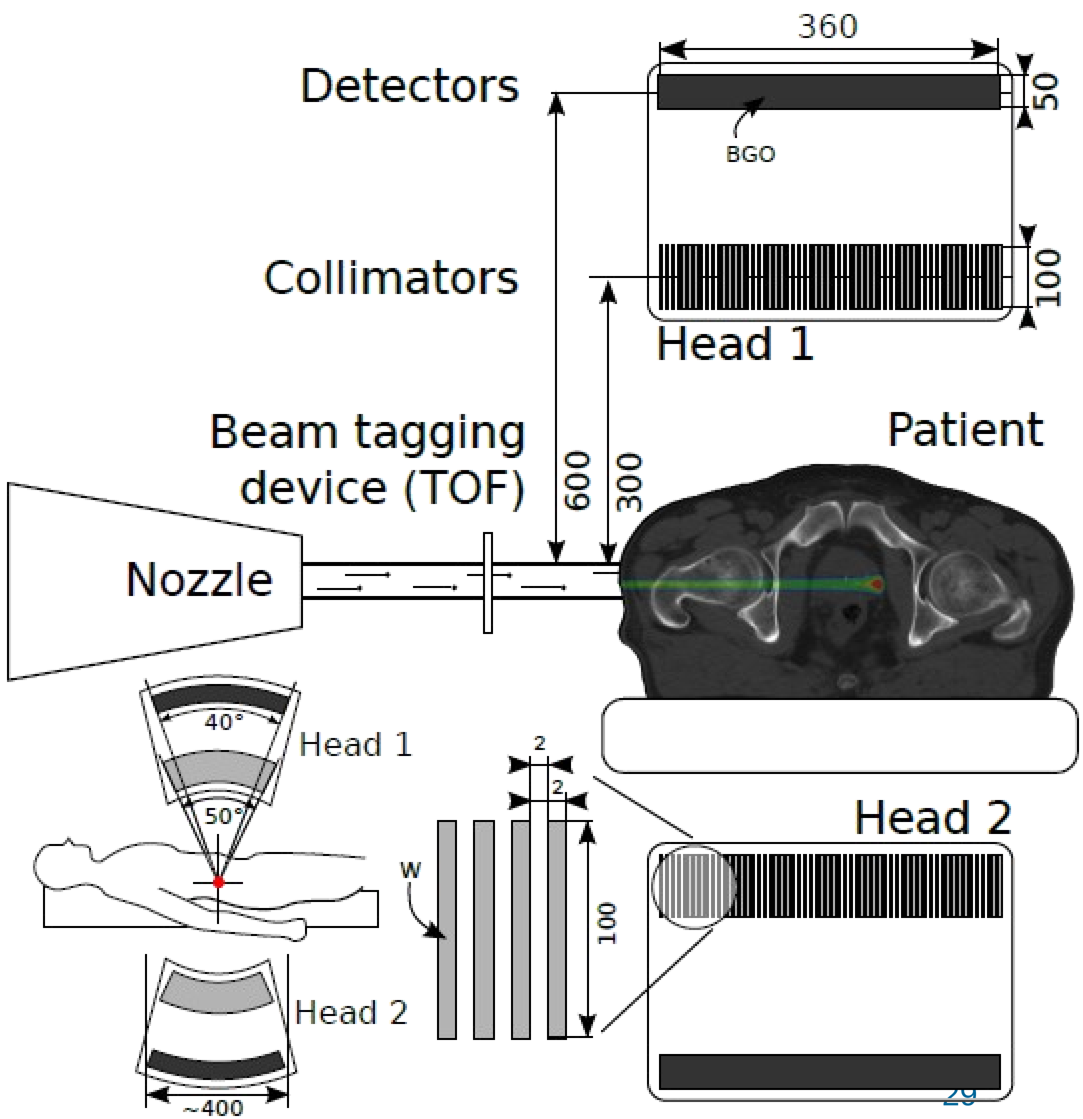
- Prompt-Gamma:
  - Emitted during inelastic interactions between incident proton and target nuclei.
  - Emitted quasi-instantaneously, decay time < 1 ps
  - Broad energy spectrum : 105 eV ; 107 eV
  - Most of them (80%) have enough energy to escape the patient

  - Correlated with the deposited dose
  - … but correlation not well known in clinical conditions

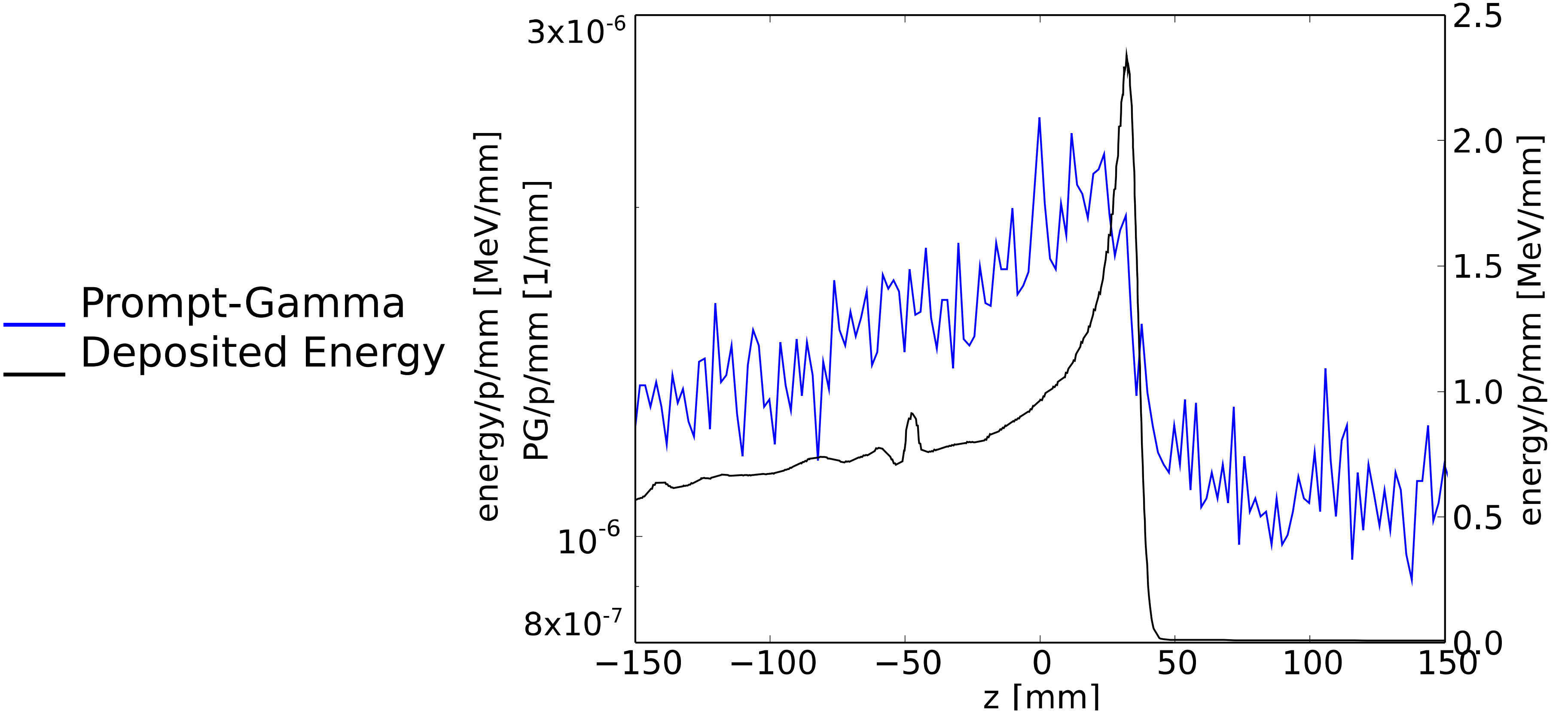
GATE simulations

- Spot-scanning protontherapy
  - [Grevillot et al, PMB 2012]
  - Realistic beam description (E, emittance etc)
  - Real treatment plan on a CT (prostate case)

- PG camera prototype
  - [Testa et al 2008]
  - two-head cylindrical collimated multi-slit detector
  - BGO scintillators
  - TOF filtering with beam tagging device (hodoscope)



Dose monitoring via prompt-gamma



Results

- Simulations : to help design of the imaging device
- Simulations : to assess new imaging device
- Simulations : to better describe the limits
  (The main concern seems to be more the counting rate than the spatial resolution).

- [Gueth et al, PMB 2013]

Machine learning-based patient specific prompt-gamma dose monitoring in protontherapy

P. Gueth[1], D. Dauvergne[2], N. Freud[1], J. M. Létang[1], C. Ray[2], E. Testa[2], D. Sarrut[1,3]

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Plan

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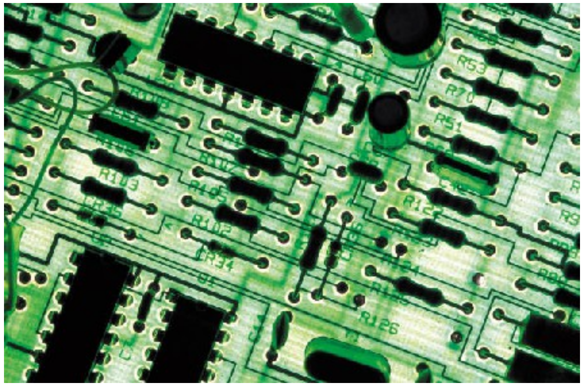
- **Conclusion**

Numerical simulations and random processes treat cancer



Conclusion

- Numerical simulations applied in medical physics
- For cancer treatment
- Imaging : X-ray, PET, SPECT, nuclear imaging etc
- Treatment: RT, hadrontherapy, brachytherapy, radioimmunotherapy etc

- Monte-Carlo simulations for particles tracking
- Open-source software (Geant4, GATE)

- Multi-disciplinary : medicine – physic – computer science