Electromagnetic Physics II

Overview of Low Energy Electromagnetic Processes

Sebastien Incerti

presenting

Geant4 Low Energy Electromagnetic working group’s slides
Low Energy Electromagnetic Physics

- Introduction
- **Photons, electrons and hadrons**
- Atomic effects
- Penelope Physics alternative
- Advanced examples
- How to use the LE package
- Summary
What is it?

• A package in the Geant4 electromagnetic package
  → in ...$G4INSTALL/source/processes/electromagnetic/lowenergy/

• A set of processes extending the coverage of electromagnetic interactions in Geant4 down to “low” energy
  – 250 eV (in principle even below this limit) / 100 eV for electrons and photons
  – down to approximately the ionization potential of the interacting material for hadrons and ions
  – up to 100 GeV (unless specified)
  – based on theoretical models and evaluated data sets; they involve two distinct phases:
    • calculation and use of total cross sections
    • generation of the final state

• Models are detailed
  – shell structure of the atom
  – precise angular distributions

• Complementary to the “standard” electromagnetic package

• Driven by requirements which come from medicine and space research and from users in HEP instrumentation
Overview of physics

- **Photons**
  - Compton Scattering
  - Compton Scattering by Linearly Polarized Gamma Rays
  - Rayleigh Scattering
  - Gamma Conversion
  - Photoelectric effect

- **Electrons**
  - Bremsstrahlung
  - Ionisation

- **Hadrons and ion ionisation**
  - Energy loss of slow & fast hadrons
  - Energy loss in compounds
  - Delta-ray production
  - Effective charge of ions
  - Barkas and Bloch effects (hadron sign + relativistic)
  - Nuclear stopping power
  - PIXE

- **Atomic relaxation**
  - Fluorescence
  - Auger process

Come in two “flavours”
- based on the Livermore Library
- à la Penelope (+ positron annihil.)
A set of LowE processes are based on the Livermore Library

User must download Geant4 version of this data, then set G4LEDATA environment variable to point to it
Photons and electrons

- Based on **evaluated data libraries from LLNL**:
  - EADL (Evaluated **Atomic** Data Library)
  - EEDL (Evaluated **Electrons** Data Library)
  - EPDL97 (Evaluated **Photons** Data Library)
  ...especially formatted for Geant4 distribution (courtesy of D. Cullen, LLNL)

- Validity range **250 eV - 100 GeV**
  - The processes can be used down to **100 eV**, with degraded accuracy
  - In principle the validity range of the data libraries extends **down to ~10 eV**

- Elements **Z=1 to Z=100**
  - Atomic relaxation : \( Z > 5 \) (transition data available in EADL)
Calculation of cross sections

→ **Interpolation** from the data libraries:

\[
\log(\sigma(E)) = \frac{\log(\sigma_1) \log(E_2 / E) + \log(\sigma_2) \log(E / E_1)}{\log(E_2 / E_1)}
\]

E₁ and E₂ are the lower and higher energy for which data (σ₁ and σ₂) are available.

→ **Mean free path** for a process, at energy E:

\[
\lambda = \frac{1}{\sum_i \sigma_i(E) \cdot n_i}
\]

nᵢ = atomic density of the iᵗʰ element contributing to the material composition.
Photons

G4CrossSectionHandler
(from DataManagement)

G4AbToMicDeexcitation
(from AtomicRelaxation)

GenerateParticle()

G4VEMDataSet
(from DataManagement)

G4LowEnergyRayleigh

G4LowEnergyPhotoElectric

GetMeanFreePath()
BuildPhysicsTable()
IsApplicable()
PostStepDoIt()

G4VProcess
(from ProcessManagement)

G4LowEnergyGammaConversion

G4LowEnergyCompton

GetMeanFreePath()
BuildPhysicsTable()
IsApplicable()
PostStepDoIt()

G4VDiscreteProcess
(from ProcessManagement)

G4LowEnergyPolarizedCompton

G4VEMDataSet
(from DataManagement)

G4CrossSectionHandler
(from OldDataManagement)

G4LowEnergyUtilities
(from DataManagement)
Compton scattering (incoherent)

Klein-Nishina cross section \((E'/E) \times \text{Scattering Function} (q)\)

\[ q = E \sin^2(\theta/2) \text{ momentum transfer} \]

- **Energy distribution** of the scattered photon according to the **Klein-Nishina** formula, multiplied by **scattering function** \(F(q)\) (Hubbel’s atomic factor) from **EPDL97** data library

- The effect of scattering function becomes significant at **low energies** in suppressing forward scattering

- **Angular distribution** of the scattered photon and the recoil electron also based on **EPDL97**
Compton scattering by linearly polarized gamma rays

Cross section

\[
\frac{d\sigma}{d\Omega} \propto \frac{1}{2} r_0^2 \frac{h\nu^2}{h\nu_0^2} \left[ \frac{h\nu_0}{h\nu} + \frac{h\nu}{h\nu_0} - 2\sin^2 \theta \cos^2 \phi \right]
\]

Scattered Photon Polarization

\[
\overline{\varepsilon}_\parallel = \frac{1}{N} \left( \cos \theta \hat{j} - \sin \theta \sin \phi \hat{k} \right) \sin \beta
\]

\[
\overline{\varepsilon}_\perp = \left( N \hat{i} - \frac{1}{N} \sin^2 \theta \sin \phi \cos \phi \hat{j} - \frac{1}{N} \sin \theta \cos \theta \cos \phi \hat{k} \right) \cos \beta
\]

\[
\cos \xi = \sin \theta \cos \phi \Rightarrow \sin \xi = \sqrt{1 - \sin^2 \theta \cos^2 \phi} = N
\]

\(\beta\) angle between \(\varepsilon\)' par and perp components

\(\theta\) Polar angle

\(\varepsilon\) Polarization vector

http://www.ge.infn.it/geant4/talks/RoundTable/depaola.ppt
Rayleigh scattering (coherent)

• Depends on charge distribution of atom

• Angular distribution

\[ F(E, \theta) = [1 + \cos^2(\theta)] \sin \theta \cdot F^2(q) \]

Rayleigh formula times \( F(q) \), the energy dependent Hubbel’s form factor obtained from EPDL97 (forward peak at high energies)

• Only available in the lowenergy package
Photoelectric effect

• Cross section
  – Integrated cross section (over the shells) from EPDL + interpolation
  – Shell from which the electron is emitted selected according to the detailed cross sections of the EPDL library

• Final state generation
  – Various angular distribution generators (“naïve”, Sauter-Gavrila, Gavrila)

• De-excitation via the atomic relaxation sub-process
  – Initial vacancy + following chain of vacancies created

• Improved angular distribution recently released
γ conversion

- The secondary $e^-$ and $e^+$ energies are sampled using Bethe-Heitler cross sections with Coulomb correction (screening)

- $e^-$ and $e^+$ assumed to have symmetric angular distribution

- Energy and polar angle sampled w.r.t. the incoming photon using Tsai differential cross section

- Azimuthal angle generated isotropically

- Choice of which particle in the pair is $e^-$ or $e^+$ is made randomly
Photons: mass attenuation coefficient

All simulation results lie within $\pm 3\sigma$ w.r.t. the corresponding NIST data (National Institute of Standards and Technologies).

Fig. 2. Mass attenuation coefficient in iron as a function of the photon incident energy for the three sets of Geant4 models under test (circles: Low Energy EPDL; squares: Low Energy Penelope; triangles: Standard); the continuous line interpolates NIST-XCOM reference data.
Photons, evidence of shell effects

Photon transmission, 1 µm Al

Photon transmission, 1 µm Pb

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![Graphs showing photon transmission through 1 µm Al and 1 µm Pb.](image_url)
Electrons
Electron Bremsstrahlung

- **Parameterisation of EEDL data**
  - 16 parameters for each atom
  - At high energy the parameterization reproduces the Bethe-Heitler formula
  - Precision is ~ 1.5 %

- Systematic verification over Z and energy planned
Bremsstrahlung Angular Distributions

Three LowE generators available in GEANT4 6.0 release:

- G4ModifiedTsai
- G4Generator2BS
- G4Generator2BN

G4Generator2BN allows a correct treatment at low energies (< 500 keV)

Sampling efficiency = ration between generated events and total number of trials
Bremsstrahlung Angular Distributions

Angular distribution is strongly model dependent

Example of validation: 500 keV electrons on Al and Fe, W.E. Dance et al., Journal of Applied Physics 39 (1968), 2881

LowE 2BN model

LowE Tsai model

precise agreement!
Electron ionisation

- **Parameterisation** based on 5 parameters for each shell

- Precision of parameterization is **better than 5%** for 50% of shells, less accurate for the remaining shells

- Work in progress to improve the parameterization and the performance
Electrons: range

- Range in various simple and composite materials
- Compared to NIST database
- All simulation results lie within ± 3σ w.r.t. the corresponding NIST data

Comparison against NIST data

Comparison of CSDA range for electrons in Uranium

The stopping power can be used to calculate the distance it takes to slow an electron down to a given energy. This distance is called the continuous slowing down approximation range, or CSDA range, because the calculation assumes that the electron slows down continuously from the initial energy $E$ to the final energy.

Fig. 7. Electron CSDA range in uranium as a function of the electron incident energy for the three sets of Geant4 models under test together with the NIST-ESTAR reference data for the three sets of Geant4 models under test (circles: Low Energy EEDL; squares: Low Energy Penelope; triangles: Standard); the continuous line interpolates NIST-ESTAR reference data.
Electrons, transmitted

20 keV electrons through 0.32 and 1.04 µm Al

![Graph showing energy of transmitted electrons vs. MeV entries]

- Geant4 Low Energy simulation
Hadrons
Hadrons and ions

Physics models handled through abstract classes

Algorithms encapsulated in objects

Transparency of physics, clearly exposed to users

Interchangeable and transparent access to data sets
Hadrons and ions

- **Variety of models**, depending on
  - energy range
  - particle type
  - charge

- Composition of models across the energy range, with different approaches
  - analytical
  - based on data reviews + parameterizations

- Specialized models for **fluctuations** (stochastic straggling)

- Open to extension and evolution
Positively charged hadrons: protons

- Bethe-Bloch model of energy loss, \( E > 2 \text{ MeV} \)
- 5 parameterization models, \( E < 2 \text{ MeV} \) based on Ziegler and ICRU reviews
- Free electron gas model below 1 keV
- 3 models of energy loss fluctuations
- Density correction for high energy
- Shell correction term for intermediate energy
- Chemical effect for compounds
- Nuclear stopping power (elastic Coulomb scattering)
- PIXE included
- Spin dependent term
- Barkas (+ vs -) and Bloch terms
### Bragg peak simulation

**PRELIMINARY!**

![Graph](image)

See CHEP2007 in September

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<tbody>
<tr>
<td><strong>Left branch (CvM)</strong></td>
<td>0.648</td>
<td>0.667</td>
<td>0.790</td>
<td>0.814</td>
<td>0.836</td>
<td>0.973</td>
<td><strong>0.977</strong></td>
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<tr>
<td><strong>Right branch (KS)</strong></td>
<td>0.760</td>
<td>0.985</td>
<td><strong>0.985</strong></td>
<td><strong>0.985</strong></td>
<td><strong>0.985</strong></td>
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</tr>
<tr>
<td><strong>Whole curve (AD)</strong></td>
<td>0.666</td>
<td>0.858</td>
<td>0.936</td>
<td>0.945</td>
<td>0.946</td>
<td>0.982</td>
<td><strong>0.994</strong></td>
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</tbody>
</table>

**Key ingredients**

- precise **electromagnetic** physics
- good **elastic scattering** model
- good **pre-equilibrium** model
Positively charged hadrons (Z > 1)

- **Scaling of Bethe-Bloch**: \( S_{\text{ion}}(T) = Z^2_{\text{ion}} S_p(T) \), \( T_p = T \frac{m_p}{m_{\text{ion}}} \)
- **0.01 < \beta < 0.05**: parameterizations, Bragg peak, based on Ziegler and ICRU reviews
- **\beta < 0.01**: Free Electron Gas Model
- Effective charge model (picks up e- in the medium)
- Nuclear stopping power (elastic Coulomb scattering with nuclei)
Models for antiprotons

- $\beta > 0.5$  
  Bethe-Bloch formula
- $0.01 < \beta < 0.5$  
  Quantum harmonic oscillator model
- $\beta < 0.01$  
  Free electron gas model
Atomic relaxation
Atomic relaxation

• The atomic relaxation can be triggered by other electromagnetic interactions such as the **photoelectric effect** or **ionisation**, which leave the atom in an **excited state**.

• The Livermore **Evaluation Atomic Data Library EADL** contains data to describe the relaxation of atoms back to neutrality after they are ionised.

• The data in EADL includes the radiative and non-radiative transition probabilities for each sub-shell of each element, for Z=1 to 100. The atom has been ionised by a process that has caused an electron to be ejected from an atom, leaving a vacancy or "hole" in a given subshell. The EADL data are then used to calculate the **complete radiative and non-radiative spectrum of X-rays and electrons emitted** as the atom relaxes back to neutrality.

Non-radiative de-excitation can occur via the **Auger effect** (the initial and secondary vacancies are in different shells) or **Coster-Kronig effect** (transitions within the same shell).
Atomic relaxation

G4 Low Energy Ionisation (from Electrons)

G4 Low Energy PhotoElectric (from Photons)

G4 Atomic Deexcitation

Generate Particle()

G4 Atomic Transition Manager

Singleton

G4 Atomic Transition

Number Of Reachable Shells()
Number Of Shells()
Reachable Shell()
Shell()
Total Non Radiative Transition Probability()
Total Radiative Transition Probability()

G4 Atomic Shell

Binding Energy()
ShellId()

G4 Shell Data
(from Data Management)

Number Of Shells()
ShellId()
Binding Energy()
Load Data()
Print Data()
Fluorescence

Microscopic validation: against reference data

Experimental validation: test beam data, in collaboration with ESA
Advanced Concepts & Science Payload Division

Fluorescent spectrum of Icelandic Basalt ("Mars-like")

S. Guatelli, A. Mantero, B. Mascialino, P. Nieminen, M. G. Pia, V. Zampichelli
Validation of Geant4 Atomic Relaxation against the NIST Physical Reference Data
Auger effect

Auger electron emission from various materials

Sn, 3 keV photon beam electron lines w.r.t. published experimental results

S. Guatelli, A. Mantero, B. Mascialino, P. Nieminen, M. G. Pia, V. Zampichelli
Validation of Geant4 Atomic Relaxation against the NIST Physical Reference Data
PIXE
(Particle Induced X-ray Emission)

- New model based on experimental data
  - Parameterisation of Paul & Sacher data library for ionization cross sections
  - Uses the EADL-based package of atomic de-excitation for the generation of fluorescence and Auger secondary products
- Current implementation: protons, K-shell
- Coming in future: protons, L-shell and $\alpha$, K-shell
Penelope
Physics
alternative
Processes à la Penelope

- The **whole** Physics content of the **Penelope Monte Carlo code** has been re-engineered into Geant4 (except multiple scattering)
  - photons: release 5.2
  - electrons: 6.0
- Physics models by F. Salvat *et al.*
- **Power of the OO technology**
  - extending the software is easy
  - all processes obey the same abstract interfaces
  - using new implementations in application code is simple
- **Profit of Geant4 advanced geometry modelling, interactive capabilities, etc...**
  - **same physics** as original Penelope
Processes à la Penelope

- Compton scattering
- Rayleigh scattering
- Gamma conversion
- Photoelectric effect
- Bremsstrahlung
- Ionisation
- Positron Annihilation

In your Physics List

G4PenelopeAnnihilation
G4PenelopeBremsstrahlung
G4PenelopeCompton
G4PenelopeGammaConversion
G4PenelopeIonisation
G4PenelopePhotoElectric
G4PenelopeRayleigh
Processes à la Penelope

• The whole physics content of the Penelope Monte Carlo code has been re-engineered into Geant4 (except for multiple scattering)
  – processes for photons: release 5.2, for electrons: release 6.0

• Analytical Physics models by F. Salvat et al.

• Power of the OO technology:
  – extending the software system is easy
  – all processes obey to the same abstract interfaces
  – using new implementations in application code is simple

• Profit of Geant4 advanced geometry modeling, interactive facilities etc.
  – same physics as original Penelope
Advanced examples
Advanced examples

Stéphane Chauvie
Pablo Cirrone
Giacomo Cuttone
Francesco Di Rosa
Alex Howard
Sébastien Incerti
Mikhail Kossov
Anton Lechner
Francesco Longo
Alfonso Mantero
Luciano Pandola
MG Pia
Michela Piergentili
Alberto Ribon
Giorgio Russo
Giovanni Santin
Bernardo Tomé
Jakub Moscicki
Andreas Pfeiffer
Witold Pokorski

Mission

• Investigate, evaluate and demonstrate Geant4 capabilities in various experimental environments

• Provide guidance to Geant4 users in realistic experimental applications

• Provide feedback to Geant4 developers about successful results, problems etc.

• Identify requirements for further Geant4 improvements and extensions to address new experimental domains

http://www.ge.infn.it/geant4/examples
Advanced examples

- in $G4INSTALL/examples/advanced

- Wide experimental coverage
  - HEP
  - Space science / astrophysics
  - Medical physics
  - Radiobiology
  - Detector technologies

- Wide Geant4 coverage
  - geometry features
  - magnetic field
  - Physics (EM and hadronic)
  - Biological processes
  - Hits & digis
  - Analysis
  - Visualization, UI

- Status
  - Released
  - In preparation
  - Published
How to use the package?
How to use the package?

**Photon processes**
- Compton scattering (class `G4LowEnergyCompton`)
- Polarized Compton scattering (class `G4LowEnergyPolarizedCompton`)
- Rayleigh scattering (class `G4LowEnergyRayleigh`)
- Gamma conversion (also called pair production, class `G4LowEnergyGammaConversion`)
- Photo-electric effect (class `G4LowEnergyPhotoElectric`)

**Electron processes**
- Bremsstrahlung (class `G4LowEnergyBremsstrahlung`)
- Ionisation and delta ray production (class `G4LowEnergyIonisation`)

**Hadron and ion processes**
- Ionisation and delta ray production (class `G4hLowEnergyIonisation`)

► The user should set the environment variable `G4LEDATA` to the directory where he/she has copied the files.

► Options are available for low energy electromagnetic processes for hadrons and ions in terms of public member functions of the `G4hLowEnergyIonisation` class:
- `SetHighEnergyForProtonParametrisation(G4double)`
- `SetLowEnergyForProtonParametrisation(G4double)`
- `SetHighEnergyForAntiProtonParametrisation(G4double)`
- `SetLowEnergyForAntiProtonParametrisation(G4double)`
- `SetElectronicStoppingPowerModel(const G4ParticleDefinition*,const G4String& )`
- `SetNuclearStoppingPowerModel(const G4String&)`
- `SetNuclearStoppingOn()`
- `SetNuclearStoppingOff()`
- `SetBarkasOn()`
- `SetBarkasOff()`
- `SetFluorescence(const G4bool)`
- `ActivateAugerElectronProduction(G4bool)`
- `SetCutForSecondaryPhotons(G4double)`
- `SetCutForSecondaryElectrons(G4double)`

The available models for ElectronicStoppingPower and NuclearStoppingPower are documented in the class diagrams.

► Options are available for low energy electromagnetic processes for electrons in the `G4LowEnergyIonisation` class:
- `ActivateAuger(G4bool)`
- `SetCutForLowEnSecPhotons(G4double)`
- `SetCutForLowEnSecElectrons(G4double)`

► Options are available for low energy electromagnetic processes for electrons/positrons in the `G4LowEnergyBremsstrahlung` class, that allow the use of alternative bremsstrahlung angular generators:
- `SetAngularGenerator(G4VBremAngularDistribution* distribution);`
- `SetAngularGenerator(const G4String& name);`

Currently three angular generators are available: `G4ModifiedTsai`, 2BGenerator and 2BSGenerator. `G4ModifiedTsai` is set by default, but it can be forced using the string “tsai”. `2BGenerator` and `2BSGenerator` can be set using the strings “2bs” and “2bn”. Information regarding conditions of use, performance and energy limits of different models are available in the Physics Reference Manual and in the Geant4 Low Energy Electromagnetic Physics Working Group homepage.

► Other options `G4LowEnergyBremsstrahlung` class are:
- `SetCutForLowEnSecPhotons(G4double)`

Refer to Geant4 User’s guide!
Example of low energy processes registration in PhysicsList.cc

```cpp
if (particleName == "gamma") {
    pmanager->AddDiscreteProcess(new G4LowEnergyCompton);
    G4LowEnergyPhotoElectric * LePeprocess = new G4LowEnergyPhotoElectric();
    LePeprocess->ActivateAuger(true);
    LePeprocess->SetCutForLowEnSecPhotons(0.250 * keV);
    LePeprocess->SetCutForLowEnSecElectrons(0.250 * keV);
    pmanager->AddDiscreteProcess(LePeprocess);
    pmanager->AddDiscreteProcess(new G4LowEnergyGammaConversion());
    pmanager->AddDiscreteProcess(new G4LowEnergyRayleigh());
    pmanager->AddProcess(new G4StepLimiter(), -1, -1, 3);
}
else if (particleName == "e-") {
    pmanager->AddProcess(new G4MultipleScattering,-1, 1 ,1);
    G4LowEnergyIonisation * LeIoprocess = new G4LowEnergyIonisation("IONI");
    LeIoprocess->ActivateAuger(true);
    LeIoprocess->SetCutForLowEnSecPhotons(0.1*keV);
    LeIoprocess->SetCutForLowEnSecElectrons(0.1*keV);
    pmanager->AddProcess(LeIoprocess, -1, -1, 2, 2);
    G4LowEnergyBremsstrahlung * LeBrprocess = new G4LowEnergyBremsstrahlung();
    pmanager->AddProcess(LeBrprocess, -1, -1, 3);
    pmanager->AddProcess(new G4StepLimiter(), -1, -1, 3);
}
else if (particleName == "e+") {
    pmanager->AddProcess(new G4MultipleScattering,-1, 1 ,1);
    pmanager->AddProcess(new G4Ionisation, -1, 2, 2);
    pmanager->AddProcess(new G4Bremsstrahlung, -1,-1 ,3);
    pmanager->AddProcess(new G4plusAnnihilation, 0,-1 ,4);
    pmanager->AddProcess(new G4StepLimiter(), -1, -1, 3);
}
else if( particleName == "mu+" ||
    particleName == "mu-" ) {
}
else if(!particle->IsShortLived()) &&
    (particle->GetPDGCharge() != 0.0) &&
    (particle->GetParticleName() != "chargedgeantino") {
    pmanager->AddProcess(new G4MultipleScattering(),-1,1,1);
    G4hLowEnergyIonisation* hLowEnergyIonisation = new G4hLowEnergyIonisation();
    pmanager->AddProcess(hLowEnergyIonisation, -1,2,2);
    hLowEnergyIonisation->SetElectronicStoppingPowerModel(particle,"ICRU_R49H e");
    hLowEnergyIonisation->SetNuclearStoppingOn();
    hLowEnergyIonisation->SetNuclearStoppingPowerModel("ICRU_R49");
    hLowEnergyIonisation->SetFluorescence(true);
    hLowEnergyIonisation->ActivateAugerElectronProduction(true);
    pmanager->AddProcess(new G4StepLimiter(), -1, -1, 3 );
}
```

Refer to Geant4 user’s guide and advanced examples!
In progress

• Extensions down to the eV scale: The Geant4 DNA project
  – in water (for radiobiology studies)
  – in semiconductor materials (for radiation damage to components)

• Difficult domain
  – models must be specialized by material
  – cross sections, final state generation, angular distributions

http://www.ge.infn.it/geant4/dna
Where to find more information?

- Physics Reference Manual
- User’s Guide: For Application Developers
- User guides
- http://www.ge.infn.it/geant4/lowE
- http://cern.ch/geant4

Low Energy Extensions
Validation of Geant4 physics models

PUBLISHED


Comparison of Geant4 electromagnetic physics models against the NIST reference data

IN PRESS

S. Chauvie, P. Nieminen, M. G. Pia
Geant4 model for the stopping power of low energy negatively charged hadrons
IEEE Transactions on Nuclear Science, in press

S. Guatelli, A. Mantero, B. Mascialino, P. Nieminen, M. G. Pia
Geant4 Atomic Relaxation

S. Guatelli, A. Mantero, B. Mascialino, P. Nieminen, M. G. Pia, V. Zampichelli
Validation of Geant4 Atomic Relaxation against the NIST Physical Reference Data

IN PREPARATION

G. A. P. Cirrone et al.
Validation of Geant4 Physics models for the simulation of the proton Bragg peak

S. Chauvie, Z. Francis, S. Guatelli, S. Incerti, B. Mascialino, P. Moretto, P. Nieminen, and M. G. Pia
Geant4 low energy physics processes for microdosimetry simulation: design foundation and implementation of the first set of models for particle interactions with water
Summary

• OO technology provides the mechanism for a rich set of electromagnetic physics models in Geant4
  – further extensions and refinements are possible, without affecting Geant4 kernel or user code

• Two main approaches in Geant4
  – standard
  – Low Energy (Livermore Library / Penelope)

   each one offering a variety of models for specialized applications

• Extensive validation activity and results

• More on Physics Reference Manual and web site

Maria.Grazia.Pia@cern.ch