Introduction and Applications of FLUKA

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for the FLUKA collaboration

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Outline

- What is FLUKA (short)
  - History
  - Collaboration
  - General structure
- Hadronic Physics in FLUKA (short)
  - Hadron-Nucleon
  - Hadron-Nucleus
  - (Nucleus-Nucleus)
  - (Real and Virtual Photonuclear interactions)
- Low energy neutron transport (short)
  - Main Features
- Hadronic (neutronic) applications
  - Examples

Special attention on recent developments

Examples of "thin target" benchmarks , essential to test and develop models

Examples of "complex" benchmarks, to illustrate the code capabilities and performances

Info: **http://www.fluka.org**

FLUKA

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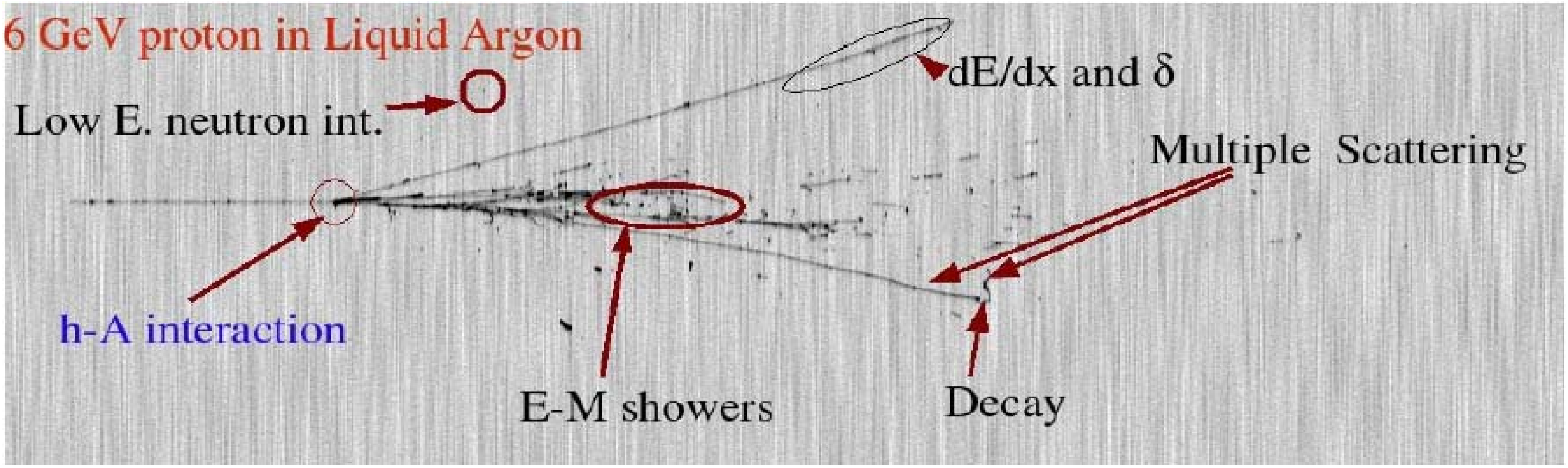
Interaction and Transport Monte Carlo code



Web site: http://www.fluka.org

FLUKA Description

- FLUKA is a general purpose tool for calculations of particle transport and interactions with matter, covering an extended range of applications
- 60 different particles + Heavy Ions
  - Hadron-hadron and hadron-nucleus interactions 0-10000 TeV
  - Electromagnetic and μ interactions 1 keV – 10000 TeV
  - Nucleus-nucleus interactions 0-10000 TeV/n
  - Charged particle transport – ionization energy loss
  - Neutron multi-group transport and interactions 0-20 MeV
  - ν interactions
  - Transport in magnetic field
  - Combinatorial (boolean) and Voxel geometry
  - ***Double capability to run either fully analogue and/or biased calculations***

- Maintained and developed under INFN-CERN agreement and copyright 1989-2006 (funding from NASA as well)
- More than 1000 users all over the world

http://www.fluka.org

Fluka Applications

- cosmic ray physics
- accelerator design (→ LHC systems)
- particle physics: calorimetry, tracking and detector simulation etc. (→ ALICE, ICARUS, ...)
- neutrino physics (CNGS, ...)
- shielding design
- dosimetry and radioprotection (standard tool at CERN and SLAC)
- space radiation (space related studies partially funded by NASA)
- hadron therapy
- neutronics
- ADS systems (→"Energy amplifier")

hN and hA inelastic interactions:

- **hN intermediate Energies**
  - $N_1 + N_2 \rightarrow N_1' + N_2' + \pi$ threshold around 290 MeV important above 700 MeV
  - $\pi + N \rightarrow \pi' + \pi'' + N'$ opens at 170 MeV

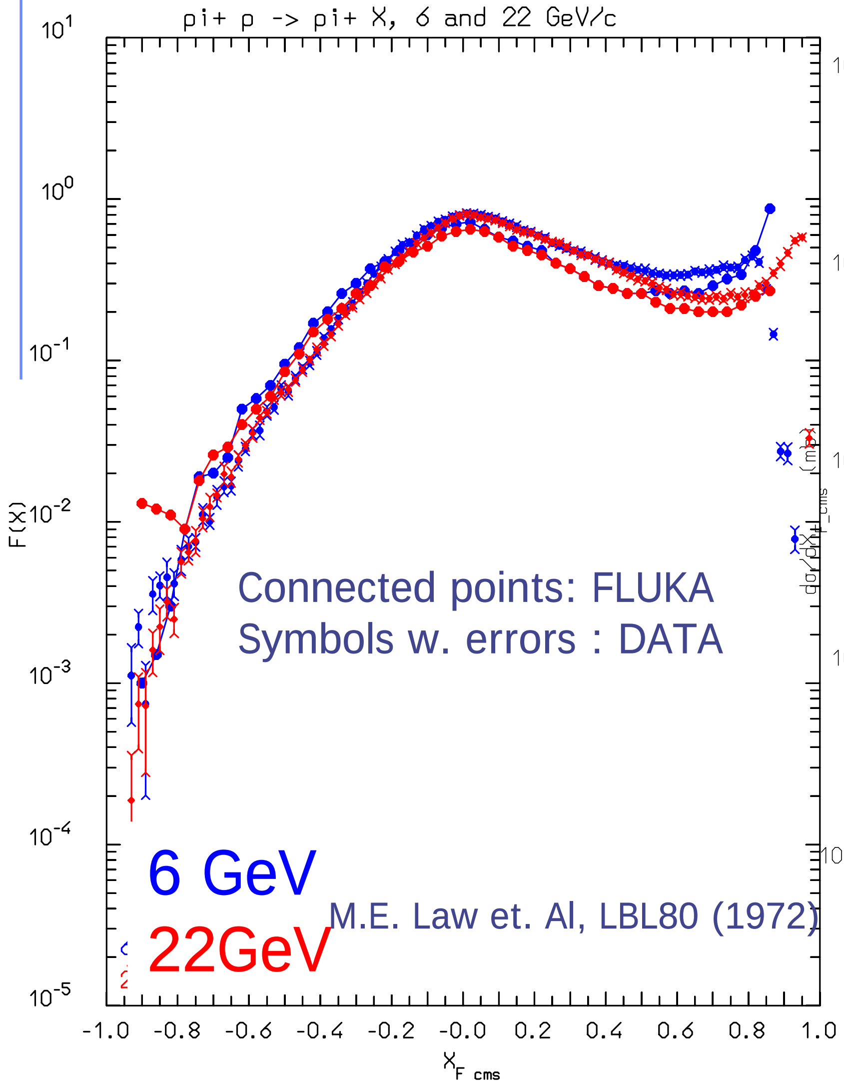
(Dominance of the $\Delta(1232)$ and of the N* resonances → reactions treated in the framework of the isobar model → all reactions proceed through an intermediate state containing at least one resonance)

- **hN high Energies: Dual Parton Model**
  - Interacting strings (quarks held together by the gluon-gluon interaction into the form of a string)
  - each of the two hadrons splits into 2 colored partons → combination into 2 colourless chains → 2 back-to-back jets
  - each jet is then hadronized into physical hadrons

- **hA: Glauber(-Gribov) cascade**
  - Quantum mechanical method to compute Elastic, Quasi-elastic and Absorption hA cross sections
  - **Field theory** formulation of Glauber model
  - Multiple collisions ↔ **Feynman diagrams** ↔ Pomeron(s) exchange
- **hA: Formation zone** (=materialization time)

Inelastic hN interactions: examples

$\pi^+ + p \rightarrow \pi^+ + X$ (6 & 22 GeV/c)

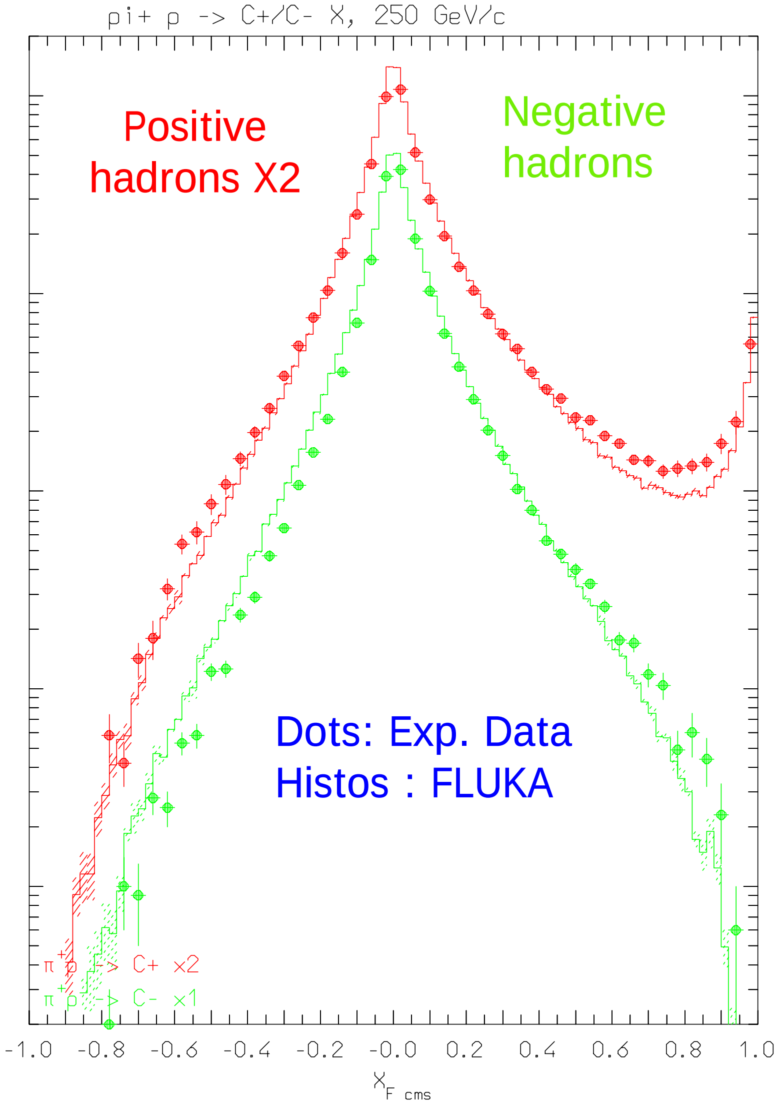


Connected points: FLUKA
Symbols w. errors : DATA

6 GeV
22GeV

M.E. Law et. Al, LBL80 (1972)

$\pi^+ + p \rightarrow Ch^+/Ch^- + X$ (250 GeV/c)



Positive hadrons X2

Negative hadrons

Dots: Exp. Data
Histos : FLUKA

The Nuclear environment: PEANUT

Pre**E**quilibrium **A**pproach to **NU**clear **T**hermalization

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

Sophisticated **Generalized IntraNuclear Cascade**

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

↓

Prequilibrium stage

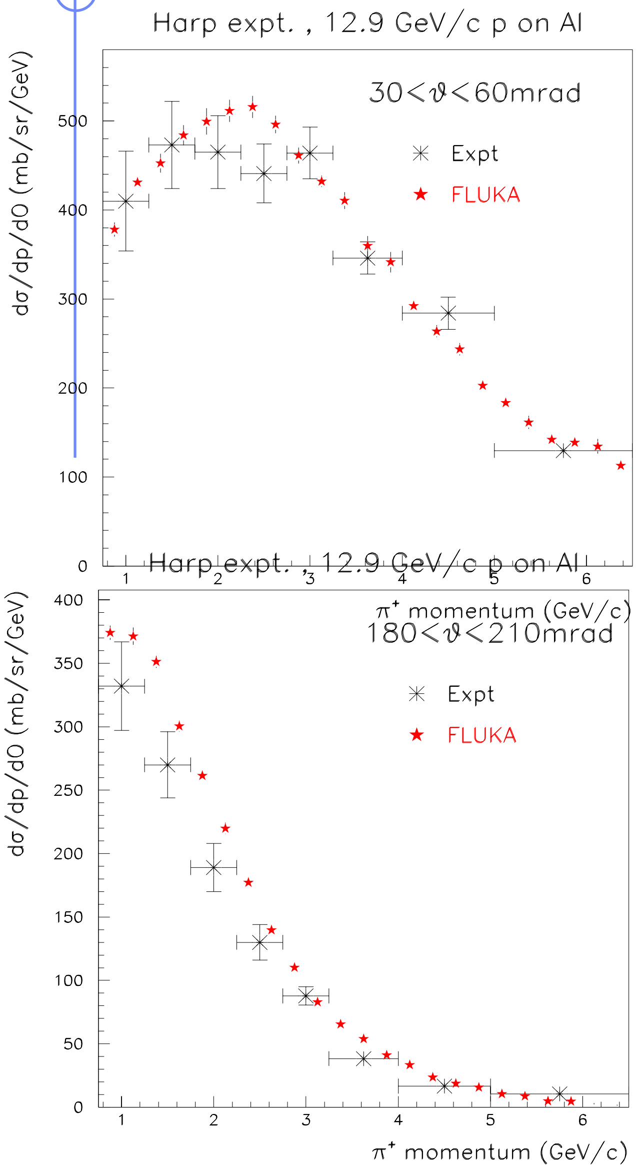
Standard Assumption on exciton number or excitation energy

↓

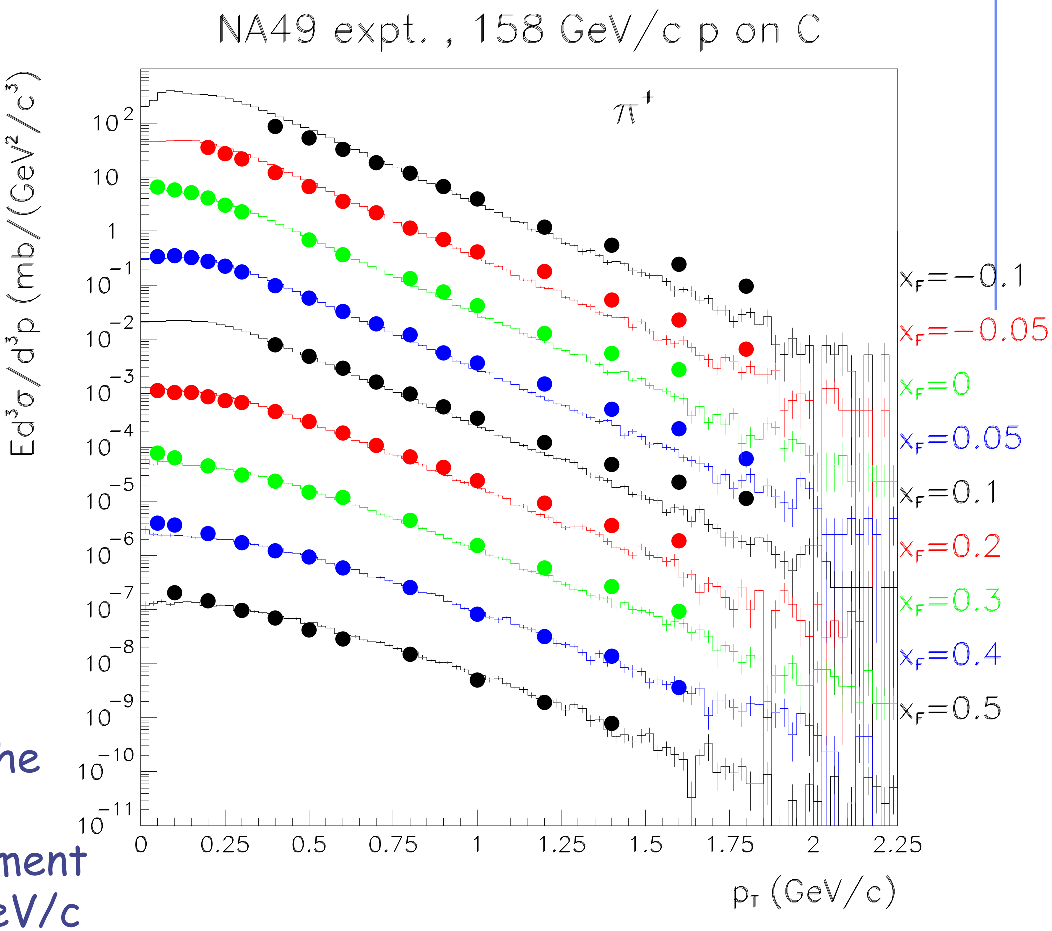
Common **FLUKA Evaporation/fission/fragmentation** model

> *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**, **muon captures**..*

Nonelastic hA interactions at high energies: examples

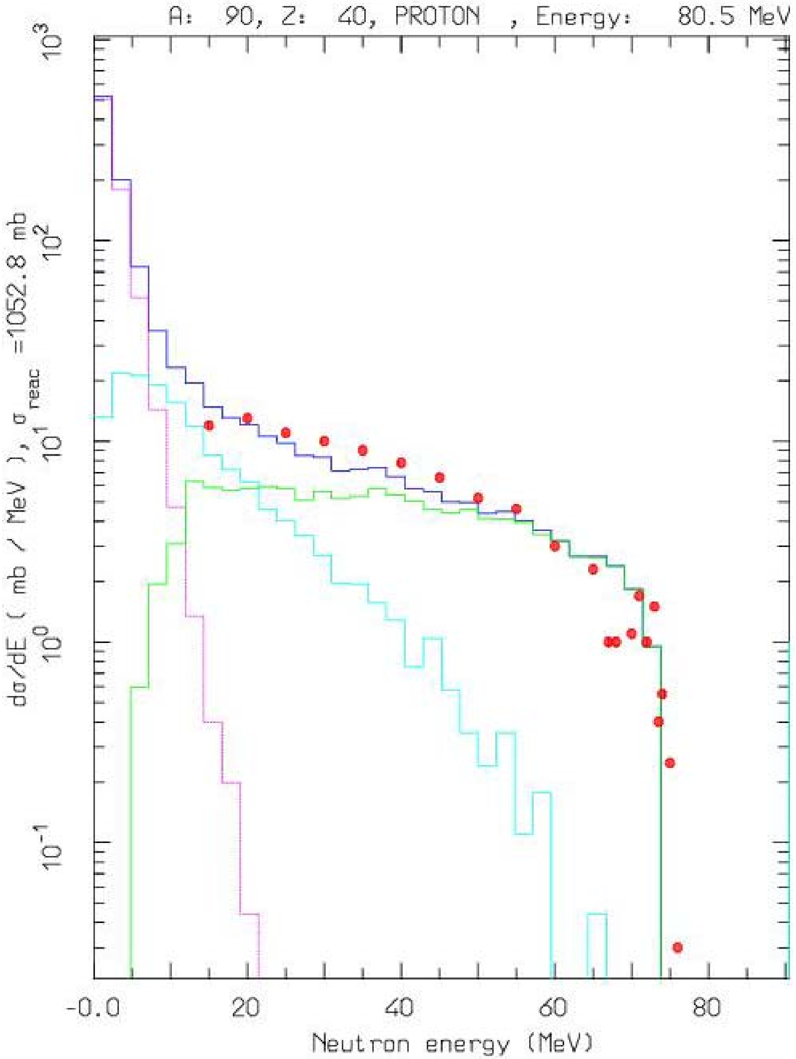


Recent results from the HARP experiment 12.9 GeV/c p on Al π^+ production at different angles



Double differential $\pi+$ production for p C interactions at 158 GeV/c, as measured by NA49 (symbols) and predicted by FLUKA (histograms)

Low energy thin target example



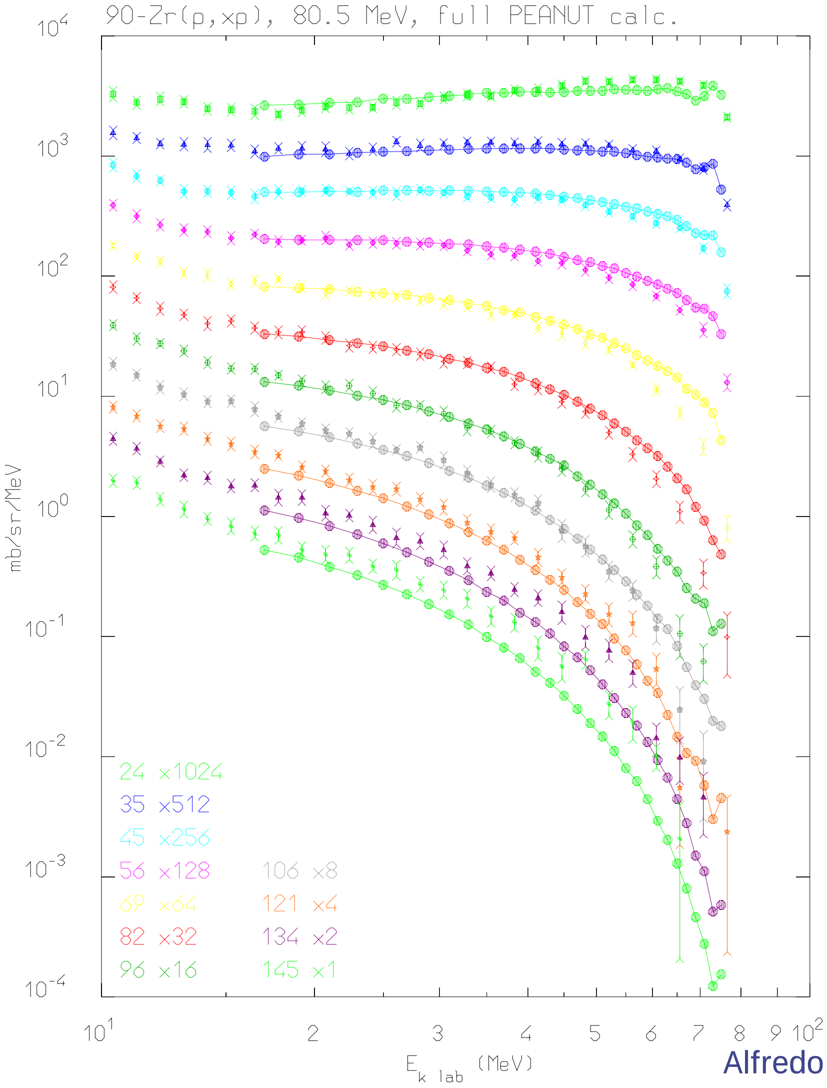
Angle-integrated ^{90}Zr(p,xn) at 80.5 MeV

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

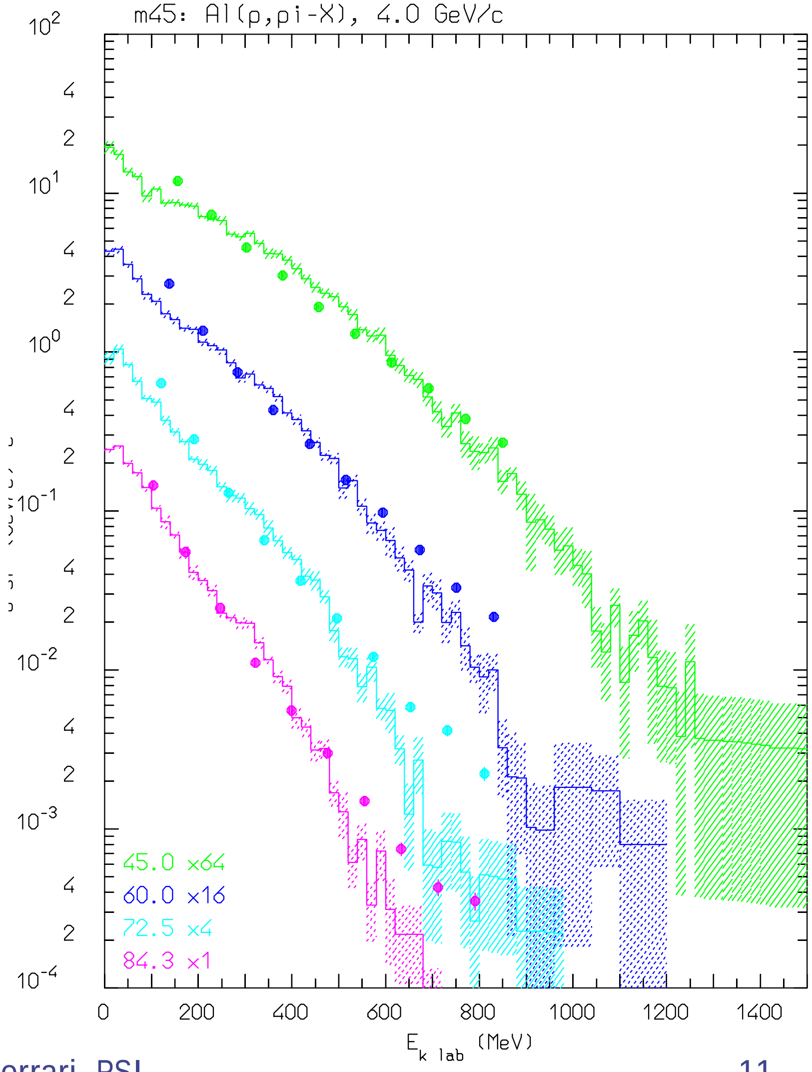
Experimental data from
M. Trabandt et al., Phys. Rev. C39, 452 (1989)

Thin target examples

p + ^{80}Zr → p + X (80 MeV)



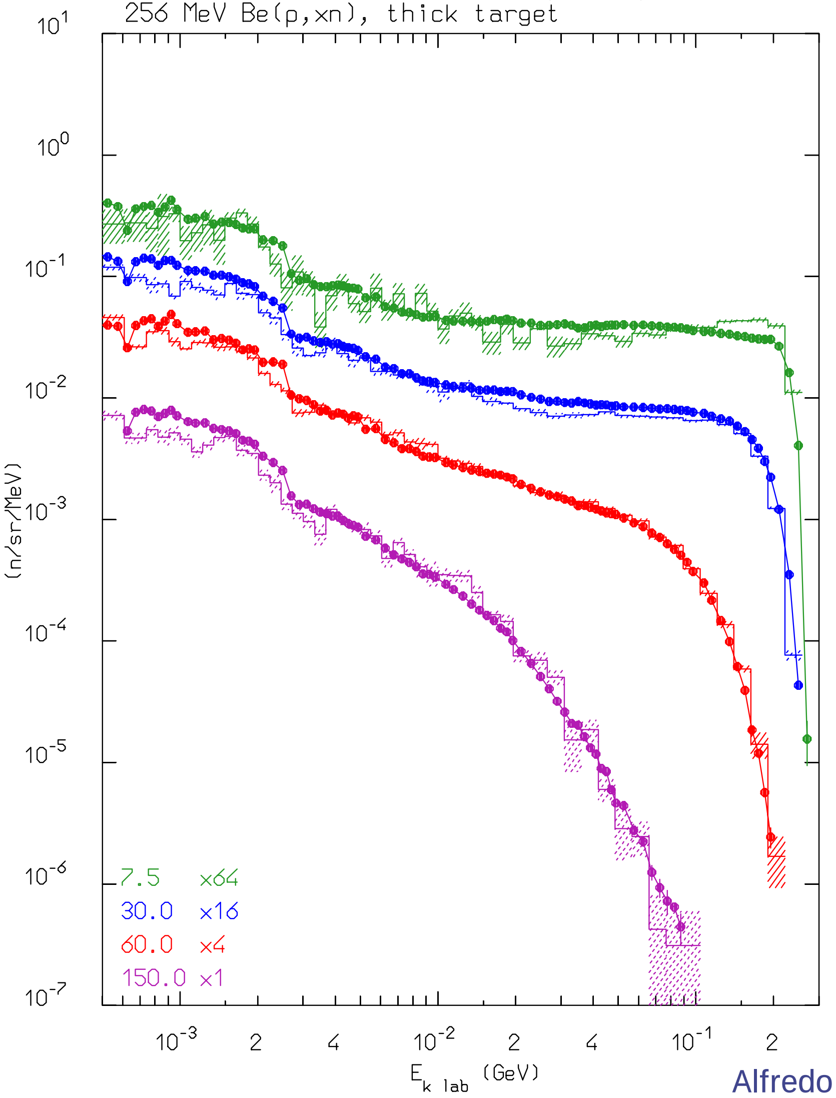
p + Al → π^- + X (4 GeV/c)



Thick/Thin target examples: neutrons

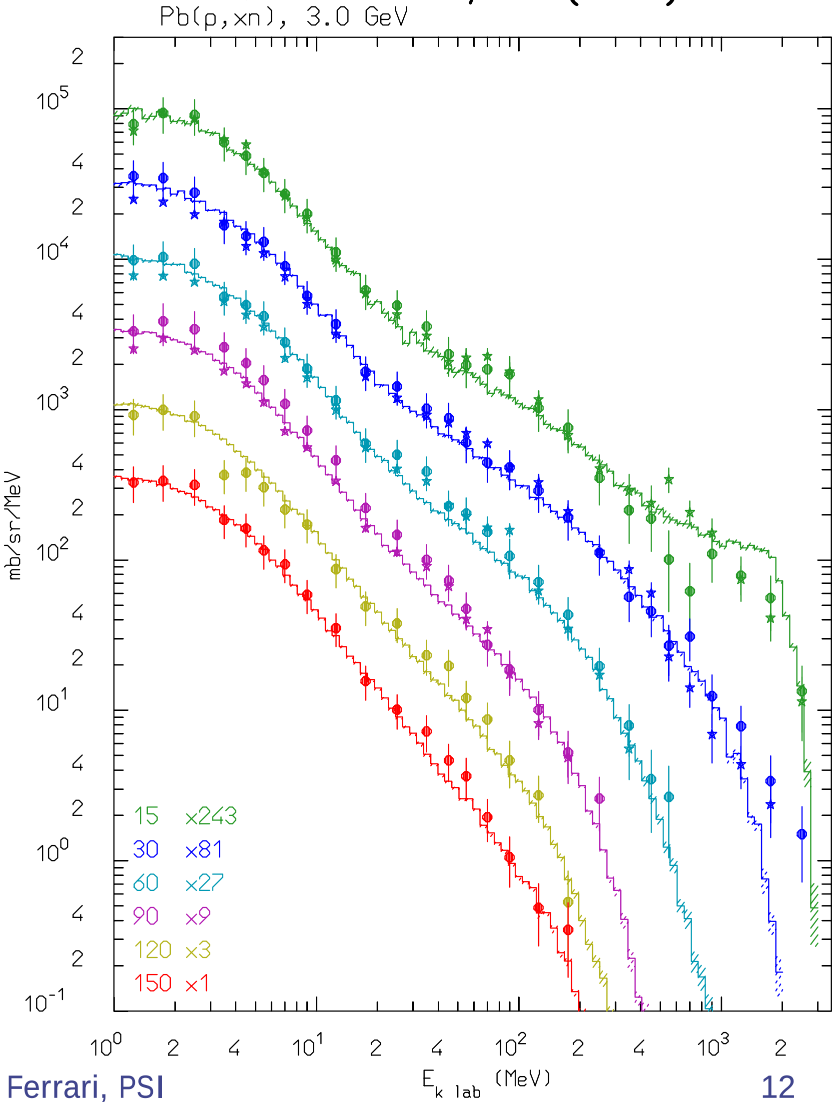
^{9}Be(p,xn) @ 256 MeV, stopping target

Data: NSE110, 299 (1992)



Pb(p,xn) @ 3 GeV, thin target

Data: NST32, 827 (1995)



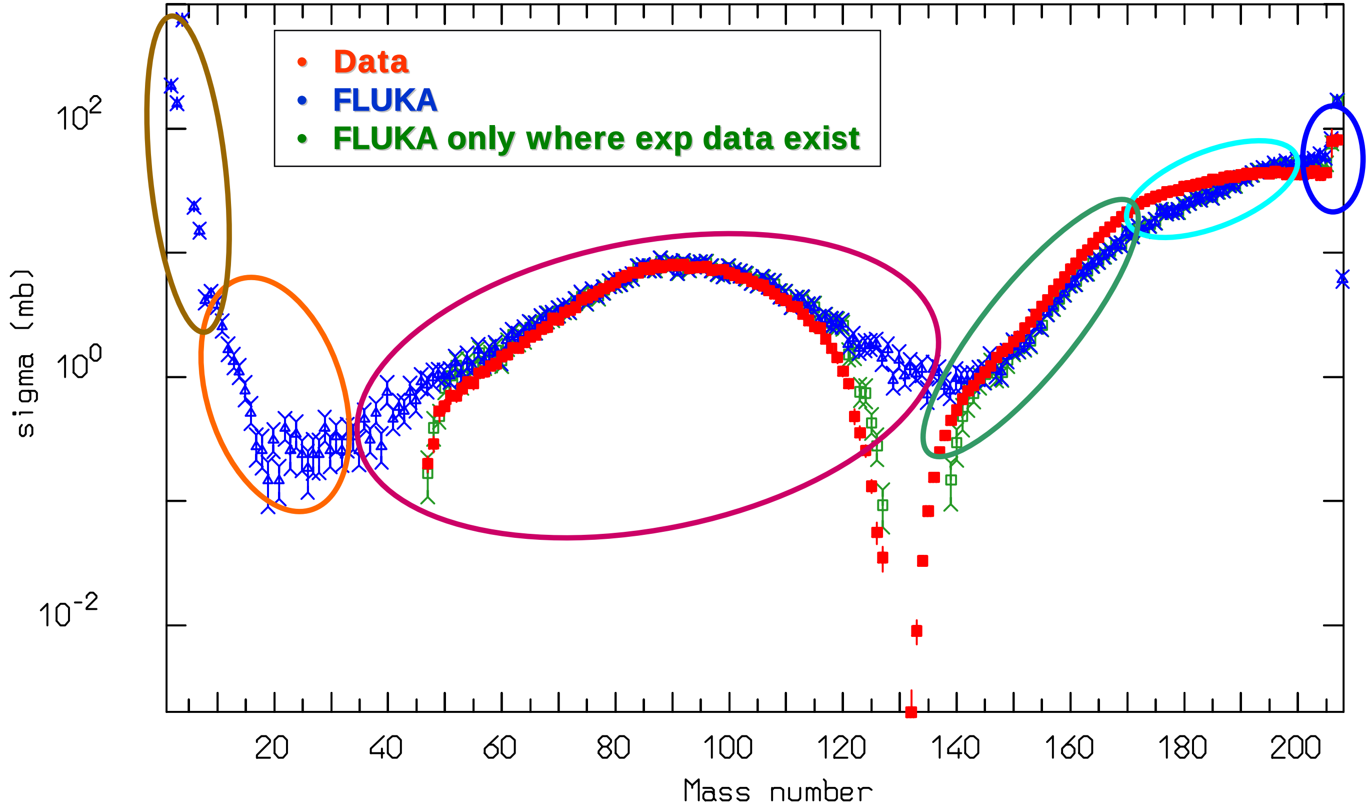
Equilibrium particle emission

- **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! New energy dependent self-consistent evaporation level densities (IAEA recommendations)
  - NEW! New pairing energies consistent with the above point
  - NEW! Extension of mass tables till A=330 using available offline calculations
  - NEW! New shell corrections coherent with the new masses
- **Fission**:
  - NEW! Actinide fission done on first principles
  - NEW! New fission barrier calculations (following Myers & Swiatecki)
  - NEW! Fission level density enhancement at saddle point washing out with excitation energy (following IAEA recommendations)
  - NEW! 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
- γ **de-excitation**: statistical + rotational + tabulated levels

Example of fission/evaporation

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

1 A GeV ^{208}Pb + p reactions Nucl. Phys. A 686 (2001) 481-524



Low-energy neutron transport in FLUKA

performed by a multigroup algorithm

- Energy range up to 19.6 MeV divided in 72 energy groups (and 22 groups for secondary gamma generation)
- The library contains 140 different materials/temperatures
- Hydrogen cross sections available for different types of molecular binding (free, H_2O, CH_2)
- Pointwise, fully correlated, with explicit generation of all secondary recoils, cross sections available for reactions in H, ^{6}Li , Ar and partially for ^{14}N and ^{10}B (^{4}He, ^{12}C and ^{16}O in preparation)
- gamma transport by the standard EM FLUKA modules
- For most materials, information on the residual nuclei produced by low-energy neutron interactions are available in the FLUKA library

The new library

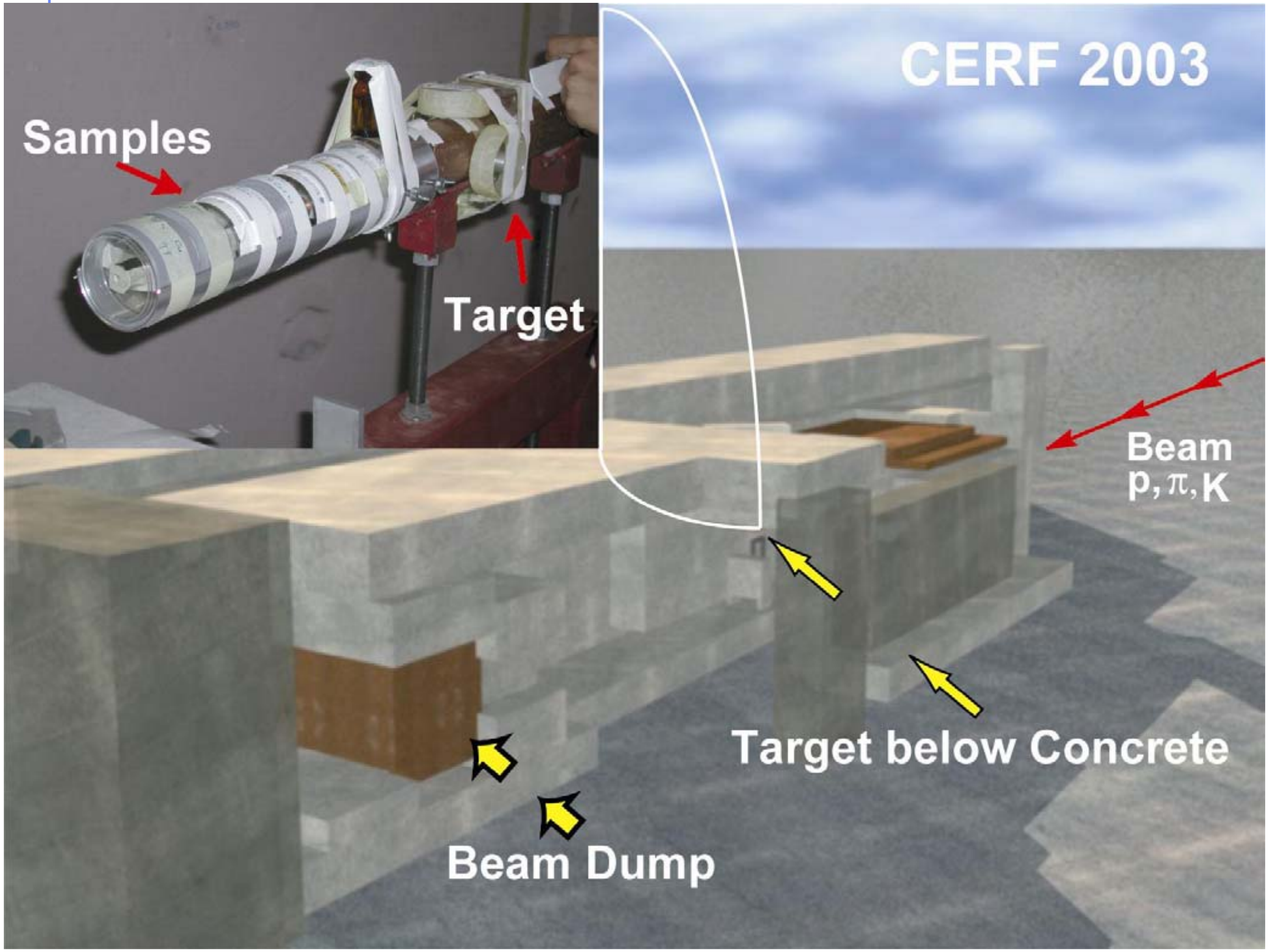
- 260 n and 40 γ groups including 30 thermal groups at different temperatures and different self-shielding (publicly available at beginning of 2007)

Online evolution of activation and residual dose

NEW

- Decay β's, γ's produced and transported "on line"
  - Screening and Coulomb corrections accounted for $\beta^{+/-}$ spectra
  - Complete database for γ lines and β spectra covering down to 0.1% branching
- Time evolution of induced radioactivity calculated analytically
  - Fully coupled build-up and decay (Bateman equations)
  - Up to 4 different decay channels per isotope
- Results for activity, energy deposition, particle fluences etc, calculated for custom irradiation/cooling down profiles

CERN-EU High-Energy Reference Field (CERF) facility



Beam : 120 GeV, mixed hadrons from CERN SPS

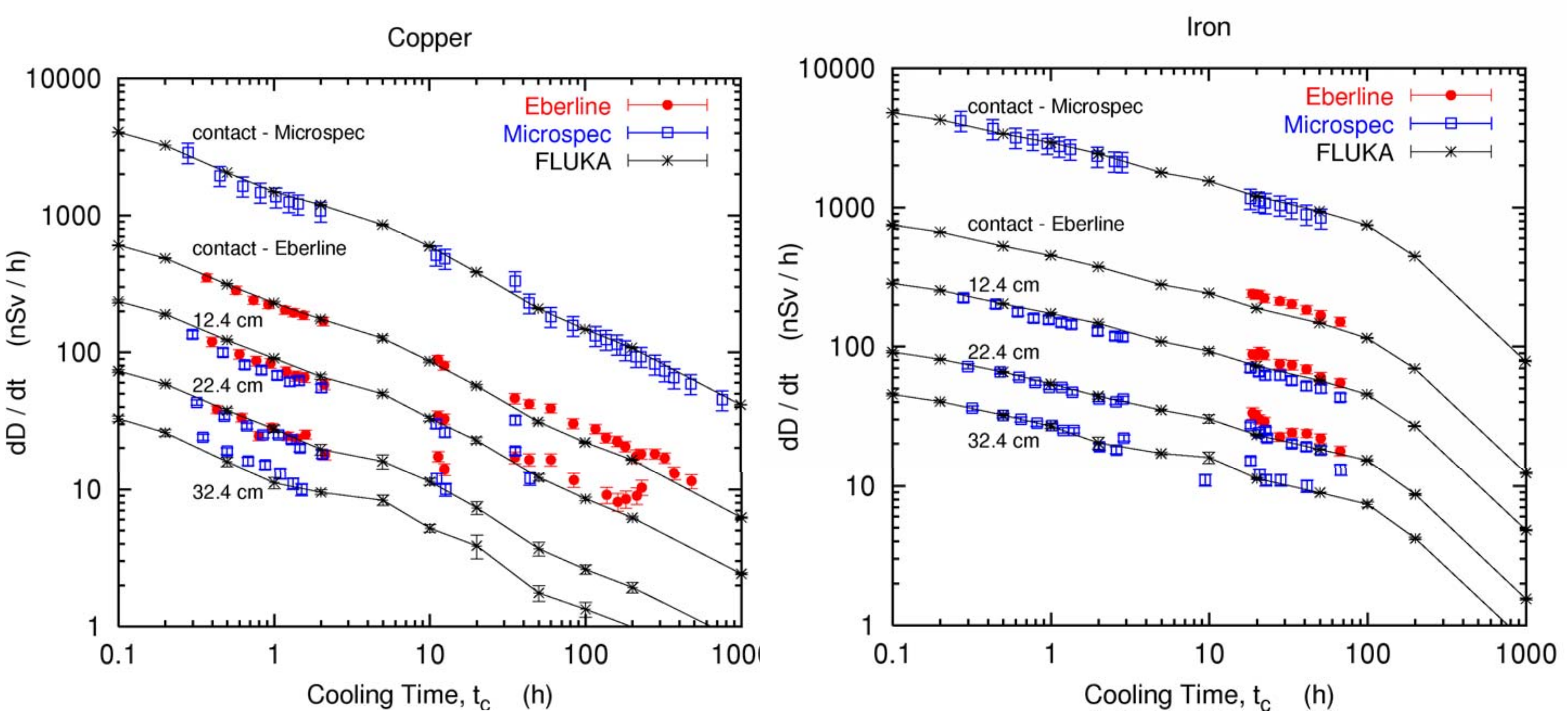
Location of Samples:

Behind a 50 cm long, 7 cm diameter copper target, centred with the beam axis

Benchmark experiment – *Results 1*

M. Brugger *et al.,* Radiat. Prot. Dosim. 116 (2005) 12-15

Dose rate as function of cooling time
for different distances between sample and detector



Activation: Stainless Steel

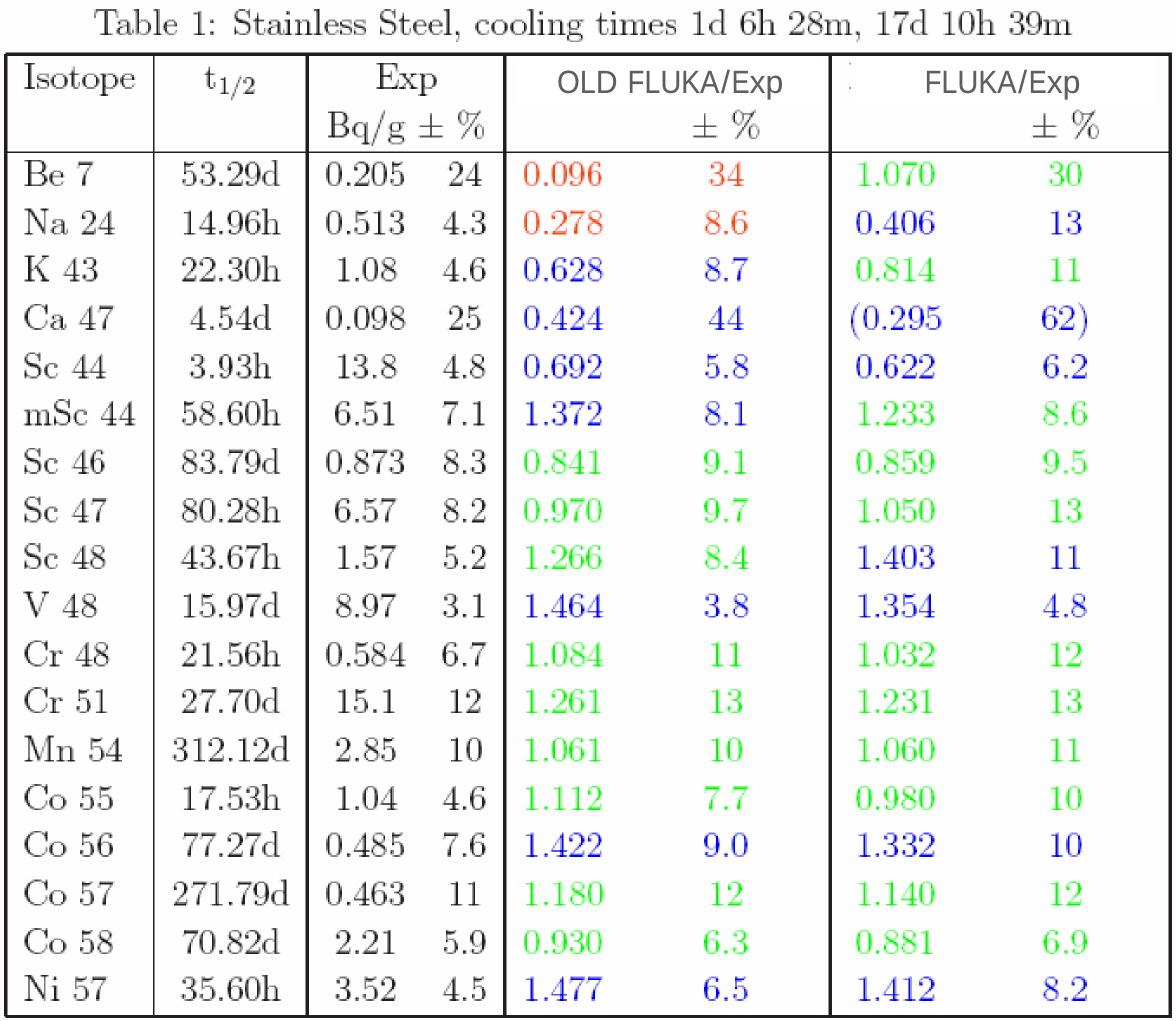
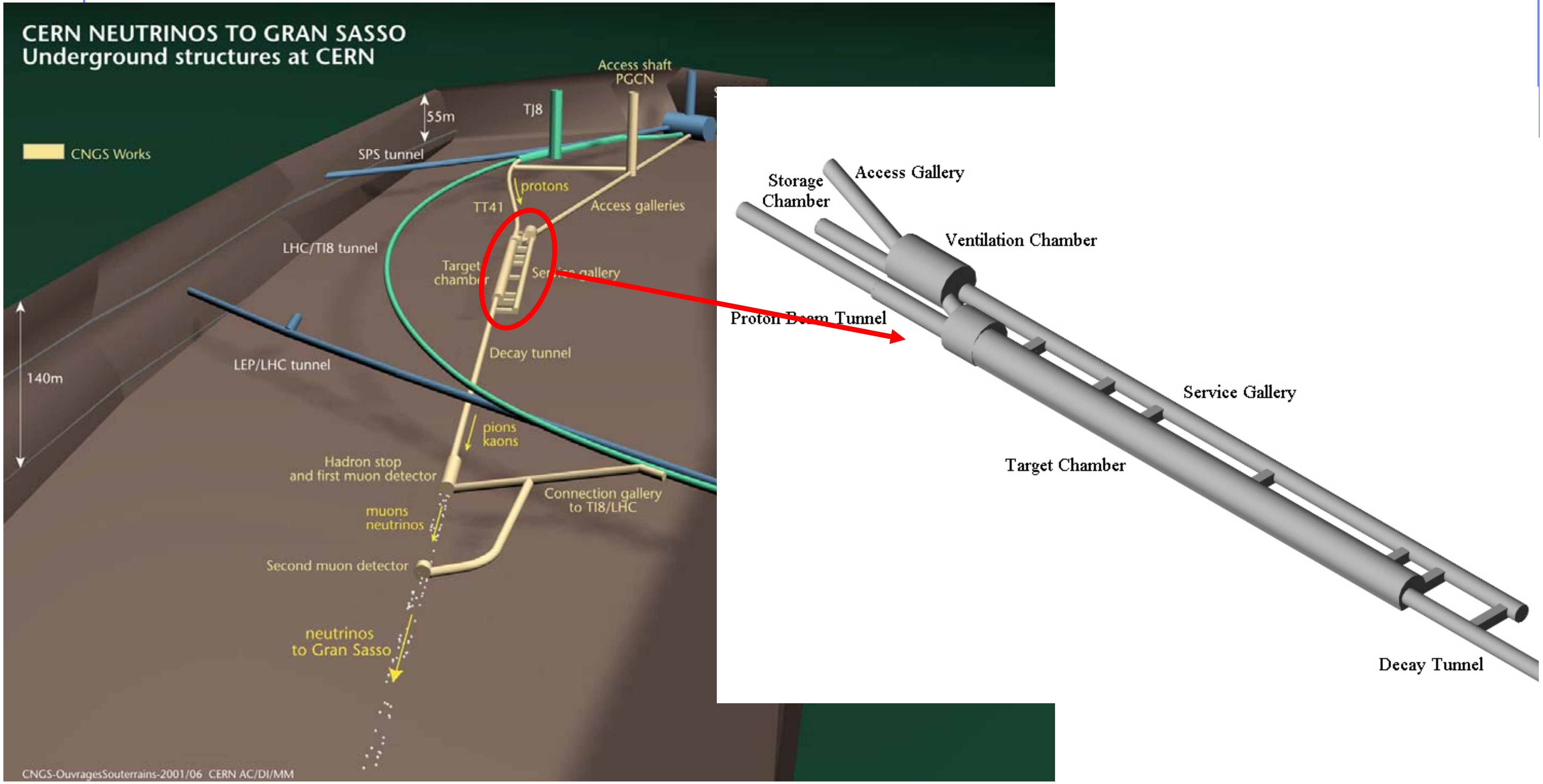


Table 1: Stainless Steel, cooling times 1d 6h 28m, 17d 10h 39m

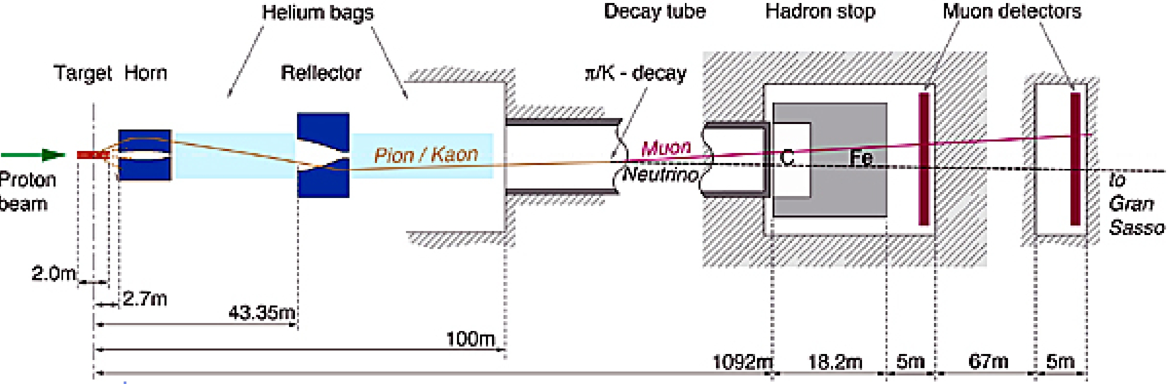
Isotope	$t_{1/2}$	Exp Bq/g	± %	OLD FLUKA/Exp	± %	FLUKA/Exp	± %
Be 7	53.29d	0.205	24	0.096	34	1.070	30
Na 24	14.96h	0.513	4.3	0.278	8.6	0.406	13
K 43	22.30h	1.08	4.6	0.628	8.7	0.814	11
Ca 47	4.54d	0.098	25	0.424	44	(0.295	62)
Sc 44	3.93h	13.8	4.8	0.692	5.8	0.622	6.2
mSc 44	58.60h	6.51	7.1	1.372	8.1	1.233	8.6
Sc 46	83.79d	0.873	8.3	0.841	9.1	0.859	9.5
Sc 47	80.28h	6.57	8.2	0.970	9.7	1.050	13
Sc 48	43.67h	1.57	5.2	1.266	8.4	1.403	11
V 48	15.97d	8.97	3.1	1.464	3.8	1.354	4.8
Cr 48	21.56h	0.584	6.7	1.084	11	1.032	12
Cr 51	27.70d	15.1	12	1.261	13	1.231	13
Mn 54	312.12d	2.85	10	1.061	10	1.060	11
Co 55	17.53h	1.04	4.6	1.112	7.7	0.980	10
Co 56	77.27d	0.485	7.6	1.422	9.0	1.332	10
Co 57	271.79d	0.463	11	1.180	12	1.140	12
Co 58	70.82d	2.21	5.9	0.930	6.3	0.881	6.9
Ni 57	35.60h	3.52	4.5	1.477	6.5	1.412	8.2

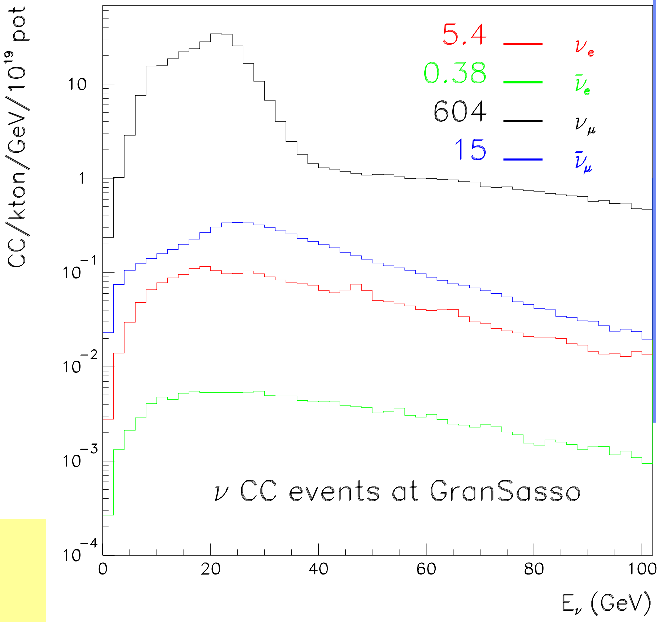
M. Brugger, *et al.*, Proceedings of the Int. Conf. on Accelerator Applications (AccApp'05), Venice, Italy, 2005

Applications – *CNGS*

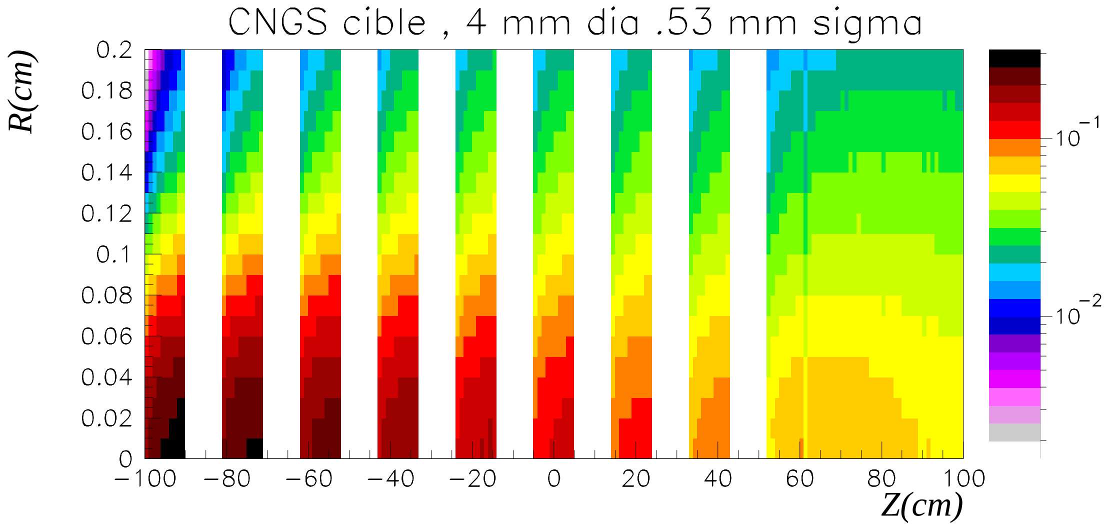


Cern Neutrino to Gran Sasso

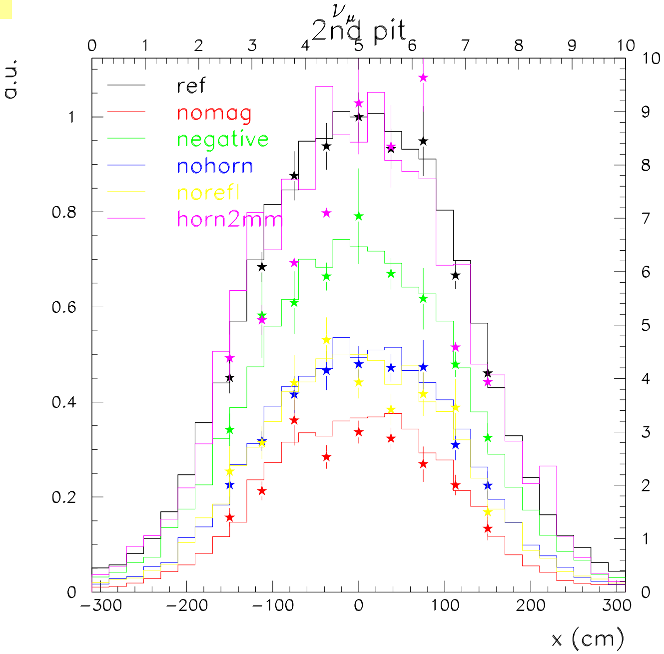




Engineering and physics: target heating, shielding, activation, beam monitors, neutrino spectra

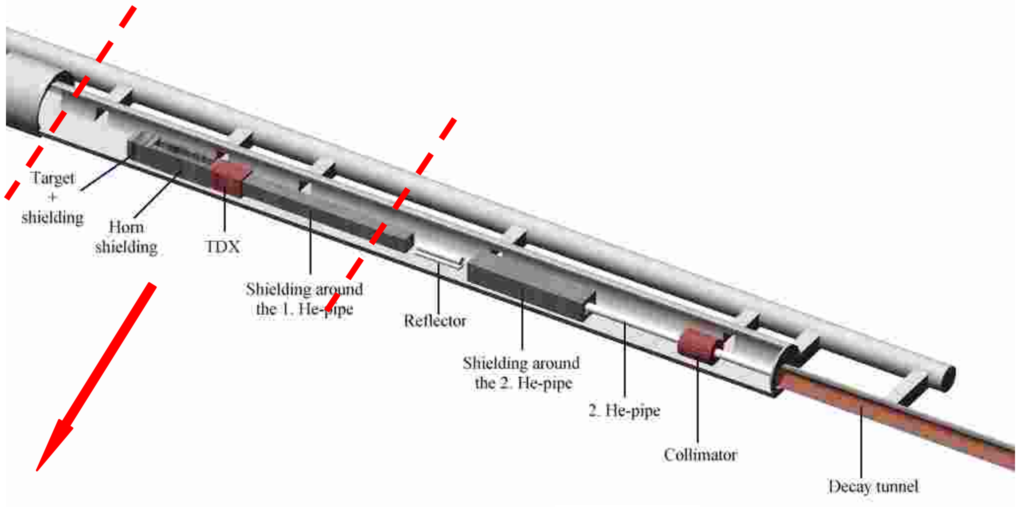


Energy dep. in CNGS target rods, GeV/cm^3/pot



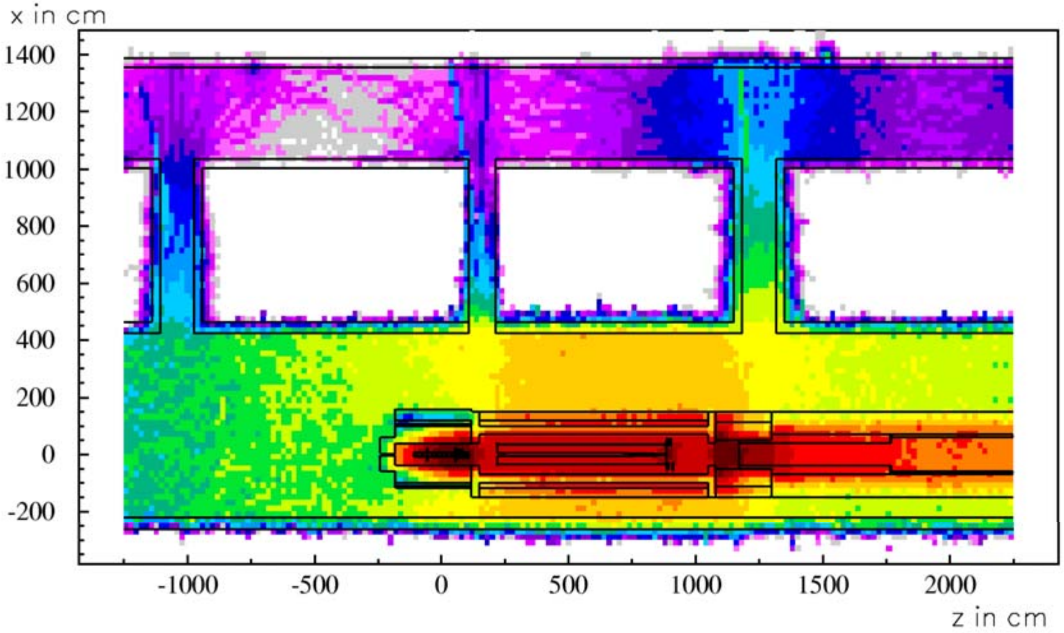
Muons in muon pit1: effect of focusing

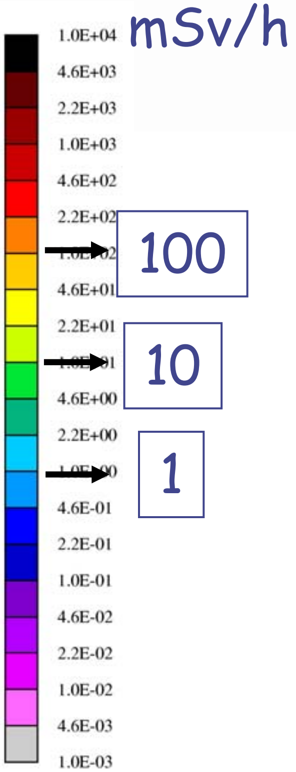
Applications – *CNGS*



Example:

t_{cool} = 1 day

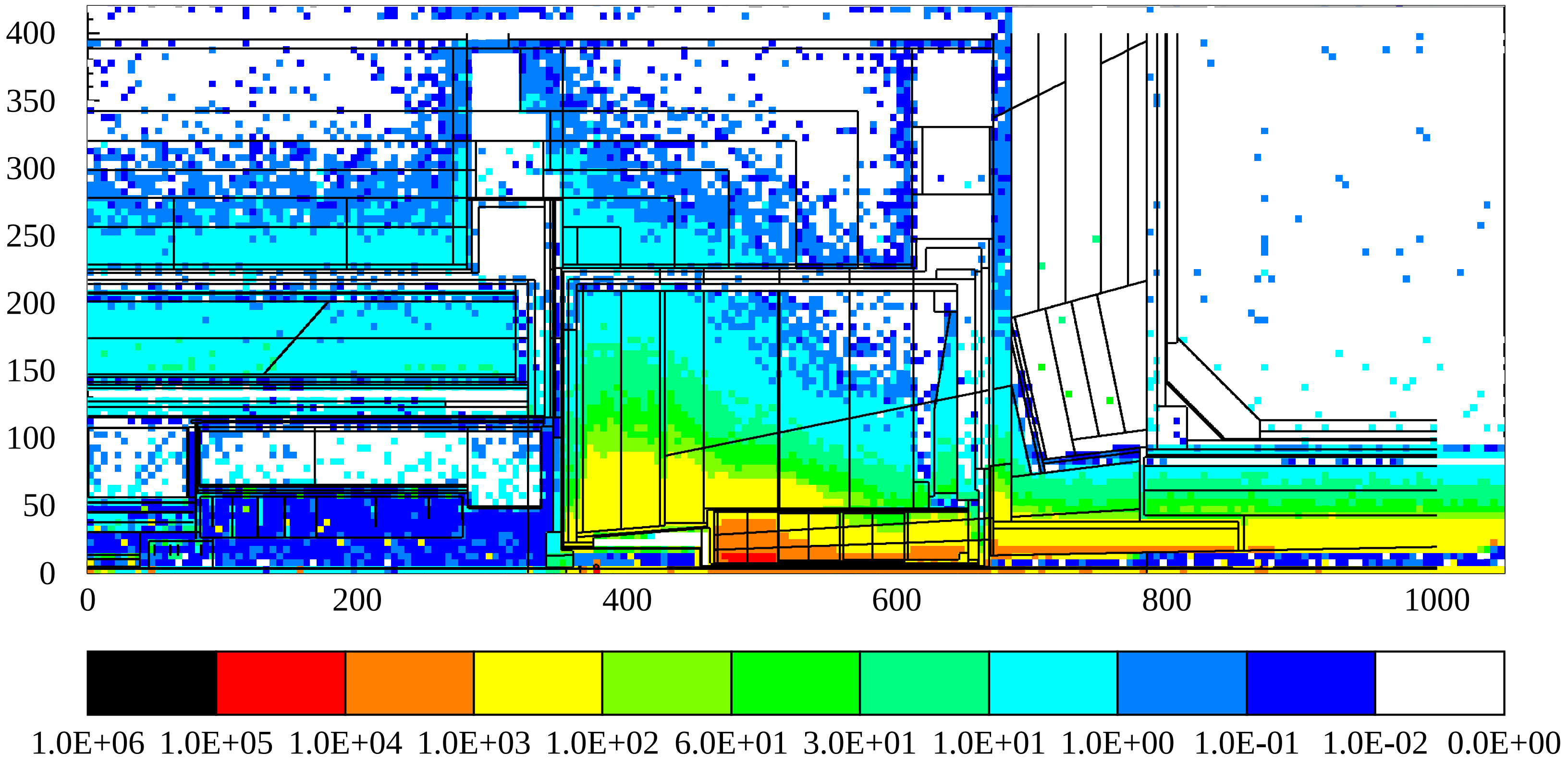




M.Lorenzo-Sentis, S.Roesler

Residual Dose Equivalent Rate (mSv/h)
200 days irradiation, 1 day cooling
8×10^{12} protons/s

Applications – ATLAS zoning



Example:

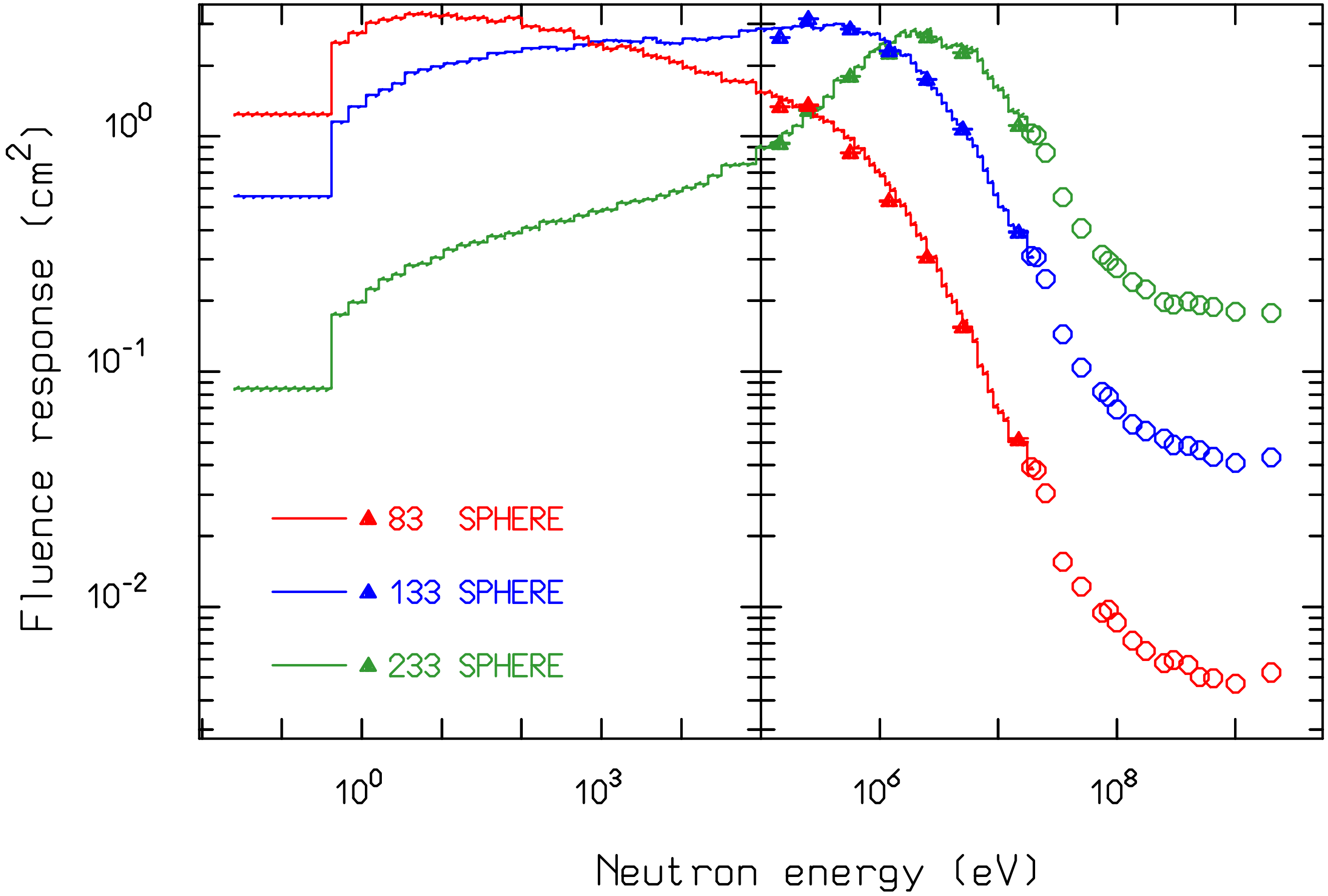
$$\sum_i \frac{A_i}{LE_i}$$

LE_i = Exemption limit for the i_{th} radioisotope

t_{irr} = 10 years
t_{cool} = 10 days

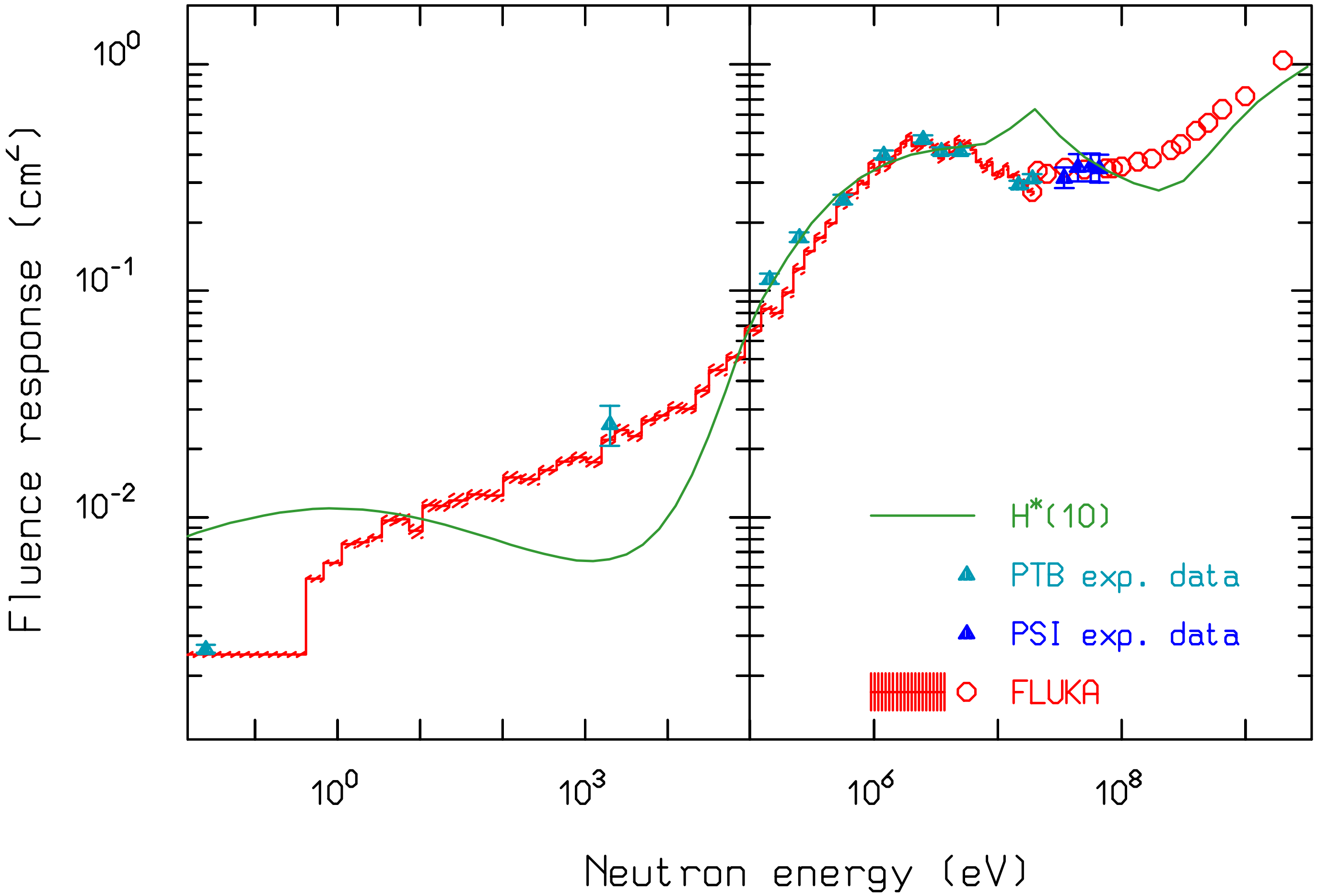
SATIF06:V.Hedberg, M.Magistris, M.N.Morev, M.Silari, and Z.Zajacova, Radioactive waste study of the ATLAS detector

Example: instrumentation calibration (PTB)



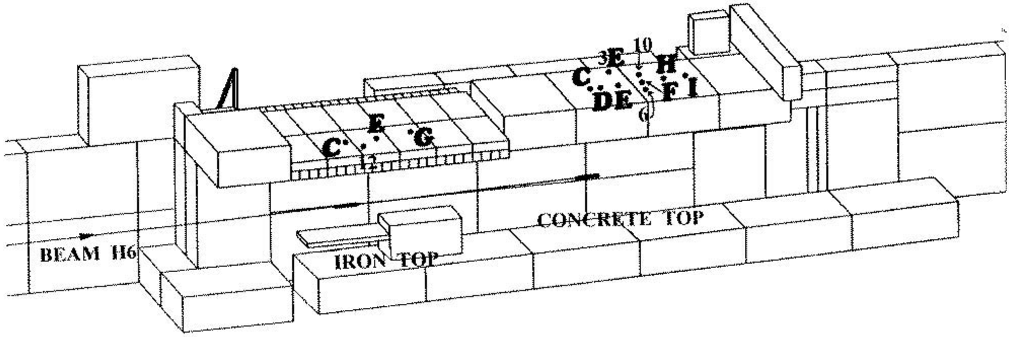
Calibration of three different Bonner spheres (with ^{3}He counters) with monoenergetic neutron beams at PTB (full symbols), compared with simulation (dashed histos and open symbols)

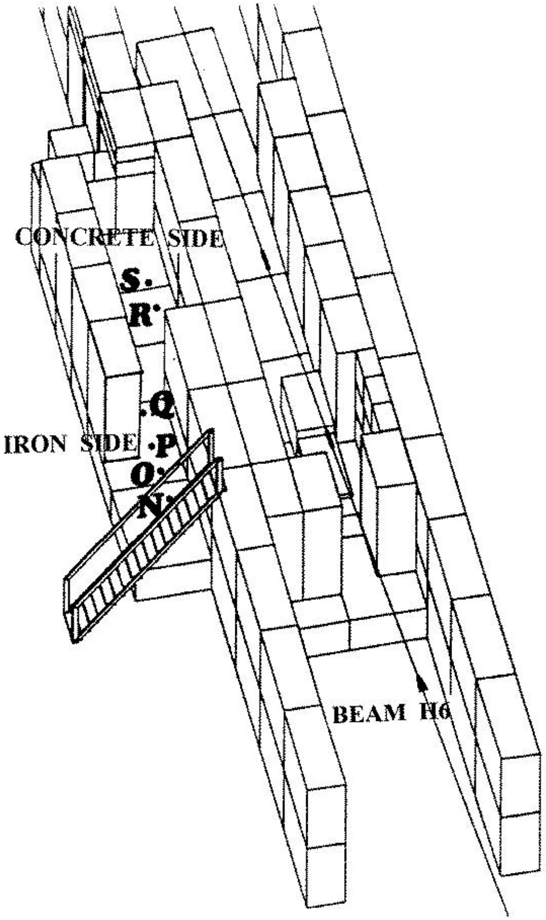
CERF: instrumentation calibration (PTB and PSI)



Calibration of the LINUS rem counter with monoenergetic neutron beams at PTB and with quasi-monoenergetic neutron beams at PSI (full symbols), compared with simulation (dashed histos and open symbols)

CERF: neutron measurements





Top (left, one side removed) and side (right, roof removed) views of the CERF facility with the measuring positions

CERF: results

	experimental		FLUKA		experimental		FLUKA	
	cts/PIC	%	cts/PIC	%	cts/PIC	%	cts/PIC	%
	CONCRETE TOP “E”				IRON TOP “C”			
LINUS rem counter*	0.364	0.36	0.409	2.2	1.78	0.30	1.68	2.1
SNOOPY rem counter*	0.200	0.59	0.207	3.3	1.83	0.75	1.71	2.0
233 sphere	0.788	0.33	0.899	3.7	9.28	0.28	9.23	2.0
178 sphere	0.989	0.36	1.01	3.4	16.1	0.24	16.9	1.9
133 sphere	1.02	0.30	0.981	3.2	19.2	0.19	21.2	1.9
108 sphere	0.942	0.35	0.883	3.1	17.7	0.20	19.2	1.9
83 sphere	0.704	0.30	0.717	3.1	11.2	0.26	12.1	1.9

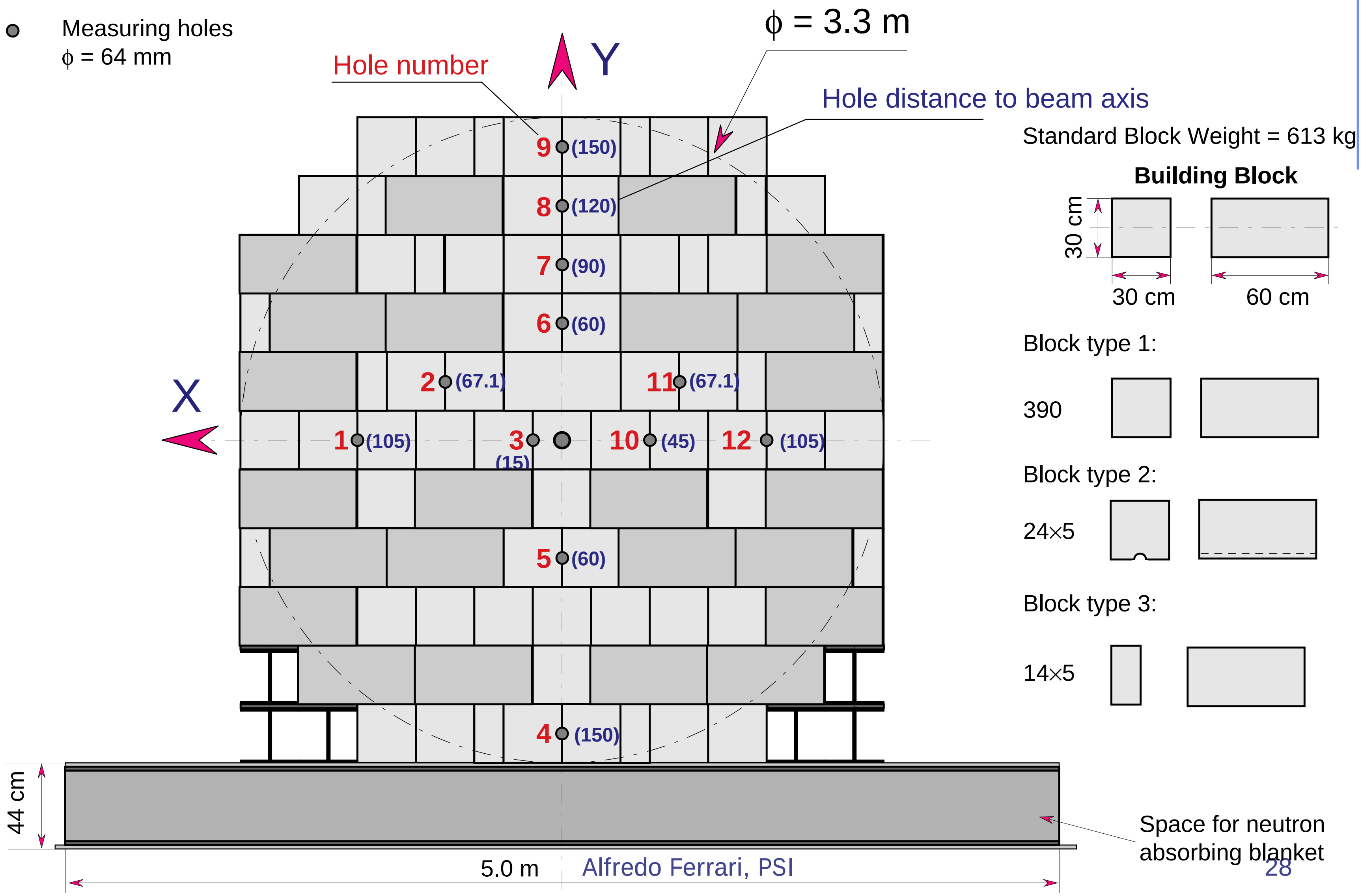
Comparison between the FLUKA predictions and the experimental response of the various detectors in stray radiation fields at CERN*. The percent statistical (%) uncertainty is indicated

* C.Birattari et al, Rad.Prot.Dos., 76 (1998), 135

The TARC experiment at CERN:

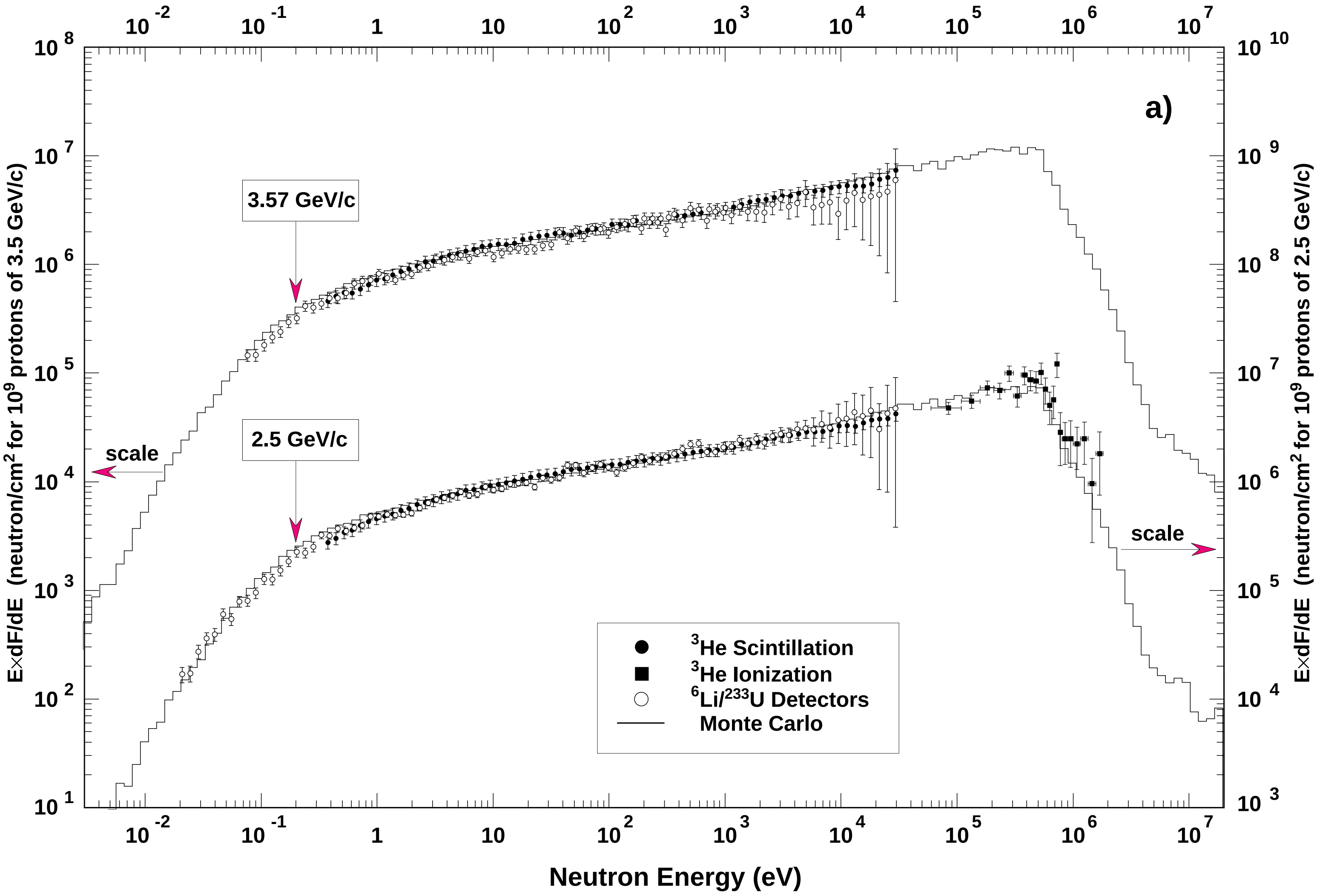
● Beam hole
ϕ = 77.2 mm

● Measuring holes
ϕ = 64 mm

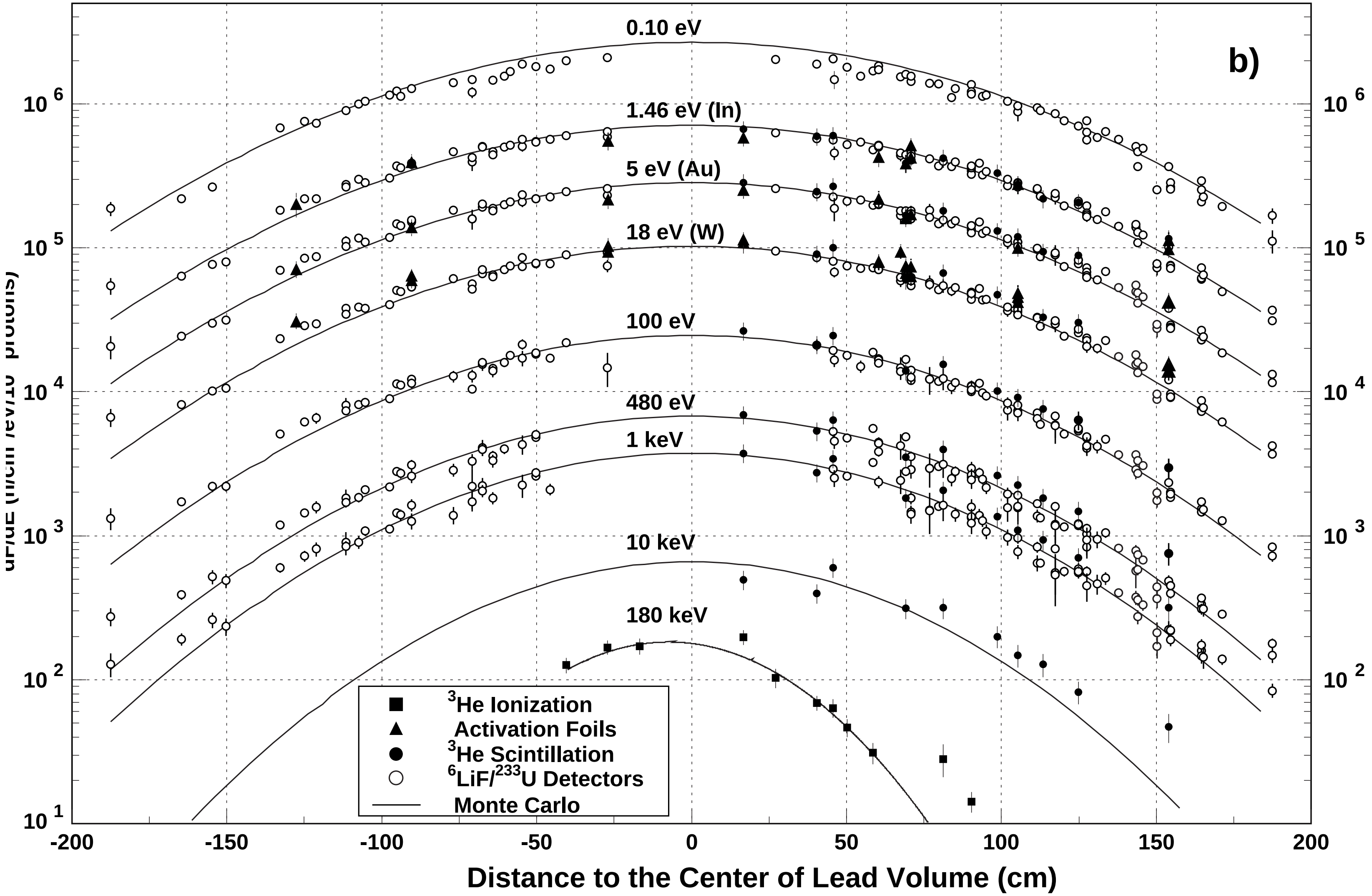


The TARC experiment at CERN: neutron spectra

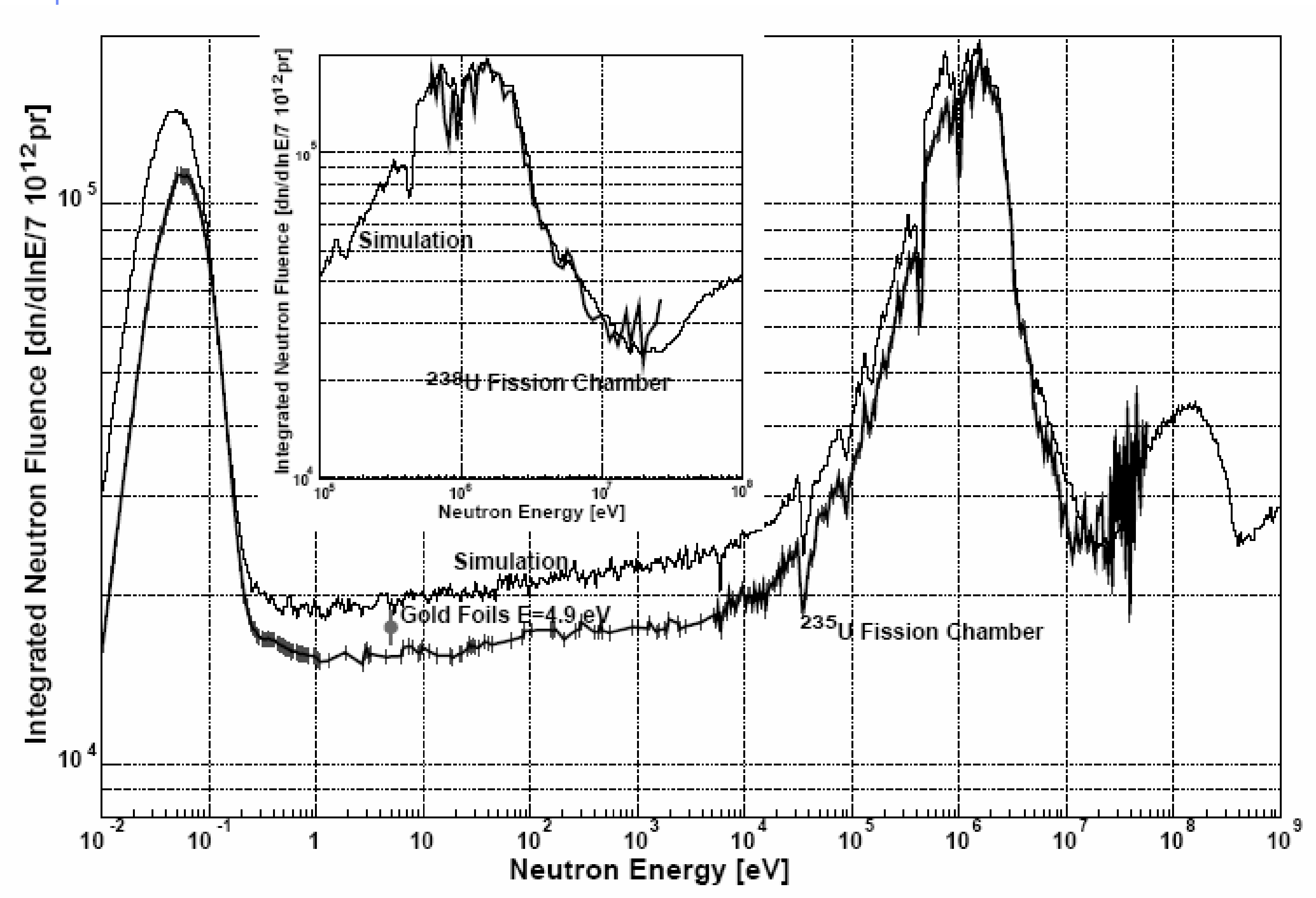
FLUKA + EA-MC (C.Rubbia et al.)



The TARC experiment at CERN: spatial distribut.



n-TOF (FLUKA + EA-MC)

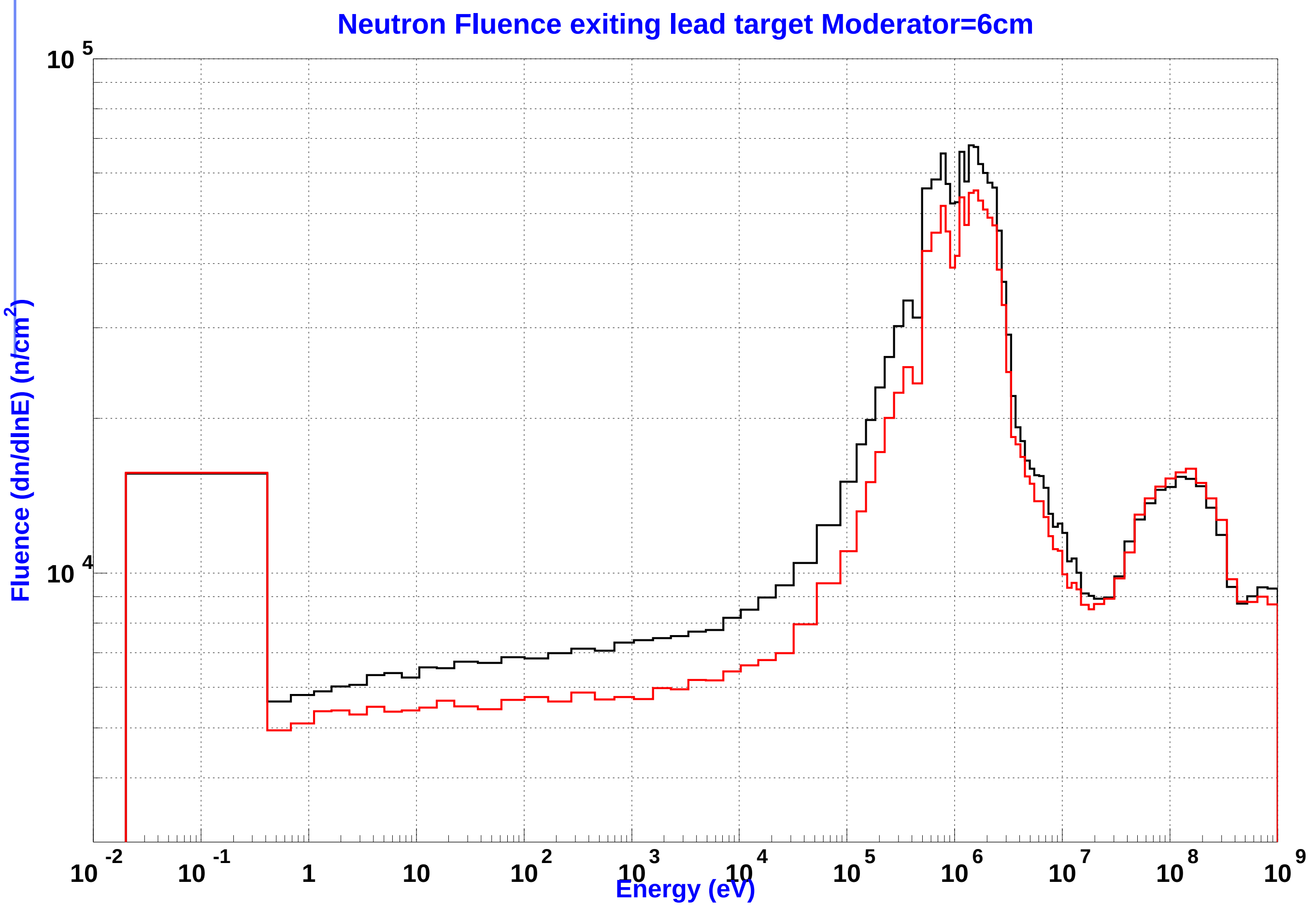


The n-tof facility at CERN: neutron beam with excellent energy resolution for cross section studies

beam from PS : 20 GeV/c protons + Huge Lead target Water moderator neutron beam line

Simulations : FLUKA + C. Rubbia's detailed low energy neutron transport
Assumption : 5 cm water moderator as in the design of the facility
Comparison with measured neutron spectrum shows up to 20% difference in the range $1\text{-}10^5$ eV (published data)

n-TOF: … surprise … surprise



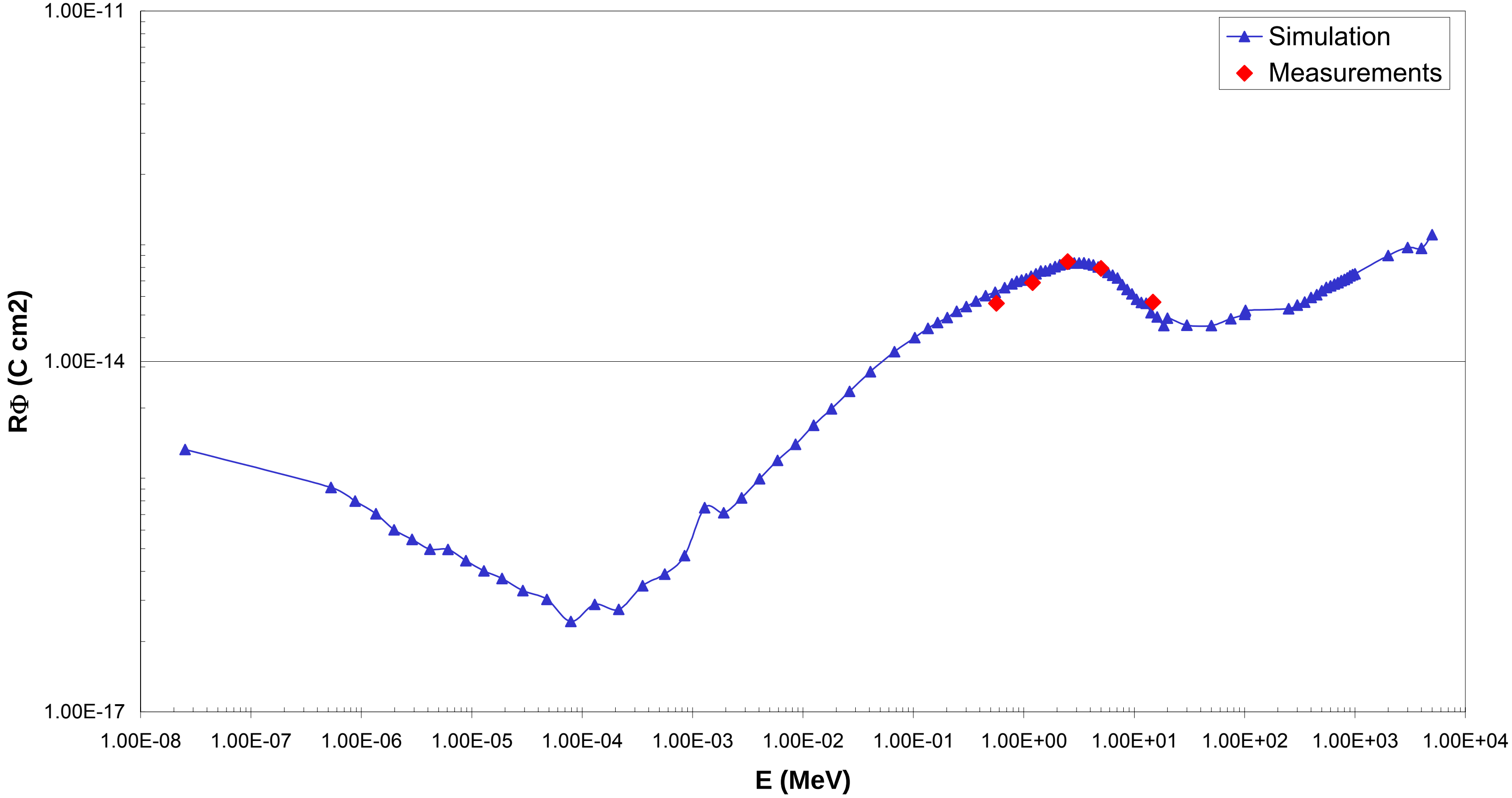
Preparing for Lead target dismount- Discovery that the water layer is 6 cm thick instead of 5

FLUKA simulations with 6 cm water (black) compared with 5 cm (red)

PRELIMINARY, thanks to V. Vlachoudis-CERN

Simulation benchmark in mono-energetic neutron fields

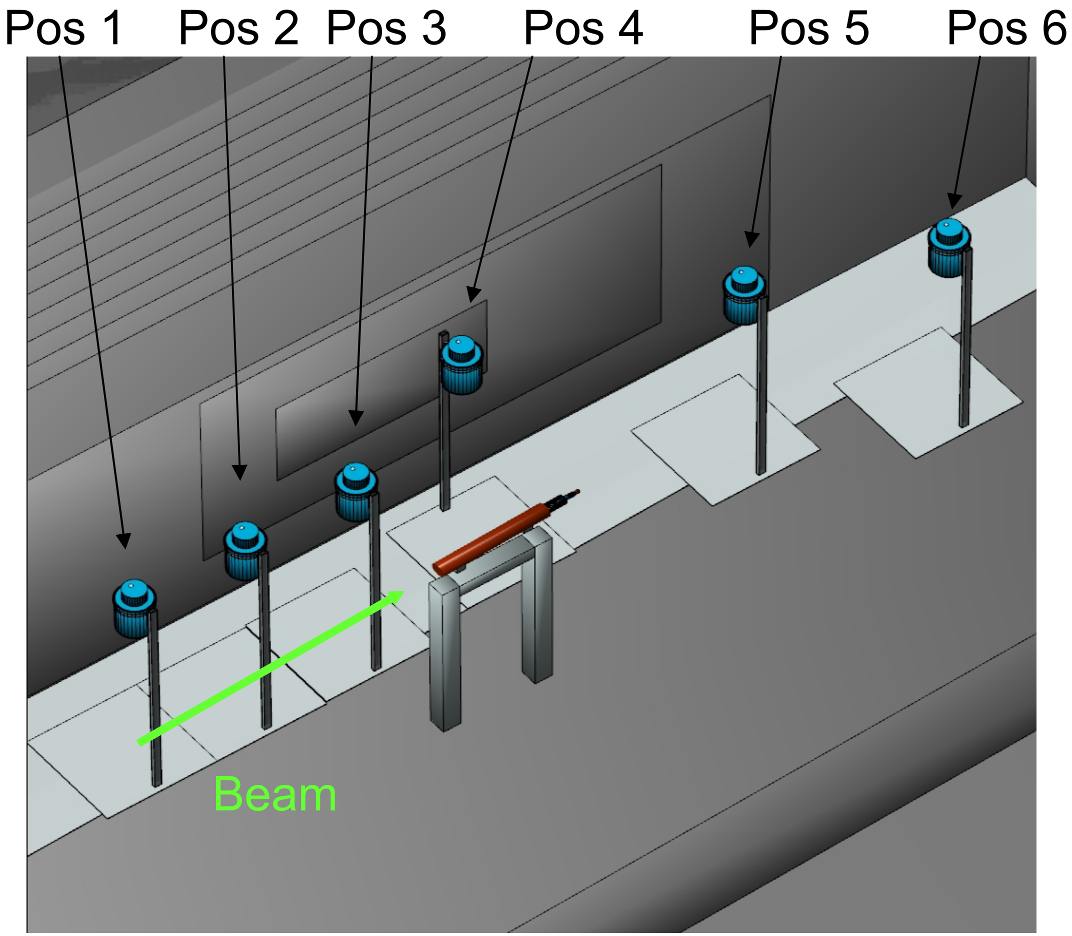
Response of hydrogen filled IG5 to neutrons

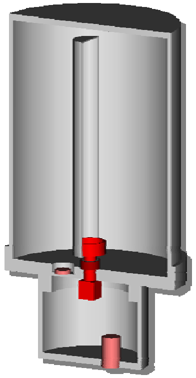


Centronic IG5-H20 ionization chamber
Active volume of 5.2l filled with hydrogen
Pressurized at 20 bars

C. Theis, D. Forkel-Wirth, D. Perrin, S. Roesler, and H. Vincke, *Characterisation of ionisation chambers for a mixed radiation field and investigation of their suitability as radiation monitors for the LHC*, Radiation Protection Dosimetry 116, pp. 170-174 (2005).

Simulation benchmark in mixed fields at the CERF facility





PTW open-air ionization chamber, active volume of 3l at atmospheric pressure

Location	Simulation/ Experiment
Pos 1	0.998 ± 0.10
Pos 2	1.031± 0.11
Pos 3	1.003 ± 0.10
Pos 4	1.080 ± 0.12
Pos 5	1.076± 0.12
Pos 6	0.936± 0.15

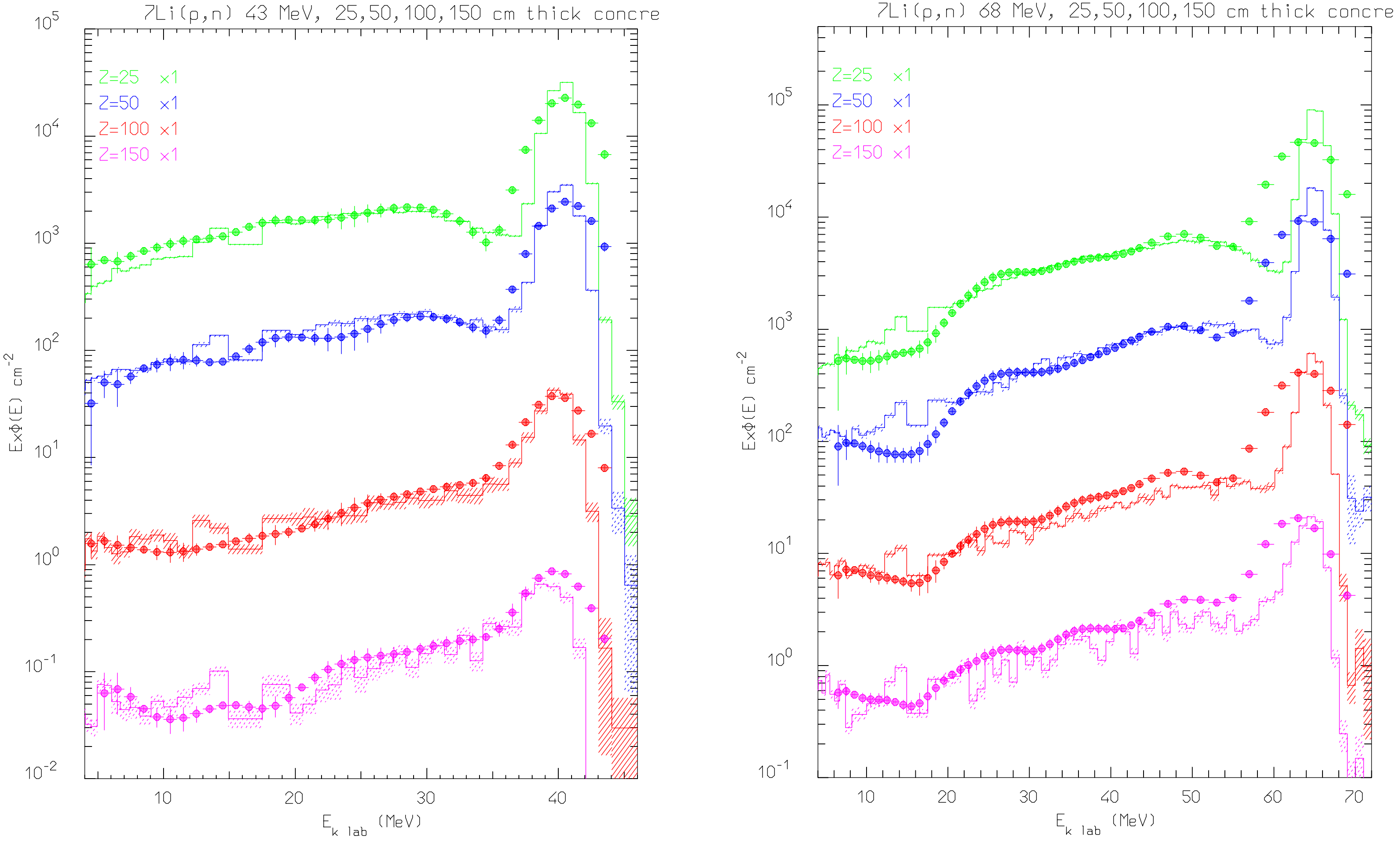
H. Vincke, D. Forkel-Wirth, D. Perrin and C. Theis,
Simulation and measurements of the response of an air ionisation chamber exposed to a mixed high-energy radiation field,
Radiation Protection Dosimetry 116, pp 380-386, (2005).

The TIARA neutron propagation experiment

- Source term: neutrons generated by 68 and 43 MeV protons on ^{7}Li carefully measured with TOF techniques → quasi-energetic neutrons of 40 and 65 MeV
- Attenuation of the neutron beam at different depths in concrete and iron shields, both on-axis and off-axis (critical for elastic scattering!)
- Emerging neutron spectra measured with liquid scintillator detectors (the high energy component) and Bonner spheres (the low energy one)

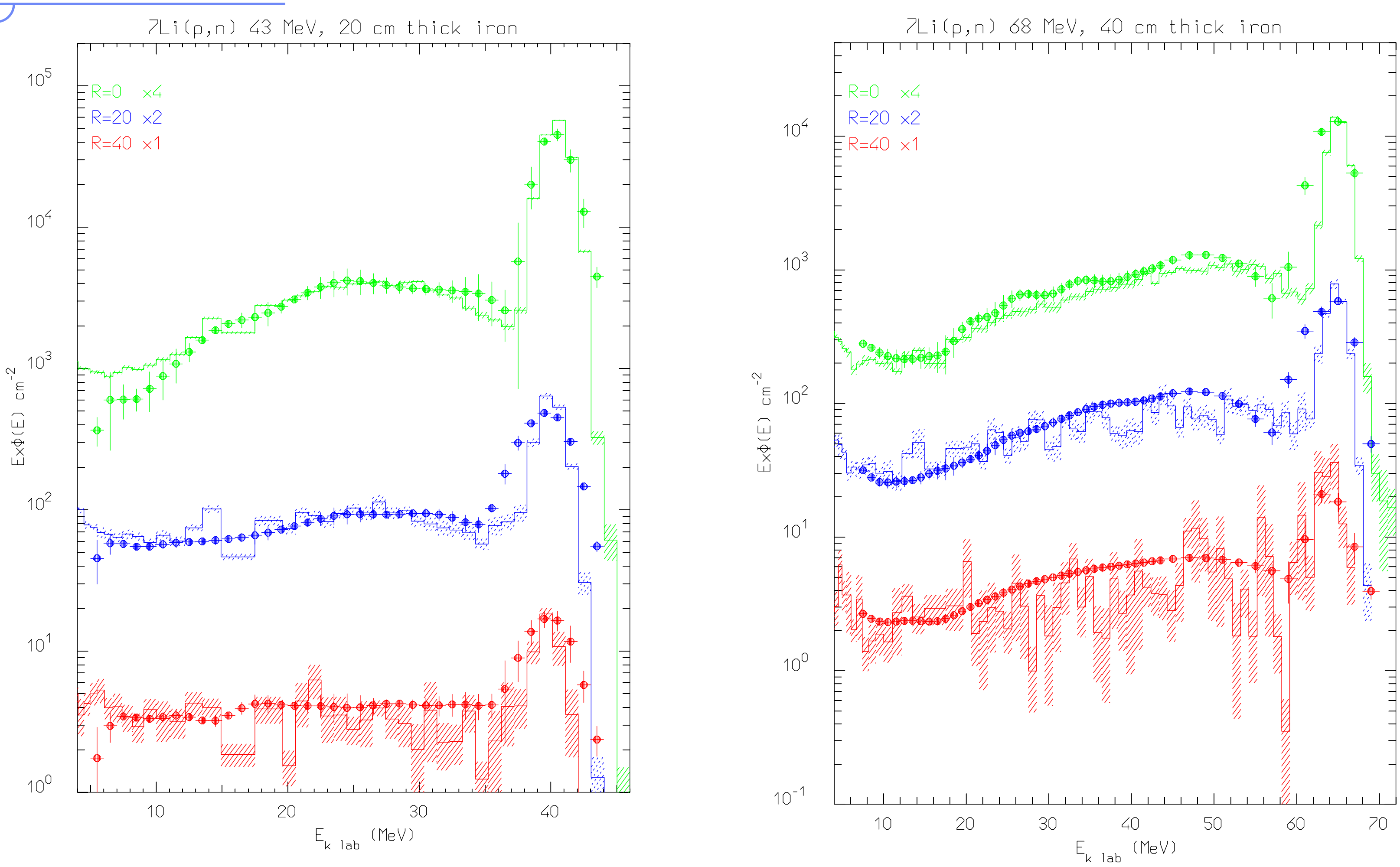
H.Nakashima et al. Nucl Sci. Eng. **124** (1996) and N.Nakao et al., Nucl. Sci. Eng. **124** (1996) 228

TIARA: concrete on-axis



Comparison of simulated (dashed histogram) and measured (symbols) neutron spectra after different concrete thicknesses (from 25 to 150 cm), on axis. The neutrons are generated by ^{7}Li(p,n) at 43 (left) and 68 MeV (right)

TIARA: iron off-axis



Comparison of simulated (dashed histogram) and measured (symbols) neutron spectra off axis (from 0 to 40 cm) after 20 (left) and 40 cm thick iron shields. The neutrons are generated by ^{7}Li(p,n) at 43 (left) and 68 MeV (right)

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

New developments:

- New QMD for 0.05 < E < 0.5 GeV/n:
- BME (Boltzmann Master Equation) for E < 0.1 GeV/n
  - FLUKA implementation of BME from E.Gadioli et al (Milan)
  - Now under test for $A \leq 16$

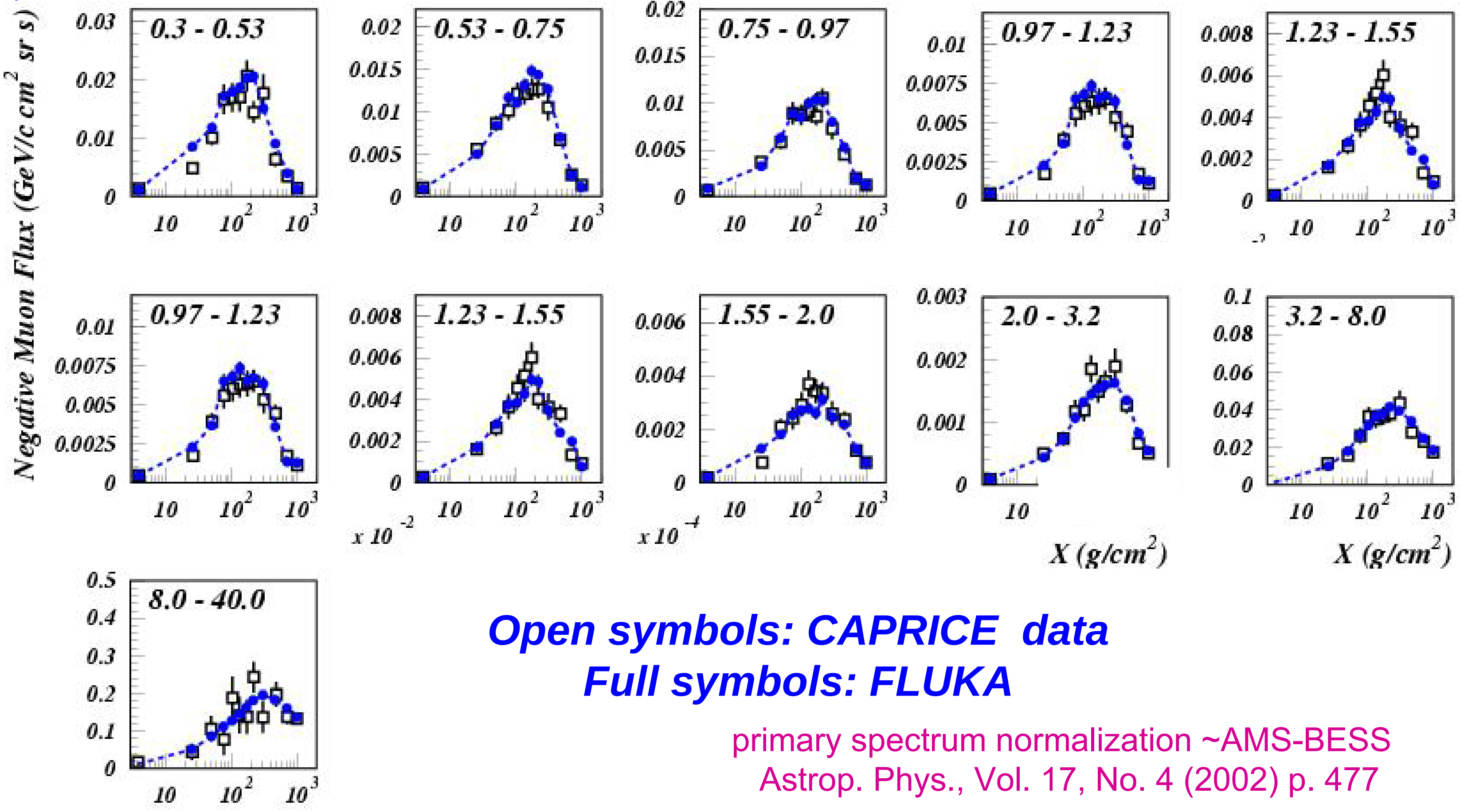
Common to all models:

- Standard FLUKA evaporation/fission/fragmentation used in both Target/Projectile final de-excitation
- Electromagnetic dissociation

Full shower + biasing : cosmic rays in atmosphere

Particle production by cosmic rays showers in the atmosphere: check of hadron-nucleus and nucleus-nucleus models, particle transport, decay, biasing…

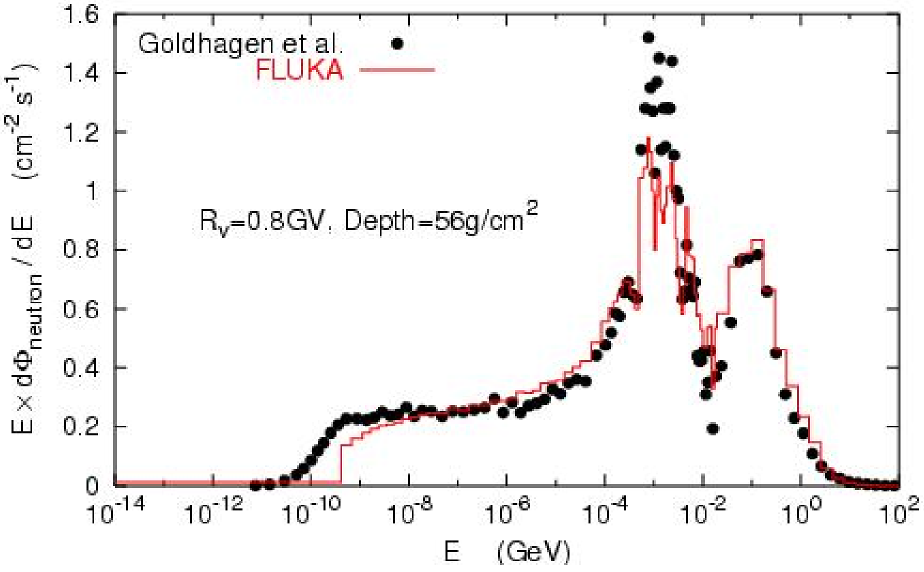
Negative muons at floating altitudes: CAPRICE94



Open symbols: CAPRICE data
Full symbols: FLUKA

primary spectrum normalization ~AMS-BESS
Astrop. Phys., Vol. 17, No. 4 (2002) p. 477

Neutrons on the ER-2 plane at 21 km altitude



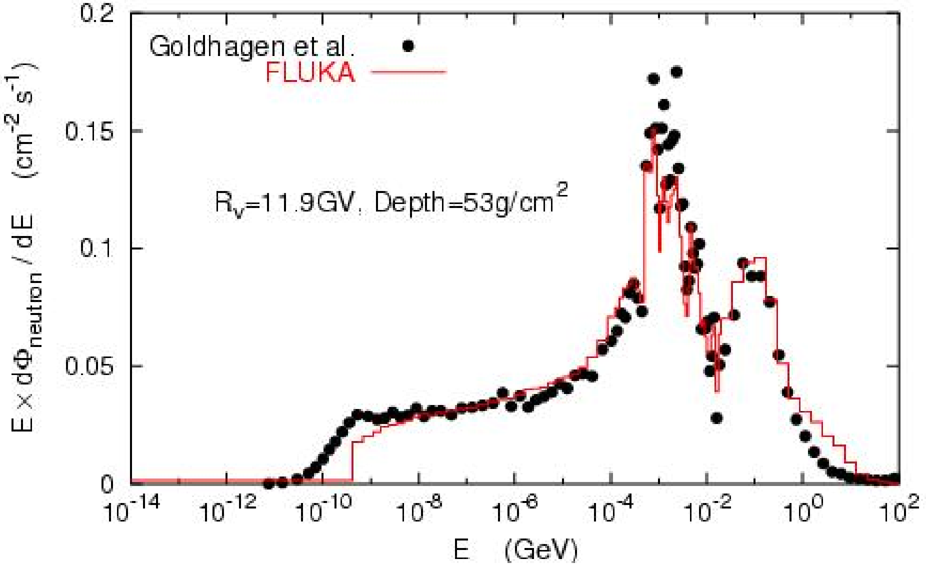
Measurements:

Goldhagen et al., NIM A476, 42 (2002)

Note one order of magnitude difference depending on latitude

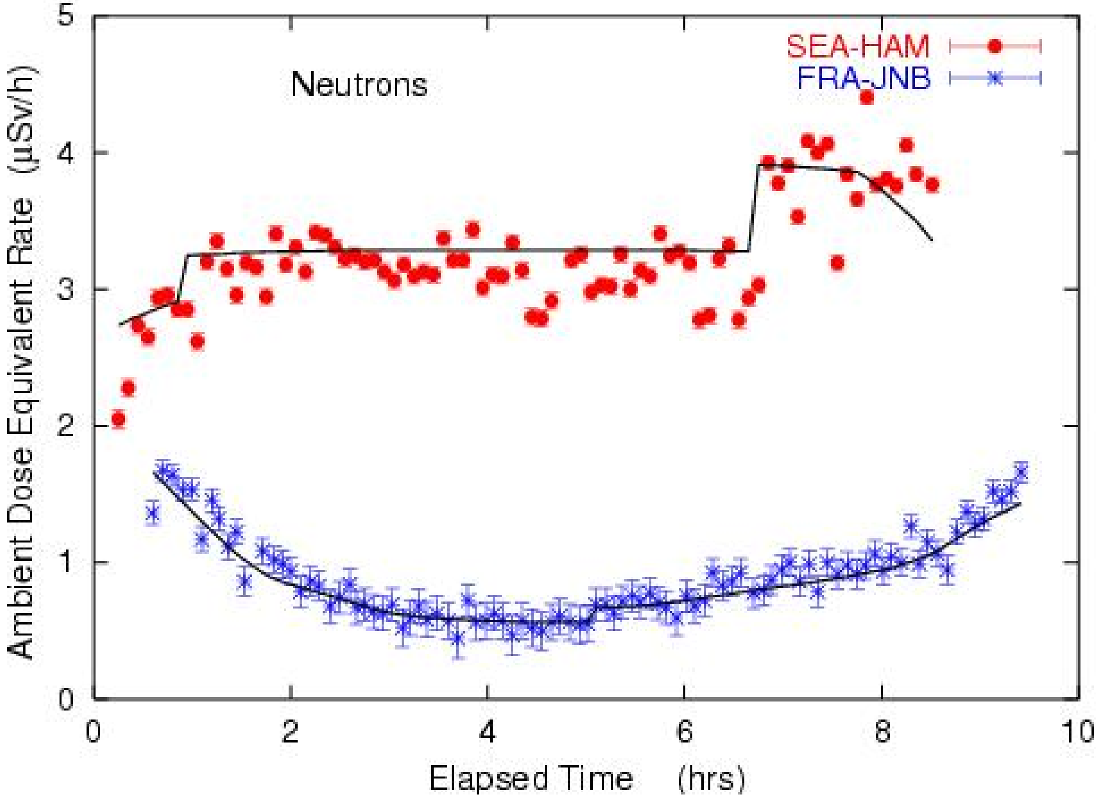
FLUKA calculations:

Roesler et al., Rad. Prot. Dosim. 98, 367 (2002)



Dosimetry Applications

Roesler et al.,
Rad. Prot. Dosim.
98, 367 (2002)



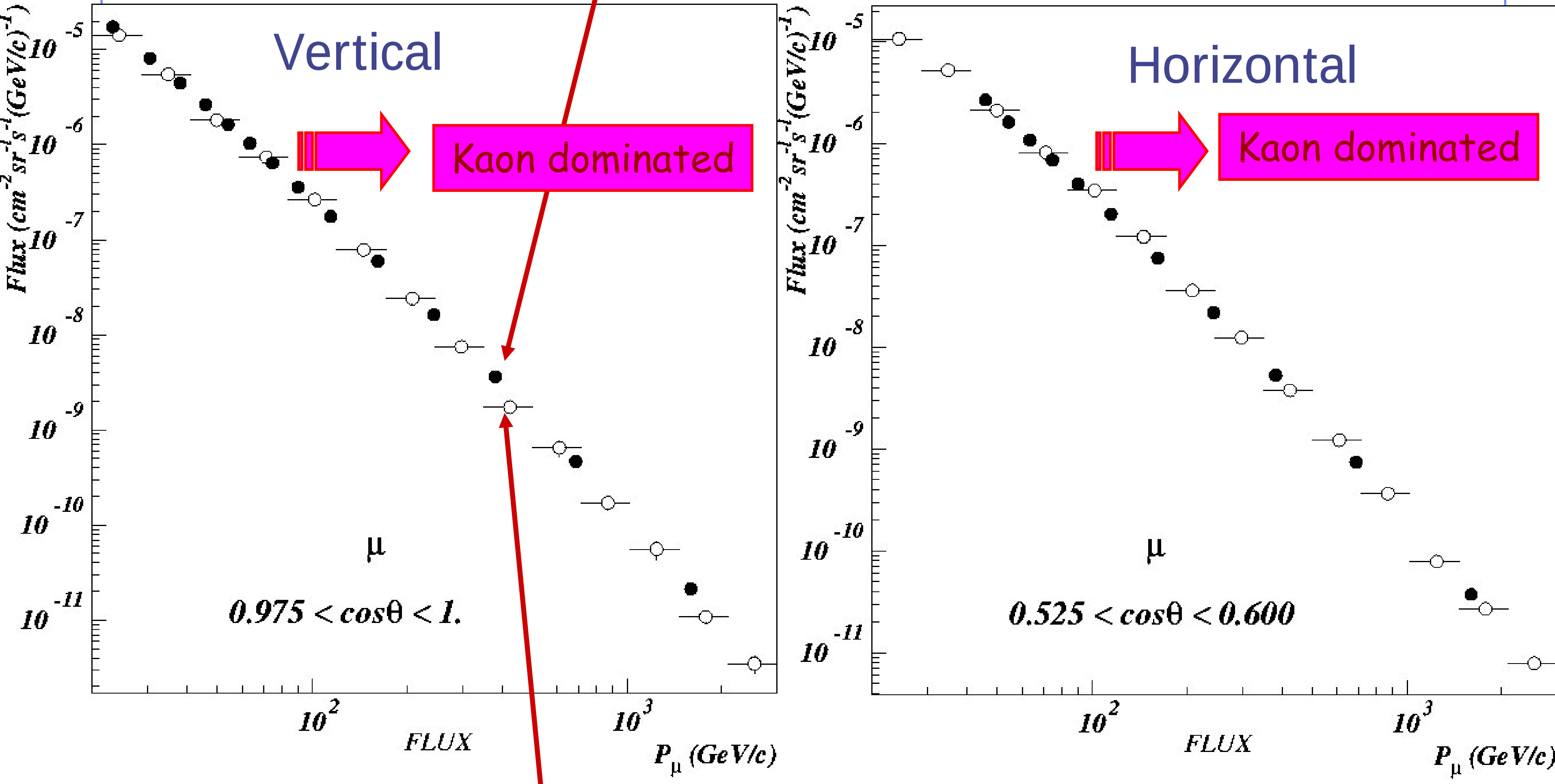
Ambient dose equivalent from neutrons at solar maximum on commercial flights from Seattle to Hamburg and from Frankfurt to Johannesburg.

Solid lines: FLUKA simulation

Some recent achievements: L3 Muons

(S.Muraro, PhD thesis Milano)

exp. data

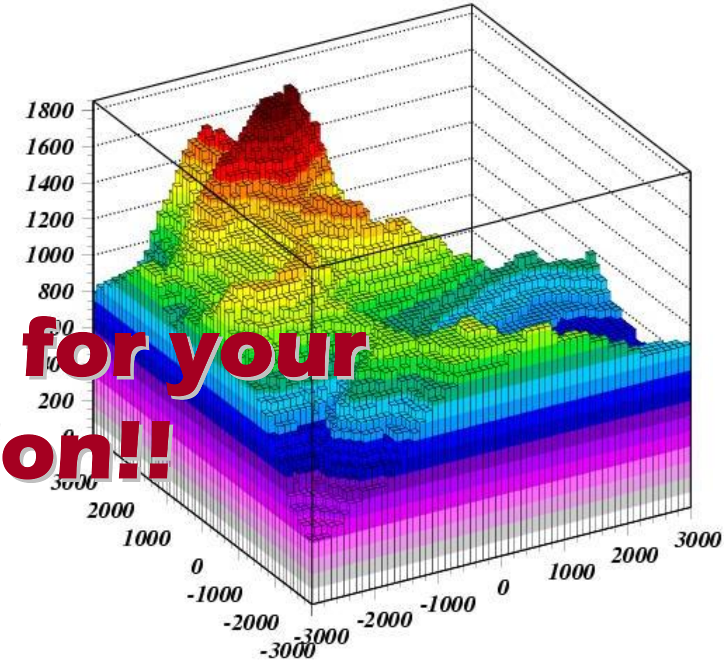


Kaon dominated

Kaon dominated

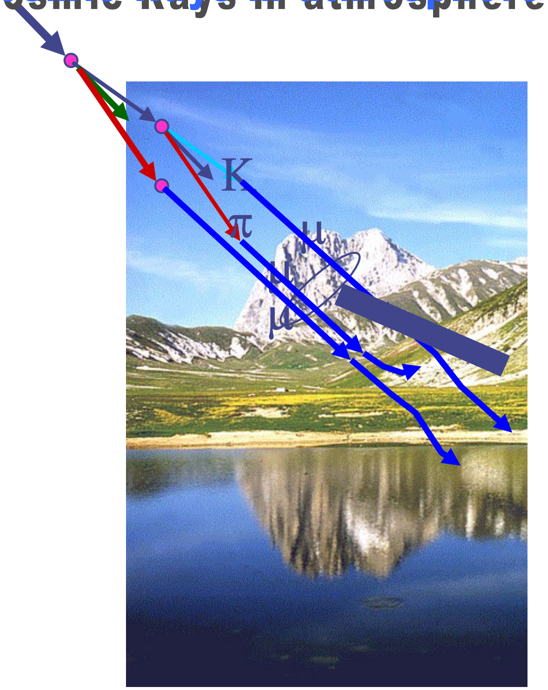
FLUKA simulation

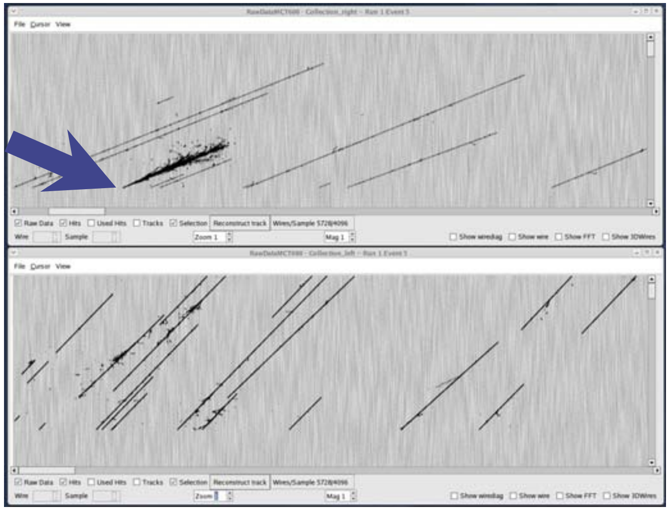
The Gran Sasso in FLUKA



Many thanks for your attention!!

Cosmic Rays in atmosphere





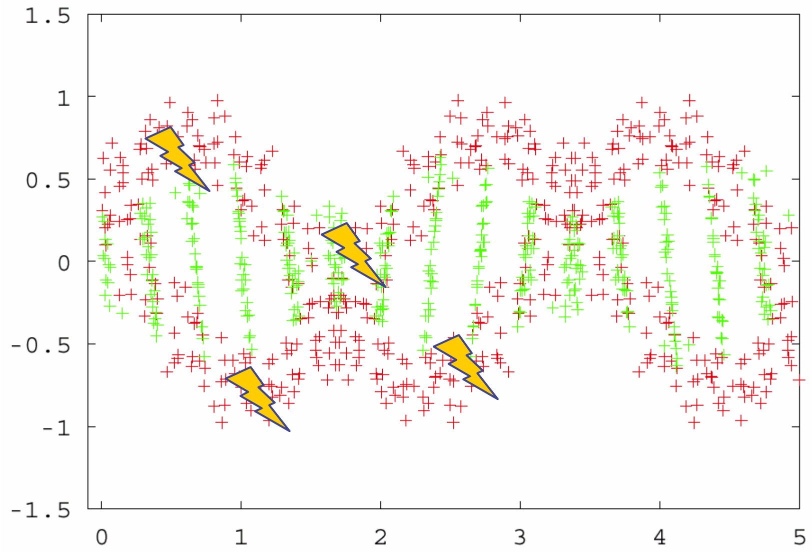
A weighted/biological dose

Radiation Protection: quality factors and weighting factors

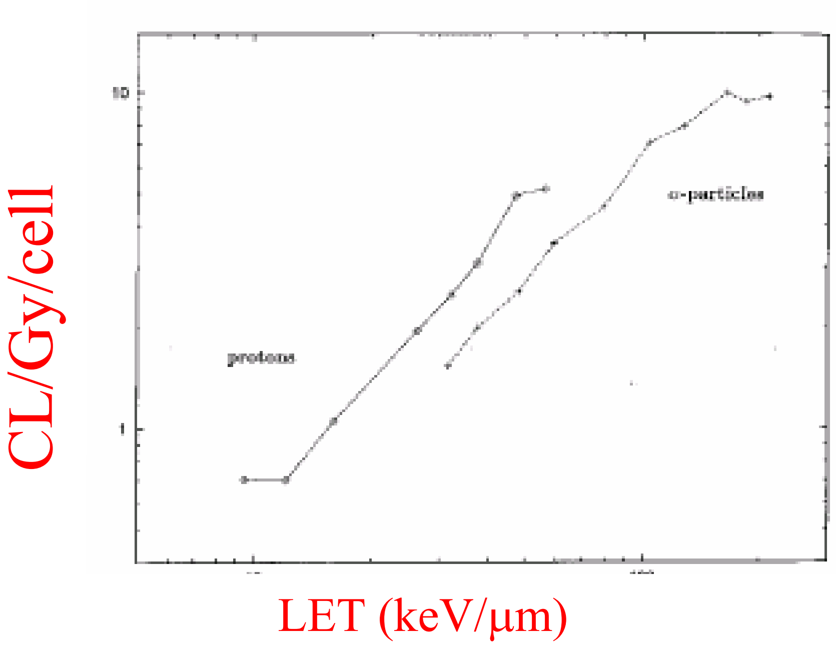
ICRP 26: quality factors Q(L) depending on the radiation LET

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

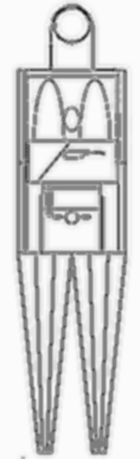
Radiobiological data and results of simulations (distributions) based on track structure codes (e.g. PARTRAC (GSF, Pavia)) and biophysical models (e.g. radiation induced CA models and codes)

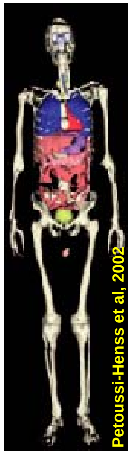
Radiation field and irradiation geometry

extended FLUKA

Doses, Fluences...;

effects at cellular, organ and organism levels

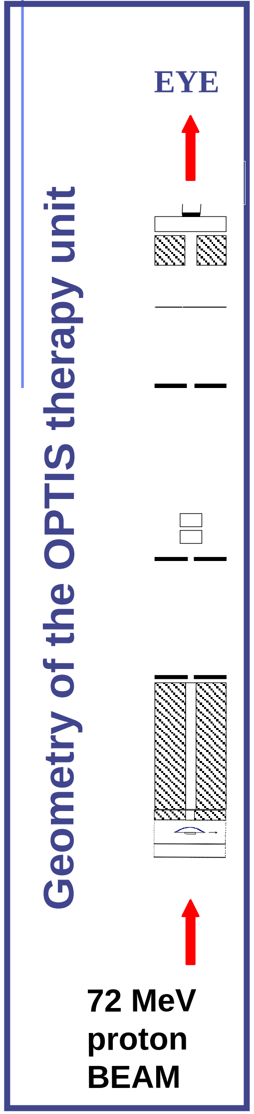




Petoussi-Henss et al, 2002

The OPTIS therapeutic proton beam

Geometry of the OPTIS therapy unit

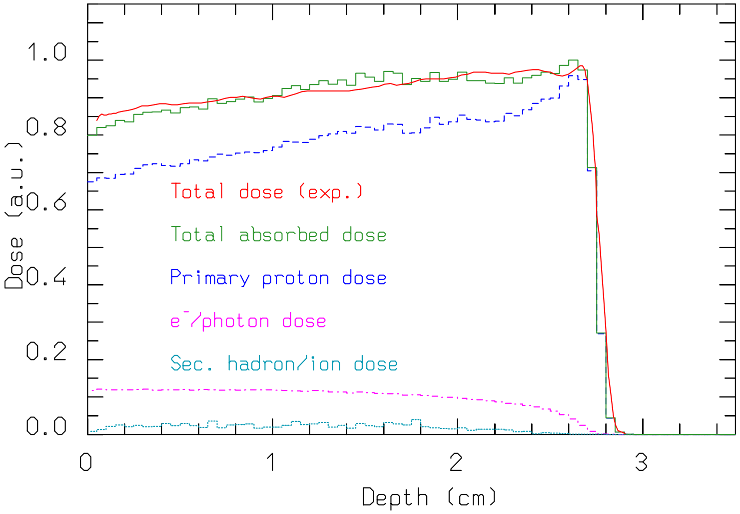


72 MeV proton BEAM

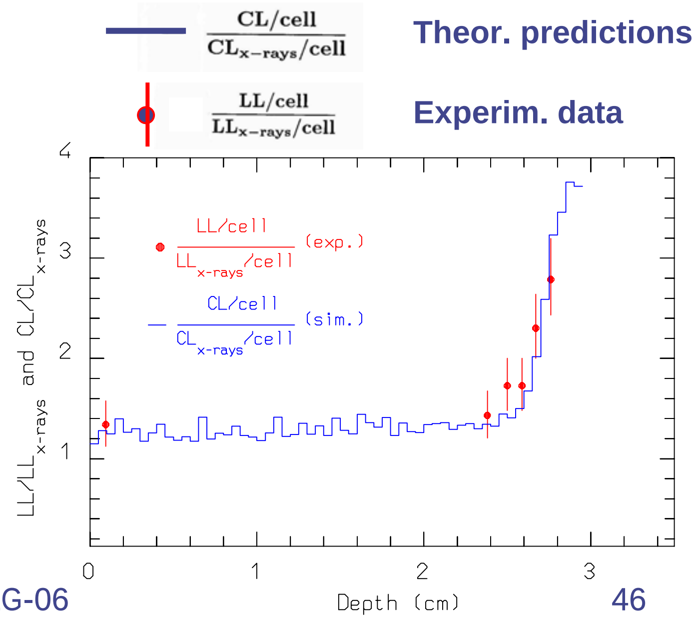
Complex Lesions as a function of LET and particle type

FLUKA CODE (EXTENDED)

PHYSICS



BIOLOGICAL EFFECTS



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

LHC Cleaning Insertions

Two warm LHC insertions are dedicated to beam cleaning

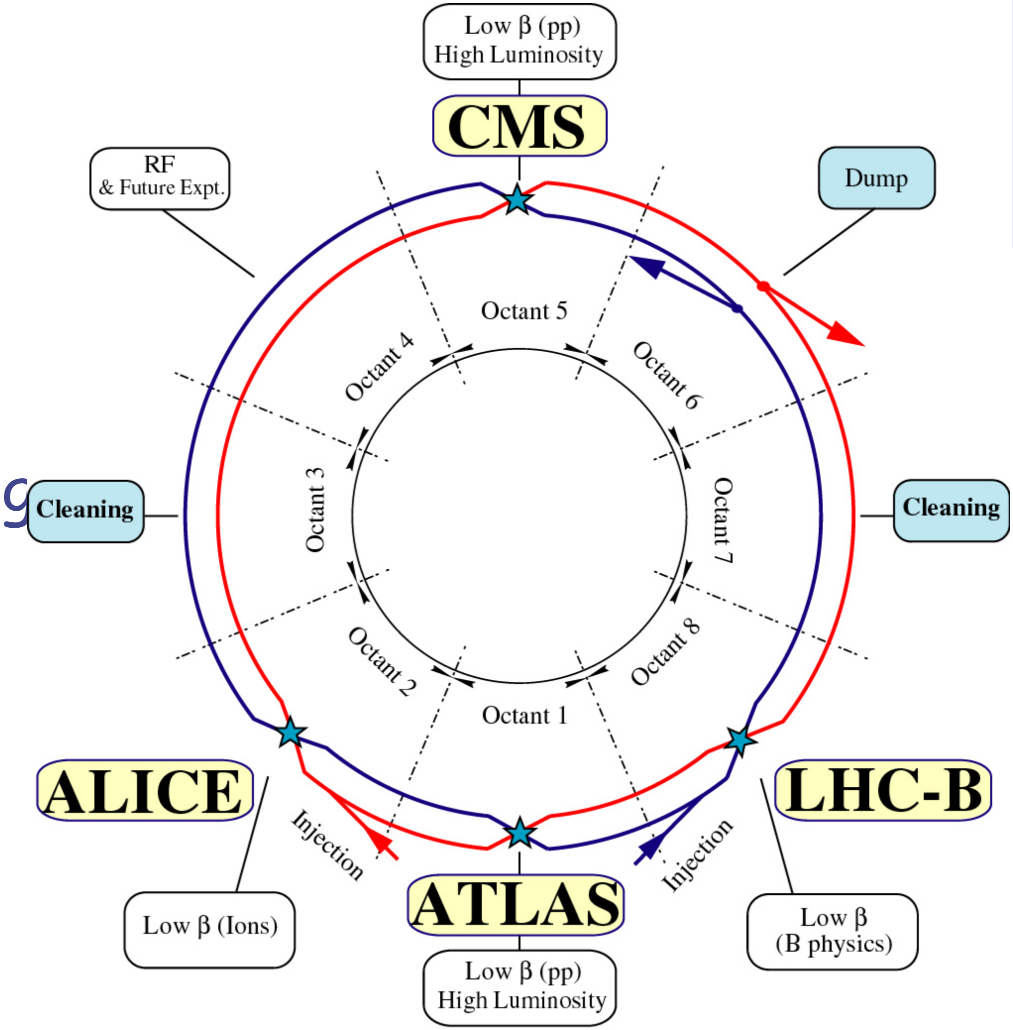
Collimation systems:

IR3: Momentum cleaning

IR7: Betatron cleaning

Normal operation:

- 0.2 hours beam lifetime
- 4×10^{11} p/s for 10 s
- Power = 448 kW

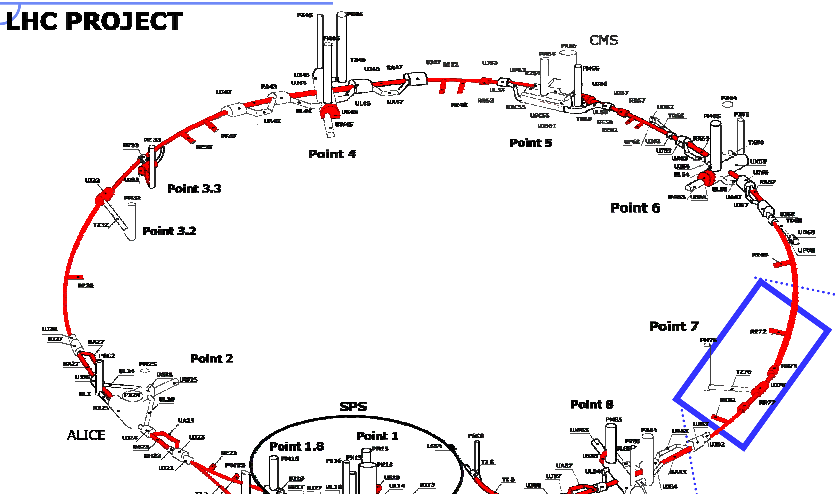


IR7: Overview

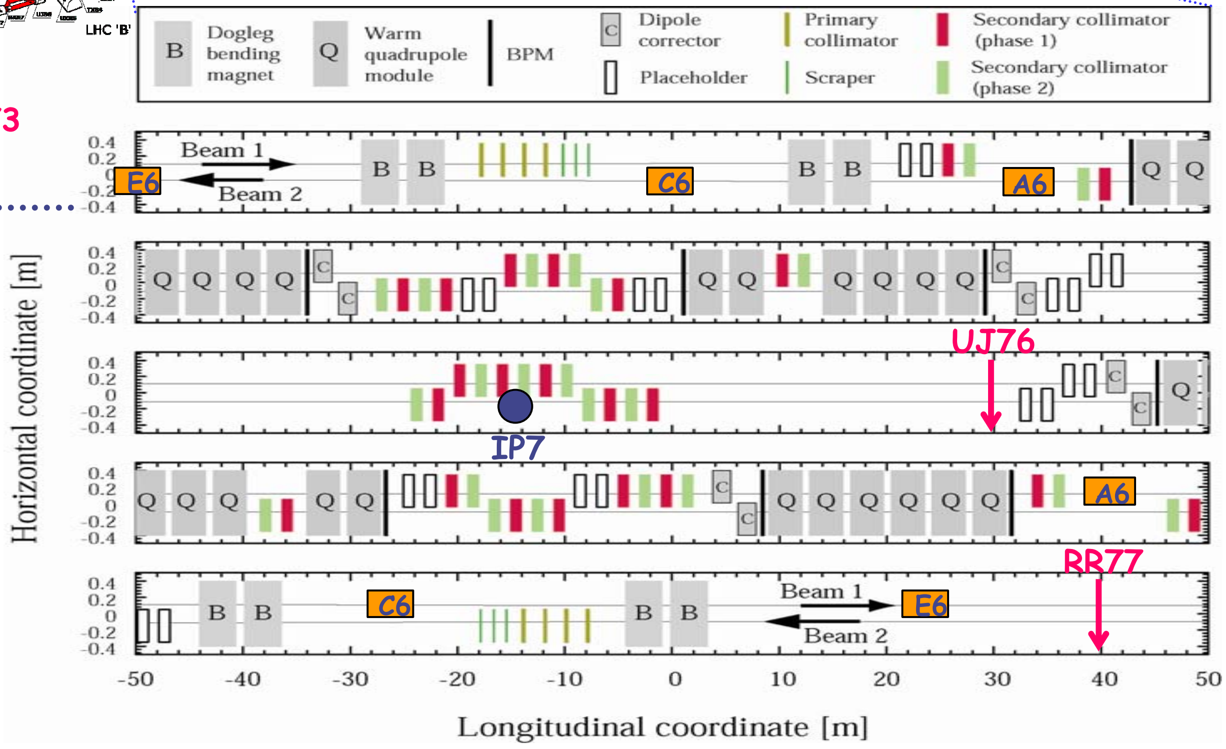
- Motivation
- Geometry and Simulation setup
- Studies:
  - Collimator robustness ⇒ Accident scenarios
  - Energy on the superconducting magnets ⇒ Active absorbers
  - Dose on warm magnets ⇒ Passive absorbers
  - Beam Loss Monitors ⇒ Signal in BLM's as a function of the loss point
- Summary

IR7 layout

LHC PROJECT



- LHC optics files
- Top beam energy
- Primary collimators: 6 σ
- Secondary collimators: 7 σ
- Absorbers: 10 σ

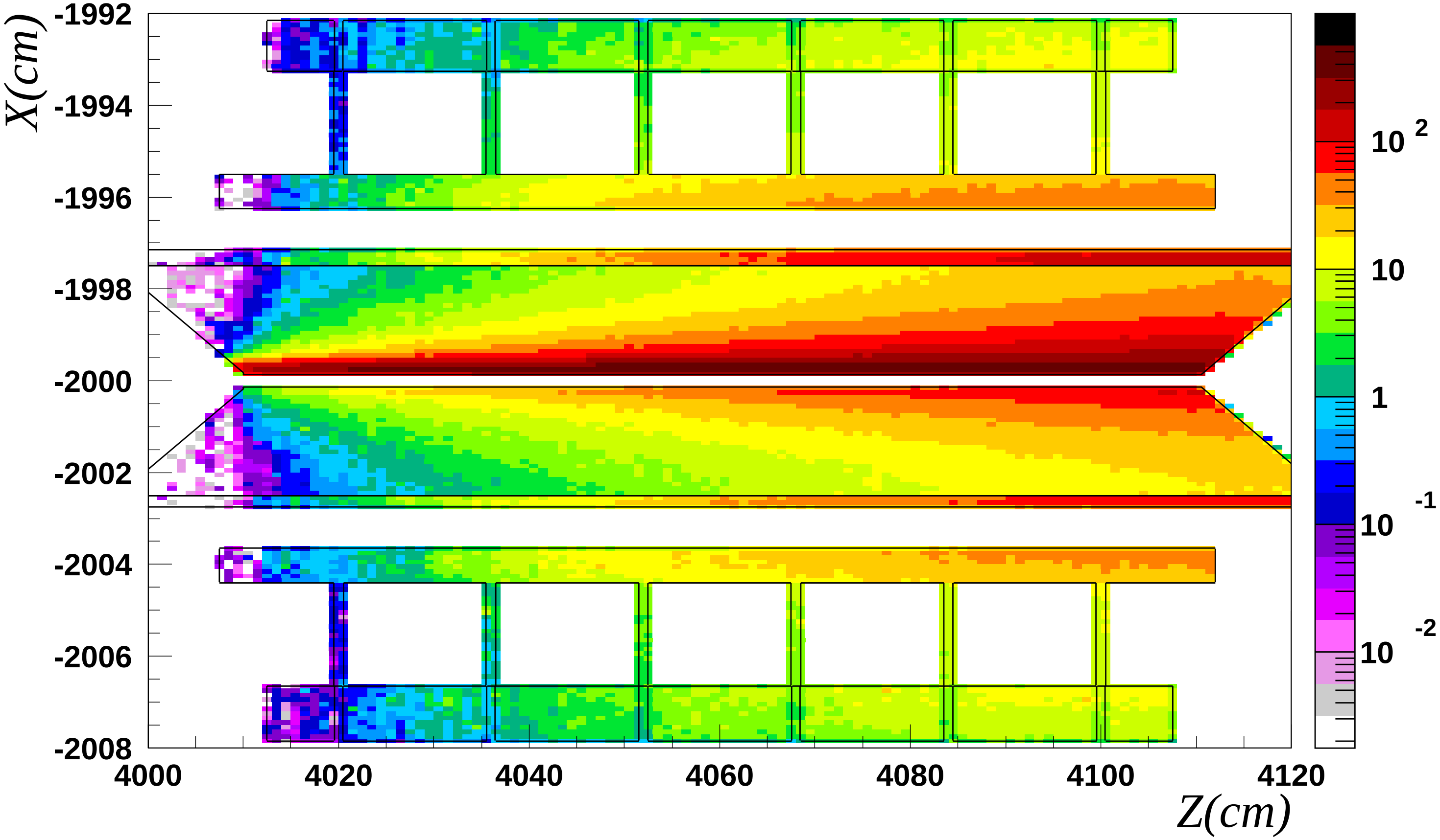


- IR7 Layout contains over 200 objects
- Warm section
- 2 Dispersion suppressors
- Collimators with variable positioning of the jaws

⇒ Challenging simulation work

IR7 Virtual Tour

Collimator robustness: C is the only viable choice

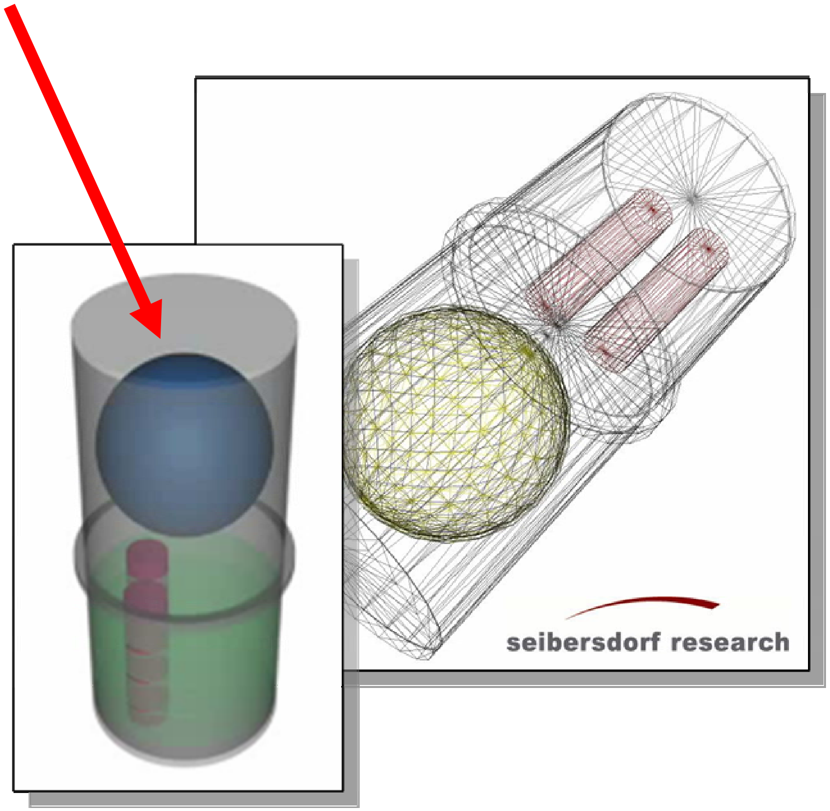


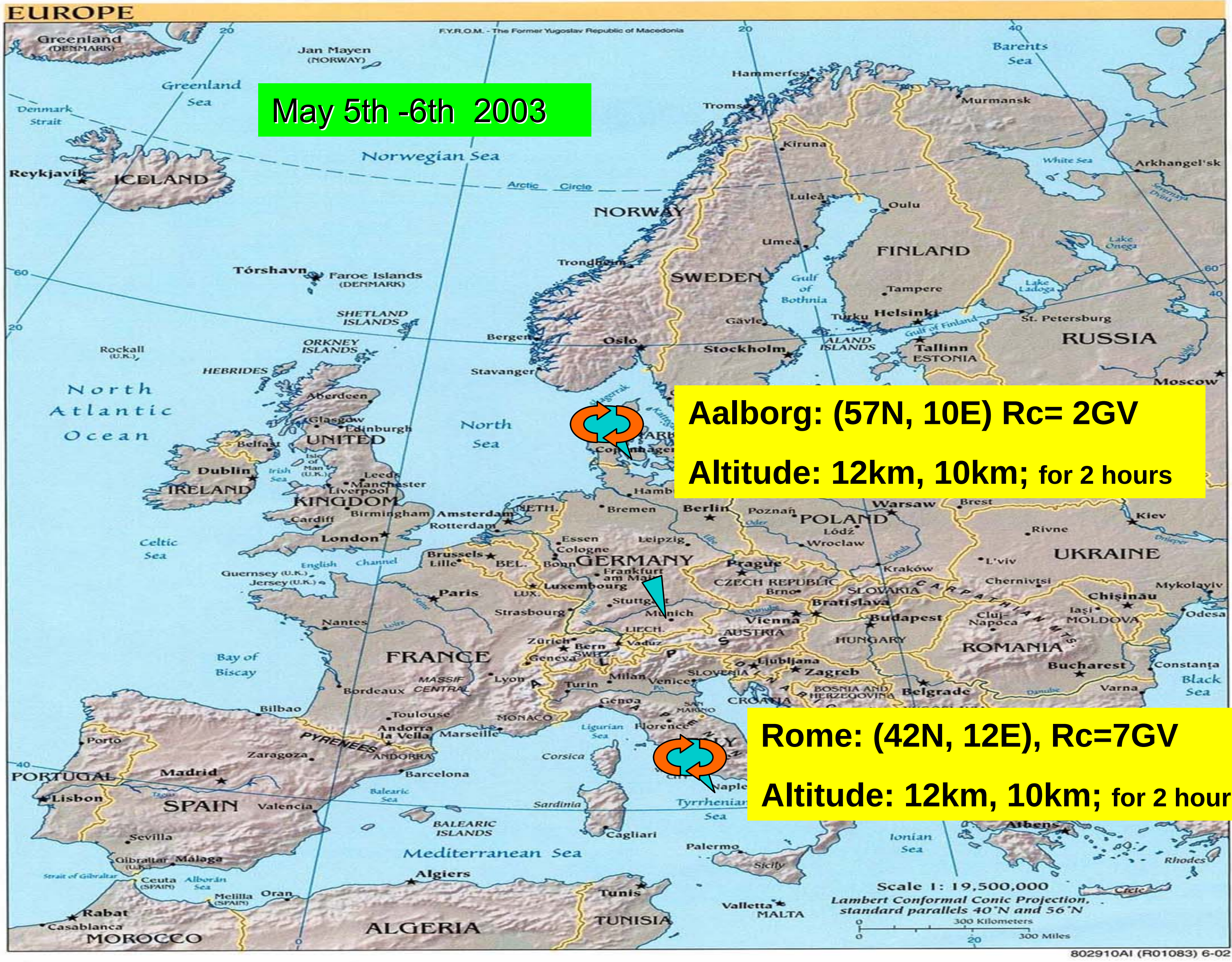
TT40 test beam: energy deposition (J/cm^3) for 3 10^{13} 450 GeV protons on the collimator prototype

TEPC – Tissue Equivalent Proportional Counter

- Absorbed Dose (Gy), Q(LET),

  Dose Equivalent (Sv)
- 0,3 µm – 10 µm tissue volume (1-2 µm)
- Microdosimetric spectra (y/kev µm^{-1})
- Measurements:
  - Photons: up to 7Mev
  - Neutrons: up to 200MeV
  - Mixed radiation field (CERF)
  - Heavy Ions





May 5th -6th 2003

Aalborg: (57N, 10E) Rc= 2GV

Altitude: 12km, 10km; for 2 hours

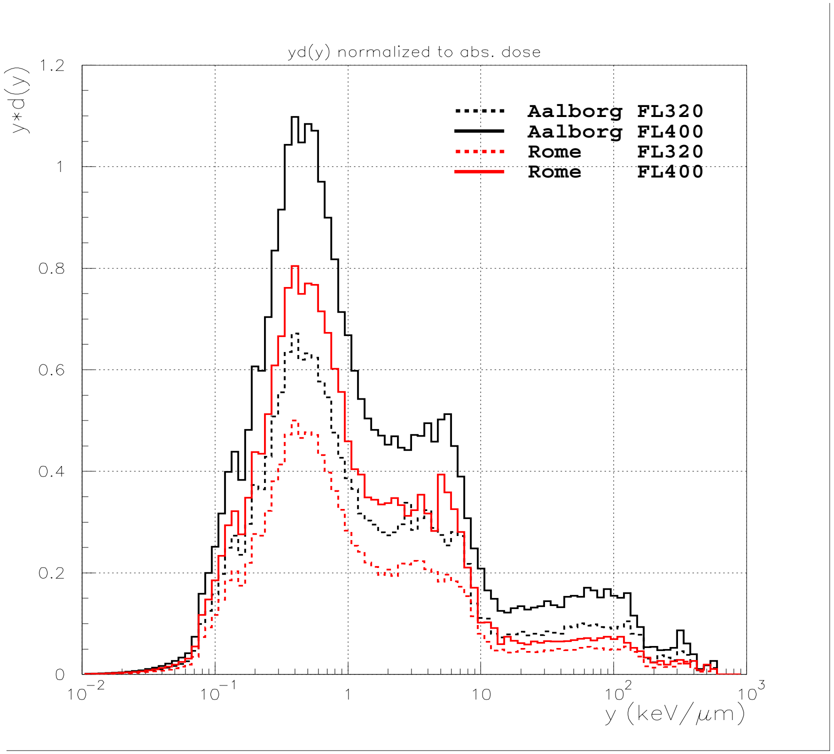
Rome: (42N, 12E), Rc=7GV

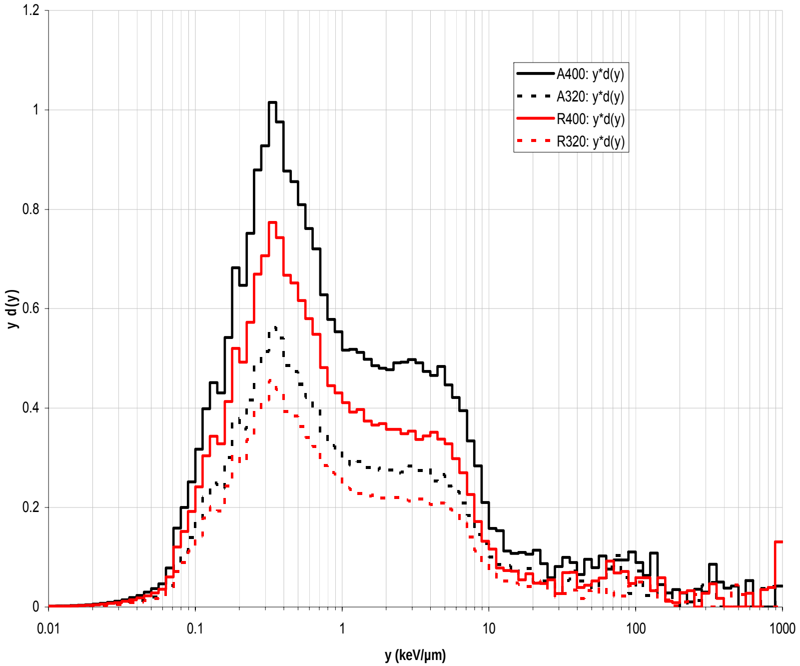
Altitude: 12km, 10km; for 2 hours

Comparison: absolute absorbed dose

Simulation

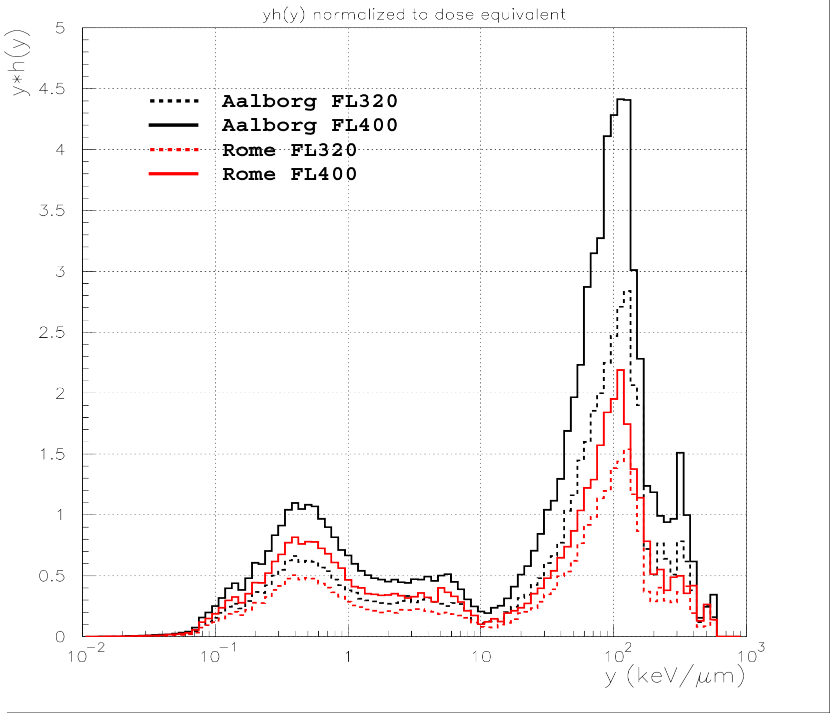
Measurements



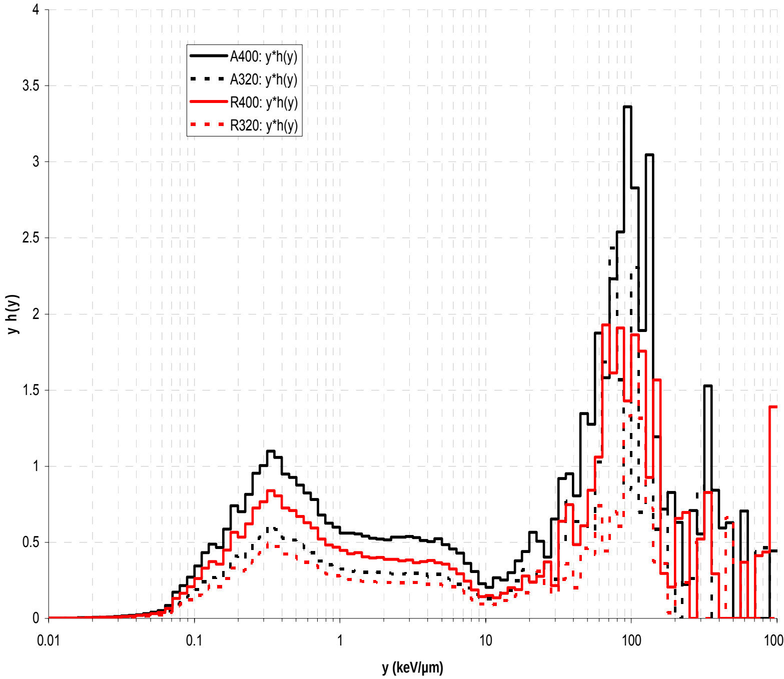


Absolute dose equivalent

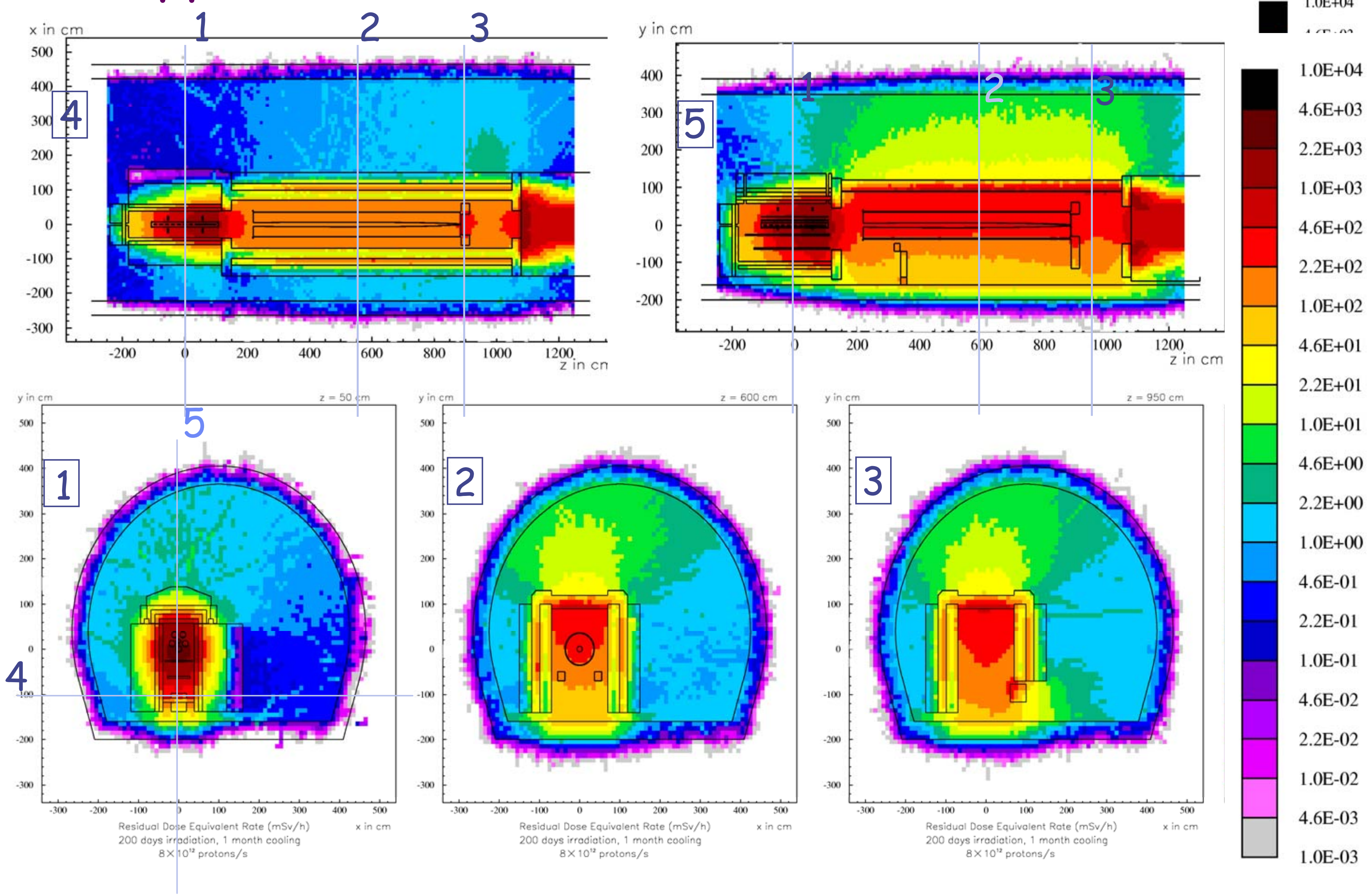
Simulation



Measurements



Applications – *CNGS*



Residual Dose Equivalent Rate (mSv/h)
200 days irradiation, 1 month cooling
8×10^{12} protons/s

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8×10^{12} protons/s

Real and Virtual Photonuclear Interactions

Photonuclear reactions

- Giant Dipole Resonance interaction (special database)
- Quasi-Deuteron effect
- 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

Virtual photon reactions

- Muon photonuclear interactions
- Electromagnetic dissociation

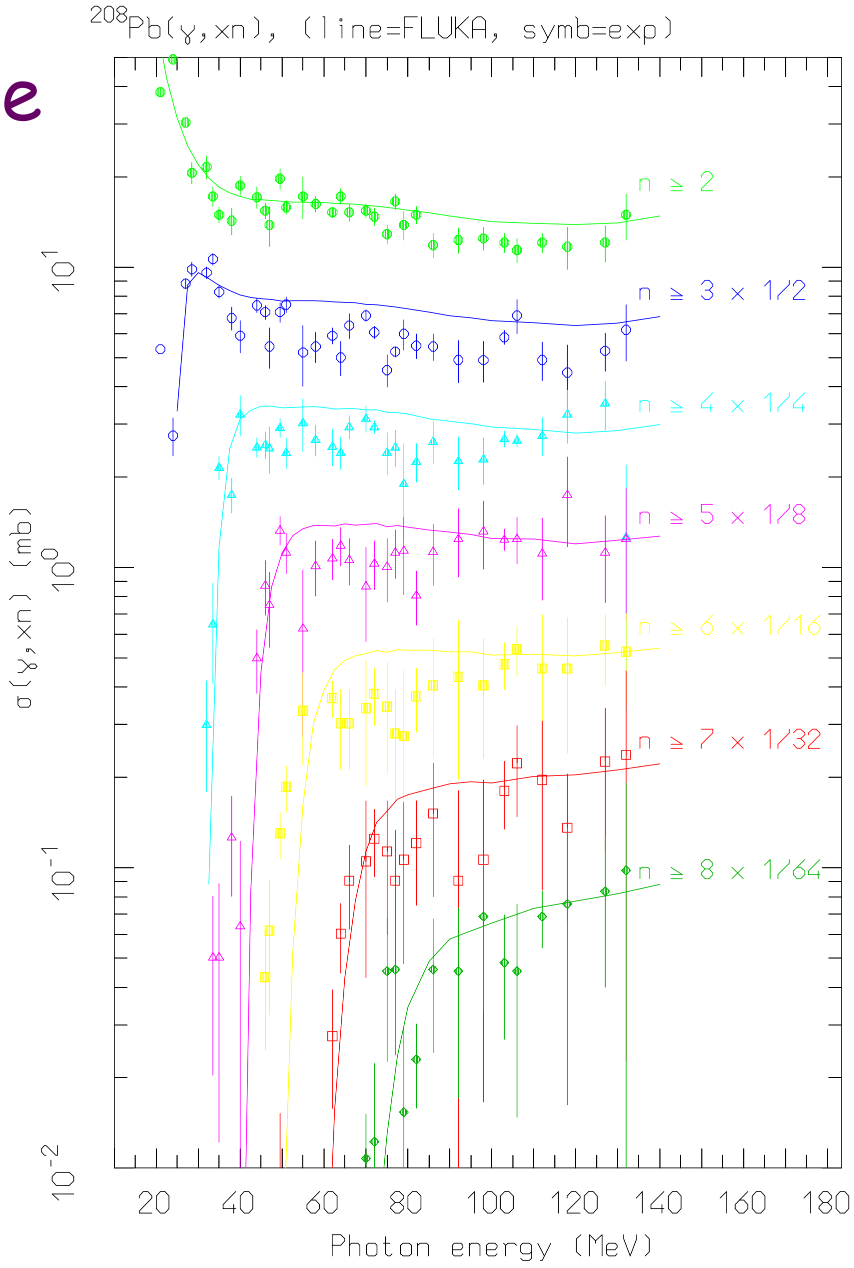
Photonuclear int.: example

Reaction:
^{208}Pb(γ,x n)
20≤Eγ ≤140 MeV

Cross section for multiple neutron emission as a function of photon energy, **Different colors refer to neutron multiplicity ≥ *n* , with 2≤*n*≤8**

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

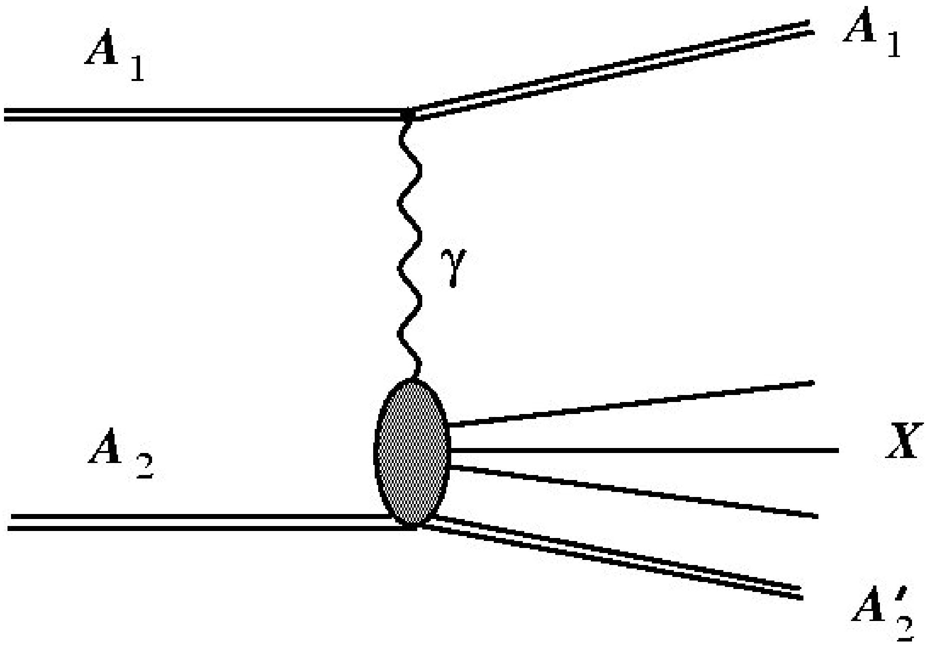
Lines: FLUKA



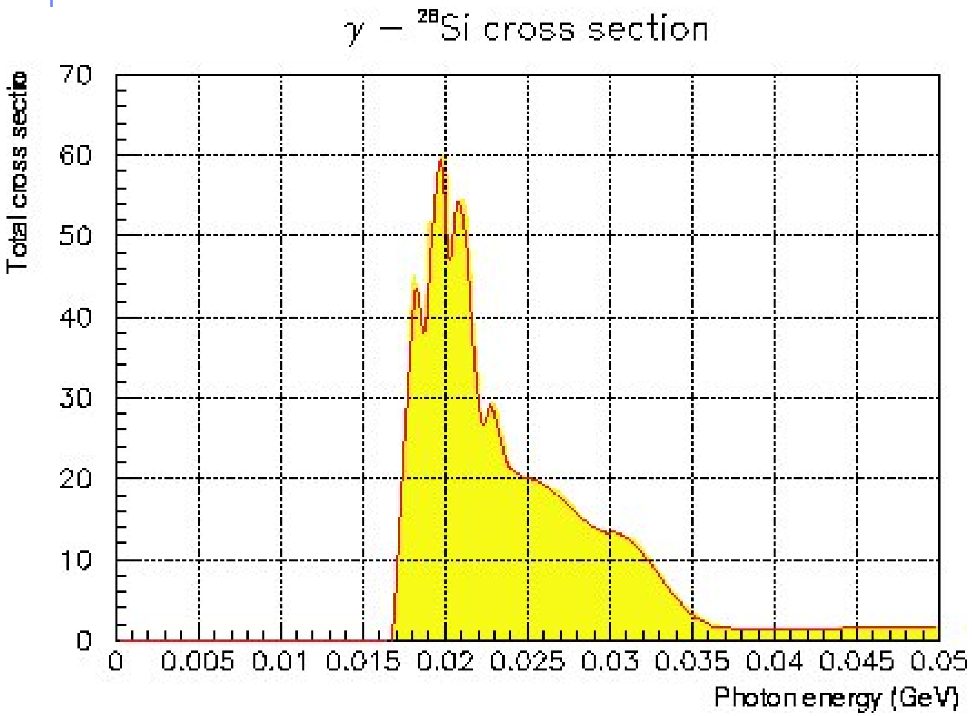
Electromagnetic dissociation

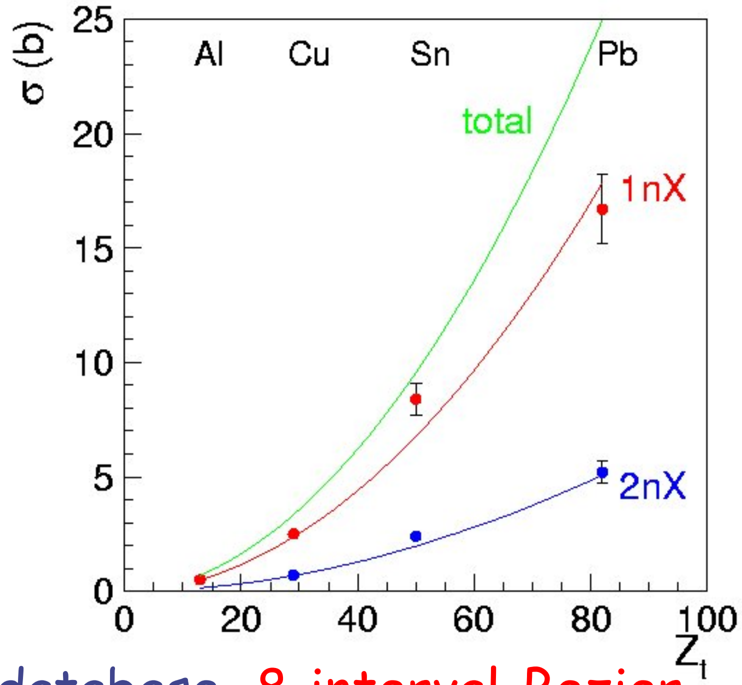
Electromagnetic dissociation: σ_{EM} increasingly large with (target) Z's and energy. Already relevant for few GeV/n ions on heavy targets (σ_{EM} ~ 1 b vs σ_{nucl} ~ 5 b for 1 GeV/n Fe on Pb)

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



Electromagnetic dissociation: example



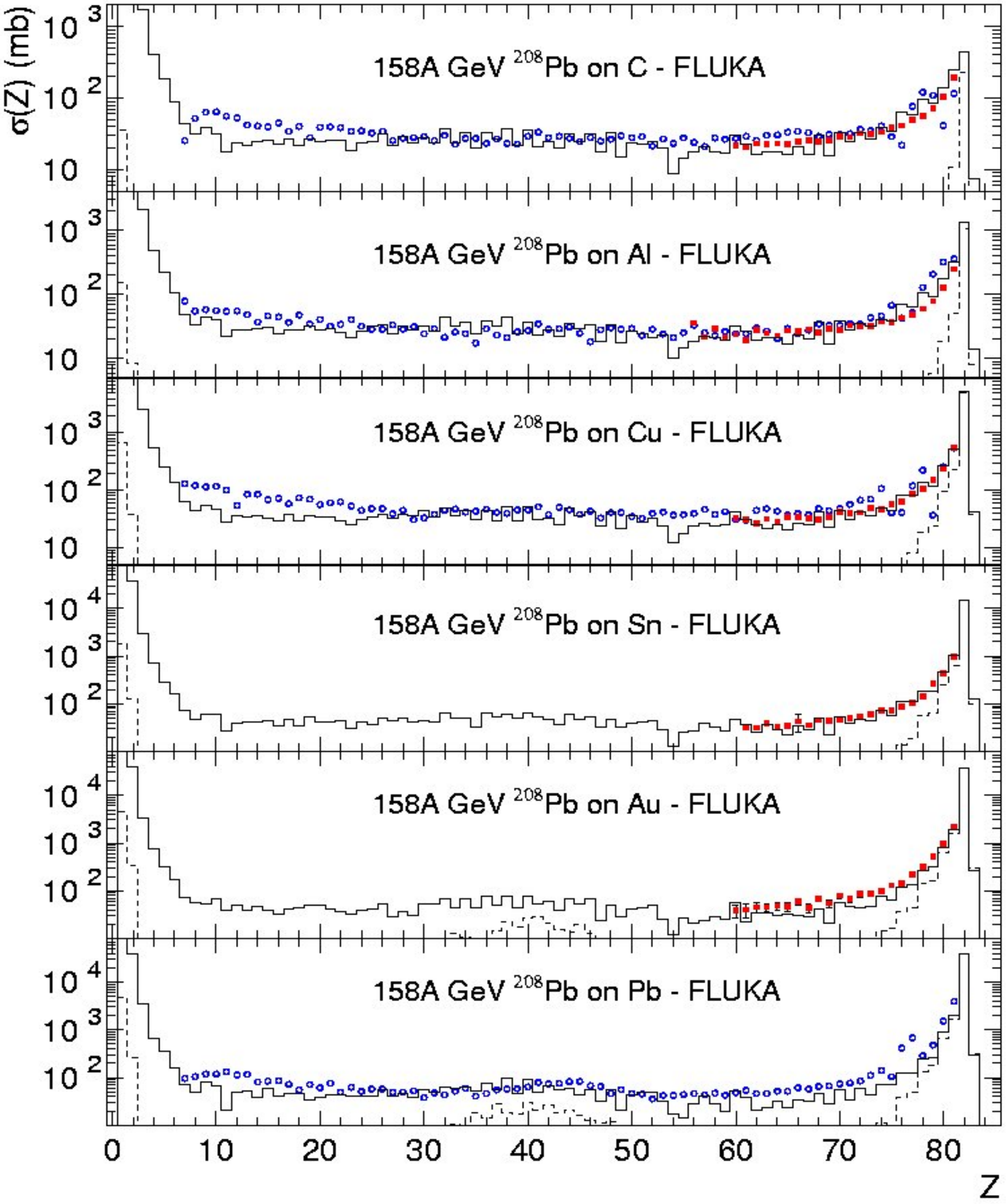


Left: ^{28}Si(g,tot) as recorded in FLUKA database, 8 interval Bezier fit as used for the Electromagnetic Dissociation event generator.

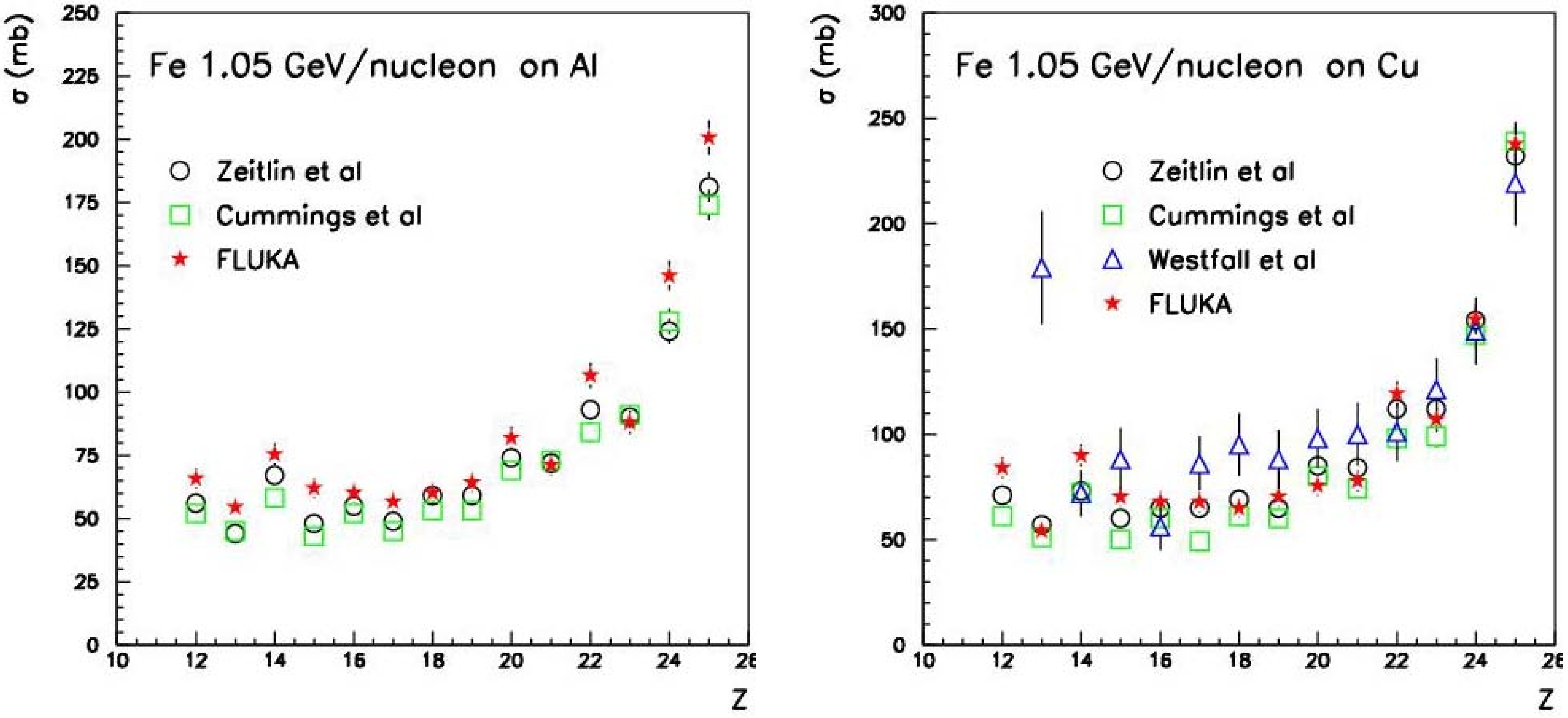
Right: calculated total, 1nX and 2nX electromagnetic dissociation cross sections for 30 A GeV Pb ions on Al, Cu, Sn and Pb targets. Points – measured cross sections of forward 1n and 2n emissions as a function of target charge (M.B. Golubeva et al., in press)

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

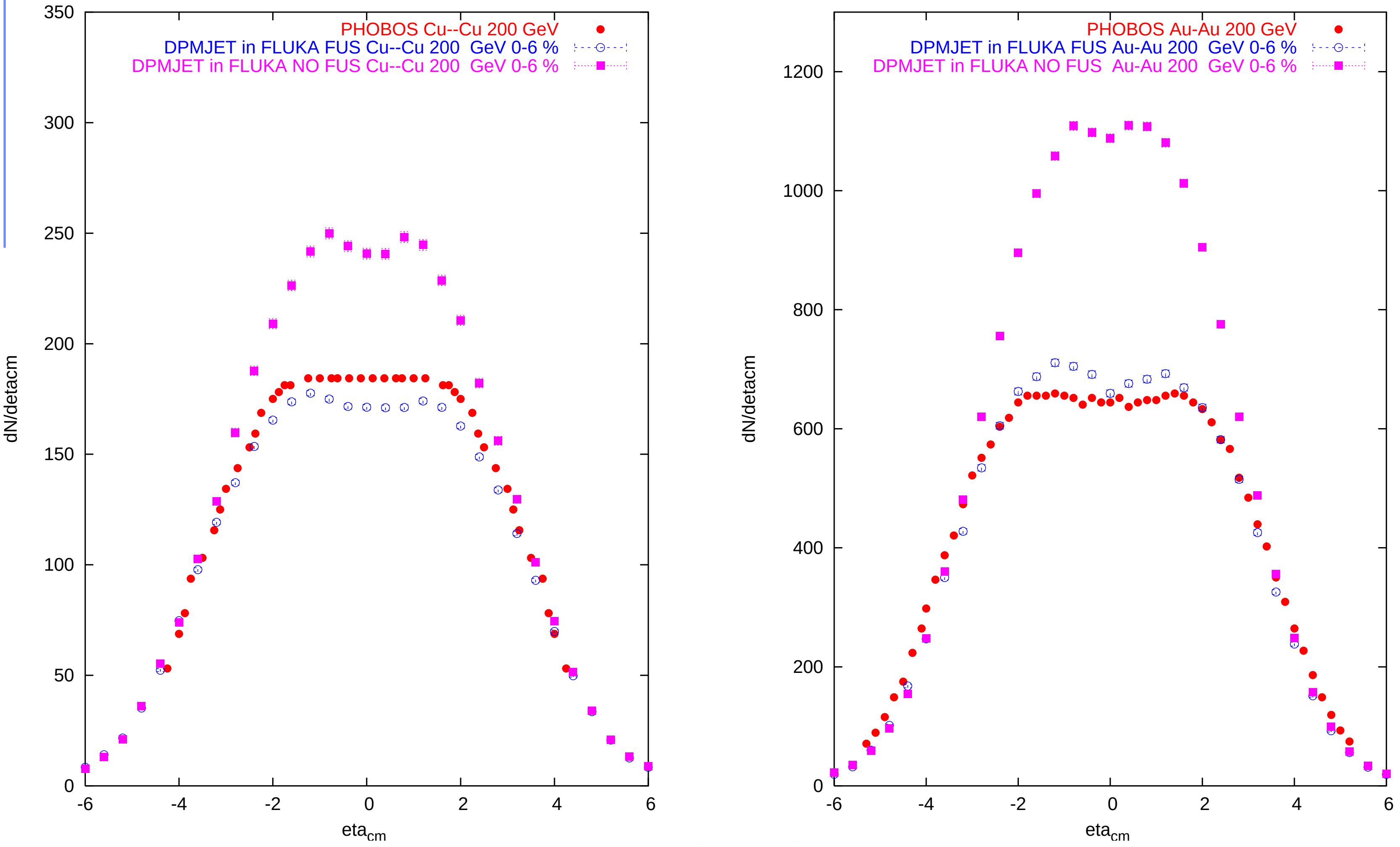


Fragment charge cross section for 1.05 GeV/n Fe ions on Al (left) and Cu (right).

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

DPMJET-3 upgrade: chain fusion

Pseudorapidity distribution of charged particles in Au-Au and Cu-Cu collisions at $\sqrt{s_{NN}}$=200 GeV: with and without chain fusion, compared to PHOBOS results at RHIC



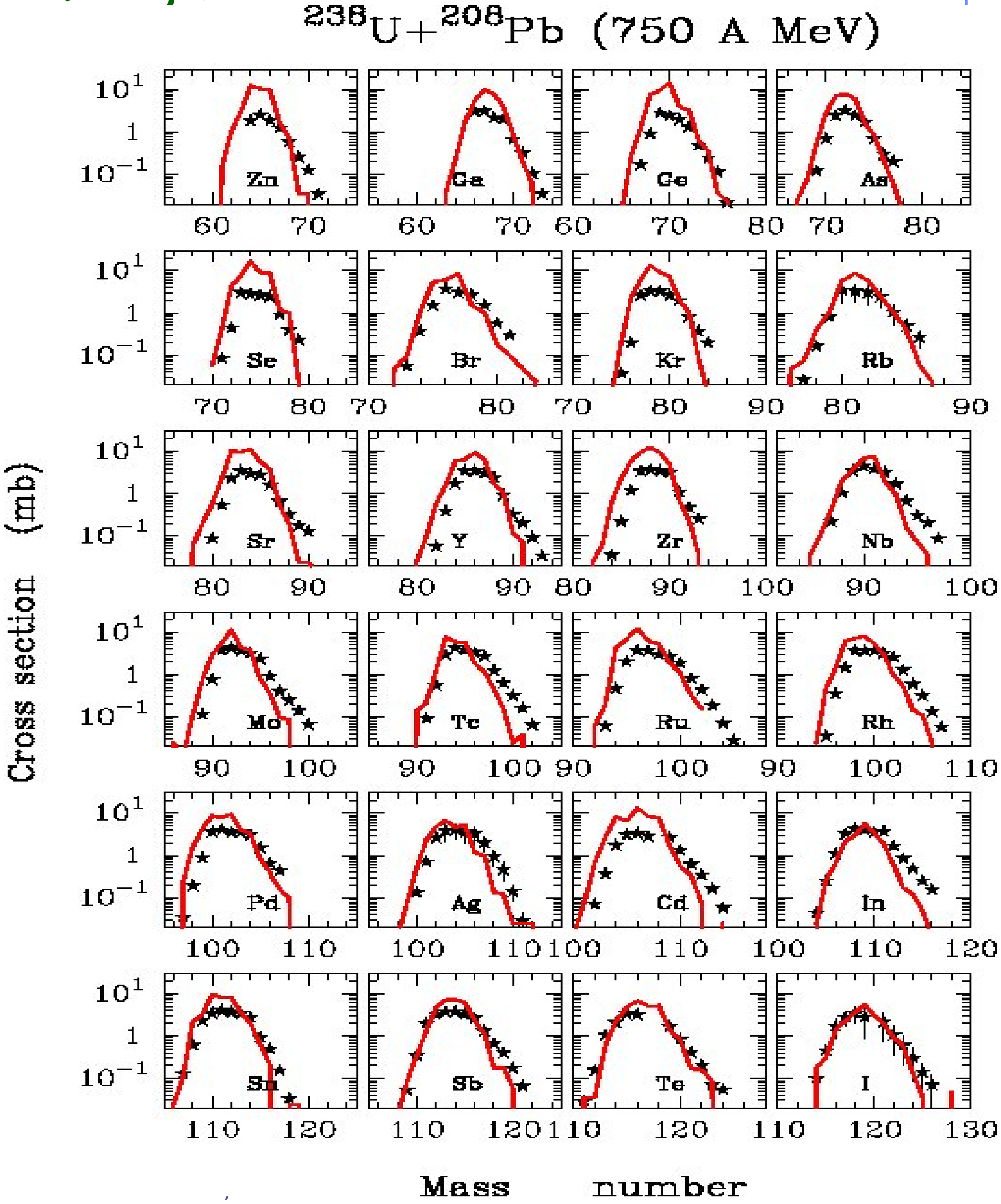
FLUKA fragmentation results

Fragment charge cross section for 750 MeV/n U ions on Pb.

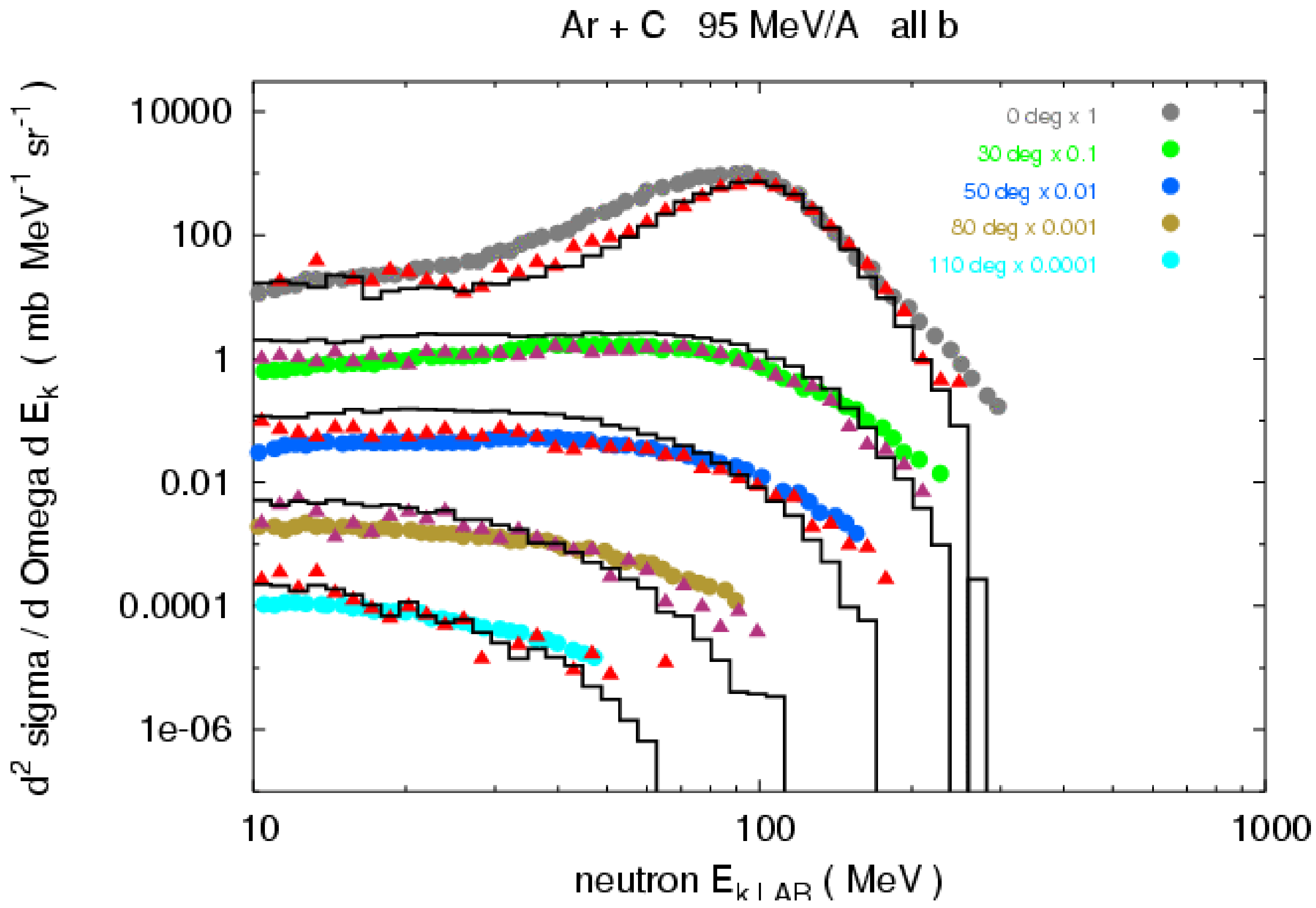
Data (stars) from

J. Benlliure, P. Ambruster et al., Eur. Phys. J. A2, 193-198 (1988).

Fission products have been excluded like in the experimental analysis



The new QMD model: (data PRC64 (2001) 034607)

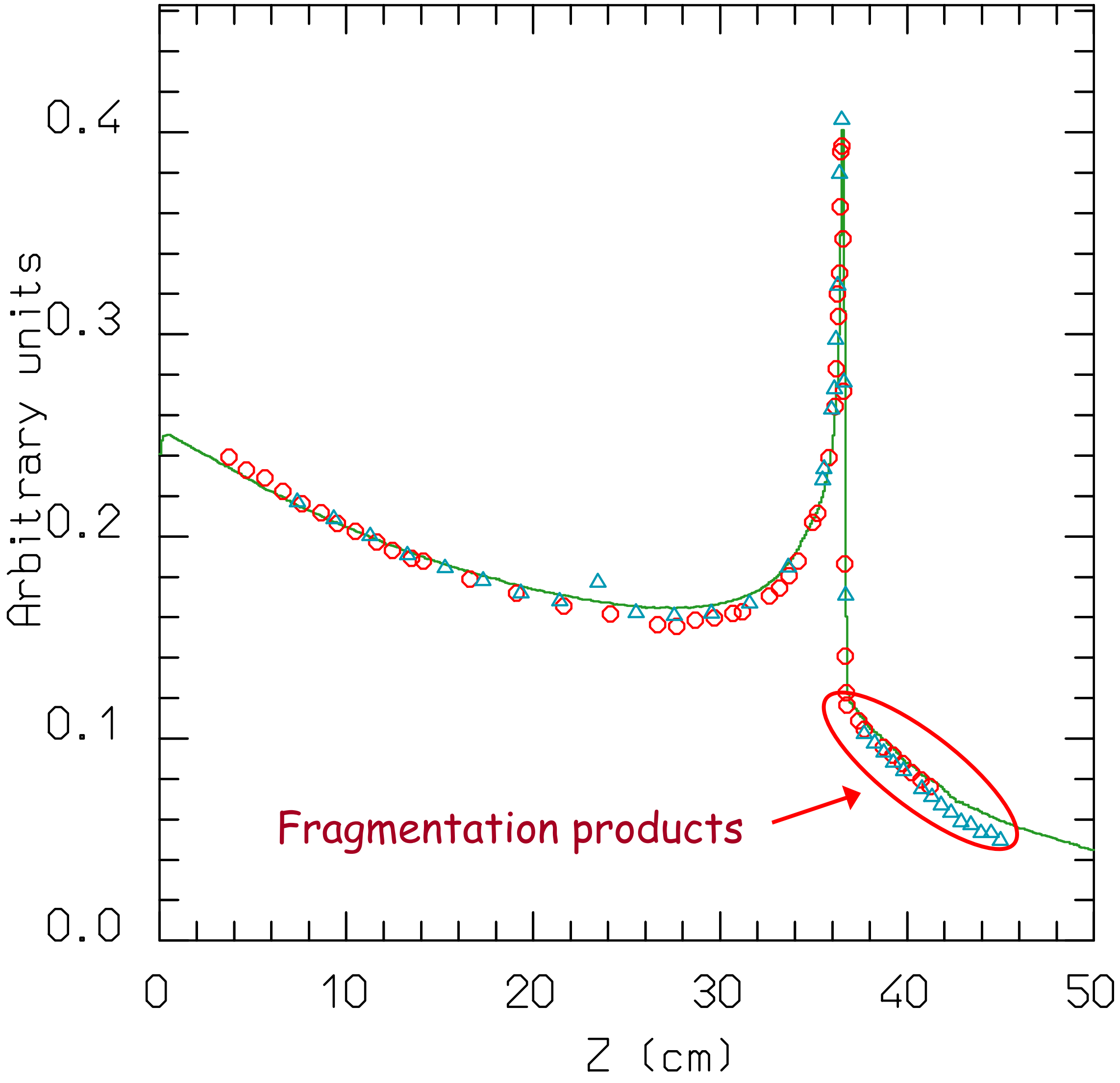


— RQMD + FLUKA ▲ QMD + FLUKA ● EXP data

Bragg peaks vs exp. data: ^{20}Ne @ 670 MeV/n

Dose vs depth distribution for 670 MeV/n ^{20}Ne ions on a water phantom.
The green line is the FLUKA prediction
The symbols are exp data from LBL and GSI

Exp. Data
Jpn.J.Med.Phys. 18, 1,1998



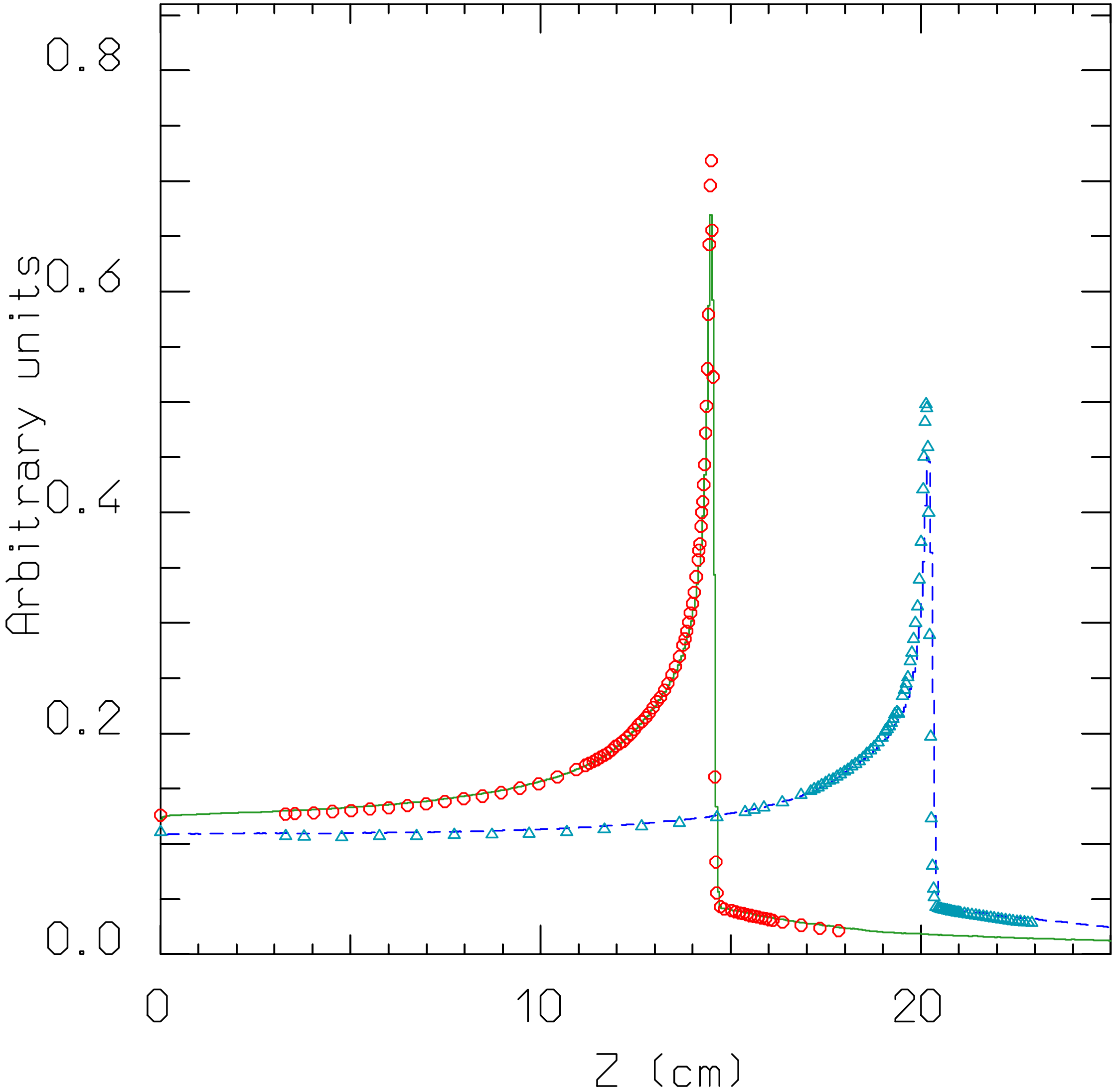
Fragmentation products

Bragg peaks vs exp. data: ^{12}C @ 270 & 330 MeV/n

Dose vs depth distribution for 270 and 330 MeV/n ^{12}C ions on a water phantom.

The full green and dashed blue lines are the FLUKA predictions

The symbols are exp data from GSI



Exp. Data
Jpn.J.Med.Phys. 18, 1,1998

Calculation of Induced Activity with FLUKA

- Simulation of particle interactions and transport in the target, the samples, as well as the tunnel/cavern walls
- Separate simulations for proton and pion beam
- Simulations of isotope production via
  - High-energy processes
  - Low-energy neutron interactions
- Transport thresholds
  - Neutrons: down to thermal energies
  - Other hadrons: until stopped or captured
  - No electromagnetic cascade was simulated
- Calculated quantities
  - Radioactive isotope production per primary particle
  - (Star density and particle energy spectra in the samples)
- Calculation of build-up and decay of radioactive isotopes for specific irradiation and cooling patterns including radioactive daughter products

Benchmark experiment – *Instrumentation 1*

M. Brugger, *et al.*, in Proceedings of the Int. Conf. on Accelerator Applications (AccApp'05), Venice, Italy, 2005

Low-background coaxial High Precision Germanium detector (Canberra)

- use of two different detectors (90 cm3 sensitive volume, 60% and 40% relative efficiency)

Genie-2000 (Ver. 2.0/2.1) spectroscopy software by Canberra and PROcount-2000 counting procedure software

- include a set of advanced spectrum analysis algorithms, *e.g.,* nuclide identification, interference correction, weighted mean activity, background subtraction and efficiency correction
- comprise well-developed methods for peak identification using standard or user-generated nuclide libraries. HERE: use of user-generated nuclide libraries, based on nuclides expected from the simulation and material composition

Efficiency calibration with LABSOCS

- allows the creation of a corrected efficiency calibration by modelling the sample taking into account self-absorption inside the sample and the correct detector geometry

Details of Samples

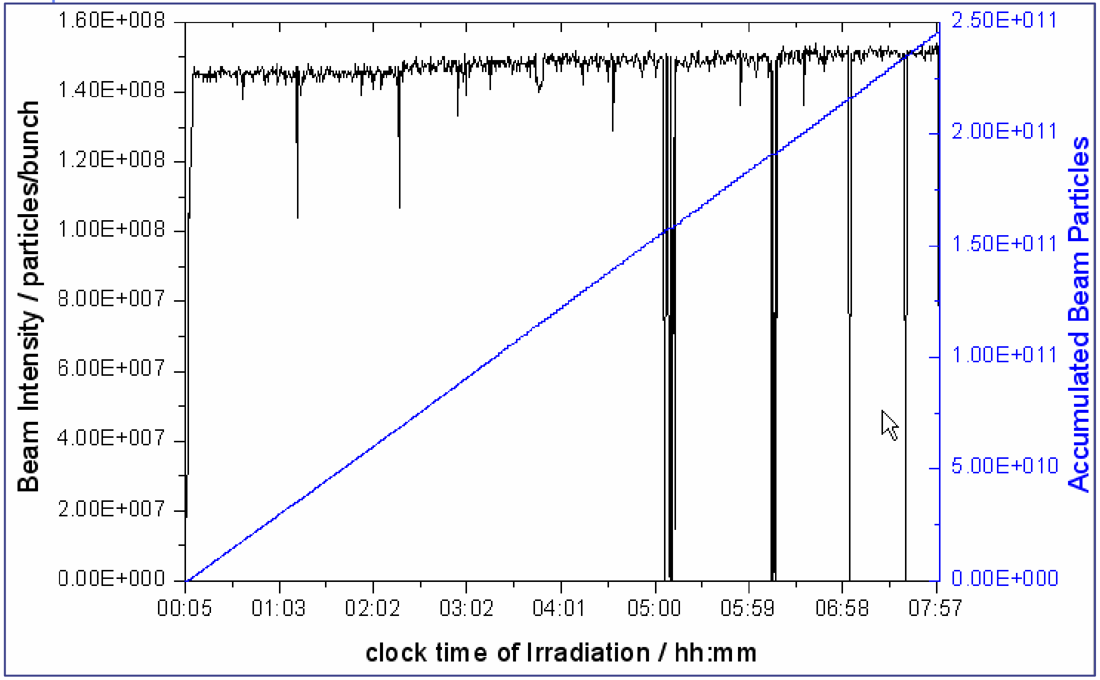
Elemental composition in percent by weight

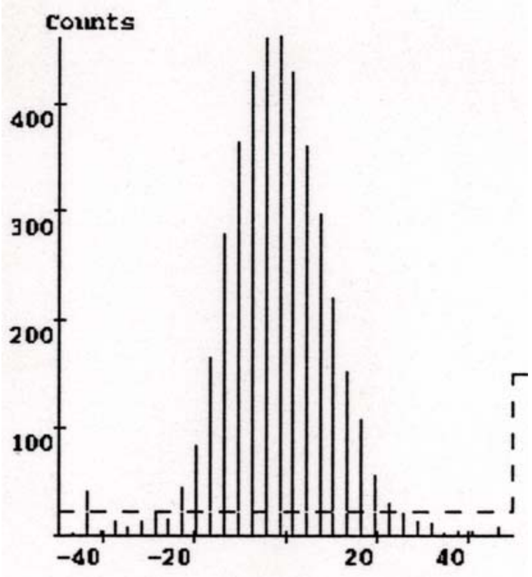
Steel		Copper		Aluminium		Concrete		Titanium		Resin	
$\rho = 7.25$ g/cm^3		$\rho = 8.89$ g/cm^3		$\rho = 2.72$ g/cm^3		$\rho = 1.70$ g/cm^3		$\rho = 4.42$ g/cm^3		$\rho = 1.24$ g/cm^3	
Fe	63.088	Cu	99.328	Al	96.4589	O	47.87	Ti	88.036	C	66.77
Cr	17.79	Al	0.4745	Si	1.08	Ca	35.4	Al	6.5	O	27.64
Mn	11.43	Si	0.13	Mg	0.83	C	9.24	V	5.28	H	5.59
Ni	6.5	Fe	0.0261	Mn	0.696	Si	4.0	Fe	0.093		
Si	0.38	S	0.0137	Fe	0.5	Al	0.97	Cr	0.05		
N	0.31	Cd	0.004	Cu	0.115	Fe	0.69	Ni	0.0116		
Co	0.11	Sb	0.004	Zn	0.1044	Mg	0.64	Cl	0.0102		
P	0.019	Cr	0.0021	Cr	0.033	H	0.6	Mn	0.0071		
C	0.095	Te	0.002	Ti	0.0302	K	0.26	Cu	0.0043		
Mo	0.09	Pb	0.002	Pb	0.0287	S	0.15	Zn	0.004		
Cu	0.085	Sn	0.002	Sn	0.0278	Ti	0.06	P	0.0038		
V	0.07	As	0.002	Ca	0.0201	Sr	0.05				
Ti	0.01	Ag	0.002	Bi	0.0161	P	0.03				
Nb	0.01	Zn	0.002	Ni	0.0128	Na	0.03				
W	0.01	Mn	0.0016	P	0.0126	Mn	0.01				
O	0.002	Se	0.0011	Ga	0.0102						
S	0.001	Bi	0.001	Cl	0.0087						
		Ni	0.001	S	0.0076						
		P	0.0004	V	0.0041						
		Co	0.0002	Zr	0.0024						
				Am	0.0014						

Beam Conditions

- 120 GeV secondary SPS mixed hadron beam
  (p 34.8%, π 60.7% and K 4.5%)
- 16.8s spill cycle, 4s burst
- ~ 5x10^{10} (short) - 1x10^{12} (long) particles hit the target during irradiation

- Beam Profile (approx. Gaussian): measured with multi-wire prop. Chamber,
  σ ~ 10 mm





Activation: Aluminum

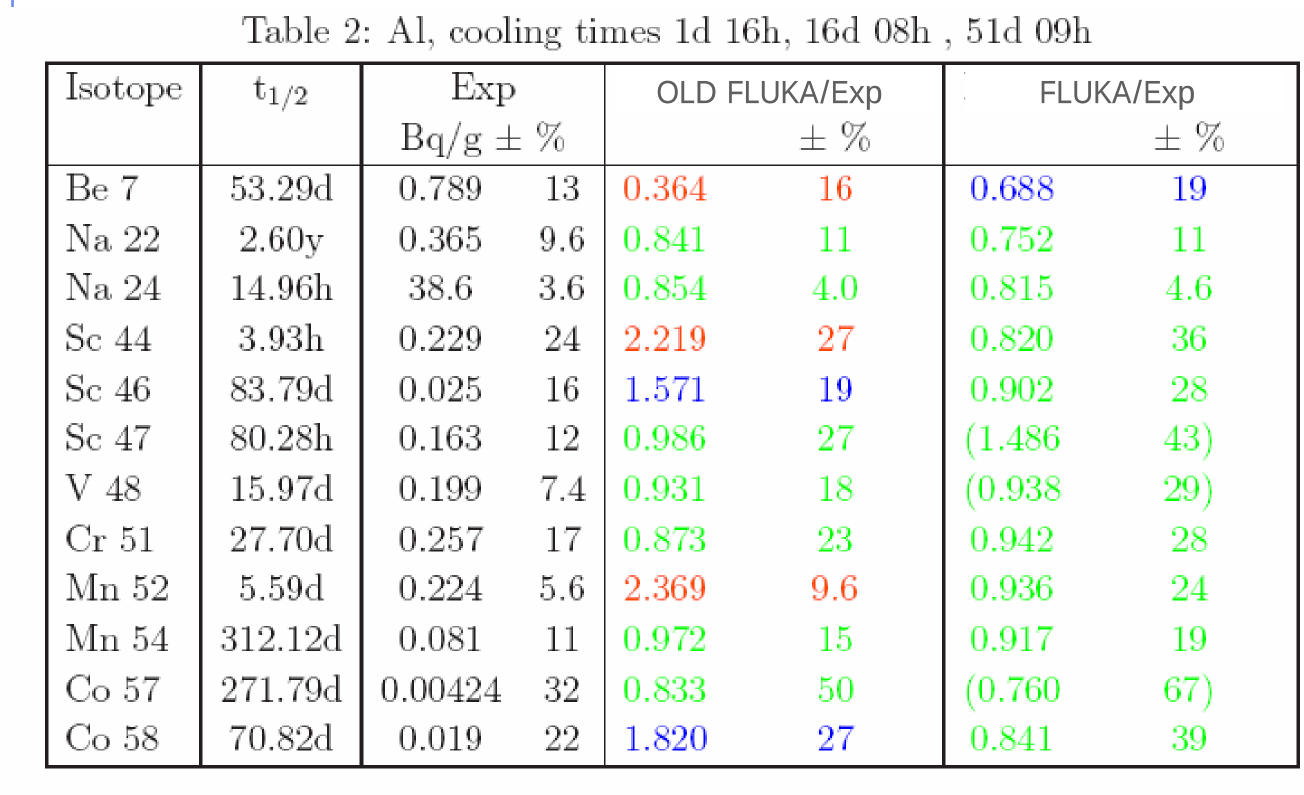


Table 2: Al, cooling times 1d 16h, 16d 08h , 51d 09h

Isotope	$t_{1/2}$	Exp		OLD FLUKA/Exp		FLUKA/Exp	
		Bq/g	± %		± %		± %
Be 7	53.29d	0.789	13	0.364	16	0.688	19
Na 22	2.60y	0.365	9.6	0.841	11	0.752	11
Na 24	14.96h	38.6	3.6	0.854	4.0	0.815	4.6
Sc 44	3.93h	0.229	24	2.219	27	0.820	36
Sc 46	83.79d	0.025	16	1.571	19	0.902	28
Sc 47	80.28h	0.163	12	0.986	27	(1.486	43)
V 48	15.97d	0.199	7.4	0.931	18	(0.938	29)
Cr 51	27.70d	0.257	17	0.873	23	0.942	28
Mn 52	5.59d	0.224	5.6	2.369	9.6	0.936	24
Mn 54	312.12d	0.081	11	0.972	15	0.917	19
Co 57	271.79d	0.00424	32	0.833	50	(0.760	67)
Co 58	70.82d	0.019	22	1.820	27	0.841	39

M. Brugger, *et al.*, Proceedings of the Int. Conf. on Accelerator Applications (AccApp'05), Venice, Italy, 2005

Activation: Copper 1st part

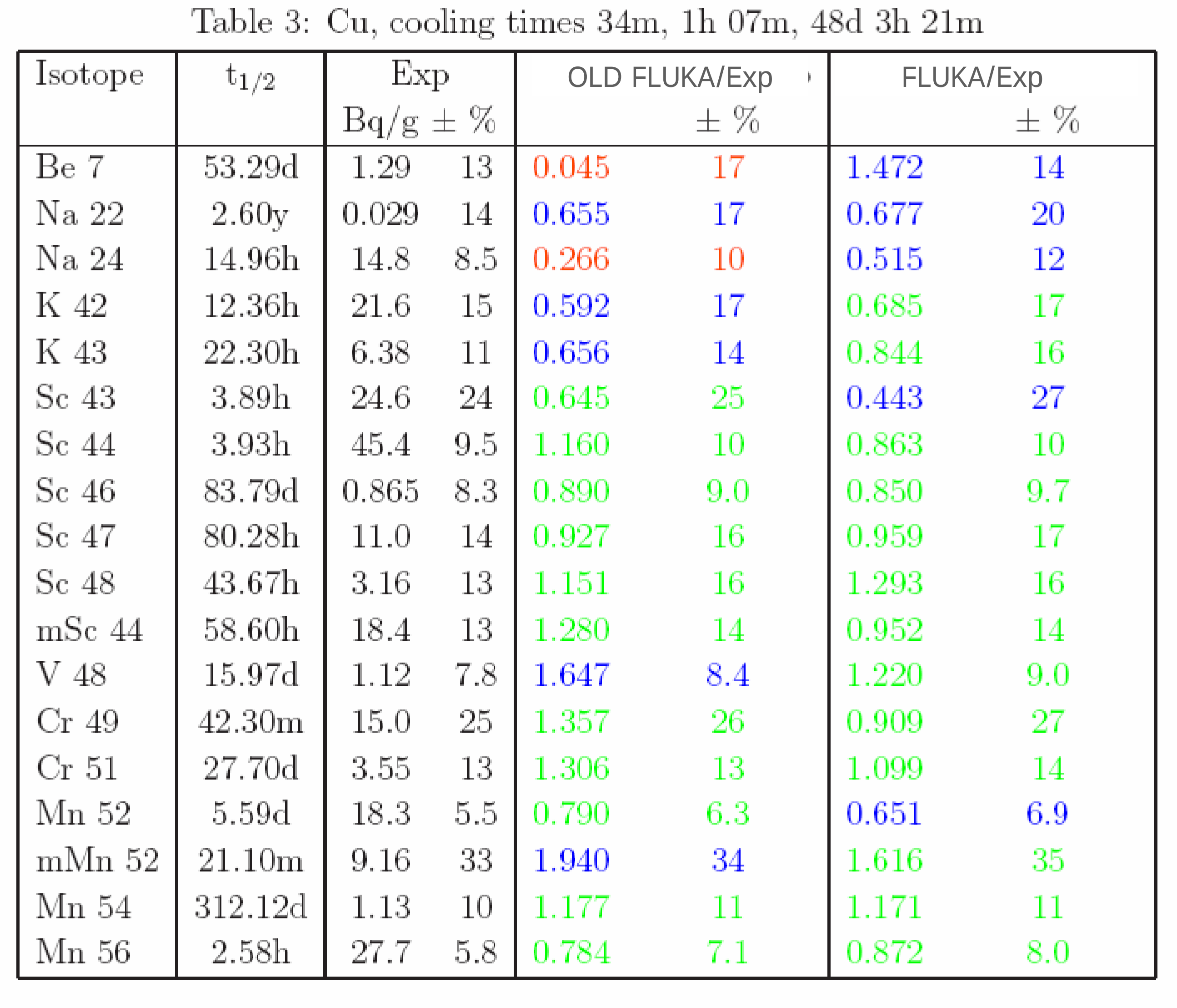


Table 3: Cu, cooling times 34m, 1h 07m, 48d 3h 21m

Isotope	$t_{1/2}$	Exp Bq/g	± %	OLD FLUKA/Exp	± %	FLUKA/Exp	± %
Be 7	53.29d	1.29	13	0.045	17	1.472	14
Na 22	2.60y	0.029	14	0.655	17	0.677	20
Na 24	14.96h	14.8	8.5	0.266	10	0.515	12
K 42	12.36h	21.6	15	0.592	17	0.685	17
K 43	22.30h	6.38	11	0.656	14	0.844	16
Sc 43	3.89h	24.6	24	0.645	25	0.443	27
Sc 44	3.93h	45.4	9.5	1.160	10	0.863	10
Sc 46	83.79d	0.865	8.3	0.890	9.0	0.850	9.7
Sc 47	80.28h	11.0	14	0.927	16	0.959	17
Sc 48	43.67h	3.16	13	1.151	16	1.293	16
mSc 44	58.60h	18.4	13	1.280	14	0.952	14
V 48	15.97d	1.12	7.8	1.647	8.4	1.220	9.0
Cr 49	42.30m	15.0	25	1.357	26	0.909	27
Cr 51	27.70d	3.55	13	1.306	13	1.099	14
Mn 52	5.59d	18.3	5.5	0.790	6.3	0.651	6.9
mMn 52	21.10m	9.16	33	1.940	34	1.616	35
Mn 54	312.12d	1.13	10	1.177	11	1.171	11
Mn 56	2.58h	27.7	5.8	0.784	7.1	0.872	8.0

M. Brugger, *et al.*, Proceedings of the Int. Conf. on Accelerator Applications (AccApp'05), Venice, Italy, 2005

Activation: Copper (2nd part)

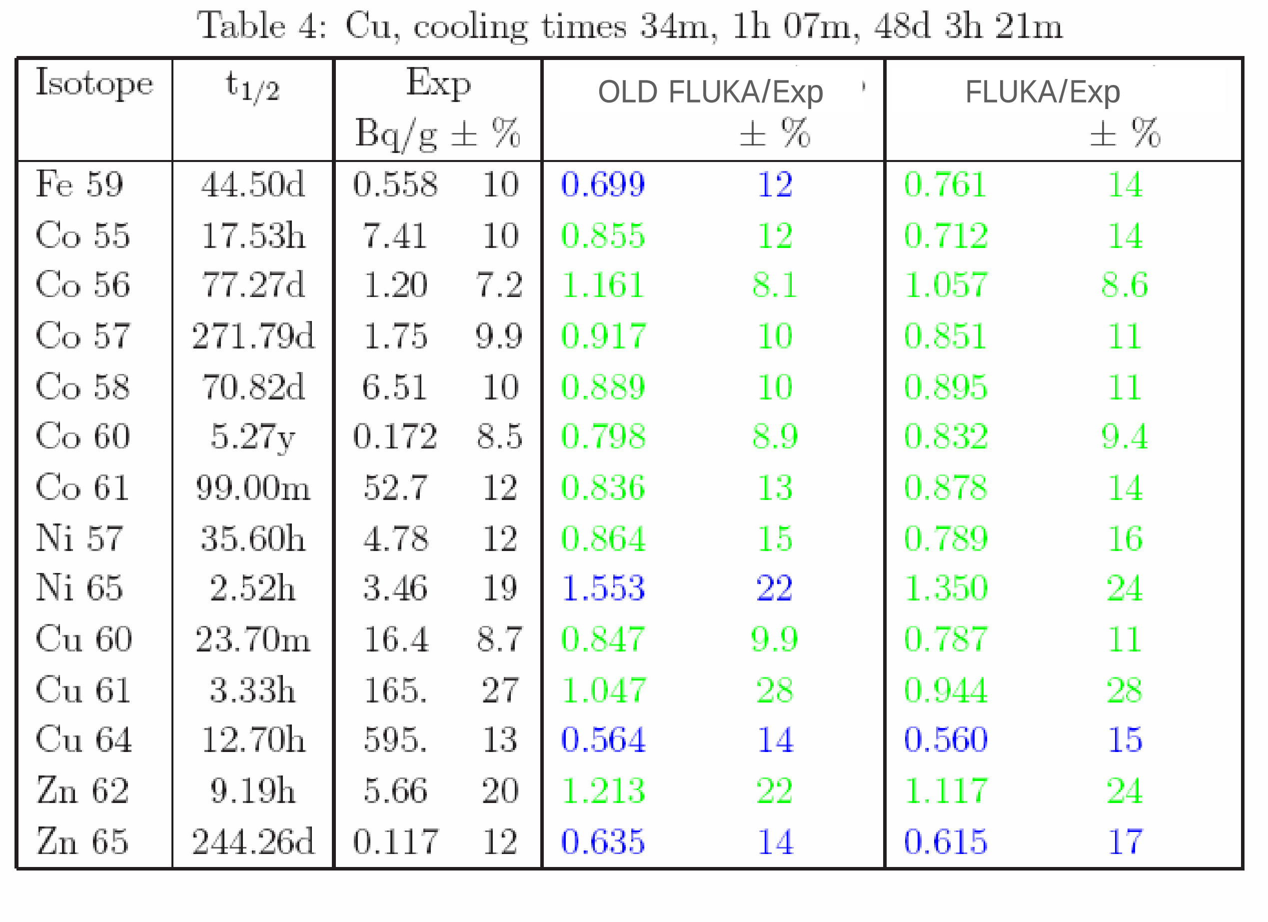


Table 4: Cu, cooling times 34m, 1h 07m, 48d 3h 21m

Isotope	$t_{1/2}$	Exp Bq/g	± %	OLD FLUKA/Exp	± %	FLUKA/Exp	± %
Fe 59	44.50d	0.558	10	0.699	12	0.761	14
Co 55	17.53h	7.41	10	0.855	12	0.712	14
Co 56	77.27d	1.20	7.2	1.161	8.1	1.057	8.6
Co 57	271.79d	1.75	9.9	0.917	10	0.851	11
Co 58	70.82d	6.51	10	0.889	10	0.895	11
Co 60	5.27y	0.172	8.5	0.798	8.9	0.832	9.4
Co 61	99.00m	52.7	12	0.836	13	0.878	14
Ni 57	35.60h	4.78	12	0.864	15	0.789	16
Ni 65	2.52h	3.46	19	1.553	22	1.350	24
Cu 60	23.70m	16.4	8.7	0.847	9.9	0.787	11
Cu 61	3.33h	165.	27	1.047	28	0.944	28
Cu 64	12.70h	595.	13	0.564	14	0.560	15
Zn 62	9.19h	5.66	20	1.213	22	1.117	24
Zn 65	244.26d	0.117	12	0.635	14	0.615	17

M. Brugger, *et al.*, Proceedings of the Int. Conf. on Accelerator Applications (AccApp'05), Venice, Italy, 2005

LHC: Conclusions on activation study

- Good agreement was found between the measured and calculated values for most of the isotopes and samples
- The large number of samples and variety of different materials offers a extensive possibility to study isotope production
- Multifragmentation (**NOW DEVELOPED AND PRESENTED AT INT. CONF. ON NUCLEAR DATA FOR SCIENCE AND TECHN. (Santa Fe 2004)**) has significantly improved the agreement for intermediate and small mass isotopes
- As a consequence, the calculation of remanent dose rates based on an explicit simulation of isotope production and transport of radiation from radioactive decay with FLUKA should also give reliable results → Part 2

Part 2: Radioactivity Produced in LHC Materials: Residual Dose Rates

- Levels of residual dose rates are an important design criterion for any high energy facility
- Residual dose rates for arbitrary locations and cooling times are so far predicted with a rather poor accuracy
  - typically based on the concept of so-called ω-factors and comprising several severe restrictions
  - layouts and material composition of beam-line components and surrounding equipment are often very complex
- A proper two-step approach based on the explicit generation and transport of gamma and beta radiation from radioactive decay should result in much more accurate results

Benchmark experiment – *Instrumentation 2*

M. Brugger *et al.*, Radiat. Prot. Dosim. 116 (2005) 12-15

Portable spectrometer Microspec

- NaI detector, cylindrical shape, 5 x 5 cm
- folds spectrum with detector response ("calibrated" with ^{22}Na source)
- physical centre of detector determined with additional measurements with known sources (^{60}Co, ^{137}Cs, ^{22}Na) to be 2.4 cm

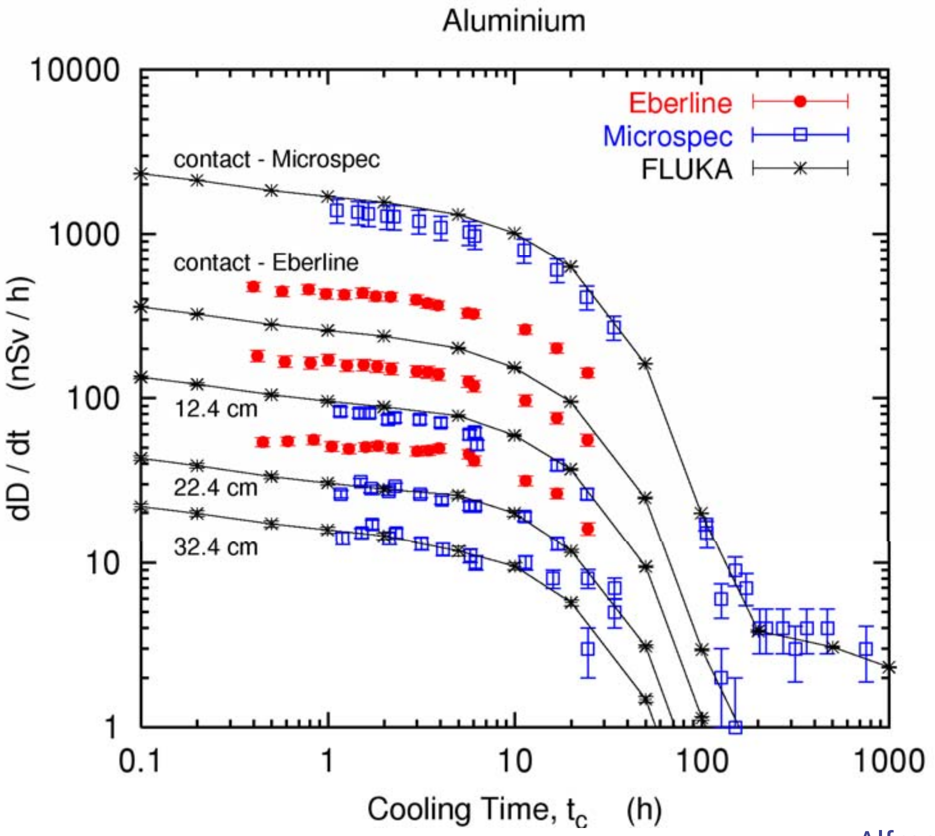
Thermo-Eberline dose-meter FHZ 672

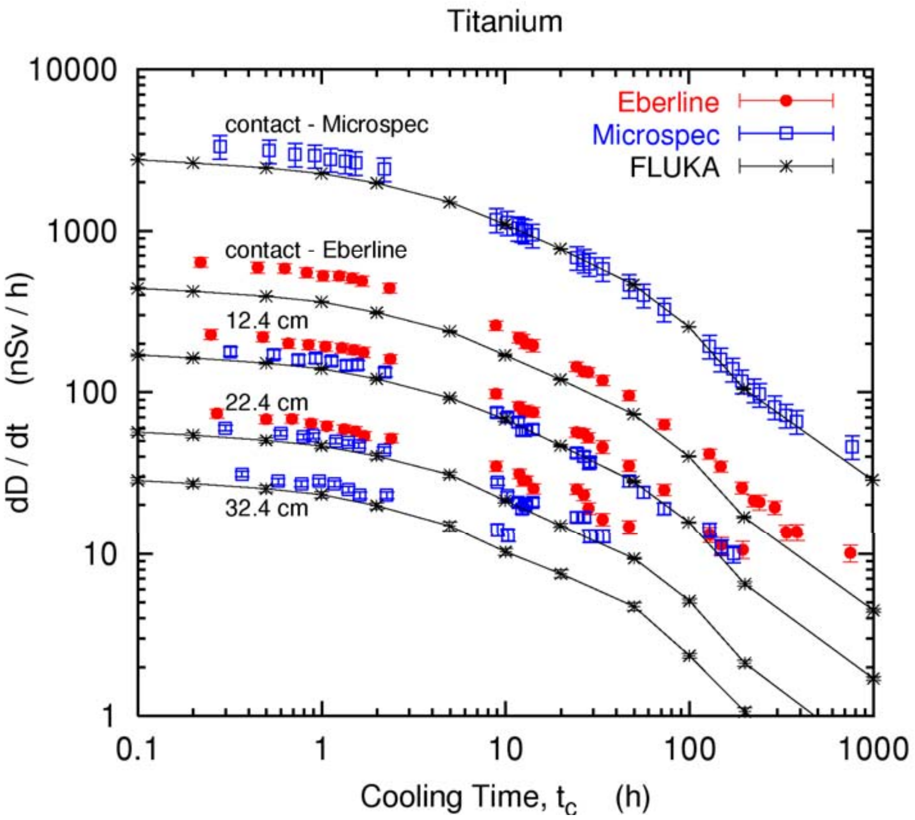
- organic Scintillator and NaI detector, cylindrical shape, 9 x 9 cm
- assumes average detector response
- physical centre of detector determined as above to be 7.3 cm

Benchmark experiment – *Results 2*

M. Brugger *et al.,* Radiat. Prot. Dosim. 116 (2005) 12-15

Dose rate as function of cooling time
for different distances between sample and detector

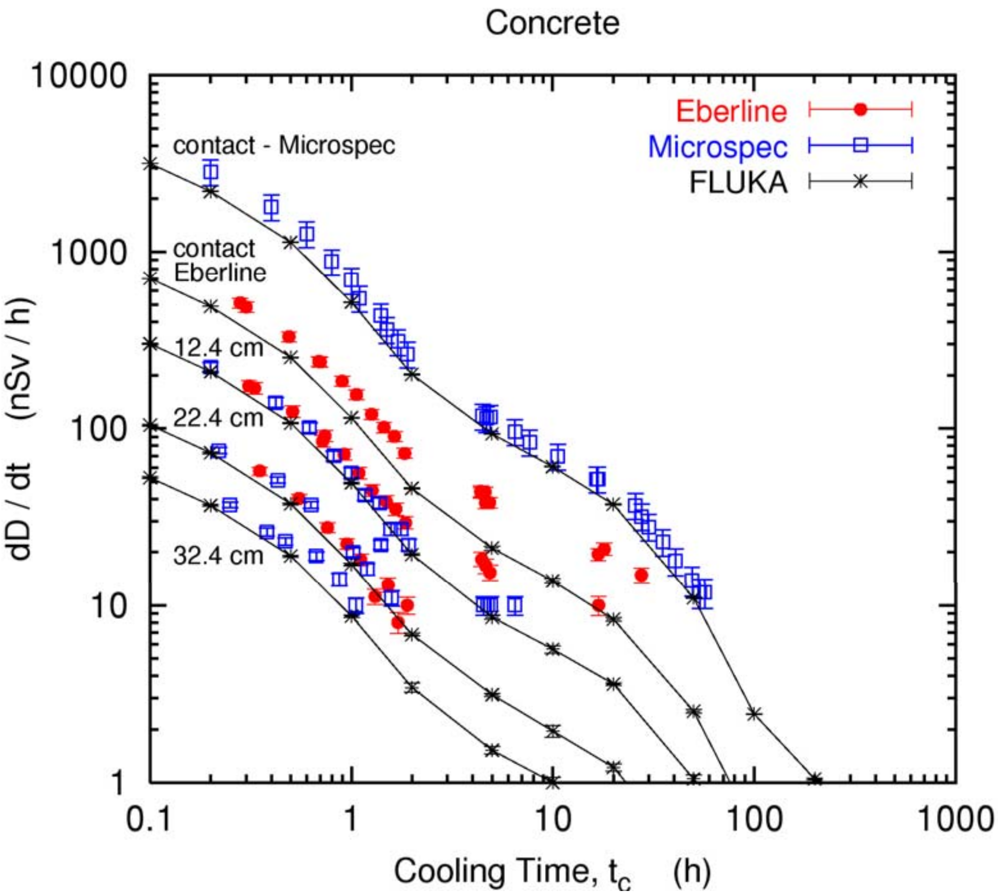




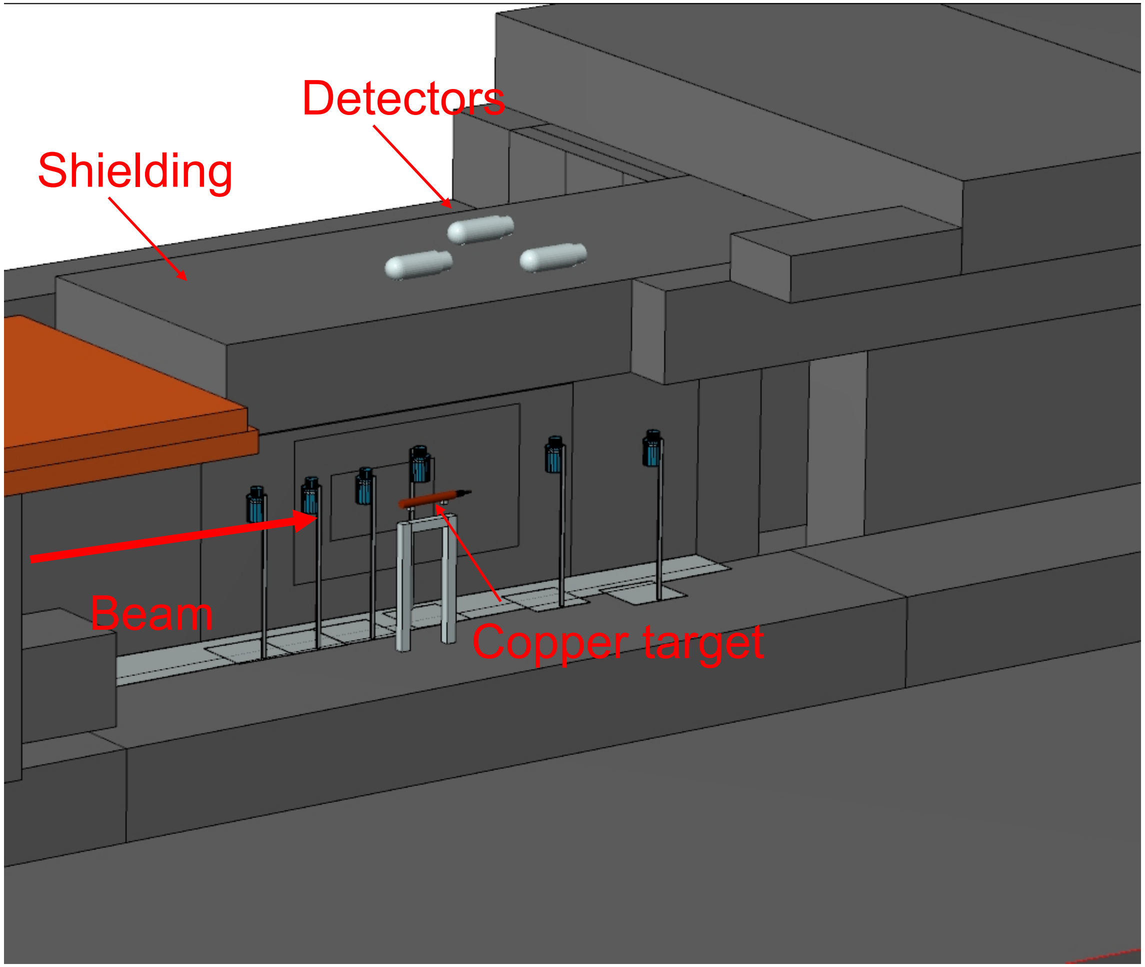
Benchmark experiment – *Results 3*

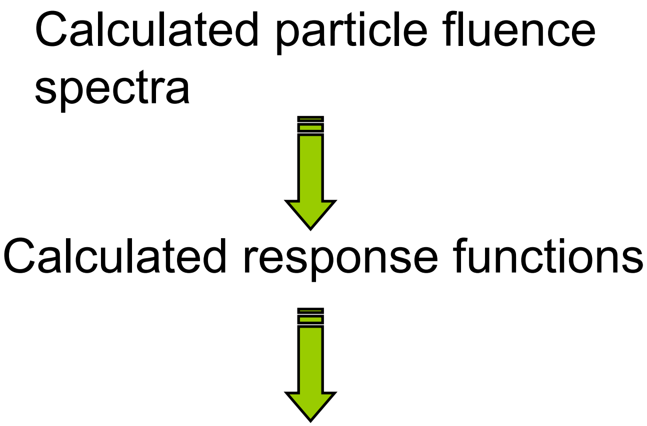
M. Brugger *et al.,* Radiat. Prot. Dosim. 116 (2005) 12-15

Dose rate as function of cooling time
for different distances between sample and detector



Simulation benchmark in mixed fields at the CERF facility





Calculated particle fluence spectra

Calculated response functions

Position	Simulation / experiment
CS2	1.11 ± 14%
CT6/10	1.10 ± 13%
CT4	1.14 ± 15%
CS-50U	1.38 ± 21%

C. Theis, D. Forkel-Wirth, D. Perrin, S. Roesler, and H. Vincke, *Characterisation of ionisation chambers for a mixed radiation field and investigation of their suitability as radiation monitors for the LHC*, Radiation Protection Dosimetry 116, pp. 170-174 (2005).

Low-energy neutron transport in FLUKA

performed by a multigroup algorithm:

- Widely used in low-energy neutron transport codes (not only Monte Carlo, but also Discrete Ordinate codes)
- Energy range of interest is divided in a given number of discrete intervals "energy groups"
- Elastic and inelastic reactions simulated not as exclusive process, but by group-to-group transfer probabilities (down-scattering matrix)
- The scattering transfer probability between different groups represented by a Legendre polynomial expansion truncated at the (N+1)th term:

$$\sigma_s(g \to g', \mu) = \sum_{i=0}^{N} \frac{2i+1}{4\pi} P_i(\mu)\,\sigma_s^i(g \to g')$$

μ = scattering angle

N = chosen Legendre order of anisotropy

FLUKA Implementation

- Both fully biased and semi-analog approaches available
- Energy range up to 19.6 MeV divided in 72 energy groups of approximately equal logarithmic width, and one thermal
- Prepared using a specialized code (NJOY) and ad-hoc programs
- Continuously enriched and updated on the basis of the most recent evaluations (ENDF/B, JEF, JENDL, etc.)
- The library contains 140 different materials/temperatures
- Cross sections of some materials are available at 2 or 3 different temperatures (0, 87 and 293° K) + Doppler broadening
- Hydrogen cross sections available for different types of molecular binding (free, H_2O, CH_2)
- Neutron energy deposition calculated by means of kerma factors
- However, H recoil protons, protons from $^{14}N(n,p)$ and $(\alpha, {}^3H)$ from neutron capture in ^6Li and ^{10}B can be produced and transported explicitly
- Pointwise cross sections available for reactions in H, ^6Li , Ar

The new library

- A new library is in preparation, based on 260 n and 40 γ groups including 30 thermal groups at different temperatures and different self-shielding

Other features

Gamma Generation

- In general, gamma generation by low energy neutrons (but not gamma transport) is treated also in the frame of a multigroup scheme
- A downscattering matrix provides the probability, for a neutron in a given energy group, to generate a photon in each of 22 gamma energy groups, covering the range from 10 keV to 20 MeV.
- The actual energy of the photon is sampled randomly in the energy interval corresponding to its gamma group. With the exception of a few important gamma lines, such as the 2.2 MeV transition of Deuterium and the 478 keV photon from $^{10}B(n,\gamma)$ reaction, all ^{40}Ar lines, and the capture lines for Cd and Xe
- The gamma generation matrix apart from capture gammas, includes also gammas produced by other inelastic reactions such as (n,n')

Residual Nuclei

- For many materials (not for all), group-dependent information on the residual nuclei produced by low-energy neutron interactions is available in the FLUKA library
- This information can be used to score residual nuclei, but the user must check its availability before requesting scoring