The FLUKA Monte Carlo code

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Overview:

Assumption:
- We presume that you are familiar with Monte Carlo foundations, Sampling techniques, Statistical issues

1) The FLUKA code
- History, general content, design criteria
- Distribution and licensing
- Short review of applications
- A few words on physics models
- The FLUKA geometry

2) Learning how to run FLUKA code
- Running FLUKA with Flair: the graphical user interface

3) The application to particle therapy
- The relevant physics
- The voxel geometry
- Import of CT scans
- Treatment Planning and PET in-beam, examples
- Simulation of instruments

Running examples
Disclaimer

- A good MC user is not one that only masters technically the program

- BUT a user that:
  - Indeed masters technically the code;
  - Know its limitations and capabilities;
  - Can tune the simulation to the specific requirements and needs of the problem under study;

but most of all

  - Knows physics
  - Understand at the least the basic content of physics moldes in the code
  - Has a critical judgment on the results
An Introduction to FLUKA: a multipurpose Interaction and Transport MC code
Main authors: A. Fassò, A. Ferrari, J. Ranft, P.R. Sala

Contributing authors: G. Battistoni, F. Cerutti, M. Chin, T. Empl, M.V. Garzelli, M. Lantz, A. Mairani, V. Patera, S. Roesler, G. Smirnov,

6 GeV proton in Liquid Argon
Low E. neutron int.

h-A interaction
E-M showers
Decay

Multiple Scattering

dE/dx and δ

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>4000 users

http://www.fluka.org
The FLUKA international Collaboration


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Alghero, June 2012 G. Battistoni
FLUKA is a fully integrated particle physics MonteCarlo simulation package. It has many applications in high energy experimental physics and engineering, shielding, detector and telescope design, cosmic ray studies, dosimetry, medical physics and radio-biology.
Registering and downloading FLUKA

Important Note:

In order to be able to download software from the FLUKA website it is mandatory to be registered as FLUKA user. Follow the registration process or proceed to the download area if you already are a registered FLUKA user.

Until you register you will have access to certain places on the website.

If you don't have your FUID assigned:  
Registered user:

If you wish to get information concerning your account and/or manage details/password etc. use Account Info functions:
FLUKA Applications

- Cosmic ray physics
- Neutrino physics
- Accelerator design (→ n_toF, CNGS, LHC systems)
- Particle physics: calorimetry, tracking and detector simulation etc. (→ ALICE, ICARUS, ...)
- ADS systems, waste transmutation, (→“Energy amplifier”, FEAT, TARC,...)
- Shielding design
- Dosimetry and radioprotection
- Space radiation
- Hadrontherapy
- Neutronics

Regions of high losses (e.g., Collimators,...)
Regions with low losses (e.g., due to residual gas)

The LHC Loss Regions

Point 1
Point 2
Point 3.2
Point 3.3
Point 4
Point 5
Point 6
Point 7
Point 8
ALICE
LHCb
Momentum Cleaning
RF
CMS
LHC Dump
Betatron Cleaning

Alghero, June 2012

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The History

The beginning:

1962: Johannes Ranft (Leipzig) and Hans Geibel (CERN): Monte Carlo for high-energy proton beams

The name:

1970: study of event-by-event fluctuations in a NaI calorimeter (FLUktuierende KAskade)

Early 70’s to ≈1987: J. Ranft and coworkers (Leipzig University) with contributions from Helsinki University of Technology (J. Routti, P. Aarnio) and CERN (G.R. Stevenson, A. Fassò)

Link with EGS4 in 1986, later abandoned

The modern code: some dates

Since 1989: mostly INFN Milan (A. Ferrari, P.R. Sala): little or no remnants of older versions. Link with the past: J. Ranft and A. Fassò

1990: LAHET / MCNPX: high-energy hadronic FLUKA generator No further update

1993: G-FLUKA (the FLUKA hadronic package in GEANT3). No further update

1998: FLUGG, interface to GEANT4 geometry

2000: grant from NASA to develop heavy ion interactions and transport

2001: the INFN FLUKA Project

2003: official CERN-INFN collaboration to develop, maintain and distribute FLUKA
The FLUKA Code design - 1

Sound and updated physics models

- Based, as far as possible, on original and well-tested microscopic models
- Optimized by comparing with experimental data at single interaction level: “theory driven, benchmarked with data”
- Final predictions obtained with minimal free parameters fixed for all energies, targets and projectiles
- Basic conservation laws fulfilled “a priori”
  - Results in complex cases, as well as properties and scaling laws, arise naturally from the underlying physical models
  - Predictivity where no experimental data are directly available

It is a “condensed history” MC code, with the possibility use of single instead of multiple scattering
The FLUKA Code design - 2

Self-consistency

- Full cross-talk between all components: hadronic, electromagnetic, neutrons, muons, heavy ions
- Effort to achieve the same level of accuracy:
  - for each component
  - for all energies
- Correlations preserved fully within interactions and among shower components

⇒ FLUKA is NOT a toolkit! Its physical models are fully integrated
The Physics Content of FLUKA

- 60 different particles + Heavy Ions
  - Nucleus-nucleus interactions from Coulomb barrier up to 10000 TeV/n
  - Electron and $\mu$ interactions 1 keV - 10000 TeV
  - Photon interactions 100 eV - 10000 TeV
  - Hadron-hadron and hadron-nucleus interactions 0-10000 TeV
  - Neutrino interactions
  - Charged particle transport including all relevant processes
  - Transport in magnetic fields
  - Neutron multigroup transport and interactions 0 - 20 MeV
  - Analog calculations, or with variance reduction
A glimpse of FLUKA
The FLUKA version

\textbf{FLUKA20xx.n(y)(.m)}

- **Major version**
- **Minor version**
- **Patch level**
- **Respin**

Since 2006 each version is going to be maintained for 2 years max.

**In this course we are using** \textbf{FLUKA2011.2}
The FLUKA license (it is not GPL):

- **Standard download: binary library + user routines.**
  - FLUKA can be used freely for scientific and academic purposes, ad-hoc agreement for commercial purposes
  - It cannot be used for weapon related applications
  - It is not permitted to redistribute the code (single user, single site)
  - Users can add their own scoring, sources, etc. through a wide set of user routines, provided they do not modify the physics
  - Relevant references for each FLUKA version can be found in the documentation

- **It is possible, by explicit signature of license, to download the source for researchers of scientific/academic Institutions.**
  
  (**!!! now from NEA as well !!!**)  
  - FLUKA can neither be copied into other codes (not even partially), nor translated into another language without permission.
  - The user cannot publish results with modified code, unless explicit authorization is granted in advance.
Using FLUKA

Platform: Linux with g77 and gfortran (only version > 4.5)

Work in progress: Mac OSX with gfortran

The code can be compiled/run only using operating systems, compilers (and associated) options tested and approved by the development team

---

Standard Input:

- Command/options driven by “data cards” (ascii file).
  Graphical interface is available!!!!

- Standard Geometry (“Combinatorial geometry”): input by “data cards”

---

Standard Output and Scoring:

- Apparently limited but highly flexible and powerful
- Output processing and plotting interface available
Code complexity

- Inelastic h-N: $\sim 72000$ lines
- Cross sections (h-N and h-A), and elastic (h-N and h-A): $\sim 32000$ lines
- (G)INC and preequilibrium (PEANUT): $\sim 114000$ lines
- Evap./Fragm./Fission/Deexc.: $\sim 27000$ lines
- $\nu$-N interactions: $\sim 35000$ lines
- A-A interactions:
  - FLUKA native (including BME): $\sim 8000$ lines
  - DPMJET-3: $\sim 130000$ lines
  - (modified) rQMD-2.4: $\sim 42000$ lines
- FLUKA in total (including transport, EM, geometry, scoring): $\sim 680000$ lines
- ... + $\sim 20000$ lines of ancillary off-line codes used for data pre-generation
- ... and $\sim 30000$ lines of post-processing codes
The FLUKA mailing lists

- fluka-users@fluka.org
  Users are automatically subscribed here when registering on the web site. It is used to communicate the availability of new versions, patches, etc.

- fluka-discuss@fluka.org
  Users are encouraged to subscribe at registration time, but can uncheck the relevant box. It is used to have user-user and user-expert communication about problems, bugs, general inquiries about the code and its physics content.

users are strongly encouraged to keep this subscription.
SOMETHING ABOUT THE PHYSICS CONTENT OF FLUKA
# The FLUKA hadronic model(s)

<table>
<thead>
<tr>
<th>Hadron-Hadron</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic, exchange</td>
<td></td>
</tr>
<tr>
<td>Phase shifts</td>
<td></td>
</tr>
<tr>
<td>Data, eikonal</td>
<td></td>
</tr>
<tr>
<td>P&lt;3-5 GeV/c</td>
<td></td>
</tr>
<tr>
<td>Resonance prod and decay</td>
<td></td>
</tr>
<tr>
<td>Low E π, K</td>
<td></td>
</tr>
<tr>
<td>Special</td>
<td></td>
</tr>
<tr>
<td>High Energy</td>
<td></td>
</tr>
<tr>
<td>DPM hadronization</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Hadron-Nucleus</th>
<th>Nucleus-Nucleus</th>
</tr>
</thead>
<tbody>
<tr>
<td>PEANUT</td>
<td>E&lt; 0.1 GeV/u BME</td>
</tr>
<tr>
<td>Sophisticated GINC</td>
<td>Complete fusion+ peripheral</td>
</tr>
<tr>
<td>Gradual onset of Glauber-Gribov multiple interactions</td>
<td>0.1&lt; E&lt; 5 GeV/u rQMD-2.4 modified new QMD</td>
</tr>
<tr>
<td>Preequilibrium Coalescence</td>
<td>E&gt; 5 GeV/u DPMJET DPM+ Glauber+ GINC</td>
</tr>
</tbody>
</table>

Evaporation/Fission/Fermi break-up
γ deexcitation
The Nuclear environment: PEANUT

PreEquilibrium Approach to Nuclear Thermalization

- PEANUT handles hadron-nucleus interactions from threshold (or 20 MeV neutrons) up to 5 GeV

Sophisticated Generalized IntraNuclear Cascade

Smooth transition (all non-nucleons emitted/absorbed/decayed + all secondaries below 30-50 MeV)

Pre-equilibrium stage

Standard Assumption on exciton number or excitation energy

Common FLUKA Evaporation/fission/fragmentation model

Peanut has proven to be a precise and reliable tool for intermediate energy hadron-nucleus reactions.

Its "nuclear environment" is also used in the modelization of (real and virtual) photonuclear reactions, neutrino interactions, nucleon decays, and muon captures..
Thin target example

Angle-integrated $^{90}$Zr(p,xn) at 80.5 MeV

The various lines show the total, INC, preequilibrium and evaporation contributions

Thin target examples

\[ p + ^{80}\text{Zr} \rightarrow p + X \ (80 \text{ MeV}) \]

\[ p + \text{Al} \rightarrow \pi^- + X \ (4 \text{ GeV/c}) \]
Thick/Thin target examples: neutrons

$^9\text{Be}(p,xn) @ 256 \text{ MeV, stopping target}
\text{Data: NSE110, 299 (1992)}$

$^9\text{Be}(p,xn), 256 \text{ MeV, thick target}$

$^\text{Pb}(p,xn) @ 3 \text{ GeV, thin target}$
\text{Data: NST32, 827 (1995)}

$^\text{Pb}(p,xn), 3.0 \text{ GeV}$
Equilibrium particle emission

- **Evaporation**: Weisskopf-Ewing approach
  - 600 possible emitted particles/states ($A<25$) with an extended evaporation/fragmentation formalism
  - Full level density formula
  - Inverse cross section with proper sub-barrier
  - Analytic solution for the emission widths
  - Emission energies from the width expression with no. approx.
  - New energy dependent self-consistent evaporation level densities (IAEA recommendations)
  - New pairing energies consistent with the above point
  - Extension of mass tables till $A=330$ using available offline calculations
  - New shell corrections coherent with the new masses

- **Fission**:
  - Actinide fission done on first principles
  - New fission barrier calculations (following Myers & Swiatecki)
  - Fission level density enhancement at saddle point washing out with excitation energy (following IAEA recommendations)
  - Fission product widths and asymmetric versus symmetric probabilities better parameterized

- **Fermi Break-up** for $A<18$ nuclei
  - ~ 50000 combinations included with up to 6 ejectiles

- **$\gamma$ de-excitation**: statistical + rotational + tabulated levels
Example of fission/evaporation

- Quasi-elastic products
- Spallation products
- Deep spallation products
- Fission products
- Fragmentation products
- Evaporation products

Heavy ion interaction models

- **DPMJET-III** for energies ≥ 5 GeV/n
  - **DPMJET** (R. Engel, J. Ranft and S. Roesler) Nucleus-Nucleus interaction model
  - Energy range: from 5-10 GeV/n up to the highest Cosmic Ray energies (10^{18}-10^{20} eV)
  - Used in many Cosmic Ray shower codes
  - Based on the Dual Parton Model and the Glauber model, like the high-energy FLUKA hadron-nucleus event generator

- **Modified and improved version of rQMD-2.4** for 0.1 < E < 5 GeV/n
  - **rQMD-2.4** (H. Sorge et al.) Cascade-Relativistic QMD model
  - Energy range: from 0.1 GeV/n up to several hundred GeV/n
  - Successfully applied to relativistic A-A particle production

- **BME (BoltzmannMasterEquation)** for E < 0.1 GeV/n
  - FLUKA implementation of BME from E.Gadioli et al (Milan)
  - Now under test for A ≤ 16

- **Standard FLUKA evaporation/fission/fragmentation** used in both Target/Projectile final deexcitation ⇒ *Projectile-like evaporation is responsible for the most energetic fragments*

- Electromagnetic dissociation
Typical neutron cross section

Resonances $\Rightarrow$ energy levels in compound nucleus $^{A+1}Z^*$

Resonance spacing too dense $\Rightarrow$ overlapping resonances

Resonance spacing few eV

Resolution region

Unresolved resonance region

$E_{\text{kin}}$: incident neutron

$\sigma_{\text{tot}}$: total cross section

$\sigma_{\infty} \approx 1/\nu$: thermal cross section
Evaluated Nuclear Data Files

- Evaluated nuclear data files (ENDF, JEFF, JENDL...) typically provide neutron $\sigma$ (cross sections) for $E<20\text{MeV}$ for all channels.
- $\sigma$ are stored as continuum + resonance parameters.
- Complex programs like NJOY, PREPRO convert the ENDF file to P-ENDF (point-wise cross sections), or G-ENDF (group-wise) including Doppler broadening etc.

Point-wise and Group-wise cross sections

- In neutron transport codes in general two approaches used: point-wise ("continuous" cross sections) and group-wise transport.
- Point-wise follows cross section precisely but is can be time and memory consuming.
- Group approach is widely used in neutron transport codes because it is fast and gives good results for most applications.
Group Transport Technique

- The energy range of interest is divided in a given number of discrete intervals ("energy groups")

- Elastic and inelastic reactions simulated not as exclusive processes, but by group-to-group transfer probabilities (downscattering matrix)

- Downscattering matrix: if a neutron in a given group undergoes a scattering event and loses energy, it will be transferred to a group of lower energy (each of the lower energy groups having a different probability)

- If the neutron does not lose enough energy to be in another group, it will stay in the same group (in-scattering).

- In thermal region neutrons can gain energy. This is taken into account by an upscattering matrix, containing the transfer probability to a group of higher energy
The FLUKA Low Energy Neutron Library

- FLUKA uses the multigroup transport technique
- The energy boundary below which multigroup transport takes over depends in principle on the cross section library used. In the present library it is 20 MeV.
- Both fully biased and semi-analog approaches are available
- Number of groups: 260 of approximately equal logarithmic with, the actual energies limits of each group can be found in the manual (or can be printed to *.out file)
- N.B. the group with the highest energy has the number 1, the group with the lowest energy has number 260
- 31 thermal groups, with 30 upscattering groups
- Energy range of library: 0.01 meV - 20 MeV
Simulation of neutron spectrum from reactor (Pavia)

Energy Spectra

MCNP from Pavia group (S. Altieri et al.)
EM Physics

- General settings
- Interactions of leptons/photons
  - Photon interactions
    - Photoelectric
    - Compton
    - Rayleigh
    - Pair production
    - Photonuclear
    - Photomuon production
  - Electron/positron interactions
    - Bremsstrahlung
    - Scattering on electrons
  - Muon interactions
    - Bremsstrahlung
    - Pair production
    - Nuclear interactions
- Ionization energy losses
  - Continuous
  - Delta-ray production
- Transport
  - Multiple scattering
  - Single scattering

These are common to all charged particles, although traditionally associated with EM
Compton profile examples

green = free electron
blue   = binding with form factors
red    = binding with shells and orbital motion

Larger effect at very low energies, where, however, the dominant process is photoelectric.
Visible: shell structure near $E' = E$, smearing from motion at low $E'$
Compton and Rayleigh

- Account for atomic bonds using inelastic Hartree-Fock form factors (very important at low E in high Z materials)
- NEW: Compton with atomic bonds and orbital motion (as better alternative to form factors)
  - Atomic shells from databases
  - Orbital motion from database + fit
  - Followed by fluorescence
- Account for effect of photon polarization
Bremsstrahlung: benchmark

2 MeV electrons on Iron, Bremsstrahlung photon spectra measured (dots) and simulated (histos) at three different angles.
Electron scattering:

Transmitted (forward) and backscattered (backward) electron angular distributions for 1.75 MeV electrons on a 0.364 g/cm² thick Copper foil. Measured (dots) and simulated (histos) data.
Photonuclear int.: example

Reaction:
$^{208}\text{Pb}(\gamma, x\ n)$
$20 \leq E_\gamma \leq 140 \text{ MeV}$

Cross section for multiple neutron emission as a function of photon energy. Different colors refer to neutron multiplicity $\geq n$, with $2 \leq n \leq 8$

Symbols: exp. data (NPA367, 237 (1981); NPA390, 221 (1982))

Lines: FLUKA
Muon-induced neutron background in underground labs

Neutron production rate as a function of muon energy

Stars+line: FLUKA simulation with a fit to a power law.

Exp. points:
- abscissa → average $\mu$ energy at the experiment's depth:
  - A) 20 m.w.e.
  - B) 25 m.w.e.
  - C) 32 m.w.e. (Palo Verde)
  - D) 316 m.w.e.
  - E) 750 m.w.e.
  - F) 3650 m.w.e. (LVD)
  - G) 5200 m.w.e. (LSD)
Charged particle $dE/dx$: Bethe-Bloch

Spin 0
(spins 1 is similar):

$$
\frac{dE}{dx}_0 = \frac{2\pi n_e r_e^2 m_e c^2 Z^2}{\beta^2} \left[ \ln \left( \frac{2m_e c^2 \beta^2 T_{\text{max}}}{I^2 (1 - \beta^2)} \right) - 2\beta^2 + 2zL_1(\beta) + 2z^2 L_2(\beta) - 2 \frac{C}{Z} - \delta + G \right]
$$

- $I$ : mean excitation energy, material-dependent
- $\delta$ : density correction
- $C$ : is the shell correction, important at low energies
- $T_{\text{max}}$ : maximum energy transfer to an electron (from kinematics)

Higher order corrections implemented in FLUKA

- $L_1$ : Barkas ($z^3$) correction responsible for the difference in stopping power for particles-antiparticles
- $L_2$ : the Bloch ($z^4$) correction
- $G$ : Mott corrections

Valid for $m \gg m_e$. However, the formulation for electron/positrons is similar, with the exception of “energetic” collisions with atomic electrons.
Discrete ionization events

Above a pre-set threshold, ionization is modeled as $\delta$ ray production (free electrons)
  - Spin 0 or 1/2 $\delta$-ray production (charged hadrons, muons)
  - Mott for heavy ions
  - Bhabha scattering ($e^+$)
  - Møller scattering ($e^-$)

Below the pre-set threshold for $\delta$ ray production:

Restricted energy losses

For particles much heavier than electrons and charge $z$, with energy transfers to atomic electrons restricted at $T_\delta$
Continuous energy losses

Below the δ-ray threshold, energy losses are treated as “continuous”, with some special features:

• Fluctuations of energy loss are simulated with a FLUKA-specific algorithm
• The energy dependence of cross sections and dE/dx is taken into account exactly (see later)
• Latest recommended values of ionization potential and density effect parameters implemented for elements (Sternheimer, Berger & Seltzer), but can be overridden by the user with (set yourself for compounds!)
Ionization fluctuations

Experimental \(^1\) and calculated energy loss distributions for 2 GeV/c positrons (left) and protons (right) traversing 100\(\mu\)m of Si \(^\text{J.Bak et al. NPB288, 681 (1987)}\)

Alghero, June 2012

G. Battistonil
Nuclear stopping power (NEW)

- Besides Coulomb scattering with atomic **electrons**, particles undergo Coulomb scattering also with atomic **nuclei**
- The resulting energy losses, called nuclear stopping power, are smaller than the atomic ones, but are important for
  - Heavy particles (i.e. ions)
  - Damage to materials
INSTALLING FLUKA
How to download and install FLUKA

Two ways of downloading the FLUKA software:

- From the FLUKA website [http://www.fluka.org](http://www.fluka.org)
- From NEA databank [http://www.nea.fr](http://www.nea.fr) through the liaison officer from your institute

It is mandatory to be registered as FLUKA user. Follow the link:

[http://www.fluka.org/download.html](http://www.fluka.org/download.html)

After registration (or using your user-id and password) you can proceed in downloading the latest official release version.
How to download and install FLUKA

First identify the location of the FLUKA distribution file: fluka2011.2-linuxAA.tar.gz
Depending on the operating system and the method you used most probably will be located in one of the following directories:

```
/media/FLUKA/Software # in case you are using the USB stick
or $HOME # if you downloaded from the web
$HOME/Desktop # depending on your browser
```

We will create a directory FLUKA under your home directory to install FLUKA. The following commands issued from a terminal/console window will perform the entire installation.

```
cd # changes directory to your home
mkdir FLUKA # creates a directory called FLUKA
cd FLUKA # changes to the FLUKA directory
tar xzf /media/FLUKA/Software/fluka2011.2-linuxAA.tar.gz # expands the FLUKA package

# set FLUPRO environment variable
export FLUPRO=$HOME/FLUKA # sets FLUPRO in bash shell or similar
or setenv FLUPRO $HOME/FLUKA # sets FLUPRO in tcsh shell or similar
make # compiles a FLUKA executable and auxiliary programs
```
Persistent settings

To make these settings persistent on your computer, i.e., you don’t have to set the FLUPRO environment variable again when you open a new terminal or log into your computer, we will add the following lines into your shell configuration file in your main directory.

**bash users:**

```
cd
emacs [or any editor] .bashrc
```

add the following:

```
export FLUPRO=${HOME}/FLUKA
export PATH=${PATH}:${FLUPRO}:${FLUPRO}/flutil
```

**tcsh users:**

```
cd
emacs [or any editor] .tcshrc
```

add the following:

```
setenv FLUPRO ${HOME}/FLUKA
setenv PATH ${PATH}:${FLUPRO}:${FLUPRO}/flutil
```

The changes will be activated on the next login or if you type the command:

```
source .bashrc
source .tcshrc
```
FLUKA release: main directory $FLUPRO

Main Library:
libflukahp.a (object collection)

Physics data files:
sigmapi.bin
elasct.bin
brems_fin.bin
cohff.bin
gxsect.bin
neuxsc-ind_260.bin
nuclear.bin
fluodt.dat
e6r1nds3.fyi
jef2.fyi
jendl3.fyi
xnloan.dat
Fad/*
DDS/*

Basic Scripts: (in $FLUPRO/flutil)
  rfluka
  lfluka
  fff

Random Number seed
  random.dat

Important Directories
  flukapro/ all FLUKA commons
  usermvax/ user routines
  flutil/ general utilities
What’s inside the physics data files:

<table>
<thead>
<tr>
<th>File</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>sigmapi.bin</td>
<td>pion-N double-diff. cross sections</td>
</tr>
<tr>
<td>elasct.bin</td>
<td>elastic scattering cross sections</td>
</tr>
<tr>
<td>brems_fin.bin</td>
<td>Bremsstrahlung cross sections</td>
</tr>
<tr>
<td>cohff.bin</td>
<td>atomic form factor tabulations</td>
</tr>
<tr>
<td>gxsect.bin</td>
<td>photon cross sections</td>
</tr>
<tr>
<td>neuxsc-ind_260.bin</td>
<td>low energy neutron multi-group cross sections (260 groups)</td>
</tr>
<tr>
<td>nuclear.bin</td>
<td>nuclear masses, mass excesses, levels, and many other nuclear data for evaporation, pre-equilibrium, Fermi break up and photonuclear cross sections gamma and beta databases</td>
</tr>
<tr>
<td>fluodt.dat</td>
<td>Fluorescence data (photoelectric effect)</td>
</tr>
<tr>
<td>e6r1nds3.fyi</td>
<td>Fission products (for neutrons with E&lt;20 MeV)</td>
</tr>
<tr>
<td>jef2.fyi</td>
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<tr>
<td>jendl3.fyi</td>
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<tr>
<td>xnloan.dat</td>
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<tr>
<td>Fad/*</td>
<td>BME pre-equilibrium particle angular distribution</td>
</tr>
<tr>
<td>DDS/*</td>
<td>BME pre-equilibrium particle energy spectra</td>
</tr>
</tbody>
</table>
Available Documentation

- fluka2011.manual  ASCII version of the manual (easy to edit)
- FM.pdf  current version of the FLUKA manual
- CERN-2005-10.pdf  official reference for FLUKA (manual not up to date)
- or navigate the manual, online version (www.fluka.org)

- or (when using FLAIR) press F1 to get an interactive manual (which can be also called on prompt level by calling 'fm.py')

- or (at a further stage) the FAQ available at: http://www.fluka.org/fluka.php?id=faq&mm2=3
- or (at a further stage) the archive of fluka-discuss: http://www.fluka.org/MailingList.html
- Release notes
USING FLUKA IN A NUTSHELL
Input example

- FLUKA is driven by the user almost completely by means of an input file (.inp) which contains directives issued in the form of DATA CARDS.
- The standard release provides a simple case to test the installation: example.inp *(Production of particles in p-Be collisions with a 50GeV/c proton beam.)*
- Different examples are used along this course, which will be varied in different ways for didactic reasons.
- For most of basic applications, users do not need to write code.
- This is of course not always possible, therefore at some time FLUKA users need to learn how to code and link User Routines...
A Simple Example

**TITLE**
FLUKA Course Exercise

**DEFAULTS**
BEAM
-3.5 -0.082425 -1.7 0.0 0.0 1.0 PROTON
BEAMPOS
0.0 0.0 0.1 0.0 0.0 0.0

**GEOBEGIN**
0 0 Cylindrical Target
SPH BLK 0.0 0.0 0.0 10000.
* vacuum box
RPP VOI -1000. 1000. -1000. 1000. -1000. 1000.
* Lead target
RCC TARG 0.0 0.0 0.0 0.0 0.0 10. 5.
END
* Regions
* Black Hole
BLKHOLE 5 +BLK -VOI
* Void around
VAC 5 +VOI -TARG
* Target
TARGET 5 +TARG
END
GEOEND

**ASSIGNMA**
BLCKHOLE BLKHOLE
VACUUM VAC
LEAD TARGET

**RANDOMIZ**
1.0
START 10.0 0.0
STOP
It is often said that Monte Carlo (MC) is a “mathematical experiment”. The MC equivalent of the result of a real experiment (i.e., of a measurement) is called an estimator.

Just as a real measurement, an estimator is obtained by sampling from a statistical distribution and has a statistical error (and in general also a systematic one).

There are often several different techniques to measure the same physical quantity: in the same way the same quantity can be calculated using different kinds of estimators.

FLUKA offers numerous different estimators, i.e., directly from the input file the users can request scoring the respective quantities they are interested in.

As the latter is implemented in a very complete way, users are strongly encouraged to preferably use the built-in estimators with respect to user-defined scoring.

For additional requirements FLUKA user routines are provided.
Built-In and User Scoring

- Several pre-defined estimators can be activated in FLUKA.
- One usually refers to these estimators as “scoring” capabilities.
- Users have also the possibility to build their own scoring through user routines, HOWEVER:
  - Built-in scoring covers most of the common needs.
  - Built-in scoring has been extensively tested.
  - Built-in scoring takes BIASING weights automatically into account.
  - Built-in scoring has refined algorithms for track subdivision.
  - Built-in scoring comes with utility programs that allow to evaluate statistical errors.
- Scoring can be geometry dependent AND/OR geometry independent.
- FLUKA can score particle fluences, current, track length, energy spectra, Z spectra, energy deposition...
- Either integrated over the “run”, with proper normalization, OR event-by-event.
- Standard scoring can be weighted by means of simple user routines.
Related Scoring Commands (main cases)

- **USRTRACK**, **USRCOLL** score average $d\Phi/dE$ (differential fluence) of a given type or family of particles in a given region.
- **USRBDX** scores average $d^2\Phi/dEd\Omega$ (double-differential fluence or current) of a given type or family of particles on a given surface.
- **USRBIN** scores the spatial distribution of energy deposited, or total fluence (or star density, or momentum transfer) in a regular mesh (cylindrical or Cartesian) described by the user.
- **USRYIELD** scores a double differential yield of particles escaping from a surface. The distribution can be with respect to energy and angle, but also other more “exotic” quantities.
- **SCORE** scores energy deposited (or star density) in all regions.
- The output of **SCORE** will be printed in the main (standard) output, written on logical output unit LUNOUT (pre-defined as 11 by default).
- All other detectors write their results into logical output units assigned by the user (the unit numbers must be >20).
** energy deposition

This is an R-Z-Φ binning (what(1)=11), scoring energy deposition (generalized particle ENERGY, or 208), writing the unformatted output on unit 40, spanning 0<R<10 in 100 bins, 0<Φ<2π in 1 bin (default), -5<z<15 in 200 bins.

** neutron fluence

This is a R-Z-Φ binning (what(1)=11), scoring neutron fluence, writing the unformatted output on unit 40, spanning 0<R<10 in 100 bins, 0<Φ<2π in 1 bin (default), -5<z<15 in 200 bins.
USRBIN → The Result

\( \text{WHAT(2)} = \text{ENERGY} \) : Energy deposition from a 3.5 GeV proton beam hitting at \([0.,0.,0.]\) directed along z results are normalized to GeV/cm\(^3\) per primary
Same, \texttt{WHAT(2)= NEUTRON} to get neutron fluence
results are normalized to particles/cm$^2$ per primary
USRBIN $\rightarrow$ The Result

Same, $\text{WHAT(2)} = \text{HAD-CHAR}$ to get charged hadron fluence results are normalized to particles/cm$^2$ per primary
User Routines

- Fluka offers a rich choice of options for scoring most quantities and for applying variance reduction techniques, without requiring the users to write a single line of code.

- However there are special cases where “ad-hoc” routines are unavoidable, because the required information cannot be obtained through standard options.

- A number of template of user routines (available in the usermvax directory) can be modified/activated by the user allow to fulfill non-standard tasks
A first look at the correspondence between some of the user routines and FLUKA commands

Emphasis of this lecture is here

- **USRGCALL**
  - usrglo.f

- **USRICALL**
  - usrini.f (usrein.f)

- **SOURCE**
  - source.f

- **MAT-PROP**
  - USRmed.f

- **USERDUMP**
  - mgdraw.f

- **USERWEIG**
  - comscw.f
  - fluscw.f
  - usrrnc.f

- **USROCALL**
  - usrout.f (usreou.f)
THE FLUKA COMBINATORIAL GEOMETRY
Introduction

Principle of Combinatorial Geometry: Basic convex shapes (bodies) such as cylinders, spheres, parallelepipeds, etc. are combined to more complex shapes called regions. This combination is done by the boolean operations union, intersection and subtraction.

The Combinatorial Geometry of FLUKA was initially similar to the package developed at ORNL for the neutron and gamma-ray transport program Morse (M.B. Emmett ORNL-4972 1975) which was based on the original combinatorial geometry by MAGI (Mathematical Applications Group, Inc., W. Guber et al, MAGI-6701 1967).
Basic Concepts

Four concepts are fundamental in the FLUKA CG:

- **Bodies** - basic convex objects, plus infinite planes, infinite cylinders and generic quadric surfaces
- **Zones** - sub-regions defined only with intersection and subtraction of bodies
- **Regions** - defined as boolean operations of bodies (union of zones)
- **Lattices** - duplication of existing objects (translated & rotated), will be explained in a separate lecture

In the original description (Morse) bodies were convex solid bodies (finite portions of space completely delimited by surfaces of first or second degree, i.e. planes or quadrics). In FLUKA, the definition has been extended to include infinite cylinders (circular and elliptical), planes (half-spaces), and generic quadrics (surfaces described by 2nd degree equations)

Use of such “infinite bodies” is encouraged since it makes input less error-prone. They also provide a more accurate and faster tracking.
Bodies

- Each body divides the space into two domains inside and outside. The outside part is pointed to by the normal to the surface.
- 3-character code of available bodies:
  - RPP: Rectangular Parallelepiped
  - SPH: SPHere
  - XYP, XZP, YZP: Infinite half space delimited by a coordinate plane
  - PLA: Generic infinite half-space, delimited by a PLAne
  - XCC, YCC, ZCC: Infinite Circular Cylinder, parallel to coordinate axis
  - XEC, YEC, ZEC: Infinite Elliptical Cylinder, parallel to coordinate axis
  - RCC: Right Circular Cylinder
  - REC: Right Elliptical Cylinder
  - TRC: Truncated Right angle Cone
  - ELL: ELLipsoid of revolution
  - QUA: QUAdric
Example of Bodies

Infinite circular cylinder

Infinite half-space parallel to coordinate axis

Arbitrarily oriented infinite half-space

Arbitrary generic quadric: corresponding to the equation:

\[ A_{xx} x^2 + A_{yy} y^2 + A_{zz} z^2 + A_{xy} xy + A_{xz} xz + A_{yz} yz + A_x x + A_y y + A_z z + A_0 = 0 \]
The Black Hole

To avoid infinite tracking the particles must be stopped somewhere. This has to be insured by the user by defining a region surrounding the geometry and assigning the material **BLCKHOLE** to it.

The outer surface of this region must be defined by a single closed body (generally an RPP or a Sphere).

All particles that enter the blackhole are absorbed (they disappear). Further blackhole regions can be defined by the user if necessary.

The blackhole is the outermost boundary of the geometry. Inside its outer surface:

**Each point of space must belong to one and only one region!**
Combinatorial Geometry Input

CG input must respect the following sequential order:

**GEOBEGIN** card

**VOXELS** card (optional, see Voxel lecture)

Geometry title (and reading format options)

Body data

**END** card (not needed in flair)

Region data

**END** card (not needed in flair)

**LATTICE** cards (optional, see Lattice lecture)

Region volumes

(optionally requested by a flag in the Geometry title, used together with the **SCORE** command)

**GEOEND** card

Cards having a * in column 1 are treated as comments.
Concept of Region

Regions are defined as combinations of bodies obtained by boolean operations:

<table>
<thead>
<tr>
<th></th>
<th>Union</th>
<th>Subtraction</th>
<th>Intersection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free Format</td>
<td></td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>Fixed format</td>
<td>OR</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>Mathematically</td>
<td>∪</td>
<td>–</td>
<td>∩</td>
</tr>
</tbody>
</table>

Regions are not necessarily simply connected (they can be made as the union of two or more non contiguous or partially overlapping zones) but must be of homogeneous material composition.
Illustration of the + and - operators
Example: build a cylindrical collimator

Define 2 coaxial cylindrical bodies (for ex. RCC) having the same length and position: $\text{Cyl1}$ and $\text{Cyl2}$

Define the region $\text{Collim}$ as the region of space inside body $\text{Cyl1}$ and outside body $\text{Cyl2}$. This is achieved by “subtracting” $\text{Cyl2}$ from $\text{Cyl1}$: $+\text{Cyl1} - \text{Cyl2}$
A better solution in FLUKA (even if it doesn’t seem obvious)

Use infinite bodyes: 2 coaxial infinite cylinders (ZCC) cut by two infinite planes (XYP)
Define this region as BLACKHOLE

Fill this region with VACUUM (or Air...)

Typical set-up
Advanced geometries

- Voxel geometry (fundamental for medical physics applications)
- Lattice geometry (to replicate in space a basic cell structure. Very useful, for example in detector simulations)
Auxiliary program: Simple Geo

SimpleGeo is an interactive solid modeler which allows for flexible and easy creation of the models via drag & drop, as well as on-the-fly inspection.

Imports existing geometries for viewing

Creating new geometries from scratch

Export to various formats (FLUKA, MCNP, MCNPX)

Download, Tutorials, etc.: http://theis.web.cern.ch/theis/simplegeo

Operating system: Windows only
Learning FLUKA at home

<table>
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<th>Download</th>
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| Last version:          | FLUKA 2011.2.13, May 15th 2012 | (last respin ) | FLAIR 0.9.5 |

| News:                  | Fluka Release (16.05.2012) | FLUKA 2011.2.13 has been released. |

- **12th FLUKA Course - Jefferson Lab 2012** *(April 30 - May 4, 2012)*
  - Jefferson Lab, Newport News, VA, USA
  - Course Website
  - [group photo]

- **11th FLUKA Course - Prague 2011** *(5 - 9 December 2011)*
  - Prague, Czech Republic
  - Course Website

- **10th FLUKA Course - Heidelberg 2011** *(28 March - 1 April 2011)*
  - Heidelberg, Germany
  - Course Website
  - [group photos]

- **1st Fluka Advanced Course and Workshop - Portugal 2010** *(4 - 8 October 2010)*
  - Ericeira, Portugal
  - Course Website
  - [group photo]
Follow all lectures and exercises!
Next courses

- 2012: Advanced course in TRIUMPH (Canada) in late September
- 2013: New beginner courses in Paris (NEA), CERN(?),...