Fragmentation of light nuclei in water phantoms studied with GEANT4

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FIAS

Cancer therapy with carbon-ion beams: a successful method

- Heavy-ion therapy – the most sophisticated method in radiotherapy (accelerator, gantry).
- Heavy-ions have higher relative biological effectiveness. High doses are well localized at the Bragg peak.
- Hundreds of patients with deep-seated tumors were successfully treated in GSI, Darmstadt, Germany, and in Chiba, Japan.
- A new proton and carbon-ion therapy center is under construction at Heidelberg, Germany.

- Centers in Italy (CNAO), France (ETOILE), Austria (MedAustron) are planned. More info on this conference !

GEANT4 as a common publicly accessible computational tool ?

- Precise delivery of high doses to tumors while minimizing irradiation of normal tissues is important !

- Developing efficient treatment procedures requires joint efforts of physicists, biologists, medical doctors, accelerator engineers and computer experts at several hadrontherapy centers.

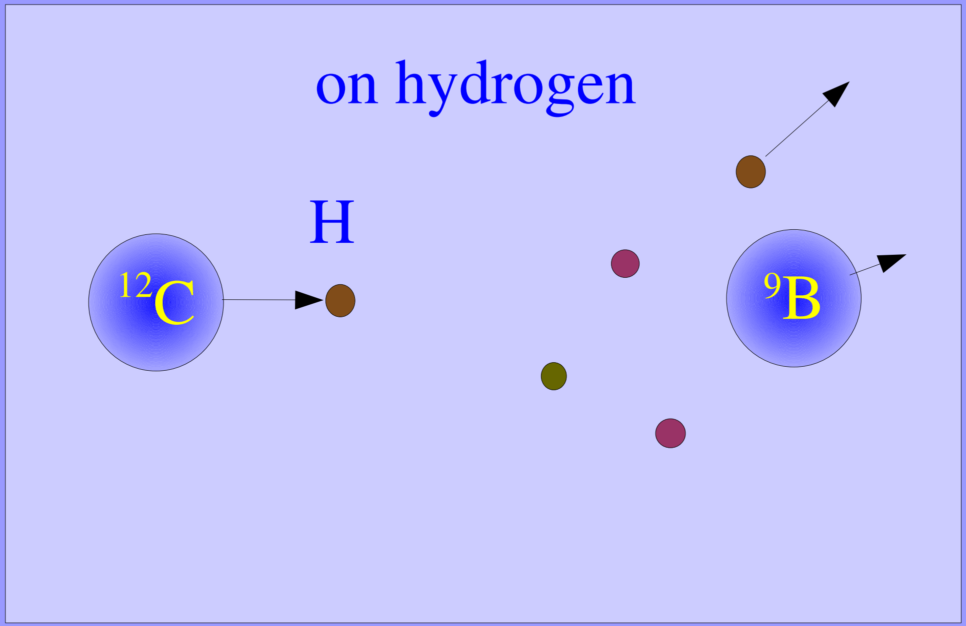
- A single center may not have enough manpower to solve the problem alone...

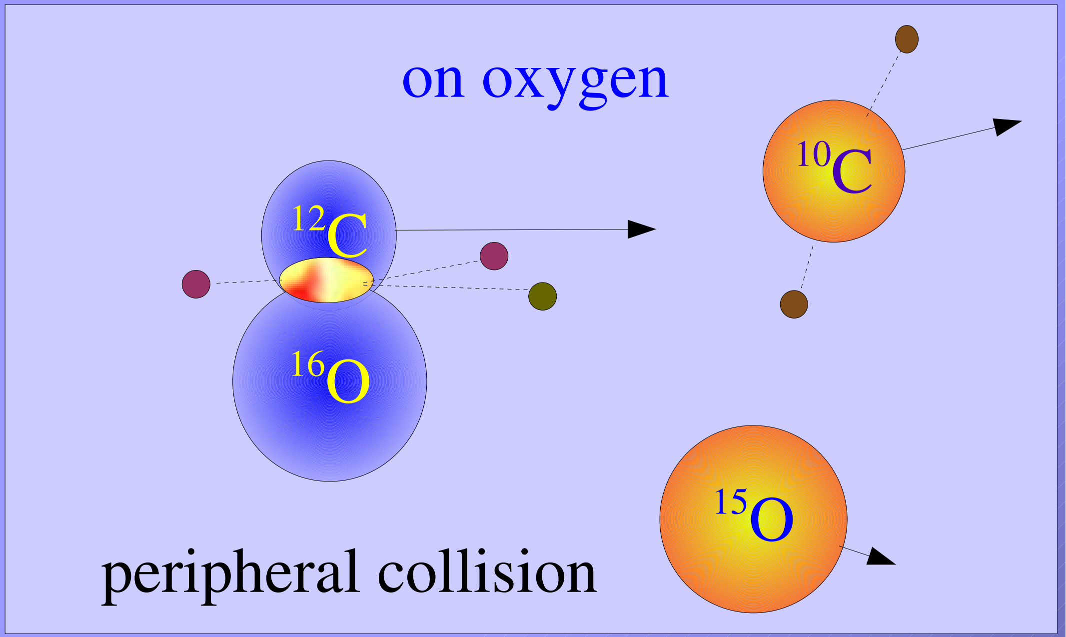
- A common computational tool is needed for exchanging information and accumulating experience obtained by different centers.

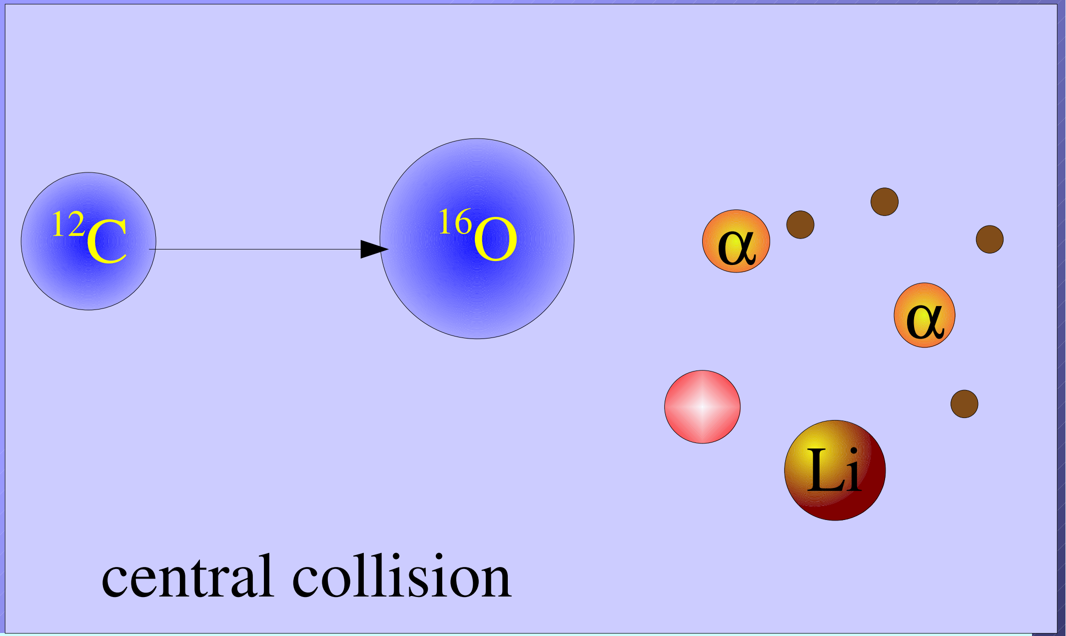
/process/list – many processes are involved

Transportation,	msc,	ionIoni,	hIoni
eIoni,	eBrem,	annihil,	phot
compt,	conv,	muIoni,	muBrems
muPairProd,	ProtonInelastic,	NeutronInelastic,	LFission
LCapture,	DeuteronInelastic,	TritonInelastic,	AlphaInelastic
IonInelastic,	He3Inelastic,	LElastic,	Decay
UserMaxStep			

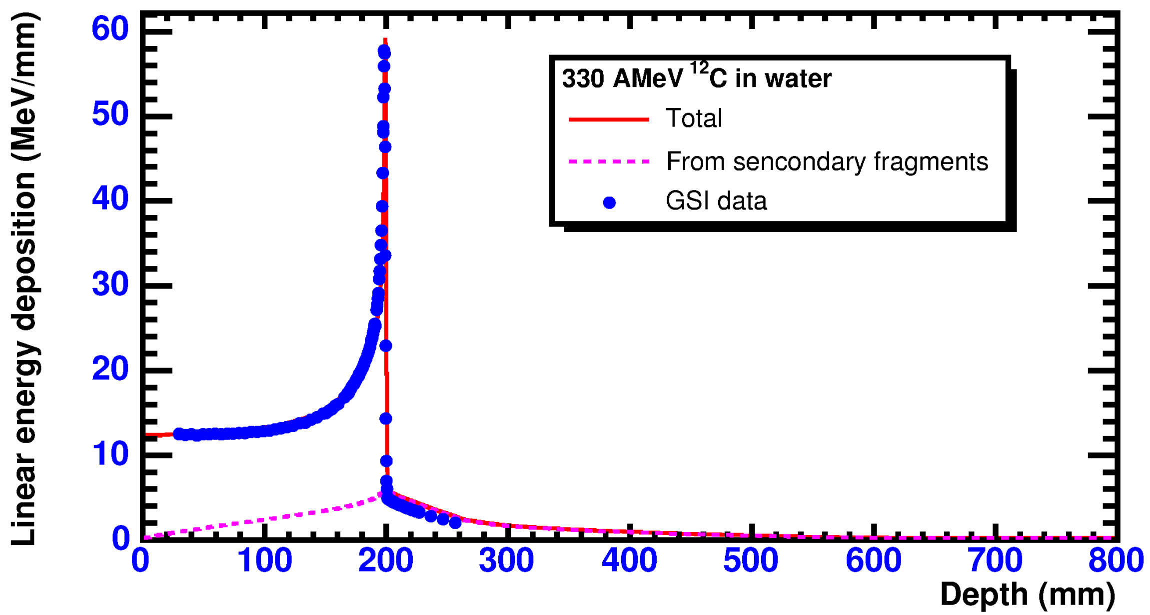
Fragmentation of ^{12}C ions in water

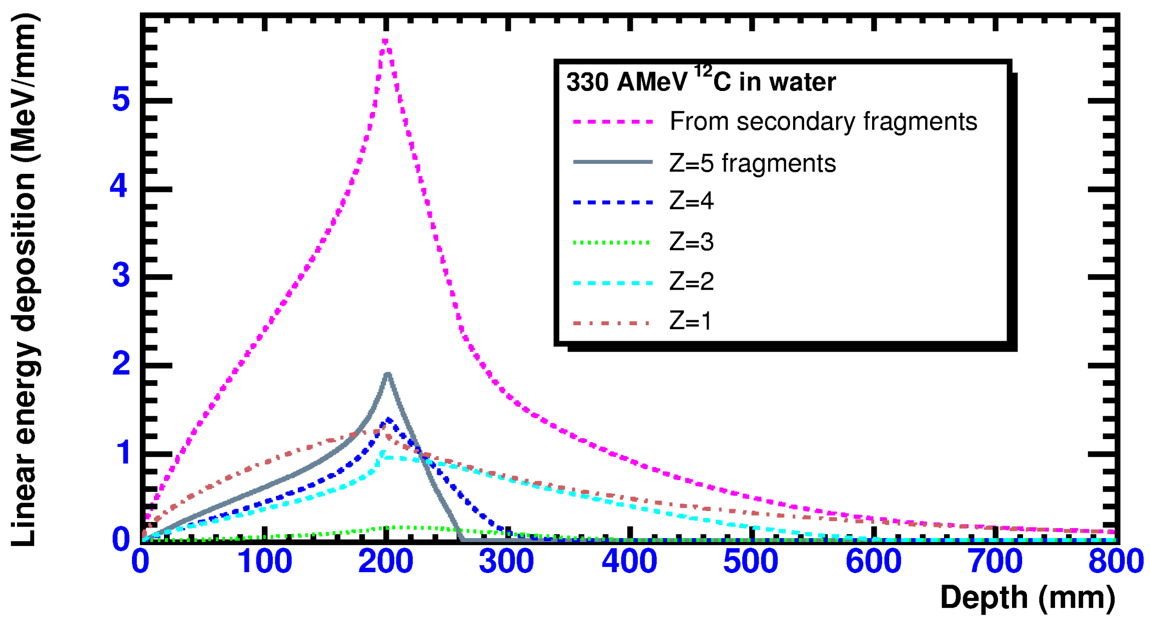






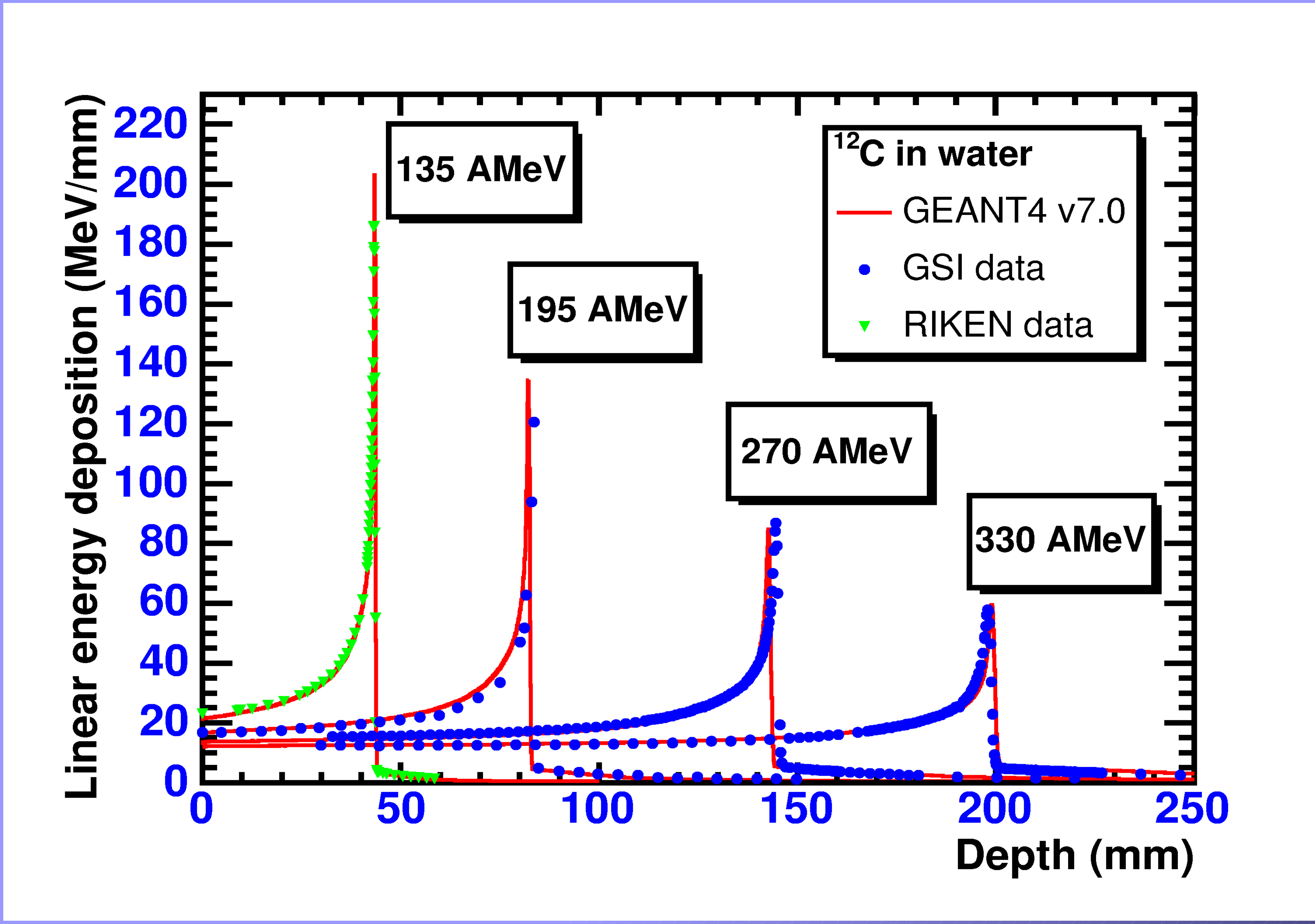
Fragmentation tail: different kinds of fragments- GEANT4 results



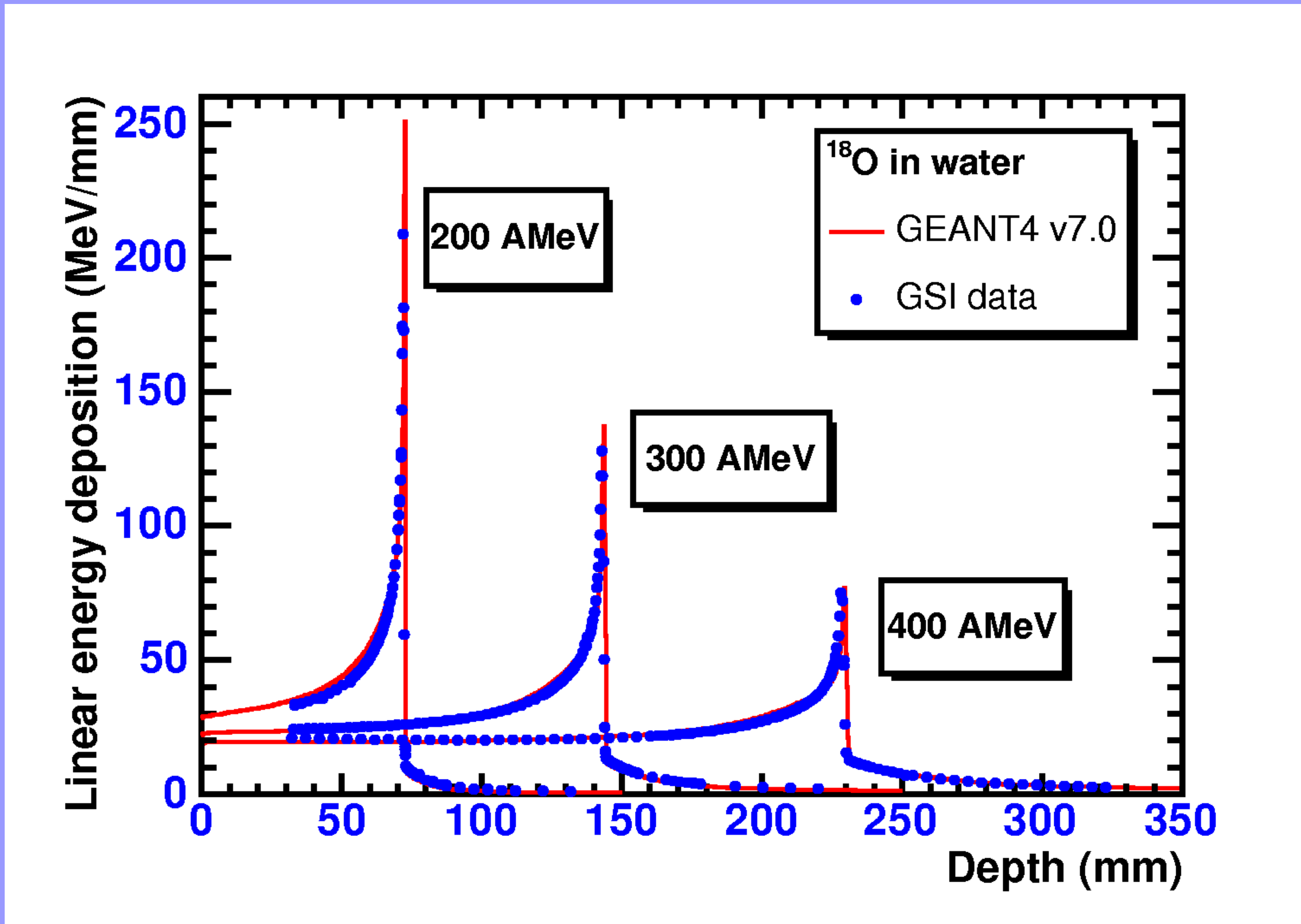


- Fragments close in mass to projectile are stopped near the Bragg peak
- p, He nuclei move beyond the peak and provide a tail of the depth-dose distribution

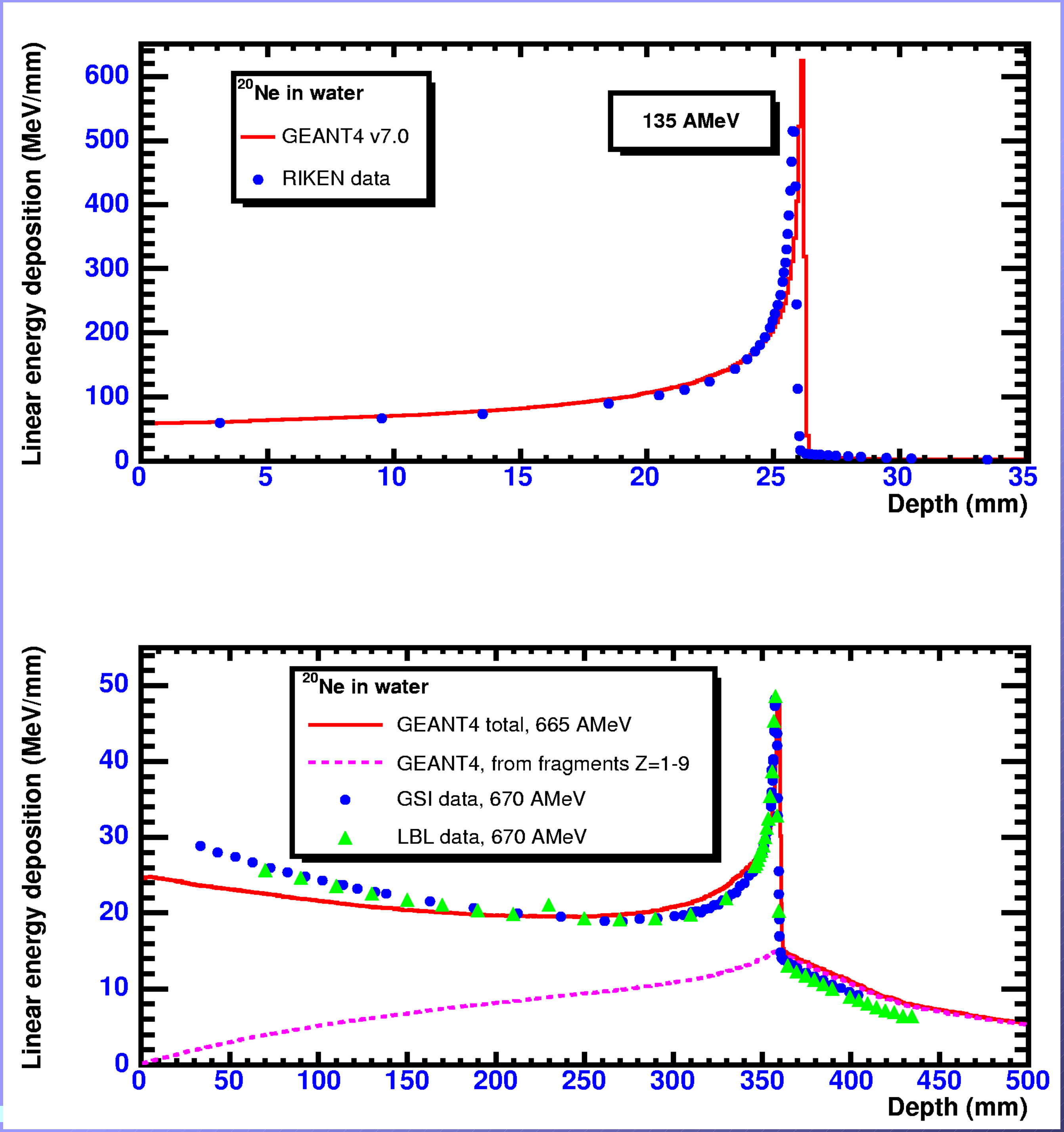
Comparison with GSI data: ^{12}C ions



Comparison with GSI data: ^{18}O ions



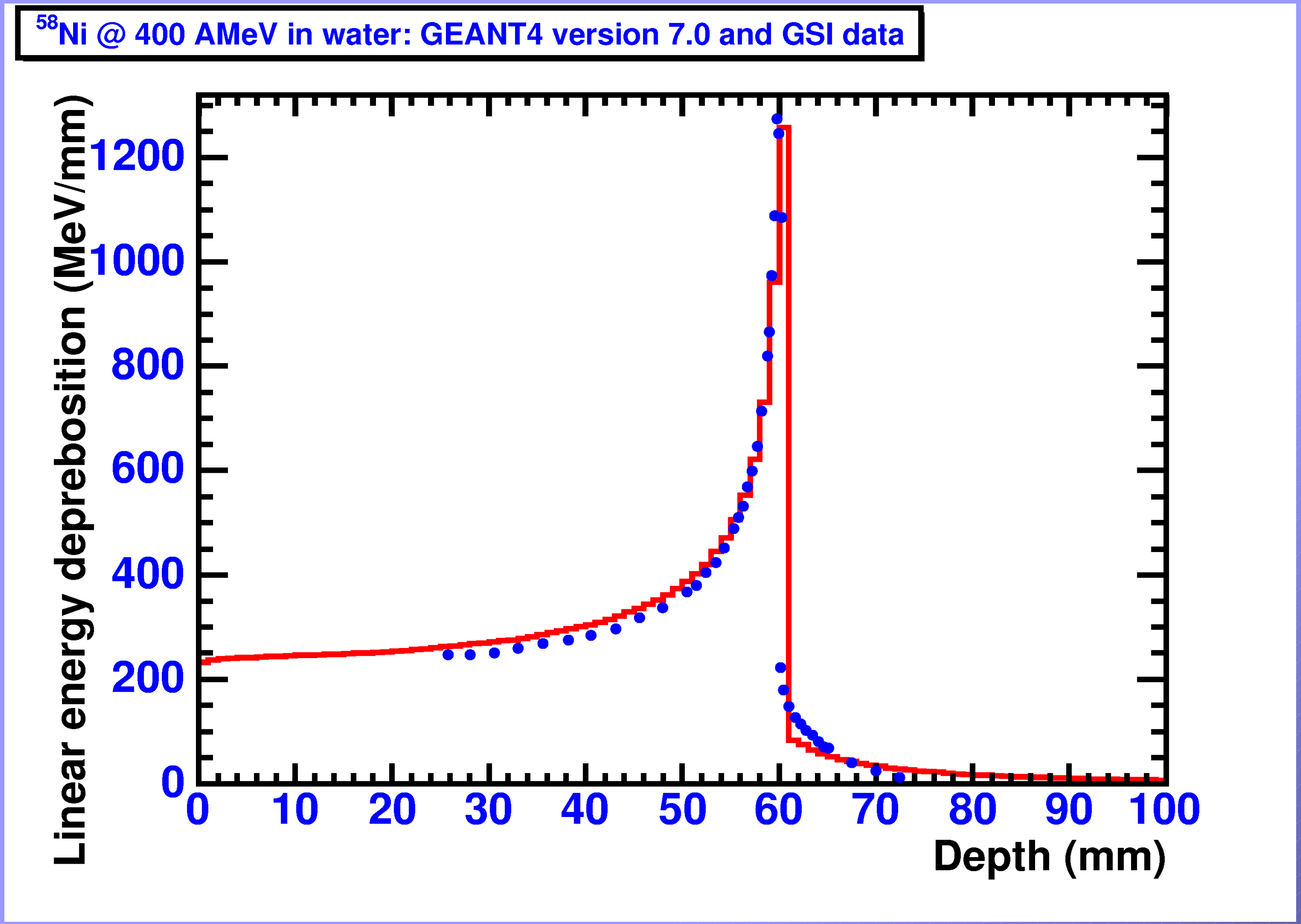
Comparison with GSI and LBL data: ^{20}Ne ions



- Ne ions are less suitable at higher energies due to increased fragmentation!

- At 670A MeV the peak value is only two times higher than the entrance dose...

An example: ^{58}Ni at 400 A MeV



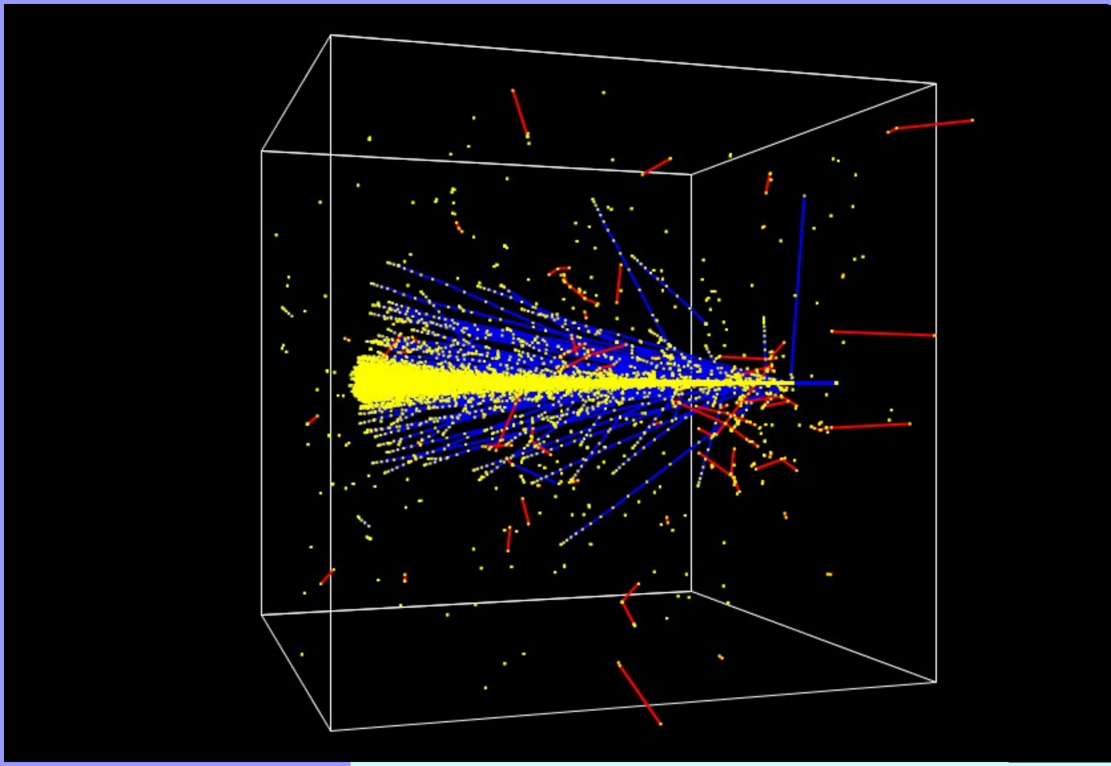
- Low penetration depth due to high EM stopping, modest fragmentation
- Can be used in the therapy of eye tumors

GEANT4 validation for heavy-ion therapy

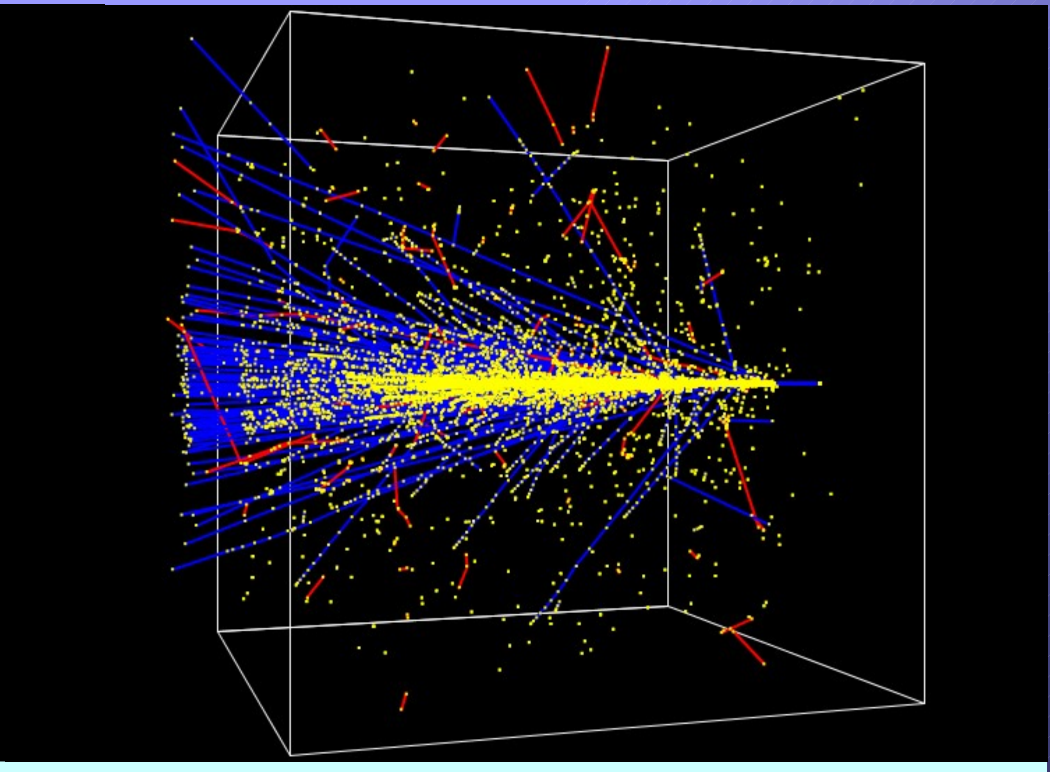
- Both Bragg peak position and shape are well described by GEANT4 v7.0 with its "standard" electromagnetic model and binary cascade/Fermi-breakup models.
- The peak position is predicted with accuracy of **~1-2 mm** for carbon and oxygen ions in the energy range from 135A to 330A MeV.
- The calculations with the mean ionization potential for water ***I*=70.89 eV** (default value) are in reasonable agreement with proton and heavy-ion data.
- The energy deposition **beyond the Bragg peak** due to projectile fragmentation can be described with an accuracy of ~10%.

GEANT4 simulation:
protons versus carbon ions: what about secondary neutrons ?

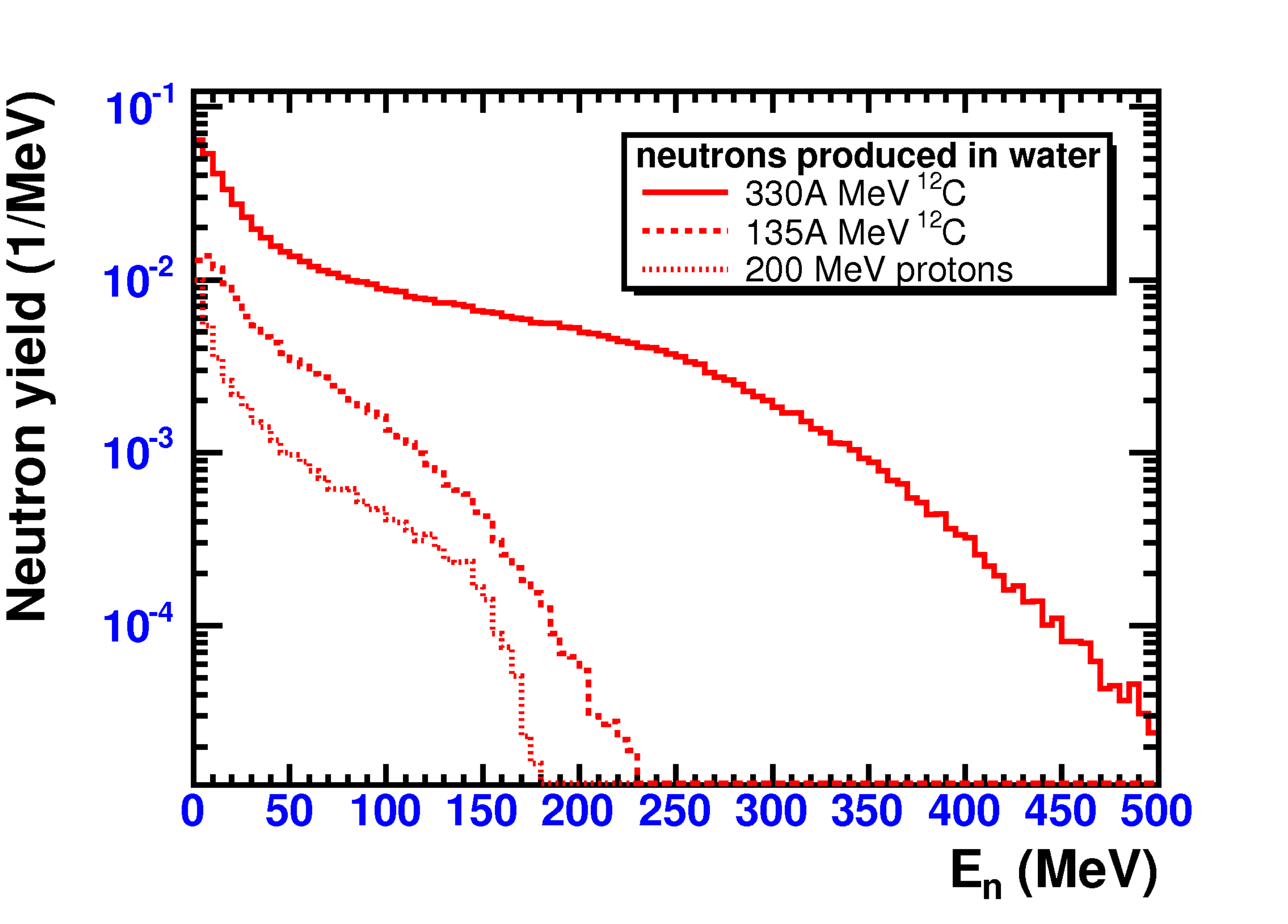
p @ 200 MeV : 600 events



^{12}C @ 330A MeV : 100 events



Spectra of secondary neutrons produced by protons and heavy ions



Neutron interactions with light nuclei

- Elastic scattering on target protons and nuclei:
  - (n,n´)p
  - (n,n´)^{16}O
- Inelastic interactions with target nuclei:
  - n +^{16}O->n+^{16}O+γ n+^{16}O->2n+p+^{14}N+2γ
  - n +^{16}O->^{13}C+α+γ n +^{16}O-> 4α + n and other channels ...
- Radiative neutron capture on target nuclei:
  - n+^{16}O->^{17}O+2γ or ^{17}O+3γ
- Mean free path for neutrons in water:
  - for 10 MeV n ~ 20 cm
  - for 100 MeV n ~ 80 cm

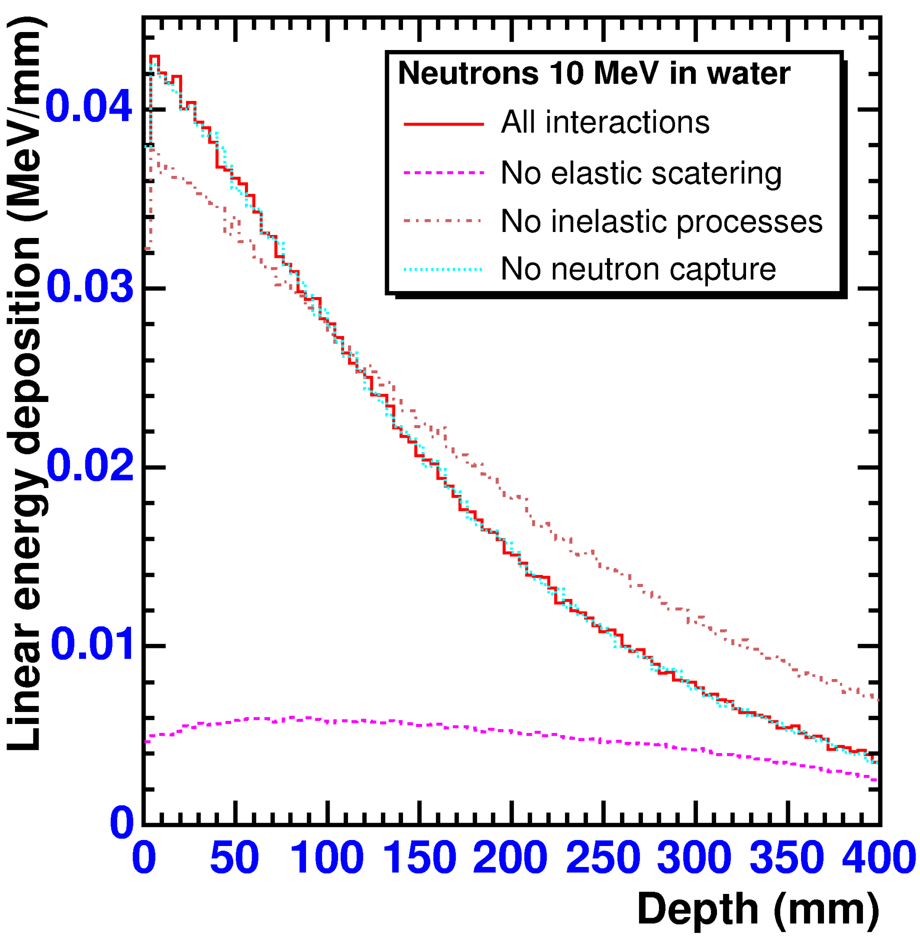
/process/dump … for neutrons

- NeutronInelastic
- LFission
- LCapture
- LElastic
- Decay

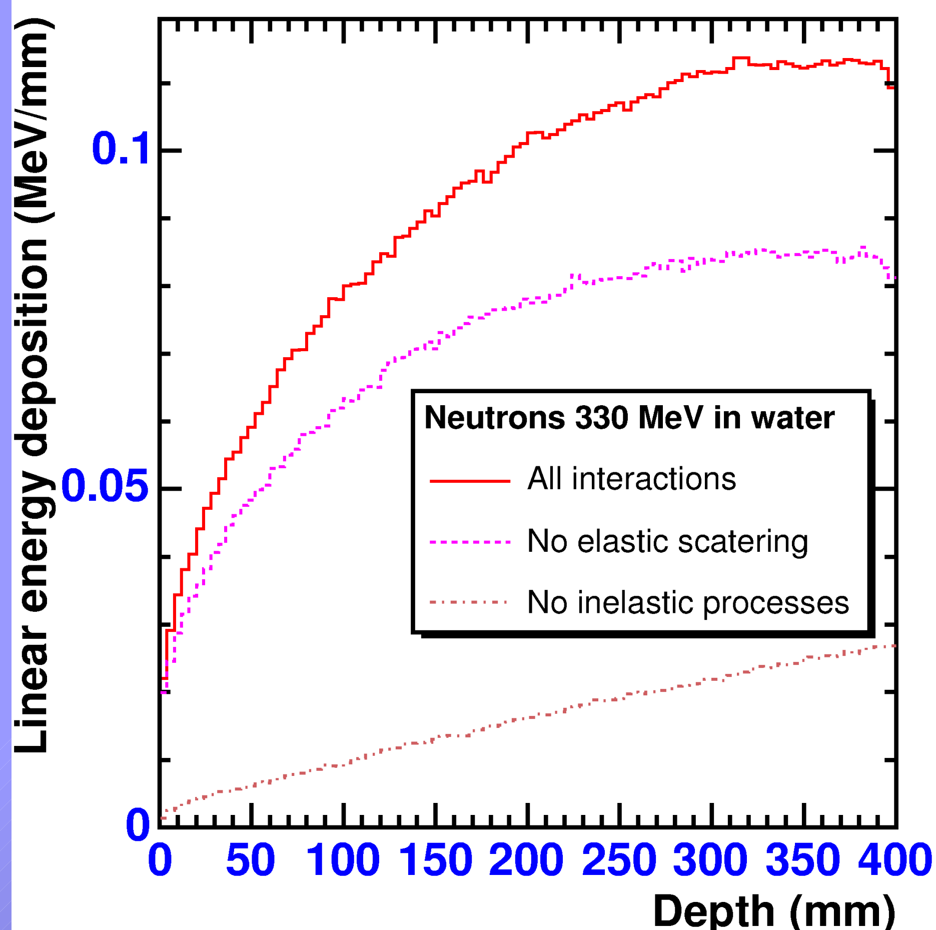
Elastic and inelastic interactions of neutrons: low and high energies

Test cases: beam of neutrons on water phantom

mostly elastic

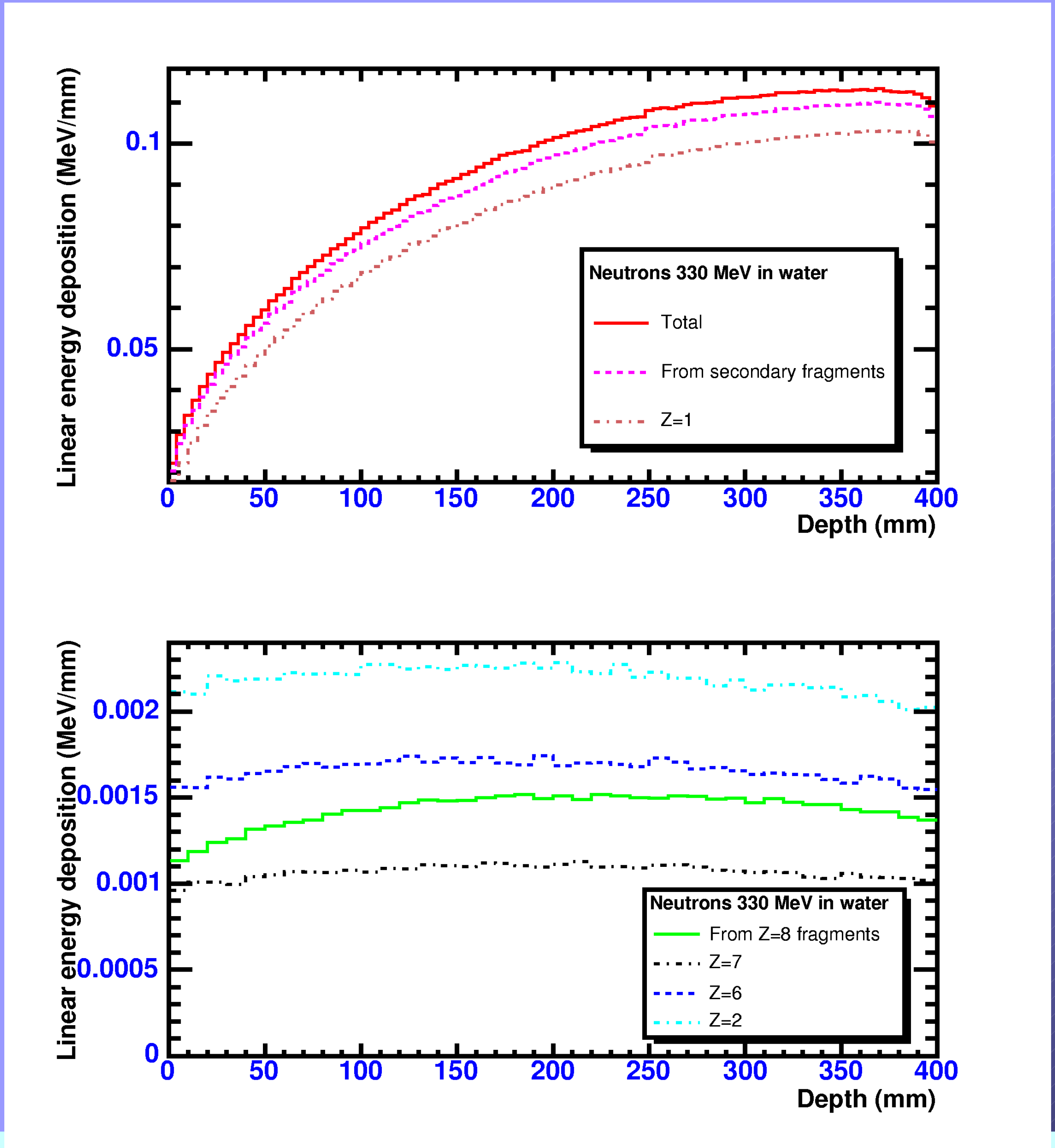


mostly inelastic



Interactions of fast neutrons: fragmentation and spallation

Test case: 330 MeV neutron beam on water phantom



Energy balance and contribution from neutrons (in %% of the beam energy)

	I protons at 200 MeV in (40 cm)^3 water cube	II ^{12}C at 330A MeV in (40 cm)^3 water cube	III ^{20}Ne at 670A MeV in (50 cm)^3 water cube
(1) Only electromagnetic interactions	100.	100.	99.997
(2) All processes including fragmentation	94.48	88.63	68.25
(3) Without neutron interactions	93.49	87.51	66.80
Contribution from secondary neutrons	0.99	1.12	1.45
Neutron dose divided by the total dose and RBE	**0.95**	**0.42**	**0.71**

Secondary neutrons from proton and ion beams: harmful ? No !

- Fast neutrons go through the phantom easily: may concern the shielding of the treatment room.
- Low energy (~ MeV) neutrons have a large probability to interact, but can deposit only low energy on average (~ 0.01 MeV/mm)
- The dose from neutrons is below 1.5% of the total dose for typical irradiation conditions.

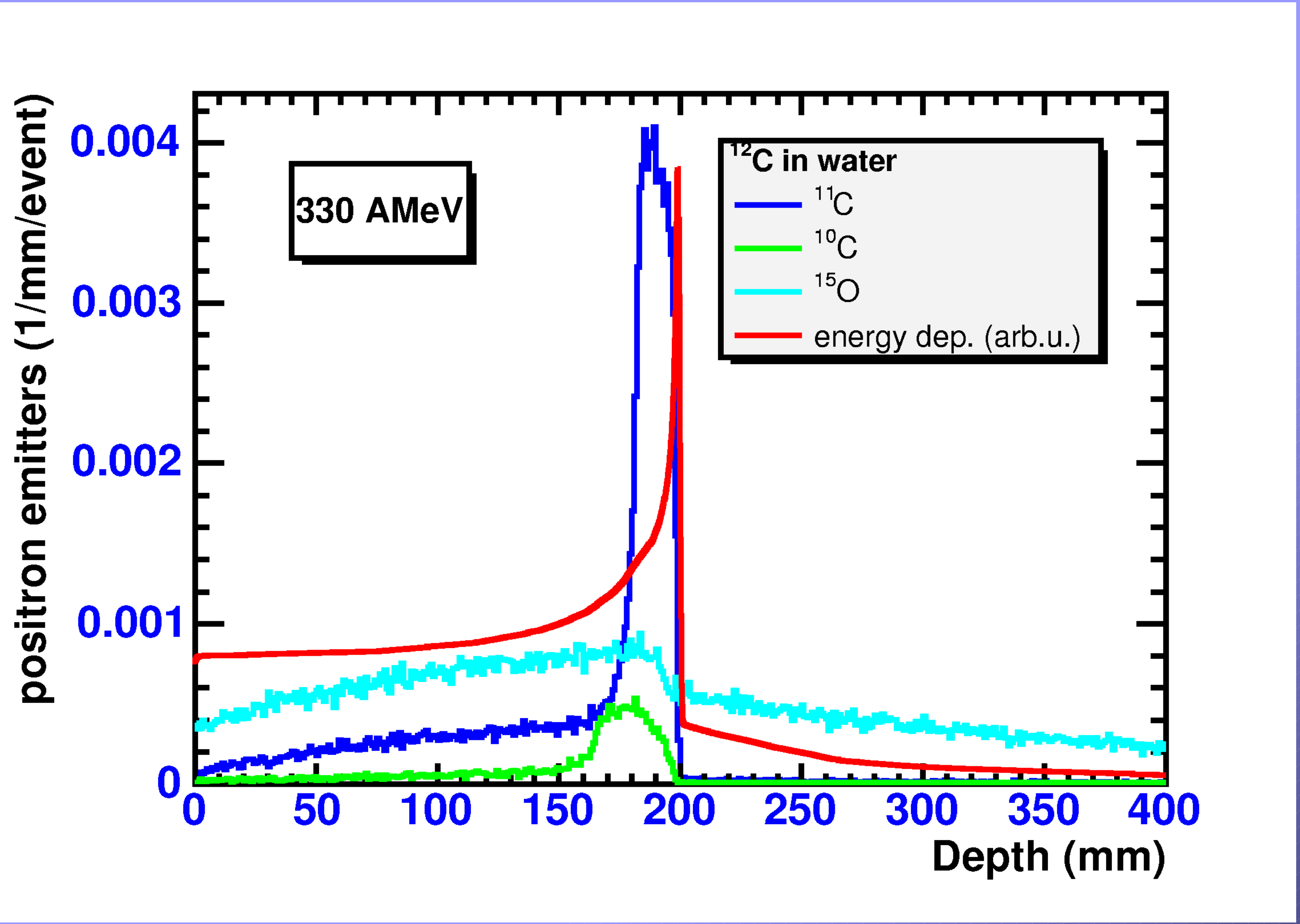
Production of positron emitting projectile fragments

- Possibility of the in-situ beam monitoring via Positron Emission Tomography (PET) .
- One- or two-neutron removal from the projectile: ^{11}C (20 min) and ^{10}C (19 sec).
- Ranges in matter are proportional to A/Z^2 at the same velocity, Bragg peaks are shifted and broadened.

  $R(^{11}C) \sim 11/12\ R(^{12}C)$

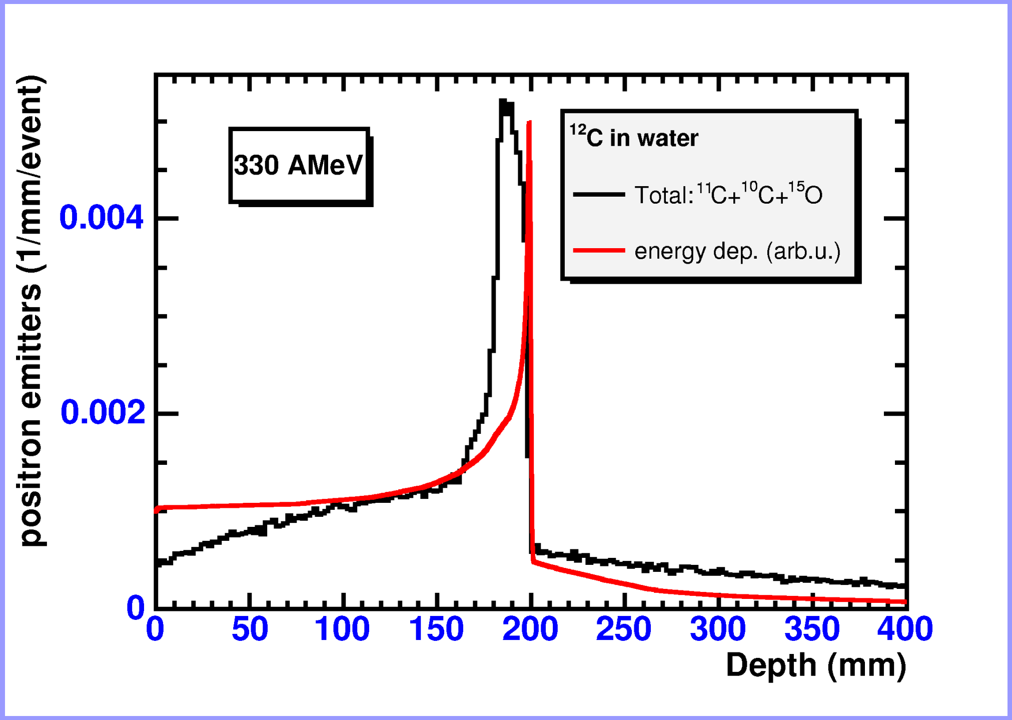
  $R(^{10}C) \sim 10/12\ R(^{12}C)$
- With proper accounting for these features PET is used for monitoring via comparison of calculated and measured distributions.

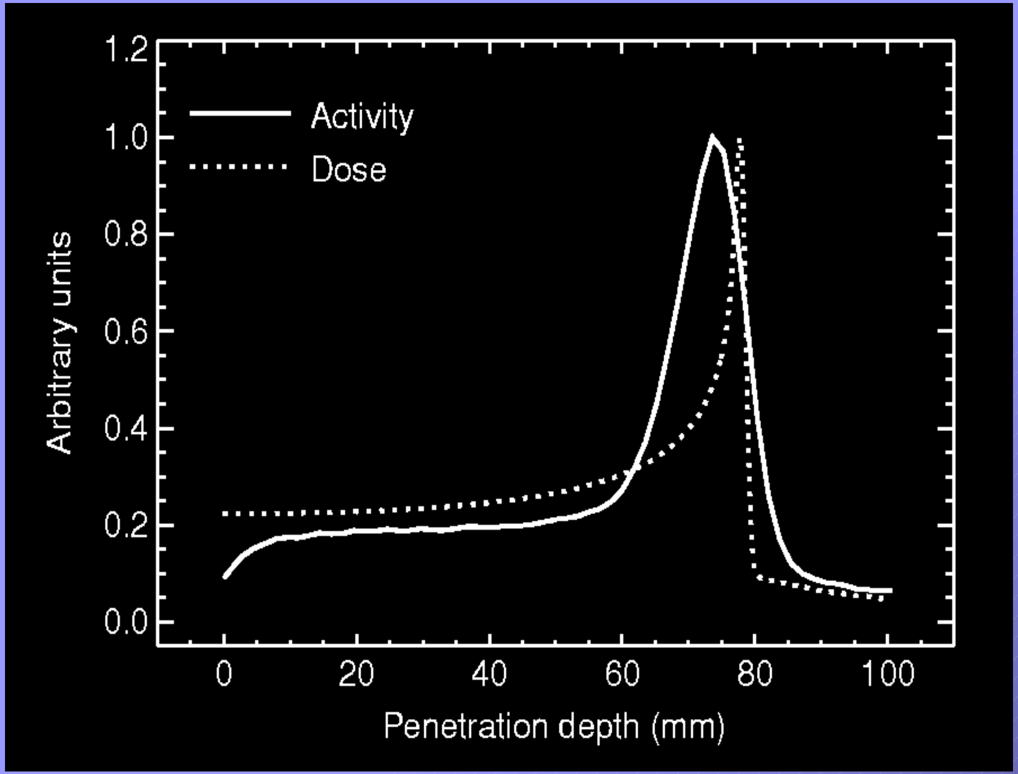
Distribution of positron emitting projectile and target fragments



Flat distribution of ^{15}O nuclei (target fragments), also beyond the Bragg peak.

Very preliminary: GEANT4 vs experiment





F.Pönisch et al. PMB 49(2004)5217

- Different energies and phantoms. No corrections for decay time in calculations – comparison is only qualitative.
- In both cases the distribution of PE nuclei does not reflect exactly the depth-dose distribution: PE distribution is shifted, broadened and has a tail die to ^{15}O.

GEANT4 for heavy-ion therapy

- Depth-dose distributions were calculated.
- Physics of secondary neutrons was studied.
- The distributions of positron emitting fragments were calculated.
- GEANT4 v7.0 seems to be well suited for heavy-ion therapy simulations !
- See details in I.A. Pshenichnov, I.N. Mishustin, W. Greiner, arXiv physics/0507091; Phys.Med.Biol., 2005, in press.

My positive experience as a GEANT4 user...

- GEANT4 examples are very didactic and provide a good starting point.
- Responses from GEANT4 developers are usually quite prompt and very instructive.
- Faced with two bugs only (e.g. GeV photons from low-energy neutron capture). Now fixed in new release.
- An AIDA implementation (PI) I used is not easy to install. It is only tested on a specific platform (Scientific Linux CERN 3).
- Good graphics (journal-ready quality) is currently provided only by ROOT toolkit. It is natural to use C-like scripting (CINT) to produce plots...