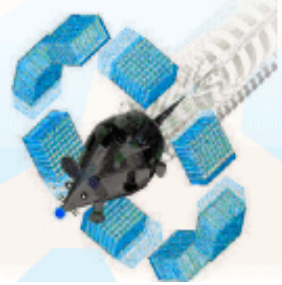


GATE
SIMULATIONS OF PRECLINICAL AND CLINICAL SCANS IN EMISSION TOMOGRAPHY

GATE-RT
Applications in Radiation Therapy

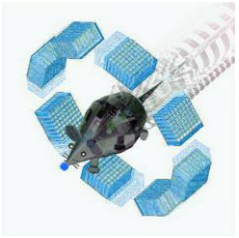
GATE Training, Orsay, April 2011

David SARRUT
Creatis - CNRS
Lyon - France

Centre Régional
Léon-Bérard
Soigner, chercher, vaincre. Ensemble

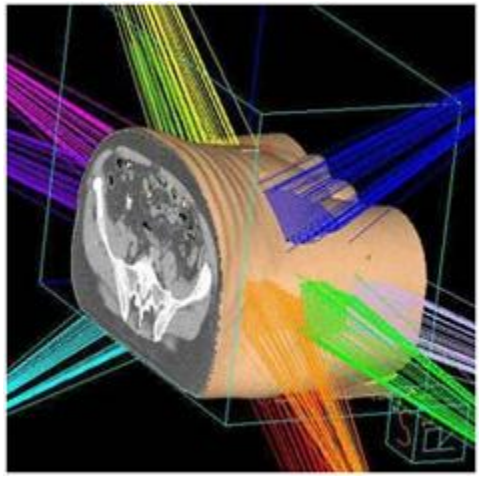
Université de Lyon

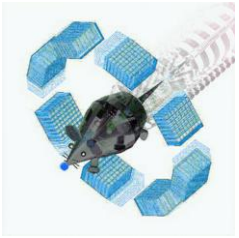
cnrs
dépasser les frontières



GATE-RT: Radiation Therapy applications

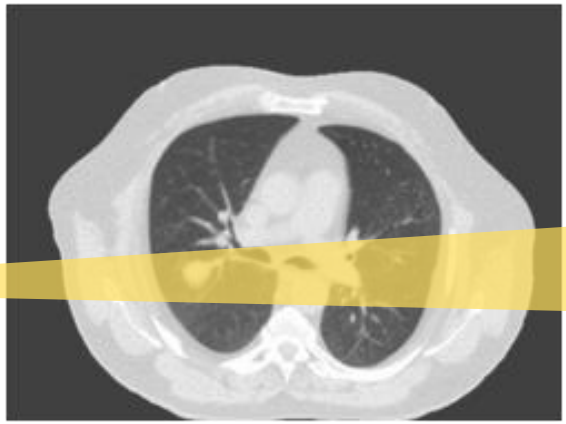
- Related to dose distribution
- Radiotherapy: therapy with photon
- Hadrontherapy: therapy with hadron (Proton, Carbon)
- Other radiation simulations
  - Brachytherapy
  - Dose during X-Ray imaging
  - Research experiments (biology, physics)
  - …





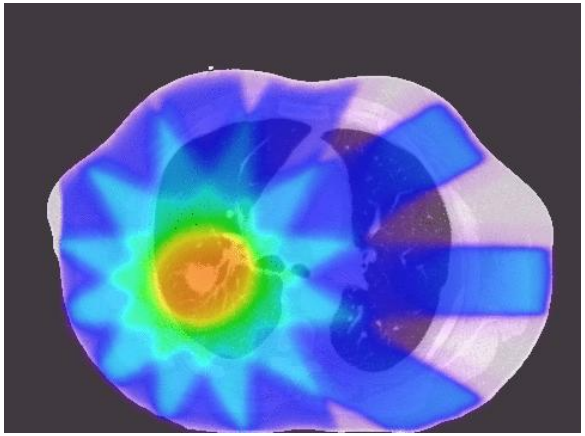
Radiation Therapy

Simulated with GATE

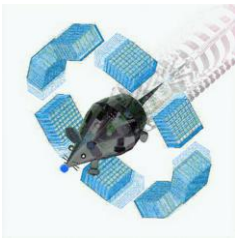


Photon beam(s)

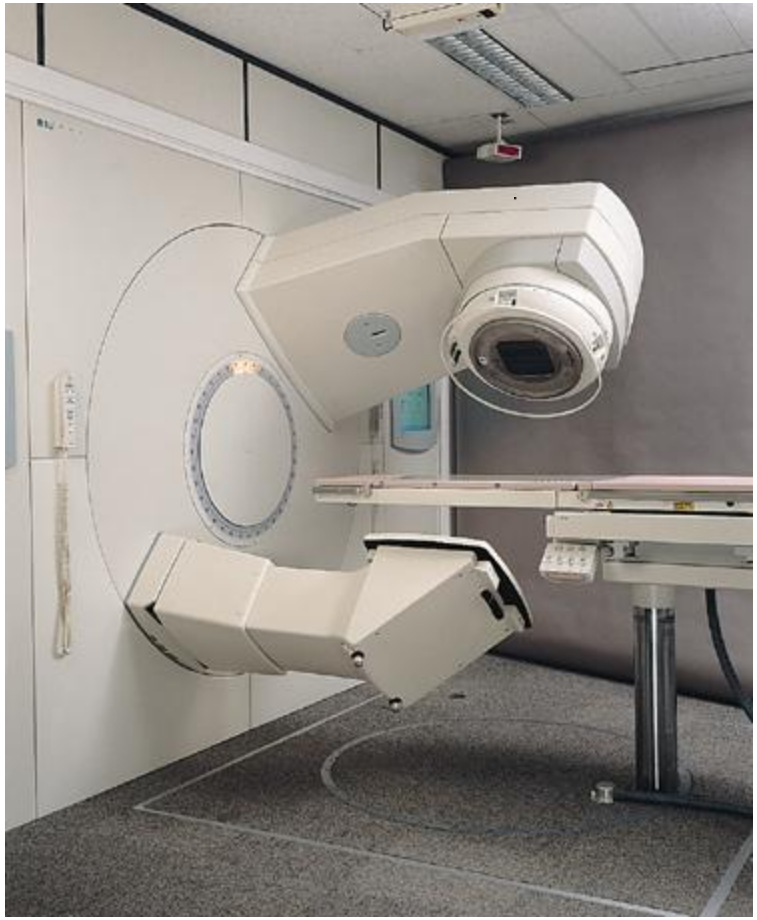
Target (CT)

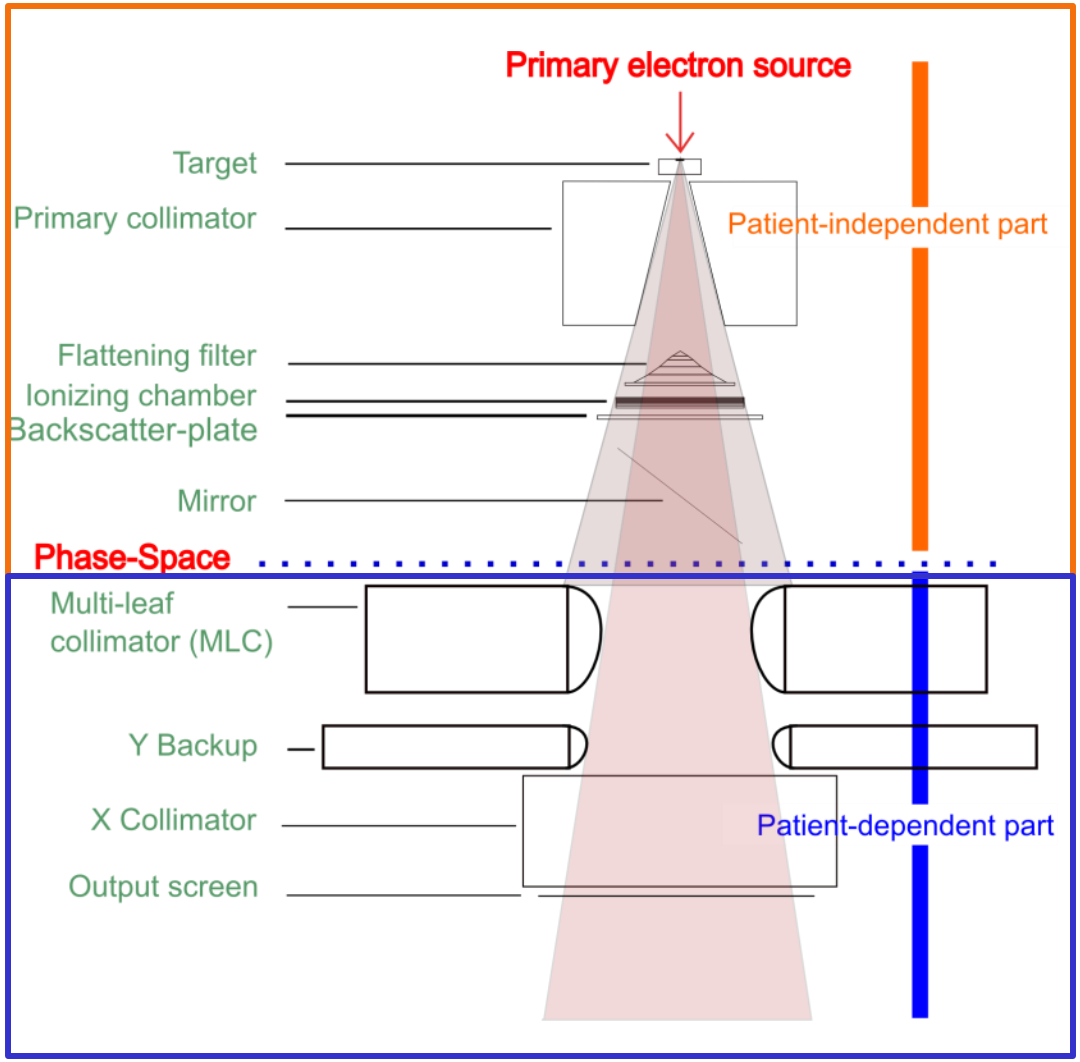


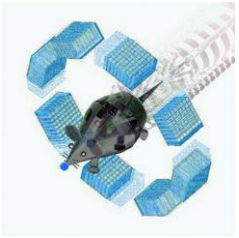
Output =
dose distribution



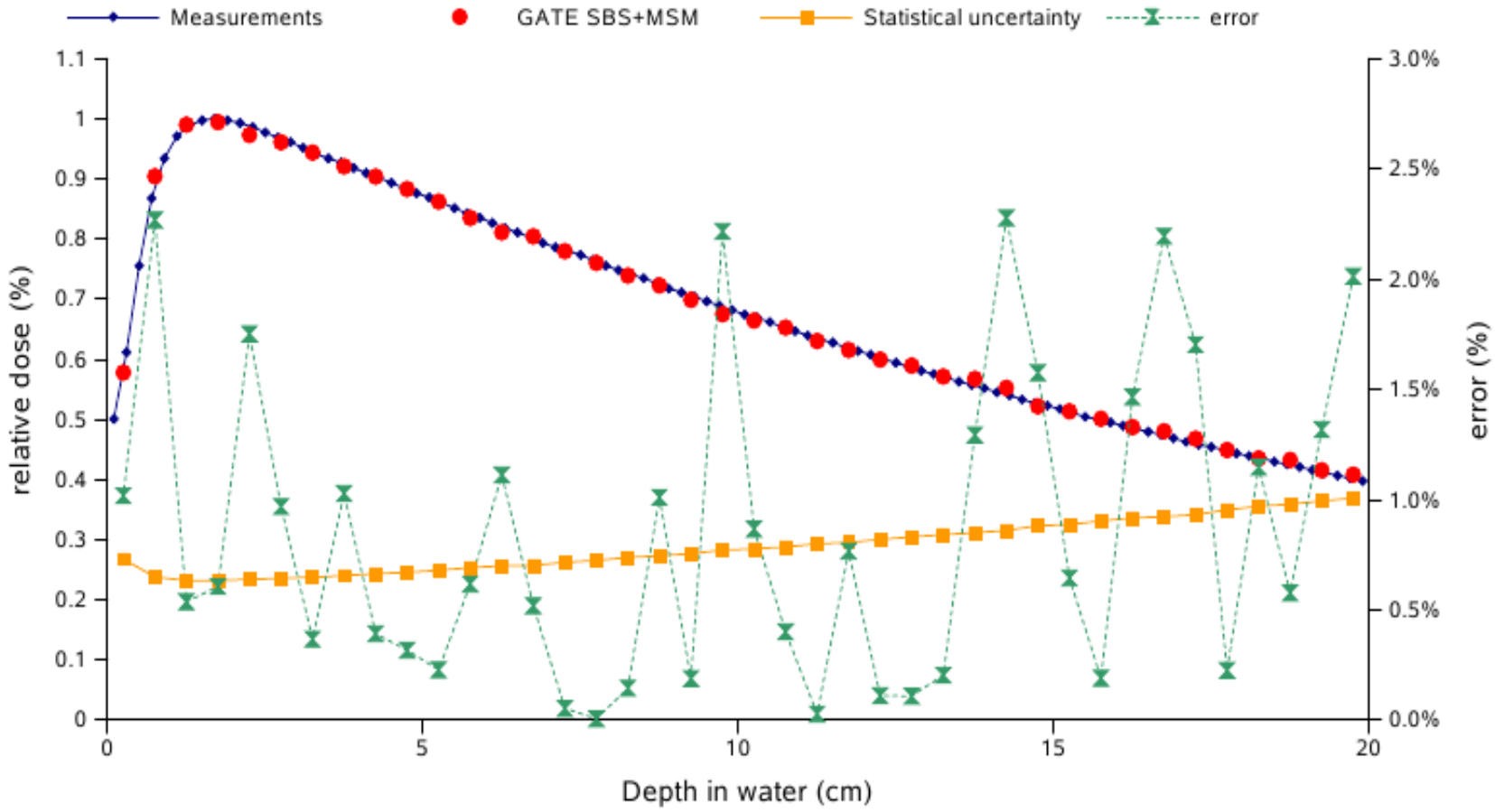
Photon Beam: LINAC



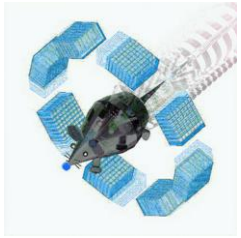




Simulation vs Measurements

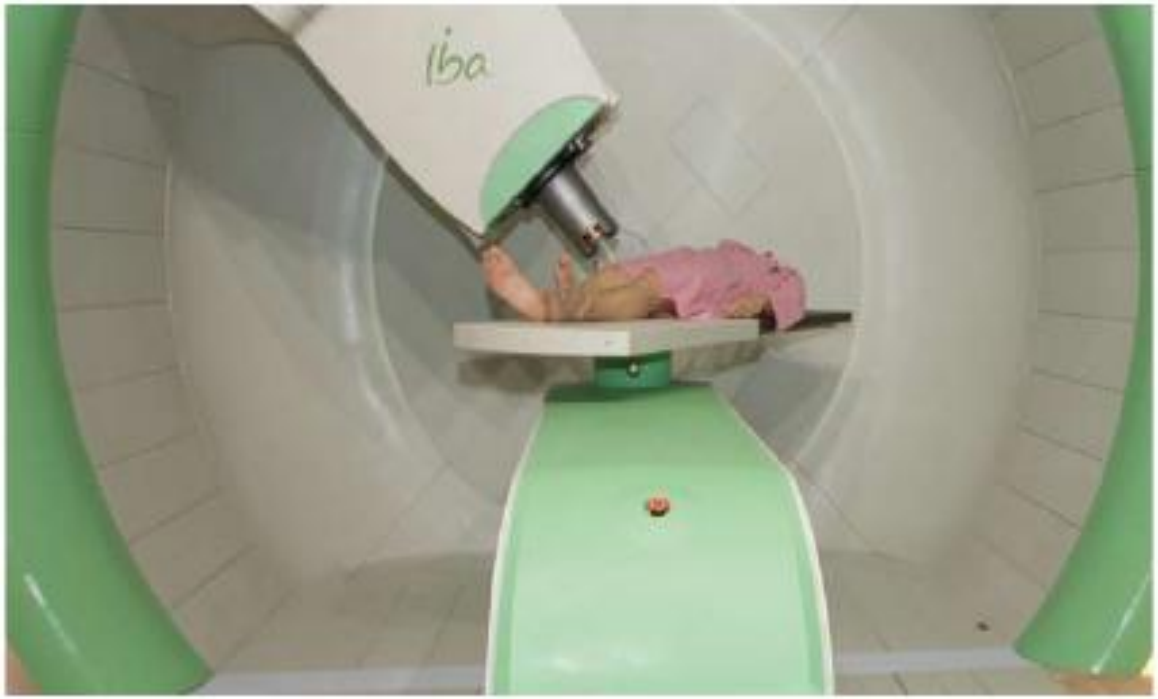


[Grevillot et al, PMB, 2011]

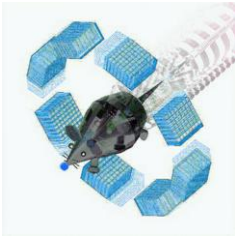


Proton beam

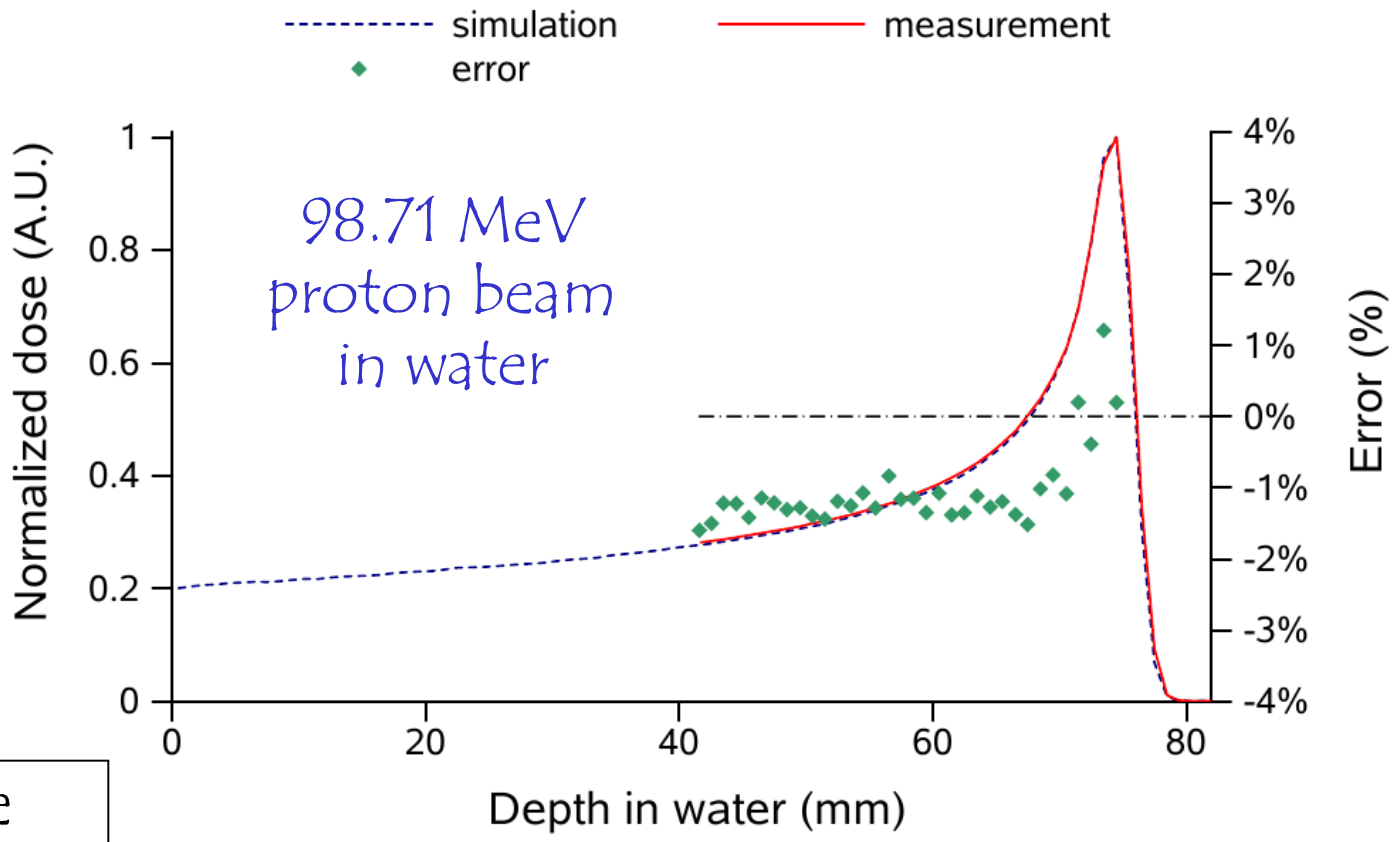
Cyclotron



The IBA Pencil Beam Scanning dedicated nozzle

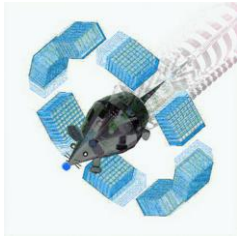


Simulation vs Measurements



Difference lower than 2%

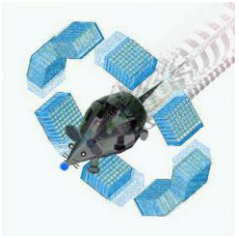
[Grevillot et al, NimB, 2010]



In-beam Hadron-PET

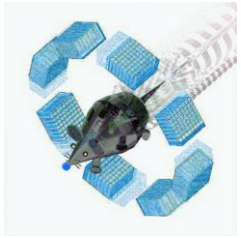
- Carbon beam
- Nuclear fragment
- B+ emitters
- Back to back photon
- Dose monitoring !

Simulation of both dose distribution and imaging



Gate potentialities

- Set of multi-purpose tools
  - Dose measurement
  - Physics list: lot of processes/models
  - Phase-Space management (read/write)
  - Some specific particles sources
  - Very flexible: highly tunable
- To be adapted for your system
- Evolving toolkit:
  - advanced users (C++) can add new functionalities



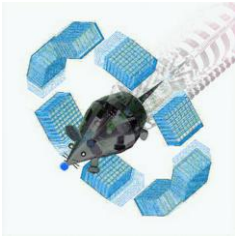
Organization

- Lecture (this presentation)
  - Too long. Serve as reference. Please consult it.
- Practical Exercices

http://wiki.opengatecollaboration.org/index.php/GateRT-PracticalExercices-2011

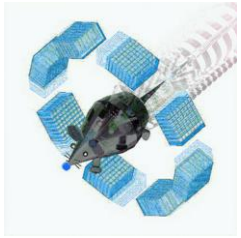
http://tinyurl.com/3cv6yta

  - PE7_1 : beam in waterbox
  - PE7_2 : phase-space with linac head
  - PE7_3 : proton beam in CT



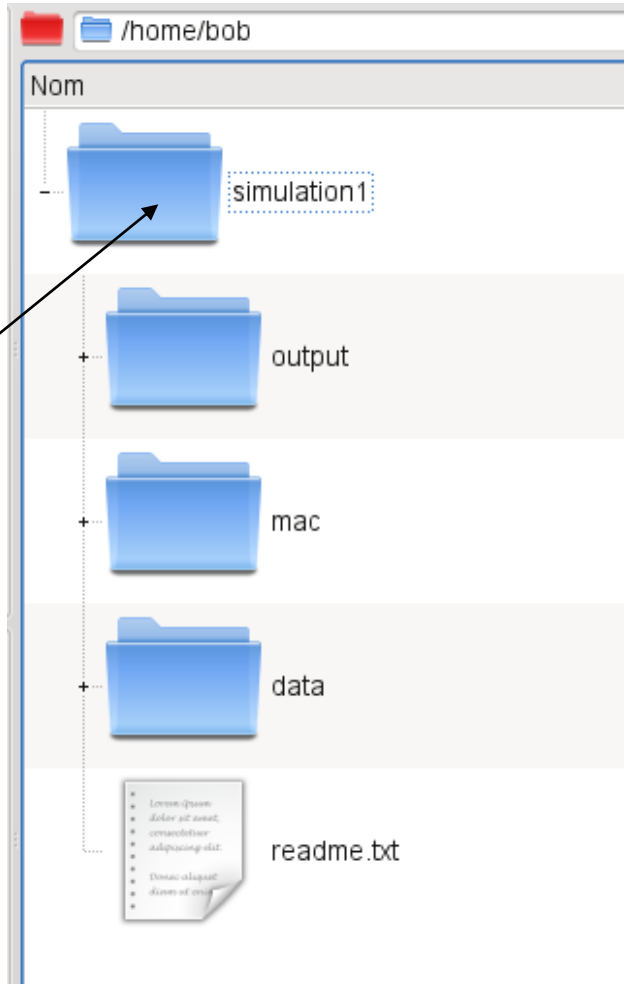
Outline

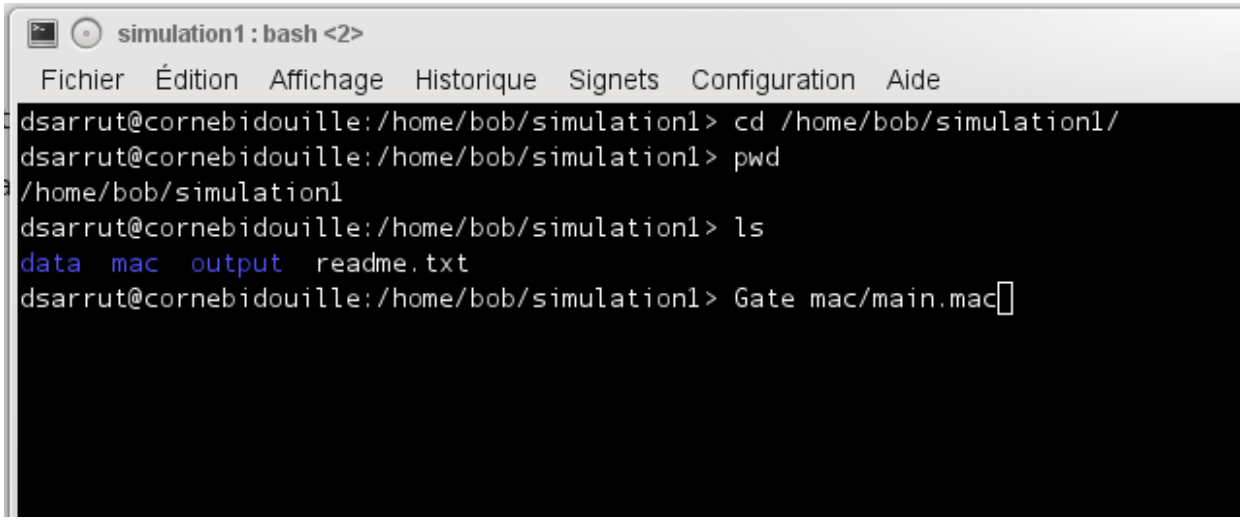
1. Introduction
2. Simulation architecture
3. Macros: geometry, physic lists
4. Macros: Actors & Filters
5. Macros: Sources
6. Macros: Phase-Space
7. Macros: insert a CT
8. Macros: DoseActor

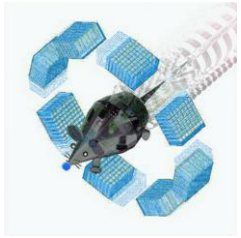


Architecture of a simulation

- Good practices
- Folders organization
  - mac output data
  - Execution from this folder







Architecture of a simulation

- Macros organization
  - All included macro files must be in mac/

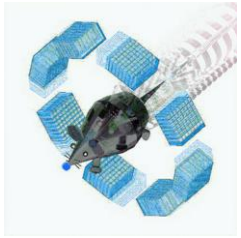
```
/control/execute mac/physic-list.mac
```

  - All included data files must be in data/

```
/gate/geometry/setMaterialDatabase data/GateMaterials.db
```

  - All output files must be in output/

```
/gate/actor/doseDistribution/save output/dose.root
```



Main macro organization

FILE : simulation1/mac/main.mac

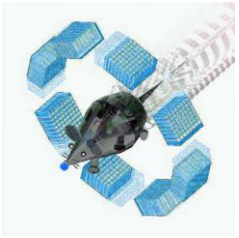
```
[ Verbose macros ]
1 - Geometry description macros
2 - Physics list related macros
2 - Detectors (output) macros
[ Visualization macros ]
4 - Sources macros
/gate/run/initialize
/gate/application/setTotalNumberOfPrimaries 50
/gate/application/start
```

Main parts

Optional

At this stage, Geant4 build the geometry and the physics tables

At this stage, Geant4 start the simulation



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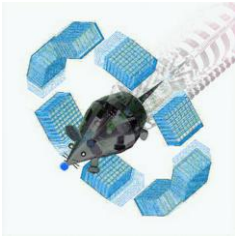


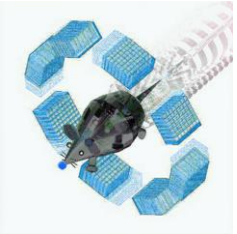
Verbose macros

```
# GATE verbose
/gate/verbose Physic     2
/gate/verbose Cuts       2
/gate/verbose SD         0
/gate/verbose Actions    0
/gate/verbose Actor      3
/gate/verbose Step       0
/gate/verbose Error      0
/gate/verbose Warning    0
/gate/verbose Output     0
/gate/verbose Beam       2
/gate/verbose Volume     0
/gate/verbose Image      0
/gate/verbose Geometry   2
/gate/verbose Core       0


# GEANT4 verbose
/run/verbose 0
/event/verbose 0
/tracking/verbose 0
```

Useful to debug physics

Useful to debug generated primary particles



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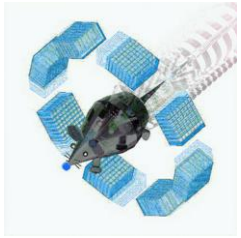


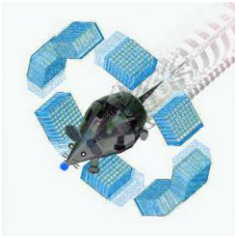
Geometry macros

Several lists of materials

```
/gate/geometry/setMaterialDatabase data/GateMaterials.db
/gate/geometry/setMaterialDatabase data/MyMaterials.db

# WORLD
/gate/world/setMaterial          Air
/gate/world/geometry/setXLength 2.0 m
/gate/world/geometry/setYLength 2.0 m
/gate/world/geometry/setZLength 2.0 m

# WATERBOX
/gate/world/daughters/name                    waterTank
/gate/world/daughters/insert                  box
/gate/waterTank/setMaterial                   Water
/gate/waterTank/geometry/setXLength           20.0 cm
/gate/waterTank/geometry/setYLength           20.0 cm
/gate/waterTank/geometry/setZLength           20.0 cm
/gate/waterTank/placement/setTranslation  0 0 -10 cm
/gate/waterTank/vis/setColor                  blue
```

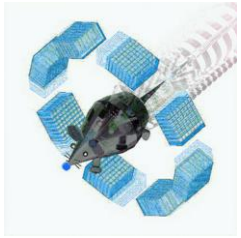
World is required

Like any others simulations



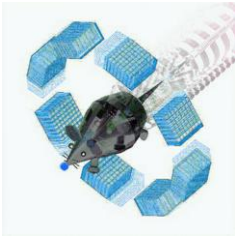
Physic lists

- A physic list is :
  - A set of processes (with options)
    If a process is not indicated in the macro, GEANT4 will ignore it
  - A set of « cuts »
    Tradeoff between simulation time/precision



Physic lists - EM

```
/gate/physics/addProcess PhotoElectric
/gate/physics/processes/PhotoElectric/setModel StandardModel

/gate/physics/addProcess Compton
/gate/physics/processes/Compton/setModel StandardModel

/gate/physics/addProcess GammaConversion
/gate/physics/processes/GammaConversion/setModel StandardModel

/gate/physics/addProcess ElectronIonisation
/gate/physics/processes/ElectronIonisation/setModel StandardModel e-
/gate/physics/processes/ElectronIonisation/setModel StandardModel e+

/gate/physics/addProcess Bremsstrahlung
/gate/physics/processes/Bremsstrahlung/setModel StandardModel e-
/gate/physics/processes/Bremsstrahlung/setModel StandardModel e+

/gate/physics/addProcess PositronAnnihilation

/gate/physics/addProcess MultipleScattering
```

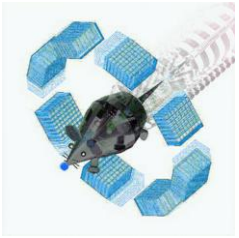


Physic lists

- For each process:
  - Several models
  - Several data (cross-section)
  - Several options

Very powerful but can be very confusing

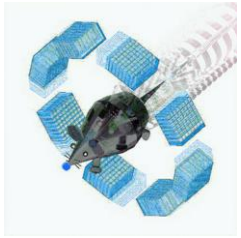
- Advice1: use the proposed PL
- Advice2: read GATE+G4 documentation
- Advice3: share your experience



Physic lists - hadronic

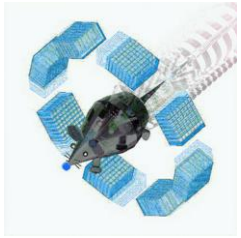
- Hadron, ion ionisation
- Elastic and inelastic processes
- Still in development

```
/gate/physics/addProcess ProtonInelastic
/gate/physics/processes/ProtonInelastic/setModel G4BinaryCascade
/gate/physics/processes/ProtonInelastic/G4BinaryCascade/setEmin 170 MeV
/gate/physics/processes/ProtonInelastic/G4BinaryCascade/setEmax 500 GeV
/gate/physics/processes/ProtonInelastic/setModel PreCompound
/gate/physics/processes/ProtonInelastic/PreCompound/setEmin 0 MeV
/gate/physics/processes/ProtonInelastic/PreCompound/setEmax 170 MeV
```



Physic lists - print for debug

```
/gate/physics/processList Available
/gate/physics/processList Enabled

/gate/physics/processList [State][Particle]
```



Physic list – cuts

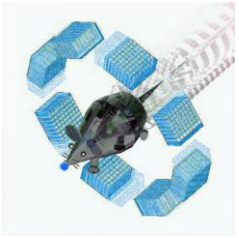
- Production cuts: do not produce secondaries if below threshold

```
/gate/physics/Gamma/SetCutInRegion       world 1 mm
/gate/physics/Electron/SetCutInRegion    world 1 mm
/gate/physics/Positron/SetCutInRegion    world 1 mm

/gate/physics/Gamma/SetCutInRegion       waterTank 0.1 mm
/gate/physics/Electron/SetCutInRegion    waterTank 0.1 mm
/gate/physics/Positron/SetCutInRegion    waterTank 0.1 mm
```

- Particles are tracked until the limits of the model

- Other limits:

```
/gate/physics/SetMaxStepSizeInRegion waterTank 0.01 mm
/gate/physics/displayCuts
```



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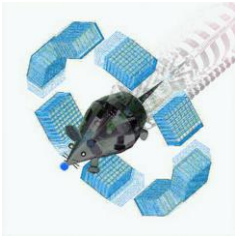
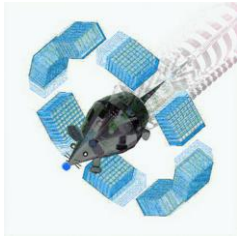


Detectors: the ACTORS

- "**Actor**" concept:
  - Generate output
  - But can also influence the simulation
- Example of actors
  - DoseActor : store deposited dose
  - SimulationStatisticActor : store number or Event, track, steps
  - KillActor : kill a particle when passing through a volume
  - TrackLengthActor : store the length of a track
  - EnergySpectrumActor: store energy distribution
  - ProductionAndStoppingActor: store positions of produced secondaries
  - PhaseSpaceActor: to store a phase space

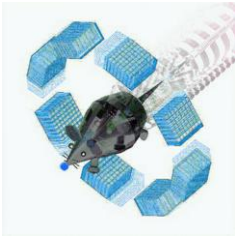


Actors

- Actor common interface

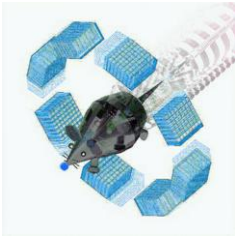
```
/gate/actor/addActor  [Actor Type]  [Actor Name]
/gate/actor/[Actor Name]/attachTo   [Volume Name]
/gate/actor/[Actor Name]/save       [File Name]
/gate/actor/[Actor Name]/saveEveryNEvents  [N]
/gate/actor/[Actor Name]/saveEveryNSeconds [N]
```

```
/gate/actor/addActor  EnergySpectrumActor  MyActor
/gate/actor/MyActor/attachTo                MyWaterBox
/gate/actor/MyActor/energySpectrum/setEmin      0 eV
/gate/actor/MyActor/energySpectrum/setEmax      10 GeV
/gate/actor/MyActor/energySpectrum/setNumberOfBins 200
/gate/actor/MyActor/save output/MyOutputFile.root
```



Actors

- Output file format
  - Depends on the actor type
  - Often ROOT files, txt file
- **www.root.cern.ch**
- Important: only activated for particles inside the *attached volume*
- For advanced users:
  - Write your own Actor (C++)
  - Like a plugin : only add your files (MyActor.hh and MyActor.cc) and compile
  - Share with colleagues !



Filters

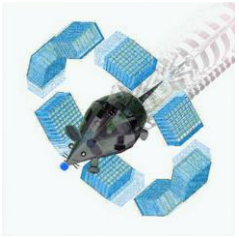
- To be combine with an actor: used to select particles
- Several types of filter

```
/gate/actor/addActor KillActor MyActor
/gate/actor/MyActor/save  output/MyOutputFile.txt
/gate/actor/MyActor/attachTo  MyVolume

/gate/actor/MyActor/addFilter particleFilter
/gate/actor/MyActor/particleFilter/addParticle e-
/gate/actor/MyActor/particleFilter/addParticle e+
```

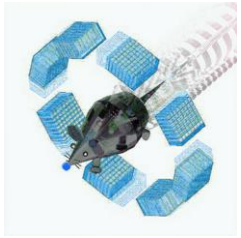
```
/gate/actor/addActor KillActor MyActor
/gate/actor/MyActor/save output/MyOutputFile.txt
/gate/actor/MyActor/attachTo  MyVolume

/gate/actor/MyActor/addFilter energyFilter
/gate/actor/MyActor/energyFilter/setEmin 5 MeV
```



Remember

- Every Volume has a type and a name
  - Examples of types: Box, Sphere …
- Every Actor has a type and a name
  - Attached to a *Volume*
  - Examples of types: DoseActor, KillActor …
- Every Filter has a type and a name
  - Attached to an *Actor*
  - Examples of types: energyFilter, particleFilter
- You could add (and combine) numerous volume, actors and filters
- Each type has specific options



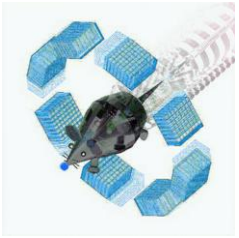
Organization

- Lecture (this presentation)
  - Too long. Serve as reference. Please consult it.
- Practical Exercices

http://wiki.opengatecollaboration.org/index.php/GateRT-PracticalExercices-2011

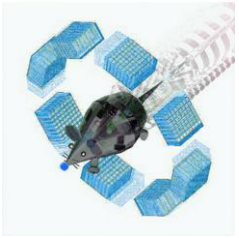
http://tinyurl.com/3cv6yta

  - PE7_1 : beam in waterbox
  - PE7_2 : phase-space with linac head
  - PE7_3 : proton beam in CT



Outline

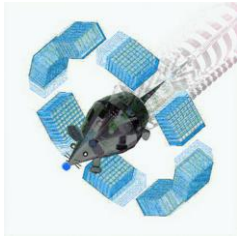
1. Introduction
2. Simulation architecture
3. Macros: geometry, physic lists
4. Macros: Actors & Filters
5. Macros: Sources
6. Macros: Phase-Space
7. Macros: insert a CT
8. Macros: DoseActor



Sources

- Several type of source. One is GPS.
- General Particle Source (GPS)
  - See doc on the wiki

- Simple parameterized source
  - *Type* of primaries particle : g, e+, p ...
  - *Energy*: monoenergetic, histogram, Gaussian ...
  - *Shape/Position*: box, sphere ...
  - *Direction*: beam like, ...



Sources (GPS)

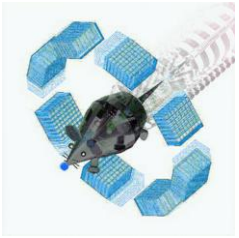
```
/gate/source/addSource mybeam gps

/gate/source/mybeam/gps/particle gamma

/gate/source/mybeam/gps/pos/type Plane
/gate/source/mybeam/gps/pos/shape Circle
/gate/source/mybeam/gps/pos/centre 0 0 0 mm
/gate/source/mybeam/gps/pos/radius 3 mm

/gate/source/mybeam/gps/direction 0 0 1

/gate/source/mybeam/gps/ene/type Gauss
/gate/source/mybeam/gps/ene/mono 18 MeV
/gate/source/mybeam/gps/ene/sigma 1.0 MeV
```



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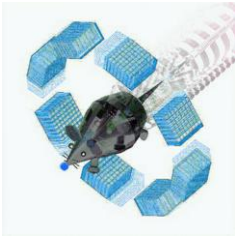
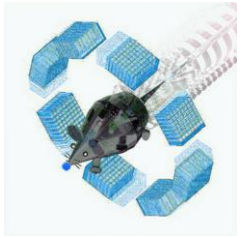


Phase-Space

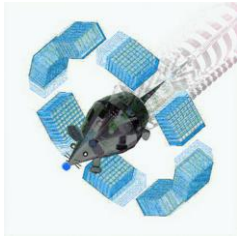
- How to create ? Specific Actor
- How to use ? Specific Source
- How to store ? ROOT / AIEA (limited)



Phase-Space: creation

- PhaseSpaceActor

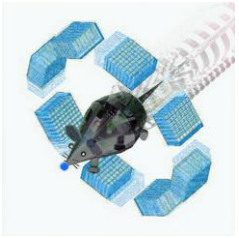
```
/gate/actor/addActor PhaseSpaceActor MyPS
/gate/actor/MyPS/attachTo MyVolume
/gate/actor/MyPS/save output/MyPS.root
/gate/actor/MyPS/useVolumeFrame
/gate/actor/MyPS/storeSecondaries false
/gate/actor/MyPS/storeOutgoingParticles
/gate/actor/MyPS/enableParticleName          true
/gate/actor/MyPS/enableProductionVolume      true
/gate/actor/MyPS/enableProductionProcess     true
```



Phase-Space: use

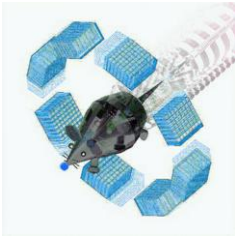
- Need to create an attached volume first
- Can use less particles than stored in the Phase-Space

```
/gate/source/addSource MyBeam phaseSpace
/gate/source/MyBeam/addPhaseSpaceFile output/MyPS.root
/gate/source/MyBeam/attachTo PhS_Plane
```



Phase-Space: file format

- Root file
  - Automatically split into 2Gb files
  - Very flexible
  - Can be analyze with Root
- AIEA file
  - Standard but limited



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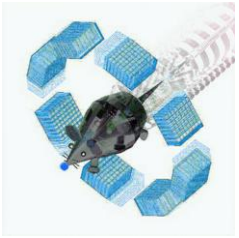
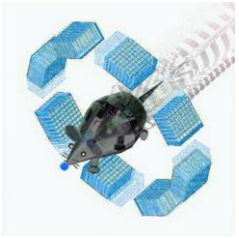


Insert a CT image

- Step1: convert Dicom image to Analyze image file format
- Step2: define HU to materials conversion
- Step3: insert image with macro



Step1: convert DICOM to HDR

- HDR/IMG : *Analyze* image file format
- An image is stored with 2 files
  - Header: *myImage.hdr*
  - Raw data: *myImage.img*
- Use the VV software
  - Open dicom
  - Save as
  - Image can resampled (2mm for example)
- **vv.creatis.insa-lyon.fr**

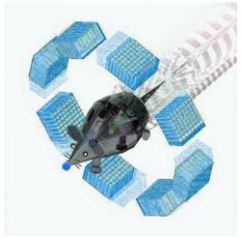


Image coordinate system

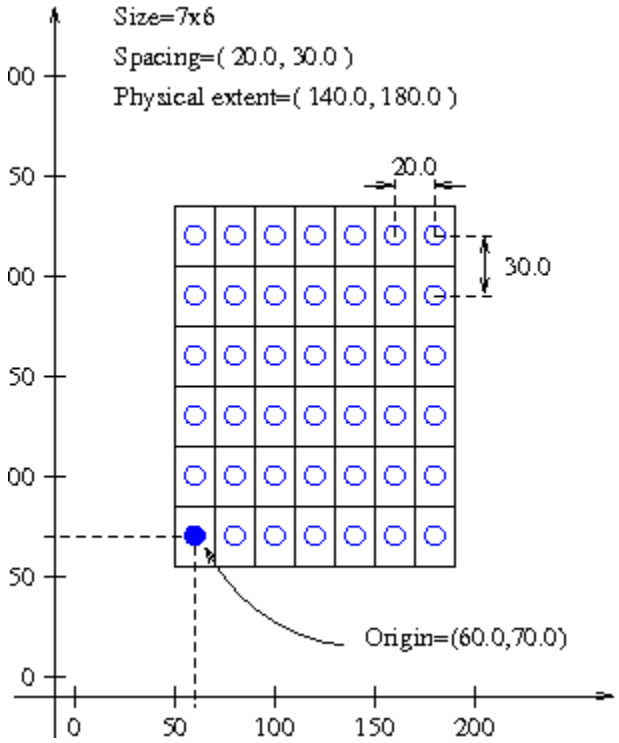
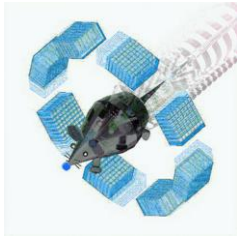


Image:

- Resolution: 512 x 512 x 120
- Spacing: 0.9 x 0.9 x 2 (mm)
- PixelType: float or unsigned short
- Origin: coord of the first pixel in « physical coordinate » (mm)
- Orientation: associated matrix

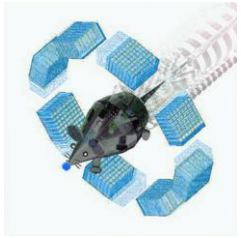
GATE DOES NOT TAKE origin/orientation into account !!



Step2: stoichiometric calibration

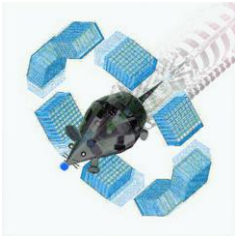
- Macros to generate HU <-> material
  - Generate a list of materials
  - Generate a list of HU to material name correspondence

```
/gate/HounsfieldMaterialGenerator/SetMaterialTable    data/MaterialsTable.txt
/gate/HounsfieldMaterialGenerator/SetDensityTable     data/DensitiesTable.txt
/gate/HounsfieldMaterialGenerator/SetDensityTolerance 0.1 g/cm3

/gate/HounsfieldMaterialGenerator/SetOutputMaterialDatabaseFilename
                                                    data/myimage-HUmaterials.db
/gate/HounsfieldMaterialGenerator/SetOutputHUMaterialFilename
                                                     data/myimage-HU2mat.txt

/gate/HounsfieldMaterialGenerator/Generate
```



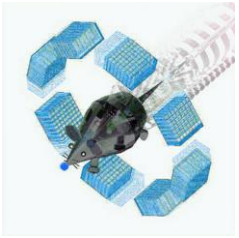
Step3: insert image as volume

```
/gate/world/daughters/name                patient
/gate/world/daughters/insert              ImageNestedParametrisedVolume
/gate/patient/geometry/SetImage                data/myimage.hdr
/gate/geometry/setMaterialDatabase             data/myimage-HUmaterials.db
/gate/patient/geometry/SetHUToMaterialFile  data/myimage-HU2mat.txt
/gate/patient/placement/setTranslation         0 0 0 mm
```



CT insertion, other options

- Alternative navigator:
  - Faster in some situation
  - Use "ImageRegionalizedVolume" instead of "ImageNestedParametrisedVolume
- Stoichiometric calibration: you need to calibrate your CT [Schneider et al 2000]
- Image file format will be improved.



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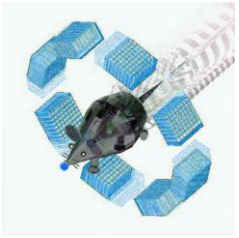
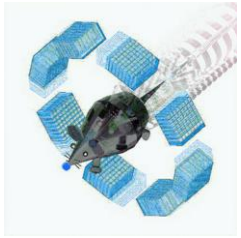


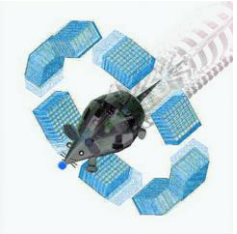
DoseActor

- Store deposited dose in a 3D matrix
- Can be used also for 1D and 2D dose map
- Can store: dose, edep, nb of hits
- Compute associated statistical uncertainty
- Size and resolution of the matrix can be specified
- Need to be attached to a volume (that can be voxelized or not)
- You can use any DoseActor, attached to the same volume or to different ones



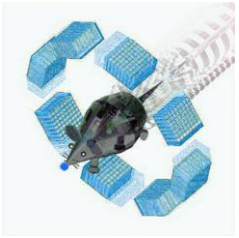
DoseActor

```
/gate/actor/addActor                    DoseActor  doseDistribution
/gate/actor/doseDistribution/attachTo                 MyVolume
/gate/actor/doseDistribution/stepHitType              random
/gate/actor/doseDistribution/setPosition              0 0 0 mm
/gate/actor/doseDistribution/setVoxelSize             2 2 2 mm
/gate/actor/doseDistribution/saveEveryNSeconds        60
/gate/actor/doseDistribution/enableEdep               true
/gate/actor/doseDistribution/enableUncertaintyEdep    true
/gate/actor/doseDistribution/enableDose               true
/gate/actor/doseDistribution/enableNumberOfHits       true
```



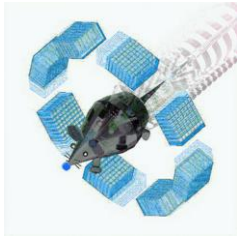
DoseActor

- Only store what happened in the attached volume, even if the size of the DoseActor is larger
- We call« dosel » the volume where is stored the dose
- Can be different from the « voxel » size of the associated image (but it is not really recommended).
- Store the dose in the dosel that contains a point randomly chosen on the step segment



DoseActor

- Output file format:
  - TXT (ASCII files): only for 1D distribution (not really recommended)
  - Root: for 1D or 2D distribution
  - HDR/IMG image (Analyze): for 3D distribution
- Need specific tools to analyze such output



DoseActor: statistical uncertainty

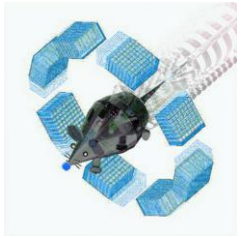
- See [Chetty et al IJROBP 2006]
  - Reporting and analyzing statistical uncertainties in Monte Carlo-Based Treatment Planning

Statistical uncertainty in dose in the voxel k

$$s_{d_k} = \sqrt{\frac{1}{N-1}\left(\frac{\sum_{i=1}^{N} d_{k,i}^{2}}{N} - \left(\frac{\sum_{i=1}^{N} d_{k,i}}{N}\right)^{2}\right)}$$

Relative percentage uncertainty in the dose per voxel

$$\varepsilon_k = 100 \times \frac{S_k}{D_k}$$

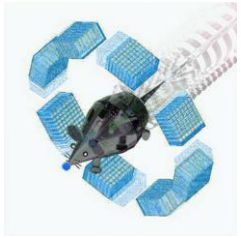


DoseActor: statistical uncertainty

- If the simulation is split into multiple jobs
  - Global statistical uncertainty **CANNOT** be computed from the uncertainties of each job
  - Instead, use SquaredDose

```
/gate/actor/addActor                    DoseActor  doseDistribution
…
/gate/actor/doseDistribution/enableDose                    true
/gate/actor/doseDistribution/enableSquaredDose             true
```

  - Then merge (addition) all output files and compute the equation.
- Tools are not (yet) provided in the Gate release. Available in VV as test. Will be provided in future release.



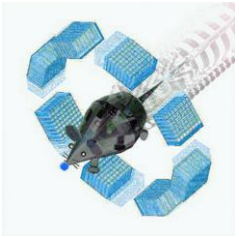
Advanced features

- Motion and time management
  - Repeater: to duplicate volume (e.g multi-leafs collimator)
  - Mover: displace volume or source according to time
  - Both together

```
/gate/mybox/repeaters/insert                          genericRepeater
/gate/mybox/genericRepeater/setPlacementsFilename     data/mybox.pls
/gate/mybox/genericRepeater/useRelativeTranslation    1
```

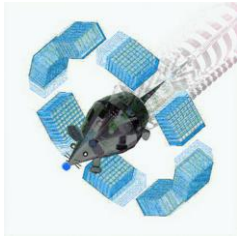
```
/gate/mybox/moves/insert                          genericMove
/gate/mybox/genericMove/setPlacementsFilename     data/mybox_move.pls
```

```
/gate/mybox/moves/insert                                  genericRepeaterMove
/gate/mybox/genericRepeaterMove/setPlacementsFilename     data/mybox_mov_rep.pls
/gate/mybox/genericRepeaterMove/useRelativeTranslation    1
```



Conclusion

- Gate is
  - A set of tools
  - A community (site, mailing list)
- Read documentation
- Improve documentation (wiki)
- Evolving code
- Advanced usage: C++



THANK YOU FOR YOUR ATTENTION

Thibault Frisson, Nabil Zahra, Loic Grevillot, Pierre Gueth, David Sarrut