Distributed Processing, Monte Carlo and CT interface for Medical Treatment Plans

http://www.ge.infn.it/geant4/talks

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ICATPP Conference
Como, 6-10 October 2003

Including contributions from:

S. Agostinelli, S. Garelli (\textit{IST Genova})
L. Archambault, L. Beaulieu, J.-F. Carrier, V.-H. Tremblay (\textit{Univ. Laval})
M.C. Lopes, L. Peralta, P. Rodrigues, A. Trindade (\textit{LIP Lisbon})
G. Ghiso (\textit{S. Paolo Hospital, Savona})

Maria Grazia Pia, \textit{INFN Genova}
The goal of radiotherapy

Delivering the required therapeutic dose to the tumor area with high precision, while preserving the surrounding healthy tissue.

Accuracy dosimetry is at the basis of radiotherapy treatment planning.

Dosimetry system

- Calculate the dose released to the patient by the radiotherapy system
- Precision
- Accurate model of the real configuration (from CT)
- Speed adequate for clinical use
- User-friendly interface for hospital usage

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The reality

- Treatment planning is performed by means of commercial software
- The software calculates the dose distribution delivered to the patient in a given source configuration

Open issues

Precision
- Commercial systems are based on approximated analytical methods, because of *speed constraints*
- Approximation in geometry modeling
- Approximation in material modeling

Cost
- Each treatment planning software is specific to one technique and one type of source
- Treatment planning software is expensive

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Commercial factors

- Commercial treatment planning systems are governed by commercial rules *(as any other commercial product...)*
  - i.e., they are produced and marketed by a company only if the investment for development is profitable

- No commercial treatment planning systems are available for non-conventional radiotherapy techniques
  - *such as hadrontherapy*
  - or for niche applications
    - *such as superficial brachytherapy*

Treatment planning systems for hadrontherapy are quite primitive
*not commercially convenient so far*
Monte Carlo methods in radiotherapy

Monte Carlo methods have been explored for years as a tool for precise dosimetry, in alternative to analytical methods

de facto,

Monte Carlo simulation is not used in clinical practice

(only side studies)

- The limiting factor is the speed
- Other limitations:
  - reliable?
  - for “software specialists only”, not user-friendly for general practice
  - requires ad hoc modeling
The challenge
Develop a precise general purpose dosimetric system with the capability of realistic geometry and material modeling and interface to CT images with a user-friendly interface at low cost performing at adequate speed for clinical usage.
A real life case

A dosimetric system for brachytherapy

(but all the developments and applications presented in this talk are general)
The prototype

Activity initiated at IST Genova, Natl. Inst. for Cancer Research (F. Foppiano et al.)
  - hosted at San Martino Hospital in Genova (the largest hospital in Europe)

Collaboration with San Paolo Hospital, Savona (G. Ghiso et al.)
  - a small hospital in a small town

Major work by **Susanna Guatelli** (Univ. and INFN Genova)


Brachytherapy is a medical therapy used for cancer treatment.

Radioactive sources are used to deposit therapeutic doses near tumors, while preserving surrounding healthy tissues.

**Techniques:**
- endocavitary
  - lung, vagina, uterus
- interstitial
  - prostate
- superficial
  - skin

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Commercial software for brachytherapy

Various commercial software products for treatment planning
  – *eg. Variseed V 7, Plato BPS, Prowes*

No commercial software available for superficial brachytherapy with Leipzig applicators

<table>
<thead>
<tr>
<th>Precision</th>
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<tbody>
<tr>
<td>Based on approximated analytical methods, because of <em>speed constraints</em></td>
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<tr>
<td>Approximation in source anisotropy</td>
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<td>Uniform material: water</td>
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<table>
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<th>Cost</th>
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<td>Each software is specific to one technique and one type of source</td>
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<td>Treatment planning software is expensive (~ hundreds K $/euro)</td>
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An open-source dosimetry application

- OO Design
- Geometry Modeling & CT interface
- Dosimetric analysis
- User Interface
- Distributed processing
- Outlook
The project is characterized by a **rigorous software process**

The process follows an **iterative and incremental model**

Process based on the Unified Process, especially tailored to the specific context of the project

RUP used as a practical guidance to the process
Requirements

**Calculation of 3-D dose distribution in tissue**
**Determination of isodose curves**

**Precision**
- Based on Monte Carlo methods
- Accurate description of physics interactions
- Experimental validation of physics involved

**Accurate model of the real experimental set-up**
- Realistic description of geometry and tissue
- Possibility to interface to CT images

**Easy configuration for hospital usage**
- Simple user interface + Graphic visualisation
- Elaboration of dose distributions and isodoses

**Speed**
- Parallelisation
- Access to distributed computing resources

**Other requirements**
- Transparent
- Open to extension and new functionality
- Publicly accessible

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Precision

Based on Monte Carlo methods

**Geant 4**

Accurate description of physics interactions

Extension of electromagnetic interactions down to low energies (< 1 keV)

Experimental validation of physics involved

Microscopic validation of the physics models

Comparison with experimental data specific to the brachytherapeutic practice

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The foundation

What characterizes Geant4

The fundamental concepts, upon which all the rest is built
“It was noted that experiments have requirements for independent, alternative physics models. In Geant4 these models, differently from the concept of packages, allow the user to understand how the results are produced, and hence improve the physics validation. Geant4 is developed with a modular architecture and is the ideal framework where existing components are integrated and new models continue to be developed.”
Software Engineering plays a fundamental role in Geant4

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

Quality Assurance
- de jure and de facto

Use of Standards
The functionality

What Geant4 can do
Geant 4

- Run, Event and Track management
- PDG-compliant Particle management
- Geometry and Materials
- Tracking
- Detector response
- User Interface
- Visualisation
- Persistency
- Physics Processes

- Code and documentation publicly distributed from web
- 1st production release: end 1998
  - 2 new releases/year since then
- Developed and maintained by an international collaboration of physicists and computer scientists

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Geometry
Detailed detector description and efficient navigation

Multiple representations
- CSG (Constructed Solid Geometries)
  - simple solids
- BREPS (Boundary REPresented Solids)
  - volumes defined by boundary surfaces
  - polyhedra, cylinders, cones, toroids etc.
- Boolean solids
  - union, subtraction…

Same abstract interface

CAD exchange: ISO STEP interface

Fields: variable non-uniformity and differentiability

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Physics processes

**Transparency**
- Tracking independent from physics
- Final state independent from cross sections
- Use of public evaluated databases

**Object Oriented technology**
- implement or modify any physics process without changing other parts of the software
- open to extension and evolution

**Electromagnetic and Hadronic Physics**
- Complementary/alternative physics models

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Electromagnetic Physics

- electrons and positrons
- $\gamma$, X-ray and optical photons
- muons
- charged hadrons
- ions

- **High energy extensions**
  - needed for LHC experiments, cosmic ray experiments…

- **Low energy extensions**
  - fundamental for space and medical applications, dark matter
  and $\nu$ experiments, antimatter spectroscopy etc.

- **Alternative models for the same process**

Hadronic physics

- **Data-driven, Parameterised and Theoretical models**
  - the most complete hadronic simulation kit on the market
  - alternative and complementary models

- **Cross section data sets:** transparent and interchangeable

- **Final state calculation:** models by particle, energy, material

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Interface to external tools

Through abstract interfaces

- no dependence
- minimize coupling of components

Similar approach

Visualisation
- (G)UI
- Persistency
- Analysis

The user is free to choose the concrete system he/she prefers for each component

AIDA (analysis)
- Anaphe
- JAS
- Open Scientist

UI

Visualisation drivers
- command-line
- X11/Motif
- GAG
- MOMO
- OPACS…

OpenGL
- OpenInventor
- X11
- Postscript
- DAWN
- OPACS
- HepRep
- VRML…
Monte Carlo methods in radiotherapy

Studies of Geant4 and commercial treatment planning systems
Central-axis depth dose curve for a 10x10 cm² field size, compared with experimental data (ionisation chamber).

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

M.C. Lopes¹, L. Peralta², P. Rodrigues², A. Trindade²

¹ IPOFG-CROC Coimbra Oncological Regional Center
² LIP - Lisbon
Comparison with commercial treatment planning systems

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

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

CT images used to define the geometry:
a thorax slice from a Rando anthropomorphic phantom

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Central-Axis depth dose

\[
\chi^2 / \text{ndf (GEANT 4)} = 0.52 \\
\chi^2 / \text{ndf (TMS)} = 0.81 \\
\chi^2 / \text{ndf (PLATO)} = 6.71
\]

Profile curves at 9.8 cm depth

PLATO overestimates the dose at ~ 5% level
An off-axis depth dose taken at one of the slices near the isocenter

PLATO fails on the air cavities and bone structures and cannot predict accurately the dose to tissue that is surrounded by air

Deviations are up to 25-30%

In some tumour sites (ex: larynx T2/T3-stage) a 5% underdosage will decrease local tumour control probability from ~75% to ~50%
Physics

Physics models in Geant4 relevant to medical applications
A set of processes extending the coverage of electromagnetic interactions in Geant4 down to “low” energy
- 250 eV \textit{(in principle even below this limit)} for electrons and photons
- down to approximately the ionisation potential of the interacting material for hadrons and ions

Processes based on detailed models
- shell structure of the atom
- precise angular distributions

Specialised models depending on particle type
- data-driven models based on the Livermore Libraries for $e^-$ and photons
- analytical models for $e^+$, $e^-$ and photons (reengineering of Penelope into Geant4)
- parameterised models for hadrons and ions (Ziegler 1977/1985/2000, ICRU49)
- original model for negative hadrons
Hadron and ion models based on Ziegler and ICRU data and parameterisations

Barkas effect (charge dependence) models for negative hadrons

Based on Penelope analytical models

Based on EPDL97, EEDL and EADL evaluated data libraries

Based on Geant4, EGS4, ITS to 1 keV

Geant3 to 10 keV

e, γ down to 250 eV

Fluorescence

Auger effect

Fe lines

GaAs lines

Atomic relaxation

shell effects

protons

antiprotons
Validation

**Microscopic validation:**
verification of Geant4 physics

**Dosimetric validation:**
in the experimental context
Microscopic validation

Stopping power

NIST
Geant4-LowE
Geant4-Standard

many more validation results available!

Photon attenuation coefficient

\[ \chi^2_{N-L} = 13.1 - \nu = 20 - p = 0.87 \]

\[ \chi^2_{N-S} = 23.2 - \nu = 15 - p = 0.08 \]

1 MeV e- ionisation losses in Tantalum

Geant4 4.1 p02
- step limit 1 mkm stan
- step limit 1 mkm lowe
- step limit 1 mm
points - Sandia data
cuts - 1 mkm

ions

proton straggling

e-, Sandia database
Dosimetric validation

Comparison to manufacturer data, protocol data, original experimental data

F. Foppiano et al., IST Genova

Ir-192

Distance along Z (mm)

G. Ghiso, S. Guatelli S. Paolo Hospital Savona

experimental measurements
General purpose system

For any brachytherapy technique

Object Oriented technology
Software system designed in terms of Abstract Interfaces

For any source type

Abstract Factory design pattern
Source spectrum and geometry transparently interchangeable
Flexibility of modeling

Configuration of
- any brachytherapy technique
- any source type

through an Abstract Factory
to define geometry, primary spectrum

CT DICOM interface
- through Geant4 parameterised volumes
  parameterisation function: material

Abstract Factory

Phantom
- various materials
  water, soft tissue, bone, muscle etc.

General purpose software system for brachytherapy

No commercial general software exists!

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Realistic model of the experimental set-up

Radioactive source

Spectrum (\(^{192}\)Ir, \(^{125}\)I)
Geometry

Patient

Phantom with realistic material model
Possibility to interface the system to CT images
Modeling the 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

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Effects of source anisotropy

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

Rely on simulation for better accuracy than conventional treatment planning software

Transverse axis of the source
Comparison with experimental data
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Longitudinal axis of the source
Difficult to make direct measurements
Modeling the patient

Modeling a phantom

of any material
(water, tissue, bone, muscle etc.)
thanks to the flexibility of Geant4 *materials* package

Modeling geometry and materials from CT data

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Computerized Tomography allows to reproduce the real 3D geometry of the patient.

DICOM is the universal standard for sharing resources between heterogeneous and multi-vendor equipment.

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Developed by L. Archambault, L. Beaulieu, V.-H. Tremblay
(Univ. Laval and l'Hôtel-Dieu, Québec)

Donated to Geant4 for the common profit of the scientific community
- under the condition that further improvements and developments are made publicly available to the community

Released with Geant4 5.2, June 2003 in an extended example
- with some software improvement by S. Guatelli and M.G. Pia

First implementation, further improvements foreseen

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From DICOM image to Geant4 geometry

- Reading image information
- Transformation of pixel data into densities
- Association of densities to a list of corresponding materials
- Defining the voxels
  - Geant4 parameterised volumes
  - parameterisation function: material

reverse engineering by S. Guatelli

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User-friendly interface to facilitate the usage in hospitals

- Dosimetric analysis
- Graphic visualisation of dose distributions
- Elaboration of isodose curves
- Web interface
- Application configuration
- Job submission
Simulation of energy deposit through Geant4 Low Energy Electromagnetic package to obtain accurate dose distribution

Production threshold: 100 µm

2-D histogram with energy deposit in the plane containing the source

Analysis of the energy deposit in the phantom resulting from the simulation

Dose distribution

Isodose curves

AIDA + Anaphe for analysis

Python for interactivity

may be any other AIDA-compliant analysis system

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Bebig Isoseed I-125 source

Dosimetry
Interstitial brachytherapy

Isodose curves

0.16 mGy = 100%

y = 0 mm

y = 2 mm

y = 5 mm

y = 1 cm
**Dosimetry**
Endocavitary brachytherapy

MicroSelectron-HDR source

**Dosimetry**
Superficial brachytherapy

Leipzig applicator

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**Application configuration**

2. Running the simulation

*In order to run your simulation*: fix the simulation parameters, the number of events of the run.

Then press **BeamOn**.

The result of the simulation is the dose distribution in the plane containing the source.

2.1 Choose the simulation parameters

2.2.1 Choose the radioactive source

Available radioactive sources: I-125, Ir-192, Leipzig

I-125

2.2.2 Choose the phantom absorber material

Available materials: water, soft tissue, air

Water

2.2.3 Choose the number of gamma delivered by the source

2.2.4 Press **beamOn** to run the simulation

** beamOn**

2.2.5 Back again to the simulation default parameters if you like!

**Reset**

**Fully configurable from the web**

Run modes:
- demo
- parallel on a cluster *(under test)*
- on the GRID *(under development)*
Speed adequate for clinic use

Parallelisation

Transparent configuration in sequential or parallel mode

Access to distributed computing resources

Transparent access to the GRID through an intermediate software layer
Monte Carlo simulation is not practically conceivable for clinical application, even if more precise.
Access to distributed computing

Previous studies for parallelisation of a Geant4 based medical application
- speed OK
- but expensive hardware investment + maintenance

Alternative strategy

Parallelisation

Access to the GRID
DIANE Distributed ANalysis Environment

Hide complex details of underlying technology

Prototype for an intermediate layer between applications and the GRID

Application components
- Geant4
- LCG
- Anaphe
- AIDA

GRID low-level modules
- security
- load balancing
- env. repl.
- configuration

Parallel cluster processing
- make fine tuning and customisation easy
- transparently using GRID technology
- application independent

Developed by J. Moscicki, CERN
http://cern.ch/DIANE

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DIANE architecture

Master-Worker model
Parallel execution of independent tasks
Very typical in many scientific applications
Usually applied in local clusters

R&D in progress for Large Scale Master-Worker Computing

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The application developer is shielded from the complexity of underlying technology via DIANE.

- Not affecting the original code of application
  - standalone and distributed case is the **same code**

- Good separation of the subsystems
  - the application does not need to know that it runs in distributed environment
  - the distributed framework (DIANE) does not need to care about what actions an application performs internally
Parallel mode: local cluster

DIANE R&D Project
http://cern.ch/DIANE

User

Master

Worker

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preliminary: further optimisation in progress

Performance: parallel mode

Endocavitary brachytherapy
1M events
4 minutes 34”

Superficial brachytherapy
1M events
4 minutes 25”

Interstitial brachytherapy
5M events
4 minutes 36”

on up to 50 workers, LSF at CERN, PIII machine, 500-1000 MHz

Performance adequate for clinical application, but…

it is not realistic to expect any hospital to own and maintain a PC farm

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Parallel mode: distributed resources

Distributed Geant 4 Simulation:
DIANE framework and generic GRID middleware
Wave of interest in grid technology as a basis for “revolution” in e-Science and e-Commerce

Ian Foster and Carl Kesselman's book:

"A computational Grid is a hardware and software infrastructure that provides dependable, consistent, pervasive and inexpensive access to high-end computational capabilities"

An infrastructure and standard interfaces capable of providing transparent access to geographically distributed computing power and storage space in a uniform way

Many GRID R&D projects, many related to HEP

US projects

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European projects
Running on the GRID

Via DIANE

Same application code as running on a sequential machine or on a dedicated cluster
- completely transparent to the user

A hospital is not required to own and maintain extensive computing resources to exploit the scientific advantages of Monte Carlo simulation for radiotherapy

Any hospital
- even small ones, or in less wealthy countries, that cannot afford expensive commercial software systems -
  may have access to advanced software technologies and tools for radiotherapy
Current #Grid setup (computing elements):
5000 events, 2 workers, 10 tasks (500 events each)

- 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

matchmaking CrossGrid computing elements

Traceback from a run on CrossGrid testbed

Resource broker running in Portugal
Other requirements

- Transparency
  - Design and code publicly distributed
  - Physics and models exposed through OO design

- Openness to extension and new functionality
  - OO technology: plug-ins for other techniques
    - Treatment head
    - Beam line for hadrontherapy
    - ...

- Publicly accessible
  - Application code released with Geant4
  - Based on open source code (Geant4, AIDA etc.)
Medical physics does not only require fast simulation and fancy analysis…

Advanced **functionality**
in geometry, physics, visualisation etc.

**Specific facilities**
controlled by a friendly UI

**Extensibility**
to accommodate new user requirements

**Transparency**
of physics

**User support**
from experts

What in HEP software is relevant to the bio-medical community?

**Adoption of standards**
wherever available

**Quality Assurance**
based on sound software engineering

**Independent validation**
by a large user community worldwide

**Use of evaluated data libraries**

**A rigorous software process**

**Transparency of physics**

Adoption of **standards** wherever available

User support from experts

Specific facilities controlled by a friendly UI

Advanced **functionality**
in geometry, physics, visualisation etc.
Configuration of

- any brachytherapy technique
- any source type

System extensible to any source configuration without changing the existing code

General dosimetry system for radiotherapy

- extensible to other techniques
- plug-ins for external beams
  (factories for beam, geometry, physics...)

Plug-ins in progress

- treatment head
- hadrontherapy
- ...

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Conclusions
Summary

- A precise dosimetric system, based on Geant4
  - Accurate physics, geometry and material modeling, CT interface
- Full dosimetric analysis
  - AIDA + Anaphe
- Simple interface
  - Configuration from WWW
- Fast performance
  - Parallel processing
- Access to distributed computing resources
  - GRID

The dream of medical physics for the past 40 years...

Beware: R&D prototype!
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”

Maria Grazia Pia, INFN Genova
Thanks!

Geant4 has fostered a collaborative aggregation of contributions from many groups all over the world

- G. Cosmo *(CERN, Geant4)*
- L. Moneta, I. Papadopoulos, A. Pfeiffer, M. Sang *(Anaphe, CERN)*
- J. Knobloch *(CERN/IT)*
- S. Agostinelli, S. Garelli *(IST Genova)*
- G. Ghiso, R. Martinelli *(S. Paolo Hospital, Savona)*
- S. Chauvie *(INFN Torino and IRCC)*
- G.A.P. Cirrone, G. Cuttone *(INFN LNS, CATANA project)*
- M.C. Lopes, L. Peralta, P. Rodrigues, A. Trindade *(LIP Lisbon)*
- L. Archambault, J.F. Carrier, L. Beaulieu, V.H. Tremblay *(Univ. Laval)*

*the authors*

- F. Foppiano *(IST)* – medical physicist
- S. Guatelli *(Univ. and INFN Genova)* – student
- J. Moscicki *(CERN)* – computer scientist
- M.G. Pia *(INFN Genova)* – particle physicist

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