Update On the Status of the FLUKA Monte Carlo Transport Code

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FLUKA: **Interaction and transport Monte Carlo code**

- Nucleus-nucleus interactions 100 MeV/n – 10000 TeV/n
  (10 MeV/n for light Ions)
- Electromagnetic and μ interactions 1 keV – 10000 TeV
- Hadron-hadron and hadron-nucleus interactions 0–10000 TeV
- Neutrino interactions
- Charged particle transport including all relevant processes
- Transport in magnetic field
- Combinatorial (boolean) and Voxel geometry
- Neutron multigroup transport and interactions 0 – 20 MeV
- Analog calculations, or with variance reduction

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Some Fluka Applications

- **Cosmic Ray Physics**
- **Accelerator Design ($\rightarrow$ LHC systems)**
- **Experimental Particle Physics: calorimetry, tracking and detector simulation etc. ($\rightarrow$ ALICE, ICARUS, ...)**
- **Shielding Design (Reactor, Accelerator, Spacecraft)**
- **Dosimetry and Radioprotection**
- **Space Radiation Simulation (NASA-supported)**
- **Hadron Therapy**
- **Neutronics**
- **ADS systems ($\rightarrow$"Energy amplifier")**

Recent PHYSICS Updates and Improvements In the Current Release: FLUKA2005.6

- a) The online time evolution of radioactive products and associated remnant dose calculation capability has been added.
- b) PEANUT has been extended to cover pbar/nbar and, the elimination of Nucriv for p, n, pi's, pbar/nbar.
- c) ElectroMagnetic dissociation of heavy ions is now incorporated.
- d) The need to produce external preprocessed files as part of the electromagnetic initialization has now been removed.
- e) New photon cross sections have been included based on the Cullen EPDL97 LLNL database.
- f) A new photon coherent scattering model has been included with updated atomic form factors. Rayleigh scattering has been reworked from scratch with a novel approach.
- g) The photon photoelectric effect model has been updated with individual edges now accounted for down to eV's
- h) The photon pair production model has been updated, and now accounts for electron/positron asymmetries at low energies, as well as for departures from the plain Bethe-Heitler formalism.
- i) Introduction of a new fragmentation model which improves the performance with respect to the residual nuclei.

Code Design

- **Sound and modern physics**
  - 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***

Code Design

- **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 FLUKA hadronic models

Hadron-Nucleon

Elastic, exchange	P<3-5GeV/c	low E π, K	High Energy
Phase shifts, data,eikonal	Resonance prod. and decay	Special	DPM hadronization

Hadron-Nucleus

P<4-5GeV/c	High Energy
PEANUT: Sophisticated GINC preequilibrium Coalescence	Glauber-Gribov multiple interactions Coarser GINC Coalescence

Nucleus-Nucleus

E> 5 GeV/u
DPMJET-III
0.1< E < 5 GeV/u
(modified) rQMD-2.4

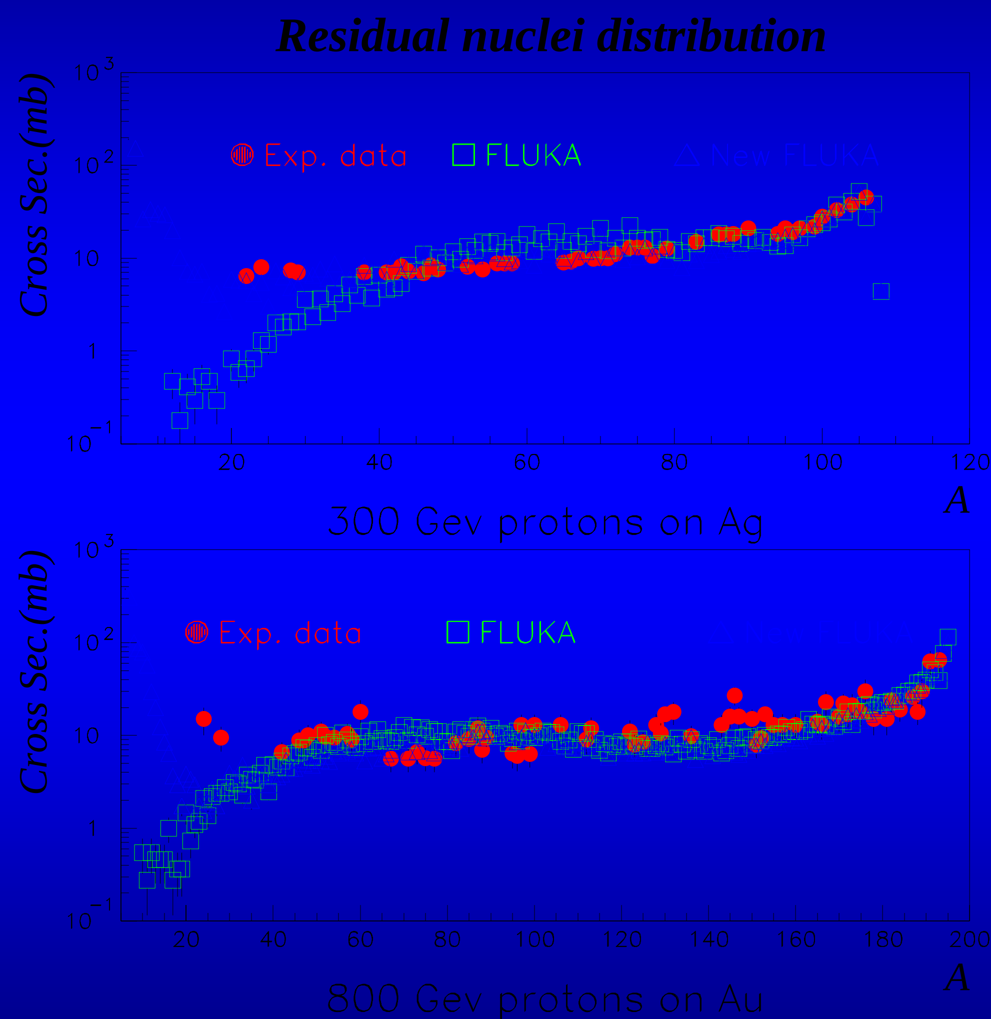
Evaporation/Fission/Fermi break-up
γ deexcitation

Residual nuclei

Experimental and computed residual nuclei mass distribution for Ag(p,x)X at 300 GeV (top) and Au(p,x)X at 800 GeV (bottom)

Data from
Phys. Rev. C19 2388 (1979) and
Nucl. Phys. A543, 703 (1992)

The new fragmentation model has recently much improved the FLUKA predictions



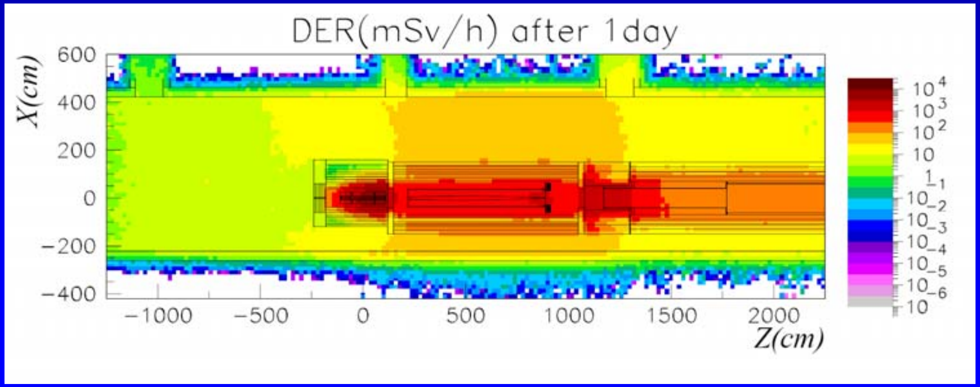
NEW

Online evolution of activation and residual dose

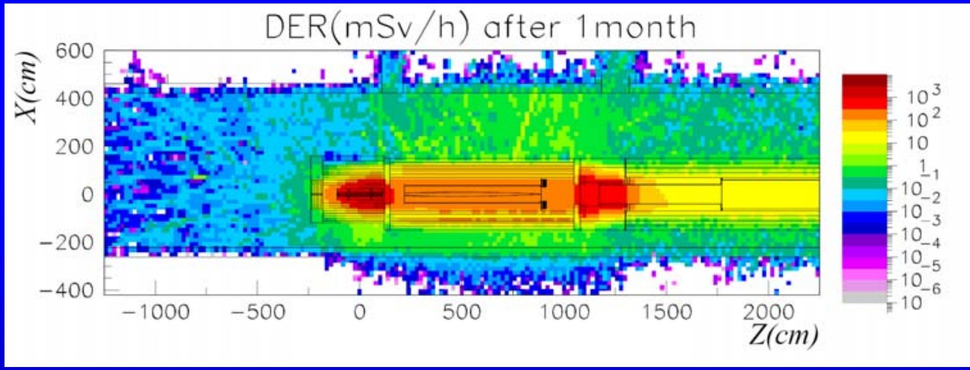
- Decay β, γ produced and transported "on line"
- Time evolution of induced radioactivity calculated analytically (Bateman eq.)
- Results for activity, energy deposition, particle fluence etc, calculated for custom irradiation/cooling down profile

Residual Dose Calculation (CNGS Neutrino Horn)

After 1 day



After 1 month



Dose Eq. Rates in mSv/h

The residual Dose Equivalent Rate (DER) due to the evolution of the activation is shown for the CNGS neutrino facility in the hottest area (target/magnetic horn).

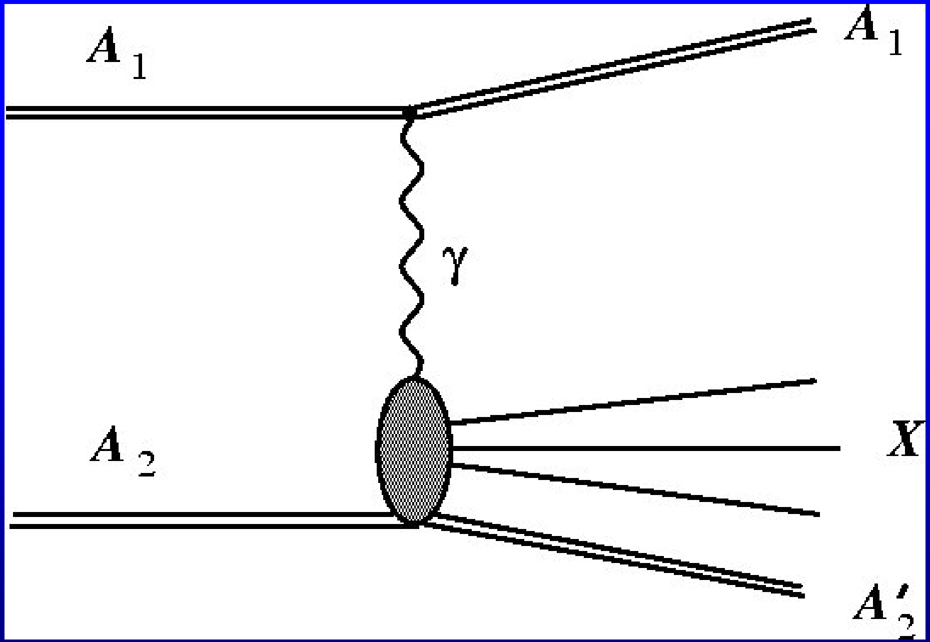
Heavy ion interaction models

- 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
- Extensively 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
- Standard FLUKA **evaporation/fission/fragmentation** used in both Target/Projectile final deexcitation
- Electromagnetic dissociation

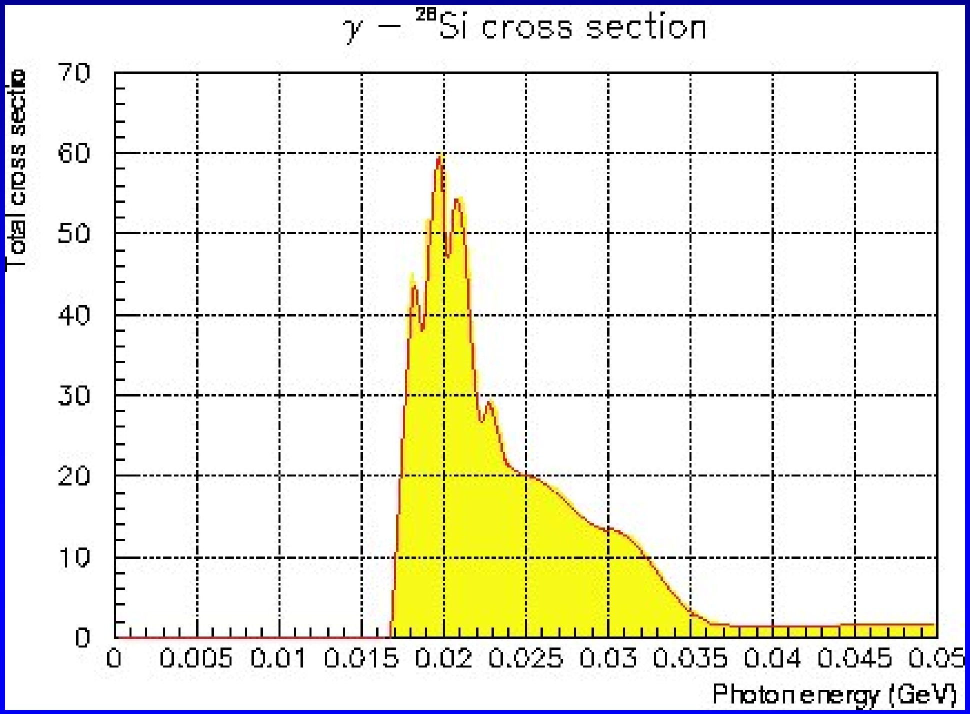
Electromagnetic dissociation

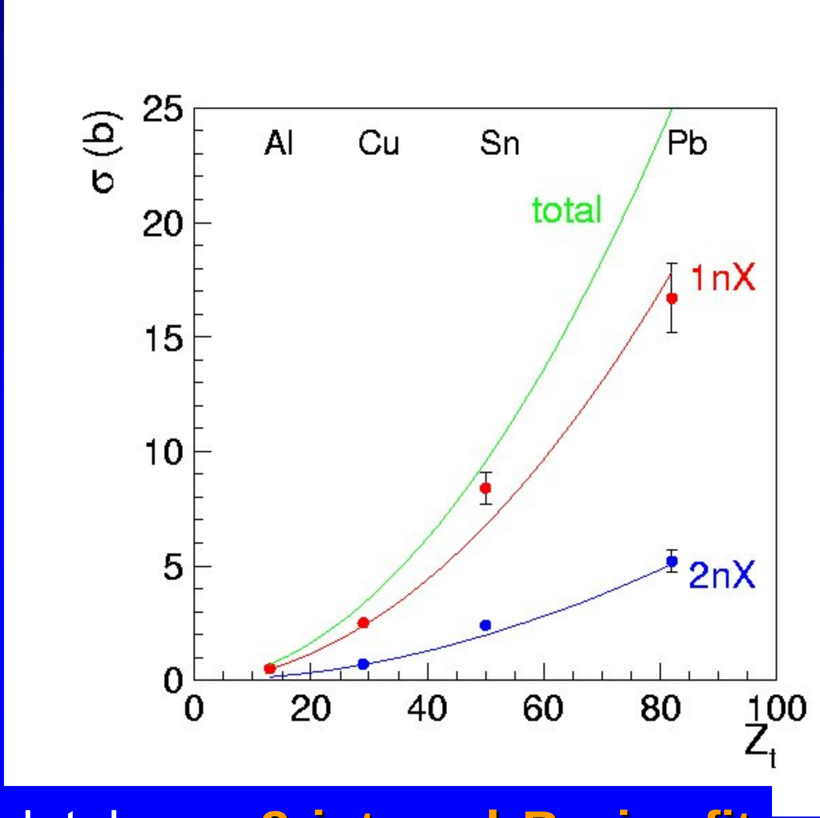
Electromagnetic dissociation: σ_{EM} increasingly large with (target) Z's and energy. Already relevant for few GeV/n ions on heavy targets ($\sigma_{EM} \sim 1$ b vs $\sigma_{nucl} \sim 5$ b for 1 GeV/n Fe on Pb)

$$\sigma_{1\gamma} = \int \frac{d\omega}{\omega} n_{A_1}(\omega)\sigma_\gamma n_{A_2}(\omega) \propto Z_1^2$$



Electromagnetic dissociation: example





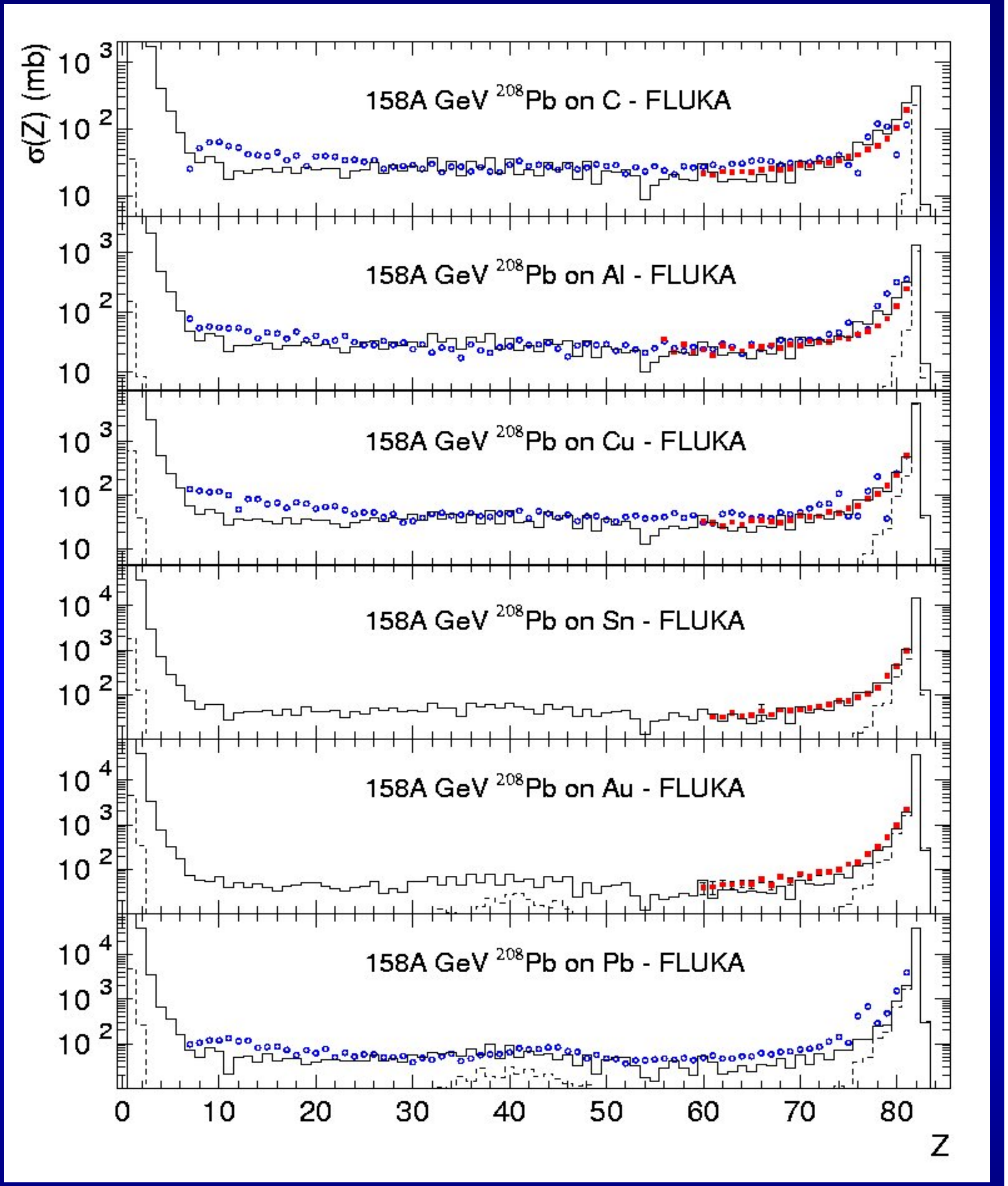
Left: ^{28}**Si(γ,tot)** as recorded in FLUKA database, **8 interval Bezier fit** as used for the Electromagnetic Dissociation event generator.

Right: calculated total, **1nX** and 2nX electromagnetic dissociation cross sections for 30 A GeV Pb ions on Al, Cu, Sn and Pb targets. Points – measured cross sections of forward 1n and 2n emissions as a function of target charge (M.B. Golubeva et al., in press)

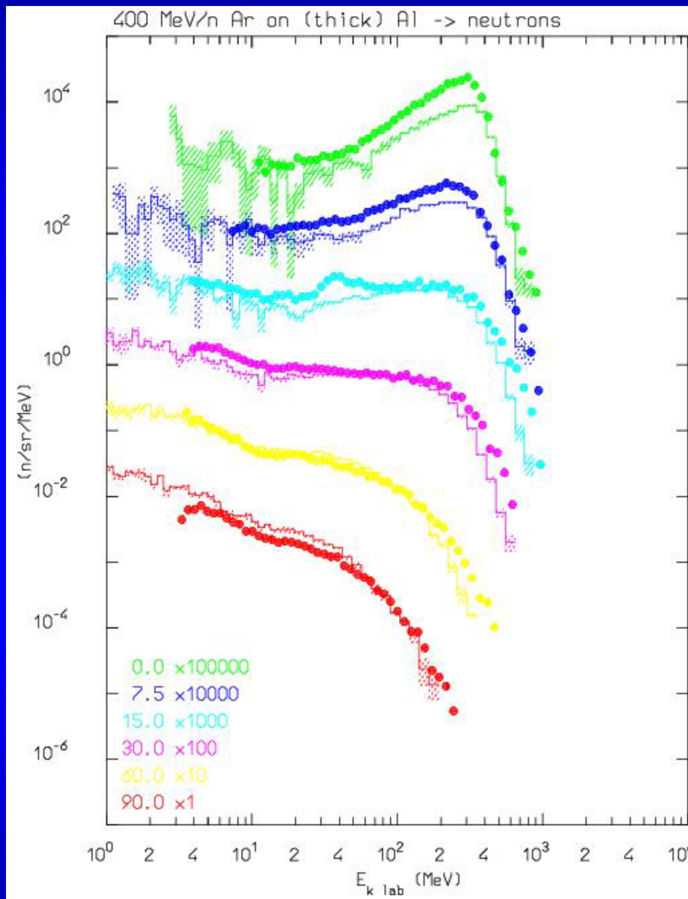
158 GeV/n fragmentation

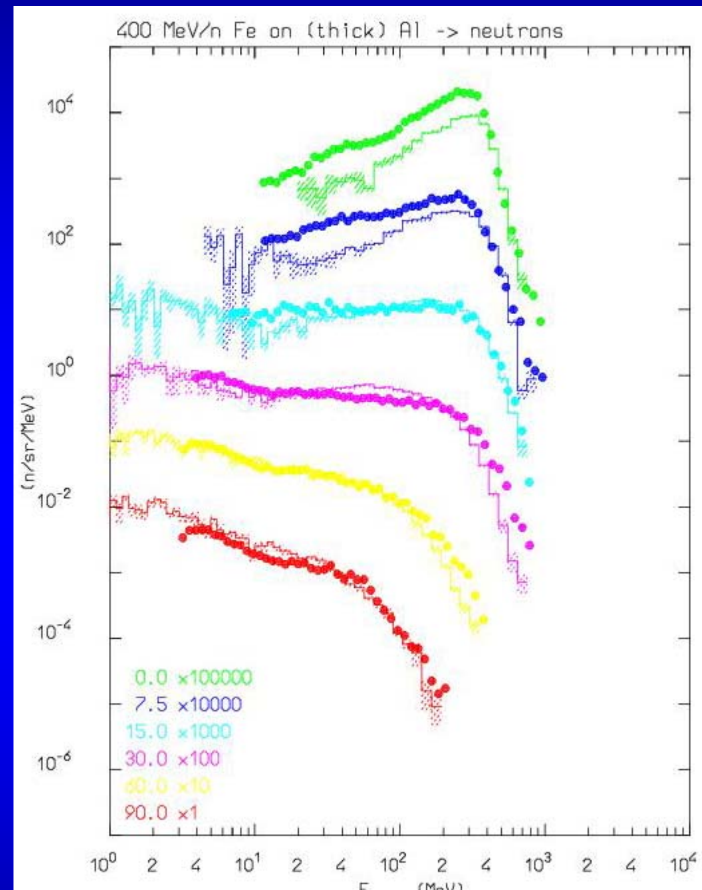
Fragment charge cross section for 158 AGeV Pb ions on various targets. Data (symbols) from NPA662, 207 (2000), NPA707, 513 (2002) (blue circles)

and from **C.Scheidenberger et al. PRC, in press (red squares),** histos are FLUKA (with DPMJET-III) predictions: the dashed histo is the electromagnetic dissociation contribution



FLUKA with modified RQMD-2.4





Double-differential neutron yield by 400 MeV/n Ar (left) and Fe (right) ions on thick Al targets
Histogram: FLUKA. Experimental data points: Phys. Rev. C62, 044615 (2000)

New developments for N-N collision at low energies in FLUKA

BME (Boltzman Master Equation model)

for ion collisions below 100 MeV/nucleon

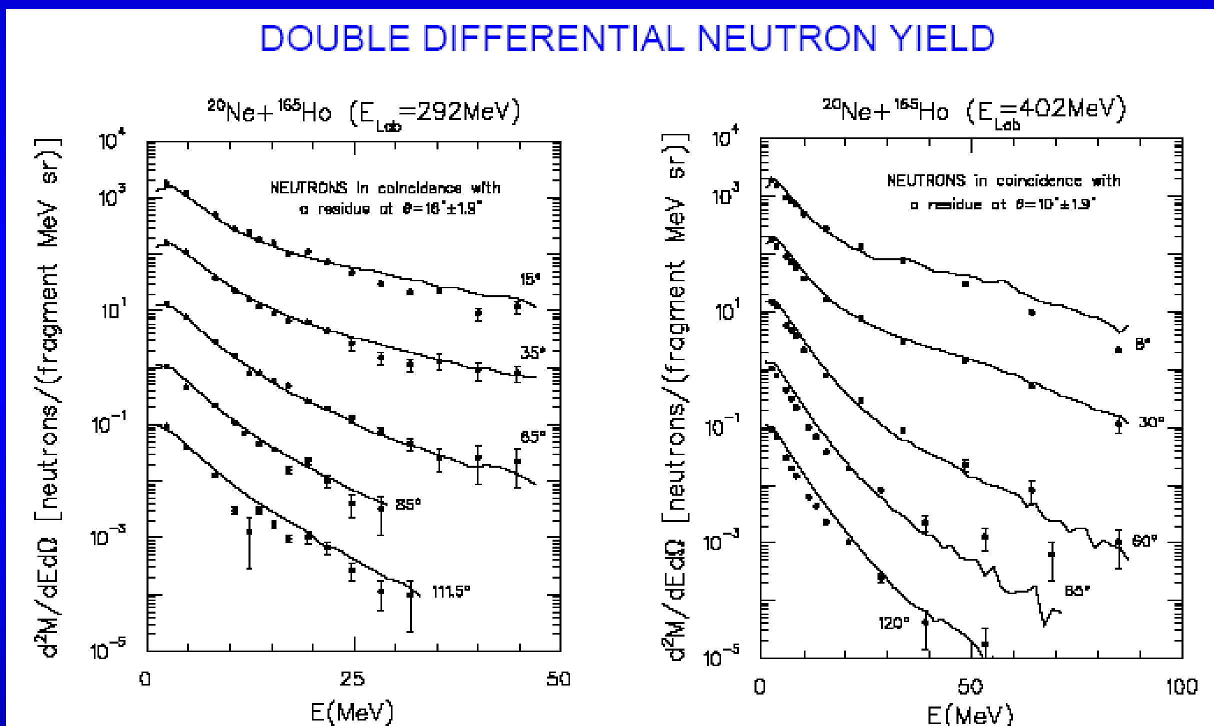
Developed in Milan, E. Gadioli group

A new QMD model fully integrated with PEANUT

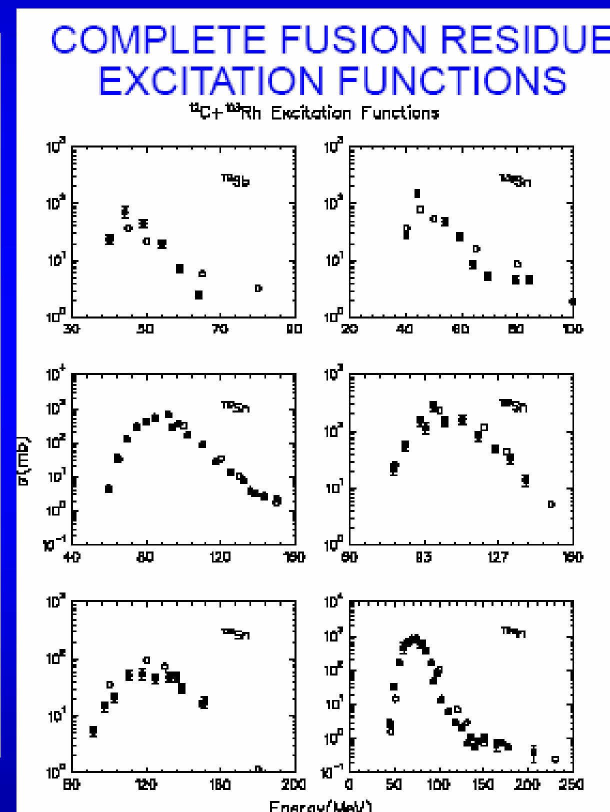
Developed in Milan, M.V.Garzelli

The BME theory

It describes the **thermalization** of the composite system formed in A-A collisions at E < 100MeV/n, via nucleon-nucleon scattering and emission into the continuum of single nucleons and nucleons bound in clusters (M. Cavinato *et al.*, Nucl. Phys. A **643**, 15 (1998); **679**, 753 (2001))



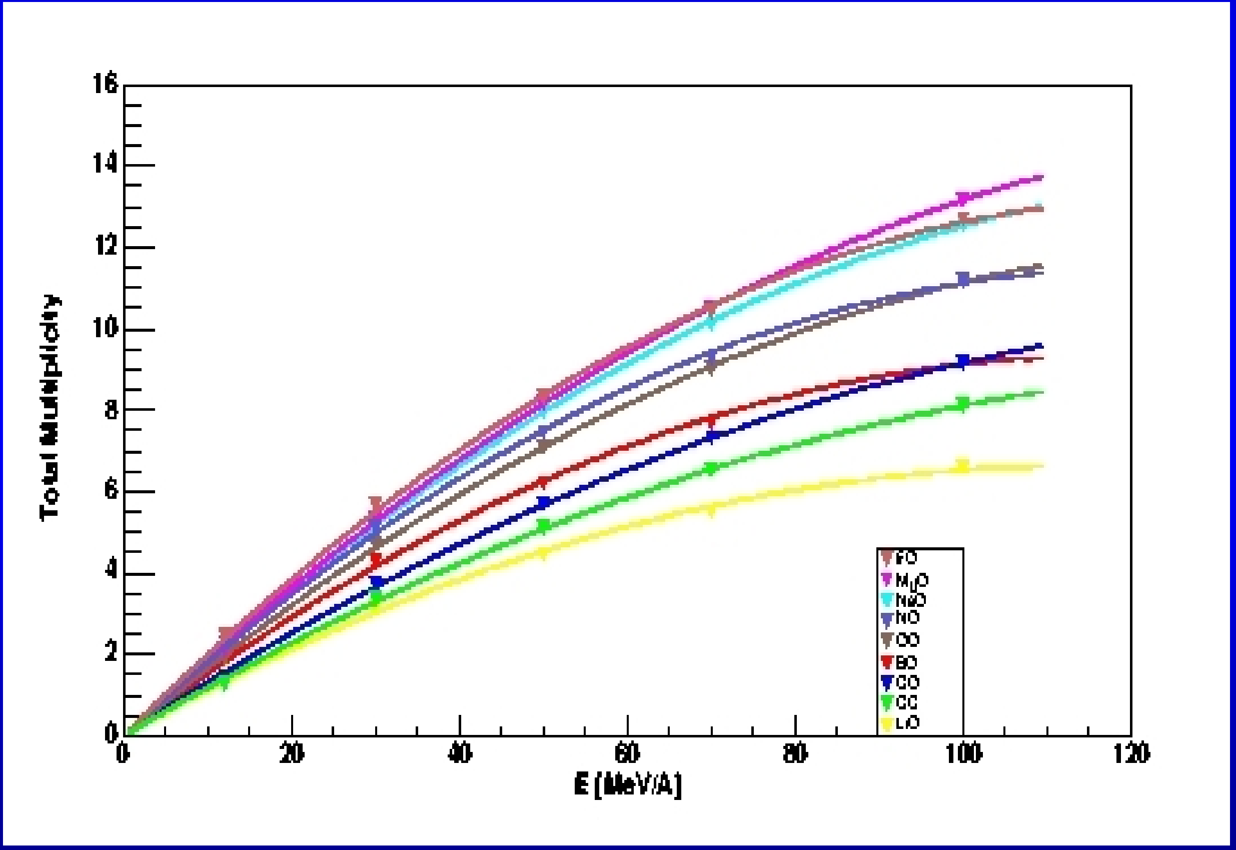
exp. data from E. Holub *et al.*, Phys. Rev. ***C* 28**, 252 (1983)



full circles *exp. data*

empty circles *theory*

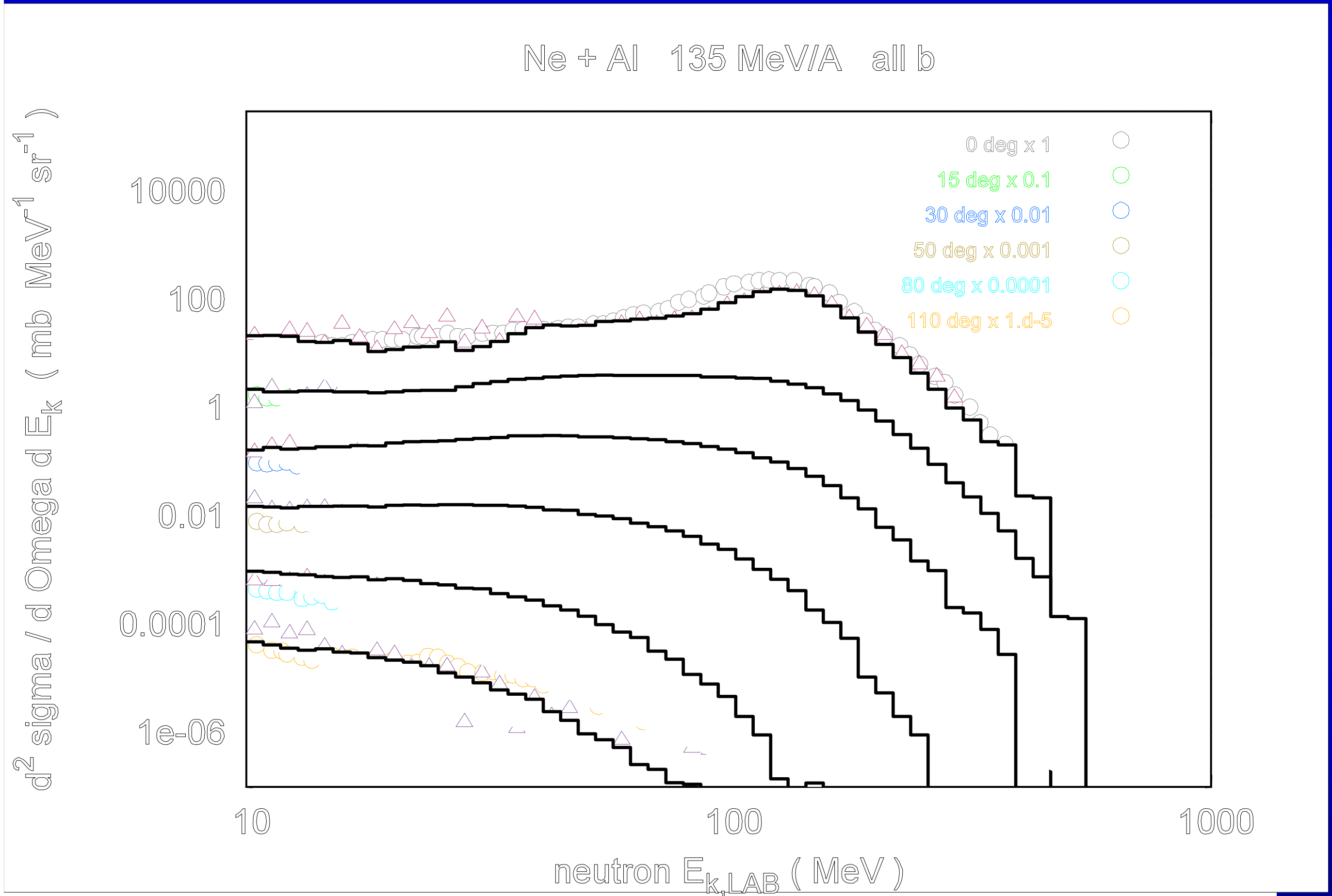
The total multiplicities for some of the complete fusion reactions implemented using the BME Model



Incident Lab Energies

New QMD

Emitted neutron spectra at various angles for 135 MeV/n Ne on Al



Circles : Exp. Data

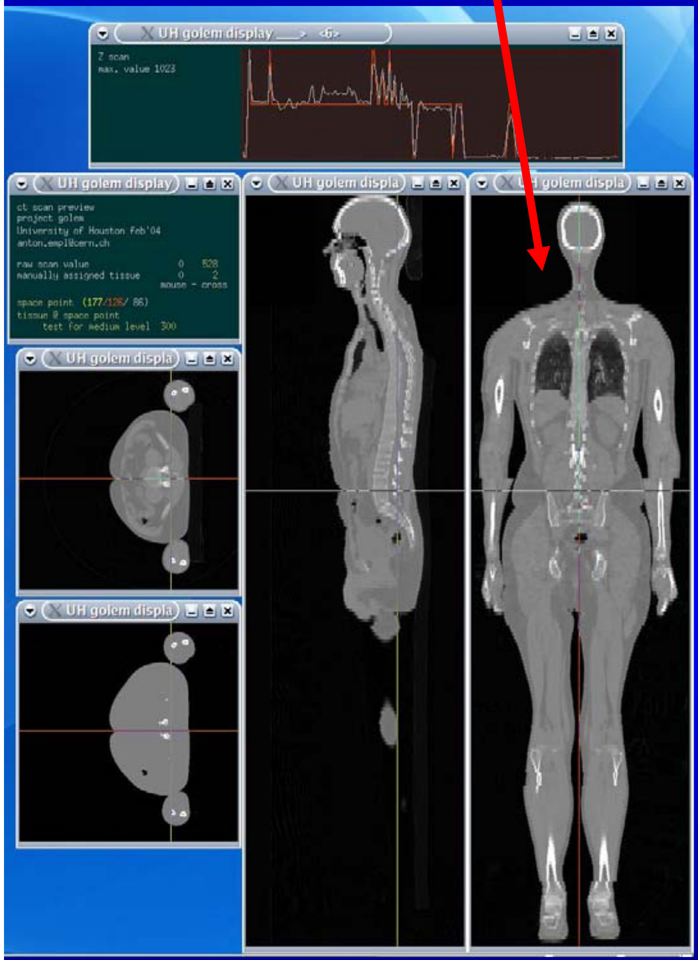
Lines: FLUKA- rQMD-2.4

(at its lower energy limit)

Triangles: new QMD

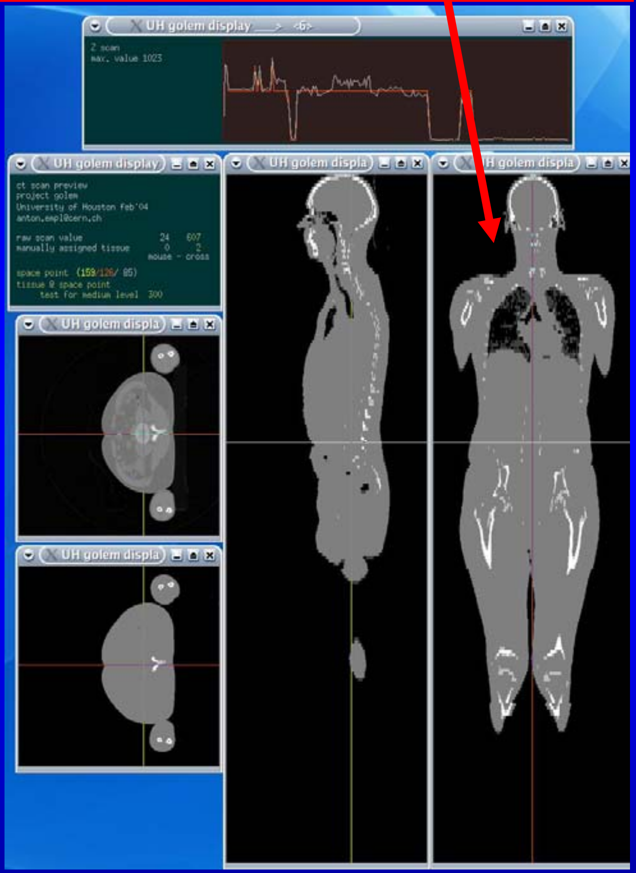
Automatic voxel type assignment

Raw GOLEM CT-SCAN



- FLUKA can embed voxel structures within its standard combinatorial geometry
- Transport through the voxels is optimized and efficient
- Raw CT-scan outputs can be imported

Automatically assigned materials



In-beam treatment control with PET

- Final goal: simulation of β^+ emitters generated during the irradiation

➡ In-beam treatment plan verification with PET

Work in progress: FLUKA validation

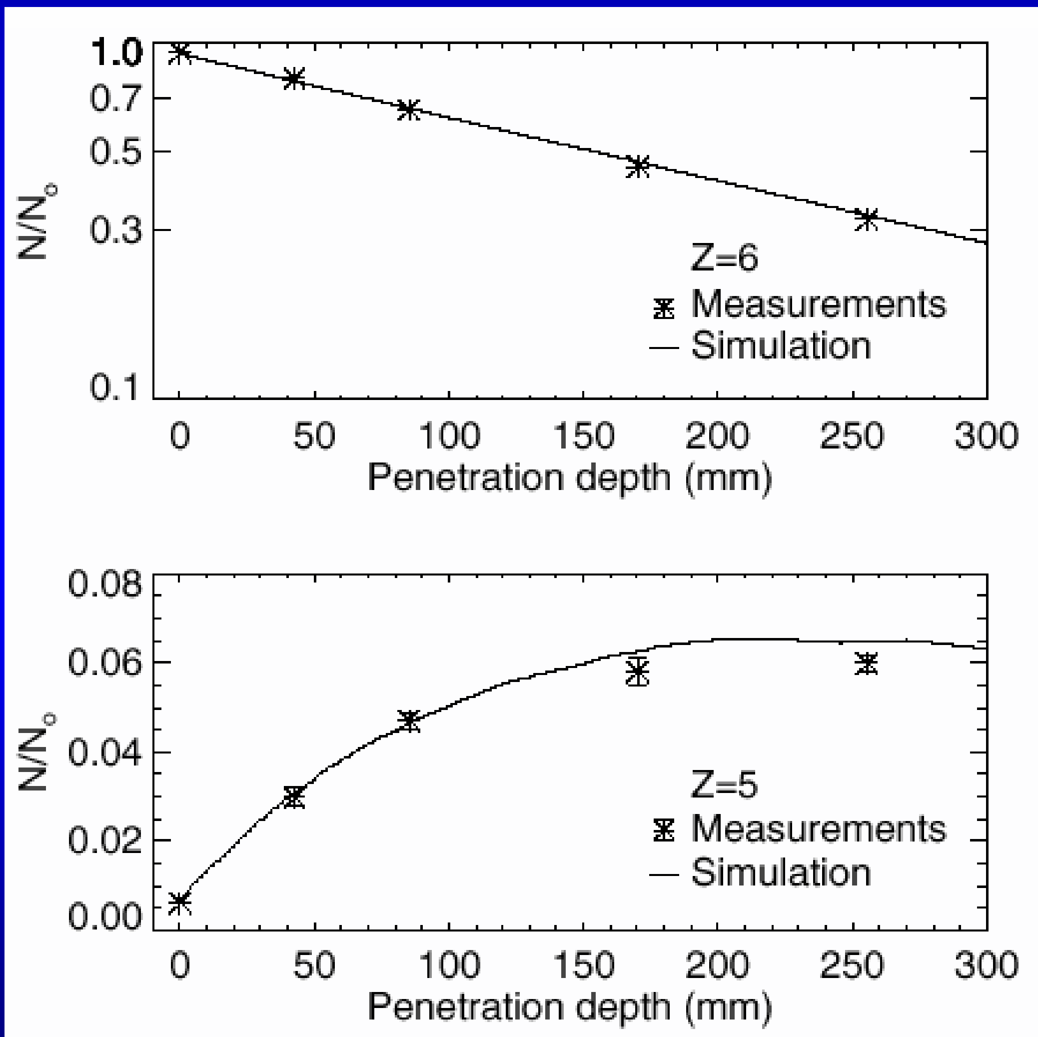
Comparison with experimental data on fragment production (Shall et al.)

- ^{12}C, ^{14}N, ^{16}O beams, 675 MeV/A
- Adjustable water column 0-25.5 cm
- Z spectra of escaping fragments

Simulations by F. Sommerer, K.Parodi, W. Enghardt, A.Aiginger

Forscungszentrum Rossendorf (Dresden) and Vienna Univ. of technology

Fragmentation of therapeutic beams



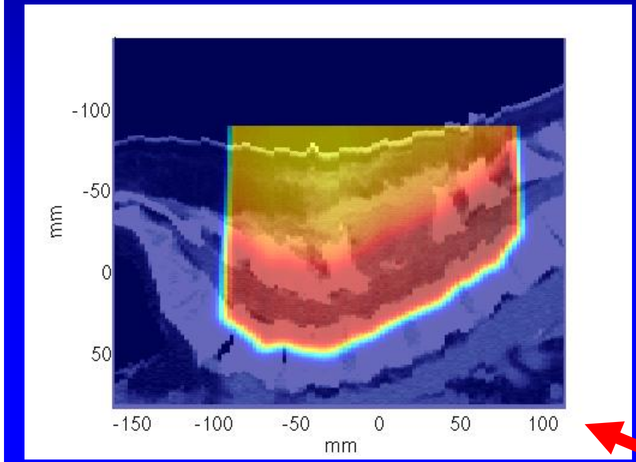
676 A MeV ^{12}C beam on a water phantom.

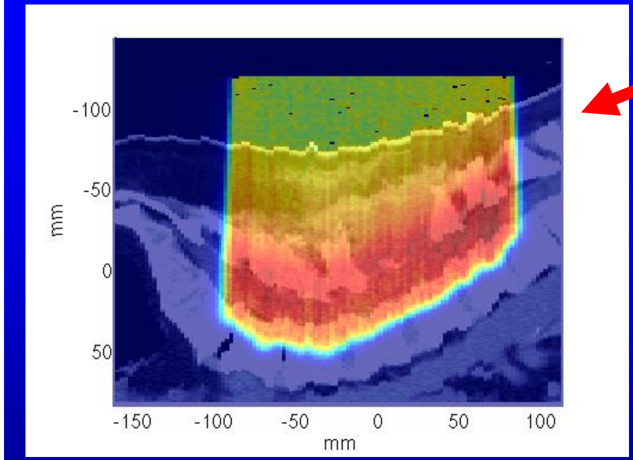
-Top: Carbon ion intensity as a function of depth.
-Bottom: Build-up of boron ions as a function of depth.

(Experimental data from Schall et al.(1996)and Schall (1994)).

A Real Case at MGH*…

Treatment Planning Predictions

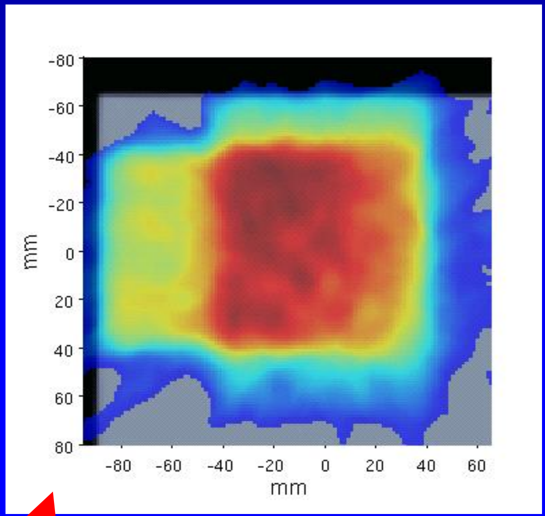


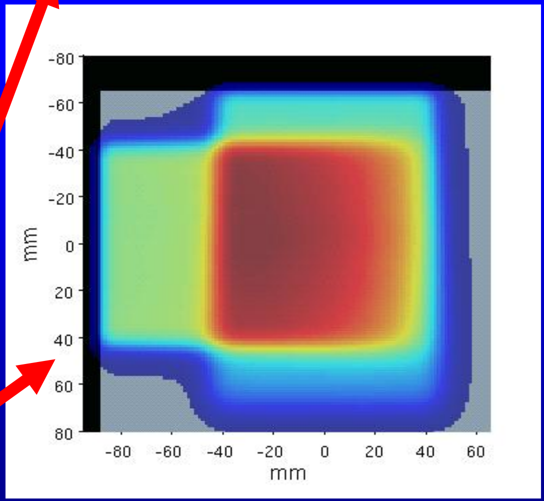


FLUKA Simulation of PET

- PET scans can be done immediately after therapeutic irradiation in proton beams to visualize the region in which the dose was delivered. The decay of ^{11}C target fragments are the source of the e^+s.
- Comparison of Treatment Planning Software and FLUKA Simulation for application of proton therapy to an spinal tumor.
- Comparison of measurement of PMMA phantom with 2 orthogonal fields and FLUKA simulation of post irradiation PET scan.

Actual Measurement





FLUKA Simulation

* K. Parodi, H. Paganetti and T. Bortfeld, **M**assachusetts **G**eneral **H**ospital

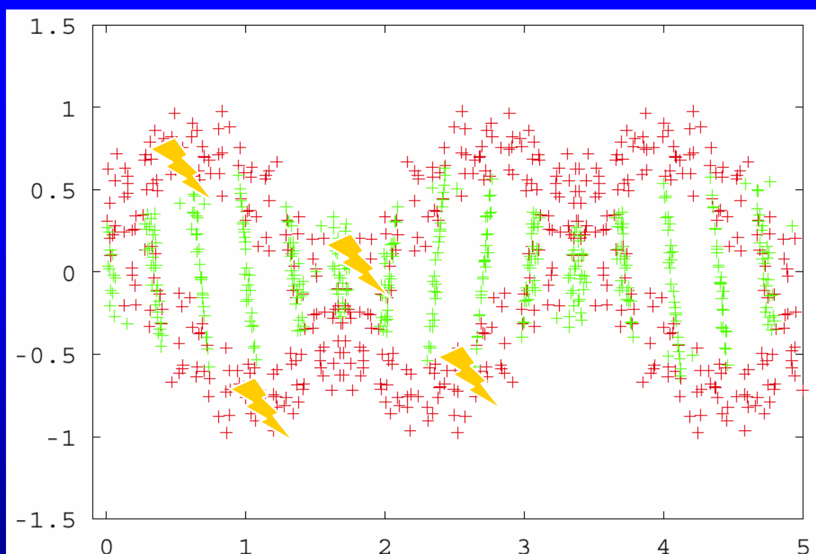
A weighted/biological dose

Radiation Protection: quality factors and weighting factors

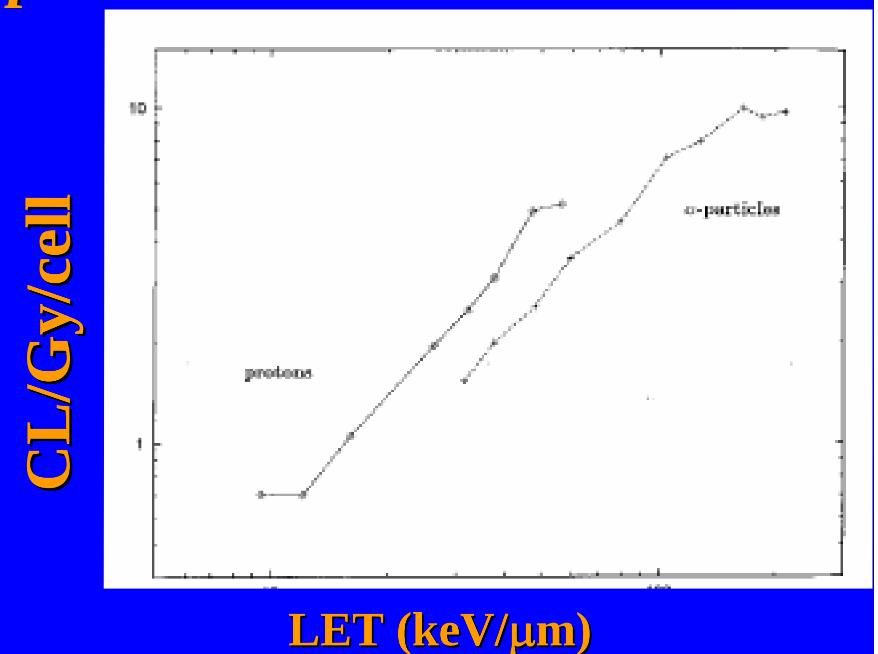
ICRP 26: quality factors Q(L) depending on the radiation LET

ICRP 60: weighting factors depending on the radiation type

Radiobiology: Complex Lesions

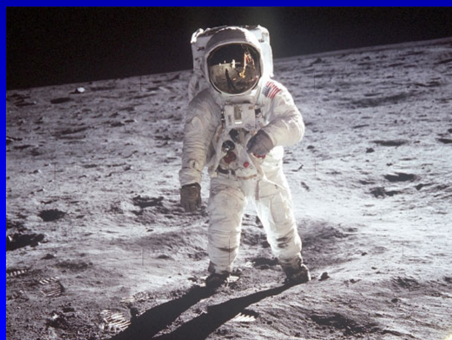


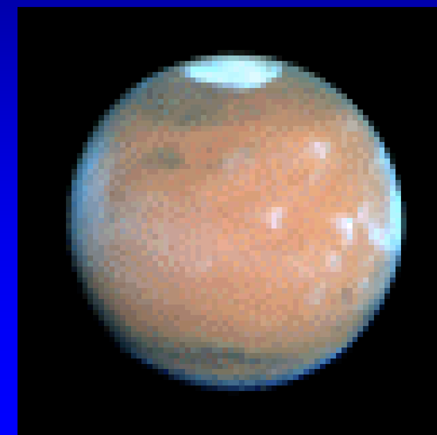
≥ 2 breaks on each strand within 10 nm

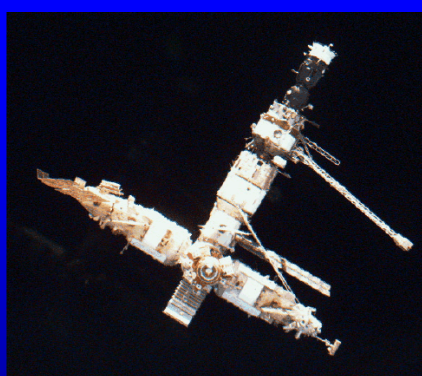


(Ottolenghi et al. 1995, Radiat. Environ. Biophys.)

Applications to Space Radiation Protection



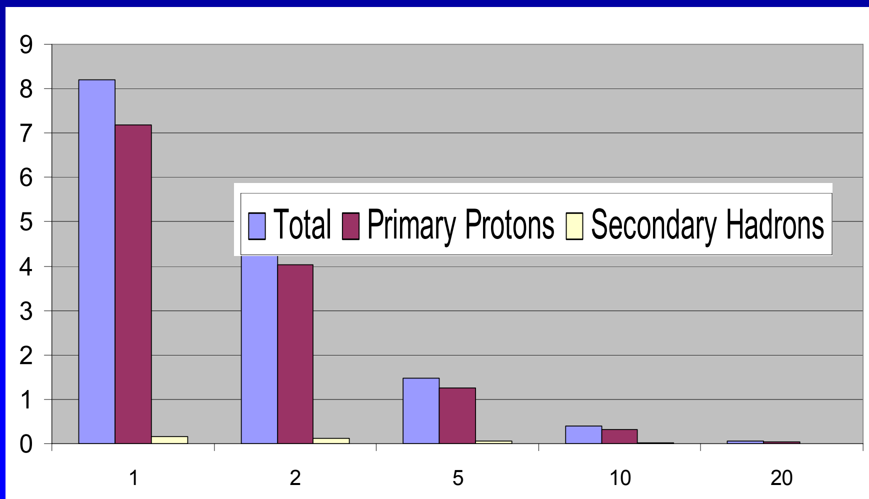




- FLUKA ⇒ spatial distribution of absorbed dose delivered by the different components of the radiation field
- "event-by-event" track structure codes ⇒ yields of CL/(Gy cell) induced by different radiation types
- integration ⇒ spatial distribution of CL/cell *("biological" dose)*

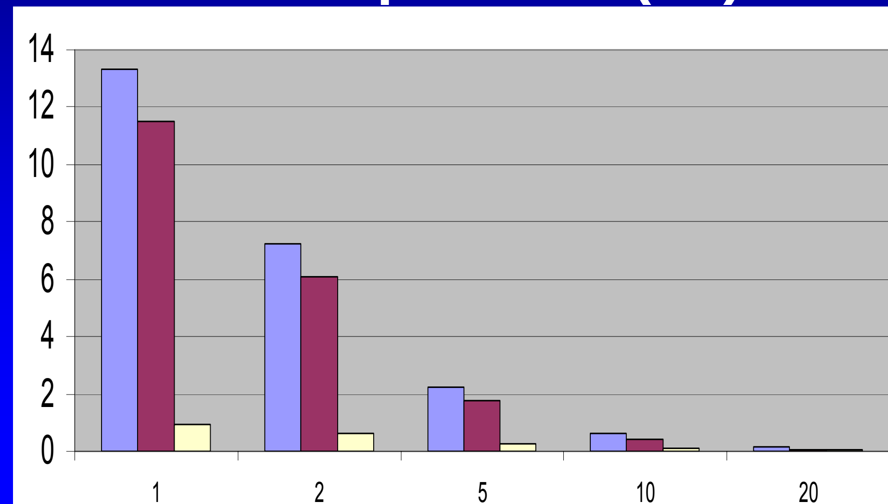
Aug. 1972 SPE - calculated skin doses

dose (Gy)



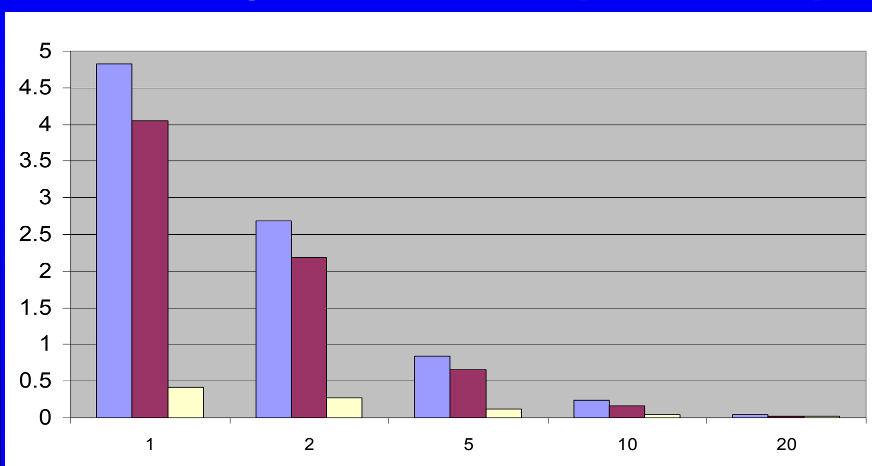
Al shield thickness (g/cm²)

dose equivalent (Sv)



Al shield thickness (g/cm²)

"biological" dose (CLs/cell)



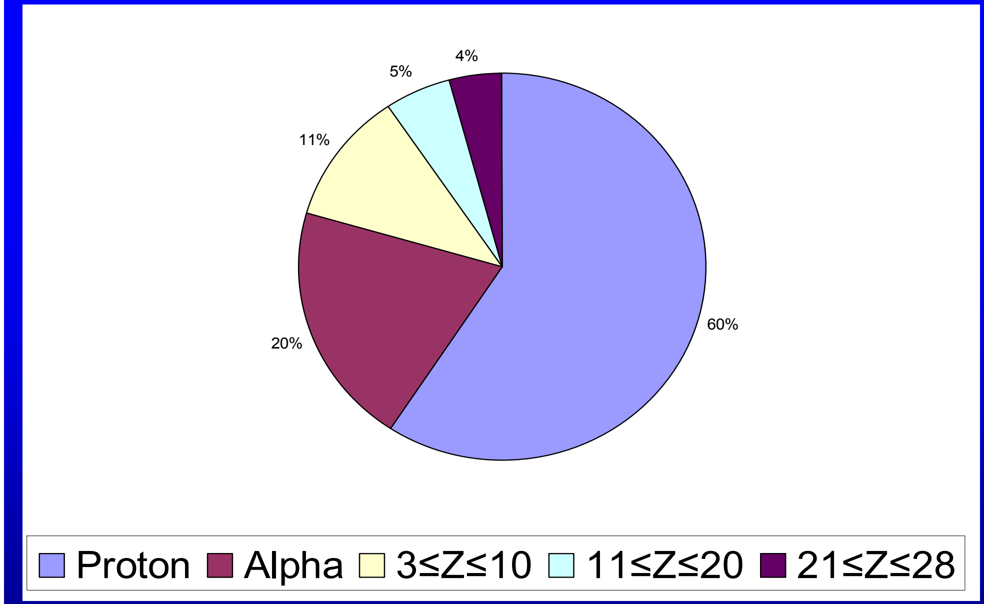
Al shield thickness (g/cm²)

- ***dramatic dose decrease with increasing shielding (i.e. from 13.3 to 0.62 Sv in the range 1-10 g/cm²)***
- ***major contribution from primary protons (the role of nuclear reaction products is not negligible only for equivalent and "biological" dose)***

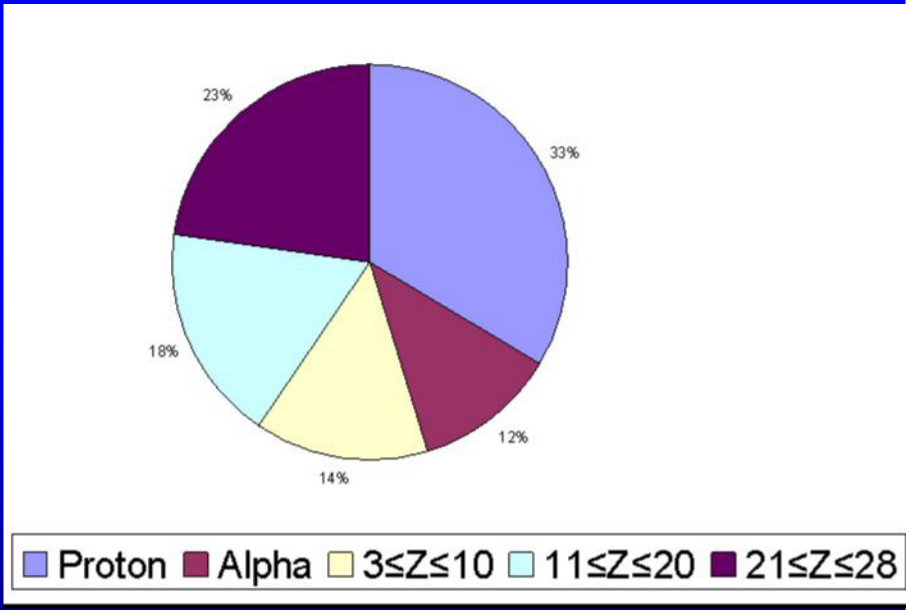
Galactic C.R. - role of the various spectrum components

(example with skin behind 5 g/cm² Al)

Skin Dose [mGy/d]



Skin Equivalent Dose [mSv/d]



Conclusions

FLUKA applications to Medicine/radiobiology
Are growing, thanks to

- ✓ Mixed field capability, including ion transport and interactions
- ✓ Accuracy
- ✓ Reliability

Improvements in the next (…) future

- New library for low-energy neutron transport
- New QMD model(s) for intermediate energy ion-ion interactions
- Finalize the implementation of BME for very low energy ion interactions
- More friendly user interface

Download and documentation : www.fluka.org

END