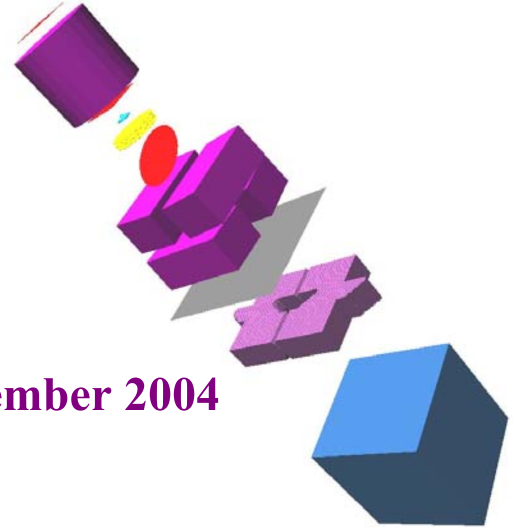
Geant 4

for Medical Physics

CERN,
15th December 2004



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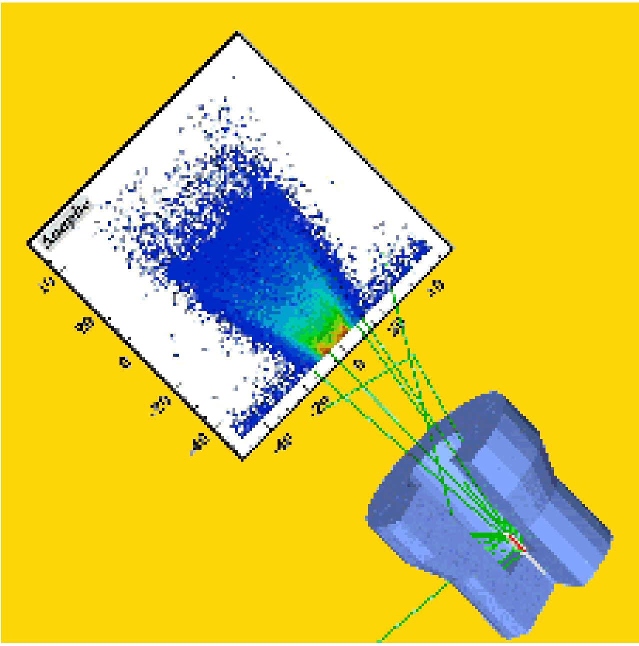

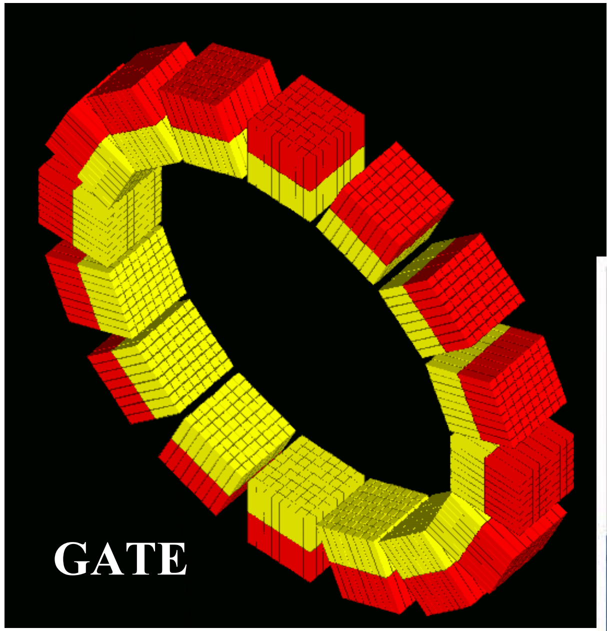

Geant 4

Contributions

- The development of Geant4 medical physics applications is born from the collaboration between Geant4 Developers and Medical Physics groups

- Contributions to this tutorial:

  K. Amako, L. Archambault, L. Beaulieu, G.A.P. Cirrone, G. Cuttone, S. Chauvie, S. Guatelli, S. Incerti, S. Larsson, M.C. Lopes, C. Morel, P. Nieminen, L. Peralta, M.G. Pia, M. Piergentili, R. Rodrigues, V.H. Tremblay, A. Trindade

Geant4 for Medical Physics

Geant4 for Medical Physics

Functionality

Testing activity

Solution to speed constraint

Overview of Geant4 Medical Physics applications


Advanced functionalities in geometry, physics, visualisation etc.
Specific facilities controlled by a friendly UI
A rigorous software process
Extensibility to accomodate new user requirements
What in Geant 4 is relevant to the bio-medical community?
Quality Assurance based on sound software engineering
Transparency of physics
Independent validation by a large user community worldwide
User support from experts
Adoption of standards wherever available (de jure or de facto)
Use of evaluated data libraries
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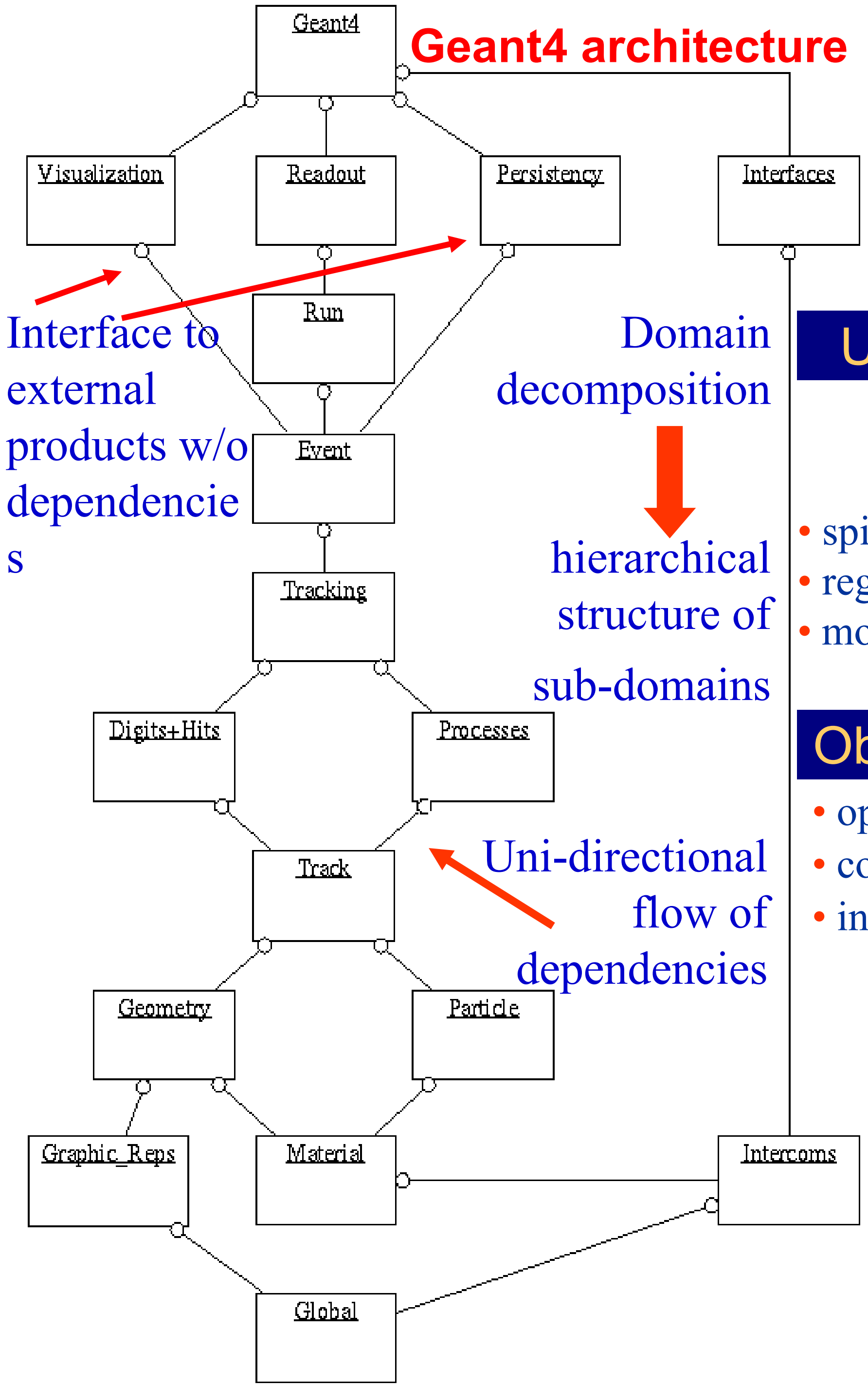
Software Engineering

plays a fundamental role in Geant4

Geant4 architecture



User Requirements
- formally collected
- systematically updated
- PSS-05 standard

Software Process
- spiral iterative approach
- regular assessments and improvements (SPI process)
- monitored following the ISO 15504 model

Object Oriented methods
- OOAD
- use of CASE tools
- openness to extension and evolution
- contribute to the transparency of physics
- interface to external software without dependencies

Quality Assurance
- commercial tools
- code inspections
- automatic checks of coding guidelines
- testing procedures at unit and integration level
- dedicated testing team

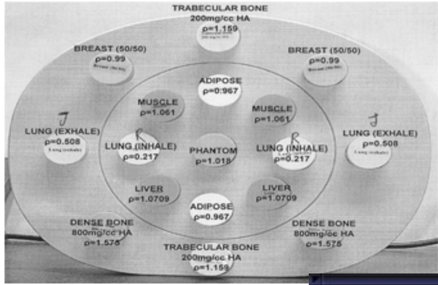
Use of Standards
- de jure and de facto

Overview

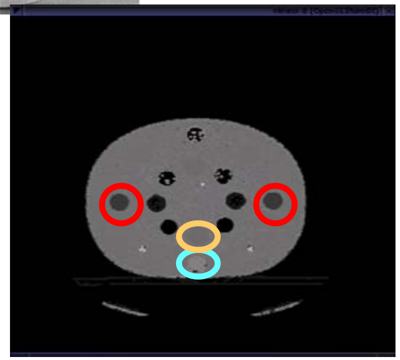
- Geant4 capability addressed to Medical Physics
  - Material and geometry modeling
  - Detector modeling
  - Physics modeling
  - User Interface
  - Visualisation
  - Analysis

Materials

- It is not necessary to approximate human tissues to water for dosimetry
- Accurate description of homogeneous and heterogeneous materials, human tissues
- Example: how to define “bone”

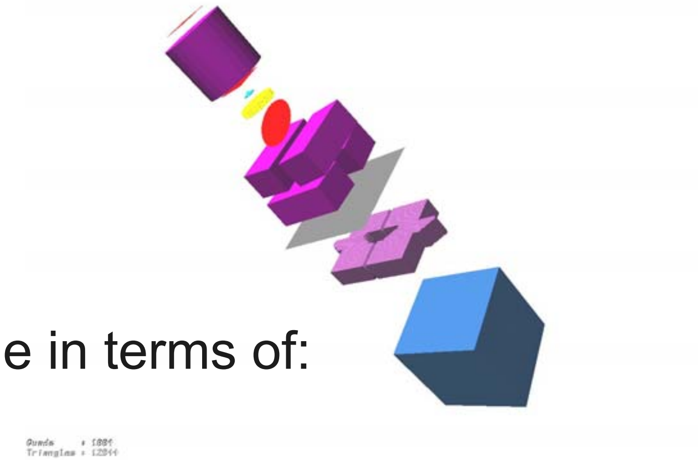


DICOM Interface



```
density = 1.85* g/cm3;
bone = new G4Material( “bone”, density, nElements = 8 );
bone -> AddElement ( elH, 0.063984 );
bone -> AddElement ( elC, 0.278 );
bone -> AddElement ( elN, 0.027 );
bone -> AddElement ( elO, 0.410016 );
bone -> AddElement ( elMg, 0.002 );
bone -> AddElement ( elP, 0.07 );
bone -> AddElement ( elS, 0.002 );
bone -> AddElement ( elCa, 0.147 )
```

Modeling a beam line

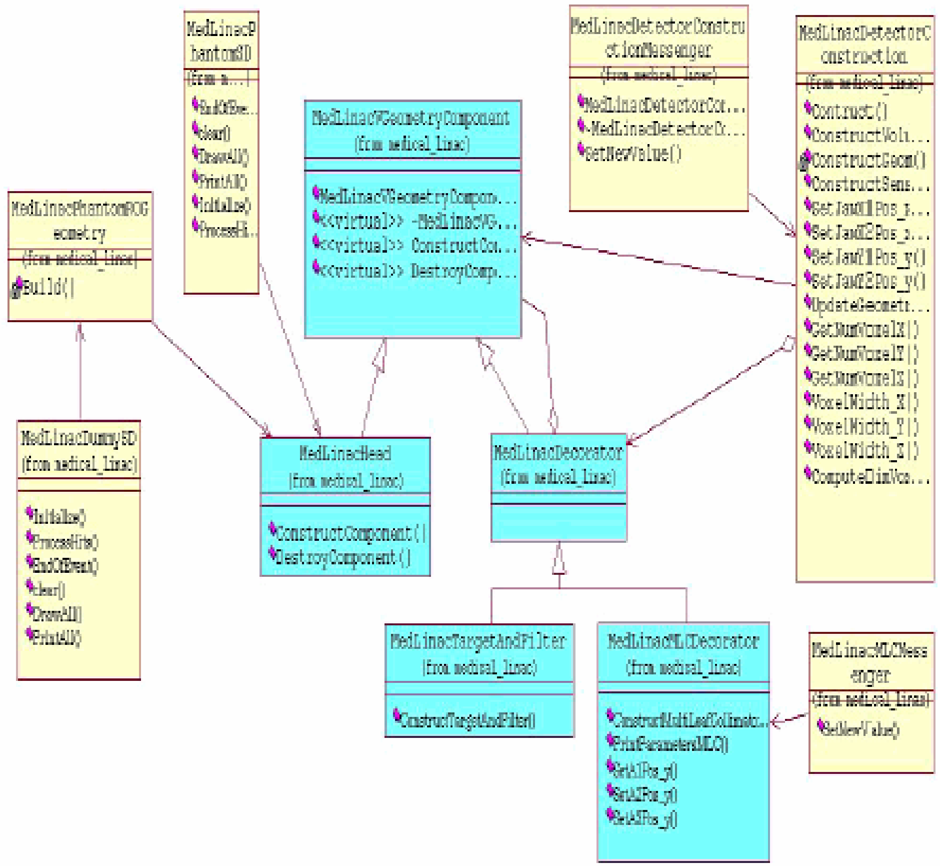


- Accurate modeling of a complete beam line in terms of:
  - Geometry:
    - Materials
    - Geometry components
    - Magnetic fields
    - Moving leafs
  - Particle beam line:
    - Define the particle type
    - Define the energy, angular distribution of the beam with a defined algorithm

- Complete tracking of primary and secondary particles in the experimental set-up

Flexibility of geometry

- Use of the **design pattern Decorator** to model geometries in the IMRT Geant4 application
- Decorator design pattern - attach additional responsibilities to an object dynamically
- **Advantage**: develop a general, flexible, extensible software with the capability of choosing a specific experimental set-up
- **Dynamically loadable geometries**:
  - Position of the collimators
  - Set the target and flattering filter in the experimental set-up



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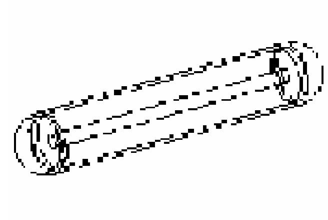
Modeling a radioactive source geometry

Precise geometry and material model of any type of source

- Iodium core
- Air
- Titanium capsule tip
- Titanium tube



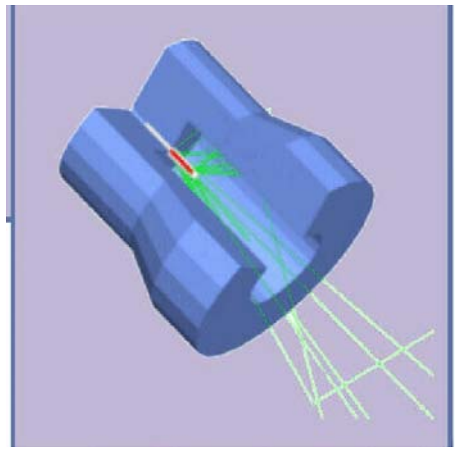
I-125 source for interstitial brachytherapy

Iodium core:
Inner radius :0
Outer radius: 0.30mm
Half length:1.75mm

Titanium tube:
Outer radius:0.40mm
Half length:1.84mm

Air:
Outer radius:0.35mm
half length:1.84mm

Titanium capsule tip:
Box
Side :0.80mm



Ir-192 source + applicator for superficial brachytherapy

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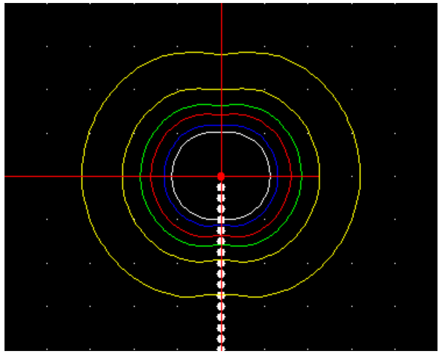
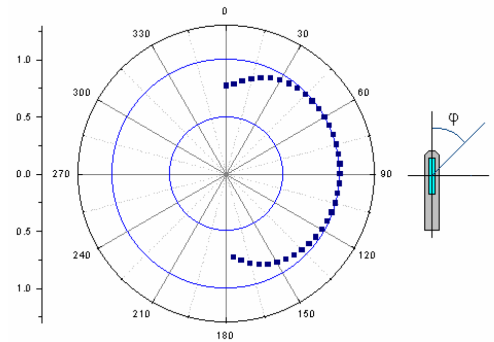
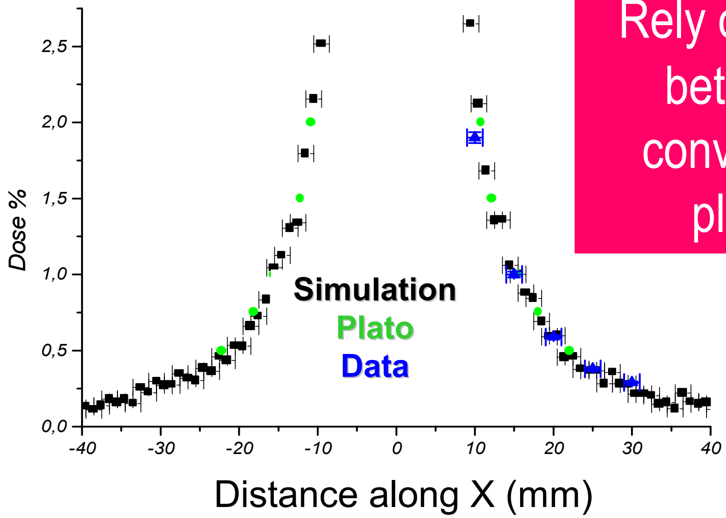
Effects of source anisotropy

Plato-BPS treatment planning algorithm makes some crude approximation (φ dependence, no radial dependence)



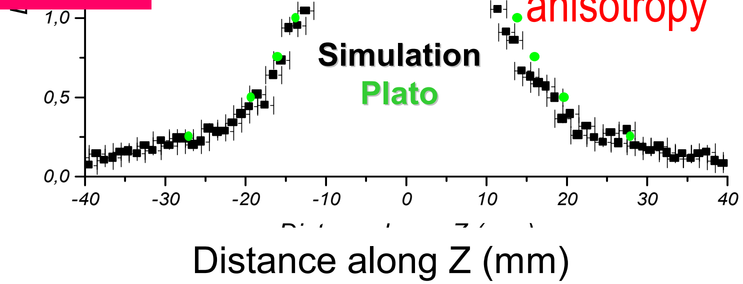


Rely on **simulation** for better accuracy than conventional treatment planning software



Transverse axis of the source

Comparison with experimental data



Longitudinal axis of the source

Difficult to make direct measurements

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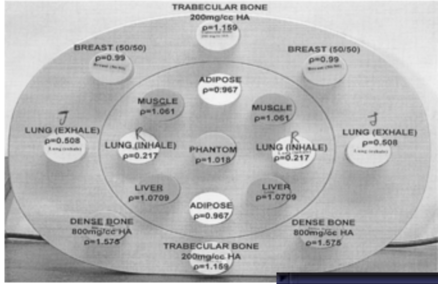
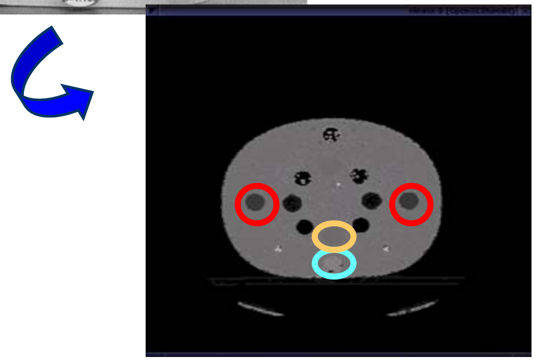
Model a human anatomy





Geant4 offers:

- Accurate description of human tissues
- Volume parameterisation to model the anatomy geometrically

Parameterised volumes: to model complex geometries with variable volume characteristics depending on one or more parameters

How to do model the anatomy:
- Divide a volume in voxels
- Associate a selected material to each voxel through a parameterisation function

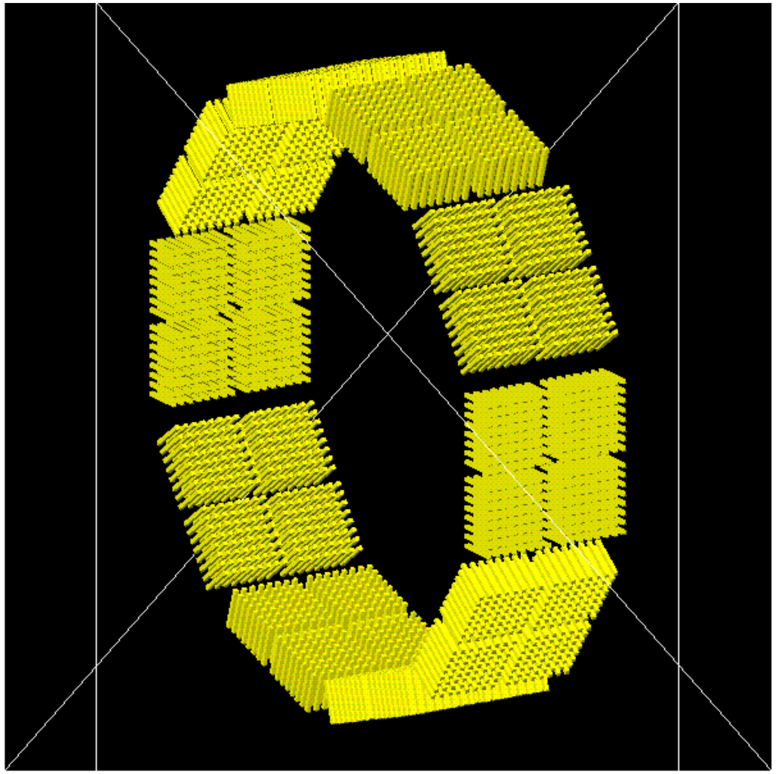
How to model detectors

PET simulation:

- Use of replica or reflections in geometry construction

- Accurate description of the crystals

- Geant4 Digit to simulate the detector response function



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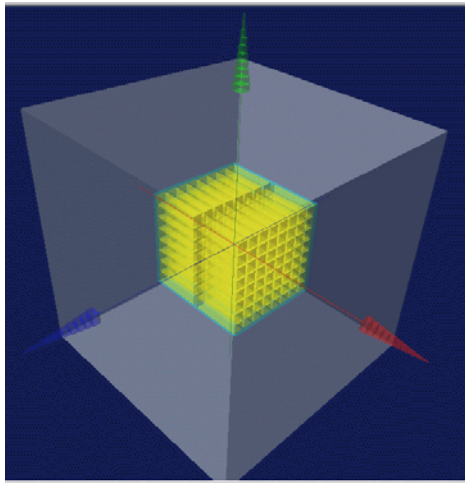
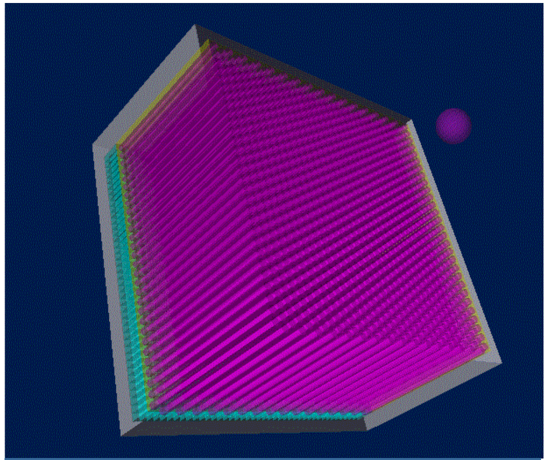
Detector and scanner geometry

Phoswich detector

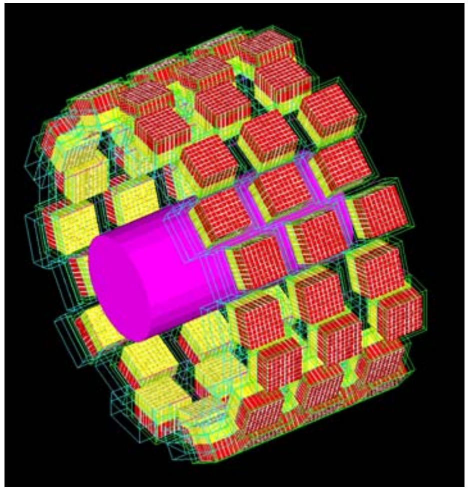


Gamma camera with collimators



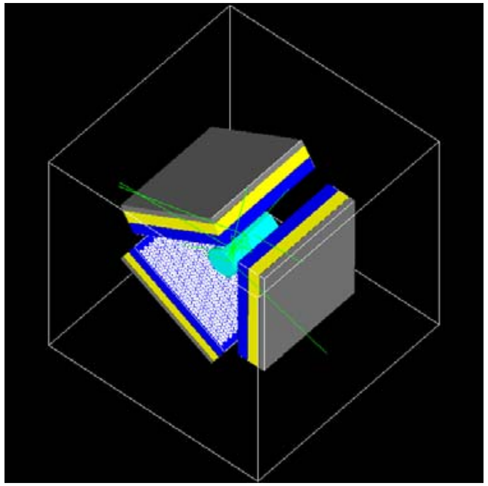
D. Lazaro, LPC, Clermont-Ferrand

LSO/LuYAP ClearPET prototype design



J.-M. Vieira, LPHE, EPF Lausanne

3-head SPECT



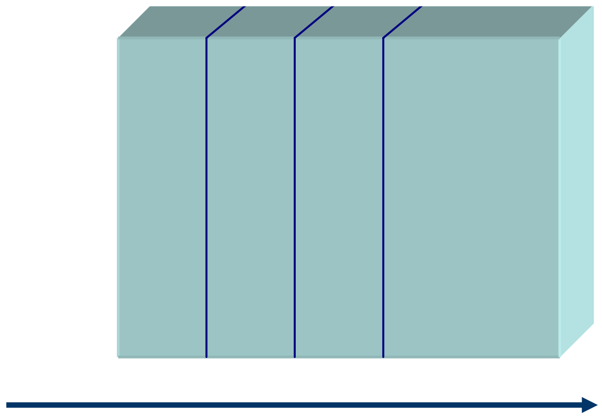
S. Staelens, ELIS, Ghent

Model a phantom

- How to retrieve the energy deposit in a phantom
  - Use the RO Geometry

Define the phantom: water box

The RO Geometry allows to put a grid on the geometry → definition of voxels



It is possible to retrieve the energy deposit of primary particles and all the secondaries generated in each voxel

Physics models

- Geant4 offers alternative and complementary physics models both in electromagnetic and hadronic physics
- The physics processes are available for photons, e-, e+, hadrons, ions
- Validation of the physics models has a center role in the Geant4 Collaboration

Electromagnetic physics

energy loss

- electrons and positrons
- γ, X-ray and optical photons
- charged hadrons
- ions
- muons

- Low energy extensions are fundamental for Geant4 Medical Physics applications
  - Model based on evaluated data libraries
  - Penelope processes completely re-engineered in Geant4 thanks to OO Technology

- Multiple scattering
- Bremsstrahlung
- Ionisation
- Annihilation
- Photoelectric effect
- Compton scattering
- Rayleigh effect
- γ conversion
- e^+e^- pair production
- Synchrotron radiation
- Transition radiation
- Cherenkov
- Refraction
- Reflection
- Absorption
- Scintillation
- Fluorescence
- Auger

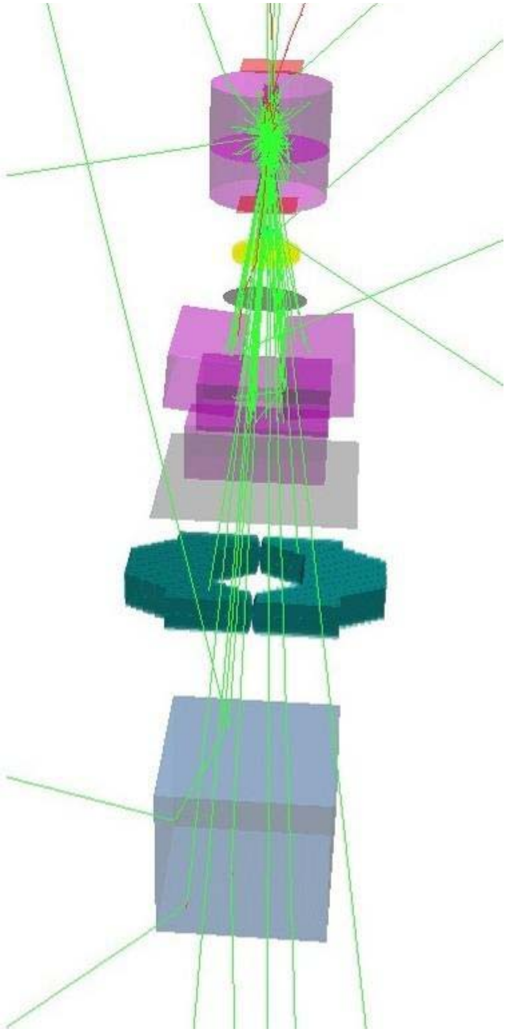
High precision dosimetry thanks to the Geant4 Low Energy Electromagnetic Package

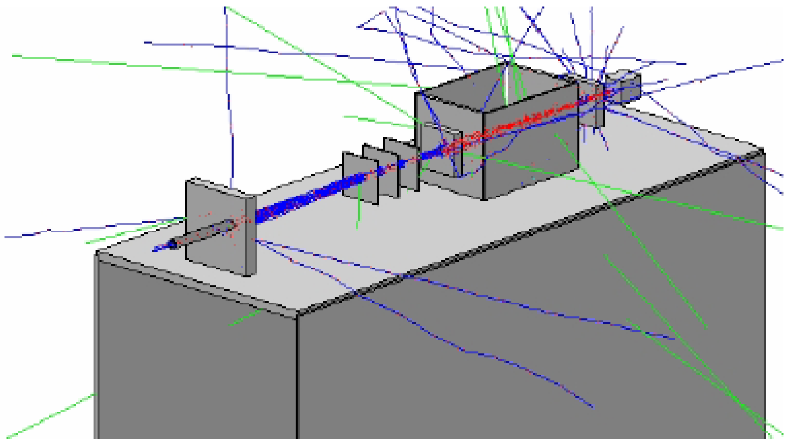
User Interface

- User-friendly user interface
- Also not software specialists can use a Geant4 application

Visualisation

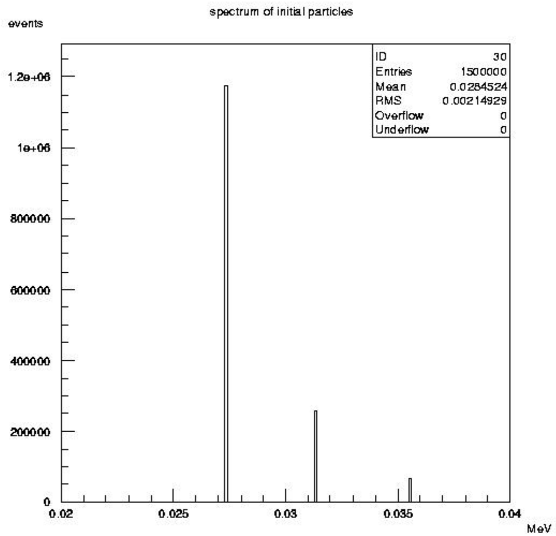
- The user can visualise both geometries and particle tracks
- Use DAVID as debugging tool to verify the correct modeling of the geometry set-up



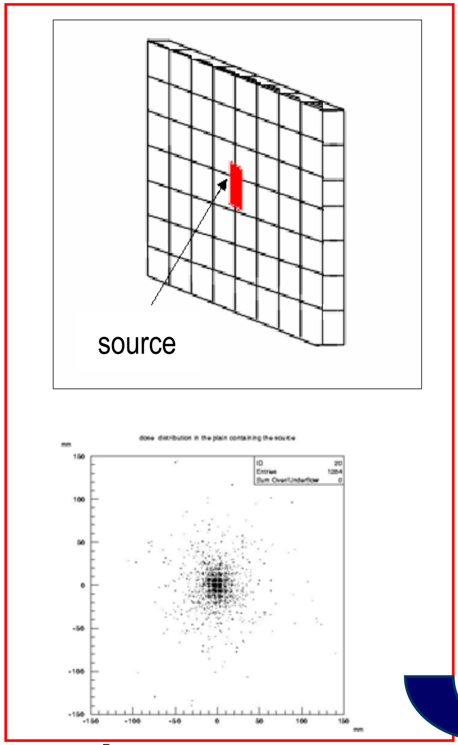


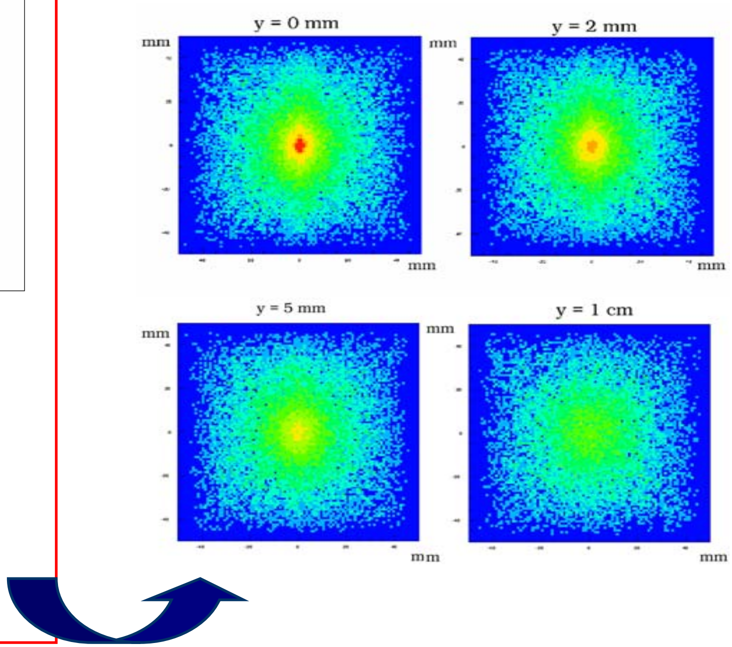
Analysis

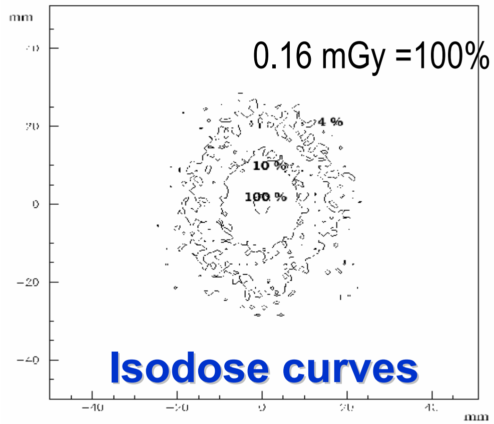
- It is possible to store information in histograms, ntuple, data set vectors, i.e. the energy deposit in a phantom
- Elaborate dose distribution from energy deposit
  - For example isodose curves



Energy spectrum of photons emitted by I-125 brachytherapic source







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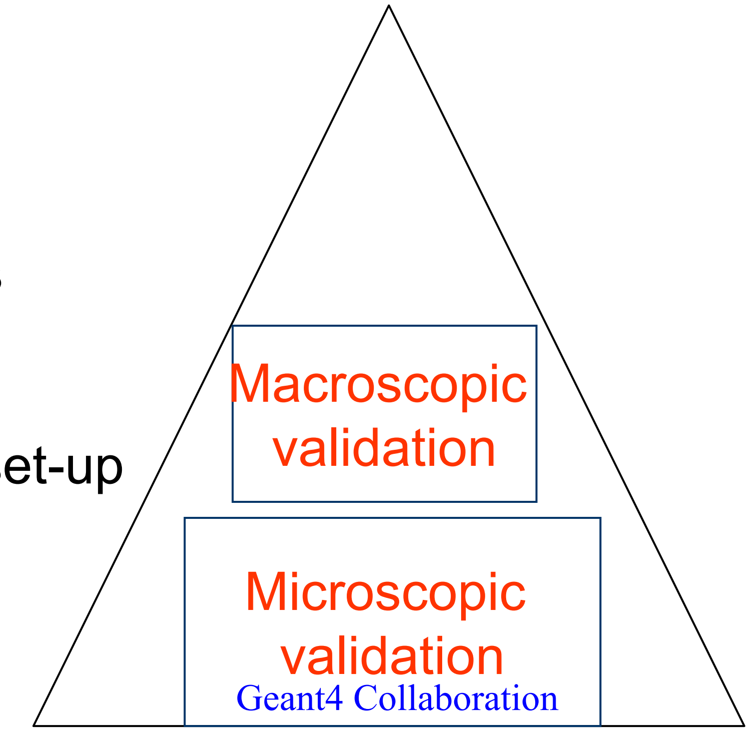
Validation for Medical Physics applications

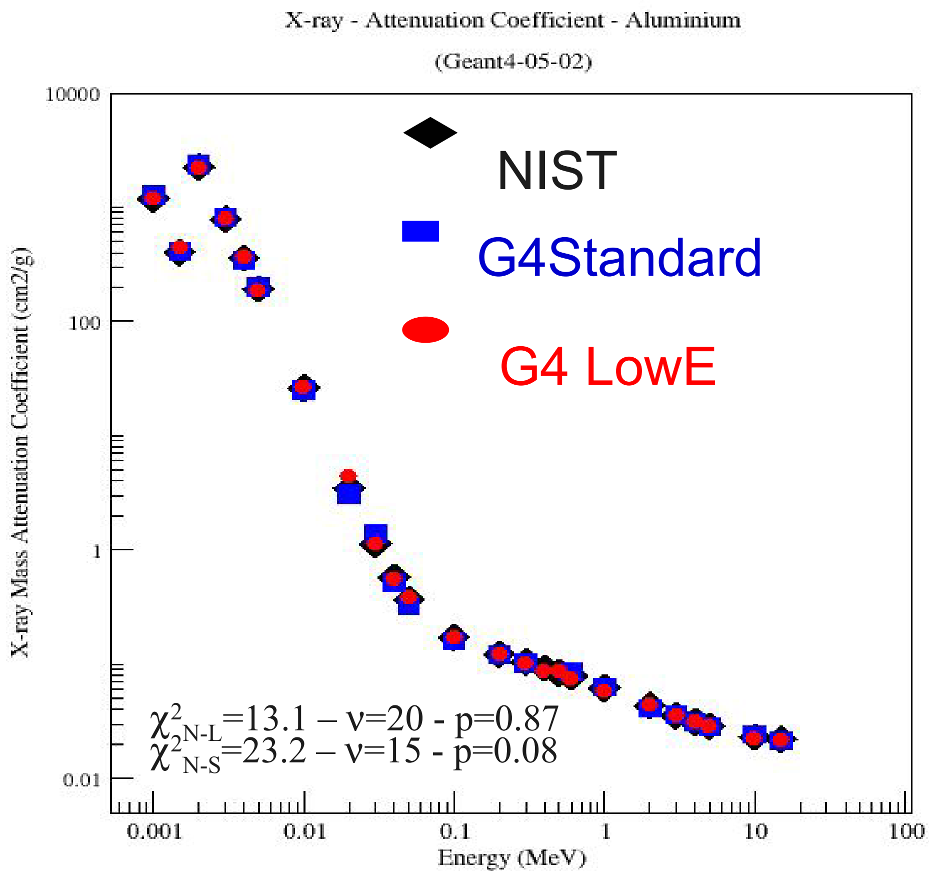
Validation is fundamental for Medical Physics Applications

Validation at different levels:

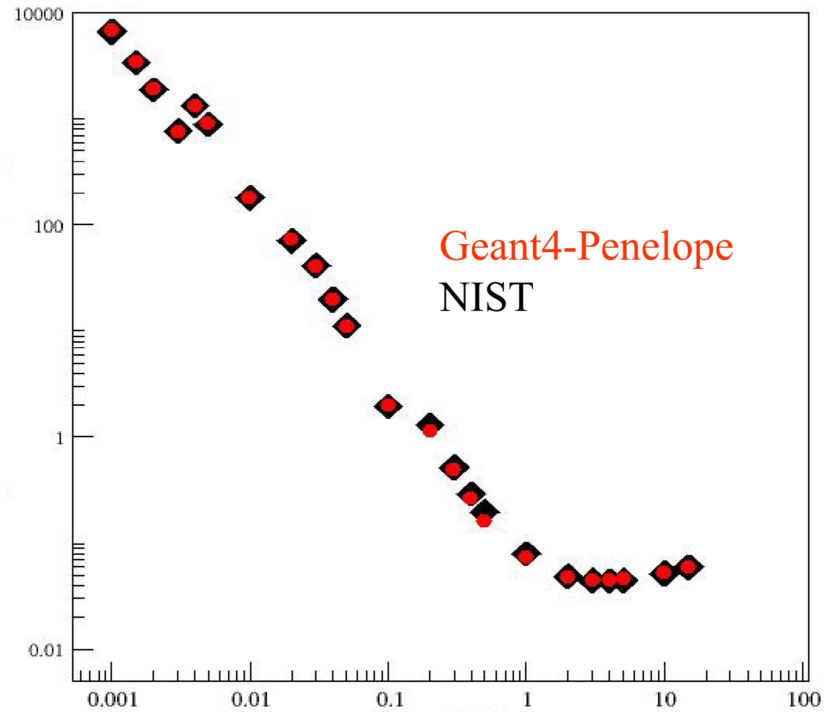
- Unit, integration, system test
- Microscopic validation - physics models validation
- Macroscopic validation - experimental set-up validation of the specific experiment
- Validation with respect to experimental measurements



Validation of physics models



- Attenuation coefficients, CSDA ranges, Stopping Power, distributions of elementary physics quantities



- Quantitative comparisons to experimental data and recognised standard references and protocols

Technology transfer

Particle physics software aids space and medicine

Geant4 is a showcase example of technology transfer from particle physics to other fields such as space and medical science […].

CERN Courier, June 2002

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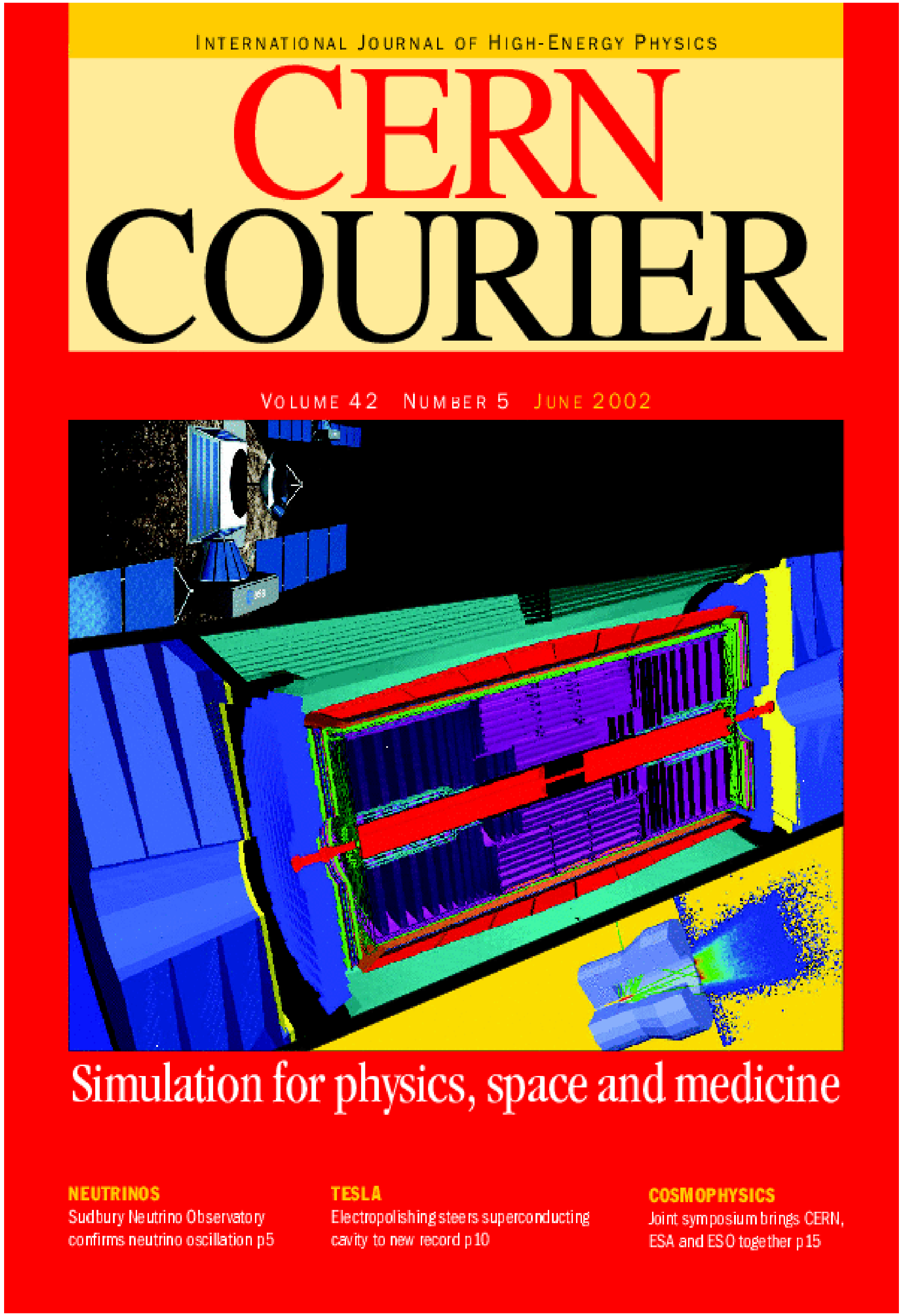


Documentation

- http://geant4.web.cern.ch/geant4/G4UsersDocuments/Overview/html/index.html
  - **User's Guide: For Application Developers**
  - **Physics Reference Manual**

- Geant4 Medical Physics advanced examples
  - **brachytherapy**, dosimetry of brachytherapic sources
  - **hadrontherapy**, simulation of a hadrontherapy beam line
  - **medical_linac**, simulation of a Linac and dosimetry for IMRT
  - **purging_magnet**, simulation of a strong purging magnet in a treatment head
  - **radioprotection**, radioprotection study in space vehicle concepts and surface habitats

http://www.ge.infn.it/geant4/examples/index.html

User support

- Hypernews, Medical Physics Hypernews
  - http://geant4-hn.slac.stanford.edu:5090/Geant4-HyperNews/index
- Problem report
  - http://pcitapiww.cern.ch/asd/cgi-bin/geant4/problemreport
- User workshops
- User support from the Geant4 Collaboration

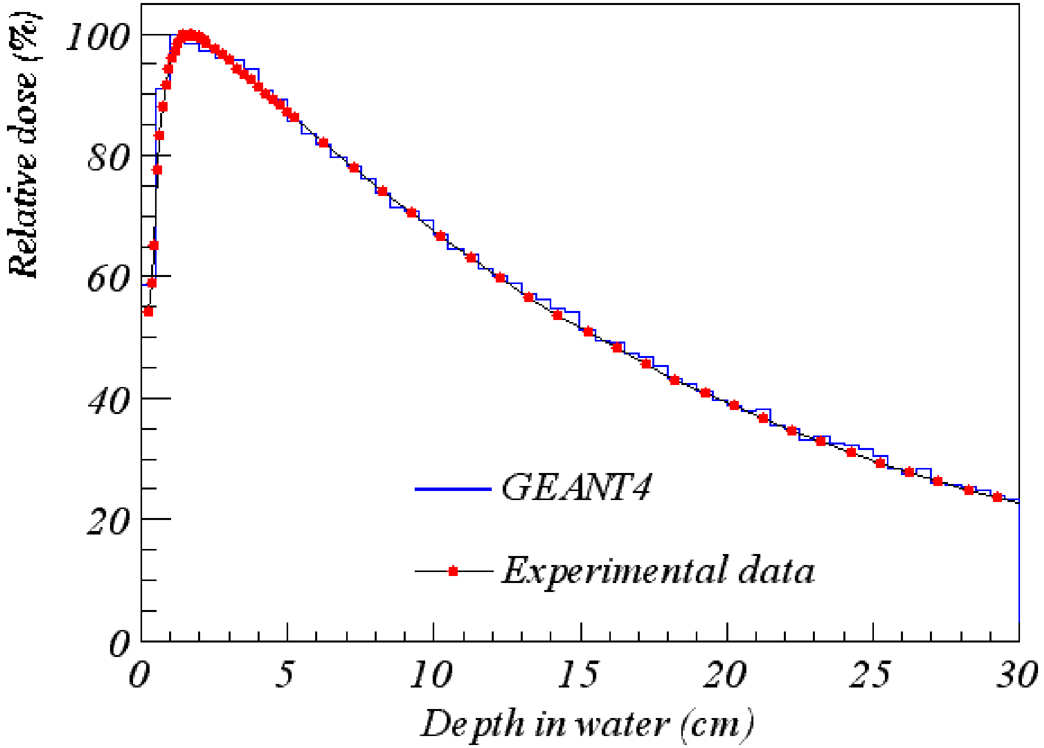
Geant4 Medical Physics applications

Verification of radiotherapy treatment planning

Investigation of innovative methods

Dosimetric studies at cellular level

Radiodiagnostics



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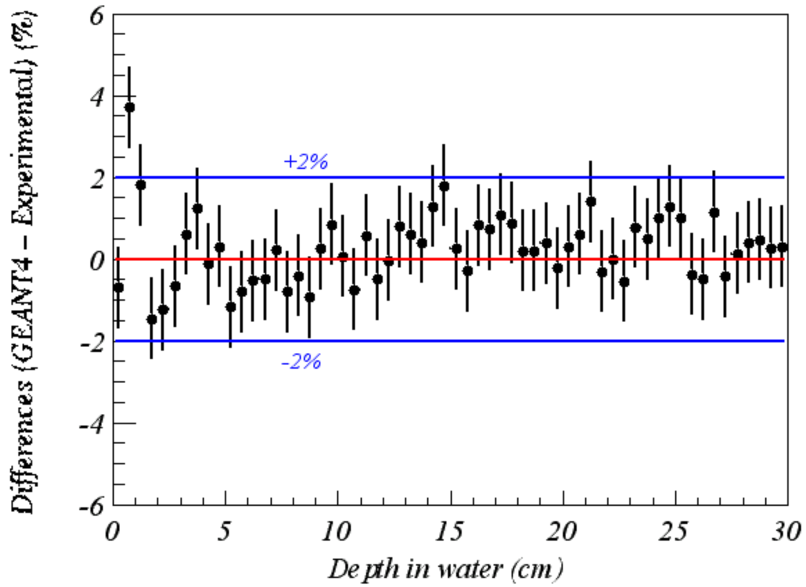
testing and validation

Validation of phase-space distributions from a Siemens KD2 linear accelerator, 6 MV photon mode



M. C. Lopes

IPOFG-CROC Coimbra Oncological Regional Center

L. Peralta, P. Rodrigues, A. Trindade

LIP - Lisbon

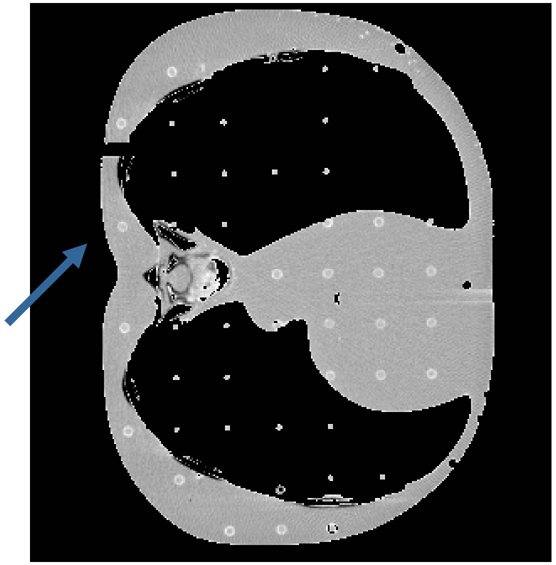
Comparison with commercial treatment planning systems

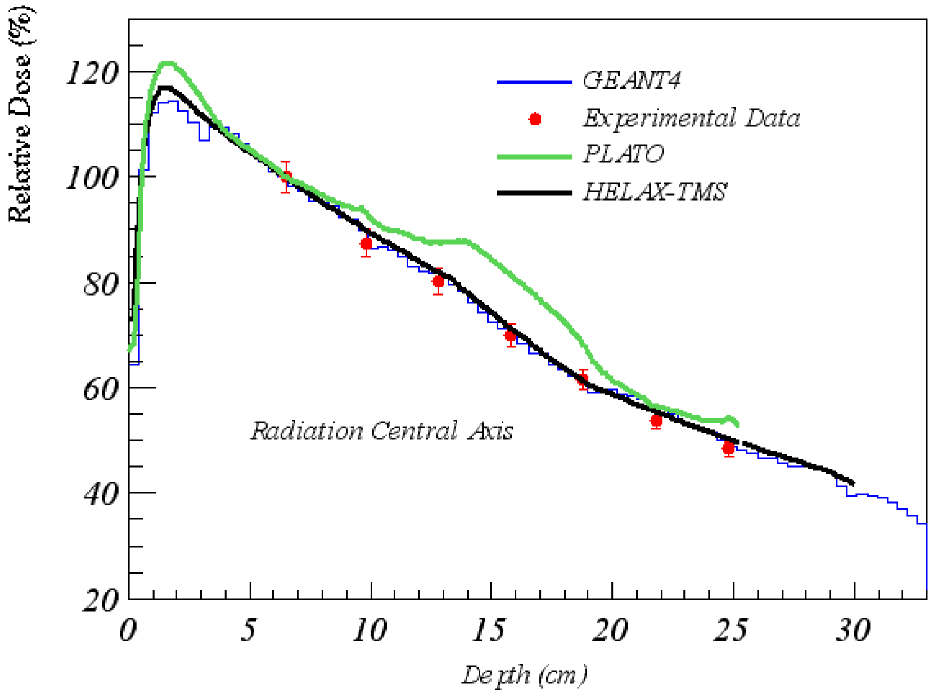
M. C. Lopes [1], L. Peralta [2], P. Rodrigues [2], A. Trindade [2]
[1] IPOFG-CROC Coimbra Oncological Regional Center - [2] LIP - Lisbon

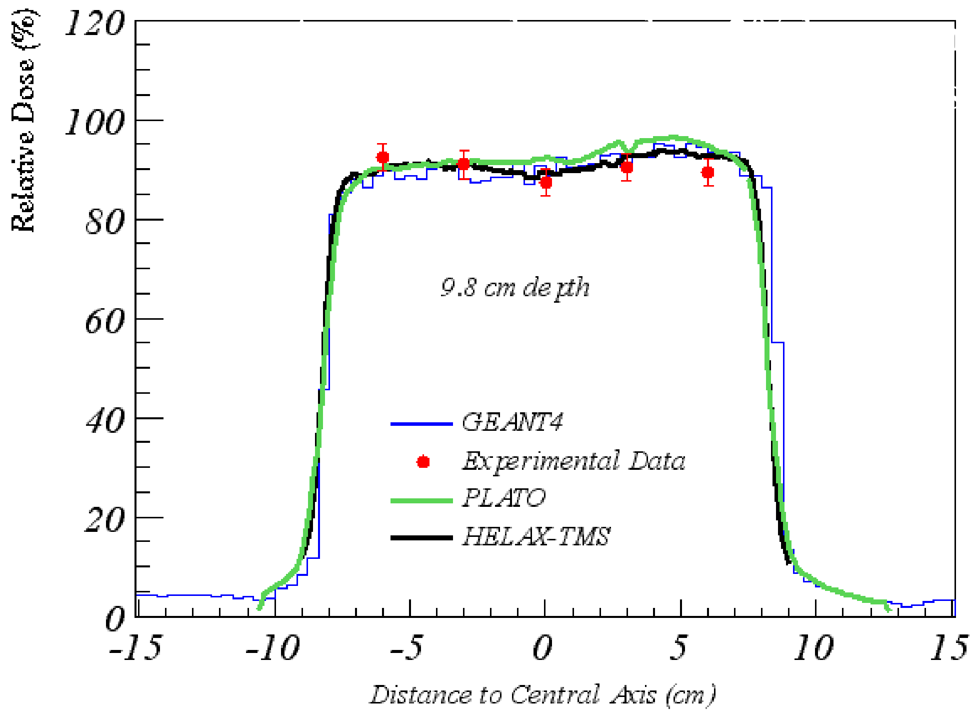
CT-simulation with a Rando phantom
Experimental data obtained with TLD LiF dosimeter

CT images used to define the geometry:

a thorax slice from a Rando anthropomorphic phantom







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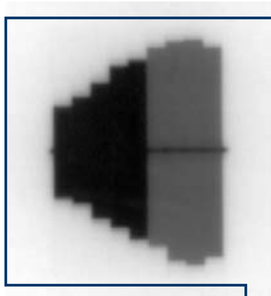
Medical Linac for IMRT

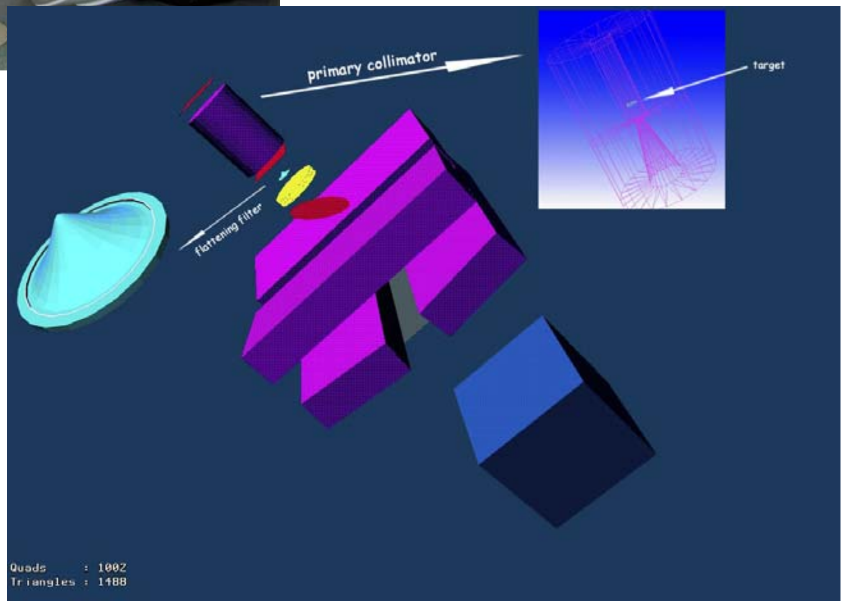
- Complex geometries
- Variety of physics processes – Low Energy Package
- Interactive facilities: visualisation, analysis, UI



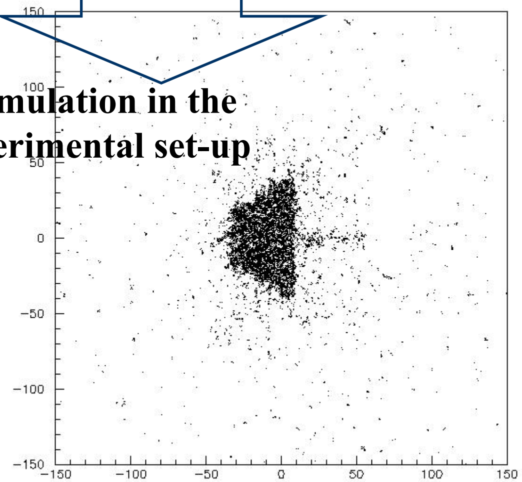
Experimental measurements with films

INFN
Istituto Nazionale di Fisica Nucleare

IST



Geant4 simulation in the same experimental set-up



Authors: F. Foppiano, M.G. Pia, M. Piergentili

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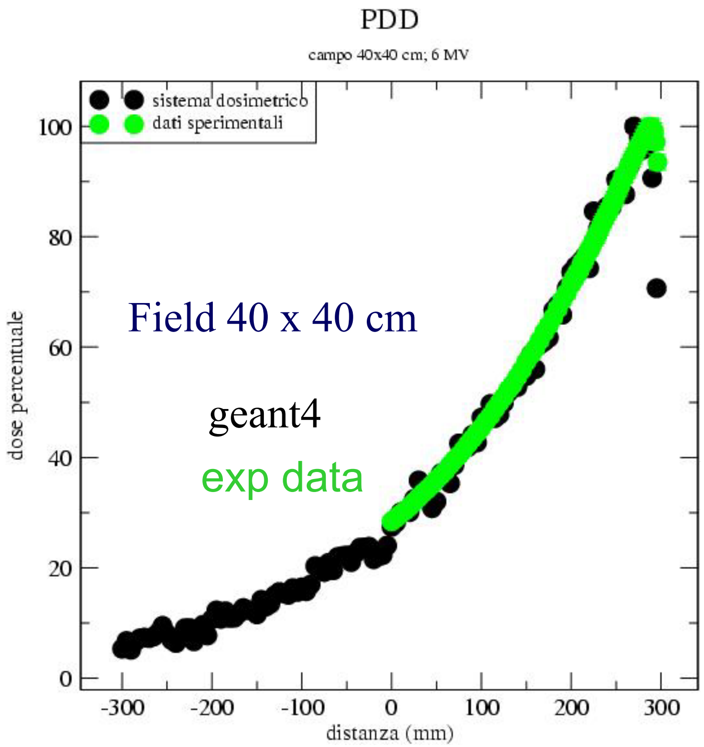
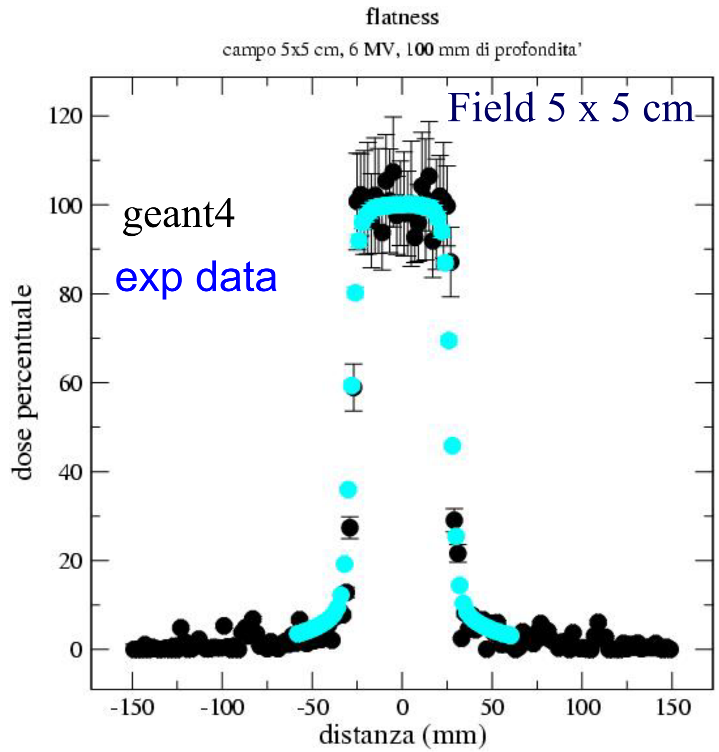
Medical Linac for IRMT

By M. Piergentili,
INFN Genova

- Comparison of Geant4 simulation results and original experimental data



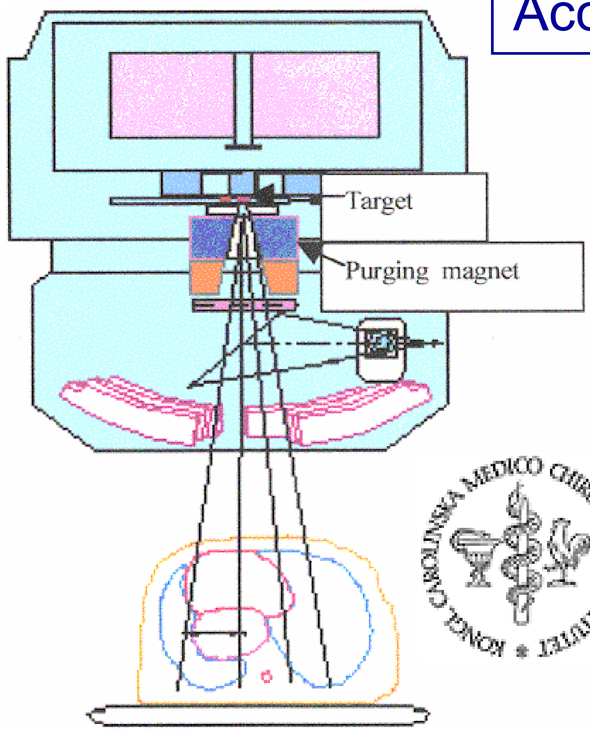
% dose with respect to the depth in the phantom



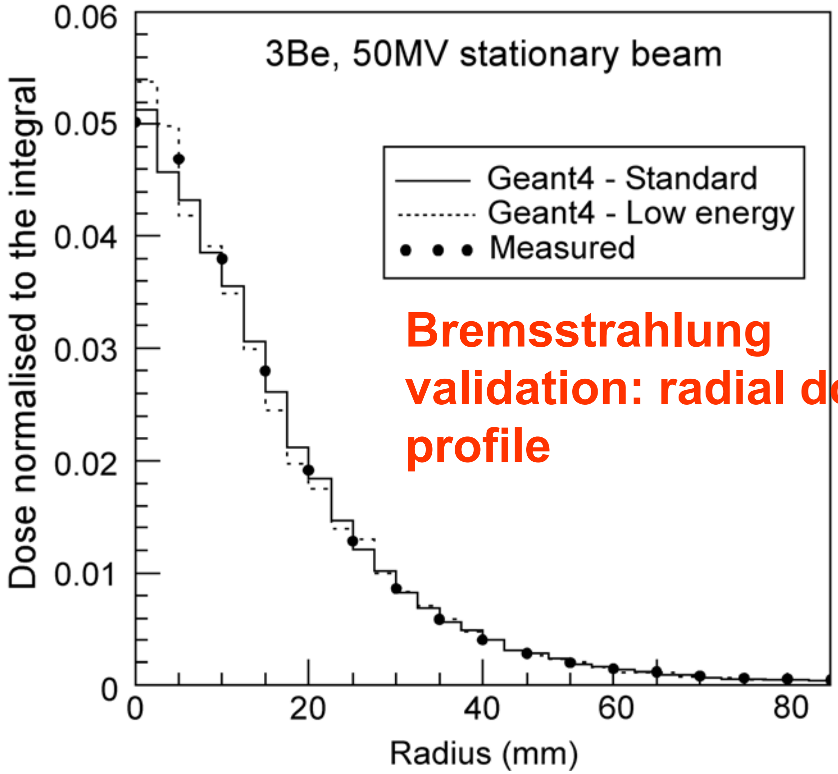
% dose at 100 mm depth in the phantom

Simulation of a treatment head

Accuracy in the geometry and magnetic field modeling



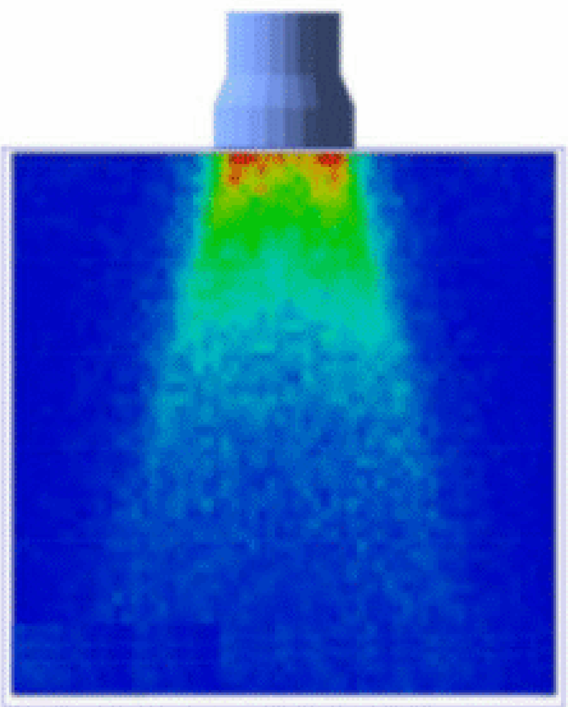
- High energy electron beam, 50 MeV
- Target 3 mm Be



Bremsstrahlung validation: radial dose profile

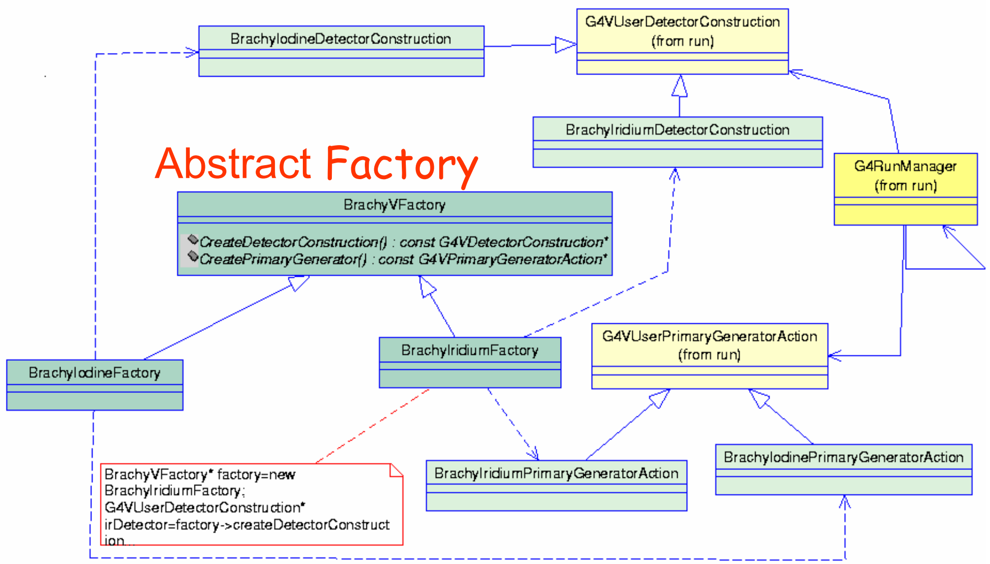
Susanne Larsson, Roger Svensson
Irena Gudowska, Björn Andreasen (Karolinska Institutet, Stockholm),
Vladimir Ivanchenko (CERN)

Brachytherapy



- Variety of physics processes
- Dosimetry for all brachytherapic devices:
  endocavitary, interstitial, superficial brachytherapy
- Interactive facilities: visualisation, analysis, UI, access to distributed resources

Example of advantages of OO Technology use



Authors:
F. Foppiano, S. Guatelli, M.G. Pia, M. Tropeano

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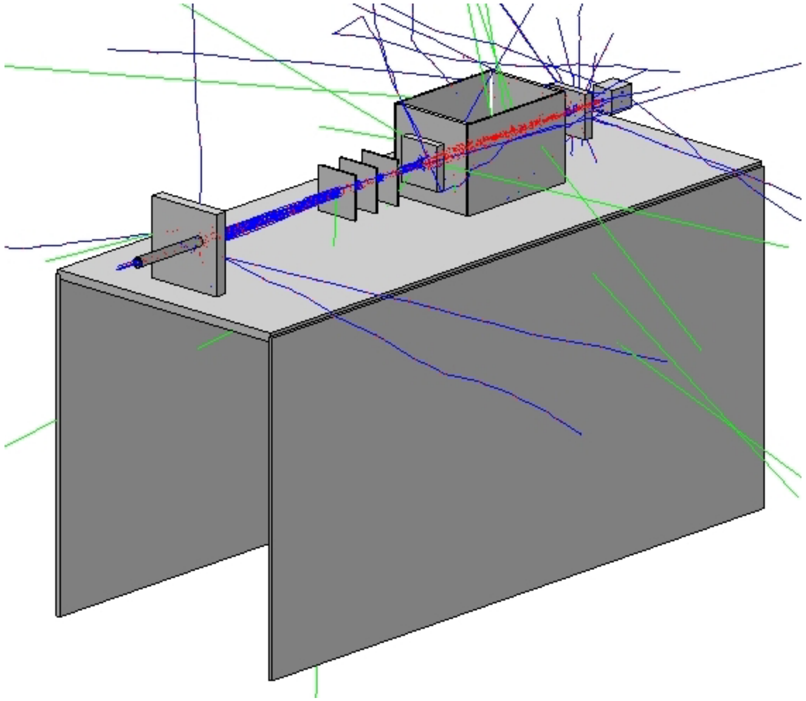
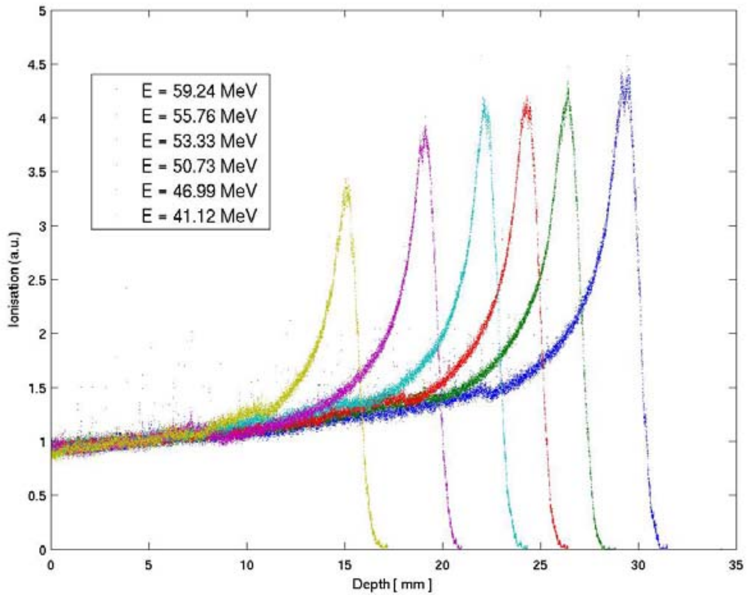
Hadrontherapy

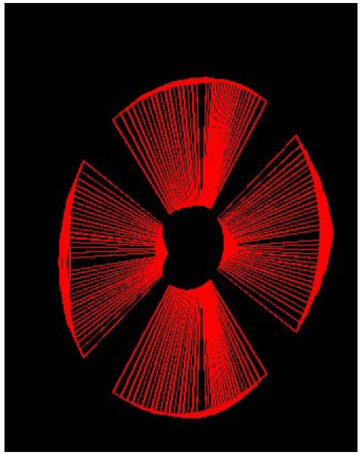
P. Cirrone, G. Cuttone, G. Russo, F. Di Rosa, LNS, Catania, Italy



- Modeling of the beam line

- Electromagnetic and hadronic interactions for protons, ions (and secondary particles)





Modulator for hadrontherapy beam line

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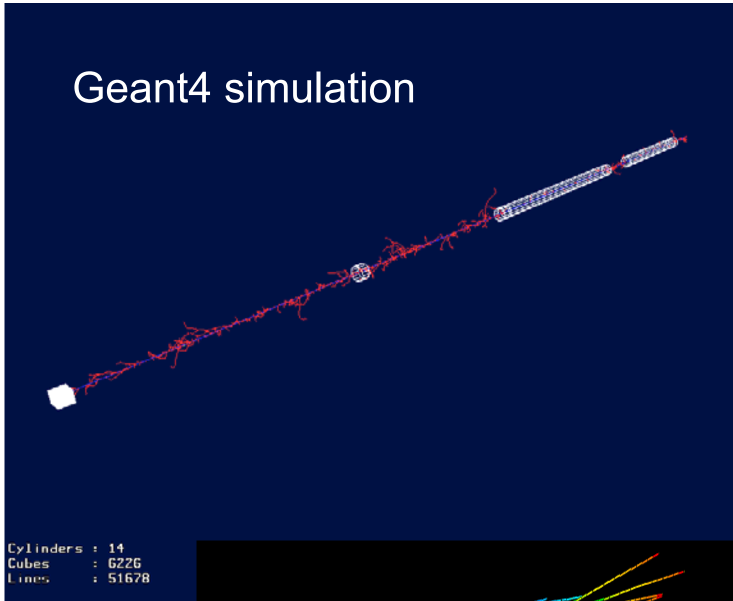
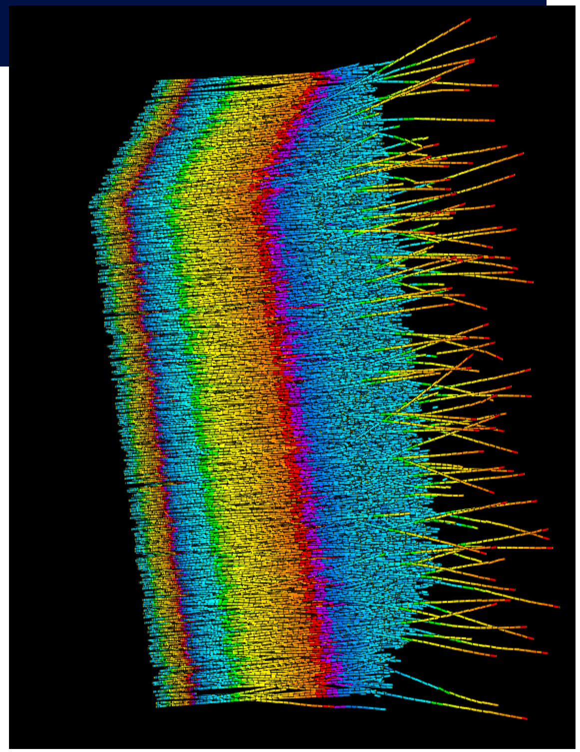
Heavy ions beams

NIRS N. Kanematsu, M. Komori - Nagoya K. Niwa, T.Toshito, T.Nakamura, T.Ban, N.Naganawa, S.Takahashi - Uchu-ken M.Ozaki, Kobe S. Aoki, Aichi Y.Kodama - Naruto H.Yoshida - Ritsumei S.Tanaka - SLAC M. Asai, T. Koi -Tokyo N.Kokubu - Gunma K. Yusa - Toho H.Shibuya, R.Ogawa, A. Shibazaki, T.Fukushima - KEK K. Amako, K.Murakami, T. Sasaki



- **Study nuclear interaction processes of medical heavy ion beam with elements of human body (Water, C, N, Ca, P) by the high spatial resolution emulsion chamber**

Geant4 allows to model heavy ions interactions



Beam Track Reconstruction
135 MeV/u ^{12}C beam

[Note]
Each film layer is colored in the cyclic sequence of violet,indigo,blue,green, yellow,orange,red

Geant 4

Shielding and radioprotection in space missions

Collaboration ESA, ALENIA SPAZIO, INFN Genova in AURORA project

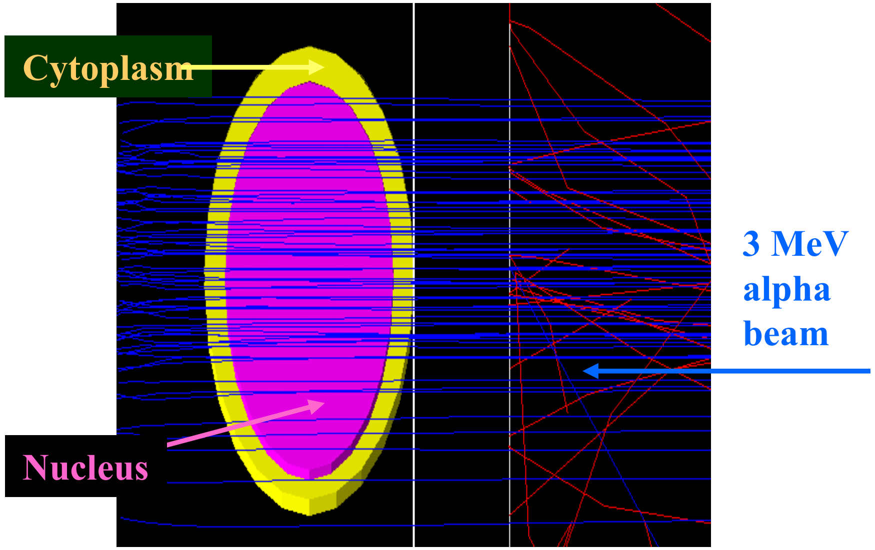
Geant4 application for shielding and astronauts' radioprotection studies in vehicles and Moon surface habitats

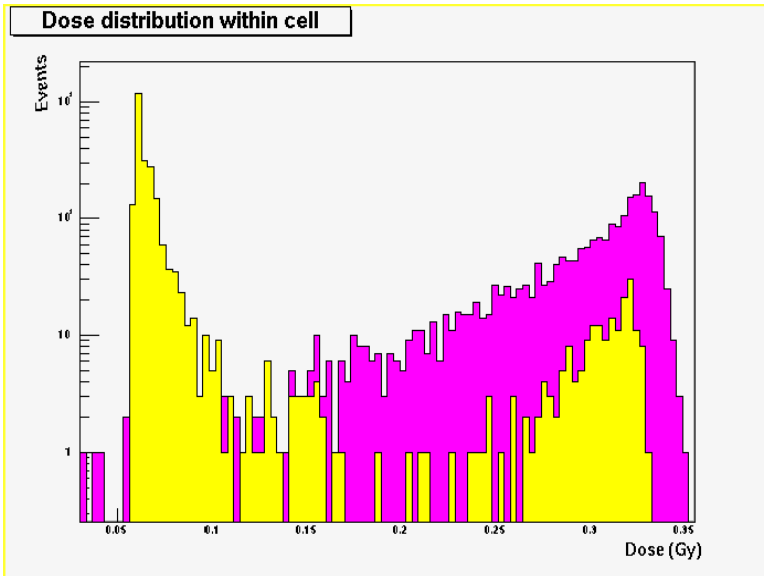
S.Guatelli [1], P. Nieminen[2], M. G. Pia[1]
1.INFN Genova, Italy, 2. European Space Agency, ESTEC

- Electromagnetic and hadronic processes for protons, alpha particles in a wide range of energy
- Accurate geometry modeling
- Interactive facilities: visualisation, analysis, UI

Geant4 dosimetry at cellular level

- Example: Geant4 application developed by S. Incerti et al. (CNRS / IN2P3)
- Scope: study the effect of low dose on human tissues
- Solution: dosimetric effect of single particle microbeams on cells
- Geant4 has the capability of:
  - Description of the beam line
  - Description of the magnetic fields
  - Description of the cell in terms of shape and materials
  - Modelling of the interactions of ions with matter
  - Dosimetry of a single particle microbeam on cells





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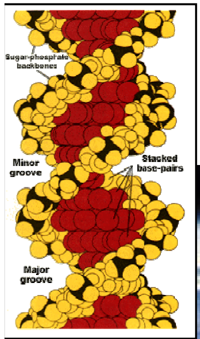
BORDEAUX 1

Geant4 - DNA

Simulation of Interactions of Radiation with
Biological Systems at the Cellular and DNA Level



Geant4 applications in chemistry and biochemistry

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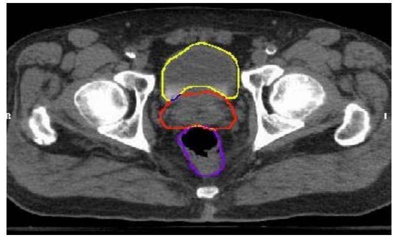
Geant4 medical physics applications in diagnostic

Geant4 DICOM Interface

Modeling complex structures



file

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L-DIEU DE QUEBEC
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SH..HNCT40238 ..

Reproduce patient's anatomy in a Geant4 application

Authors: L. Archambault, L. Beaulieu, V.-H. Tremblay

(Univ. Laval and l'Hôtel-Dieu, Québec)

Pavillon L'Hôtel-Dieu
Centre hospitalier universitaire de Québec

UNIVERSITÉ LAVAL

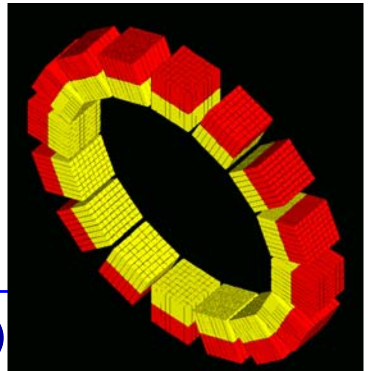
Geant 4

GATE Collaboration

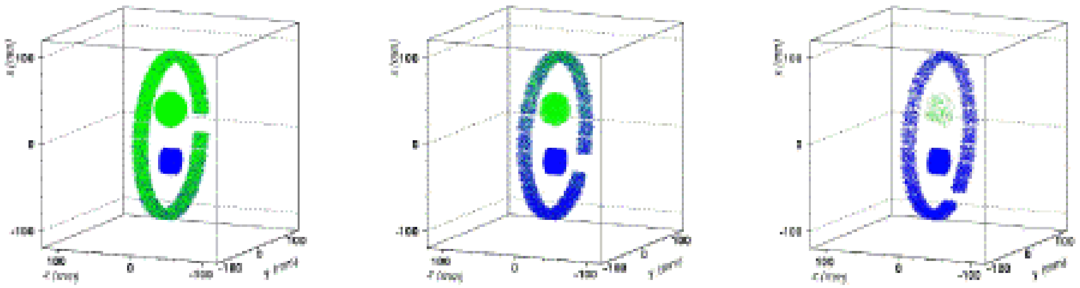
http://www-lphe.epfl.ch/~PET/research/gate/

Geant4 Application for Tomographic Emission (GATE)

- Accurate description of **time-dependent phenomena** such as source or detector movement
- Realistic simulations of data acquisitions in time thanks to the ability to **synchronize all time-dependent components**
- Modeling of the detector response: **use of digitization**
- Use of **decay module** to model the source decay kinetic



Simulation of the decay of O-15 (in green) and C-11 (in blue) sources throughout 3 time frames



0 - 2 min   7 - 9 min   14 - 16 min

Other applications

Power and flexibility of the toolkit

Openness to extension and evolution

Speed constraint

Parallelisation

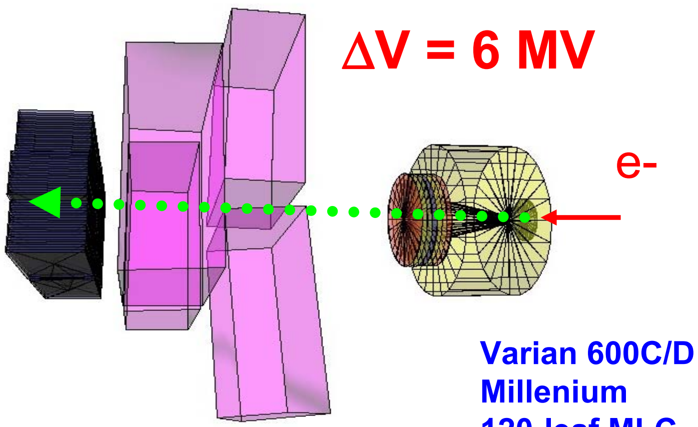
Use of local cluster

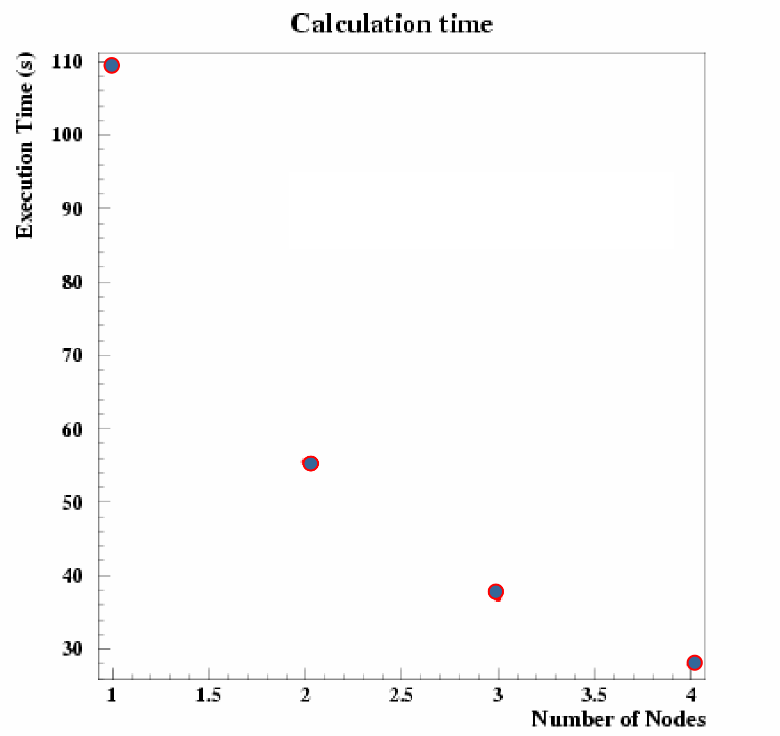
Use of geographically distributed computing resources

Parallelisation

- Parallelisation is a possible solution to speed constraint

- Example: parallelisation is the solution adopted for a Geant4 IMRT application





Stéphane Chauvie[1], Giuseppe Scielzo[2]

1. Ordine Mauriziano
2. INFN Turin, AO S CROCE E CARLE, Cuneo

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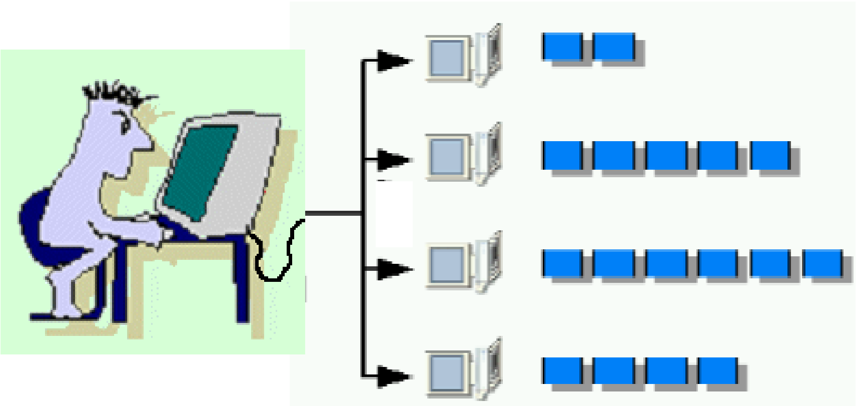
Improve the performance of the simulation in terms of speed

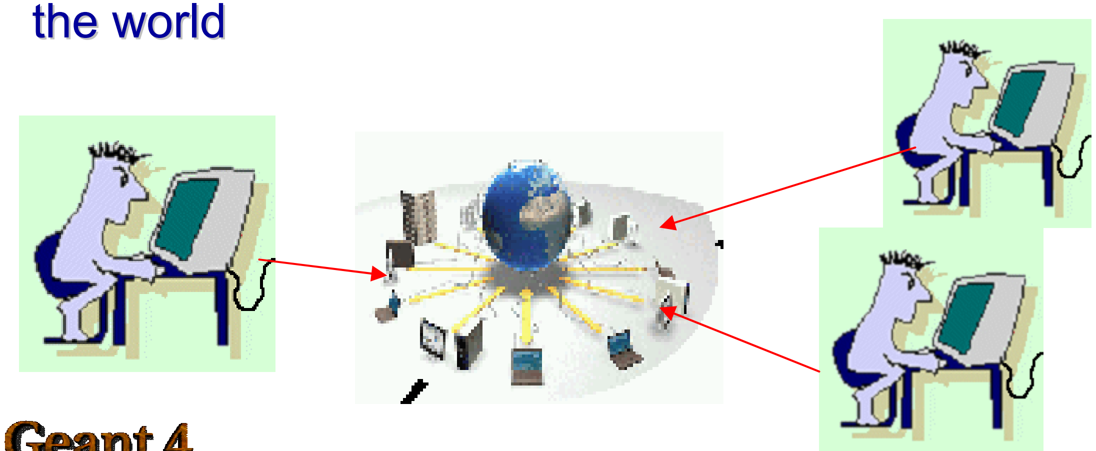
- Parallelisation of the Geant4 application on a local cluster



But a institute or hospital may not own a sufficient computer farm …

- Access to distributed computing resources

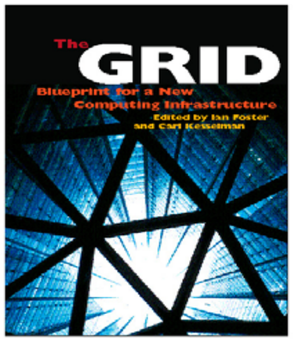
Share with other institutes computing resources geographically distributed around the world



Parallel mode: distributed resources

Distributed Geant 4 Simulation:

DIANE framework and generic GRID middleware



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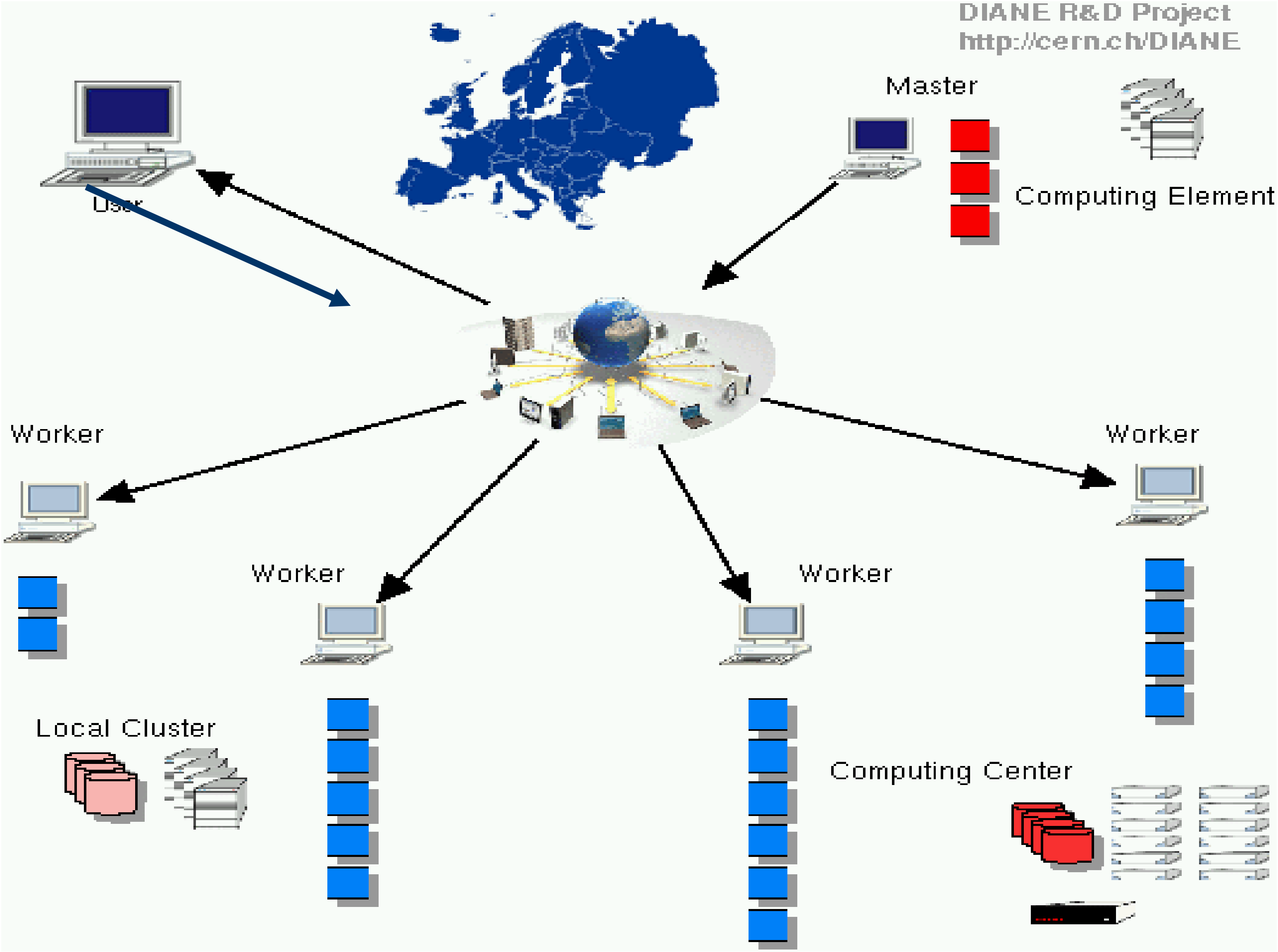
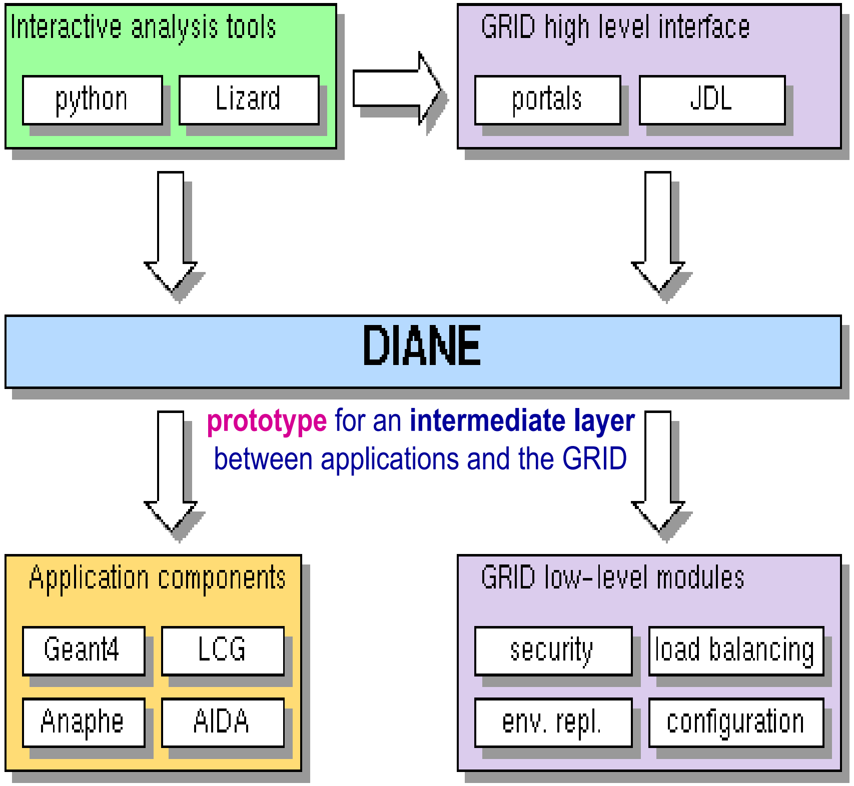


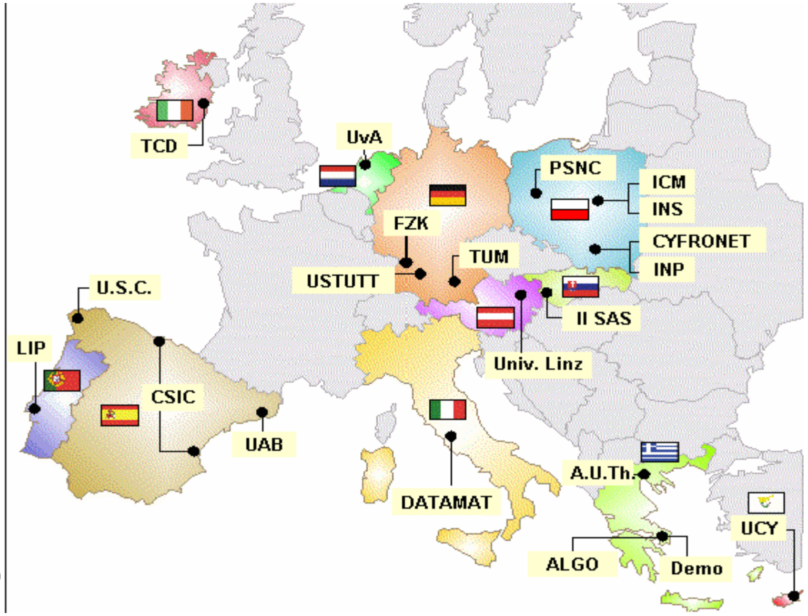
DIANE



- DIANE is a intermediate layer between applications and a local cluster or the GRID
- Same application code as running on a sequential machine or on a dedicated cluster or on the GRID completely transparent to the user

J. Moscicki (CERN)
www.cern.ch/diane

Traceback from a run on **CrossGrid** testbed



Resource broker running in Portugal

Current #Grid setup (computing elements):
5000 events, 2 workers, 10 tasks (500 events each)

matchmaking CrossGrid computing elements

- aocegrid.uab.es:2119/jobmanager-pbs-workq
- bee001.ific.uv.es:2119/jobmanager-pbs-qgrid
- cgnode00.di.uoa.gr:2119/jobmanager-pbs-workq
- cms.fuw.edu.pl:2119/jobmanager-pbs-workq
- grid01.physics.auth.gr:2119/jobmanager-pbs-workq
- xg001.inp.demokritos.gr:2119/jobmanager-pbs-workq
- xgrid.icm.edu.pl:2119/jobmanager-pbs-workq
- zeus24.cyf-kr.edu.pl:2119/jobmanager-pbs-infinite
- zeus24.cyf-kr.edu.pl:2119/jobmanager-pbs-long
- zeus24.cyf-kr.edu.pl:2119/jobmanager-pbs-medium
- zeus24.cyf-kr.edu.pl:2119/jobmanager-pbs-short
- ce01.lip.pt:2119/jobmanager-pbs-qgrid

Spain

Greece

Poland

Portugal

Conclusion

- Geant4 offers the capability to model accurately human anatomies, beam lines, radioactive sources, phantoms, detectors
- Geant4 offers alternative and complementary models both in e.m. and hadronic physics for photons, e-, e+, p, n, alpha, heavy ions
- Geant4 is used as MC Toolkit in a wide set of Medical Physics applications both in radiotherapy and diagnostic