The FLUKA code: new developments and application to 1 GeV/n Iron beams

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H.Aiginger[8], V.Andersen[3], F.Ballarini[2], G.Battistoni[1], M.Campanella[1], M.Carboni[10], F.Cerutti[1], A.Empl[3], W.Enghardt[7], A.Fassò[4], A.Ferrari[0,$], E.Gadioli[1], M.V.Garzelli[1,3], K.Lee[3], A.Ottolenghi[2], K.Parodi[7], M.Pelliccioni[10], L.Pinsky[3], J.Ranft[5], S.Roesler[0], P.R.Sala[1], D.Scannicchio[2], G.Smirnov[6], F. Sommerer[7,8], T.Wilson[9], N.Zapp[9]

[0] CERN, Geneva, Switzerland
[1] University of Milan and INFN, Italy
[2] University of Pavia and INFN, Italy
[3] Houston University, Texas, USA
[4] SLAC, Stanford, USA
[5] Siegen University, Germany
[6] JINR, Dubna, Russia
[7] Forschungszentrum Rossendorf (Dresden), Germany
[8] Vienna University of Technology, Austria
[9] NASA/JSC, USA
[10] Laboratori Nazionali di Frascati, INFN, Italy
[$] On leave from INFN Milan

FLUKA

Authors: **A. Fassò[†], A. Ferrari[&], J. Ranft[*], P.R. Sala[#]**

Interaction and Transport MonteCarlo code

Hadrons, leptons, (incl. ν), photons, heavy ions, low energy neutrons from thermal or few keV to cosmic ray energies

- Each component is treated as far as possible with the same accuracy
- All components in a single run, without intermediate steps.
- FLUKA can be run in fully analog mode. Its *microscopic* interaction models reproduce internal correlations.
- It can also be run in biased mode
- Ion interactions based on DPMJET-III[1] *(New!!)* and a considerably improved version of rQMD-2.4[2]

[1] S.Roesler, R,Engel, J.Ranft, Proc. MC2000 Conf., 1033, Springer-Verlag (2001)
[2] PRC52 3291 (1995), Ann. Phys. 192 266 (1989), NPA498 567c (1989)

http://www.fluka.org

FLUKA Topics

Descriptions of FLUKA models and extensive benchmarking can be found in the literature (see the web page)

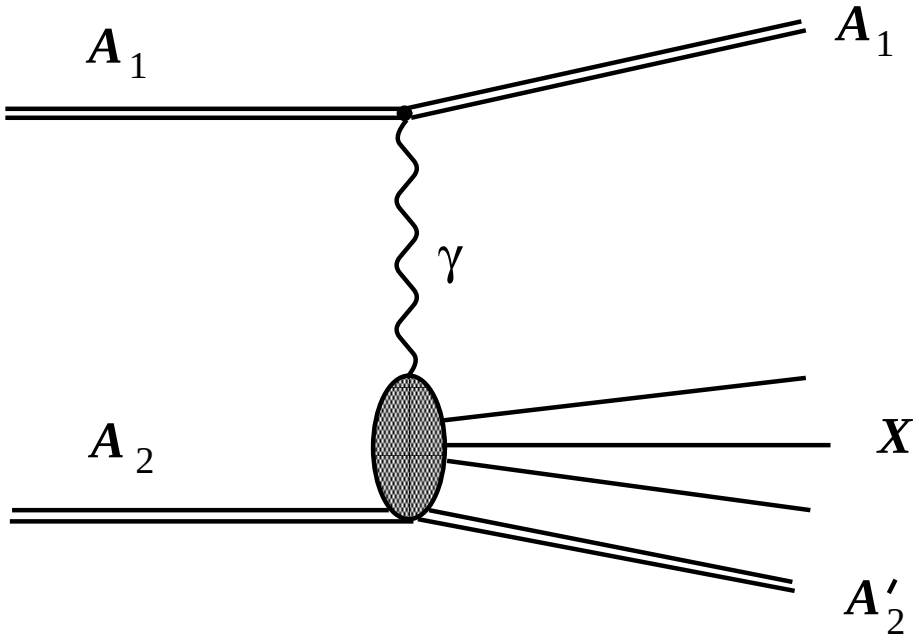
A few recent, (ion-related) developments will be presented here

- Physics: Electromagnetic Dissociation and several fragmentation benchmarks
- Application: preliminary results for therapeutic beams
- Application: a few quantities computed for 1 GeV/n Iron beams on different materials

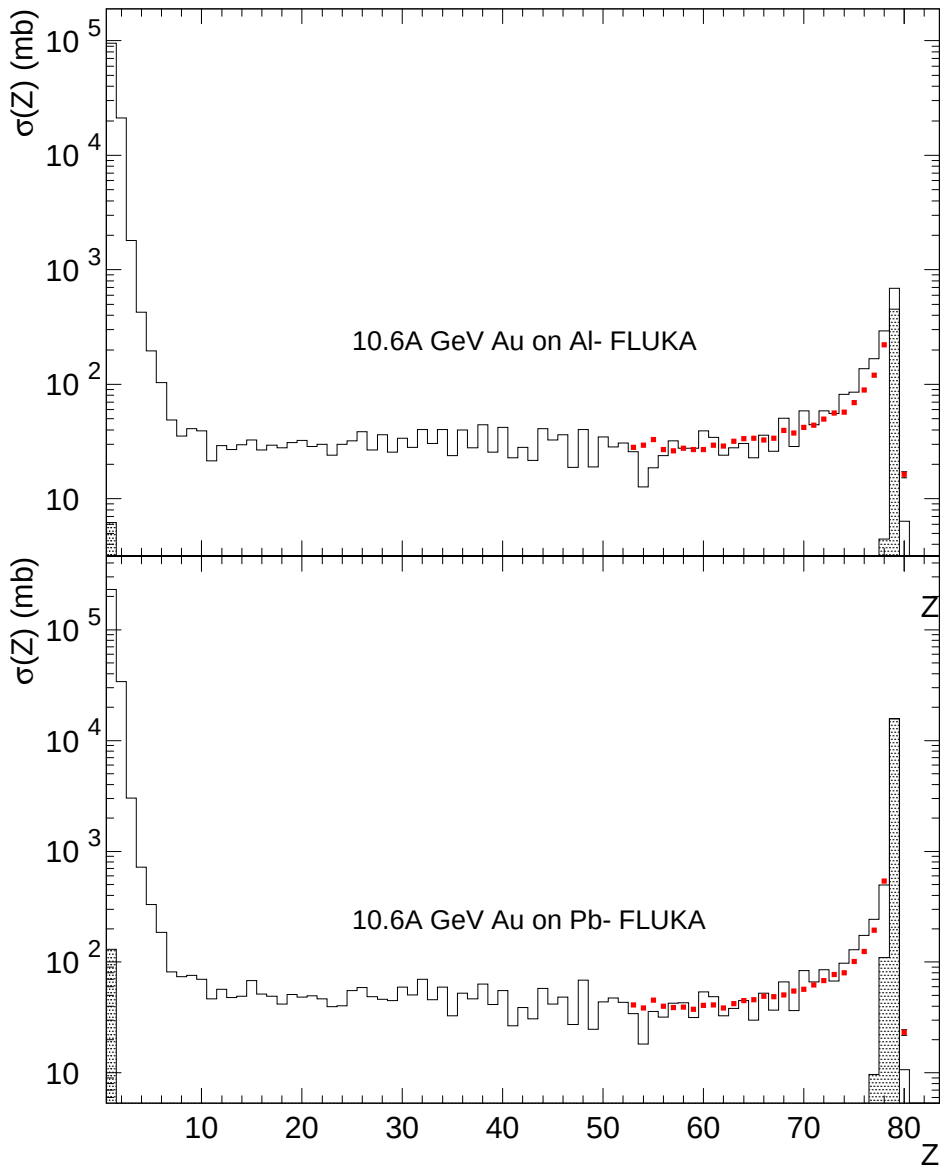
Electromagnetic Dissociation

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

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

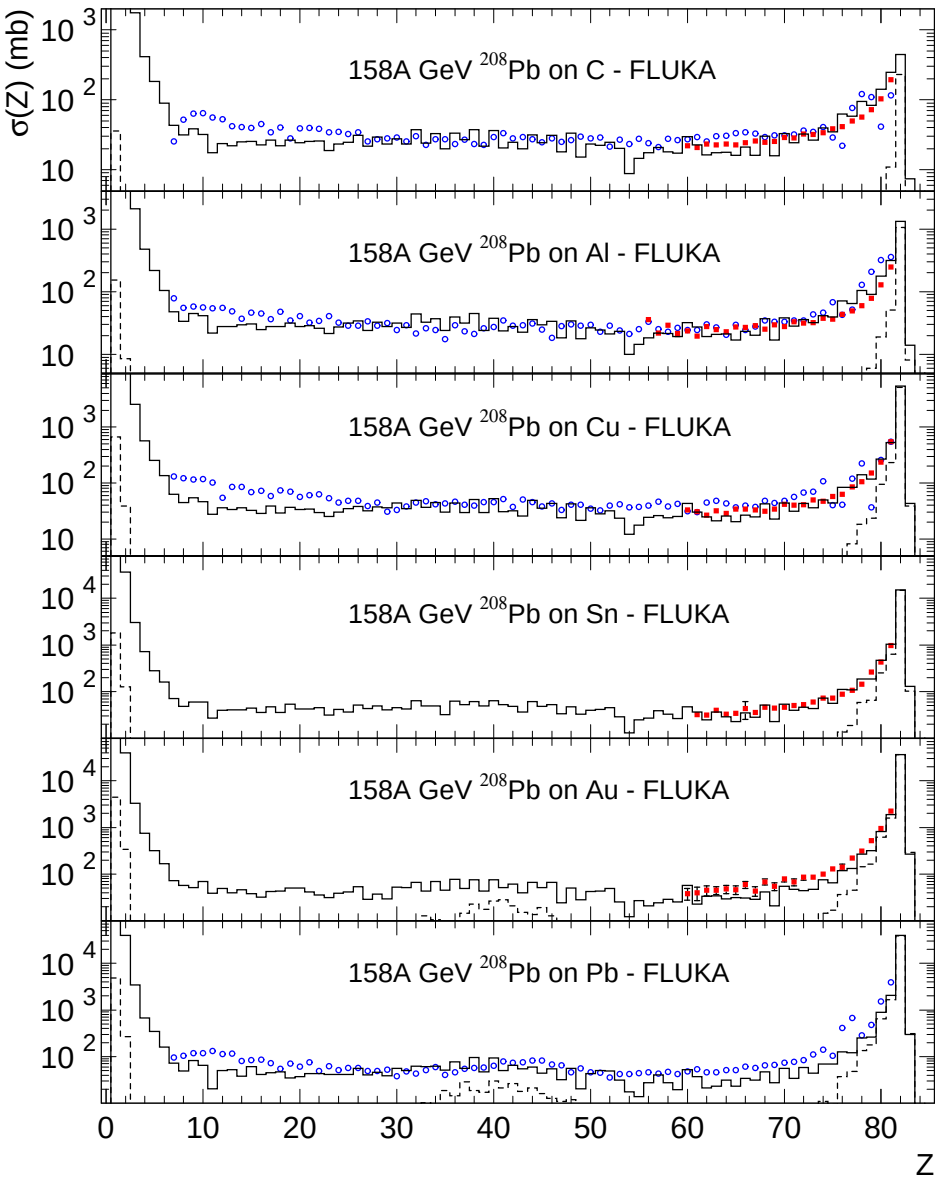


10.6 GeV/n fragmentation

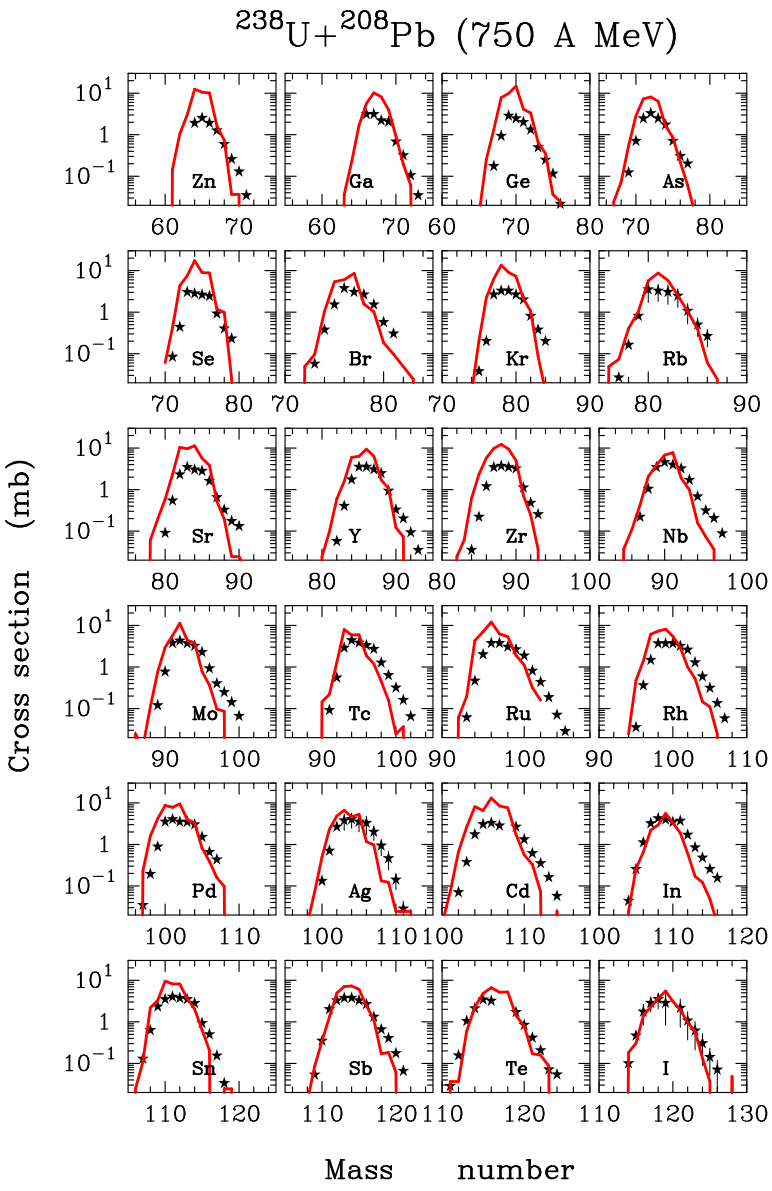


Fragment charge cross sections for 10.6 AGeV Au ions on Aluminium and Lead. Data (symbols) from PRC52, 334 (1995), histos are FLUKA (with DPMJET-III) predictions: the hatched histo is the electromagnetic dissociation contribution

158 GeV/n fragmentation

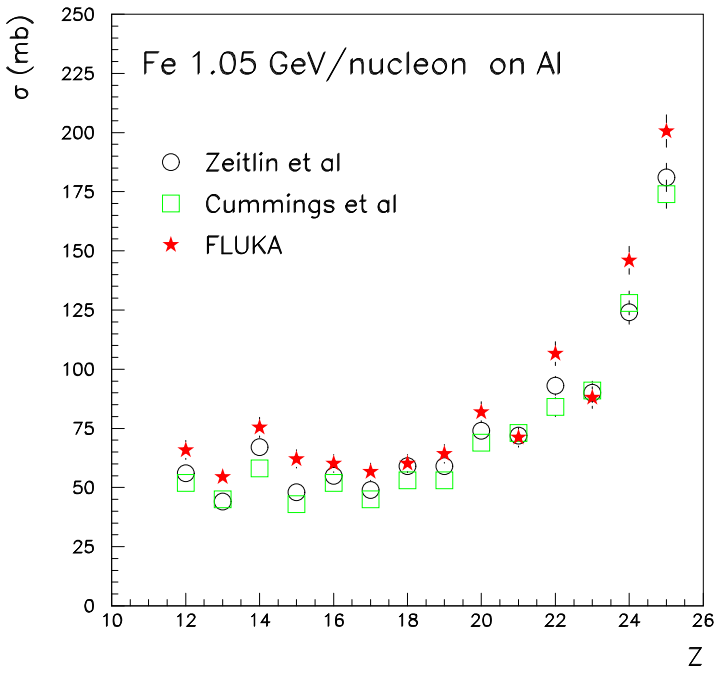


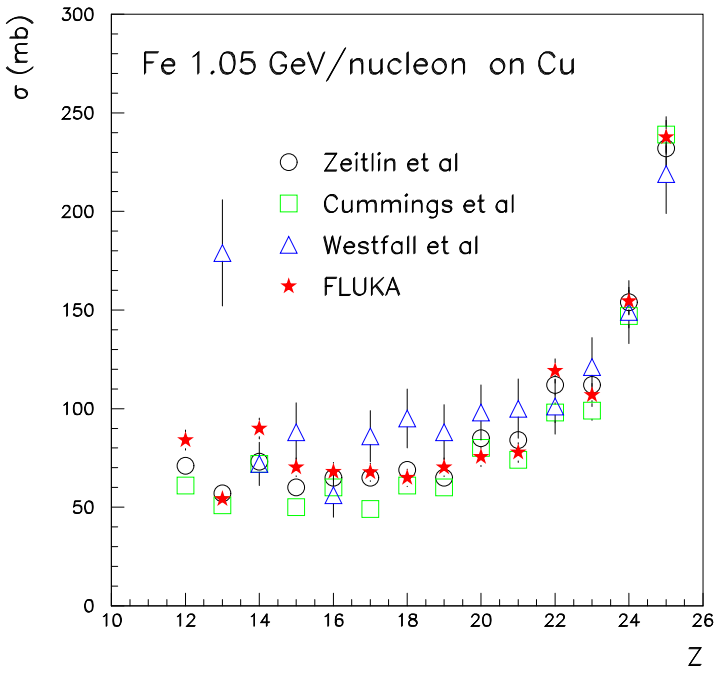
Fragment charge cross sections for 158 AGeV Pb ions on various targets. Data (symbols) from NPA662, 207 (2000), NPA707, 513 (2002) (blue circles) and from C. Scheidenberger et al PRC, in press (red squares), histos are FLUKA (with DPMJET-III) predictions: the dashed histo is the electromagnetic dissociation contribution



Fragment charge cross sections for 750 MeV/n U ions on Pb. Data (stars) from J. Benlliure, P. Armbruster et al. Eur. Phys. J A 2, 193-198 (1998). Fission products have been excluded like in the experimental analysis.

FLUKA - fragmentation results





Fragment charge cross sections for 1.05 GeV/n Fe ions on Al (left) and Cu (right). stars FLUKA, circles PRC56 (1997) 388, squares PRC42 (1990) 5208 (at 1.5 GeV/n), triangles PRC19 (1979) 1309 (at 1.88 GeV/n).

FLUKA - fragmentation of therapeutic beams

Experiment:

- ^{12}C, ^{14}N and ^{16}O at $\approx$ 675 AMeV
- adjustable water column (0–25.5 cm)
- Z spectra of escaping particles (I. Schall et al, NIM B 117 (1996) 221)

Simulation:

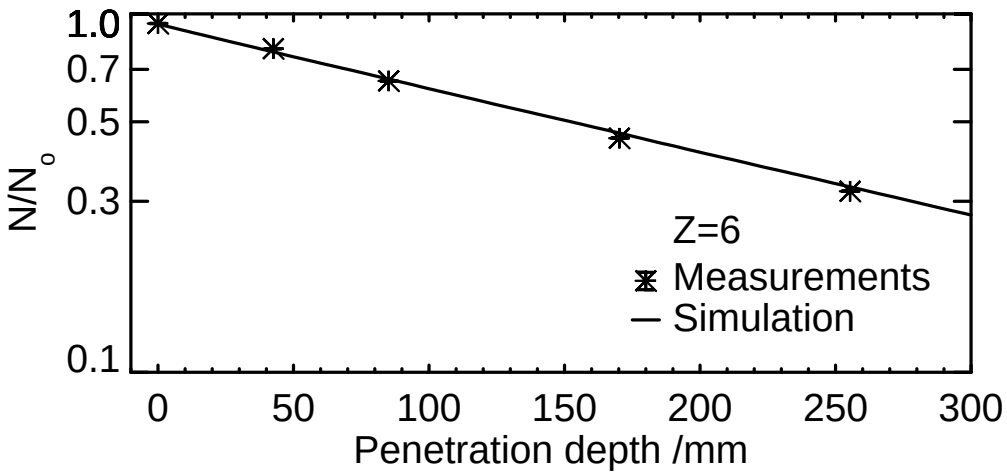
- 25.5 cm long water phantom
- Calculation of particle fluence in slices perpendicular to the beam axis
- All studies carried out by F. Sommerer[1,2], K. Parodi[1], W. Enghardt[1], H. Aiginger[2],
  [1] Forschungszentrum Rossendorf (Dresden), [2] Vienna University of Technology

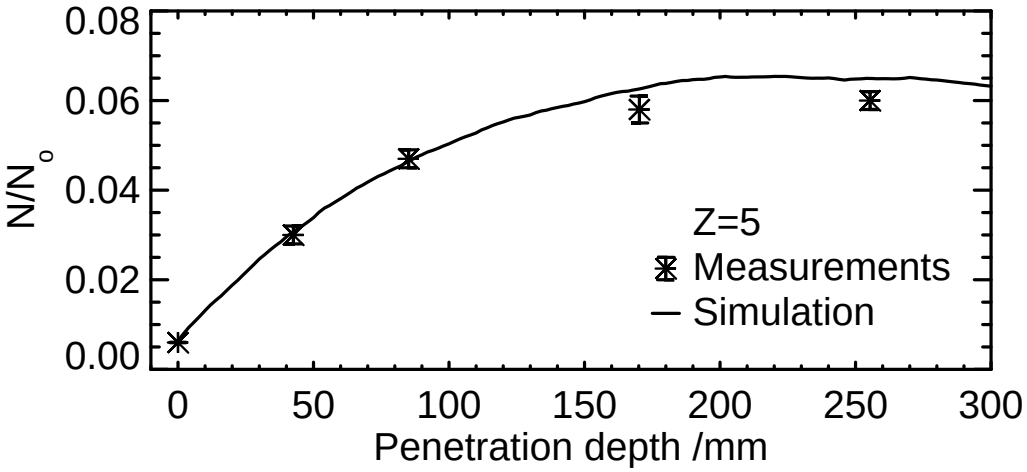
Preliminary results

Work in progress for better validation of FLUKA:

- Production rate of Z $\leq$ 4
- More realistic modelling of the setup
- (Final goal) Prediction of β^+ emitting nuclei generated during the irradiation for in-situ treatment plan verification by means of PET

FLUKA - fragmentation of therapeutic beams, ^{12}C

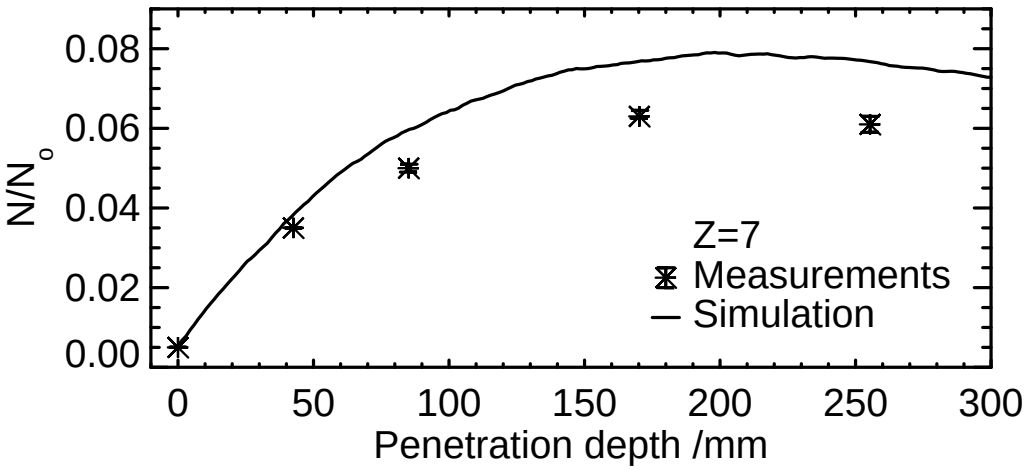


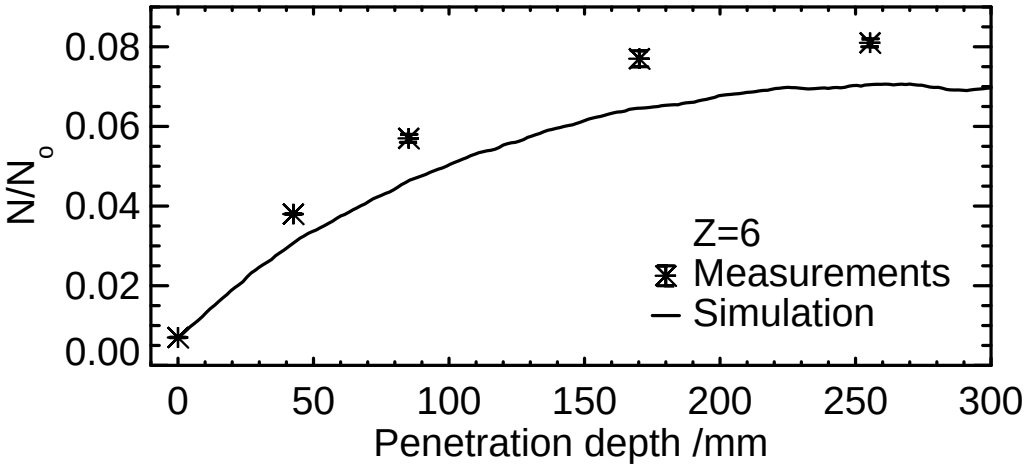


Top: Carbon ion intensity as a function of depth

Bottom: Boron ion intensity as a function of depth

FLUKA - fragmentation of therapeutic beams, ^{16}O





Top: Nitrogen ion intensity as a function of depth

Bottom: Carbon ion intensity as a function of depth

1 GeV/n Fe ions

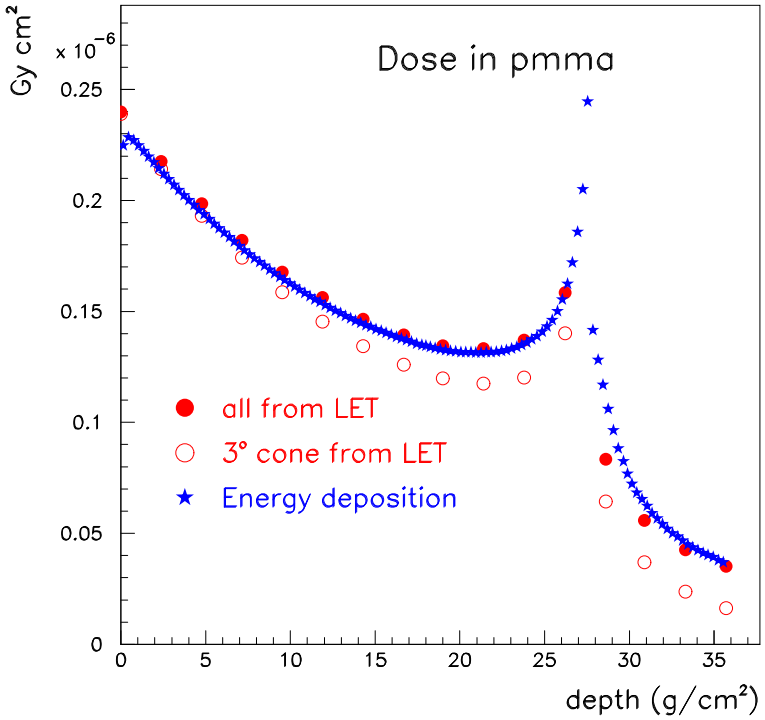
Simulated setups:

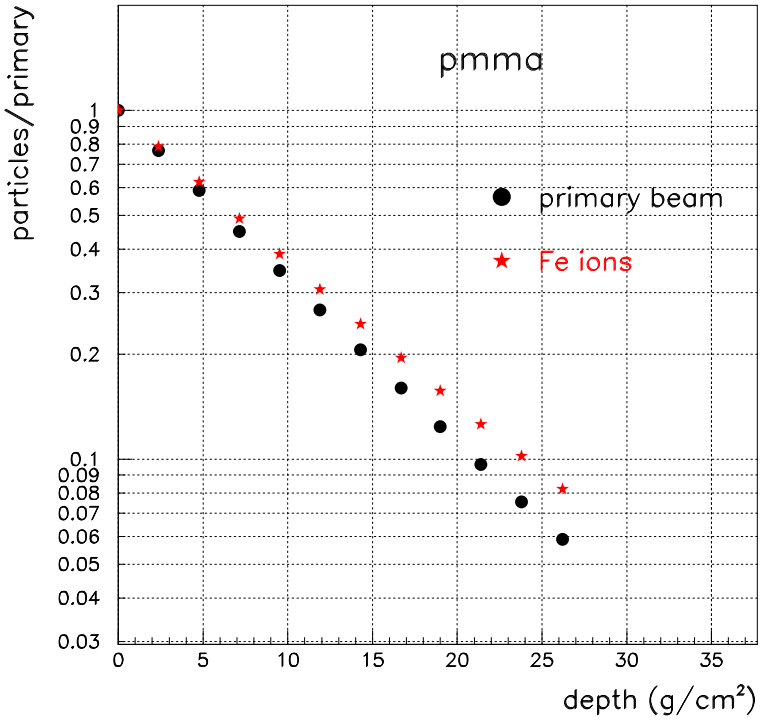
- "Ideal case": infinite uniform and parallel 1 GeV/n Fe beam, spectra, doses and LET's per unit fluence
- Two "real" cases, PMMA (23 g/cm^2), and Al (7 g/cm^2)
  - 1 GeV/n Fe ions with 2 MeV/n FWHM, 5 mrad divergence, 7 cm radius and intensity 85% at R=7 cm, or
  - ... 1 GeV/n Fe ion pencil beam
  - Si detectors (3 or 5 mm thick) in the positions indicated by J. Miller

obtaining:

- Fragment spectra
- Energy deposition (dose)
- LET-derived dose $D_L = \int \mathrm{d}L \cdot L \cdot n(L)/\cos(\theta)$
- Track-average LET $L_T = \int \mathrm{d}L \cdot L \cdot f(L)$
- Dose-average LET $L_D = \int \mathrm{d}L \cdot L^2 \cdot f(L)/L_T$
- Energy deposition spectra in Si

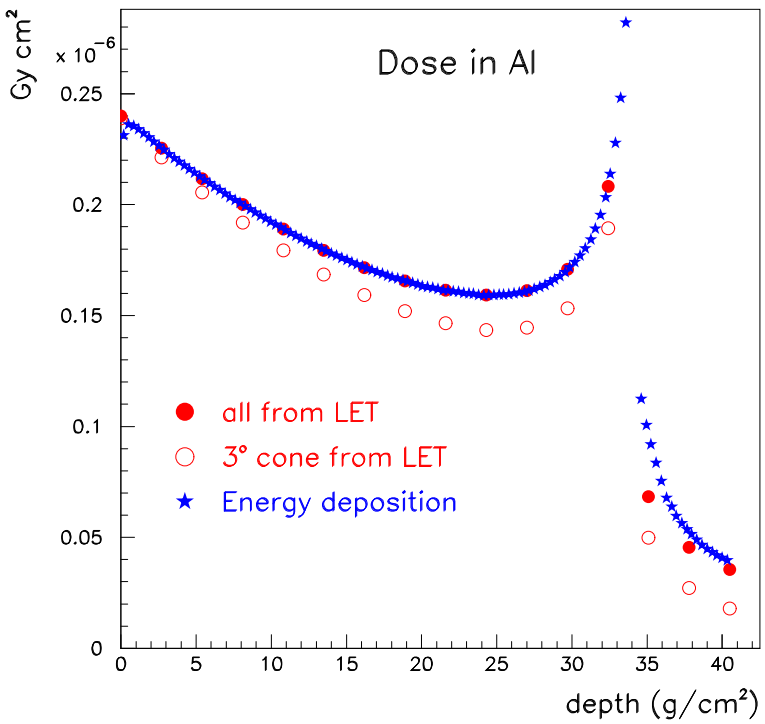
FLUKA - 1 GeV/n Fe "perfect beam" on PMMA

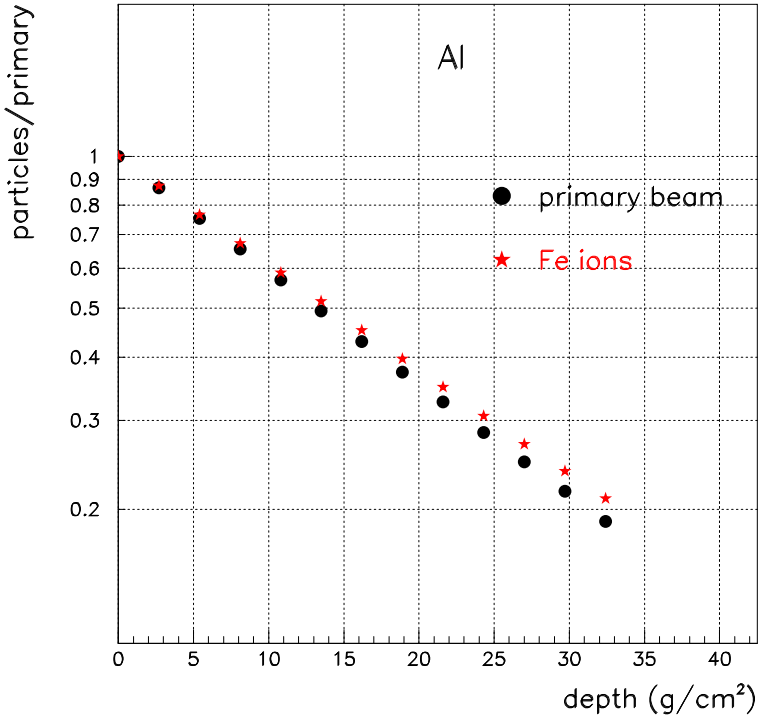




Left: absorbed dose as a function of depth in PMMA ("true" and as derived from the charged particle LET)
Right: uncollided ("primary") and Z=26 ion survival in PMMA

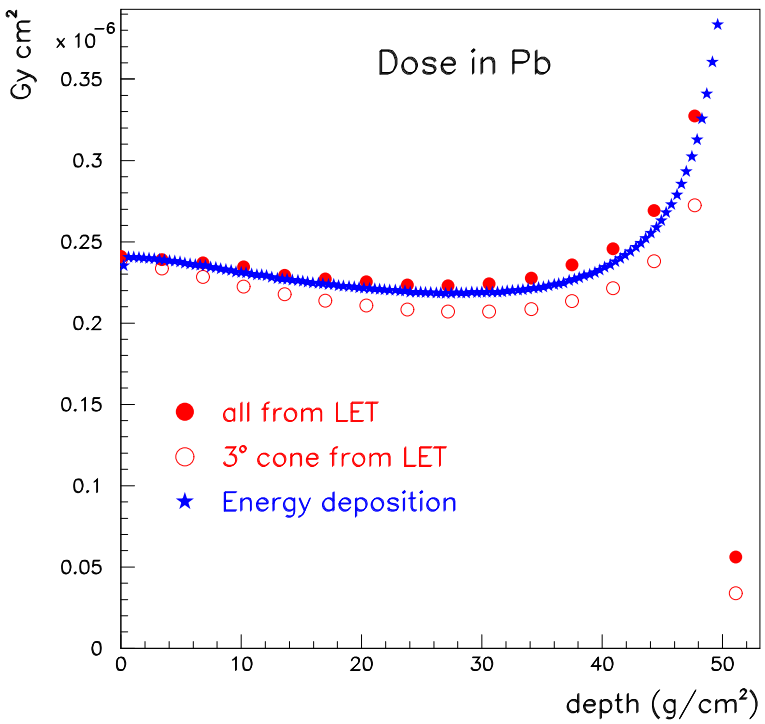
FLUKA - 1 GeV/n Fe "perfect beam" on Al

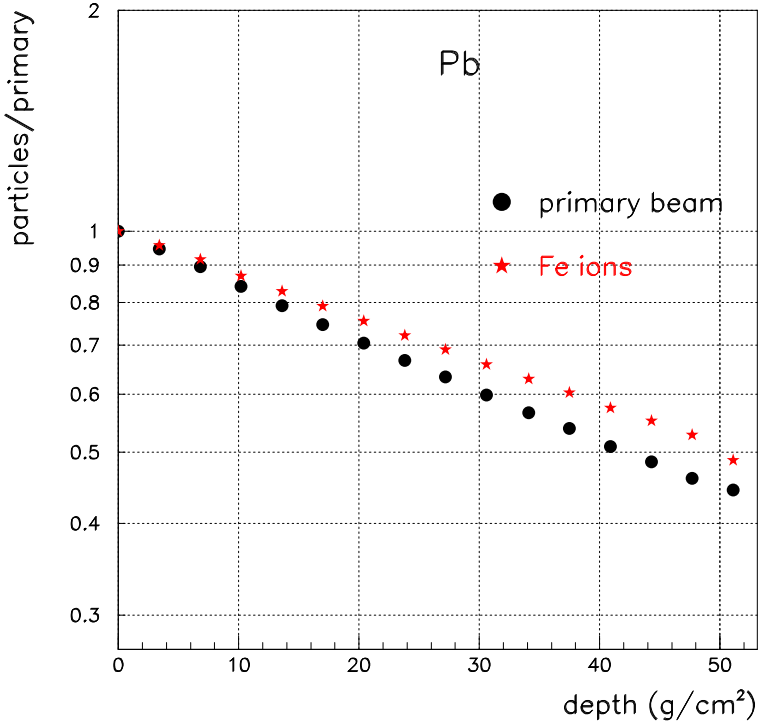




Left: absorbed dose as a function of depth in Aluminium ("true"x1.26 and as derived from the charged particle LET)
Right: uncollided ("primary") and Z=26 ion survival in Aluminium

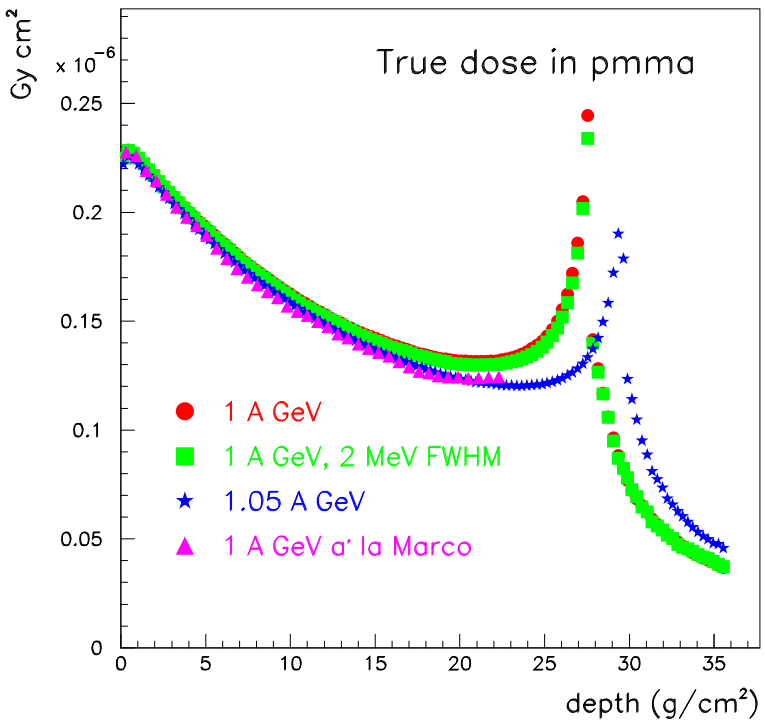
FLUKA - 1 GeV/n Fe "perfect beam" on Pb

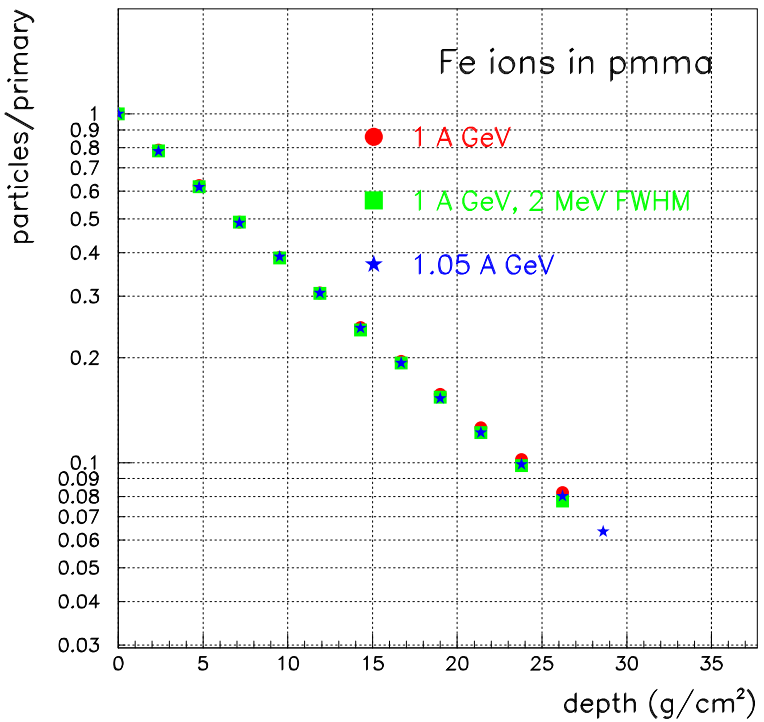




Left: absorbed dose as a function of depth in Lead ("true"x1.86 and as derived from the charged particle LET)
Right: uncollided ("primary") and Z=26 ion survival in Lead

FLUKA - 1 GeV/n Fe beam parameters - PMMA

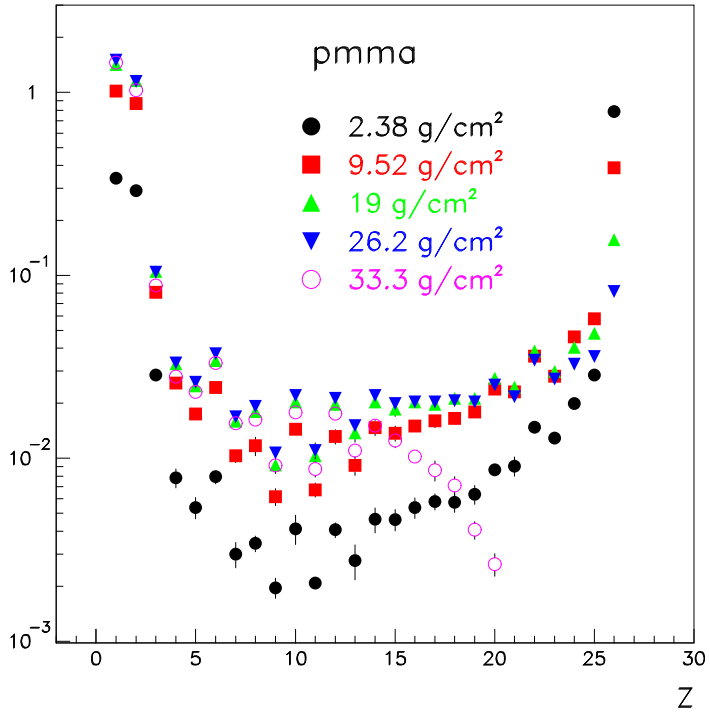


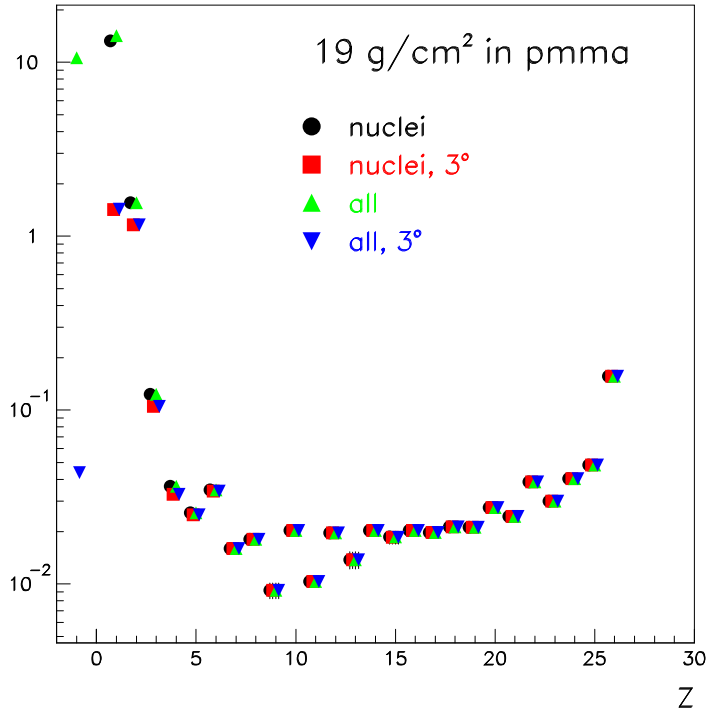


Left: absorbed dose as a function of depth in PMMA for a parallel Fe beam of 1 GeV/n (no spread), 1 GeV/n (2 MeV/n FWHM), 1.05 GeV/n (2 MeV/n FWHM) 1 GeV/n, "real" target, à la Marco

Right: Z=26 ion survival in PMMA for a parallel Fe beam of 1 GeV/n (no spread), 1 GeV/n (2 MeV/n FWHM), 1.05 GeV/n (2 MeV/n FWHM)

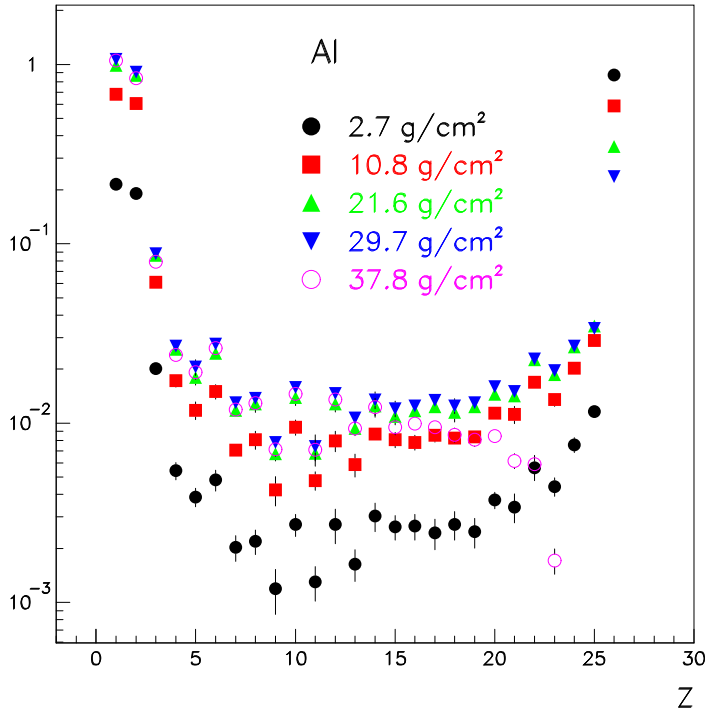
FLUKA - 1 GeV/n Fe "perfect beam" on PMMA

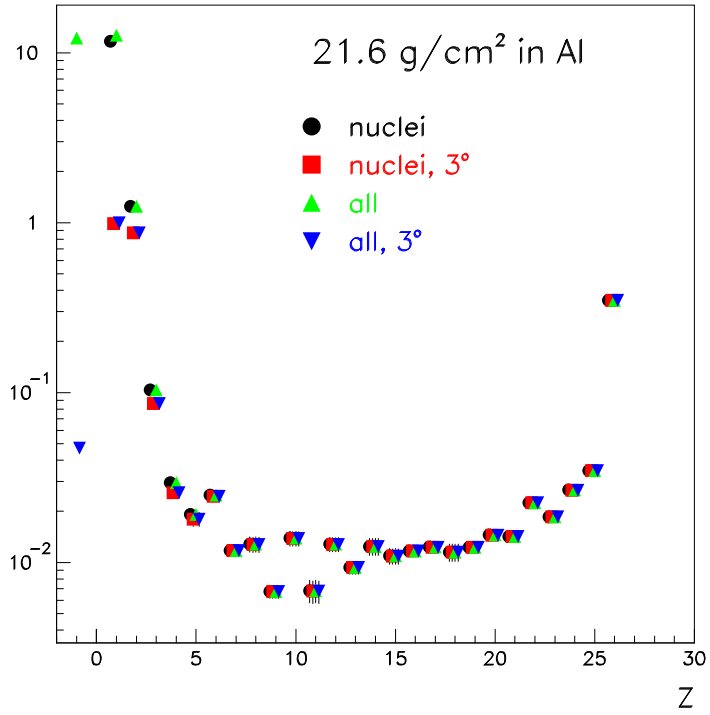




Left: fragment spectra as a function of depth in PMMA (nuclei only, 3^o cone)
Right: fragment spectra at 19 g/cm^2 in PMMA for all charged, nuclei only, and with or without a 3^o cut

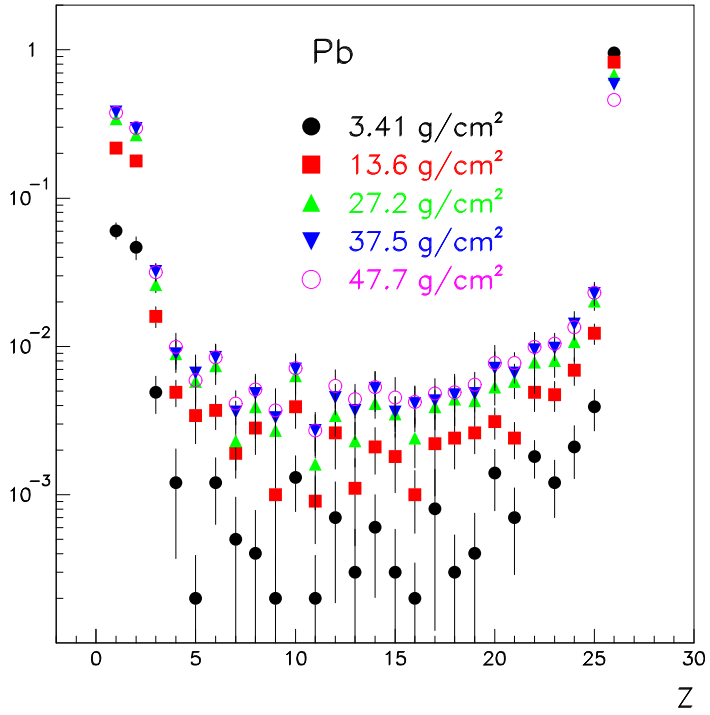
FLUKA - 1 GeV/n Fe "perfect beam" on Al

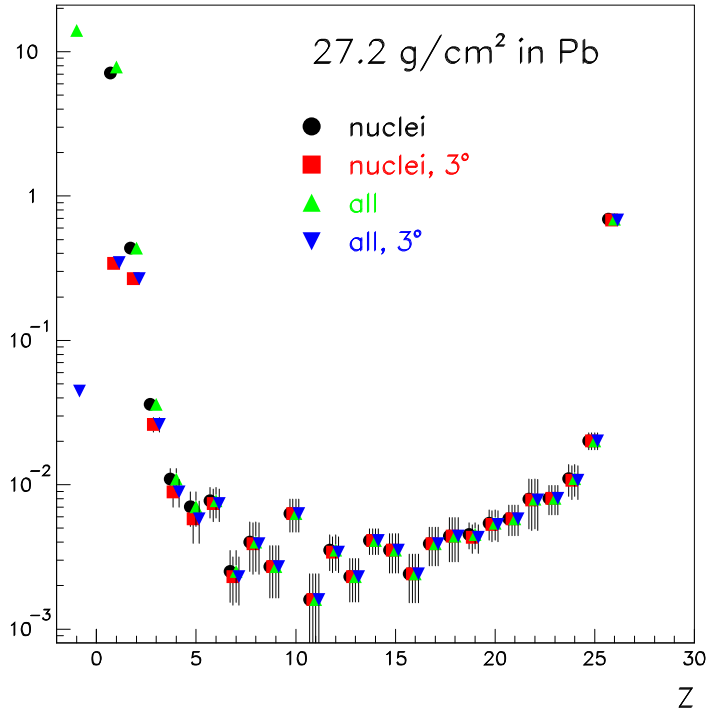




Left: fragment spectra as a function of depth in Aluminium (nuclei only, 3^o cone)
Right: fragment spectra at 21.6 g/cm^2 in Aluminium for all charged, nuclei only, and with or without a 3^o cut

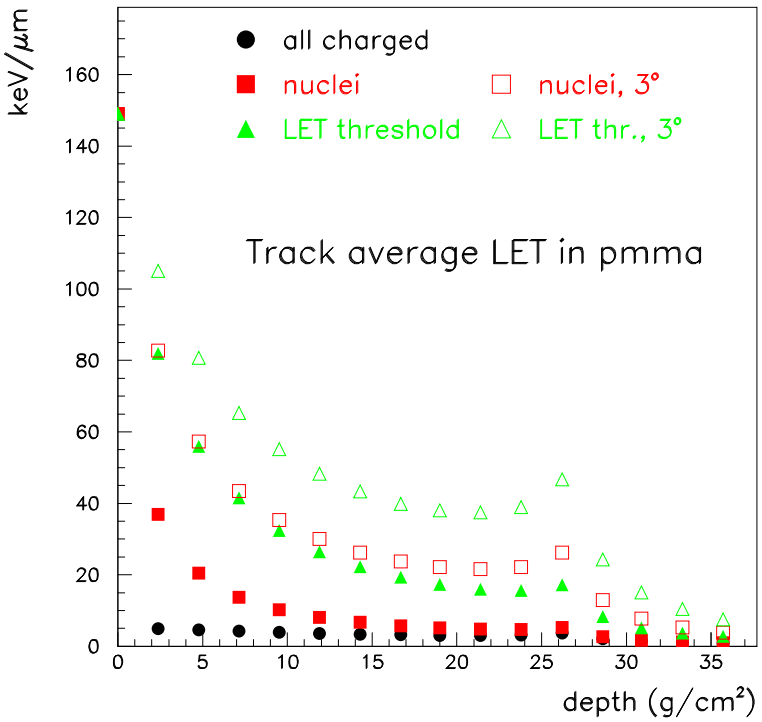
FLUKA - 1 GeV/n Fe "perfect beam" on Pb

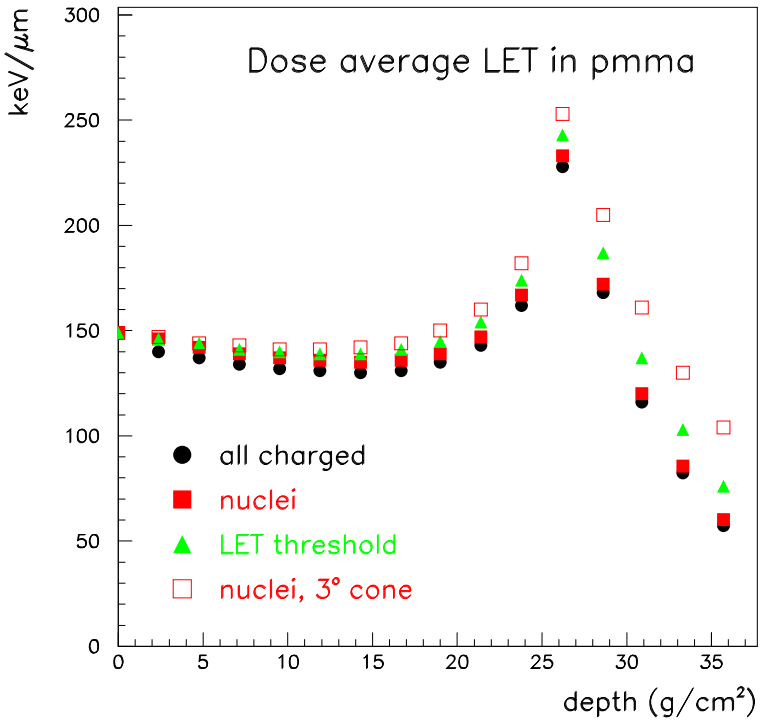




Left: fragment spectra as a function of depth in Lead (nuclei only, 3^o cone)
Right: fragment spectra at 27.2 g/cm^2 in Lead for all charged, nuclei only, and with or without a 3^o cut

FLUKA - 1 GeV/n Fe "perfect beam" on PMMA

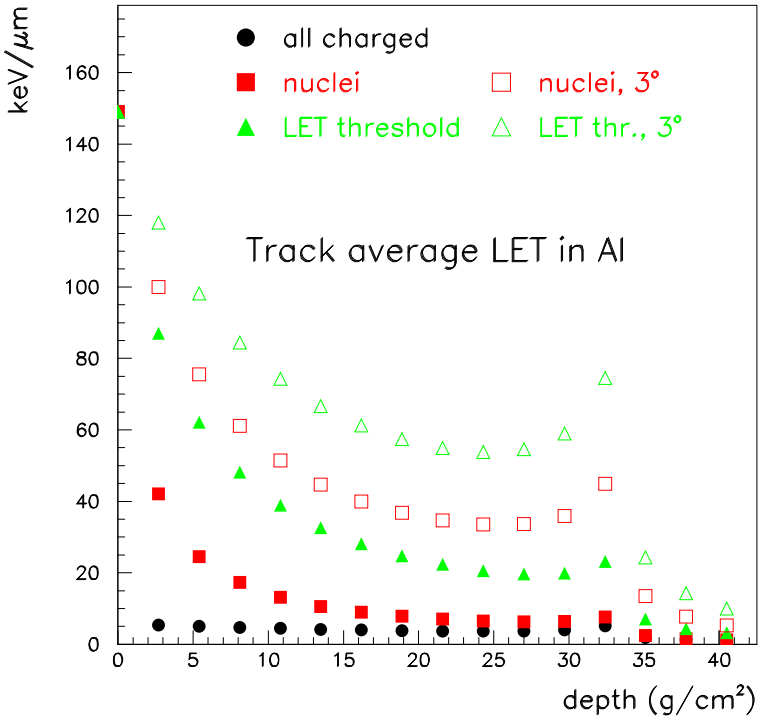


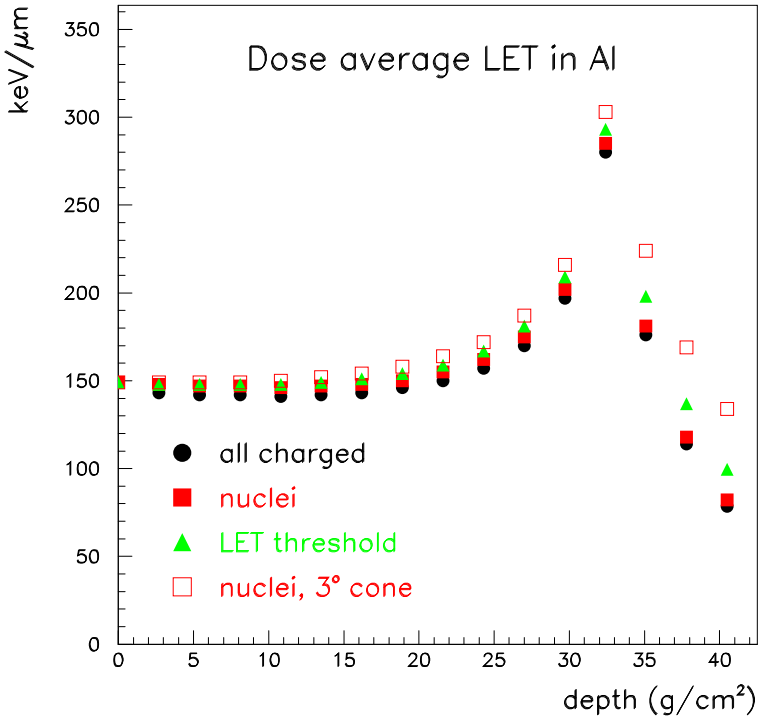


Left: track-average LET as a function of depth in PMMA ("true", nuclei only, restricted to a 3^o cone, with and w/o a cut corresponding to electron elimination)

Right: dose-average LET as a function of depth in PMMA ("true", with and w/o a cut roughly corresponding to electron elimination, nuclei only with and w/o a 3^o cone restriction)

FLUKA - 1 GeV/n Fe "perfect beam" on Al

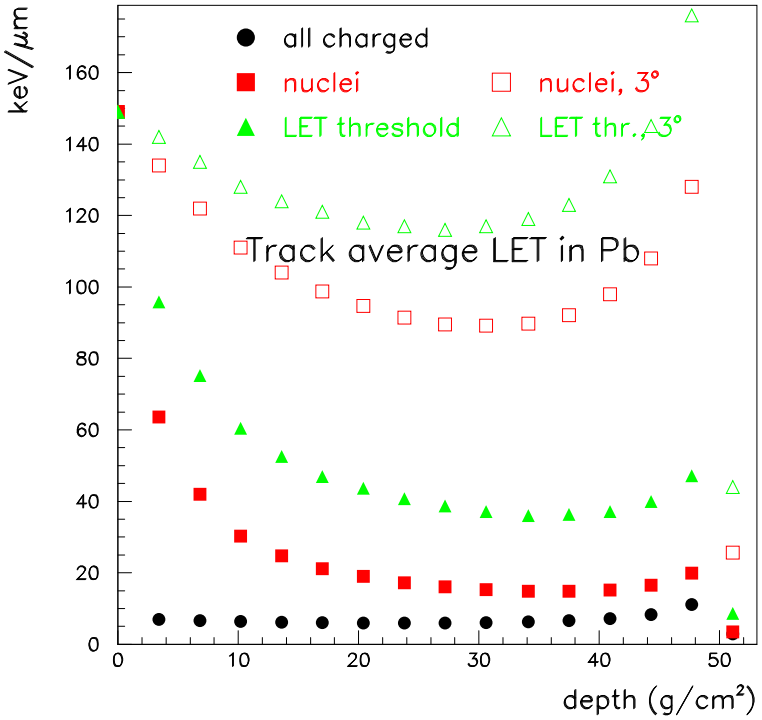


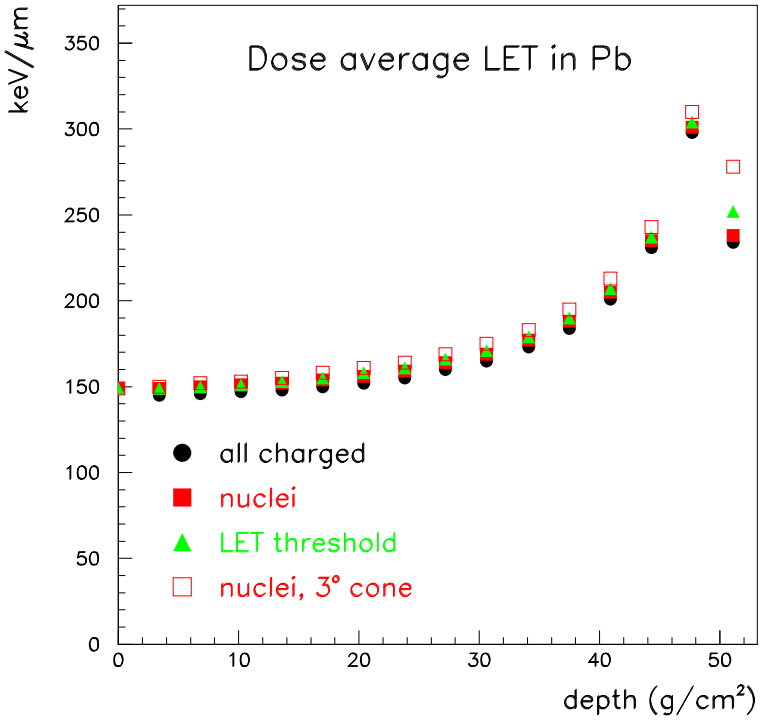


Left: track-average LET as a function of depth in Al. ("true", nuclei only, restricted to a 3^o cone, with and w/o a cut corresponding to electron elimination)

Right: dose-average LET as a function of depth in Al. ("true", with and w/o a cut roughly corresponding to electron elimination, nuclei only with and w/o a 3^o cone restriction)

FLUKA - 1 GeV/n Fe "perfect beam" on Pb

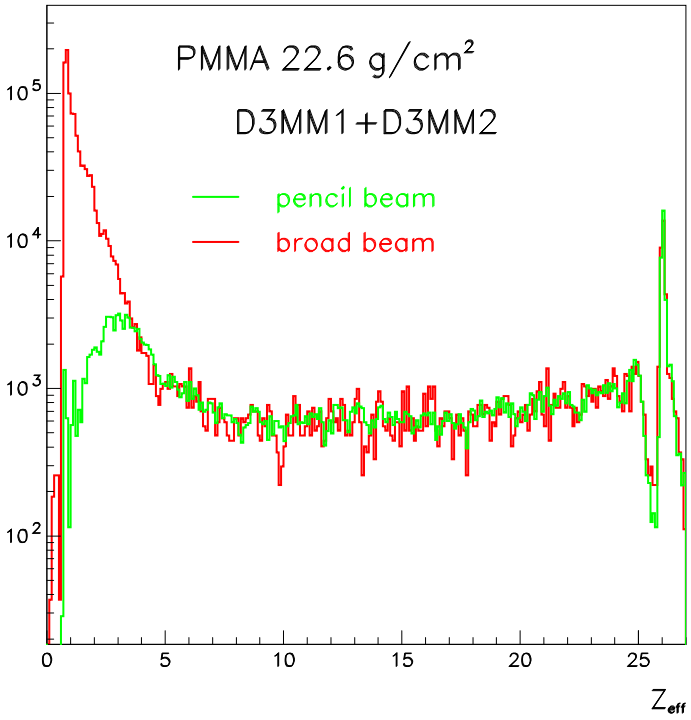


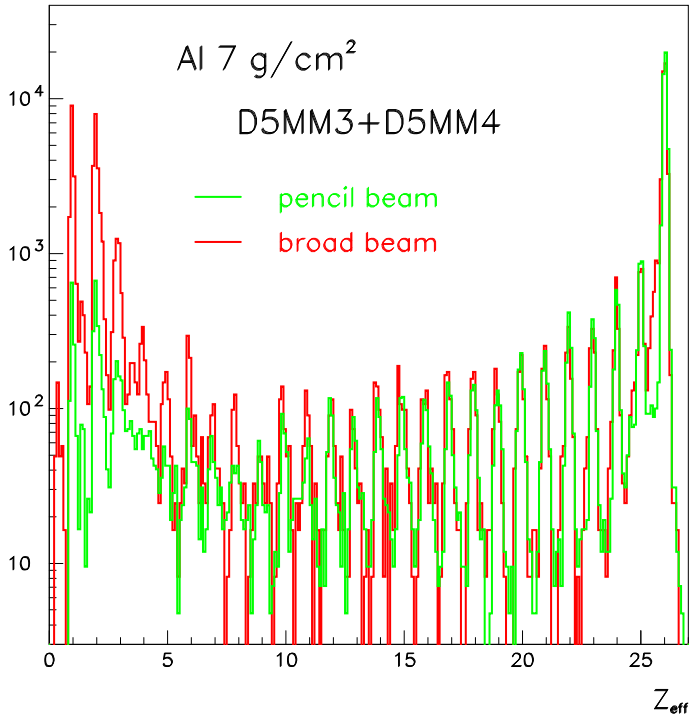


Left: track-average LET as a function of depth in Lead ("true", nuclei only, restricted to a 3^o cone, with and w/o a cut corresponding to electron elimination)

Right: dose-average LET as a function of depth in Lead ("true", with and w/o a cut roughly corresponding to electron elimination, nuclei only with and w/o a 3^o cone restriction)

FLUKA - 1 GeV/n Fe, "real" cases





$Z_{eff} = 26 \times \sqrt{\Delta E / \Delta E_{peak}}$ as reconstructed from simulated Si energy deposition events for PMMA (23 g/cm^2, left) and Al (7 g/cm^2, right). The only cut performed requires $\Delta E_{1(3)}$ and $\Delta E_{2(4)}$ consistent within 30%. Calculations for nominal (R=7 cm) and pencil beams are shown, normalized to the same Z=26 peak integral

FLUKA - 1 GeV/n Fe, "real" cases

Det.	Track-average LET (keV/μm)						Dose-average LET (keV/μm)					
1	5.1	6.6	29	51	45	17	161	162	171	178	174	163
2	5.3	6.9	30	51	47	17	167	169	178	184	182	170
3	9.8	12	31	58	45	13	177	178	188	195	190	163
4	8.8	13	31	61	47	13	186	187	199	208	202	175

Various estimations of Track-average LET and Dose-average LET at silicon detector level for the 23 g/cm^2 case *(Note that the beam is 1 GeV/n, not 1.05!!)*

- From (all) particle counting
- From (nuclei only) particle counting
- From Si en. dep., loose cuts
- From Si en. dep., 45^o "strict" cut among all dets
- From Si en. dep., 45^o "strict" cut among 1-2 or 3-4
- Like the previous one, but assuming the detector has a 100 "pixel-like" granularity

Conclusions

- FLUKA: new/improved ion capabilities
- Good results against fragmentation data over a wide energy range
- First applications for therapy beams
- 1 GeV/n Fe ions: several quantities reported in ideal and "close" to experiment conditions
  - (Relative) contribution of light ions highly sensitive to beam/target/detector geometry
  - For medium/thick targets, meaningful comparisons should be better aimed at raw detector data
  - Track average LET estimations appear hopelessly sensitive to experimental conditions/thresholds

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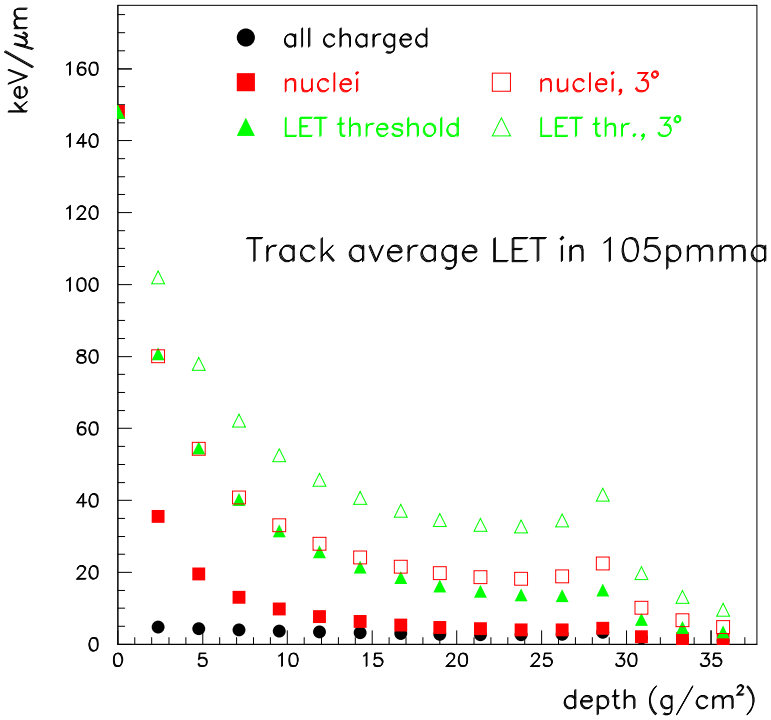
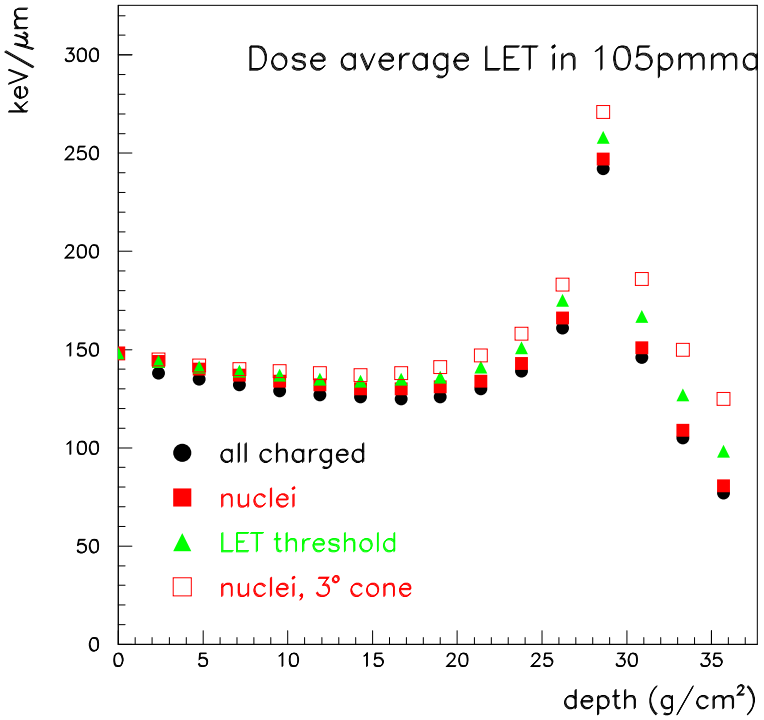
- ASI Contract I/R/320/02
- European Union contract no. FI6R-CT-2003-508842, "RISC-RAD"

1.05 GeV/n Fe, 2 MeV/n FWHM "perfect beam" on PMMA

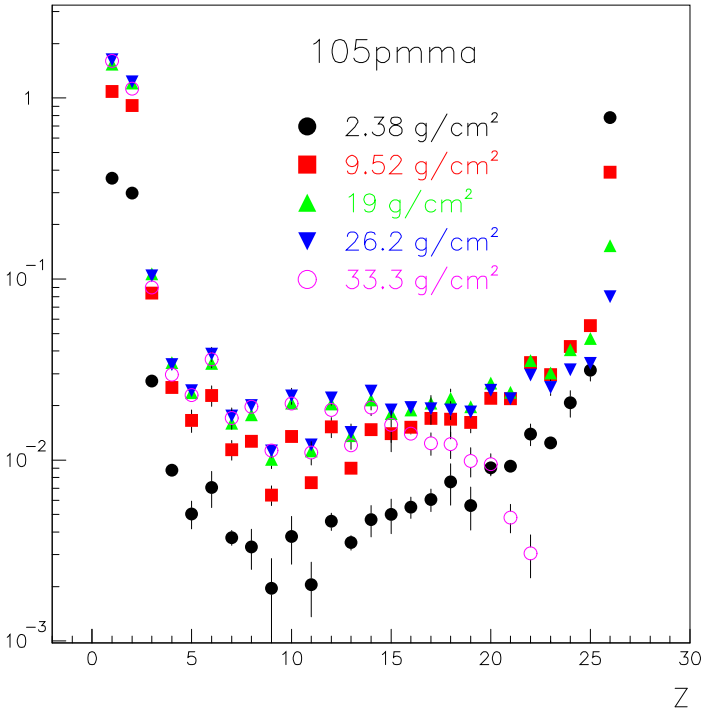


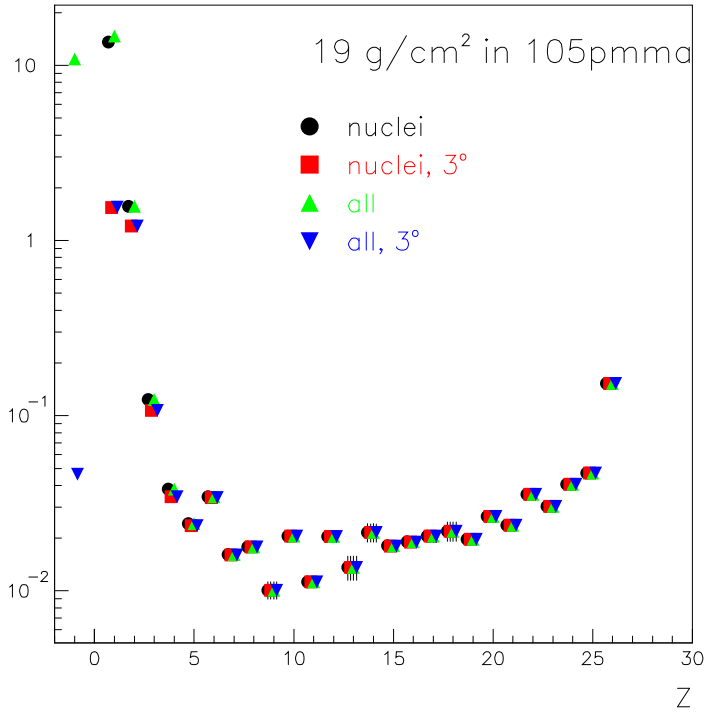


Left: track-average LET as a function of depth in PMMA ("true", nuclei only, restricted to a 3^o cone, with and w/o a cut corresponding to electron elimination)

Right: dose-average LET as a function of depth in PMMA ("true", with and w/o a cut roughly corresponding to electron elimination, nuclei only with and w/o a 3^o cone restriction)

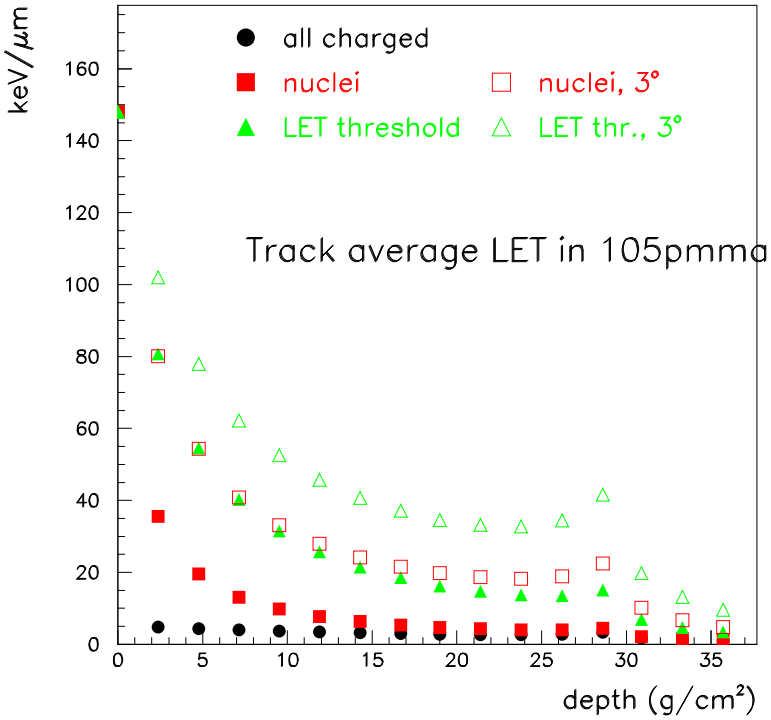
1.05 GeV/n Fe, 2 MeV/n FWHM "perfect beam" on PMMA

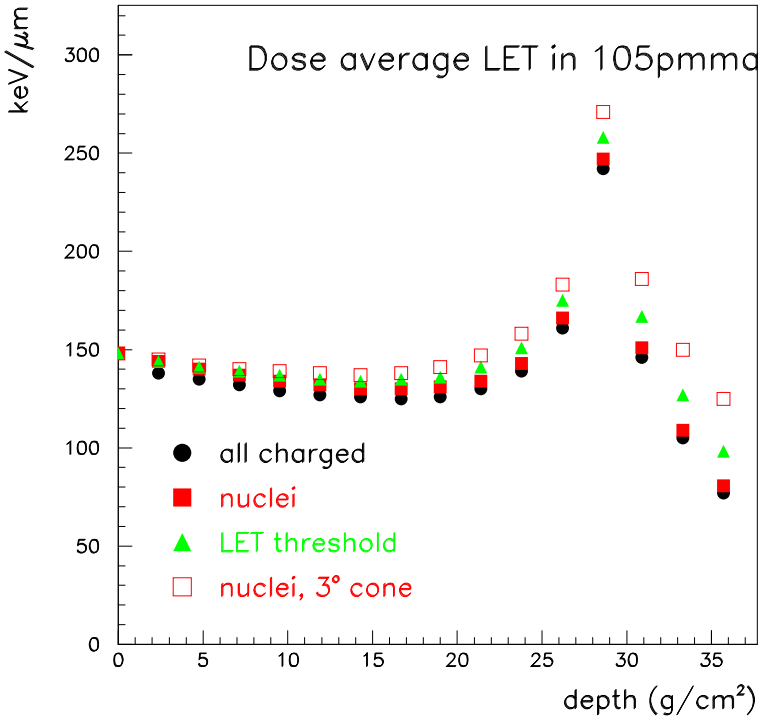




Left: fragment spectra as a function of depth in PMMA (nuclei only, 3^o cone)
Right: fragment spectra at 19 g/cm^2 in PMMA for all charged, nuclei only, and with or without a 3^o cut

1.05 GeV/n Fe, 2 MeV/n FWHM "perfect beam" on PMMA

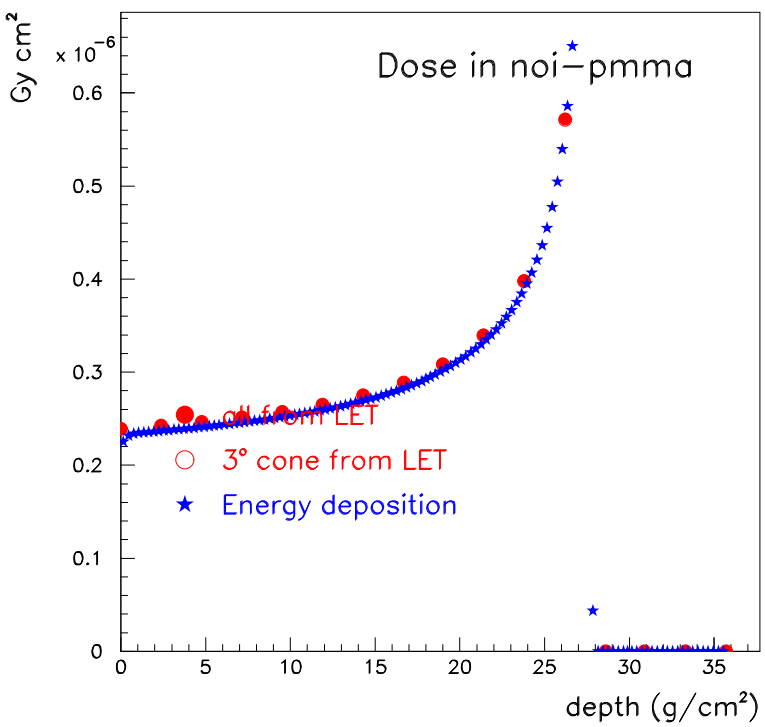


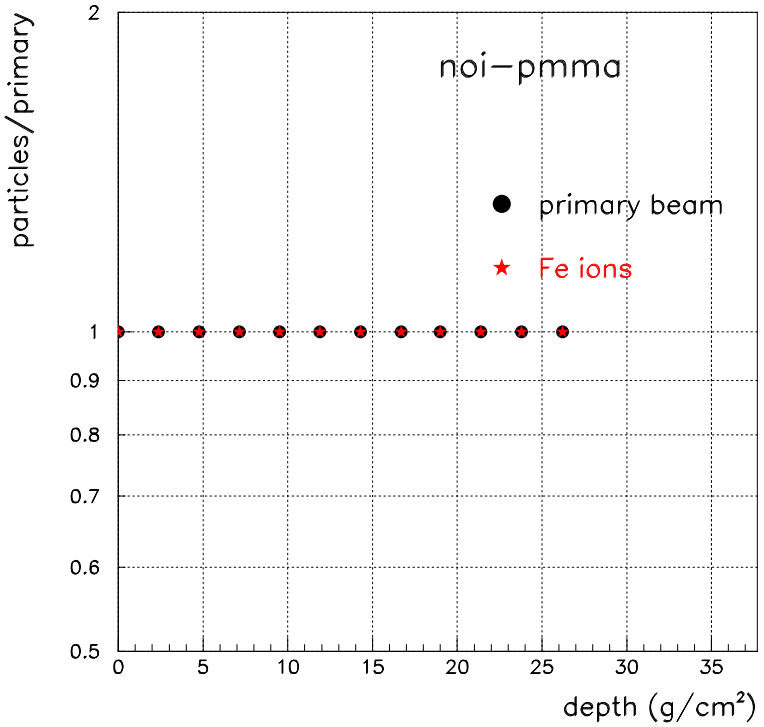


Left: track-average LET as a function of depth in PMMA ("true", nuclei only, restricted to a 3^o cone, with and w/o a cut corresponding to electron elimination)

Right: dose-average LET as a function of depth in PMMA ("true", with and w/o a cut roughly corresponding to electron elimination, nuclei only with and w/o a 3^o cone restriction)

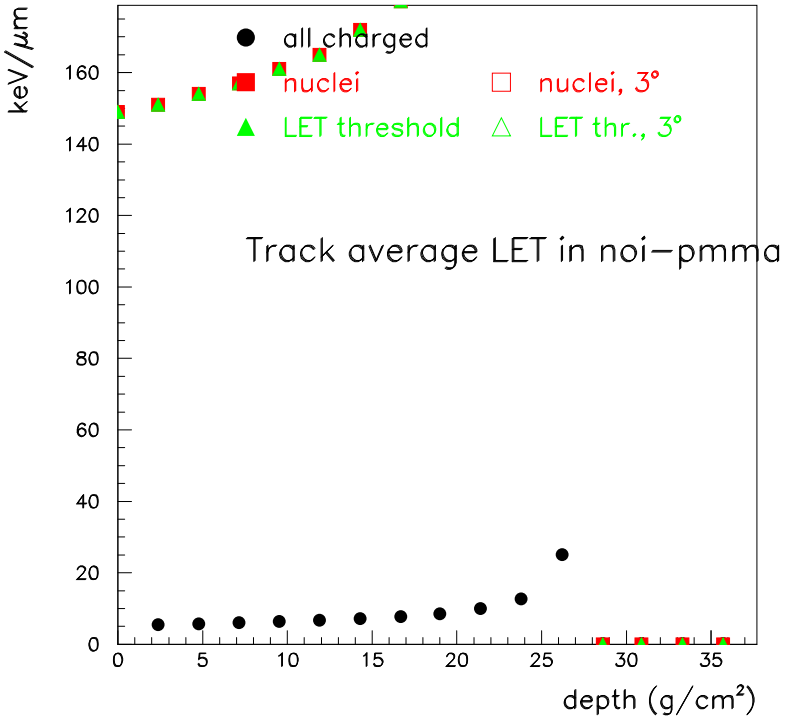
1 GeV/n Fe "perfect beam" on PMMA, no interactions

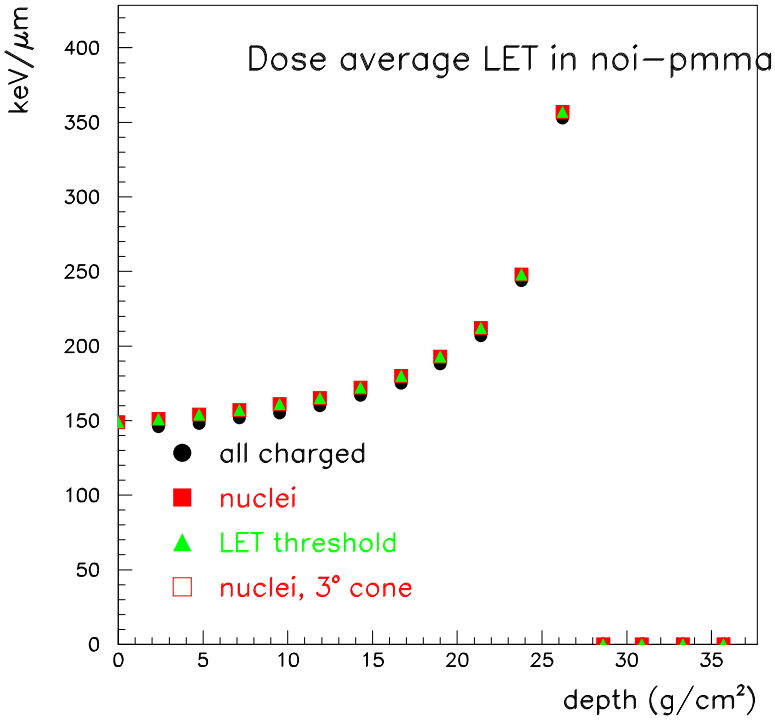




Left: absorbed dose as a function of depth in PMMA ("true" and as derived from the charged particle LET)
Right: uncollided ("primary") and Z=26 ion survival in PMMA

1 GeV/n Fe "perfect beam" on PMMA, no interactions

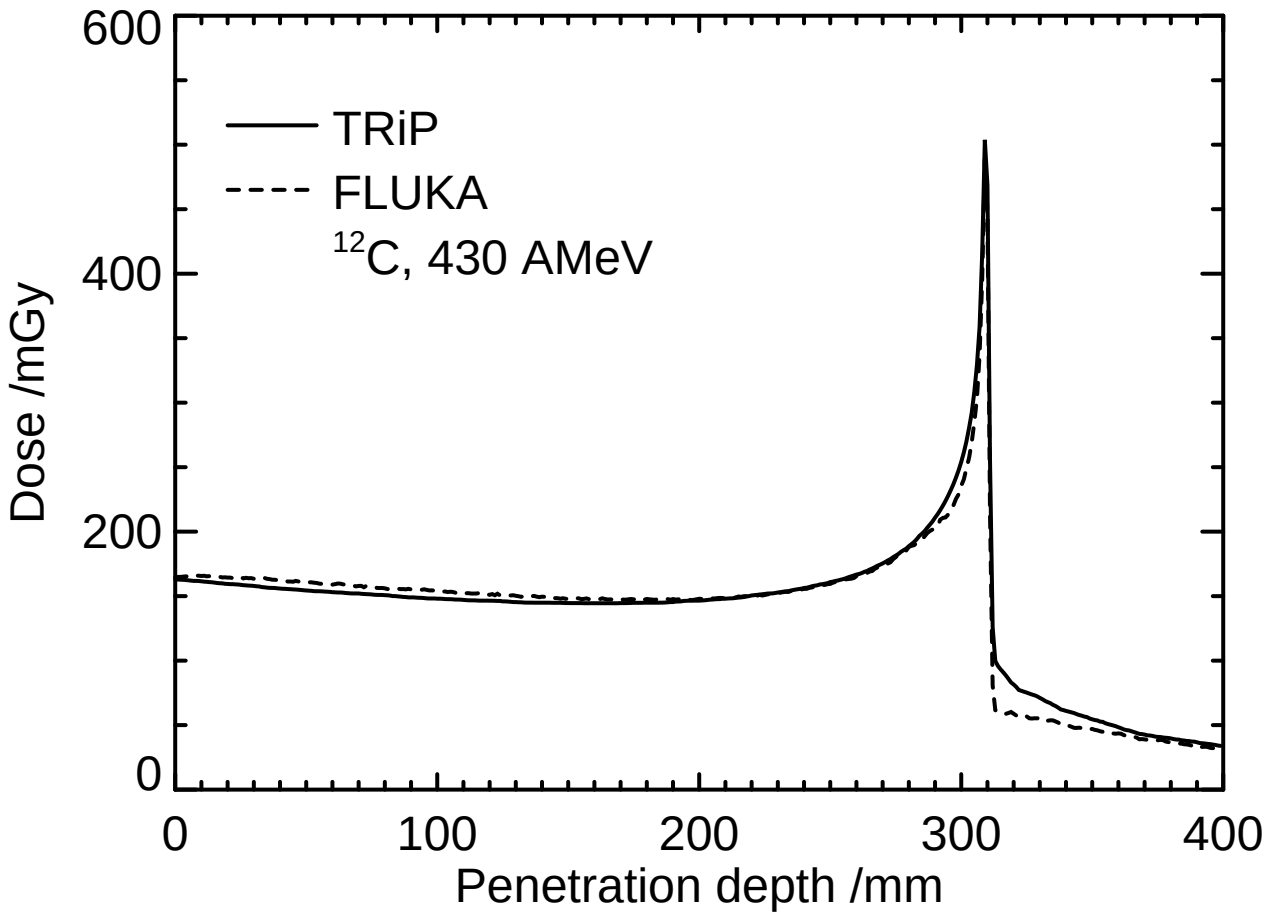




Left: track-average LET as a function of depth in PMMA ("true", nuclei only, restricted to a 3^o cone, with and w/o a cut corresponding to electron elimination)

Right: dose-average LET as a function of depth in PMMA ("true", with and w/o a cut roughly corresponding to electron elimination, nuclei only with and w/o a 3^o cone restriction)

Therapeutic beam (430 MeV/n) ^{12}C



Dose/depth

distribution for FLUKA and TRIP