Electron-Photon Transport

in FLUKA:

Status

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Some People Still Believe That. . .

- FLUKA is mainly a hadron code *This was true 13 years ago!*

  FLUKA is now an *all-particle* code, as good for electrons as for hadrons, muons and low-energy neutrons (and soon heavy ions. . .)

- Electron-photon transport in FLUKA is the same as EGS

  This was true 10 years ago!

  FLUKA has now evolved in a very different direction

- FLUKA is not available to the public

  This was true 5 years ago. Just ask us for it

- The source code is not generally available to the public

  This will still be true for a while

  (Isn't it the same true for many other codes presented here?)

Electrons and Photons in FLUKA

- **EMF** (**E**lectro**M**agnetic **F**luka) at a glance
- Physical Interactions
- Transport
- Technical Artefacts
- Biasing

EMF at a Glance

- Energy range for e^+,e^-,γ: 1 keV – 1000 TeV
- Full coupling in both directions

  with hadrons and low-energy neutrons
- Accuracy:
  - ⋆ table look-up privileged compared to analytical formulae
  - ⋆ energy conserved within computer (double) precision
- Speed:

  analytical sampling preferred to rejection technique
  (whenever possible)

Photoelectric Effect

- detailed treatment of fluorescence
  (all K and L shells and subshells down to 1 keV),
- photoelectron angular distribution
  according to relativistic theory of Sauter
- approximate treatment of Auger effect
- effect of photon polarization

Compton and Rayleigh Effects

- account for atomic bonds using inelastic Hartree-Fock form factors
- effect of photon polarization

Pair production

- detailed and correlated angular and energy distribution at all energies
  (in some codes, approximations are used to sample the electron energy at low photon energies)

Photonuclear Reactions

- Giant Resonance interaction
- Quasi-Deuteron effect
- interaction in the Delta Resonance energy region
- Vector Meson Dominance in the high energy region
- INC, preequilibrium and evaporation via the PEANUT model
- Possibility to bias the photon nuclear inelastic interaction length to enhance interaction probability

In not many other existing transport codes photonuclear reactions are simulated over the whole energy range

Electron Energy Loss

Discrete events:

delta-ray production above a user-defined threshold via

- Bhabha scattering
- Møller scattering

Continuous energy loss below threshold:

- latest recommended values of ionization potential and density effect parameters implemented (Sternheimer, Berger & Seltzer), but can be overridden on user's request
- special treatment of positron dE/dx (Kim et al. 1986)
- a new general approach to ionization fluctuations *(see later)*

Energy Dependent Quantities in an Electron Step (I)

- Most electron transport programs sample the next collision point evaluating the cross section at the beginning of the step, neglecting its energy dependence and the electron energy loss
- The cross section for δ ray production at low energies is roughly inversely proportional to electron energy
$\Longrightarrow$ a typical 20% fractional energy loss per step would correspond to a similar variation in the cross section
- Some codes use a rejection technique based on the ratio between the cross section values at the two step endpoints, but this approach is valid only for a monotonically decreasing cross section

Energy Dependent Quantities in an Electron Step (II)

FLUKA takes into account exactly the continuous energy dependence of:

- discrete event cross-section
- stopping power

basing the rejection technique on the ratio between the cross section value at the second endpoint and its maximum value between the two endpoint energies.

Ionization Fluctuations (I)

The Landau distribution is limited in several respects:

- Max. energy of δ rays assumed to be ∞ $\Longrightarrow$ cannot be applied for long steps or low velocities
- cross section for close collisions assumed equal for all particles
- fluctuations connected with distant collisions neglected $\Longrightarrow$ cannot be applied for short steps
- incompatible with explicit δ-ray production

The Vavilov distribution overcomes some of the Landau limitations, but is difficult to compute if step length or energy are not known *a priori*.

Ionization Fluctuations (II)

The FLUKA approach:

- based on general statistical properties of the cumulants of a distribution (in this case a Poisson distribution convoluted with $\mathbf{d}\boldsymbol{\sigma}/\mathbf{d}\boldsymbol{E}$)
- integrals can be calculated analytically and exactly *a priori* $\Longrightarrow$ minimal CPU time
- applicable to any kind of charged particle, taking into account the proper (spin-dependent) cross section for δ ray production
- the first 6 moments of the energy loss distribution are reproduced

Bremsstrahlung

- Energy-differential cross sections from Seltzer and Berger, interpolated to a finer energy mesh
- finite value at tip energy
- Extended to 1000 TeV taking into account the LPM effect
- Soft photon suppression (Ter-Mikaelyan) polarization effect
- Special treatment of positron bremsstrahlung
- Detailed photon angular distribution fully correlated to energy

Positron annihilation

at rest and in flight according to Heitler

Step Length Effects (I)

In many electron transport codes, results depend strongly on step size:

- Path Length Correction (PLC) required to account for straggling
- In general, PLC accuracy decreases with increasing step length
  $\Longrightarrow$ PLC can be overestimated even by large factors
  (especially in old codes based on Fermi-Eyges theory)
- Most Multiple Coulomb Scattering (MCS) models applicable only if step length is within some limits (energy and material-dependent)
- Effective scattering angle and lateral displacement
  are correlated with step length (and with each other)
- Magnetic fields and spatial boundaries (real or fictitious) affect the situation in a complex way

Step Length Effects (II)

- A solution often adopted: very short steps. But it is time consuming and there is no easy rule on “how short” they should be
- If steps are too short, the MCS model might fail
  (It can be proved that Fermi-Eyges algorithms may not even converge in high-Z materials, however small the steps!)
- FLUKA’s special algorithm *) makes results practically independent of step size, even when thin layers or magnetic fields are present, and does not require any “tuning”
- The FLUKA MCS algorithm can deal successfully even with backscattering problems at low energy, which are among the most difficult to simulate

*) Nucl. Instr. Meth. **B71** (1992) 412

Multiple Coulomb Scattering (I)

The FLUKA transport algorithm:

- More accurate PLC

  (not the average value but sampled from a distribution), giving a complete independence from electron step size
- Correct lateral displacement even near a boundary

  (not obtainable by Fermi-Eyges theory!)
- Correlations

$$\left\{ \begin{array}{ccc} \text{PLC} & \Longleftrightarrow & \text{lateral deflection} \\ \text{lateral displacement} & \Longleftrightarrow & \text{longitudinal displacement} \\ \text{scattering angle} & \Longleftrightarrow & \text{longitudinal displacement} \end{array} \right.$$

- variation with energy of the screening correction

Multiple Coulomb Scattering (II)

- spin-relativistic corrections (1^{st} or 2^{nd} Born approximation) and effect of nucleus finite size (form factors)
- special geometry tracking near boundaries, with automatic control of the step size
- on user request, single scattering automatically replaces multiple scattering for steps close to a boundary or too short to satisfy Molière theory. A full Single Scattering option is also available.
- Molière theory used strictly within its theoretical limits of validity
- combined effect of MCS and magnetic fields

Multiple Coulomb Scattering (III)

- As a result, FLUKA can correctly simulate electron backscattering even at very low energies and in most cases without switching off condensed history transport *(a real challenge for an algorithm based on Molière theory!)*
- The sophisticated treatment of boundaries allows also to deal successfully with gases, very thin regions and interfaces
- The same algorithm is used for charged hadrons and muons

Single Scattering

In very thin layers, wires, or gases, Molière theory does not apply.

In FLUKA, it is possible to replace the standard multiple scattering algorithm by single scattering in defined materials.

- cross section as given by Molière (for consistency)
- integrated analytically without approximations
- nuclear and spin-relativistic corrections are applied in a straightforward way by a rejection technique

Electron Backscattering

Energy (keV)	Material	Experim. (Drescher et al. 1970)	FLUKA Single scattering	FLUKA Multiple scattering	CPU time ratio single/mult.
9.3	Be	0.050	0.044	0.040	2.73
	Cu	0.313	0.328	0.292	1.12
	Au	0.478	0.517		1.00
102.2	Be	0.035	0.036	0.031	5.48
	Cu	0.291	0.307	0.288	3.00
	Au	0.513	0.499	0.469	1.59

Table 1: Fraction of normally incident electrons backscattered out of a surface. All statistical errors are less than 1%.

Boundary Crossing

Boundary crossing is not treated in any multiple scattering theory.

Critical situations such as a wiggly path repeatedly crossing a boundary are difficult to simulate correctly even when the boundary is not a real boundary between different materials, but has been introduced for scoring or biasing purposes.

In FLUKA:

- smooth approach to boundaries, obtained by progressively shortening the step as the charged particle approaches the boundary
- "one step back" correction, applied to steps truncated at a boundary, replaces the last step by one or more single scatterings

Scoring energy deposition in small volumes

In some problems, it is important to calculate spatial distributions of energy deposition with high resolution.

- Many Monte Carlo programs can only score energy deposition in regions defined for geometrical tracking
- If a detailed deposition pattern is required, a very large number of regions must be defined $\Longrightarrow$ very expensive in CPU time
- FLUKA provides a general facility (“binnings”) to score energy deposition in small volumes independent from geometry
- If the bin dimensions are smaller than an electron step, the energy lost in the step is not deposited at a single point, but is apportioned to the various bins traversed, according to the correspondent segments

Biasing

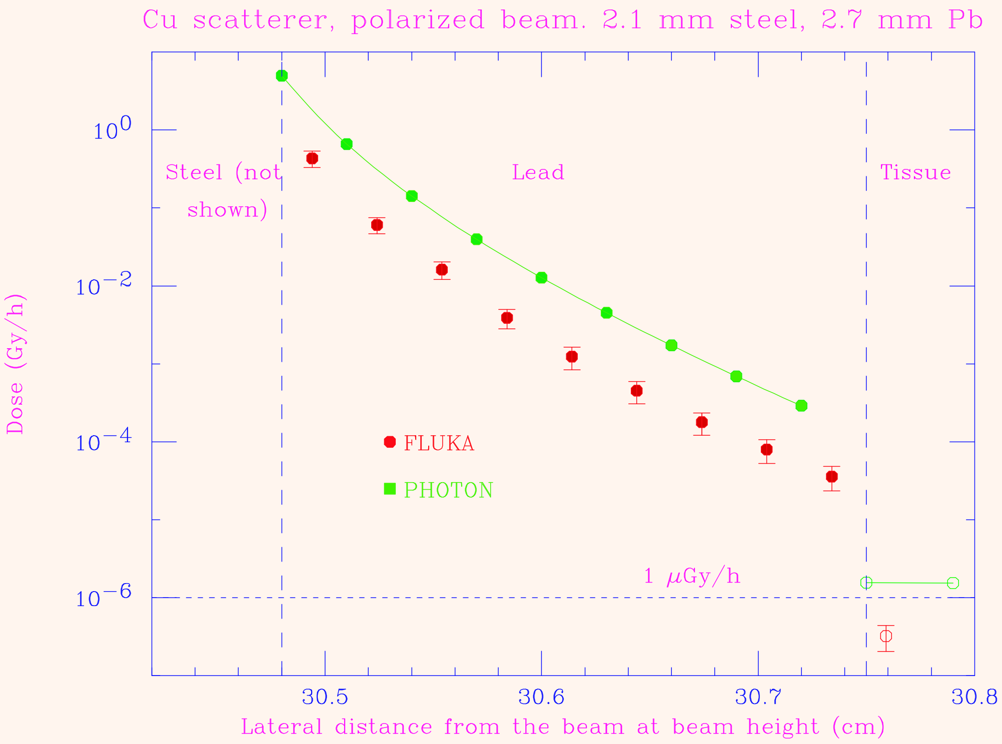
- The most important biasing techniques available in FLUKA (Importance Biasing, Weight Windows) can be applied to electrons and photons as well as to other particles
- Biasing of the nuclear inelastic mean free path is possible for all hadrons, but is especially useful with photons
- One particular technique, Leading Particle Biasing, is specific to EM particles:

  At each EM interaction, there are two particles in the final state. One of the two particles is discarded by a random test, while the other one is kept with an adjusted weight (the probability ratio being equal to the ratio of the respective energies).

Leading Particle Biasing

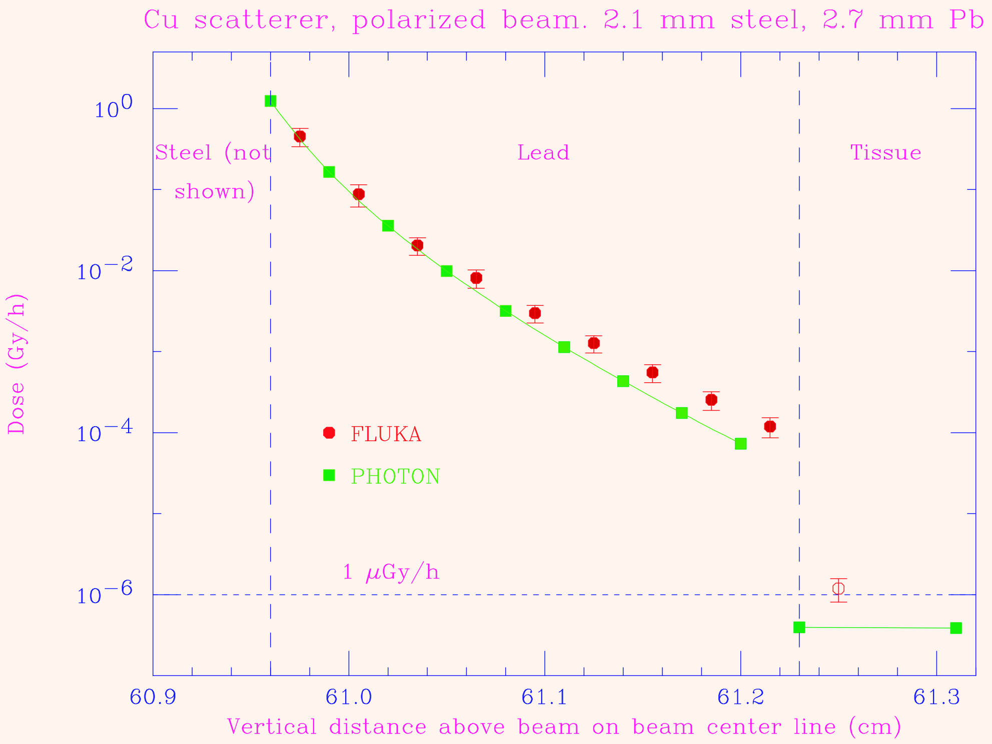
- CPU time increases linearly with primary energy, rather than exponentially
- Very useful for deep penetration calculations (punchthrough)
- Found (surprisingly) acceptable also for energy deposition
- Even better results if coupled with Weight Window fluctuation compression
- Very useful also for EM showers generated by π° in hadronic cascades
- Can be tuned by region, particle, energy and type of interaction

Synchrotron radiation



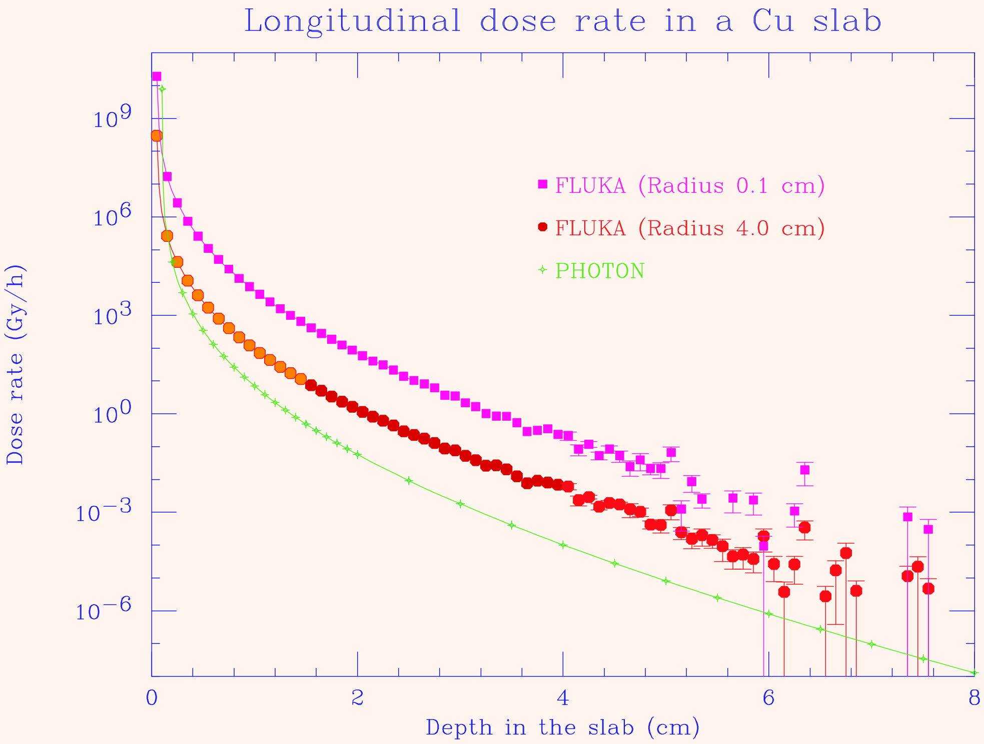
Attenuation of scattered SR in the lateral hutch shielding wall

Synchrotron radiation



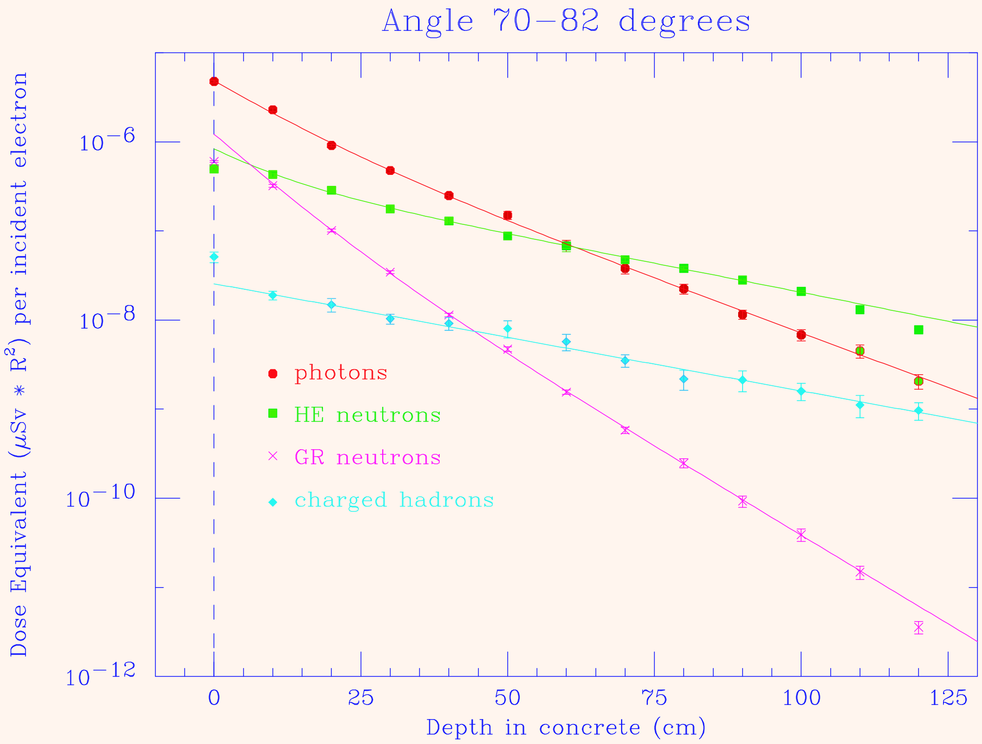
Attenuation of scattered SR in the hutch roof shielding

Synchrotron radiation



Attenuation of SR incident on a copper slab

Electron accelerator shielding

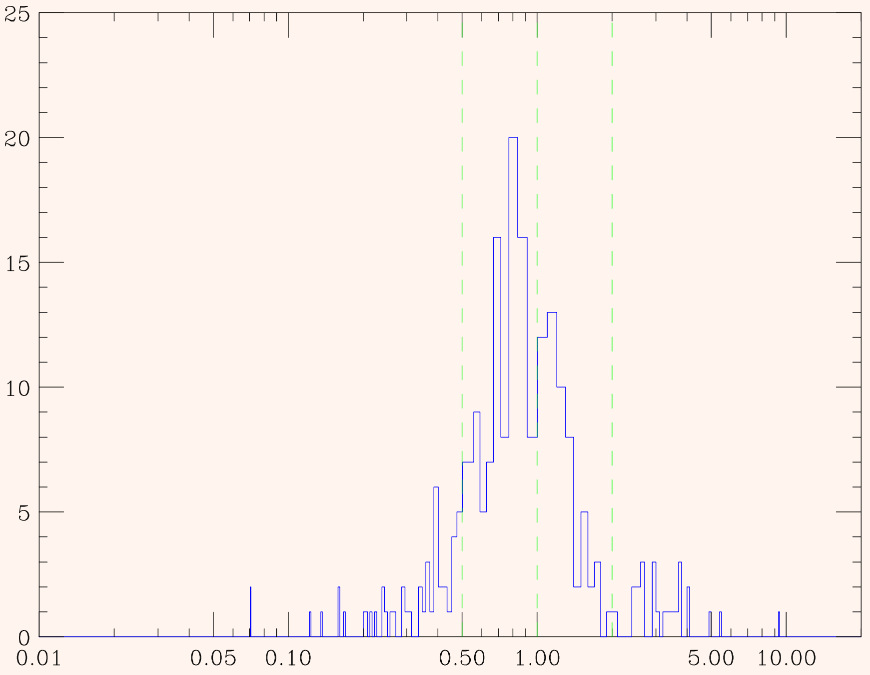


Attenuation in concrete of different radiation components

Residual nuclei

- FLUKA can also score directly residual nuclei produced in inelastic interactions
- Not perfect (poor prediction of nuclides with A $\ll$ parent nucleus due to lack of a fragmentation model), but already found useful to predict I.R. by proton beams
- Recent attempts to calculate residual nuclei produced in an EM cascade look promising
- At SLAC, the benchmark experiment of Sato et al. has been simulated, where thin Al, Fe, Cu and Nb foils were irradiated at different depths inside a thick Cu target in a 2.5 GeV electron beam

Simulation of an electron activation experiment



Distribution of ratios between FLUKA predictions and measured activities in the experiment of Sato et al. Dashed lines indicate a factor 2 about the measured value (69% of the points are contained in the corresponding band)

Simulation of an electron activation experiment

- Only one radionuclide (^{24}Na in Fe) was completely absent in the FLUKA results. Several others were predicted which were not measured in the experiment: ^{26}Al, ^{45}Ti, ^{55}Fe, ^{64}Cu, etc.
- Other nuclides for which FLUKA predictions are poor:
  ^{83}Sr and ^{86}Zr in Nb (overestimated by factor 3 to 4)
  and ^{84}Rb in Nb (underestimated by a factor 14)
- About 69% of the calculated values agree within a factor 2
- Best FLUKA results: ^{18}F in Al, ^{44}Sc, ^{48}V, ^{52}Fe, ^{51}Cr, ^{54}Mn in Fe, ^{52}Mn, ^{57}Co, ^{58}Co, ^{59}Fe in Cu, ^{88}Zr, ^{89}Zr, ^{88}Nb, ^{90}Nb in Nb

Residual nuclei in LEP

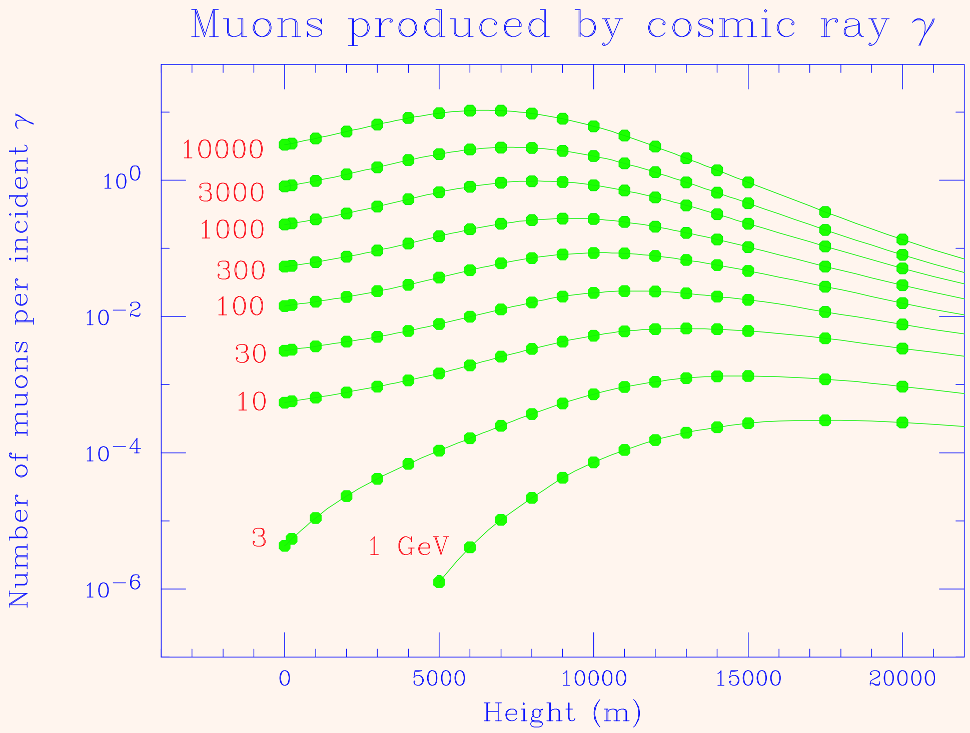
- Calculation of low level I.R. in materials present in LEP components (Al, Pb, stainless steel, Fe, Cu, iron-laminated concrete)
- Samples irradiated on the e^+ and e^- dumps during the entire LEP operation at 92 GeV (1997) and at 94.5 GeV (1998)
- Results:
  - ⋆ Most of the radionuclides produced in the materials considered were predicted by FLUKA
  - ⋆ Agreement with experimental data within a factor 2 in about 2/3 of the cases (sometimes even better)
  - ⋆ As expected, nuclides with $A \ll$ target nuclide were not predicted with good accuracy (^{7}Be in Al and ^{56}Co in Pb)
  - ⋆ Largest discrepancy: ^{52}Mn (prediction $\approx$ 4–5 times larger than experiment). In the comparison with the Sato experiment, the discrepancy was a factor 2–3

Residual nuclei in LEP

Radio nuclide	$T_{1/2}$	Specific Activity (Bq/g)			Ratio
		Exp.	FLUKA	(%)	F/E
^{46}Sc	83.8d	0.13	0.065	12	0.5
^{48}V	15.97d	0.31	0.52	7	1.7
^{51}Cr	27.7d	4.12	2.7	5	0.65
^{52}Mn	5.6d	0.17	0.74	6	4.3
^{54}Mn	312.2d	3.54	2.9	2	0.82
^{59}Fe	44.5d	0.028	0.0088	27	0.31
^{56}Co	77.7d	0.29	0.46	7	1.6
^{57}Co	271.8d	1.3	1.1	4	0.85
^{58}Co	70.9d	2.65	1.4	3	0.52
^{60}Co	5.27y	0.18	0.085	21	0.47
^{95}Nb	34.9d	0.038	0.013	27	0.34

Table 2: Stainless steel sample on the LEP electron dump. Exp. points ± 20%

Photoproduction of muons in atmosphere



Number of muons produced by photons vertically incident on the atmosphere, as a function of height for different γ energies