GEANT4

Introduzione alla fisica di Geant4

Maria Grazia Pia

INFN, Sezione di Genova

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- ✓ Overview
- ✓ Fundamental concepts in Geant4 physics
- ✓ Electromagnetic physics
- ✓ Hadronic physics
- ✓ Fast simulation
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Physics

From LCB minutes:

"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."

Keywords

"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."*

- Ample variety of independent, alternative physics models available in Geant4
- No more black boxes of packages (as it used to be in Geant3)
- The users are directly exposed to the physics they use in their simulation
- This approach is fundamental for the validation of the experiments' physics results

Main features of Geant4 physics design

- **Abstract interface to physics processes**
  - Tracking is independent from processes
  - Distinction between processes and models
  - Often multiple models for the same process
- **Data encapsulation and polymorfism**
  - Transparent access to cross-sections, from files, interpolation from tables, analytical formulae etc.
  - Distinction between the calculation of cross sections and their use
  - Calculation of the final state independent from tracking
- **Uniform treatment of electromagnetic and hadronic physics**
- **Open system**
  - users can easily **create** and **use** their <u>own models</u>

Data libraries

- Systematic collection and evaluation of experimental data from many sources worldwide
- ***Databases***
  - ENDF/B, JENDL, FENDL, CENDL, ENSDF,JEF, BROND, EFF, MENDL, IRDF, SAID, EPDL, EEDL, EADL, SANDIA, ICRU etc.
- ***Collaborating distribution centres***
  - NEA, LLNL, BNL, KEK, IAEA, IHEP, TRIUMF, FNAL, Helsinki, Durham, Japan etc.
- *The use of evaluated data is important for the **validation** of physics results of the experiments*

Electromagnetic physics

- Comparable to Geant3 and EGS already in the α-release (1997)
- <u>Substantial extensions provided in the production releases</u>

- Models for μ **up to PeV**
- e, γ down to **250 eV**
  - (EGS, ITS etc. to 1 KeV, Geant3 to 10 KeV))
- Low energy extensions for **hadrons** and **ions**
  - Ziegler and ICRU models, corrections for chemical formulae, Barkas effect for charge dependence etc.
- **Multiple alternatives** for various processes

Electromagnetic processes

- ✓ Multiple scattering
- ✓ Energy loss
- ✓ Bremsstrahlung
- ✓ Ionisation
- ✓ Annihilation
- ✓ Photoelectric effect
- ✓ Compton scattering
- ✓ Pair production
- ✓ Auger (in progress)

- ✓ Syncrotron radiation
- ✓ Transition radiation
- ✓ Cherenkov
- ✓ Rayleigh effect
- ✓ Rifraction
- ✓ Reflection
- ✓ Absorption
- ✓ Scintillation
- ✓ Fluorescence

…*many with alternative models*

Hadronic physics

- **Completely different approach w.r.t. the past**
  - transparent
  - native, no longer interface to external packages
  - clear separation between data and their use in algorithms
- **Cross section data sets**
  - transparent and interchangeable
- **Final state calculation**
  - models by particle, energy, material...

Completeness of G4 hadronic physics

❇ Ample variety of models

- the **most complete** hadronic simulation kit on the market
- **all** the existing approaches to hadronic physics are present in Geant4
- **alternative** and **complementary** models
- it is possible to **mix-and-match,** with fine granularity
- data-driven, parameterised and theoretical models

⇨ *Consequences for the users*

- *no more confined to the black box of a package*
- *the user **has control on the physics** used in the simulation, which contributes to the **validation** of physics results*

Hadronic physics
Parameterised and data-driven models

- Models based on experimental data
- Some models derived originally from GHEISHA
  - *but* have been completely **reengineered** into OO design
  - *and* exploit **new refined physics parameterisations**

- ***New parameterisations***
  - pp, elastic differential cross section
  - nN, total cross section
  - pN, total cross section
  - np, elastic differential cross section
  - πN, total cross section
  - πN, coherent elastic scattering

New parameterised models

- *Other models are completely new, such as*
  - **stopping particles** (π^-, K^-)
  - **neutron transport**
  - **isotope production**
- <u>**All**</u> databases existing worldwide used in neutron transport
  - Brond, CENDL, EFF, ENDFB, JEF, JENDL, MENDL...

Hadronic physics -Theoretical models

- ***They fall into different parts***
  - the ***evaporation phase***
  - the low energy range, O(100 MeV), ***pre-equilibrium***
  - the intermediate energy range, O(100 MeV) to O(5 GeV), ***intra-nuclear transport***
  - the high energy range, ***hadronic generator*** régime
- Geant4 provides complementary models to cover all the various parts
- Geant4 provides alternative models within the same part
- All this is made possible by the powerful Object Oriented design of Geant4 hadronic physics
- Easy evolution: new models can be easily added, existing models can be extended

Theoretical hadronic models

- ***Ample variety of models***
- Two String Models (Diffractive, Dual-Parton)
  - possibility to interface to Pythia7 for hard scattering
- Traditional Cascade (HETC), Kinetic Model, QMD
  - some are still in progress
- Precompound Model
- Evaporation, Fission, Fermi break-up, Multifragmentation, Photon Evaporation
- Lepton-hadron interactions
  - μ–nucleus interactions, photo-fission, γ-meson conversion

...and more: several areas under active development

Fast simulation - Overview

- Geant4 allows to perform **full simulation** and **fast simulation <u>in the same environment</u>**

- Geant4 ***parameterisation*** produces a direct detector response, from the knowledge of particle and volume properties
  - *hits, digis, reconstructed-like objects (tracks, clusters etc.)*

Fast simulation: what it can do

Geant4 Fast Simulation provides a great flexibility

- *Activate fast /full simulation* ***by detector***
- example: full simulation for inner detectors, fast simulation per calorimeters
- *Activate fast /full simulation* ***by geometry region***
- example: fast simulation in central areas and full simulation near cracks
- *Activate fast /full simulation* ***by particle type***
- example: in electromagnetic calorimeter e/γ parameterisation and full simulation of hadrons
- ***Parallel geometries*** *in fast/full simulation*
- example: inner and outer tracking detectors distinct in full simulation, but handled together in fast simulation

Practical details about Geant4 physics

- The following transparencies are courtesy of
  Makoto Asai, Hiroshima Institute of Technology
  (coordinator of Geant4 Event, Run, Hits&Digi categories and of Geant4 Examples)

  Have a look at Makoto's excellent **Geant4 introductory course** at
  http://arkhp2.cc.it-hiroshima.ac.jp/~asai/LecNotes/Geant4Intro/index.html

  accompanied by his introductory C++/OOP notes at
  http://arkhp2.cc.it-hiroshima.ac.jp/~asai/LecNotes/oop_lecture/

Basic concepts

- Physics processes describe how particles interact with material or volume itself.
- There are 7 major process categories
  - Electromagnetic
  - Hadronic
  - Photolepton_hadron
  - Decay
  - Optical
  - Transportation
  - Parameterization

Basic concepts 2

- In Geant4 two kinds of member functions of processes play an important role in tracking.
  - GetPhysicalInteractionLength (identified as GPIL)
    - GPIL method gives the step length from the current space-time position to the next space-time point where the DoIt method should be invoked.
  - DoIt
    - The DoIt method describes what happens in the interaction.
    - It provides change of energy and momentum direction, change of position, and secondary tracks by using G4VParticleChange.

Basic concepts 3

- There are three kinds of DoIt methods, together with three GPIL methods corresponding to each DoIt.
  - AtRestDoIt
    - rest process (e.g. absorption at rest)
  - AlongStepDoIt
    - continuous process (e.g. ionization loss)
  - PostStepDoIt
    - discrete process (e.g. decay)

Basic concepts 4

- AtRestDoIt is selectively applied to a step
- All AlongStepDoIt are accumulatively applied to a step
- PostStepDoIt is selectively applied to a step
- Each process can have one or more DoIt methods, corresponding to its nature
  - Eg. multiple scattering process
    - "Continuous-Discrete" process which has AlongStepDoIt and PostStepDoIt

Electromagnetic processes 1

- Examples of Photon processes
  - Compton scattering, Pair production, Photoelectric effect
- Examples of Electron/positron processes
  - Bremsstrahlung, Ionisation and delta ray production, Positron annihilation, Synchrotron radiation
  - Energy loss process is the one which handles the continuous energy loss of the particles; this continuous energy loss comes from the ionisation and Bremsstrahlung processes

Electromagnetic processes 2

- Hadron (e.m.) processes
  - Ionisation, Energy loss
- muon processes
  - Bremsstrahlung, Ionisation and delta ray/knock on electron production, Direct pair production, Energy loss process
- X-ray production processes
  - Cherenkov process, Transition radiation

Multiple scattering

- The class name "G4MultipleScattering" is a general process in the sense that the same process/class is used to simulate the multiple scattering of all the charged particles (i.e. it is used for e+/e-,muons/charged hadrons) .
- The multiple scattering process in Geant4 gives not only randomization of momentum direction but also randomized path and displacement of a track.
- Step length, time of flight, and energy loss along the step are affected by multiple scattering.

Hadronic processes 1

- Each hadronic process object (derived from G4HadronicProcess) may have one or more cross section data sets associated with it.
- The term “data set” is meant in a broad sense to be an object that encapsulates methods and data for calculating total cross sections for a given process.
- The methods and data may take many forms, from a simple equation using a few hard-wired numbers to a sophisticated parameterization using large data tables.

Hadronic processes 2

- At Rest processes
  - pion absorption
  - kaon absorption
  - neutron capture
  - antiproton annihilation
  - antineutron annihilation
  - mu- capture
- At Rest processes may generate secondaries after some time interval. This is one of the new features which GEANT3 couldn’t do.

Decay

- A G4DecayTable object is associated to each G4ParticleDefinition.
- Use SetPDGStable(G4bool) method of G4ParticleDefinition to make a particle stable regardless of its lifetime.
- G4DynamicParticle can have a decay channel. If it has, it exactly decays through this channel without randomizing by the decay ratio.

Optical processes 1

- Geant4 has a particle named as “Optical Photon”, which is distinguished from gamma. It interacts by optical processes.
- Optical photons are generated if one or more following processes are activated:
  - Cerenkov radiation
  - Transition radiation
  - Scintilation

Optical processes2

- Optical processes
  - Absorption
  - Rayleigh scattering
  - Boundary Processes (reflection, refraction)
- Optical properties, e.g. dielectric coefficient, surface smoothness, can be set to a G4LogicalVolume.

Shower parameterization

- Geant4 has a built-in shower parameterization scheme. The user's concrete parameterization should be assigned to a logical volume, which is then called as an "envelope".
  - Regardless of the existence of granular daughter geometry, a particle comes into the envelop is fully treated by the parameterization. The user still have a dynamic choice to take his parameterization or to follow the ordinary tracking.
  - The parameterization can directly contact to a sensitive detector associating to the volume to produce more than one distributed hits.

Event biasing

- Geant4 has an event biasing option for the transportation of slow neutrons.
  - The formulae are derived from MARS95.
  - Producing small number of secondaries which are artificially recognized as huge number of particles by their statistical weights.

Thanks!

Thanks to

<u>Makoto Asai</u>

for letting us use his lecture notes!

To learn more about Geant4 physics

General references

- *About the physics content:*

  Geant4 Physics Reference Manual

  http://wwwinfo.cern.ch/asd/geant4/G4UsersDocuments/UsersGuides/PhysicsReferenceManual/html/PhysicsReferenceManual.html

- *About how to use Geant4 physics in an application:*

  Geant4 User's Guide: For Application Developers

  http://wwwinfo.cern.ch/asd/geant4/G4UsersDocuments/UsersGuides/PhysicsReferenceManual/html/PhysicsReferenceManual.html

- *About the OO design of Geant4 physics:*

  Geant4 User's Guide: For Toolkit Developers

  http://wwwinfo.cern.ch/asd/geant4/G4UsersDocuments/UsersGuides/ForToolkitDeveloper/html/index.html

To learn more about Geant4 physics

<u>Specific references</u>

- Many papers available from
  http://wwwinfo.cern.ch/asd/geant4/reports/reports.html
  - various papers on electromagnetic and hadronic physics models
  - a comprehensive and detailed report on Geant4 theoretical hadronic models
  - a collection of results from comparisons of Geant4 physics models and data
  - and much more...
- An excellent source of documentation on Geant4 electromagnetic physics is
  http://wwwinfo.cern.ch/asd/geant4/reports/gallery/electromagnetic/

Stato di Geant4

- **Primo release di produzione Geant4 0.0**
  - dicembre 1998
- **Secondo release di produzione Geant4 0.1**
  - luglio 1999
  - transizione a STL
  - estensione della fisica elettromagnetica a 250 eV per elettroni e fotoni
  - raffinamento del modello dell'evaporazione di fotoni
- **Terzo release di produzione Geant4 1.0**
  - 7 dicembre 1999
  - contiene molti nuovi sviluppi di fisica adronica ed elettromagnetica

User support

What do do if

- you need **consultancy** about Geant4 physics (or Geant4 in general)?
- you find a **bug** in Geant4 physics (or Geant4 in general)?

- To do first:
  - read the existing Geant4 User Documentation carefully

    in most cases the answer to your problems is there!
  - consult the Italian User Support web page

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

Supporto Utenti
Notifica e correzione di bachi

- **Procedura automatica di notifica dei bachi**
- **Web form**
- Notifica del ricevimento del 'bug report' entro **24 ore** lavorative
  Assegnazione automatica ad esperto
- Traccia dello stato del baco disponibile su web
  - assegnato, aperto, risolto etc.
- *Esperienza non infrequente: errori segnalati come deficienze del codice Geant4 sono risultati essere deficienze del codice di esperimento*
- ***Nota:*** *<u>i bachi notificati sono corretti, i bachi non notificati non possono essere corretti</u>*

User support with human interface

- It covers:
  - *the help and analysis of code-related problems*
  - *the consultancy*
  - *the requests for enhancement or new developments*
  - *the investigation of anomalous results*
- It is available through the **Geant4 Technical Board Representatives**
- Italian Technical Board Representative:

  Maria Grazia Pia, INFN Genova, pia@ge.infn.it

Supporto Utenti

Esempio di richiesta di estensioni di Geant4 (INFN)

- **Nuovi requirements fondamentali per vari esperimenti INFN** (non compresi nell'URD di RD44)
  - estensioni di fisica elettromagnetica a basse energie per adroni e ioni
- Espressione delle esigenze alla Rappresentante TSB: giugno 1999
- **URD** (secondo lo standard PSS05): 30 giugno 1999
  - http://www.infn.it/geant4/support/URDLowE.html
- Discussione e approvazione dell'URD: 7 luglio 1999
  - Modifica delle priorità di Geant4
  - Allocazione di risorse (ESA, CMS, Common...)
- **Modello per adroni disponibile in CVS repository:** 31 luglio 1999
- **Modello per ioni disponibile in CVS repository:** 18 settembre 1999
- **Pubblicati** in INFN/AE-99/20, INFN/AE-99/21
- *Utenti (Torino): confronto con dati sperimentali e validazione fisica*

Supporto Utenti

Esempio di supporto a ‘novice’ (INFN)

- ***Laureanda senza nessun supporto locale di esperienza di Geant4***
- ***Nessuna conoscenza preliminare di C++***
- Ha chiesto User Support alla sua *Rappresentante TSB* (settembre 1999)
- Consulenza per Software Management **(CERN)**
- Consulenza per Examples **(Atlas-Giappone)**
- Consulenza per Event Generator **(KEK)**
- Consulenza per Geometria **(CERN)**
- Consulenza per Fisica Elettromagnetica standard **(IN2P3, CMS)**
- Consulenza per Fisica Elettromagnetica Low Energy **(INFN, ESA, Common)**
- *Rappresentante TSB* ha reso disponibile codice non ancora in release pubblico
- Risultato: laurea il 21/10/1999 con tesi interamente basata su Geant4
  - geometria, risposta di rivelatore, fisica, confronto fra simulazione e dati sperimentali

Fattori di rischio per Geant4

- Performance e adeguatezza di C++ e tecnologie OO per la simulazione furono considerate fattore di rischio all’inizio del progetto
  - dimostrazione che le riserve non erano fondate
- **Maturità della comunità HEP?**
  - ad apprezzare la necessità di un nuovo ambiente di simulazione, caratterizzato dalla trasparenza della fisica
  - a muoversi ad un ambiente di sviluppo di simulazione basato sul software engineering
  - ad investire nell’apprendimento e padronanza di nuove tecnologie
- *(LCB-97-4)*

Chi usa Geant4?

- I seguenti sono alcuni esempi di uso attivo di Geant4
- La lista non è esaustiva!

Grossi esperimenti HEP

- **CMS**
  - prototipo funzionale Dicembre 1999
  - geometria con Geant4 in fase avanzata
  - simulazione di test beam con Geant4
  - confronti con dati sperimentali
  - ha deciso di rifare tutti gli studi di radiation background con Geant4
- **LHCB**
  - ha deciso di basarsi su Geant4
  - in fase iniziale di sviluppo
- **ALICE, ATLAS**
  - in fase meno avanzata di CMS
- **BaBar**
  - fast simulation completamente con Geant4 in produzione da febbraio 1999
  - full simulation basata su Geant4 in corso di sviluppo
- **FNAL, CLEO etc...**
  - contatti in corso

Esperimenti con neutrini, cosmici, astrofisica, etc.

- **Borexino**
  - simulazione con Geant4 in fase avanzata
- **Basse attività al Gran Sasso**
  - simulazione basata su Geant4 in corso di sviluppo
- **LUNA**
  - in fase iniziale
- **Antares**
  - richiede modelli per interazioni elettromagnetiche ad altissime energie
  - in fase iniziale
- **Boulby Mine Dark Matter**
  - risultati controversi non interpretabili con le simulazioni attuali
  - in fase iniziale
- **Auger**
  - inizio di attività con Geant4 previsto prossimamente
- **X-ray analysis (PIXE)**
  - in fase iniziale
- **ATHENA**
  - ha richiesto estensioni di fisica

Applicazioni di fisica medica

- Attività in corso nell'INFN (Torino, Novara), TRIUMF, ESA etc.
- Piani di terapia
- Interfaccia generale a TAC
- Studi di fattibilità per nuovi progetti di adroterapia
- Studi di danneggiamento da radiazione a livello di DNA
  - Progetto europeo interdisciplinare basato su Geant4 finanziato dall'ESA, in collaborazione con l'INFN
- Inizio di attività basata su Geant4 all'Istituto Nazionale per la Ricerca sul Cancro

Space applications

- **ESA participates in the Geant4 Collaboration**
  - Extensive experience at ESA with all the main simulation packages on the market, including Geant3
- Comparative evaluation of the main existing simulation packages:
  - Geant3
  - ESABASE
  - Shieldose
  - HETC
  - LHI
  - MORSE
  - MCNP
  - ITS
  - MICAP
  - CEPX-ONELD
  - EGS

Space applications 2

- **Specific requirements for space applications**
  - **environment**
    - *cosmic rays*
    - *Van Allen belts*
    - *fluxes of energetic particles (solar flares)*
  - **simulation studies <u>(mission critical!)</u> for**
    - *degradation of electronic components*
    - *single event logic-flips in electronic equipment*
    - *backgrounds*
    - *risks for astronauts etc....*
- Don't forget the related interest for HEP experiments, like AMS and ACCESS on the International Space Station!

Space applications 3

- **ESA projects in Geant4**
  - Low energy extensions of electromagnetic physics
  - Source Particle Module
  - Delayed Radioactivity Module
  - Sector Shielding Analysis Tool
  - CAD Front-End Tool

- *Recent success: the ESA XMM X-ray telescope has been launched following an analysis of the lifetime of its CCDs based on Geant4*

  The NASA Chandra X-ray telescope had its CCD damaged (launched in August 1999, damage observed in September 1999): the damage to Chandra's CCDs has been quantitatively assessed by the Geant4 simulation performed by ESA & Collaborators

Fisica teorica

- **Uso di componenti di Geant4 per studi teorici**
- Utilizzazione dei modelli teorici di Geant4 di fisica adronica
  - calcoli e uso di componenti per altri modelli teorici
- Componenti del Kinetic Model usate da teorici per modelli di Quantodinamica Molecolare e studi per Ioni Pesanti
  - risonanze, Scatterer, trasporto intra-nucleare etc.
- Reso possibile dal design OO della fisica di Geant4
- Attività in fase iniziale