E-M FLUKA (EMF)

EM interactions and options

7th Fluka Course

NEA Paris Sept.29-Oct.3, 2008

Topics

- General settings
- Interactions of leptons/photons
  - Photon interactions
    - Photoelectric
    - Compton
    - Rayleigh
    - Pair production
    - Photonuclear
    - Photomuon production
  - Electron/positron interactions
    - Bremsstrahlung
    - Scattering on electrons
  - Muon interactions
    - Bremsstrahlung
    - Pair production
    - Nuclear interactions
- Ionization energy losses
  - Continuous
  - Delta-ray production
- Transport
  - Multiple scattering
  - Single scattering

These are common to all charged particles, although traditionally associated with EM

Ionization energy losses

- Charged hadrons
- Muons
- Electrons/positrons

All share the same approach

- Heavy Ions

They need some extra features

Discrete ionization events

Above a pre-set threshold, ionization is modeled as δ ray production (free electrons)

- Spin 0 or 1/2 δ-ray production (charged hadrons, muons)
- Bhabha scattering (e^+)
- Møller scattering (e^-)

The threshold refers to the kinetic energy of the emitted δ ray

For Electrons : set by EMFCUT with the PROD-CUT sdum

For charged hadrons/muons:

```
DELTARAY δThresh Ntab Wtab    Mat1    Mat2    Step    PRINT
```

δThresh = production threshold, in materials Mat1→ Mat2
Ntab, Wtab control the accuracy of dp/dx tabulations (advanced user)
If PRINT is set (not def.) dp/dx tabulations are printed on stdout

Continuous energy losses

Below the δ-ray threshold, energy losses are treated as "continuous", with some special features:

- Fluctuations of energy loss are simulated with a FLUKA-specific algorithm
- The energy dependence of cross sections and dE/dx is taken into account exactly (see later)
- Latest recommended values of ionization potential and density effect parameters implemented for elements (Sternheimer, Berger & Seltzer), but can be overridden by the user with (set yourself for compounds!)

```
STERNHEI C      X0      X1      a       m       δ0      MAT
```

```
MAT-PROP Gasp   Rhosc   Iion    Mat1    Mat2    Step
```

Ionization fluctuations -I

The Landau distribution is limited in several respects:

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

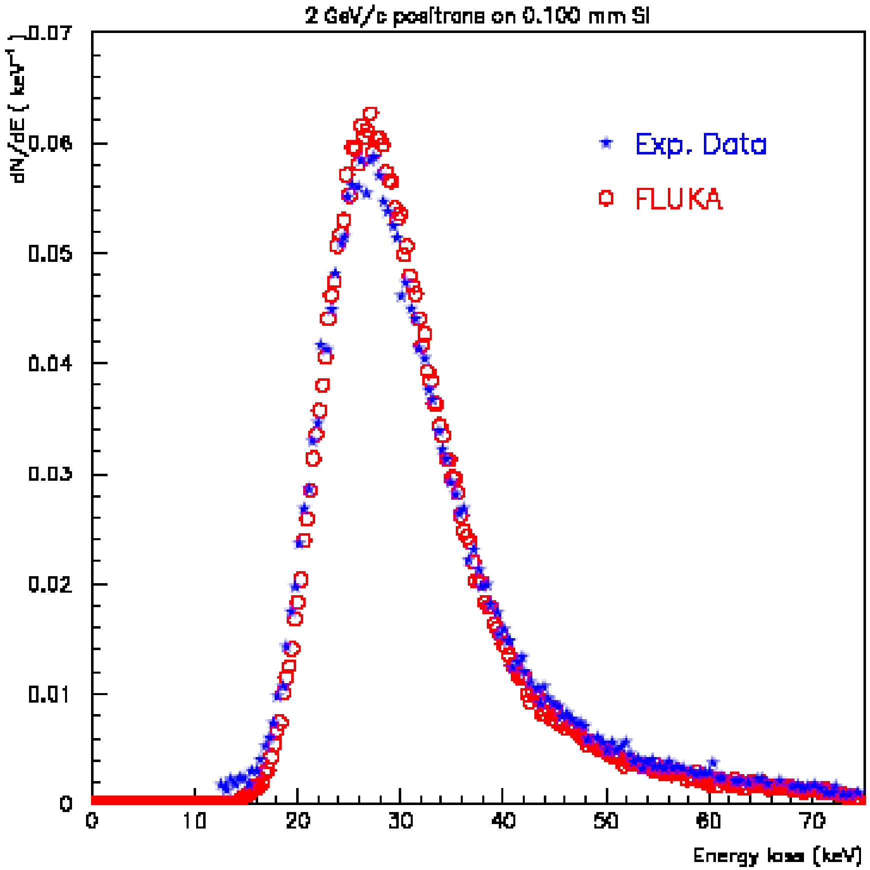
The Vavilov distribution overcomes some of the Landau limitations, but is difficult to compute if step length or energy are not known *a priori*.

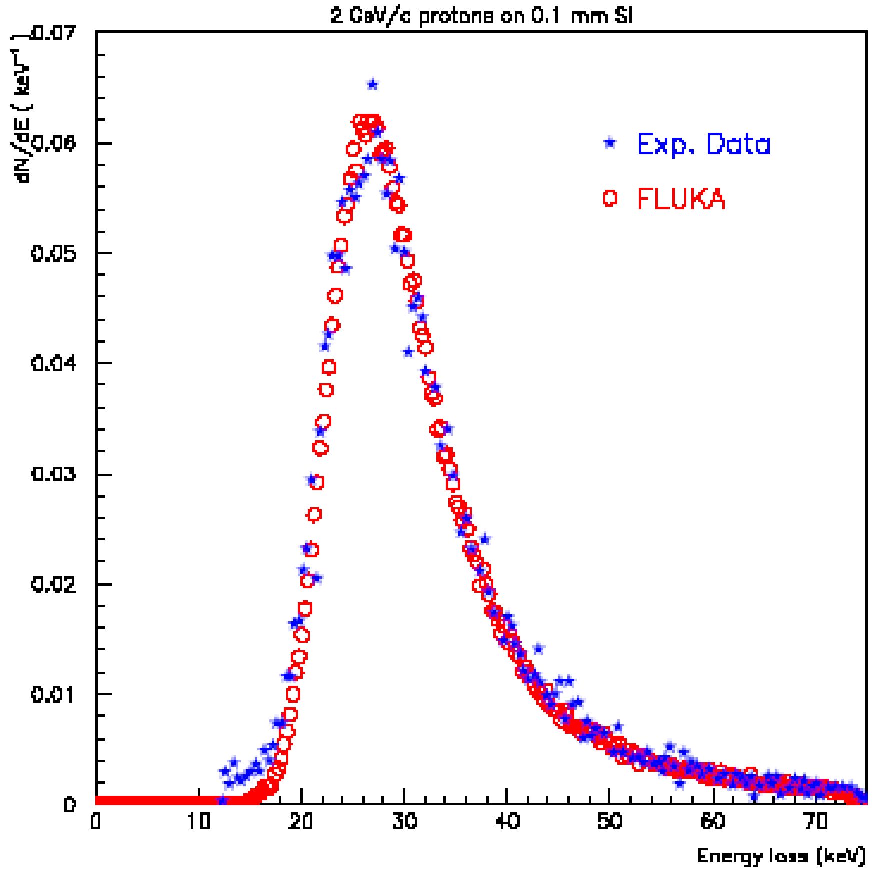
Ionization fluctuations -II

The FLUKA approach:

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

Ionization fluctuations -III





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)

Energy dependent quantities I

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

Energy dependent quantities II

FLUKA takes into account exactly the continuous energy dependence of

- discrete event cross-section
- stopping power

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

Ionization fluctuation options

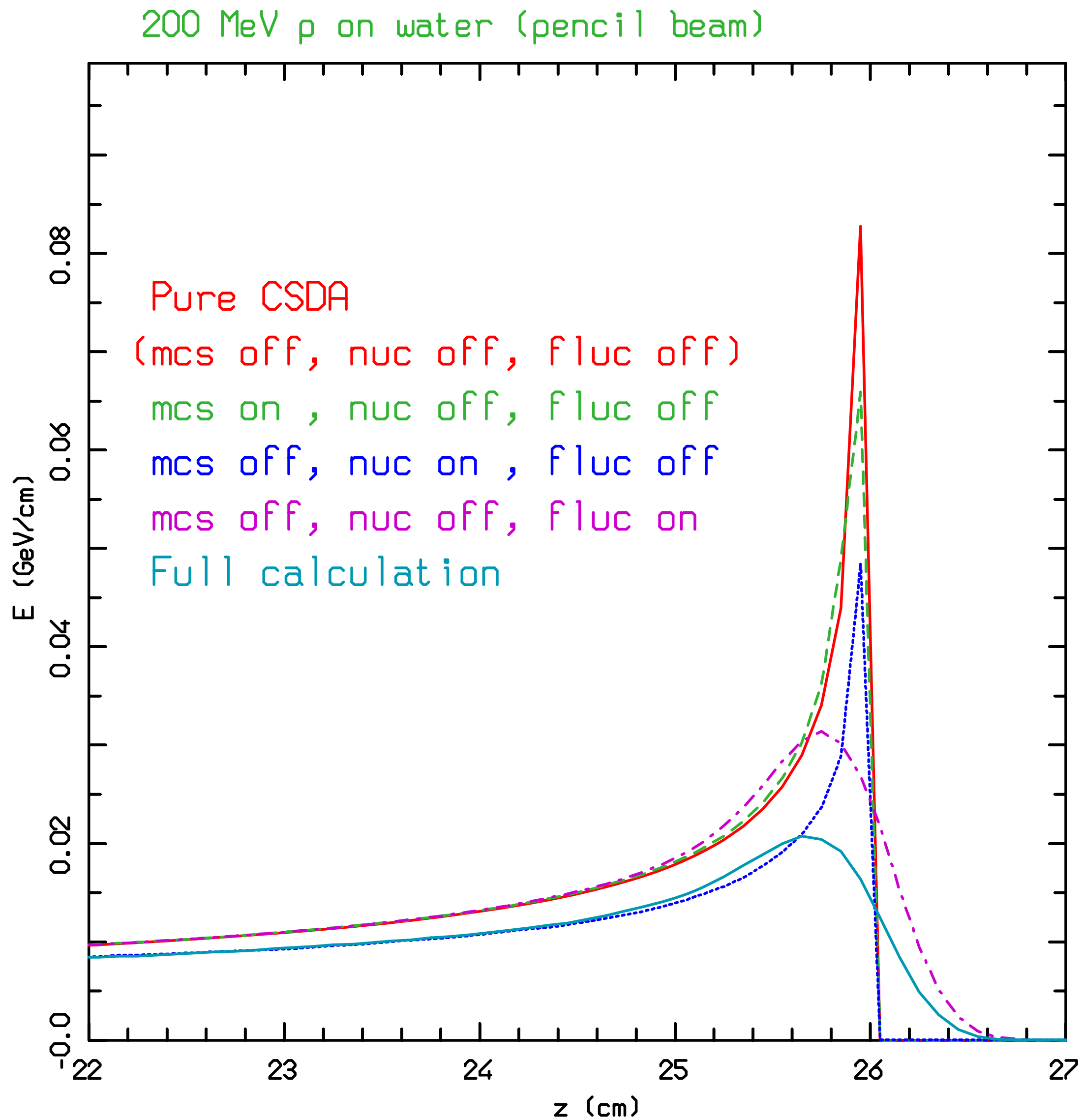
Ionization fluctuations are simulated or not depending on the DEFAULTS used. Can be controlled by

```
IONFLUCT FlagH FlagEM  Accuracy Mat1  Mat2    STEP
```

Remember always that δ-ray production is controlled independently and cannot be switched off for e^+/e^- (it would be physically meaningless)

Playing with a proton beam

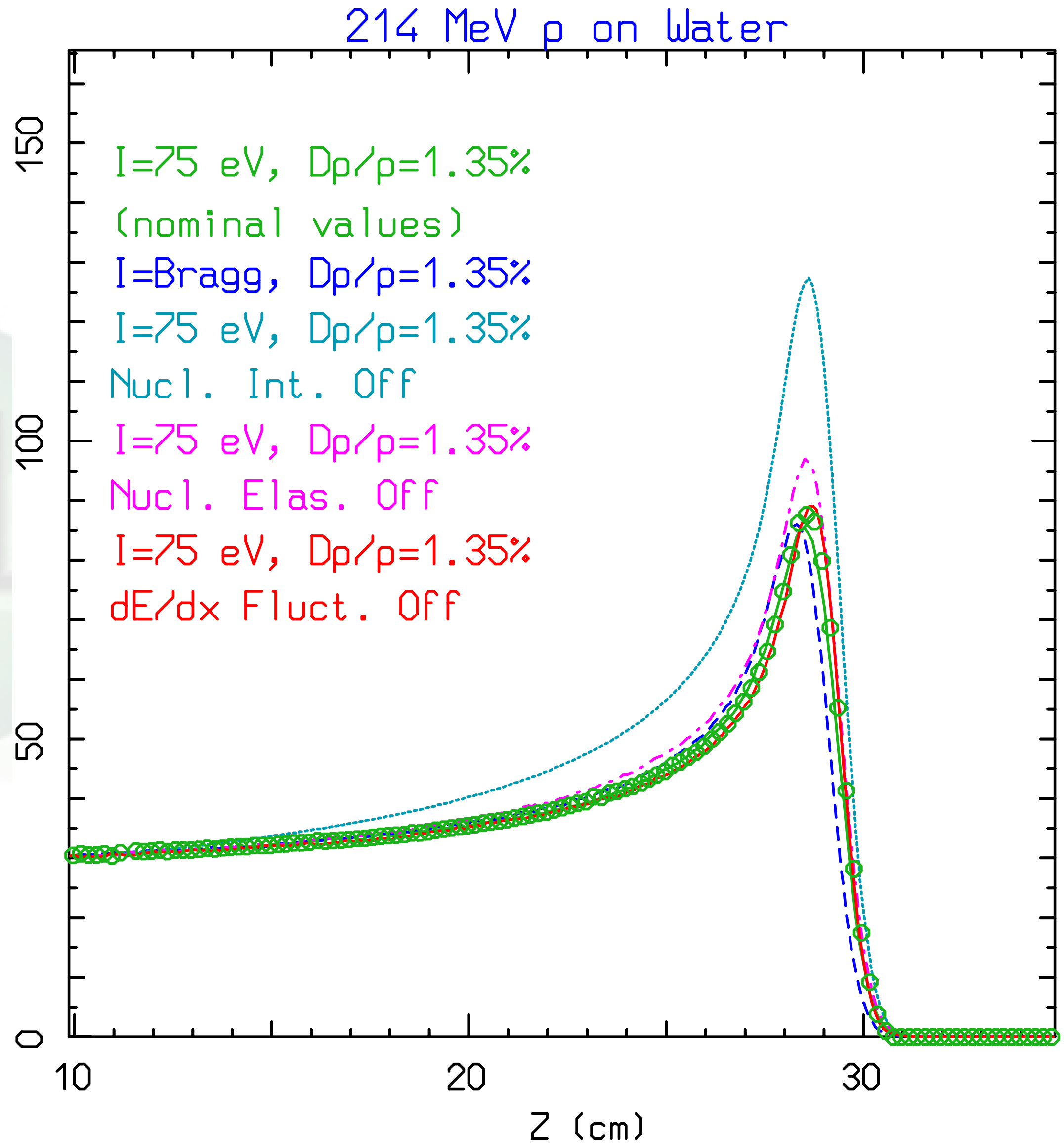
Dose vs depth energy deposition in water for a 200 MeV p beam with various approximations for the physical processes taken into account



Playing with a proton beam II part

Dose vs depth energy deposition in water for a 214 MeV real p beam under various conditions.

Exp. Data from PSI

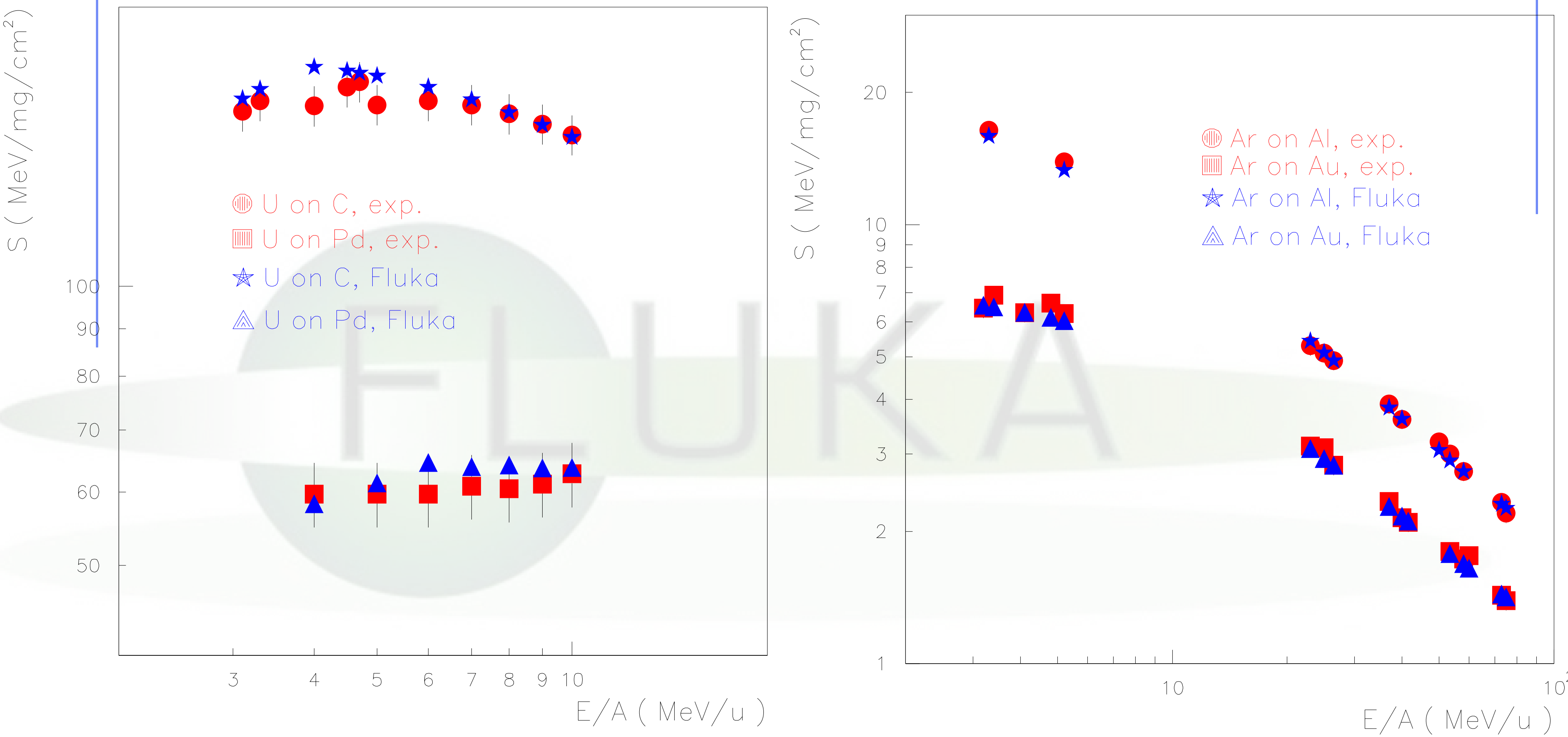


Heavy ions

Ionization energy losses

- Up-to-date effective charge parameterizations
- Energy loss straggling according to:
  - "normal" first Born approximation
  - Charge exchange effects (dominant at low energies, ad-hoc model developed for FLUKA)
  - Mott cross section (high energies, not yet fully implemented)
  - Nuclear form factors (high energies)
  - Direct e+/e- production

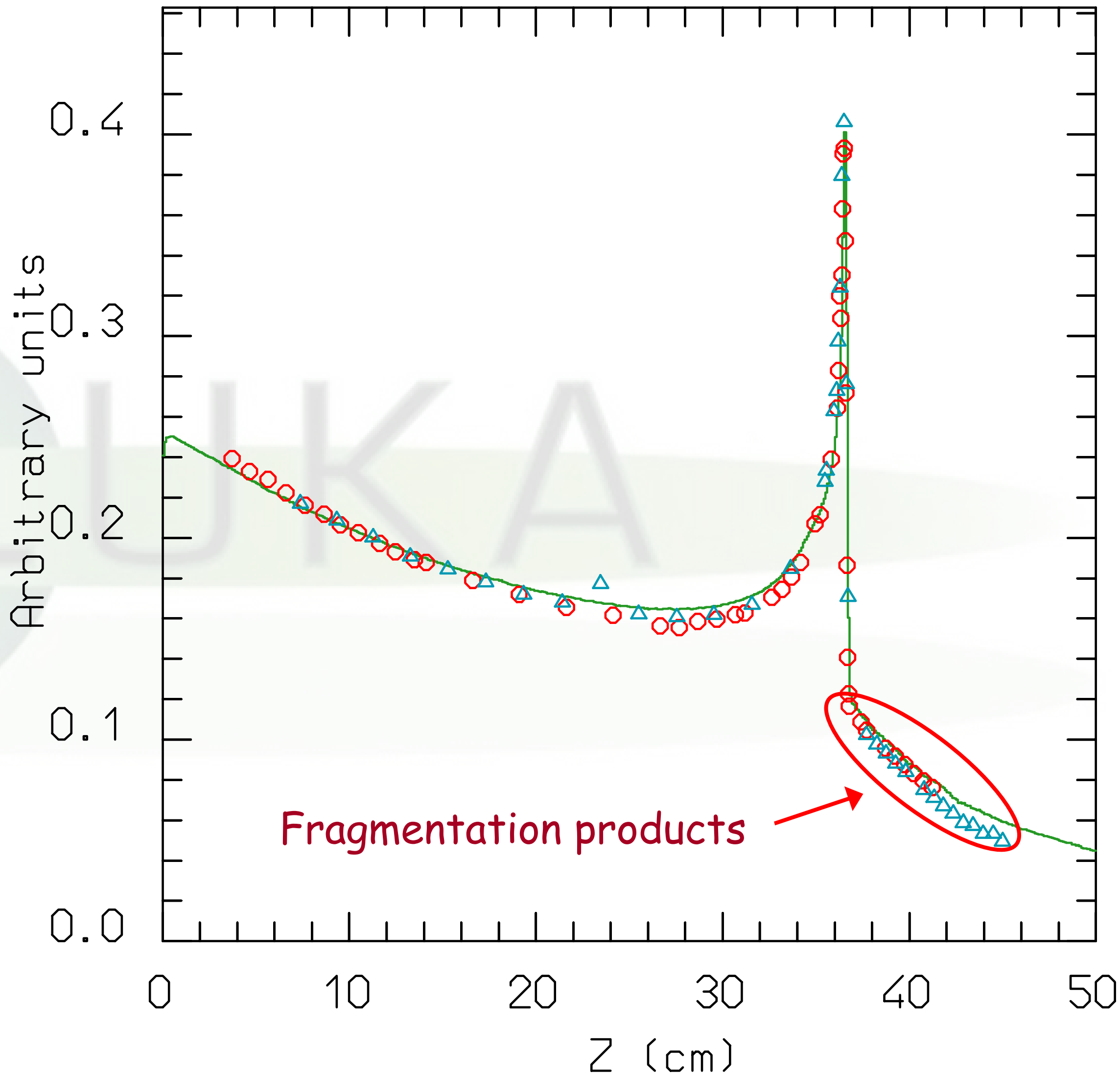
Heavy ions dE/dx



Comparison of experimental (R.Bimbot, NIMB69 (1992) 1) (red) and FLUKA (blue) stopping powers of Argon and Uranium ions in different materials and at different energies.

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



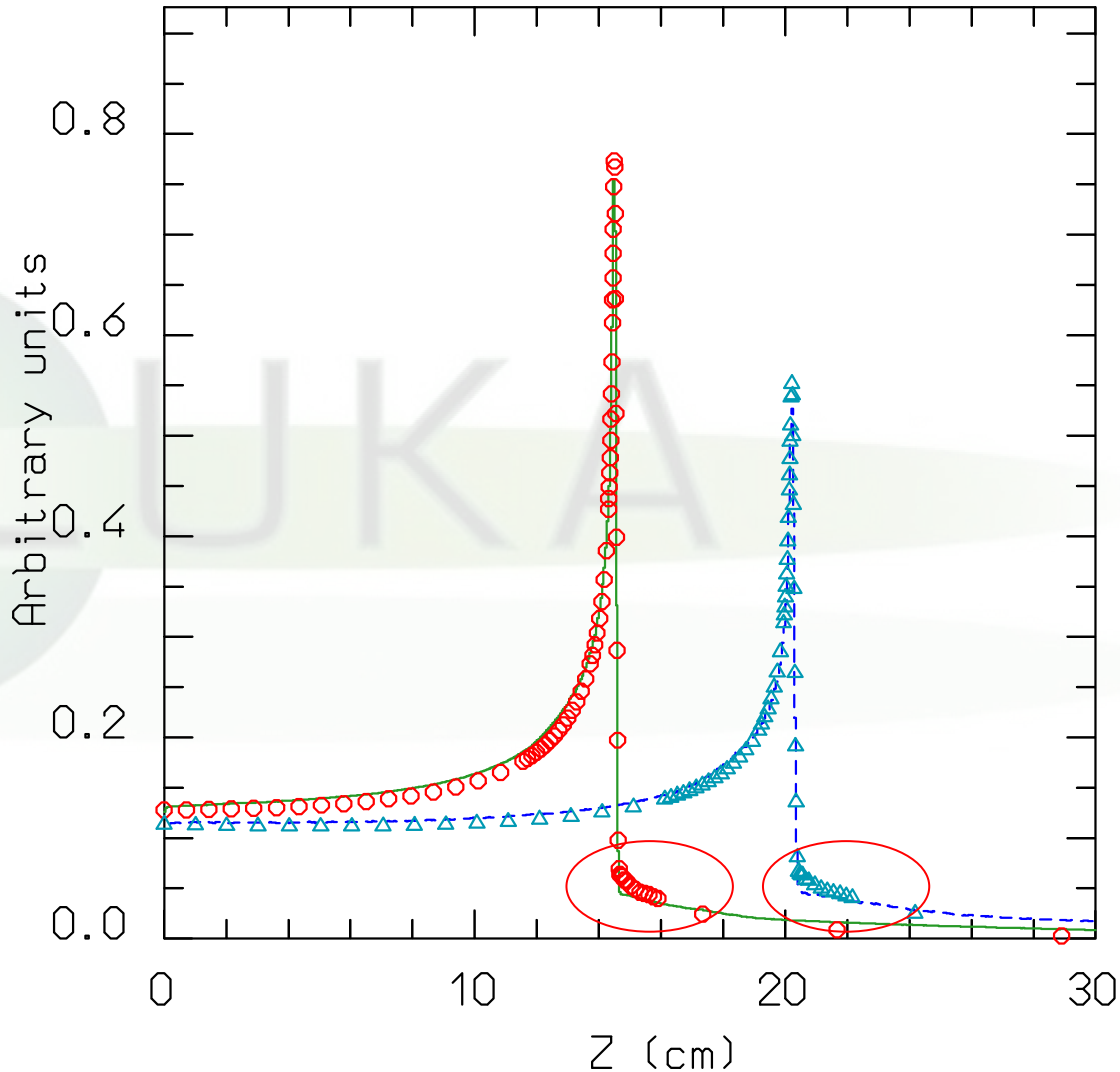
Exp. Data Jpn.J.Med.Phys. 18, 1,1998

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



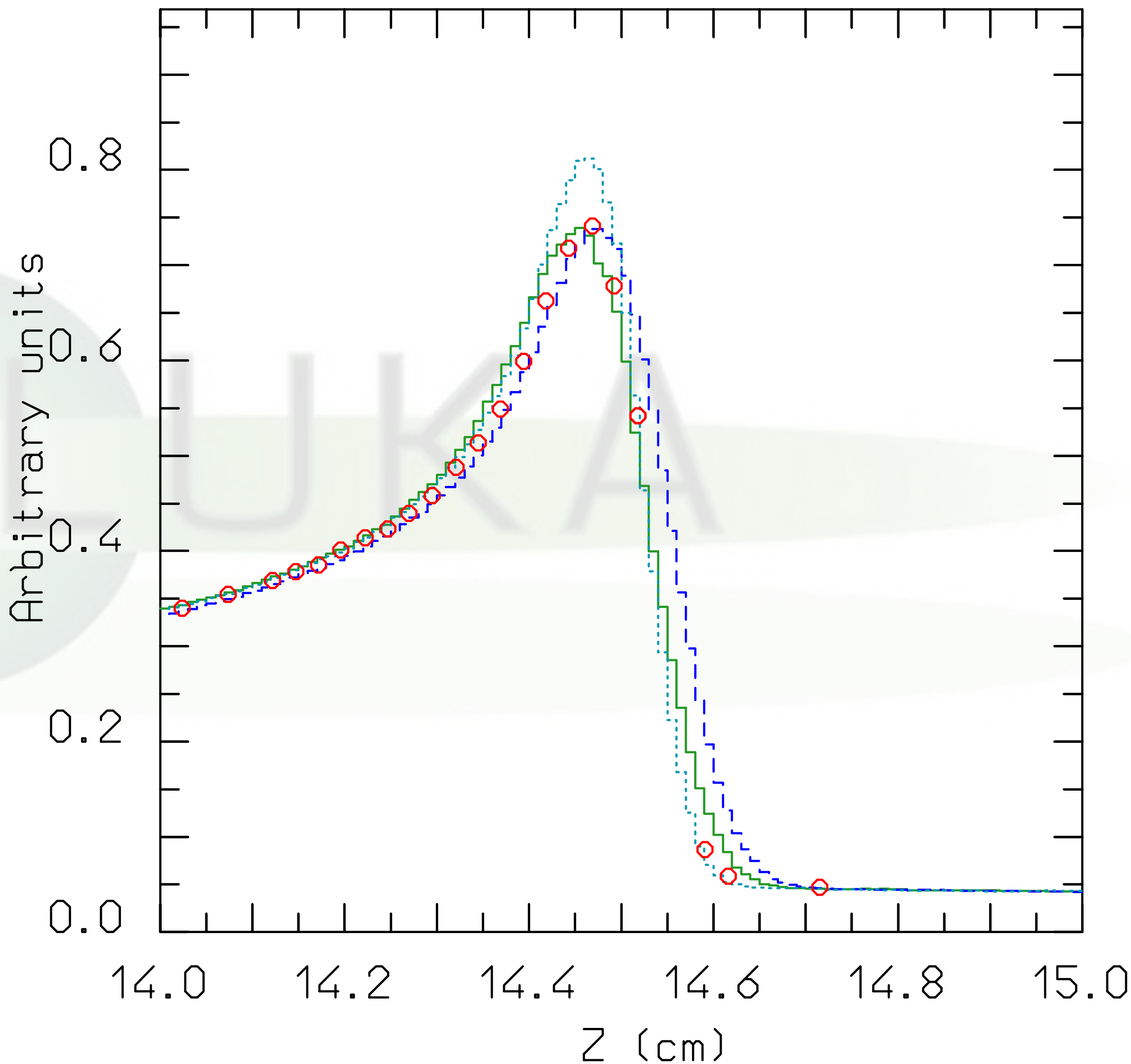
Exp. Data Jpn.J.Med.Phys. 18, 1,1998

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

Close-up of the dose vs depth distribution for 270 MeV/n ^{12}C ions on a water phantom.

The green line is the FLUKA prediction with the nominal 0.15% energy spread

The dotted light blue line is the prediction for no spread, and the dashed blue one the prediction for *I* increased by 1 eV



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