Geant4 10.6 beta

Electromagnetic Physics I

Geant4 Tutorial at Chalk River

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slides based on those of Mihaly Novak (CERN)

28 August 2019

Outline

- Electromagnetic (EM) physics overview
  - Introduction, structure of Geant4 EM physics
  - Standard EM physics constructors
  - How to extract EM physics related quantities

- Special EM topics:
  - EM models per region
  - Atomic de-excitation
  - Energy loss fluctuation
  - Multiple Coulomb scattering

- Where to find help

Code Location: source/processes/electromagnetic/

- /standard
  - γ, e^{+-} up to 100 TeV
  - hadrons up to 100 TeV
  - ions up to 100 TeV
- /muons
  - up to 1 PeV
  - energy loss propagator
- /xrays
  - Cerenkov, transition, synchrotron radiation
- /highenergy
  - e.g. γ to $\mu^+ \mu^-$ pairs, $e^+ e^-$ to $\pi^+ \pi^-$
- /polarisation
  - models, processes for polarized beams
- /utils
  - model/process interfaces, utilities
- /lowenergy
  - Livermore library: γ, e^- [10 eV – 1 GeV]
  - Penelope models (2008): γ , e^{+-} , [100 eV – 1 GeV]
  - Livermore polarized processes
  - hadrons and ions up to 1 GeV
  - atomic de-excitation (Auger, fluor.)
- /dna
  - DNA models, processes (0.025 eV to 10 MeV)
  - microdosimetry models for radiology
  - many models are material-specific (water)
- /adjoint
  - reverse Monte Carlo
  - very fast, limited applications

Standard EM Interactions

- Photon (γ) :
  - conversion to $e^- e^+$ pairs
  - Compton (incoherent) scattering
  - photo-electric effect
  - Rayleigh (coherent) scattering
  - photo-nuclear interaction (see hadronic)

- Electron and positron interactions :
  - ionization
  - Coulomb (elastic) scattering
  - bremsstrahlung photon emission
  - positron annihilation
  - electron- and positron-nuclear interactions (see hadronic)

Standard EM Interactions

- Example of photon interactions (from log file)

```
phot:    for  gamma      SubType= 12  BuildTable= 0
       LambdaPrime table from 200 keV to 100 TeV in 61 bins
       ===== EM models for the G4Region  DefaultRegionForTheWorld ======
 LivermorePhElectric :  Emin=        0 eV    Emax=      100 TeV   Angular

compt:    for  gamma     SubType= 13  BuildTable= 1
       Lambda table from 100 eV  to 1 MeV, 7 bins per decade, spline: 1
       LambdaPrime table from 1 MeV to 100 TeV in 56 bins
       ===== EM models for the G4Region  DefaultRegionForTheWorld ======
        Klein-Nishina :  Emin=        0 eV    Emax=      100 TeV

conv:    for  gamma      SubType= 14  BuildTable= 1
       Lambda table from 1.022 MeV to 100 TeV, 18 bins per decade, spline:
       ===== EM models for the G4Region  DefaultRegionForTheWorld ======
         BetheHeitler :  Emin=        0 eV    Emax=       80 GeV   Angular
      BetheHeitlerLPM :  Emin=       80 GeV   Emax=      100 TeV   Angular

Rayl:    for  gamma      SubType= 11  BuildTable= 1
       Lambda table from 100 eV  to 100 keV, 7 bins per decade, spline: 0
       LambdaPrime table from 100 keV to 100 TeV in 63 bins
       ===== EM models for the G4Region  DefaultRegionForTheWorld ======
    LivermoreRayleigh :  Emin=        0 eV    Emax=      100 TeV   CullenG
```

Structure of Geant4 EM Physics

- Uniform, coherent design approach covering EM sections
    - standard and low-energy EM models/processes can be combined
- Physical interactions described by processes (e.g. G4ComptonScattering)
    - assigned to a particle in the physics list (G4ComptonScattering assigned to photon)
- Processes categorized by their interfaces:
    - G4VEmProcess for discrete EM processes like Compton
    - G4VEnergyLossProcess for continuous-discrete ionization and bremsstrahlung
    - G4VMultipleScattering for the condensed history description of multiple Coulomb scattering (along a given step)

- A given EM process can be described by one or more models:
    - an EM model can handle the interaction in a given energy range
    - naming convention: G4ModelNameProcessNameModel (e.g. G4KleinNishinaComptonModel describes Compton scattering of photons as implemented by the Klein-Nishina differential cross section
    - each EM model follows the G4VEmModel interface:
        - computation of interaction cross section (and stopping power, if any)
        - computation/generation of the interaction final state (kinematics, secondaries, etc.)

Standard EM Example

- Gamma conversion process described by two EM models

```
phot:   for  gamma    SubType= 12  BuildTable= 0
      LambdaPrime table from 200 keV to 100 TeV in 61 bins
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
 LivermorePhElectric :  Emin=        0 eV     Emax=      100 TeV   AngularGenSauter(

compt:   for  gamma    SubType= 13  BuildTable= 1
      Lambda table from 100 eV  to 1 MeV, 7 bins per decade, spline: 1
      LambdaPrime table from 1 MeV to 100 TeV in 56 bins
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
       Klein-Nishina :  Emin=        0 eV     Emax=      100 TeV

conv:   for  gamma    SubType= 14  BuildTable= 1
      Lambda table from 1.022 MeV to 100 TeV, 18 bins per decade, spline: 1
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
        BetheHeitler :  Emin=        0 eV     Emax=       80 GeV   AngularGenUrban
     BetheHeitlerLPM :  Emin=       80 GeV    Emax=      100 TeV   AngularGenUrban

Rayl:   for  gamma    SubType= 11  BuildTable= 1
      Lambda table from 100 eV  to 100 keV, 7 bins per decade, spline: 0
      LambdaPrime table from 100 keV to 100 TeV in 63 bins
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
    LivermoreRayleigh :  Emin=        0 eV     Emax=      100 TeV   CullenGenerator
```

Standard EM Physics Constructors

- Physics processes are assigned to particles in the physics list
- Particles to which EM physics processes can be assigned:
  - γ, $e^{+/-}$, $\mu^{+/-}$, $\pi^{+/-}$, p, $\Sigma^{+/-}$, Ξ^{-}, Ω^{-}, anti ($\Sigma^{+/-}$, Ξ^{-}, Ω^{-})
  - $\tau^{+/-}$, $B^{+/-}$, $D^{+/-}$, $D_S^{+/-}$, Λ_C^{+}, Σ_C^{+}, Σ_C^{++}, Ξ_C^{+}, anti (Λ_C^{+}, Σ_C^{+}, Σ_C^{++}, Ξ_C^{+})
  - d, t, ^{3}He, α, generic ion, anti (d, t, ^{3}He, α)

- Each particle type is a static object which has its own G4ProcessManager
  - manager maintains list of assigned processes

- Modular physics lists (G4VModularPhysicsList) allow building up a complete physics list from "physics modules"
  - physics module handles well-defined subset of physics (EM physics, decay physics, etc.)
  - G4VPhysicsConstructor is the interface class describing such subsets
- Several pre-defined EM physics constructors are available in Geant4

Standard EM Physics Constructors for HEP

- Description of Coulomb scattering is the same for three of these:
  - $e^{+/-}$: Urban-MSC model below 100 MeV and the Wentzel-WVI + single scattering model above 100 MeV
  - muons and hadrons: Wentzel-WVI + single scattering model
  - ions: Urban-MSC model
- But different MSC stepping algorithms or parameters are used to optimize either speed or accuracy

Constructor	Components	Comments
G4EmStandardPhysics	Default: nothing or **_EM0** (QGSP_BERT, FTFP_BERT,…)	for ATLAS and other HEP simulation applications
G4EmStandardPhysics_option1	Fast: due to **simpler MSC step limitation**, cuts used by photon processes (FTFP_BERT**_EMV**)	similar to one used by CMS; good for crystals but not good for sampling calorimeters (i.e. with more detailed geometry)
G4EmStandardPhysics_option2	Experimental: similar to option1 with updated photoelectric model **but no-displacement in MSC** (FTFP_BERT**_EMX**)	similar to one used by LHCb

Hybrid EM Physics Constructors

- Primary goal: best physics accuracy
- Combine standard and low energy EM models to do this
- More accurate $e^{+/-}$ MSC models (Goudsmit-Saunderson) and/or more accurate stepping algorithms (compared to HEP)
- More stringent continuous step limitations due to ionization
- Recommended for more sensitive applications: medical, space

Constructor	Components	Comments
`G4EmStandardPhysics_option3`	Urban MSC model for all particles	proton/ion therapy
`G4EmStandardPhysics_option4`	most accurate combination of models (particle type and energy); GS MSC model with Mott correction and error-free stepping for $e^{\pm}$)	the ultimate goal is to have the most accurate EM physics description
`G4EmLivermorePhysics`	Livermore models for e^{-}, γ below 1 GeV and standard above; same GS MSC for $e^{\pm}$ as in `option4`)	accurate Livermore based low energy e^{-} and γ transport
`G4EmPenelopePhysics`	PENELOPE models for $e^{\pm}$, γ below 1 GeV and standard above; same GS MSC for $e^{\pm}$ as in `option4`)	accurate PENELOPE based low energy e^{-}, e^{+} and γ transport

Experimental EM Physics Constructors

- Usually used only by developers for validation and model improvement
- Main difference is in description of Coulomb scattering (GS, WVI, SS)

Constructor	Components	Comments
`G4EmStandardPhysicsGS`	standard EM physics and the GS MSC model for $e^{\pm}$ with HEP settings	may be considered as an alternative to EM0 i.e. for HEP
`G4EmStandardPhysicsWVI`	WentzelWVI + Single Scattering mixed simulation model for Coulomb scattering	high and intermediate energy applications
`G4EmStandardPhysicsSS`	single scattering (SS) model description of the Coulomb scattering	validation and verification of the MSC and mixed simulation models
`G4EmLowEPPhysics`	Monarsh University Compton scattering model, 5D gamma conversion model, WVI-LE model	testing some low energy models
`G4EmLivermorePolarized`	polarized gamma models	a (polarized) extension of the Livermore physics models

Comments on EM Physics Constructors

- Physics lists may be built from scratch by any user
  - this was original recommendation from Geant4, but not now

- Recommend using one of the existing EM constructors
  - can use as a starting point
  - most users pick one and do not modify it

- Why so many EM constructors provided?
  - different application areas have different physics/computing requirements
  - each constructor is used and validated by several user groups -> code is tested and stable
  - all constructors maintained and tested by Geant4 developers

Extracting EM Physics-related Quantities

- You may want to know cross sections, energy loss, etc.
- Use the G4EmCalculator object
  - include the following lines in your application:

```
#include "G4EmCalculator.hh"
...
G4EmCalculator emCalculator;

G4Material* material = G4NistManager::Instance()->FindOrBuildMaterial(matName);
G4double    macXSec  = emCalculator.ComputeCrossSectionPerVolume (energy,
                                                                 partDefinition,
                                                                 procName,
                                                                 material);
G4cout << G4BestUnit(macXSec, "1/Length") << G4endl;
```

  - make sure physics list is initialized first

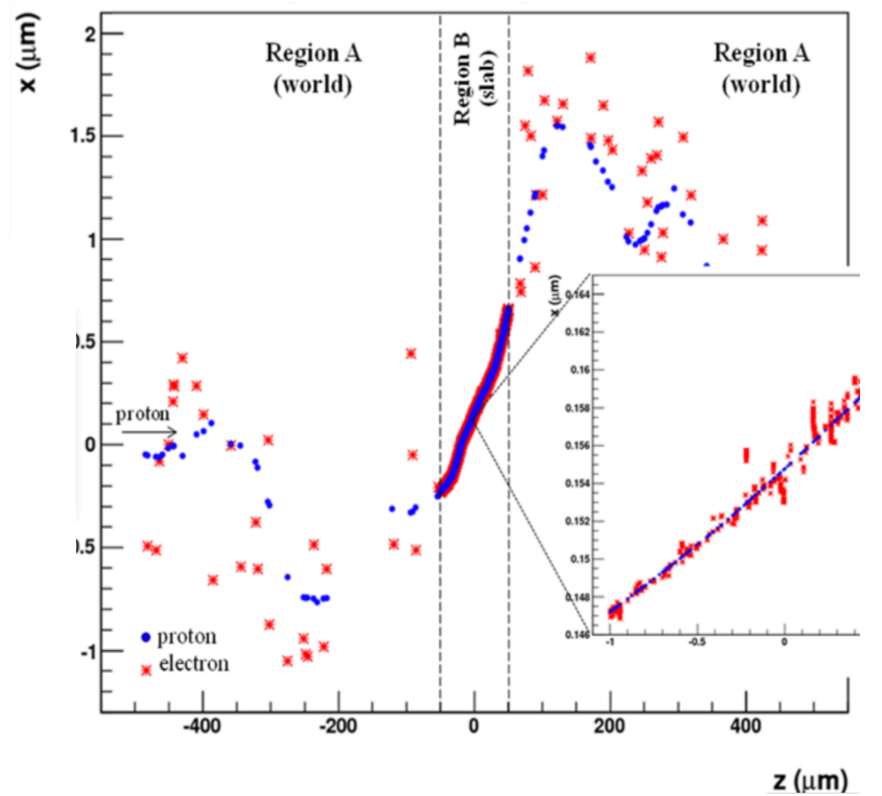
- A good example of all the things you can do:
  - /examples/extended/electromagnetic/TestEm0
  - see especially RunAction::BeginOfRun() method

EM Special Topics

EM Models per Region

- Special models may be used in a particular G4Region, while all other parts of detector use general models
- Example: Geant4-DNA physics in a slice of volume (Region B) nested in World (Region A) which uses standard EM

- Use G4EmConfigurator to select special model, set energy limits within region
- UI commands allow optimization and easy configuration of models
- Can be used on top of any EM constructor:
  - /process/em/AddPAIRegion proton MYREGION pai
  - /process/em/AddMicroElecRegion MYREGION
  - /process/em/AddDNARegion MYREGION opt0

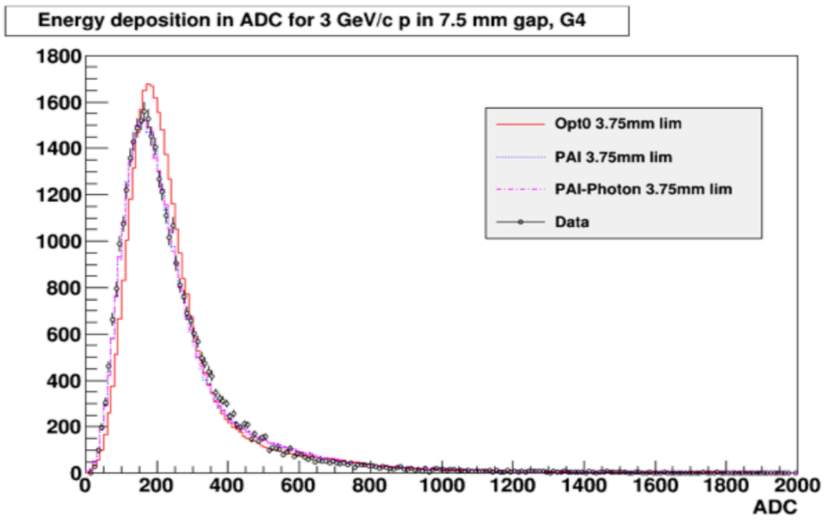


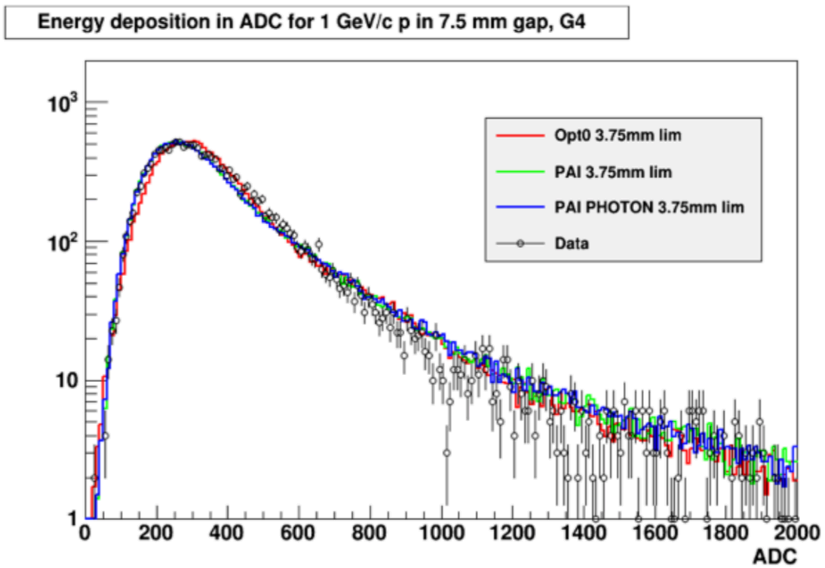
Atomic De-excitation

- Initiated by other physics interactions
  - e.g. photoelectric effect, ionization, radioactive decay
  - interactions leave target atom in excited state
- Evaluated Atomic Data Library (EADL) contains transition probabilities for:
  - radiative transitions (fluorescence photon emission)
  - Auger e- emission (initial and final vacancies are in different shells)
  - Coster-Kronig e- emission (initial and final vacancies are in same shell)
- Due to a common interface, Geant4 atomic de-excitation is compatible with both standard and low energy EM categories
  - can be enabled and controlled by UI commands (before initialization):
    - /process/em/fluo true
    - /process/em/auger true
    - /process/em/augerCascade true
    - /process/em/pixe true
    - /run/initialize
  - fluorescence transition is active by default in some EM constructors

Energy Loss Fluctuation

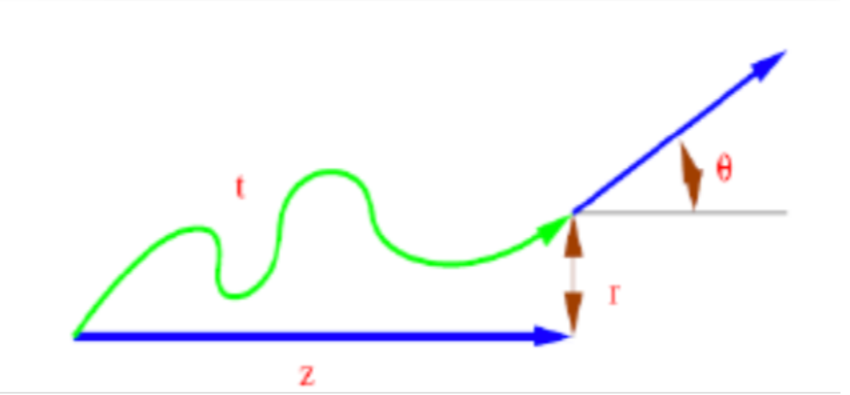
- For condensed history models:
  - secondary photons (e-) with initial energy below the photon (e-) production threshold, are not generated in bremsstrahlung (ionization)
- Corresponding energy loss (that would have been taken away by these secondaries) is counted as continuous energy loss of primary particle along its step
- Mean value of energy loss along step (due to these sub-threshold secondaries) can be calculated using the restricted stopping power
- So we have the mean – what about the distribution?
  - energy loss fluctuation models will tell us
- Urban and PAI models available in Geant4

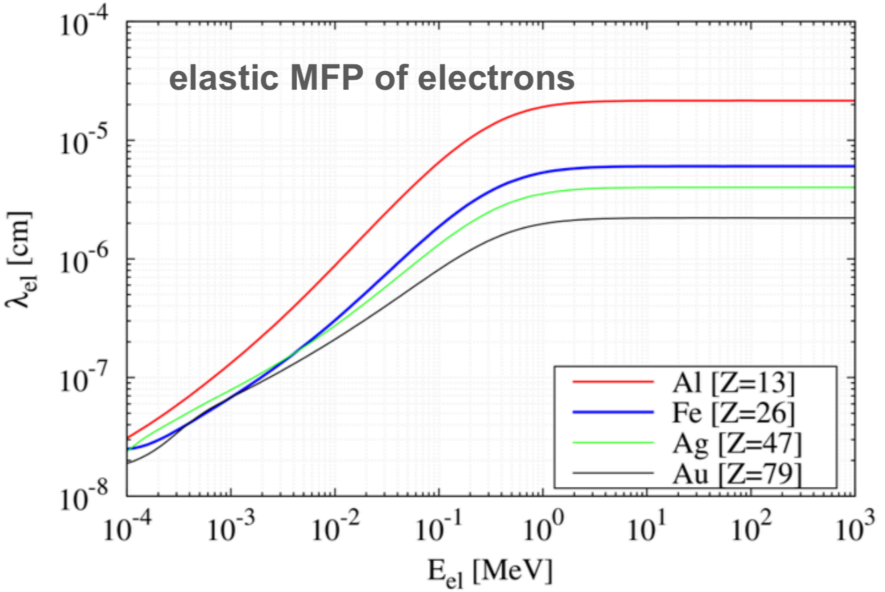




Multiple Coulomb Scattering

- Elastic scattering of charged particles by the atomic potential
- Event-by-event modeling of elastic scattering is feasible only if mean number of interactions per track is less than a few hundred
- Detailed simulation therefore limited to electrons with low kinetic energies (< 100 keV) or thin targets
- Electrons with E_{kin} > 100 keV undergo a large number of elastic while slowing down in thick targets → condensed history approach
- MSC models simulate each particle by allowing individual steps which are much larger than average step length between two successive elastic scatterings → only summed effects are modeled





Geant4 Multiple Scattering Models

Model	Particle type	Energy limit	Specifics and applicability
Urban (L. Urban 2006)	Any	-	Default model (i.e. in EM-opt0) for electrons and positrons below 100 MeV, (Lewis 1950) approach, tuned to data, used for LHC production.
Screened Nuclear Recoil (Mendenhall and Weller 2005) TestEm5	p, ions	< 100 MeV/A	Theory based, providing simulation of nuclear recoil for sampling of radiation damage, focused on precise simulation of in case of space applications
Goudsmit-Saunderson	e^+, e^-	-	Theory based angular distributions (Goudsmit and Saunderson 1950). Mott correction and several stepping option including error-free (Kawrakov et al. 1998), precise electron transport
Coulomb scattering (2008)	Any	-	Theory based (Wentzel 1927) single scattering model, uses nuclear form-factors (Butkevich et al. 2002), focused on muons and hadrons
WentzelVI (2009) LowEnergyWentzelVI (2014)	Any	-	Mixed simulation model: MSC for small angles, Coulomb Scattering (Wentzel 1927) for large angles. Focused on simulation for muons and hadrons; low-energy model is applicable for low-energy e-
Ion Coulomb scattering (2010) Electron Coulomb scattering (2012)	Ions e^+, e^-	-	Model based on Wentzel DCS + relativistic effects + screening effects for projectile & target.

Getting Help

- EM physics processes and models developed and maintained by the electromagnetic working groups of the Geant4 collaboration :
  - https://geant4.web.cern.ch/collaboration/working_groups

- Geant4 extended and advanced examples show how to use the available EM processes, models, functionality

- Visit the web-based verification and validation tools
  - https://geant-val.cern.ch

Summary

- EM processes and models are available to cover all "long-lived" charged particles and photons
- Energy range covered: few eV up to ~PeV
  - often more than one model required for this coverage
- EM physics constructors build the models, cross sections and processes
  - many pre-packaged constructors have been prepared and tested by Geant4 developers – pick one
  - but you can still build your own!
- It is possible to use different EM physics constructors in different regions of your geometry
- The correct multiple scattering model is crucial to simulations
  - several provided by Geant4
- Validation plots available!