FLUKA for Medicine and Radiobiology

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INFN & Univ. Milano INFN & Univ. Pavia INFN Frascati CERN Univ. of Houston SLAC Univ. of Siegen NASA-Houston

Interaction and transport Monte Carlo code

- Nucleus-nucleus interactions 100 MeV/n – 10000 TeV/n
- 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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http://www.fluka.org

Fluka Applications

- **cosmic ray physics**
- **accelerator design (→ LHC systems)**
- **particle physics: calorimetry, tracking and detector simulation etc. (→ ALICE, ICARUS, ...)**
- **shielding design**
- **dosimetry and radioprotection**
- **space radiation**
- **hadron therapy**
- **neutronics**
- **ADS systems (→"Energy amplifier")**

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

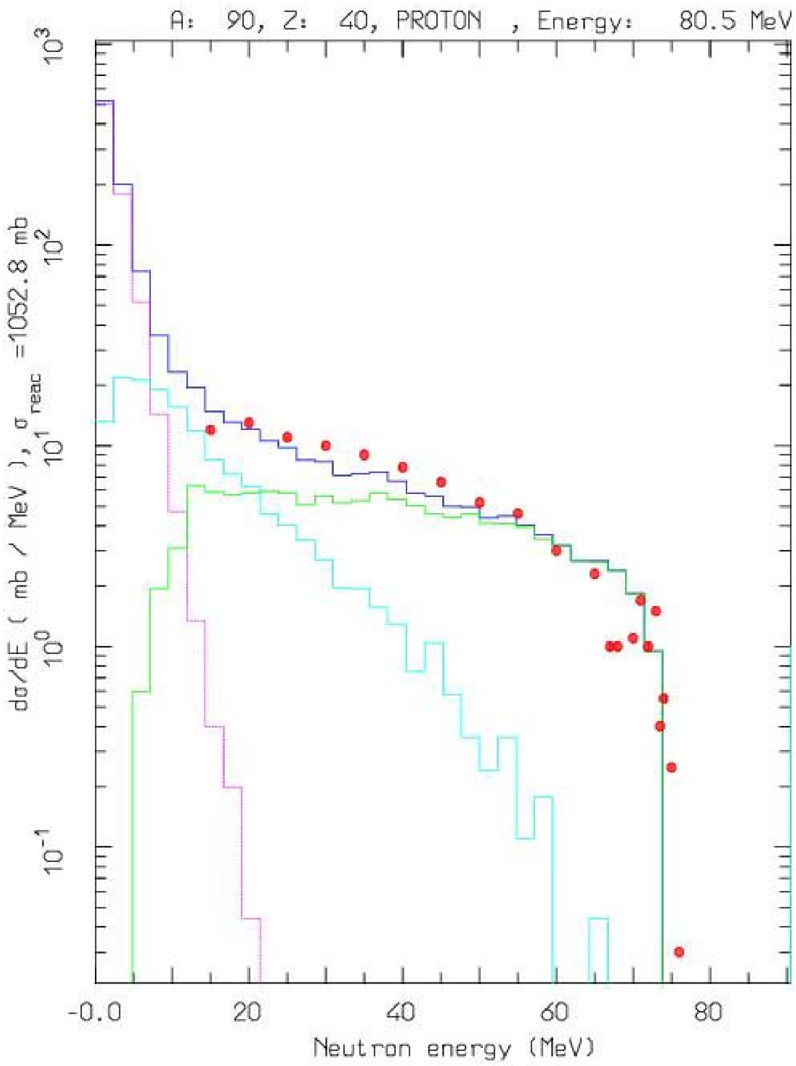
Nucleus-Nucleus

E$>$ 5 GeV/u
DPMJET-III

0.1$<$ E $<$ 5 GeV/u
(modified) rQMD-2.4

Evaporation/Fission/Fermi break-up
γ deexcitation

Thin target example

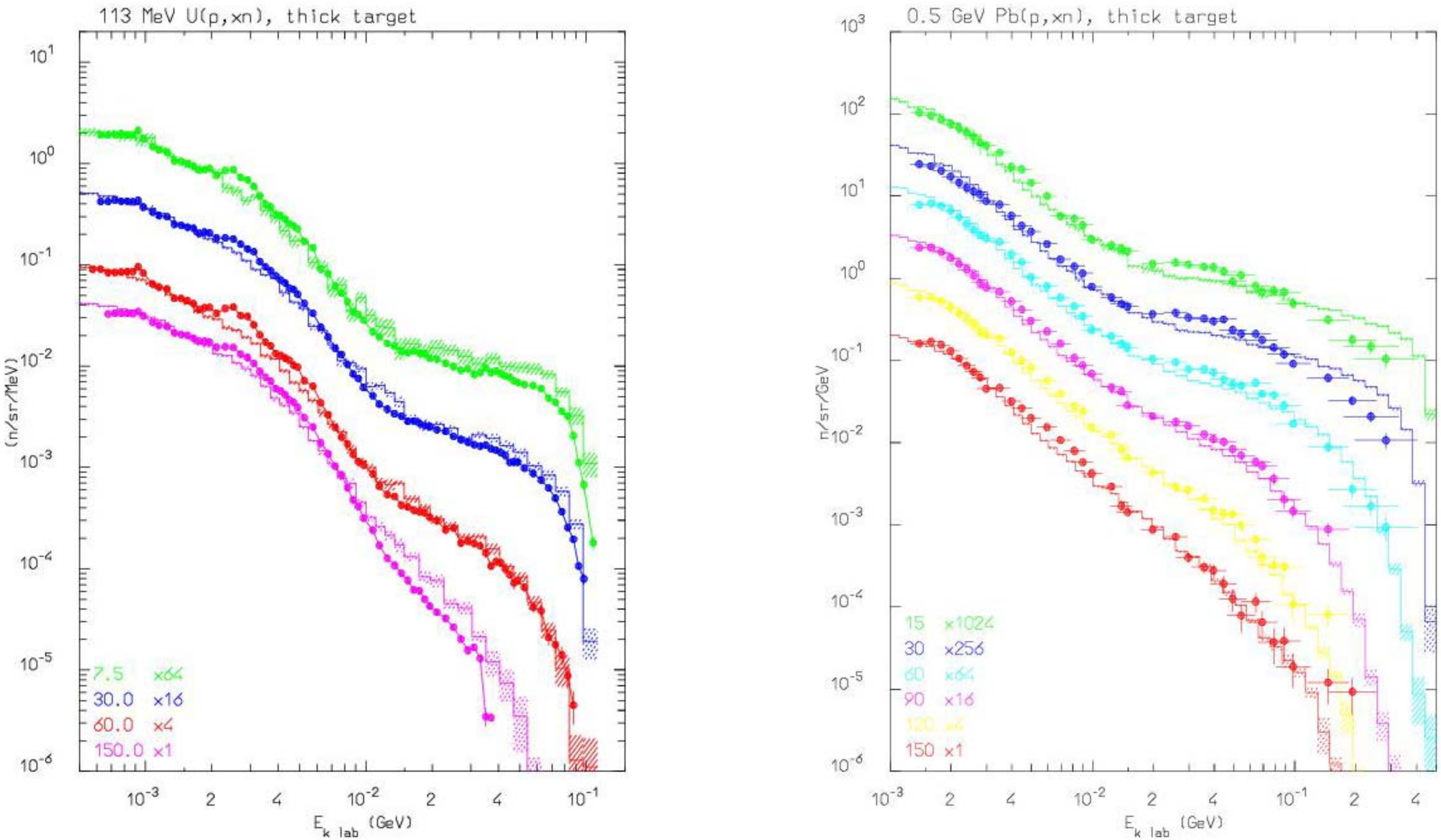


Angle-integrated ^{90}Zr(p,xn) at 80.5 MeV

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

Experimental data from M. Trabandt et al., Phys. Rev. C39, 452 (1989)

Thick target example



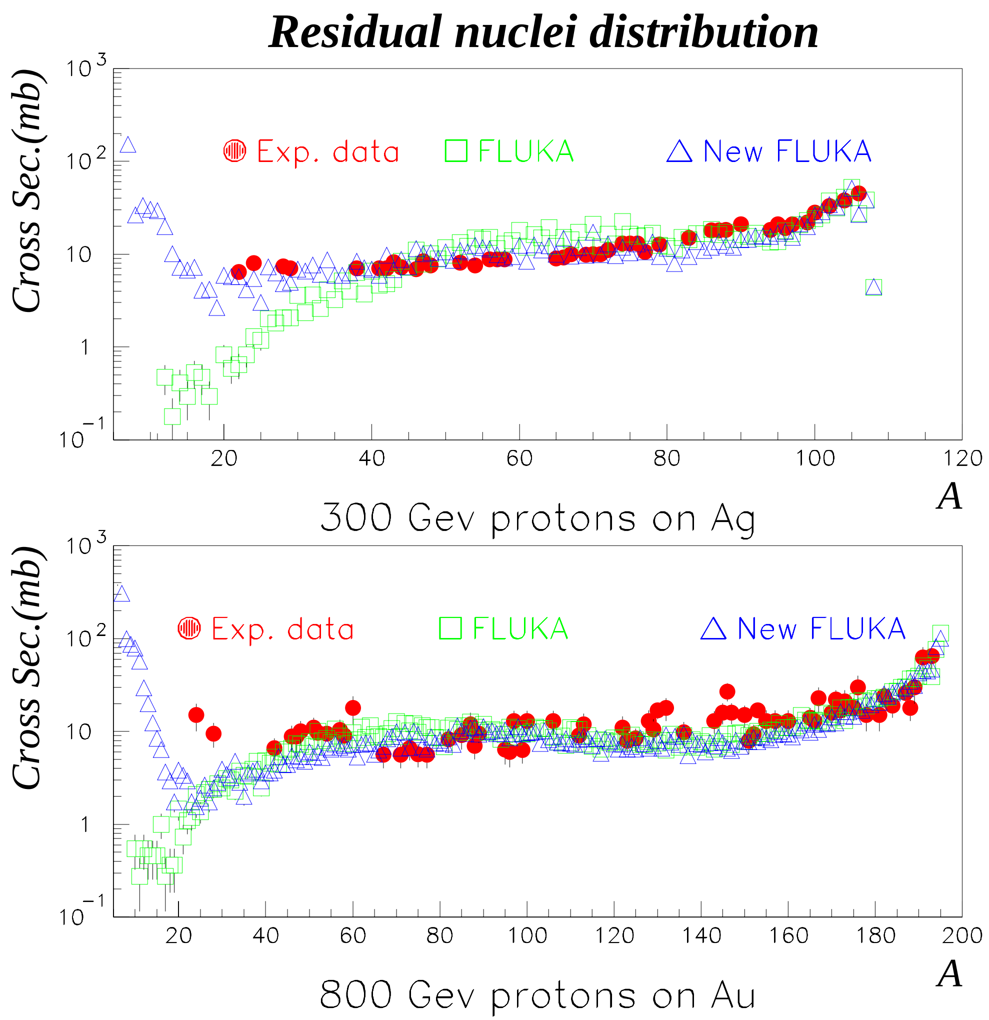
Neutron 2-differential distributions from protons on stopping-length targets: 113 MeV on U (left) and 500 MeV on Pb (right). Exp. data from Meier et al., Nucl. Sci. Eng. 110, 299 (1992) and Meigo et al., JAERI-Conf. 95-008

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)

A new fragmentation model has recently much improved the FLUKA predictions



Online evolution of activation and residual dose

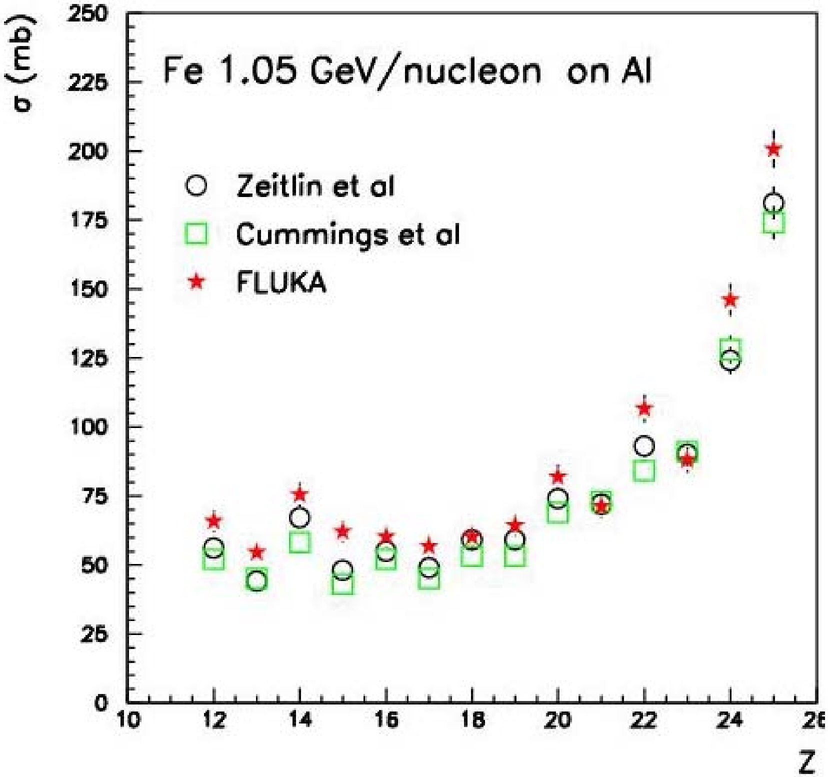
NEW

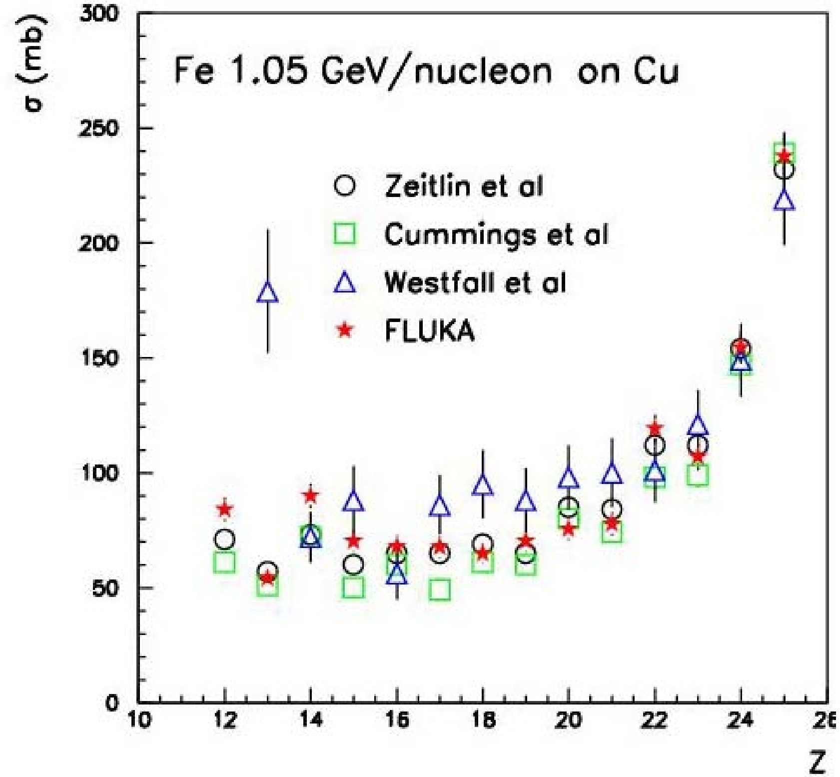
- Decay β, γ produced and transported "on line"
- Time evolution of induced radioactivity calculated analytically (Bateman eq.)
- Results for activity, energy deposition, particle fluence etc, calculated for custom irradiation/cooling down profile

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

FLUKA with modified RQMD-2.4

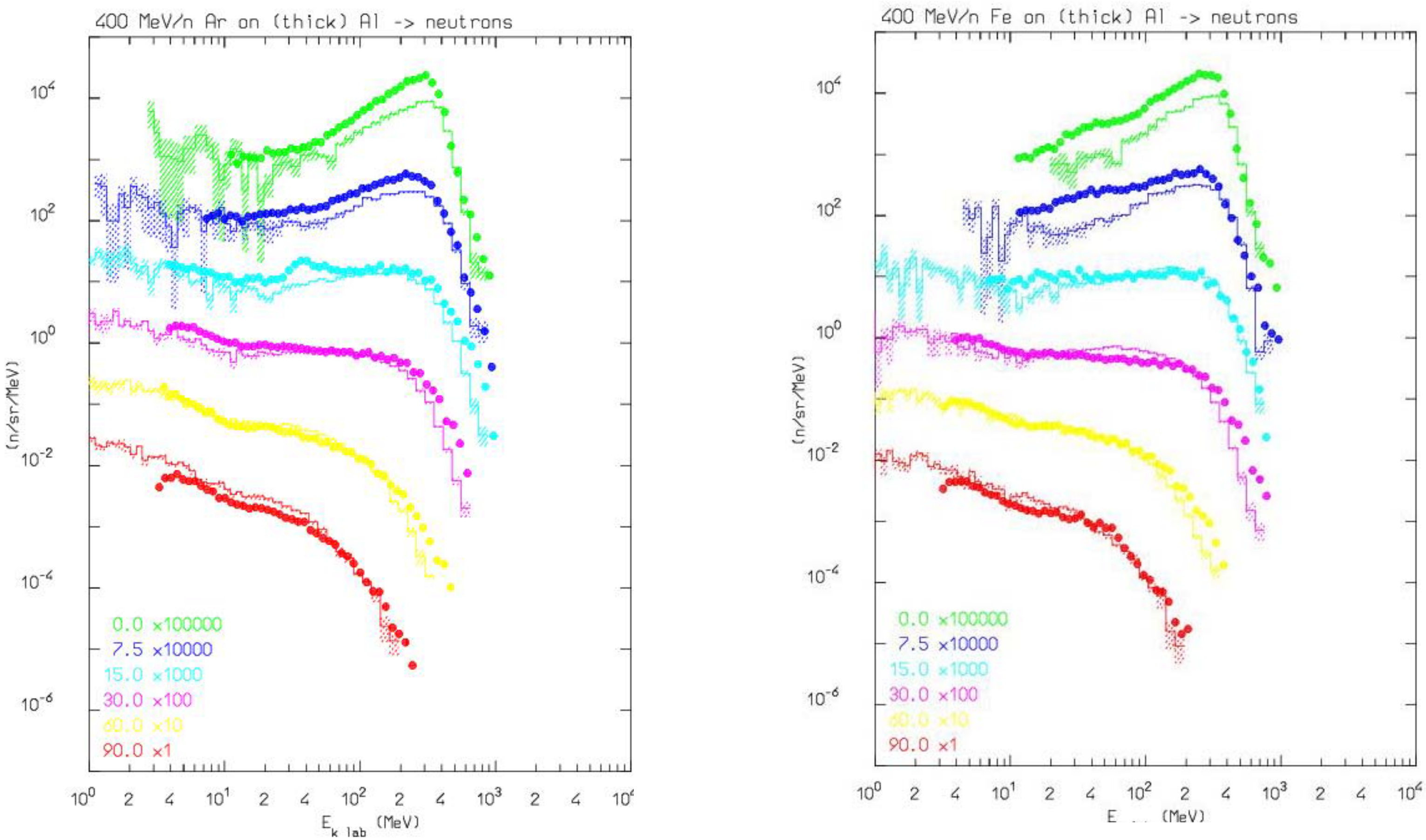




Fragment charge cross section for 1.05 GeV/n Fe ions on Al (left) and Cu (right).

★: FLUKA, ○ : PRC 56, 388 (1997), □ : PRC42, 5208 (1990), Δ: PRC 19, 1309 (1979)

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)

FLUKA

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

BME (Boltzman Master Equation model)

for ion collisions below 100 MeV/nucleon

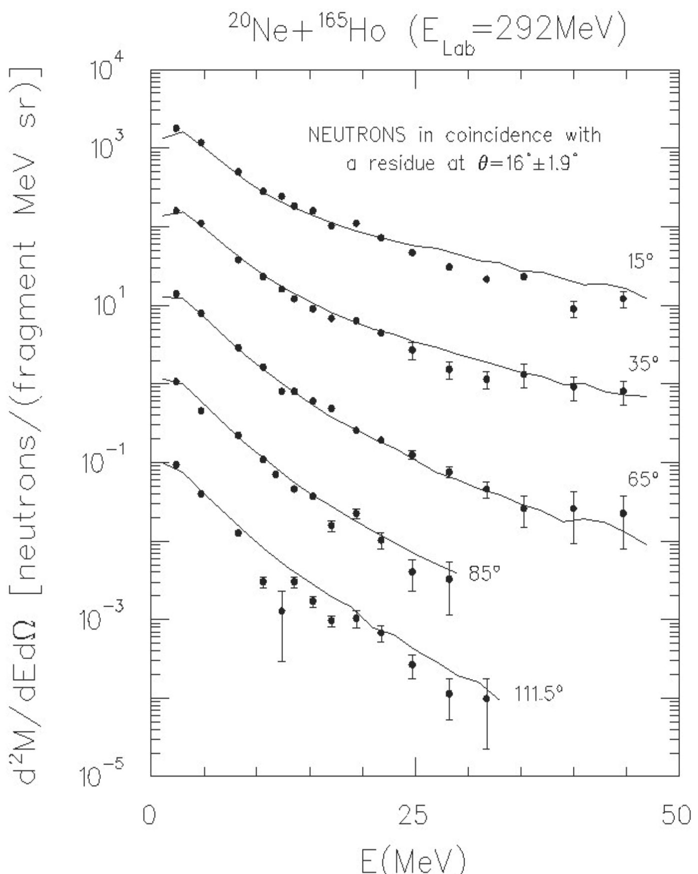
Developed in Milan, E. Gadioli group

A new QMD model fully integrated with PEANUT

Developed in Milan, M.V.Garzelli

BME and its Monte Carlo implementation

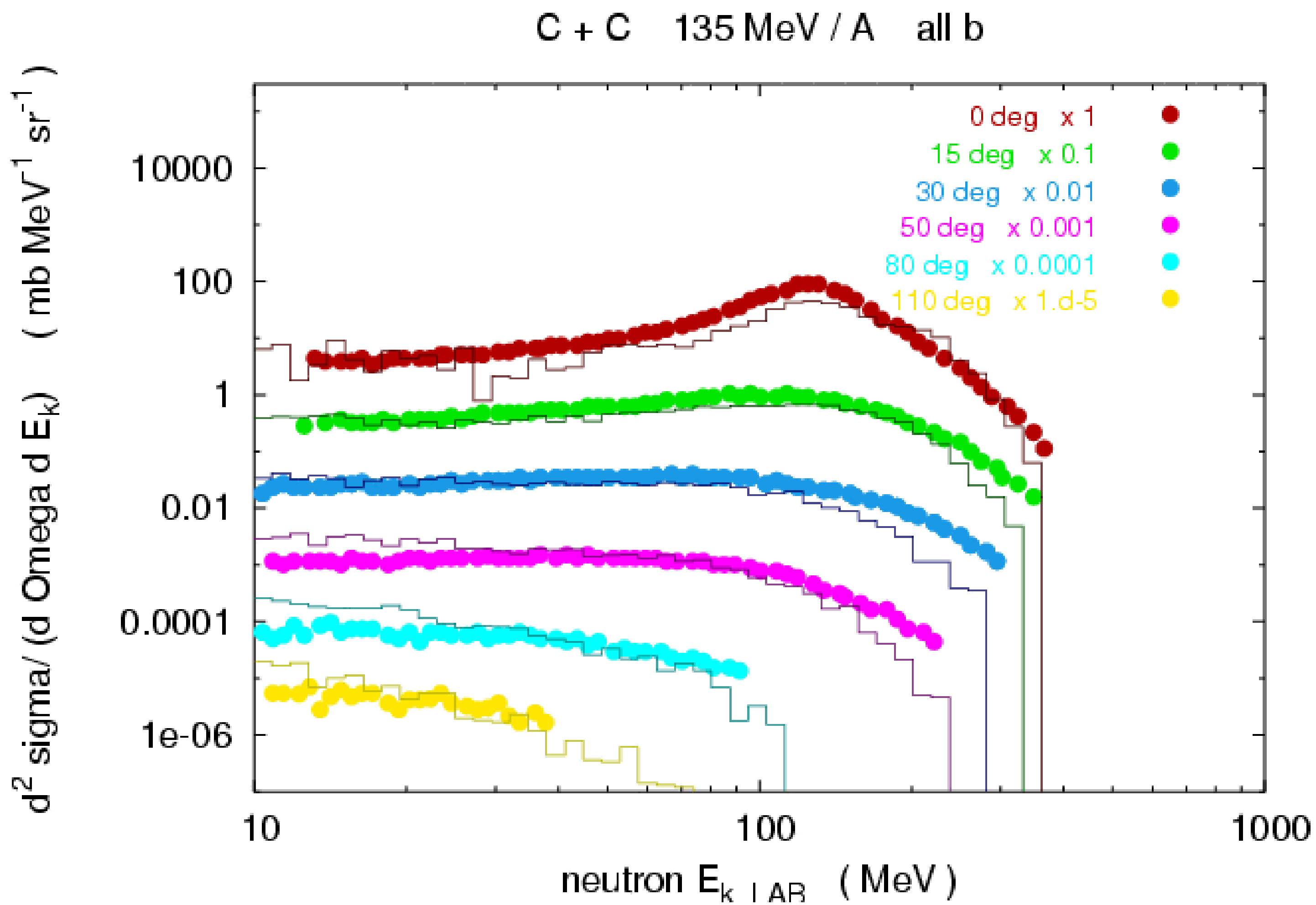
•it describes the thermalization of composite systems resulting from A-A collisions (E< 100 MeV/n) (evolution of the phase space bin occupation of nucleons)
•Provides inclusive spectra of emitted nucleons and "cluster" of nucleons → fragments



Double differential neutron yield in ^{20}Ne + ^{185}Ho (Elab = 292 MeV)

Data from E.Holub et al, PRC 28 (1983) p.252

New QMD



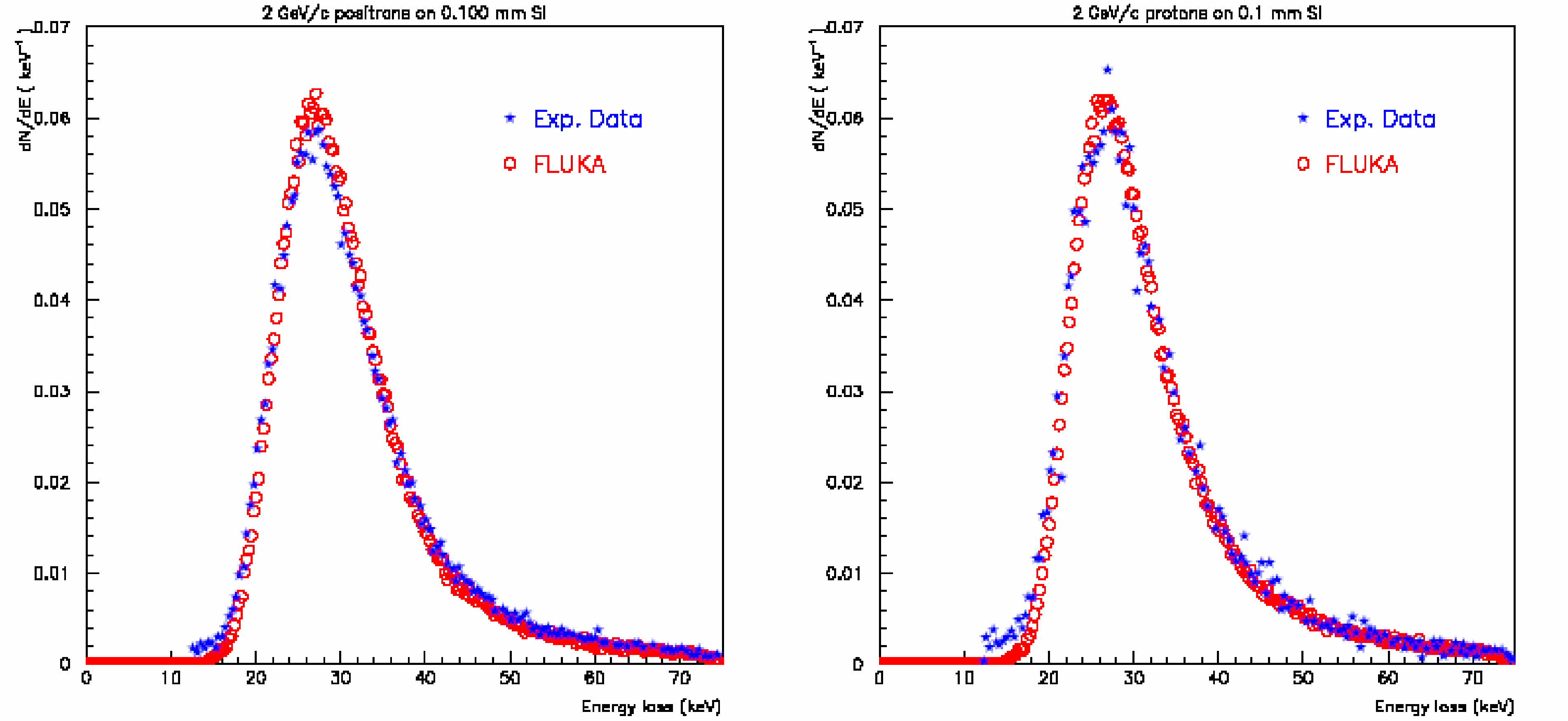
C + C 135 MeV / A all b
0 deg x 1
15 deg x 0.1
30 deg x 0.01
50 deg x 0.001
80 deg x 0.0001
110 deg x 1.d-5
10000
100
1
0.01
0.0001
1e-06
10
100
1000
neutron E$_{k\ LAB}$ (MeV)
d^2 sigma/ (d Omega d E$_k$) (mb MeV^{-1} sr^{-1})

EMF ElectroMagneticFluka

- Photoelectric : fluorescence, angular distribution, Auger , polarization
- Compton and Rayleigh : atomic bonds, polarization
- Pair production correlated angular and energy distribution; also for μ
- Photonuclear interactions; also for μ
- Bremsstrahlung : LPM, angular distribution, ... also for μ
- Bhabha and Möller scattering
- Positron annihilation at rest and in flight
- μ capture at rest
- Optical photon (Cherenkov) production and transport

Ionization Energy Losses

Cumulants approach to dE/dx fluctuations

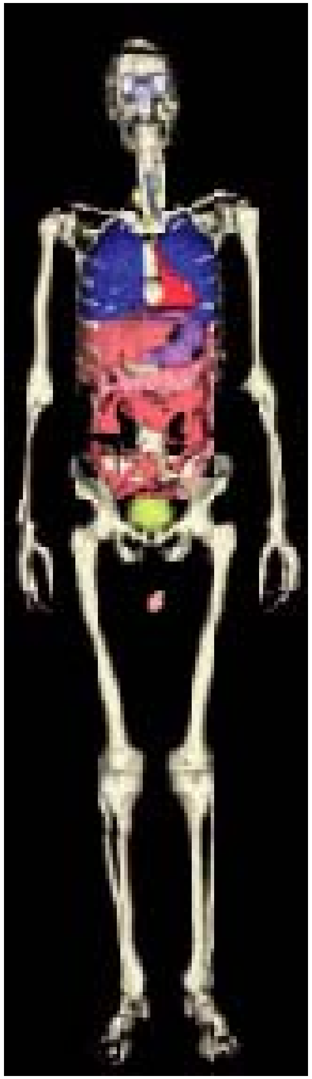


Experimental[1] and calculated energy loss distributions for 2 GeV/c positrons (left) and protons (right) traversing 100μm of Si

J.Bak et al. NPB288, 681 (1987)

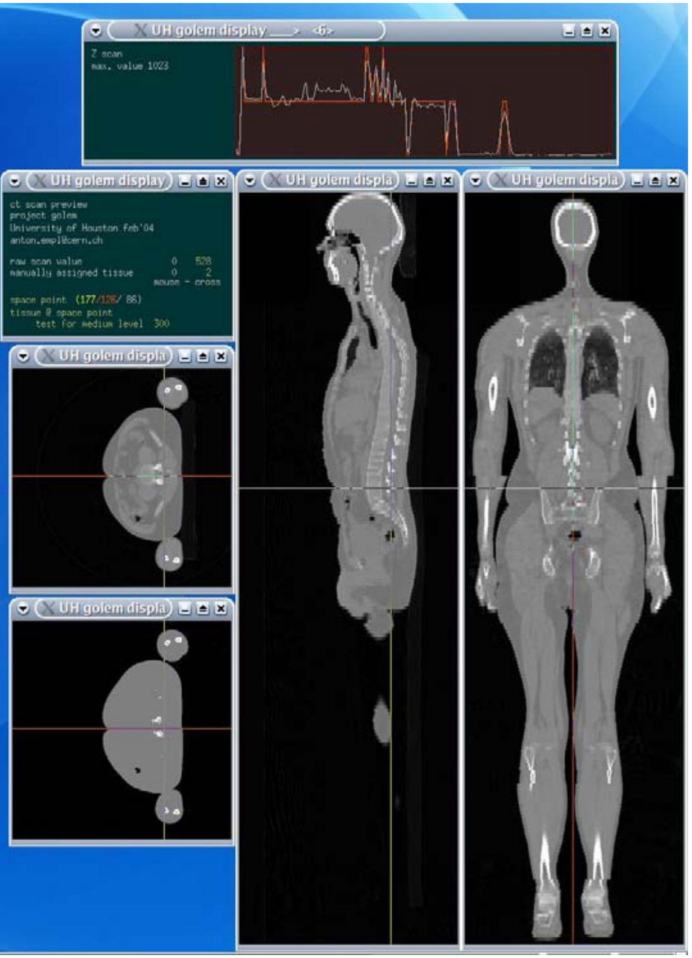
The voxel geometry

- 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



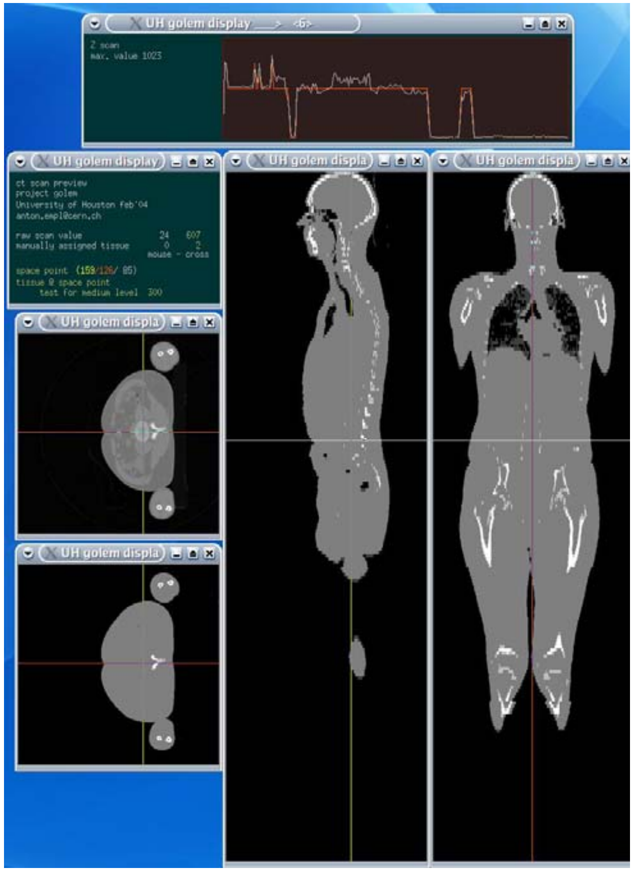
The GOLEM phantom
Petoussi-Henss et al, 2002

Automatic voxel type assignment



Raw GOLEM CT-SCAN

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

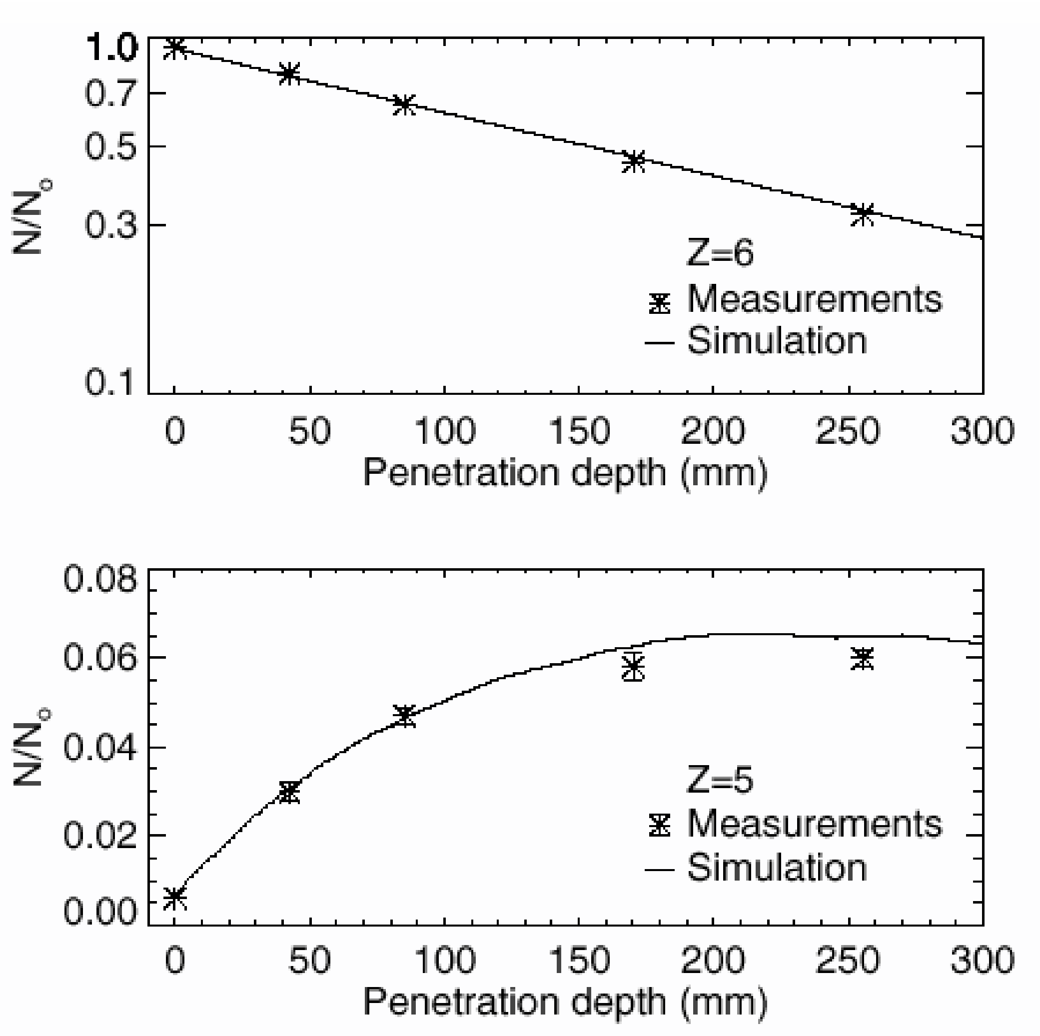
Comparison with experimental data on fragment production (Shall et al.)

  - ^{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.

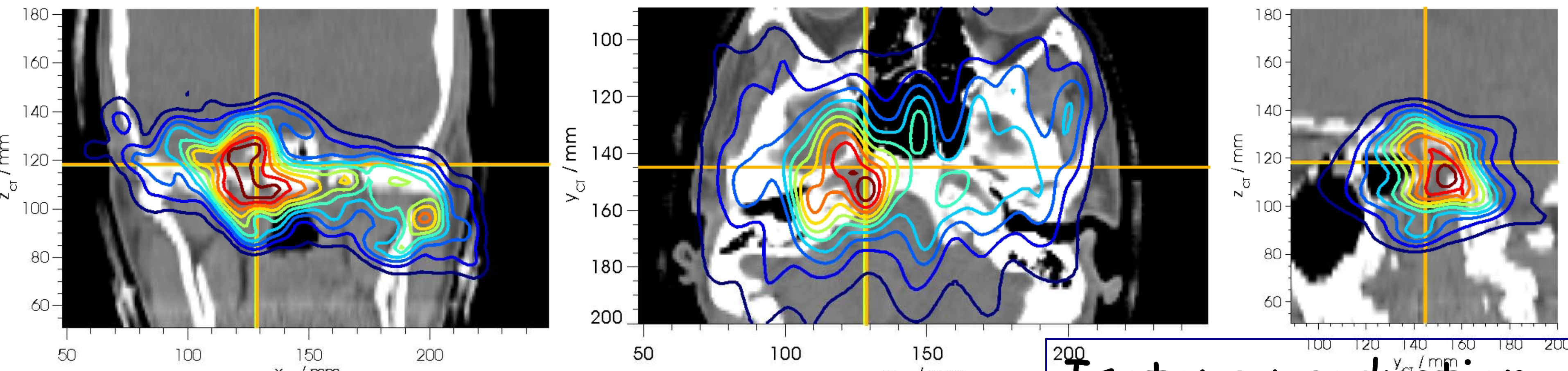
-Bottom: Build-up of boron ions as a function of depth.

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

A real case at GSI

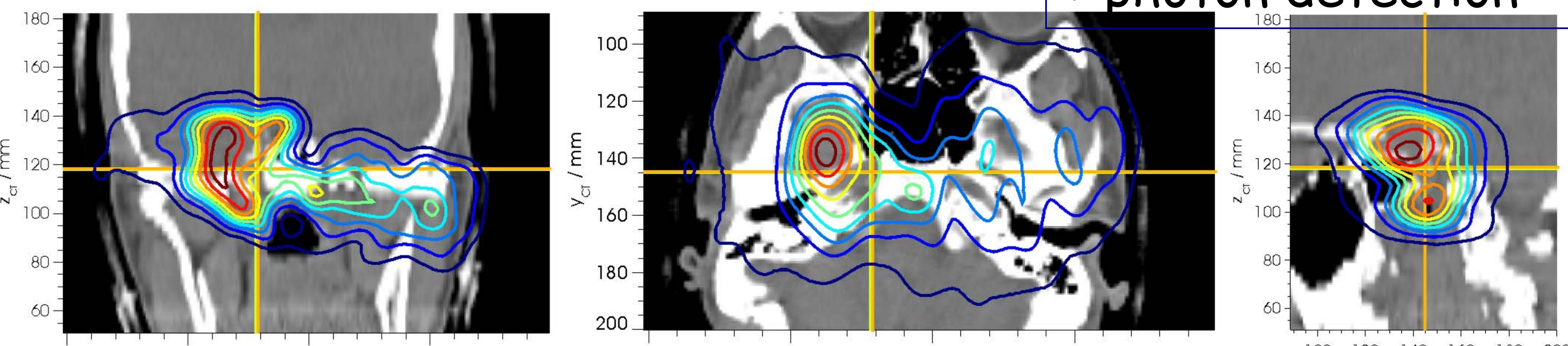
Positron emitters distribution following C irradiation

Measurement



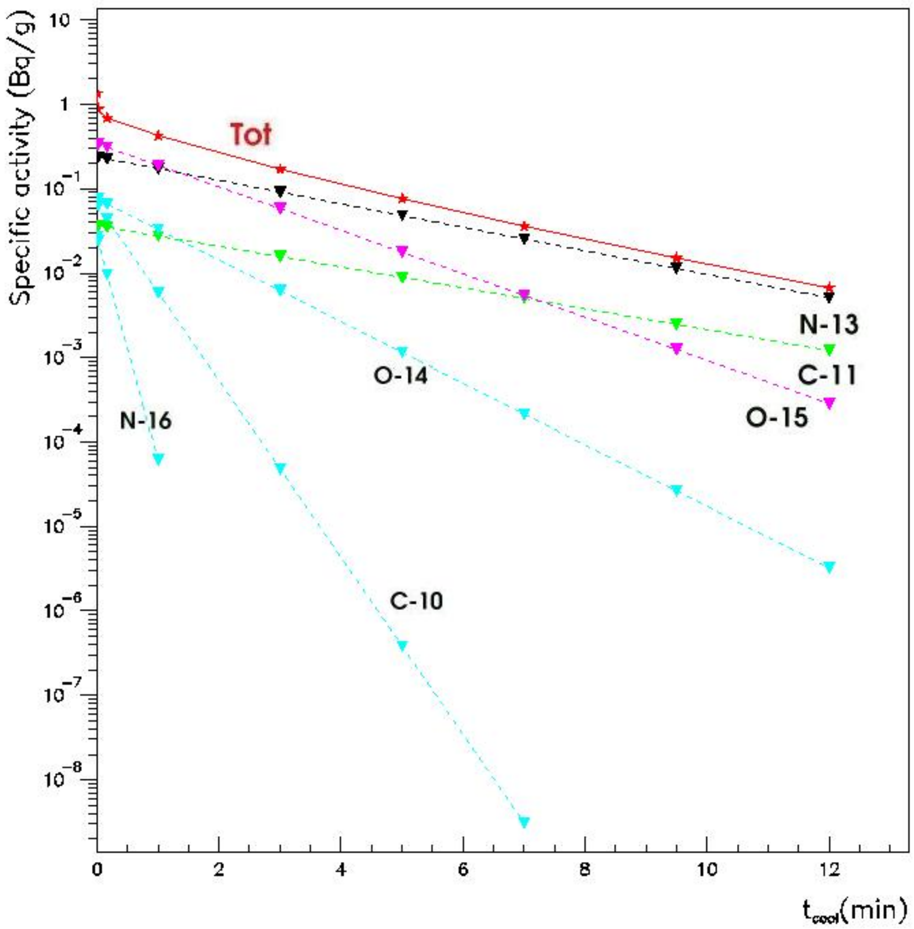
Simulation **PRELIMINARY**

Isotope production
+ e⁺ transport
+ photon detection



W. Enghardt, F. Fiedler, F. Sommerer, FZ Rossendorf, TU Wien&CERN

Application to The CNAO project



Future Treatments rooms:

Air activation from beam and secondary particles:

Beam :C ions, 400 MeV/u

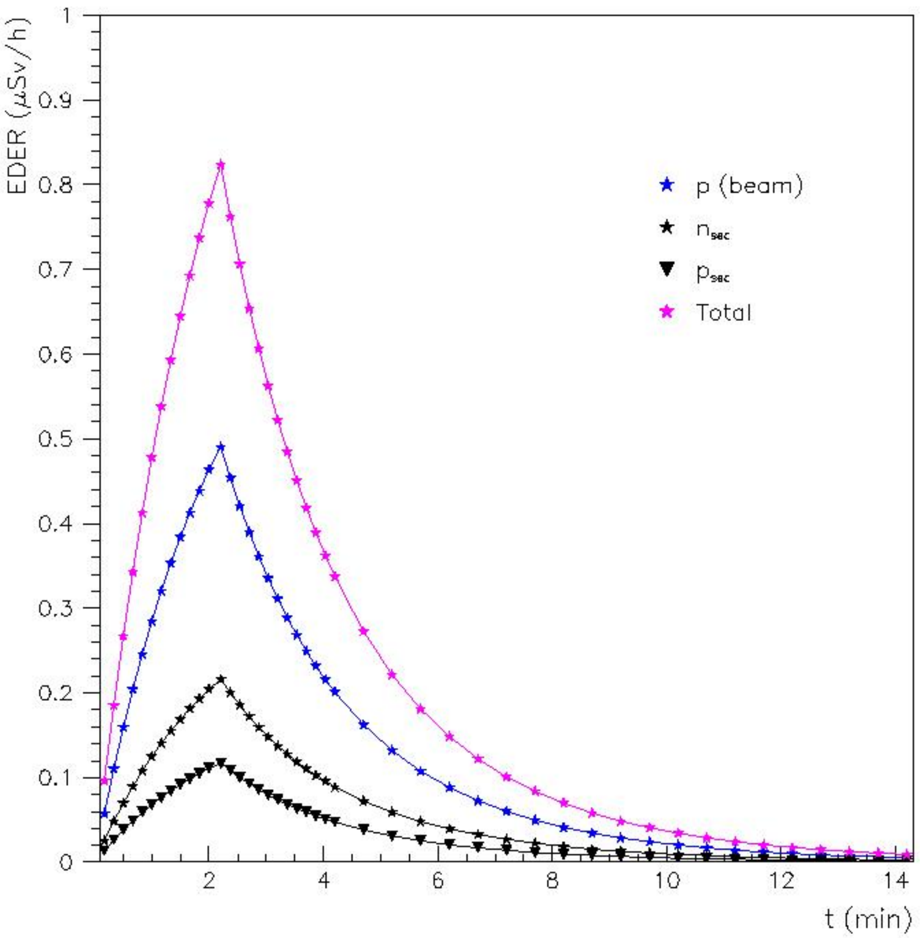
3 min treatment, 12 min interval

Target: equipments + patient phantom

Here : Specific activity of produced radionuclides as a function of time since the end of treatment.

M.Pelliccioni, Anna Ferrari, LNF

Application to The CNAO project



Future Treatments rooms:

Air activation from beam and secondary particles:

Beam :p, 250 MeV

3 min treatment, 12 min interval

Target: equipments + patient phantom

Here : Dose rate as a function of time, with partial contributions.

M.Pelliccioni, Anna Ferrari, LNF

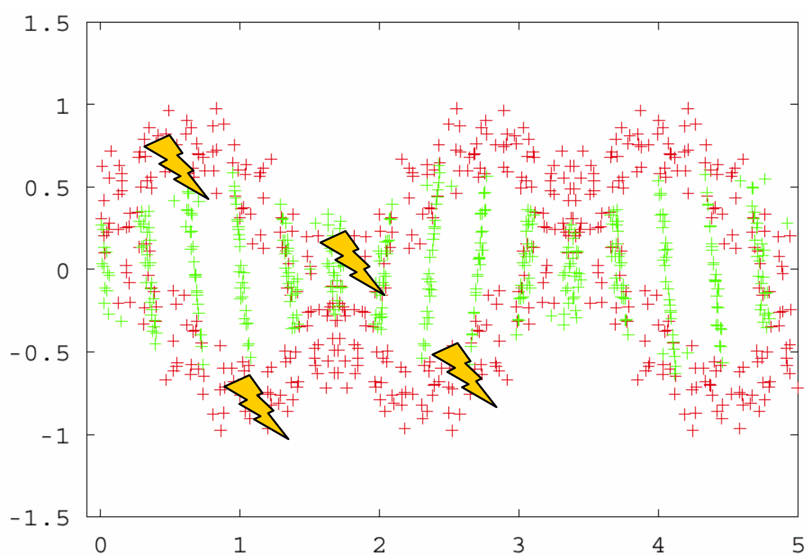
A weighted/biological dose

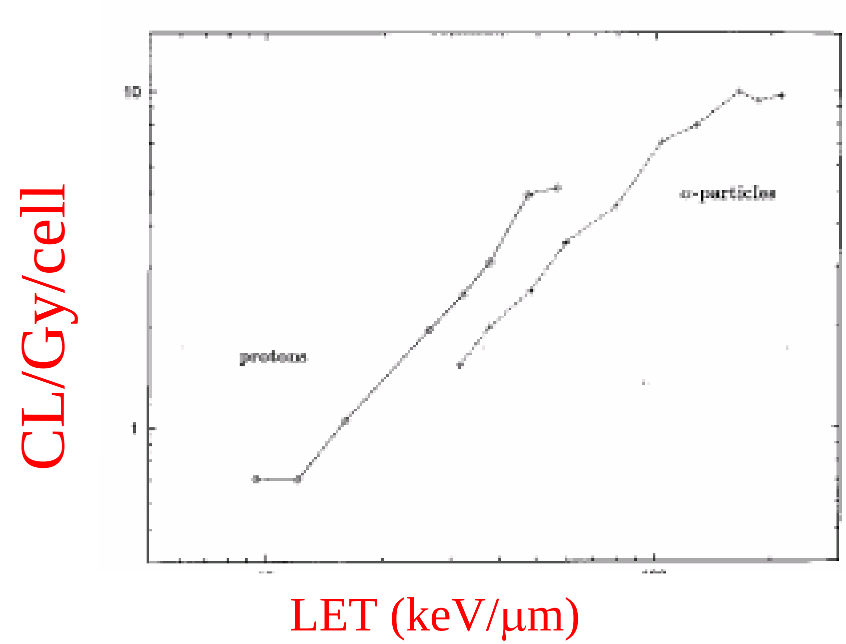
Radiation Protection: quality factors and weighting factors

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.)

INTEGRATION OF RADIOBIOLOGICAL DATA AND CALCULATIONS INTO FLUKA

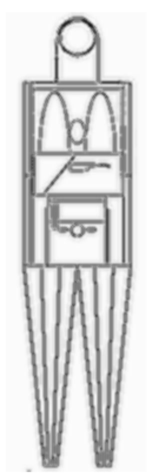
Radiobiological data and results of simulations (distributions) based on track structure codes (e.g. PARTRAC (GSF, Pavia)) and biophysical models (e.g. radiation induced CA models and codes)

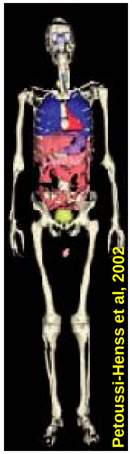
Radiation field and irradiation geometry

extended FLUKA

Doses, Fluences...;

effects at cellular, organ and organism levels



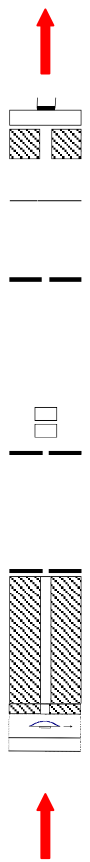


The OPTIS therapeutic proton beam

FLUKA

Geometry of the OPTIS therapy unit

EYE

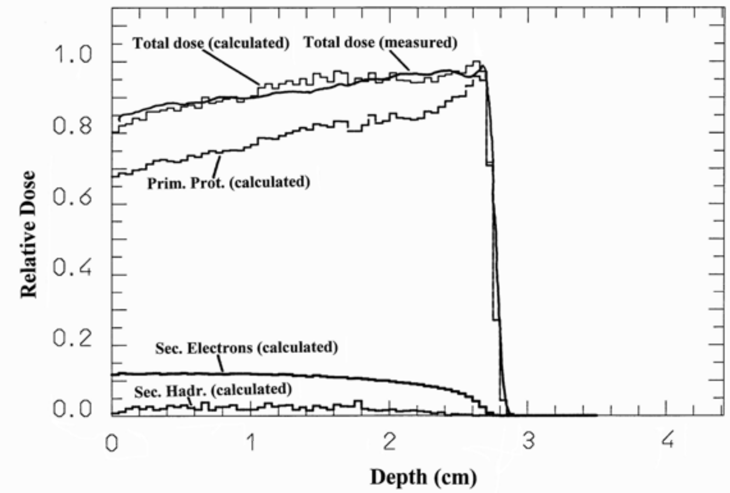


72 MeV proton BEAM

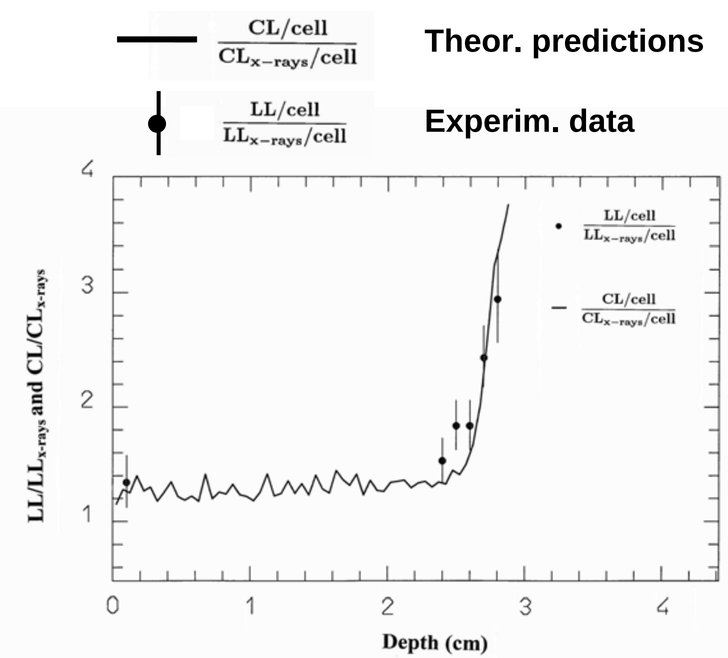
Complex Lesions as a function of LET and particle type

FLUKA CODE (EXTENDED)

PHYSICS

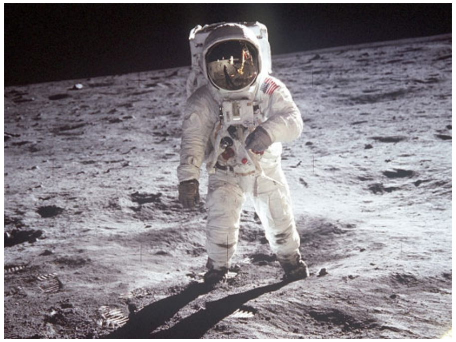


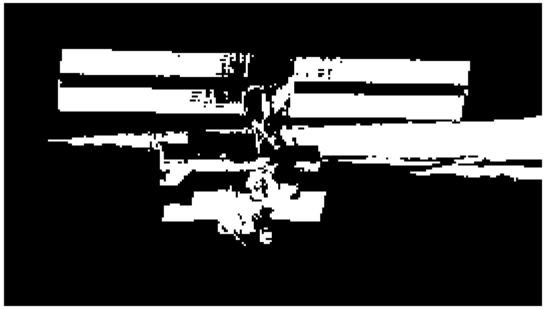
BIOLOGICAL EFFECTS

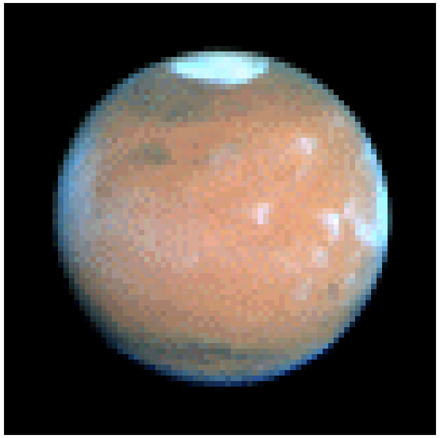


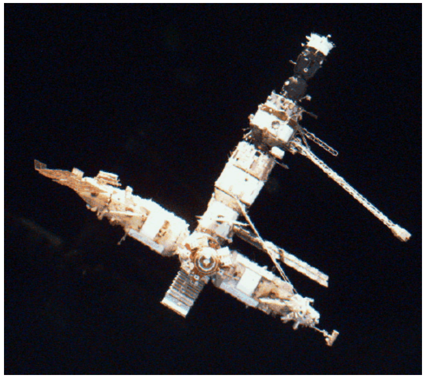
Biaggi et al NIM-B, 1999, 159,89-100

Applications to Space Radiation Protection









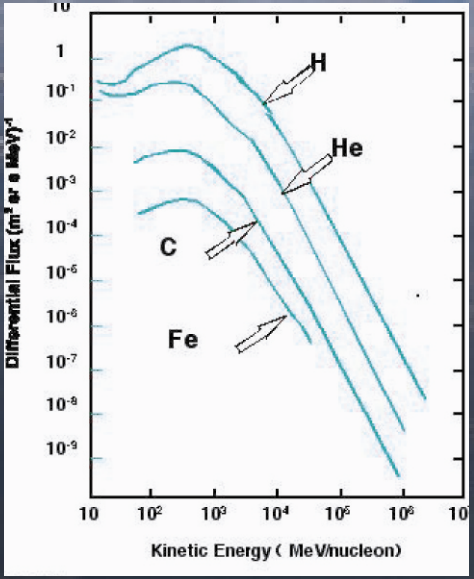
- FLUKA ⇒ spatial distribution of absorbed dose delivered by the different components of the radiation field
- "event-by-event" track structure codes ⇒ yields of CL/(Gy cell) induced by different radiation types
- integration ⇒ spatial distribution of CL/cell *("biological" dose)*

Radiation sources in space

Galactic Cosmic Rays

spectrum: 87% protons, 12% He ions and 1% heavier ions (in fluence) with peaks at 1 GeV/n

flux: ~4 particles/(cm^2 s) at solar min.



NASA pub. 1998

dose:

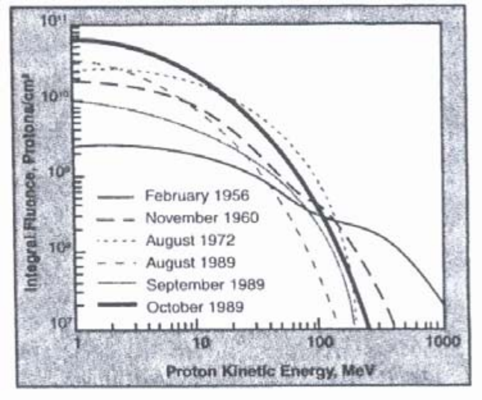
~1 mSv/day

Solar Particle Events

spectrum: 90% protons, 10% heavier ions with energy mainly below ~200 MeV

flux: up to ~10^{10} particles/cm^2 in some hrs.

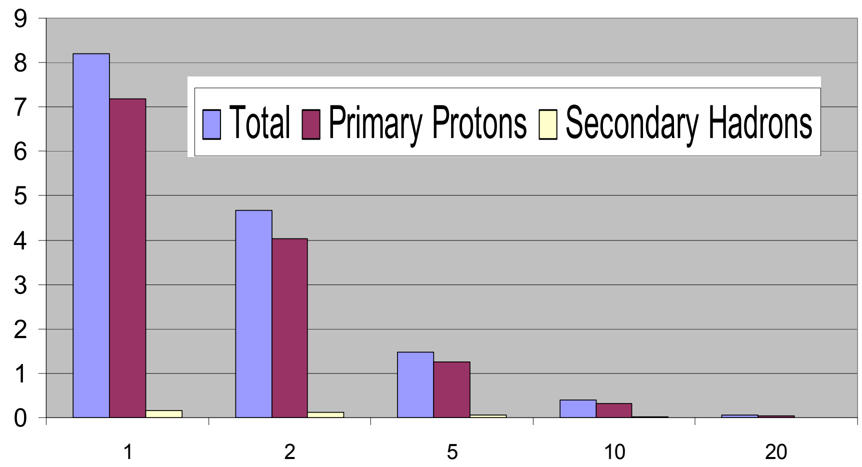
dose: order of Sv, strongly dependent on shielding and organ



NASA pub. 1998

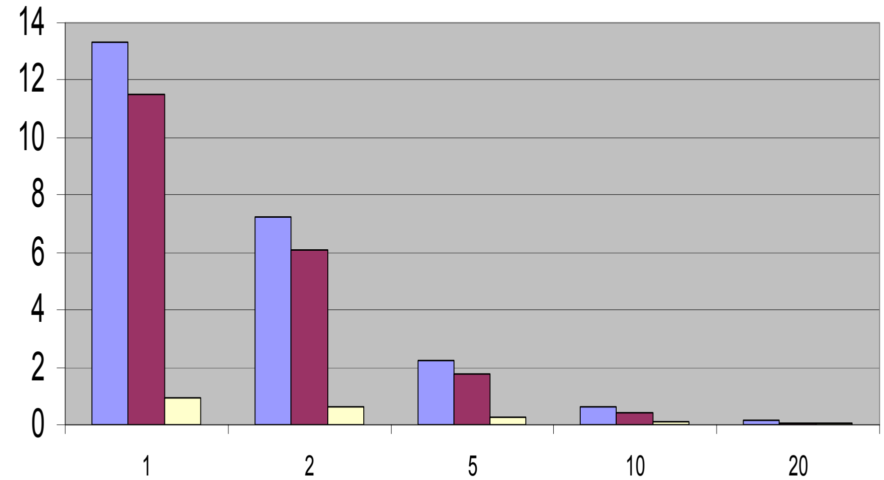
Aug. 1972 SPE - calculated skin doses

dose (Gy)



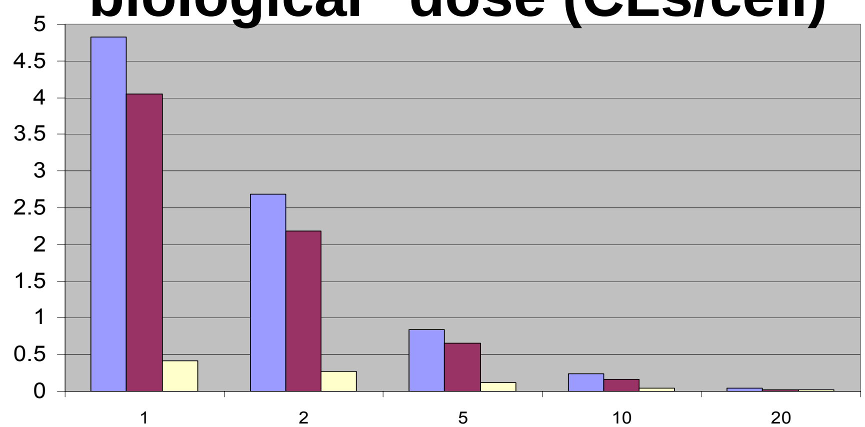
Al shield thickness (g/cm²)

dose equivalent (Sv)



Al shield thickness (g/cm²)

“biological” dose (CLs/cell)



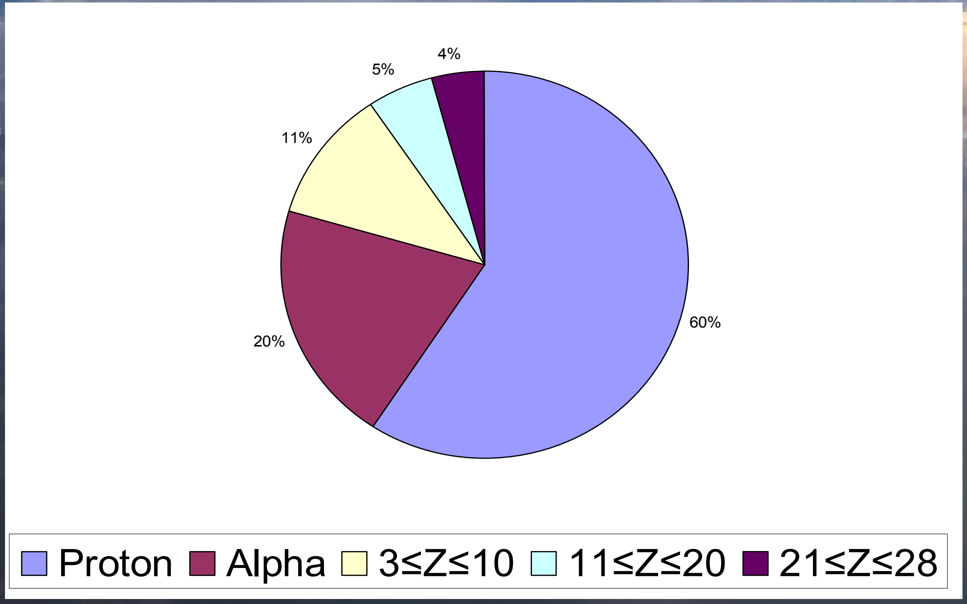
Al shield thickness (g/cm²)

- ***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)***

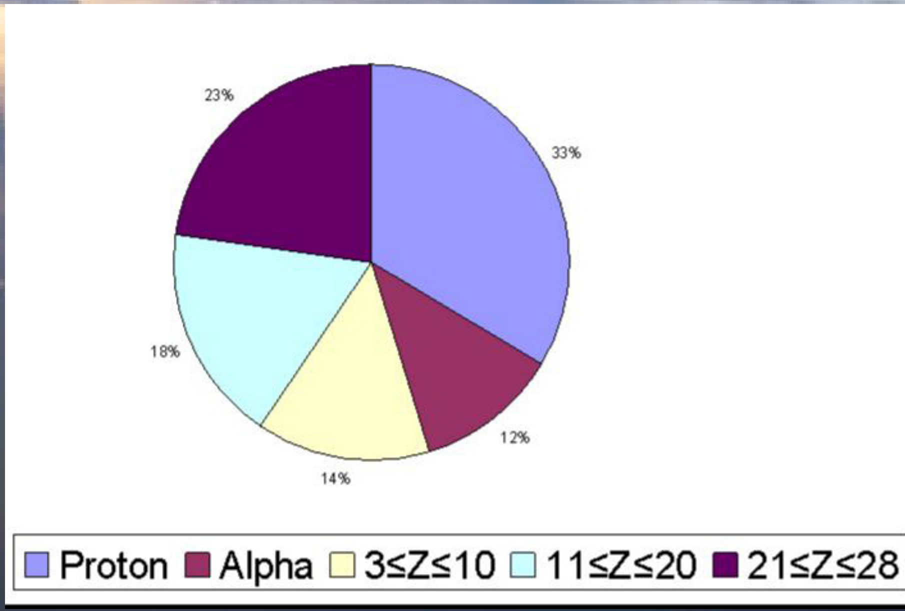
Galactic C.R. - role of the various spectrum components

(example with skin behind 5 g/cm² Al)

Skin Dose [mGy/d]



Skin Equivalent Dose [mSv/d]



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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
- – Implementation of BME for very low energy ion interactions
- – More friendly user interface

Download and documentation : www.fluka.org

END