Frontier Science '05
Milano Bicocca
15 Sept 2005

Geant4 for the Medicine

Giovanni Santin

Space Environments
and Effects Section
ESA / ESTEC

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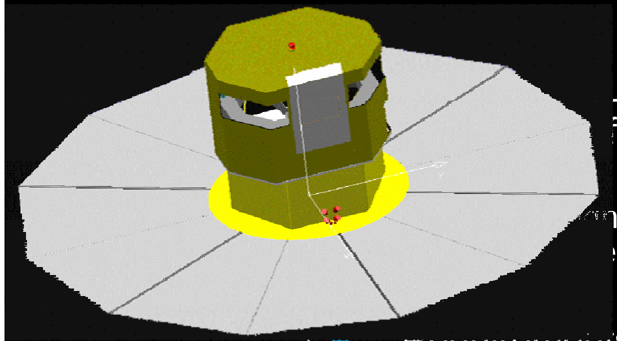
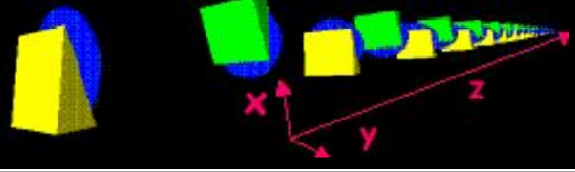
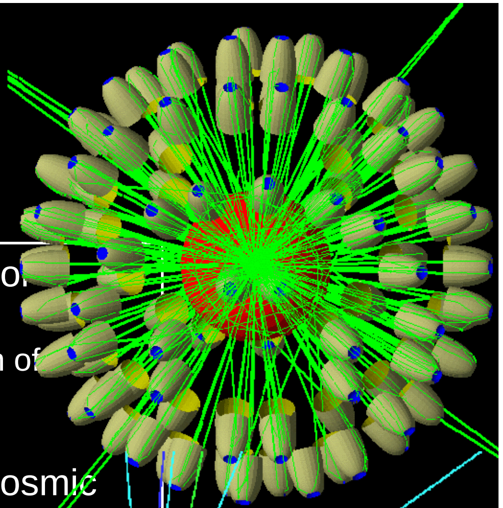
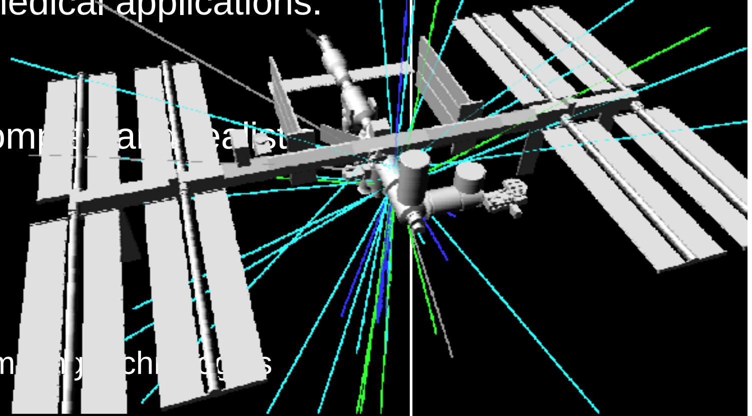
Geant4



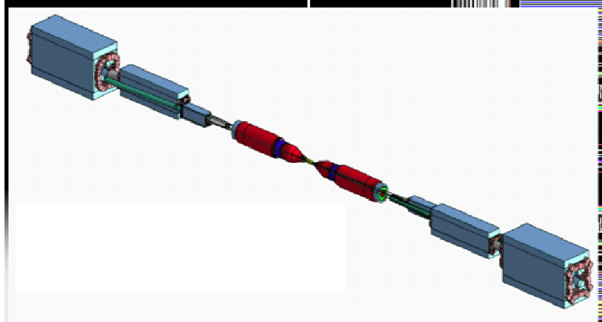


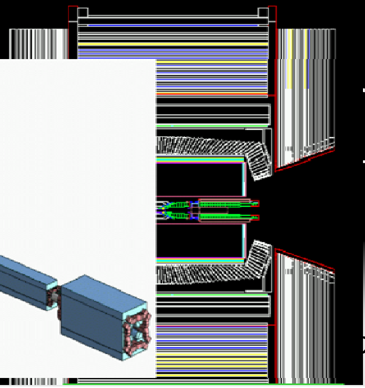


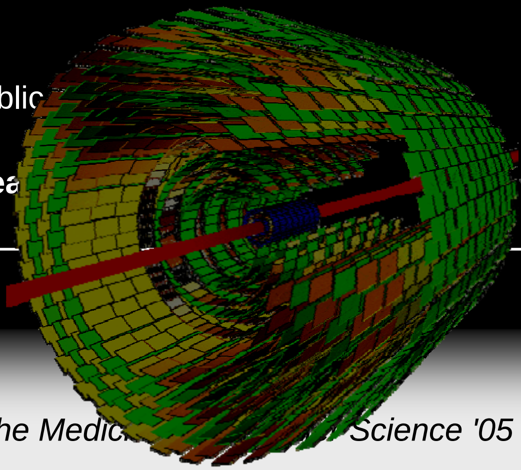
- …f GEANT3, world-wide used toolkit for HEP detector…
  - …n of a major HEP software package for the next generation of …nts using an Object-Oriented environment.
- …Requirements from heavy ion physics, CP violation physics, cosmic ray physics, astrophysics, space science and medical applications.
  - Large degree of functionality and flexibility

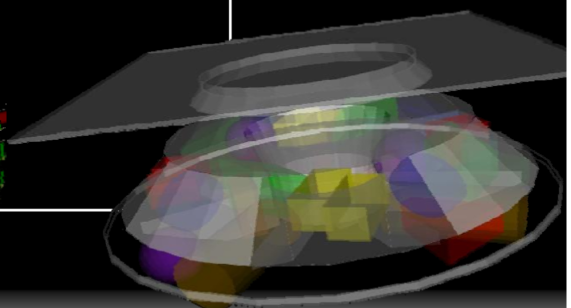


- Several types of geometrical descriptions for com… realist… models
- Everything is open to the user
  - Choice of physics processes/models
  - Choice of GUI/Visualization/persistency/histogram… technologies
- Timeline
  - Dec '94 - Project start
  - … public…
  - … relea…



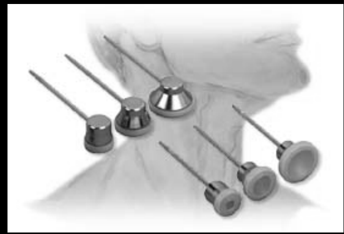






Simulations in the medical field

- Radiotherapy
  - Goal:
    Delivering the required therapeutic dose to the tumour area with high precision, while preserving the surrounding healthy tissue
  - Treatment planning usually performed with commercial software
    - MC *de facto* not used
  - Open issues
    - Precision:
      analytical models (speed constraints)
      geometry and material approximations
    - Cost
      Each (expensive) treatment planning software is specific to one technique / one source
    - Speed



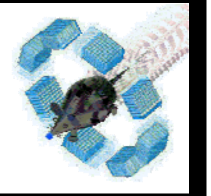
- Functional imaging
  - Goal:
    Scanner design, image reconstruction, scatter correction, protocol optimisation,…
  - Monte Carlo simulations are now widely used in parallel to analytical computations or experimental studies for PET/SPECT
  - Open issues
    - Many programs: PETsim, SimSET, EIDOLON, SIMIND, SimSPECT, SORTEO, MCMATV, PET-EGS, …
    - Speed

Two communities of simulation users

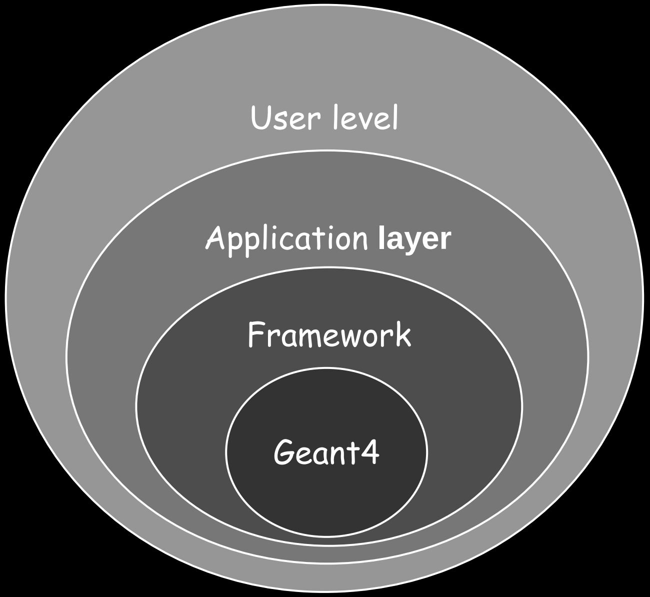
- Research groups
  - (Almost) No particle physics background
  - Heavy duties from hospital
  - Need for ease of use
- Clinical use
  - Commercial interests/pressures
  - Official protocols
  - Speed in treatment planning
  - User-friendly interfaces for hospital usage

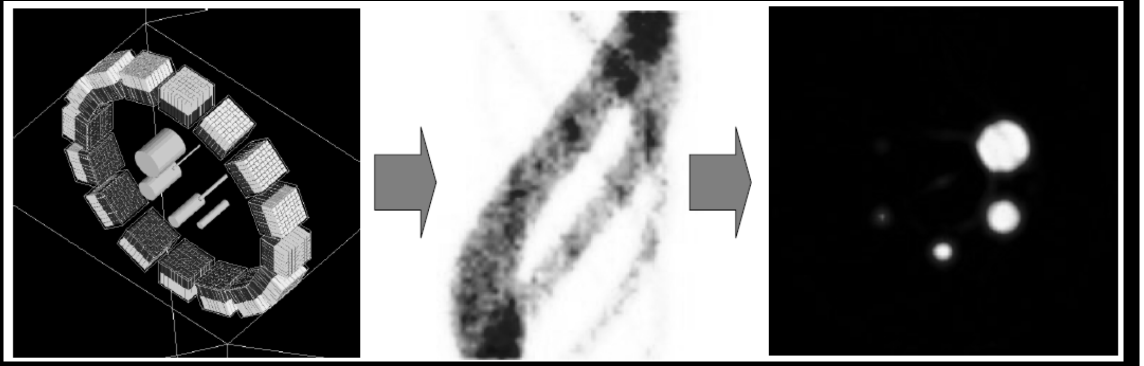
PET, SPECT: the example of GATE

Geant4 Application for Tomographic Emission



- Old approach: dedicated simulation programs (PETsim, SimSET, Eidolon,…)
  - Pros:
    Fast development, Optimized on application
  - Cons:
    Simple geometry, limited number of requirements, Limits in the physics description, Maintenance, upgrades?
- The main GATE features are:
  - Modelling of Time
    - decay kinetics, movement, randoms…
  - Ease-of-use, interactivity
    - use of a scripting language
    - Voxel geometries
    - Interface to STIR library
  - Versatility
    - geometry and simulation fully scripted
  - Modular design
    - new extensions easily added
  - Shared development
    - OpenGATE collaboration
    - long-term support

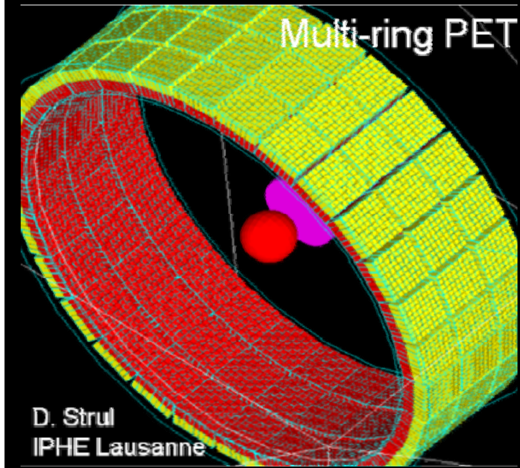


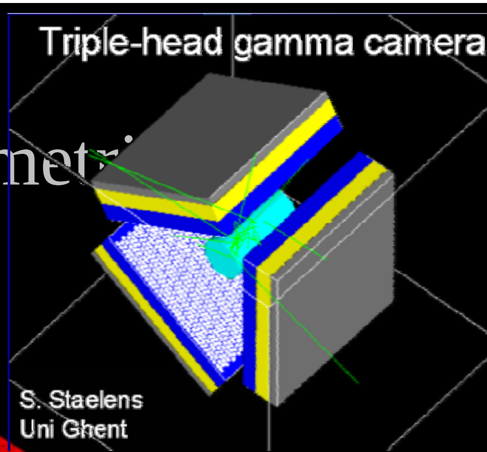


http://www.opengatecollaboration.org

GATE

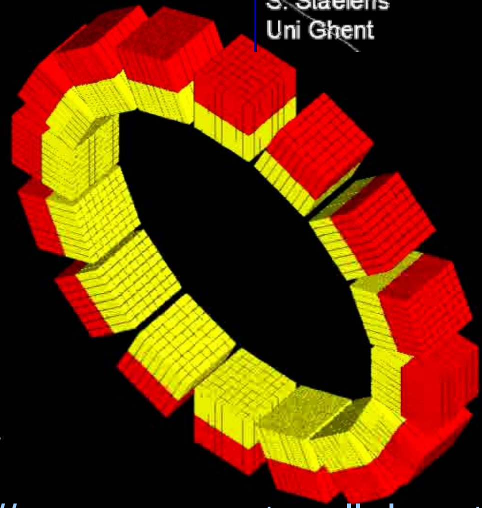
(moving) scripted geometries






```
# CRYSTAL
/block/daughters/name crystal
/block/daughters/insert box
/crystal/geometry/setXLength 30 mm
/crystal/geometry/setYLength 4.4 mm
/crystal/geometry/setZLength 4.4 mm
/crystal/setMaterial BGO
# REPEAT CRYSTAL INSIDE BLOCK
/crystal/repeaters/insert cubicArray
/crystal/cubicArray/setRepeatNumberX 1
/crystal/cubicArray/setRepeatNumberY 8
/crystal/cubicArray/setRepeatNumberZ 8
/crystal/cubicArray/setRepeatVector 0. 4.5 4.5 mm

# REPEAT BLOCK INSIDE RING
/block/placement/setTranslation 125. 0. 0. mm
/block/repeaters/insert ring
/block/ring/setRepeatNumber 18
```



A.S.Kirov, C.R.Schmidtlein, S.Nehmeh et al.
MSKCC and GE Medical Systems

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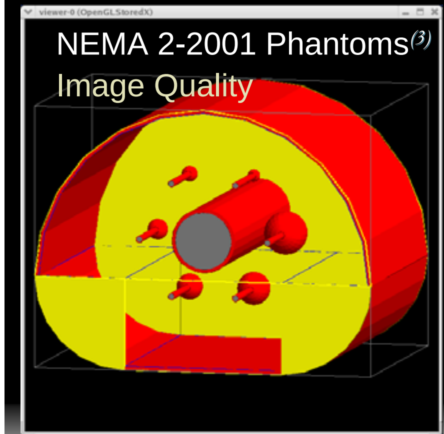
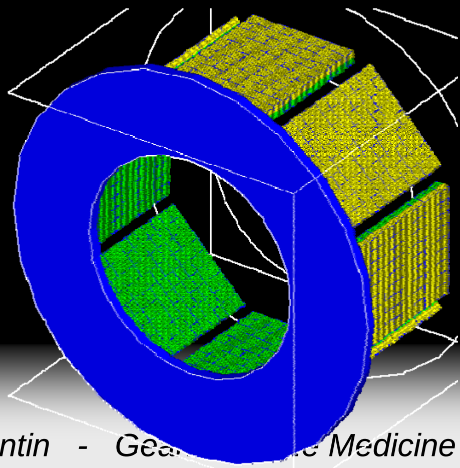
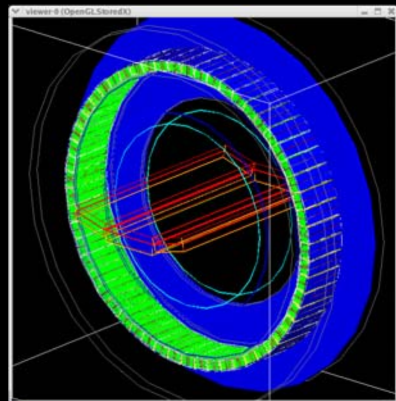
MSKCC and GE Medical Systems



http://www.opengatecollaboration.org



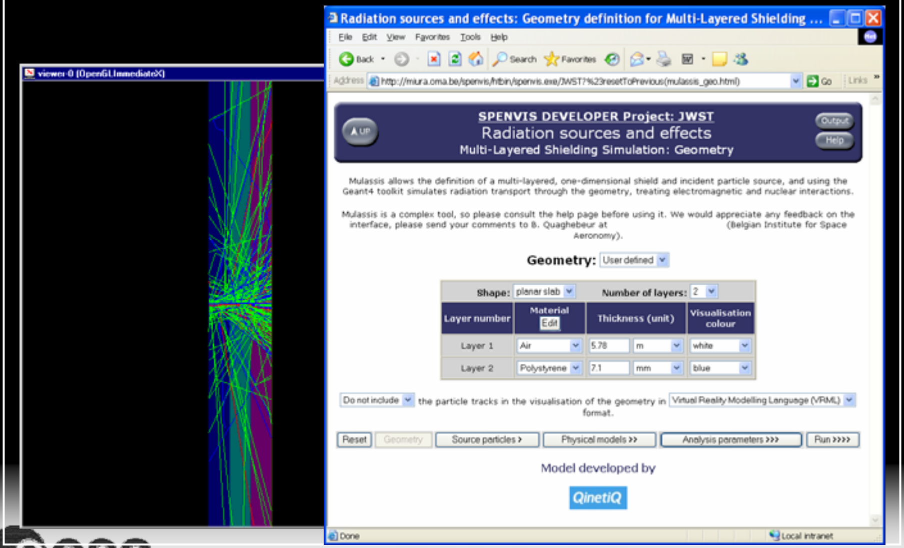
D.Guez, S.Kerhoas,
F.Bataille, C.Comtat,
S.Jan
DAPNIA and SHJF



Geant4-based analysis tools
MULASSIS, GRAS

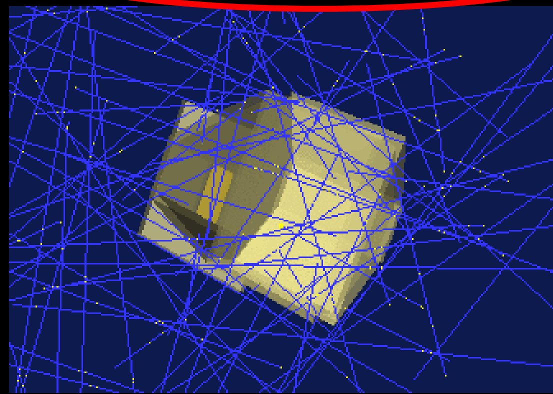
MULASSIS

- Layer Geometry
- Physics list choice
- Space primary spectrum: interface to SPENVIS
  - Trapped protons
  - Solar protons
  - Trapped electrons
  - …
- Analysis options
  - Dose
  - Pulse Height Spectrum
  - Dose equivalent NEW
- Web interface: www.spenvis.oma.be

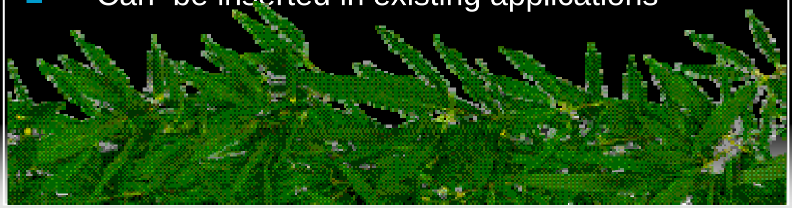


GRAS

- 3D geometry (GDML, C++)
- Analysis types
  - Dose, Fluence, NIEL, Charging, Activation… for support to engineering and scientific design
  - Dose Equivalent, Equivalent Dose,… for ESA exploration initiative



- Full Geant4 physics
- Different analyses set without re-compilation
- Modular / extendable design
- Can be inserted in existing applications

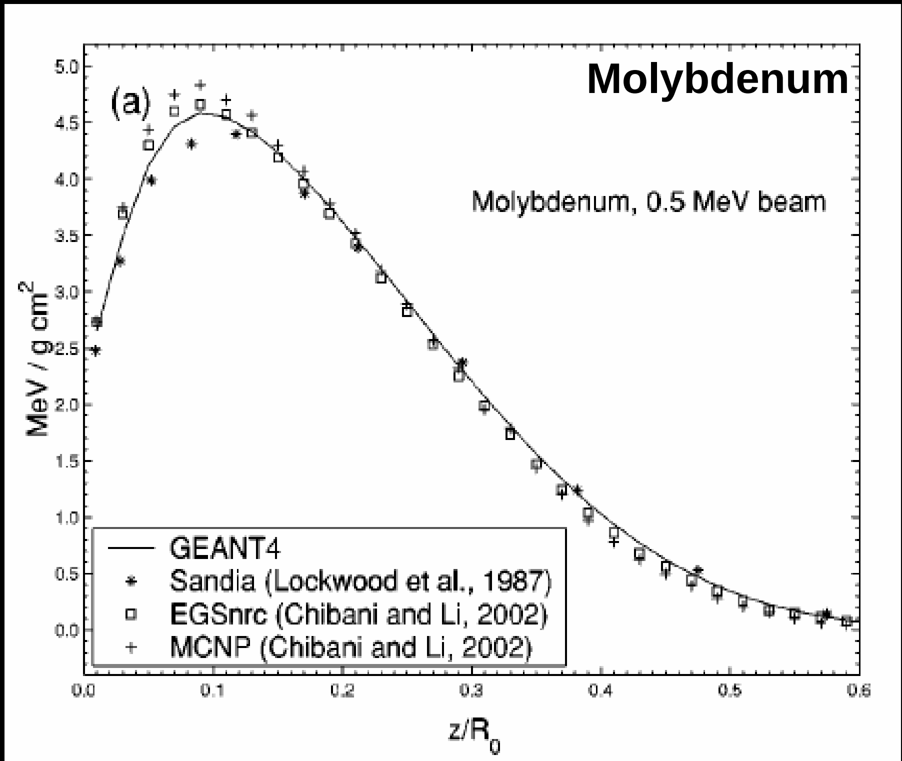


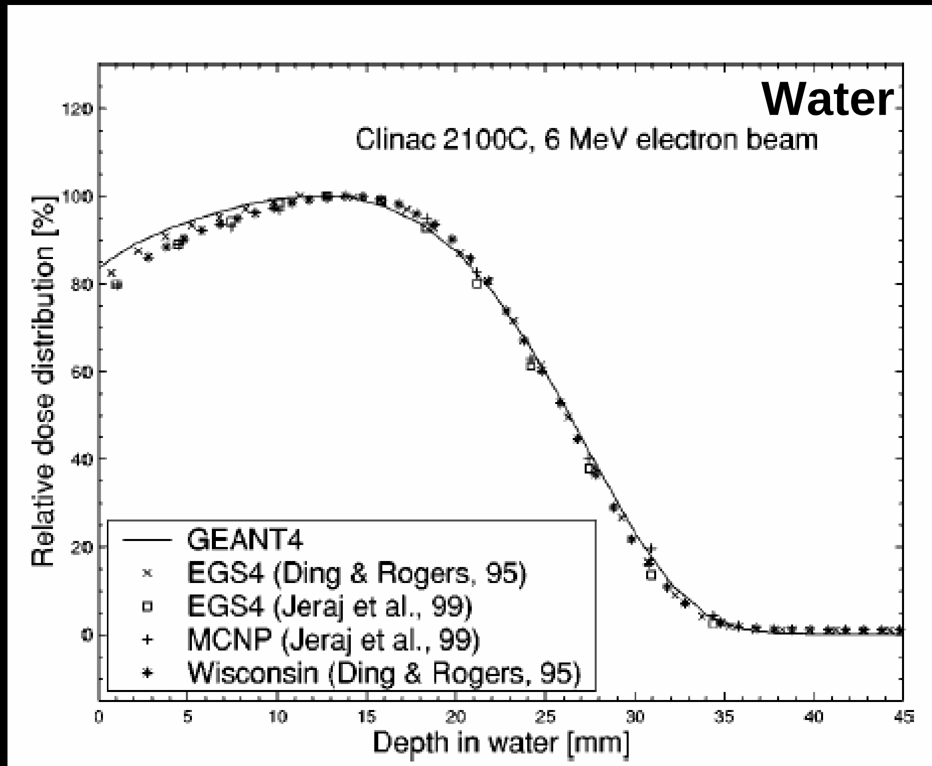
Validation issues

- Accurate dosimetry is at the basis of radiotherapy treatment planning
- Microscopic validation:
  - verification of Geant4 physics
- Dosimetric validation:
  - in the experimental context

Validation

Depth dose curves

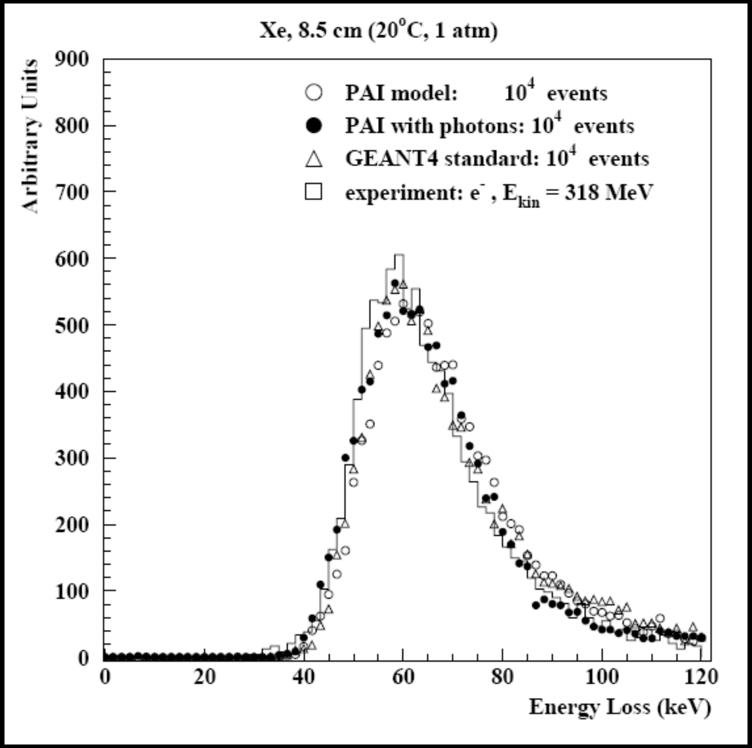


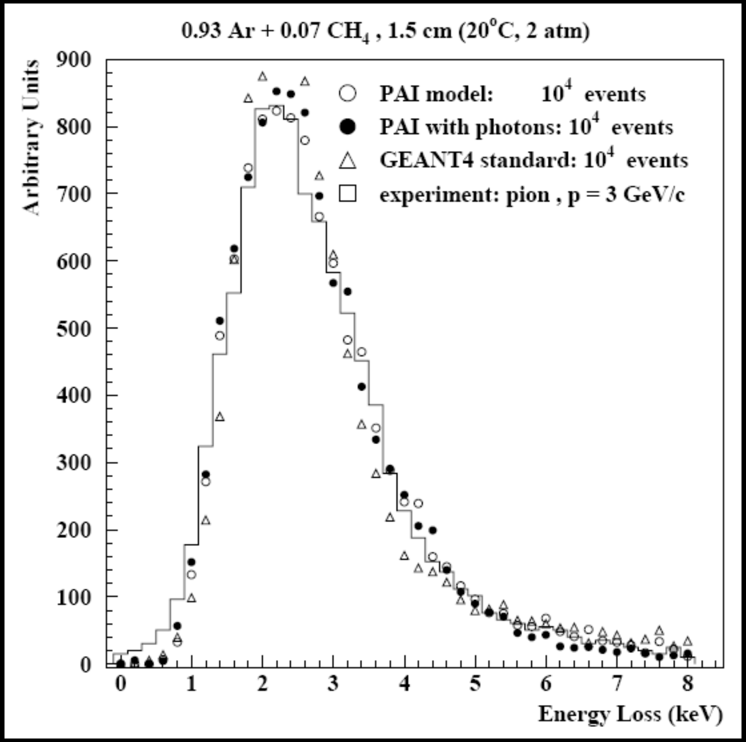


- Carrier et al, Med. Phys. 31, 484, (2004)

Validation
Microdosimetry

- Dose in Micro-volumes mimicked by gas chambers
- Geant4 PAI model



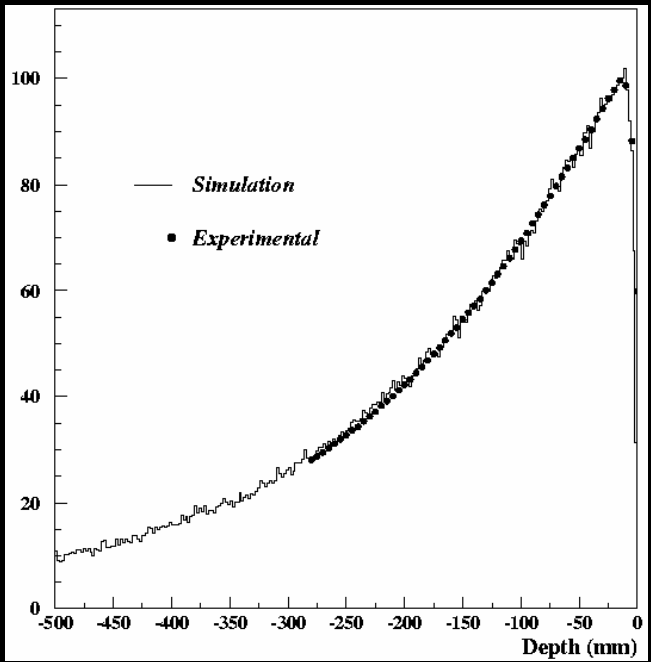


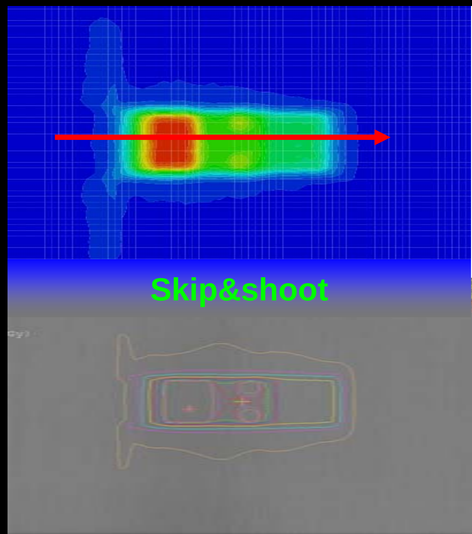
Validation
Dosimetry for IMRT

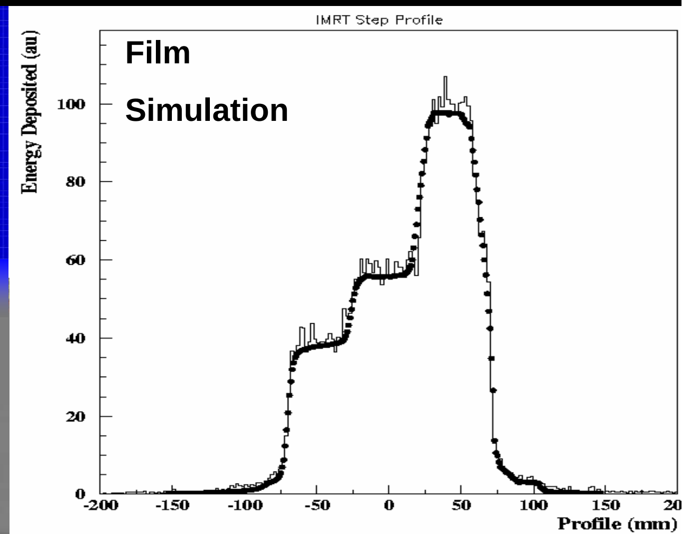
- Monte Carlo "all inclusive" simulation of IMRT treatments

Scielzo G, Chauvie S, Stasi M, Emanuelli S, Gabriele P
Medical Physics Unit -- Mauriziano Hospital - IRCC, Turin, Italy

Water PDD





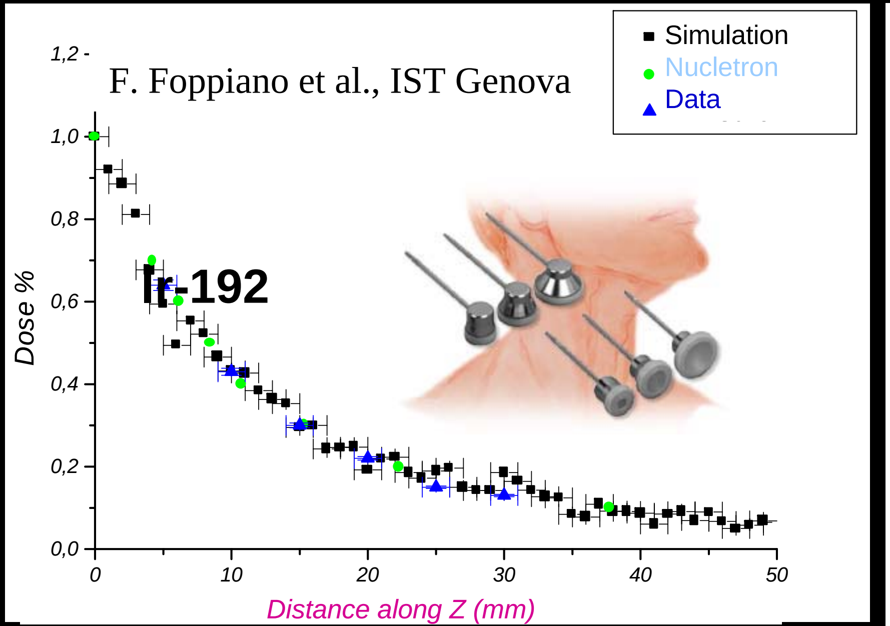


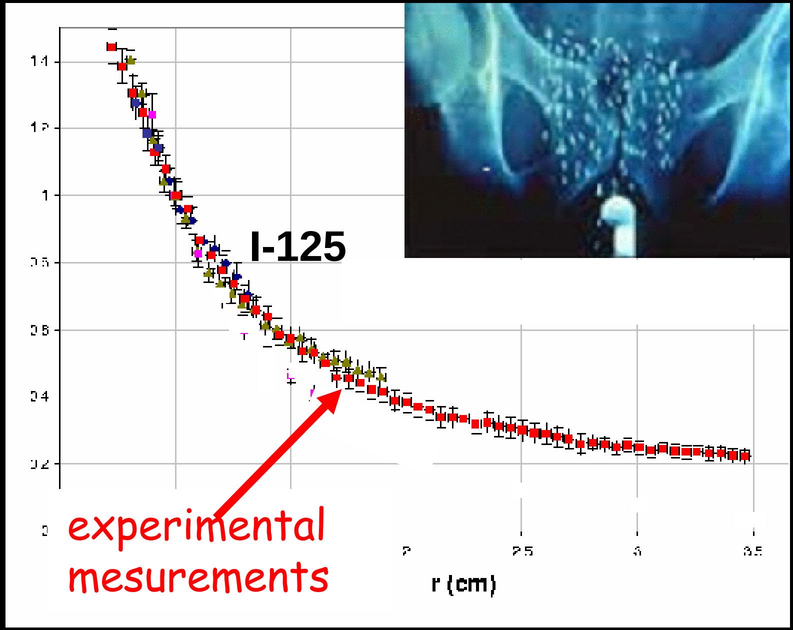
Validation

Dosimetry for Brachytherapy

- Geant4 simulation against experimental data

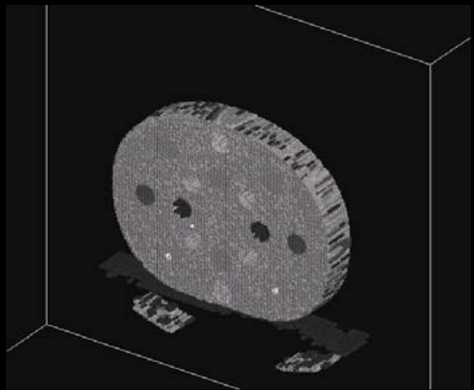
G. Ghiso, S. Guatelli
S. Paolo Hospital Savona



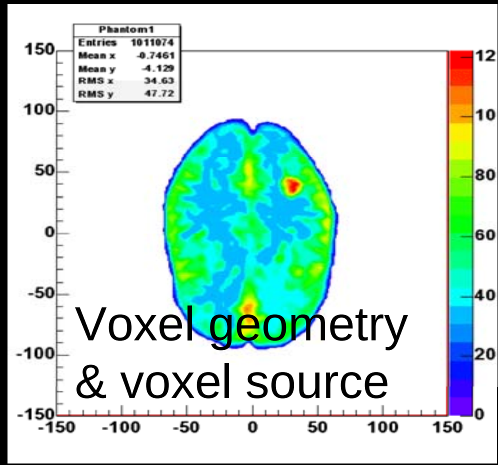


Patient models

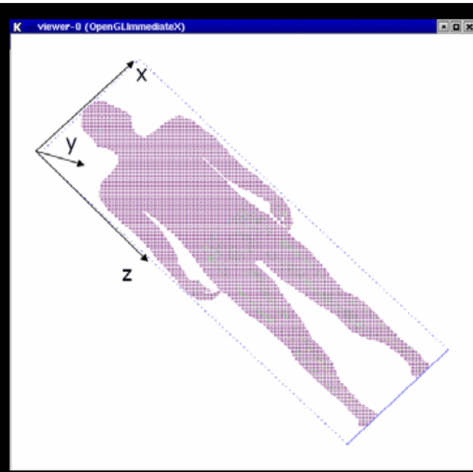
Voxel geometries



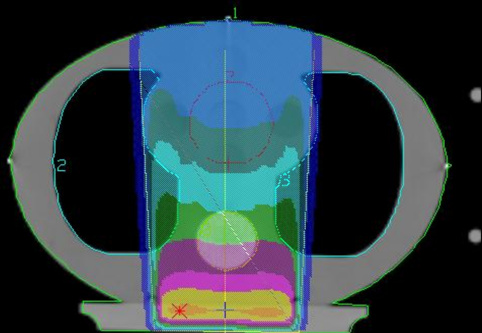
L. Archambault, L. Beaulieu, V.-H. Tremblay
(Univ. Laval and l'Hôtel-Dieu, Québec)



GATE – Hoffmann Phantom
S.Staelens, Gent University



Courtesy S.Paganini et al.,
CRCN, Recife, Brazil



Scielzo G, Chauvie S, Stasi M, Emanuelli S, Gabriele P
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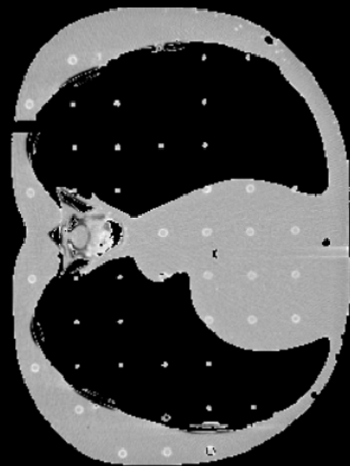


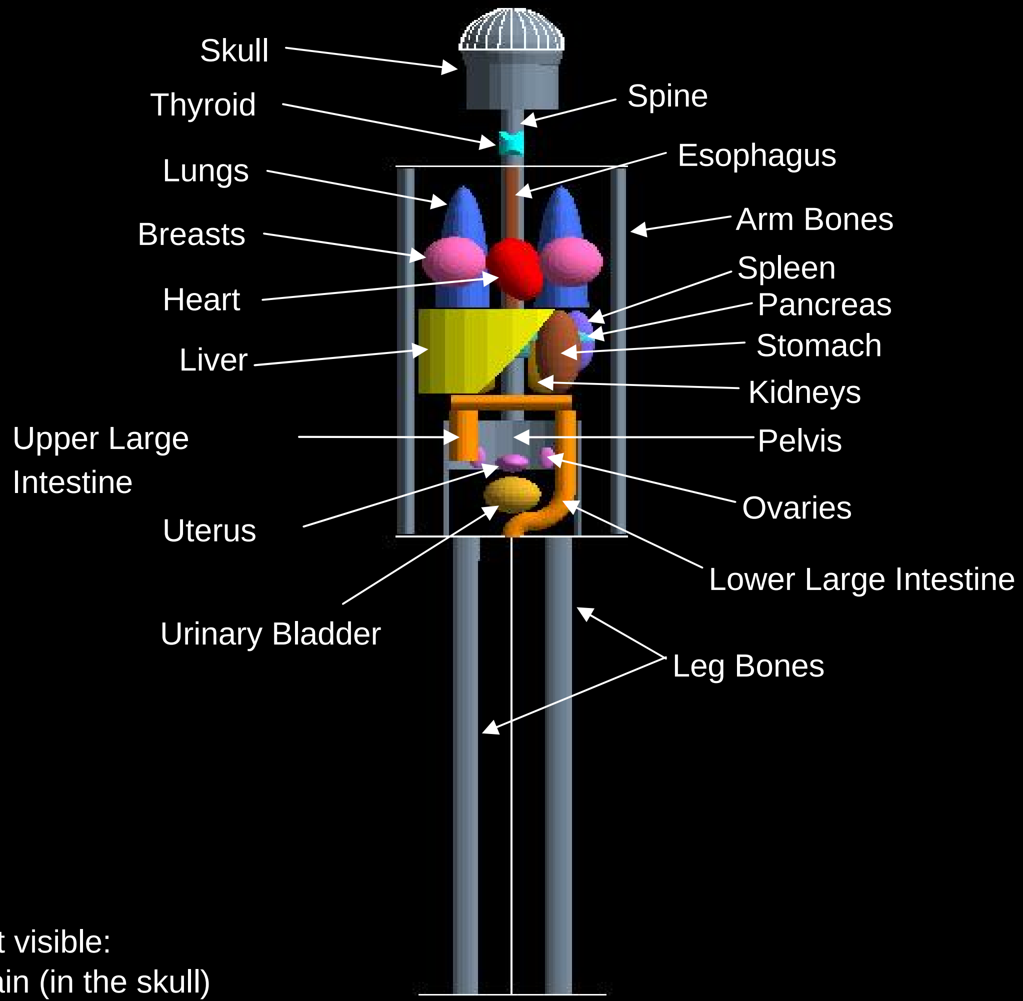
MC.Lopez, L.Peralta, P.Rodrigues, A.Trindade,
IPOFG-CROC Coimbra and LIP Lisbon

Patient models

Anthropomorphic phantoms

- Human phantom library
- Useful for radiation protection, therapy protocol studies

- Other phantoms developed by Geant4 users, not public
  - Gibbs Phantom (1984)
  - NORMAN Phantom (MRI data of a volunteer)
  - Zubal Phantom (from CT and MRI data)



- Analytical model

G.Guerrieri

INFN Genova

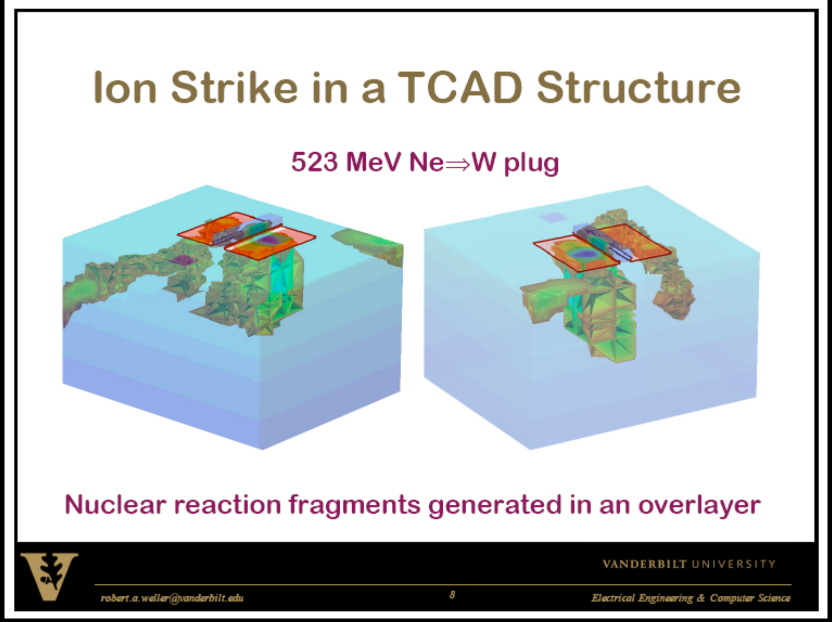
Geant 4 DNA

Not visible:
Brain (in the skull)

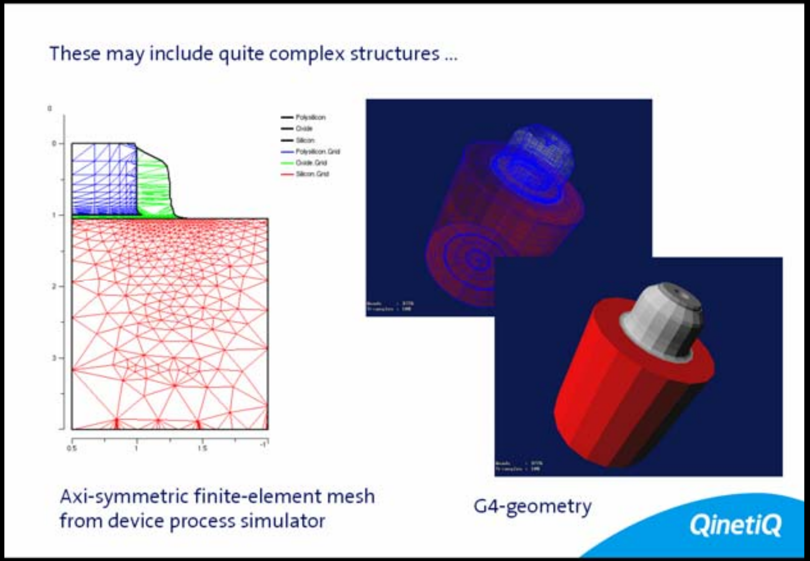
Patient and Experimental Setup models

Interfaces to CAD models

- Synergy medical / space applications ?
  - Geant4 extensions for study of effects to microelectronics
  - Microdosimetry



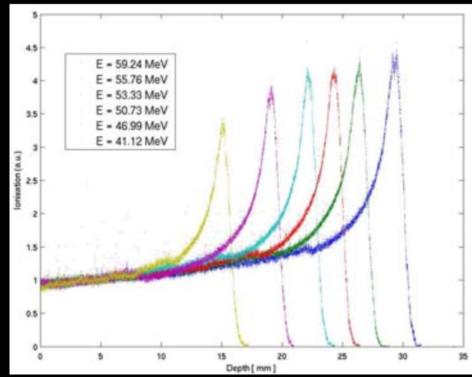
Vanderbilt University (2005)



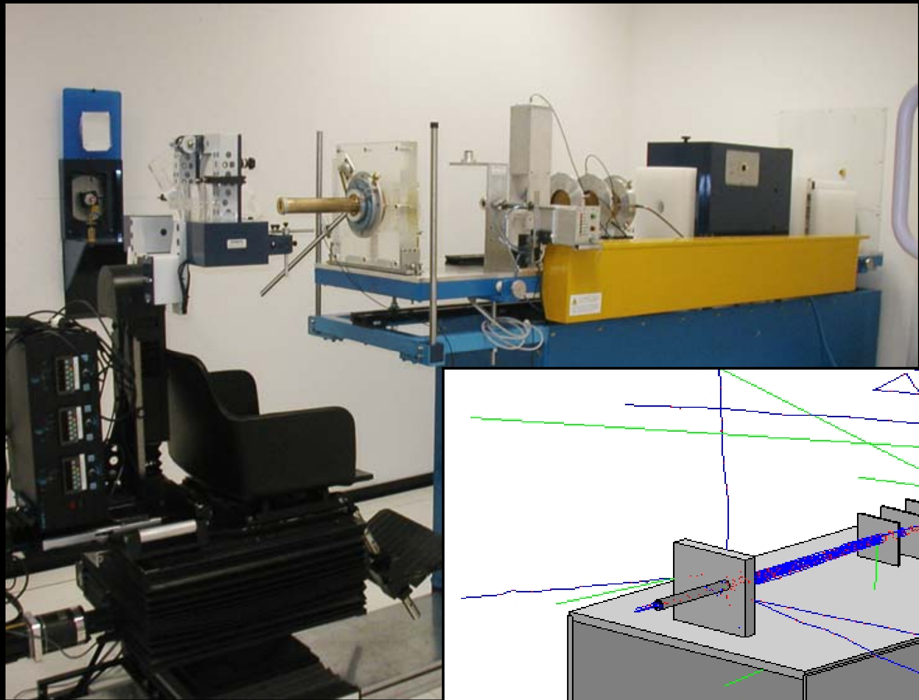
QinetiQ (2005)

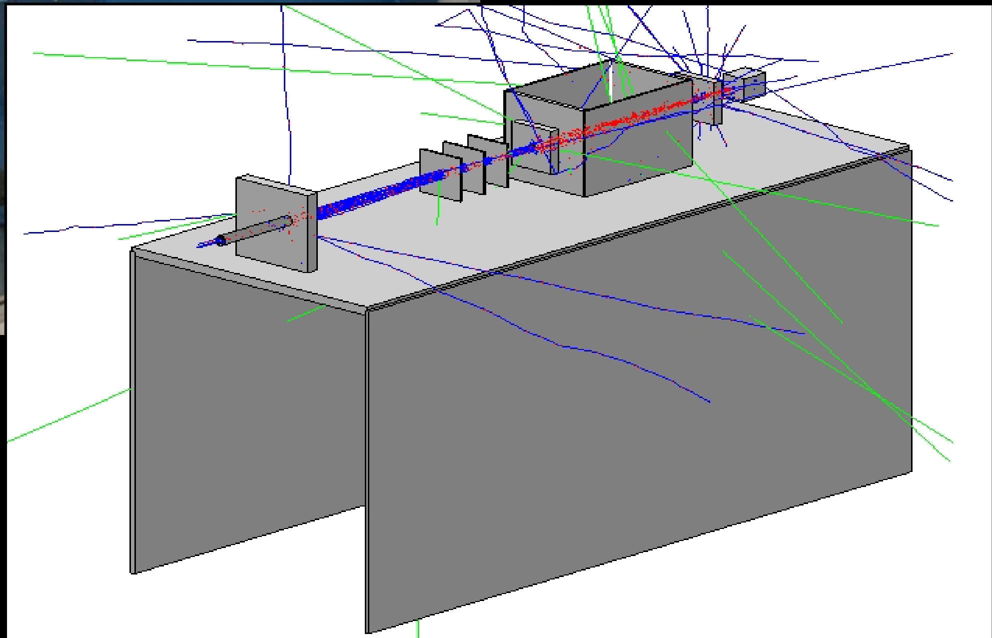
Complete simulations

CATANA hadrontherapy



- Proton Bragg peak validation





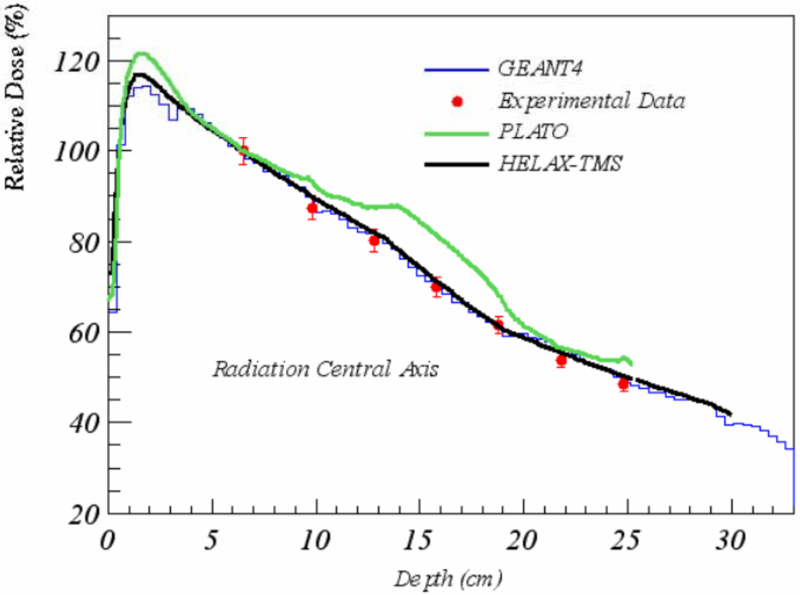
GEANT4 simulation

G.A.P. Cirrone, G. Cuttone
INFN LNS, CATANA project

Comparison with commercial treatment planning systems

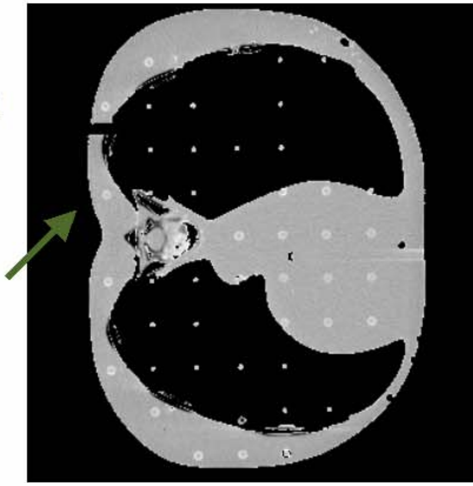
M. C. Lopes [1], L. Peralta [2], P. Rodrigues [2], A. Trindade [2]
[1] IPOFG-CROC Coimbra Oncological Regional Center - [2] LIP - Lisbon

CT-simulation with a Rando phantom
Experimental data obtained with TLD LiF dosimeter

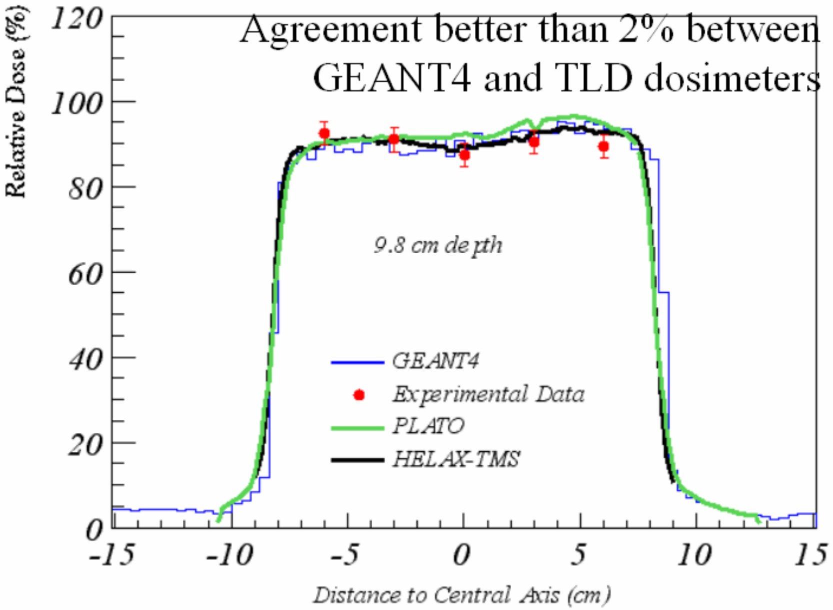


CT images used to define the geometry:

a thorax slice from a Rando anthropomorphic phantom



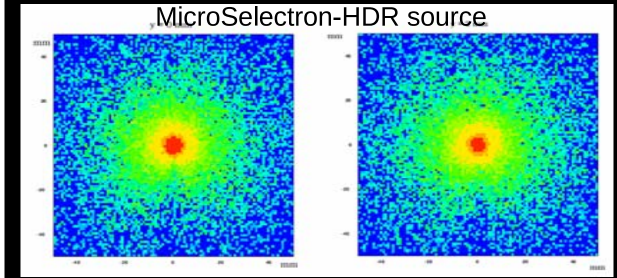
Agreement better than 2% between GEANT4 and TLD dosimeters



Complete simulations

Dosimetry for Brachytherapy

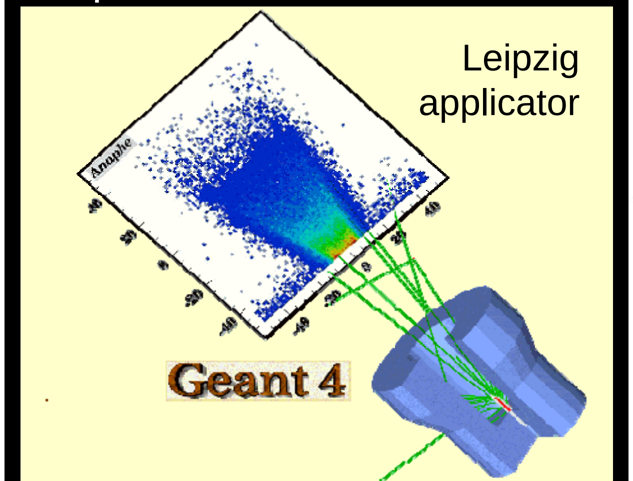
J. Moscicki, CERN

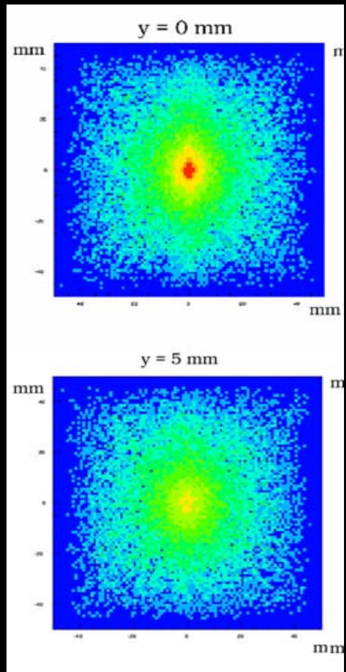


Endocavitary

Interstitial

Superficial





S.Guatelli, INFN Genova

DIANE

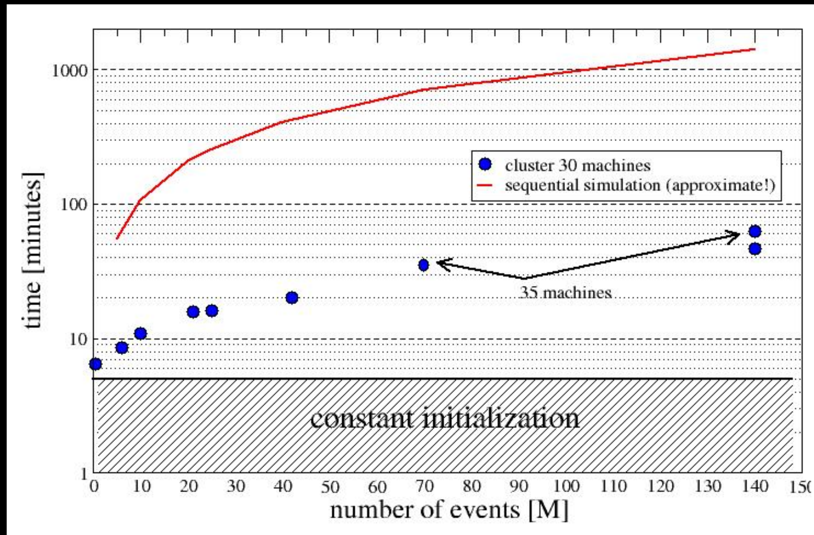
DIstributed **AN**alysis **E**nvironment

DIANE

Transparent access
to a distributed computing environment

Parallelisation

Access to the GRID



Space Exploration

On-going activities for a Geant4-based radioprotection programme

Sources

(Extra) Galactic and anomalous Cosmic Rays

Protons and Ions

<E> ~ 1 GeV, $E_{max} > 10^{21}$ eV

Continuous low intensity

Jovian electrons

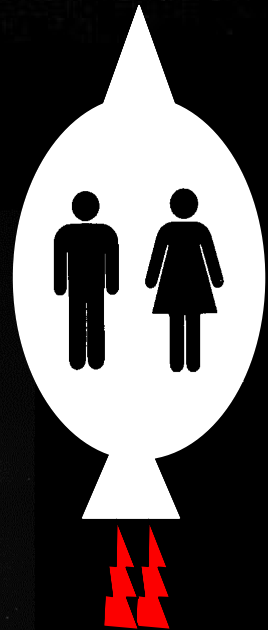
Dominant in quiet time

Solar radiation

Protons, some ions, electrons, neutrons, gamma rays, X-rays…

Softer spectrum

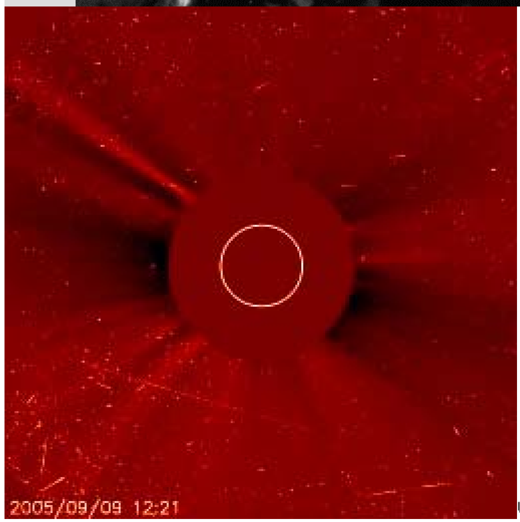
Event driven – occasional high fluxes over short periods.

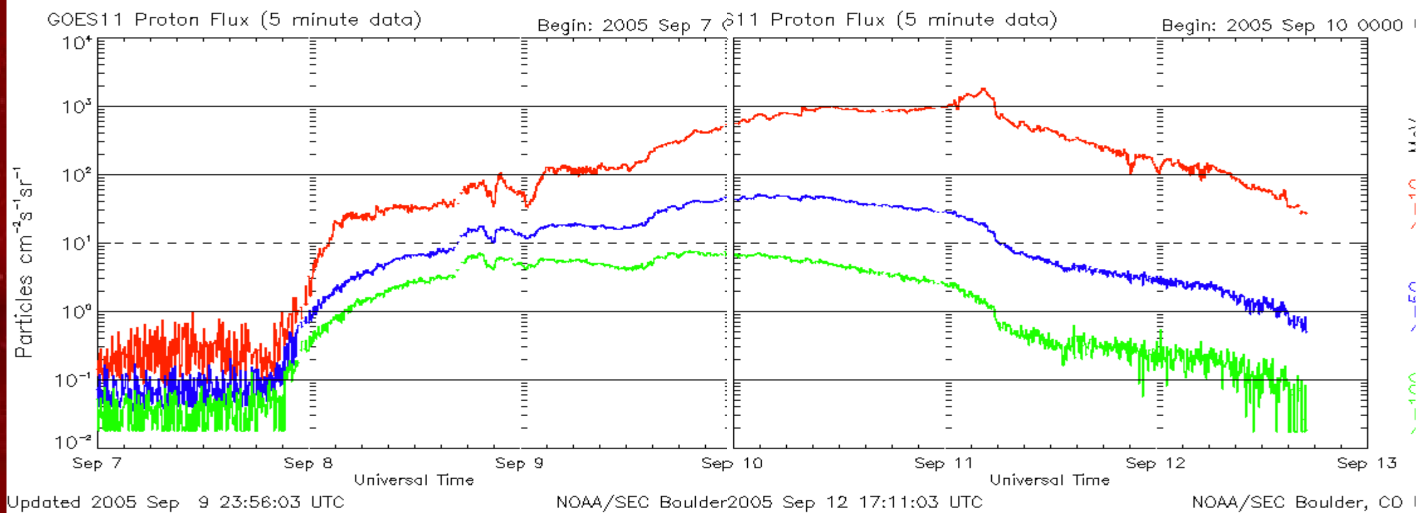


Trapped radiation

Electrons ~< 10 MeV

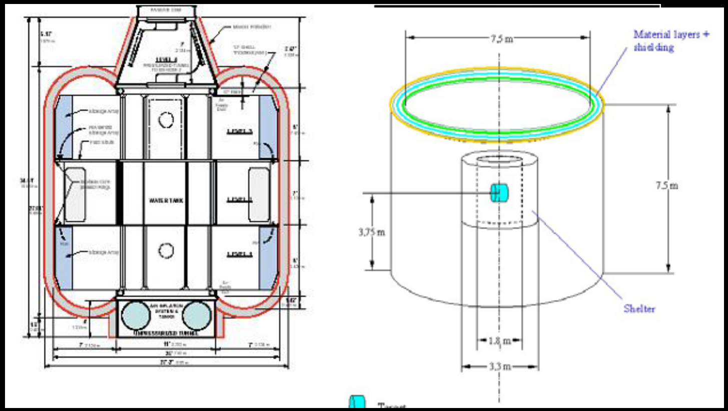
Protons ~< 10^2 MeV



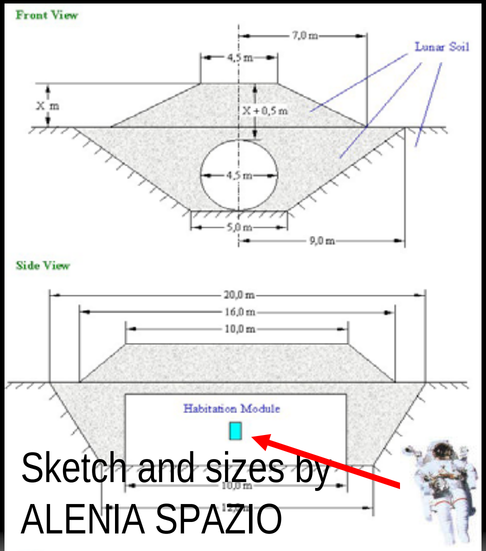


REMSIM

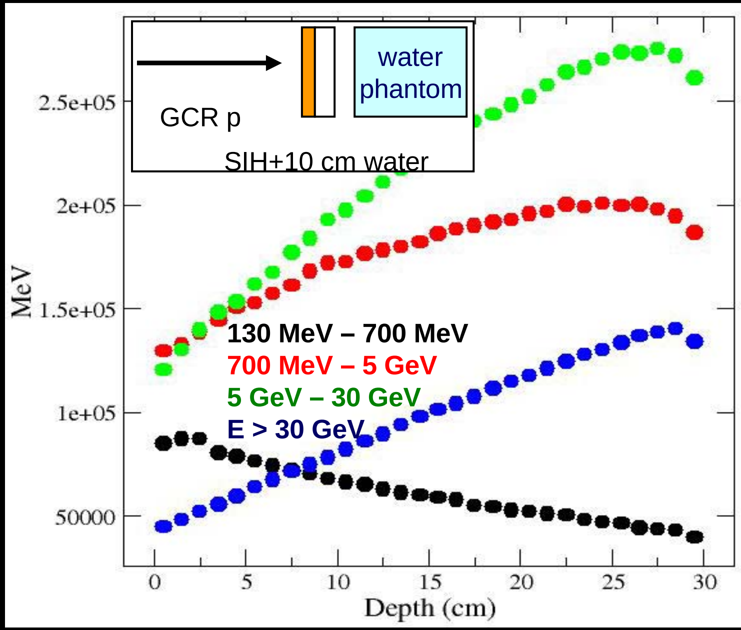
Radiation Exposure and Mission Strategies for Interplanetary Manned Missions



SIH - Simplified Inflatable Habitat



S.Guatelli, INFN Genova



- ESA Aurora Programme

DESIRE

Dose Estimation by Simulation of the ISS Radiation Environment

http://www.particle.kth.se/desire/

T. Ersmark[1], P. Carlson[1], E. Daly[2], C. Fuglesang[3], I. Gudowska[4], B. Lund-Jensen[1], R. Nartallo[2], P. Nieminen[2], M. Pearce[1], G. Santin[2], N. Sobolevsky[5]

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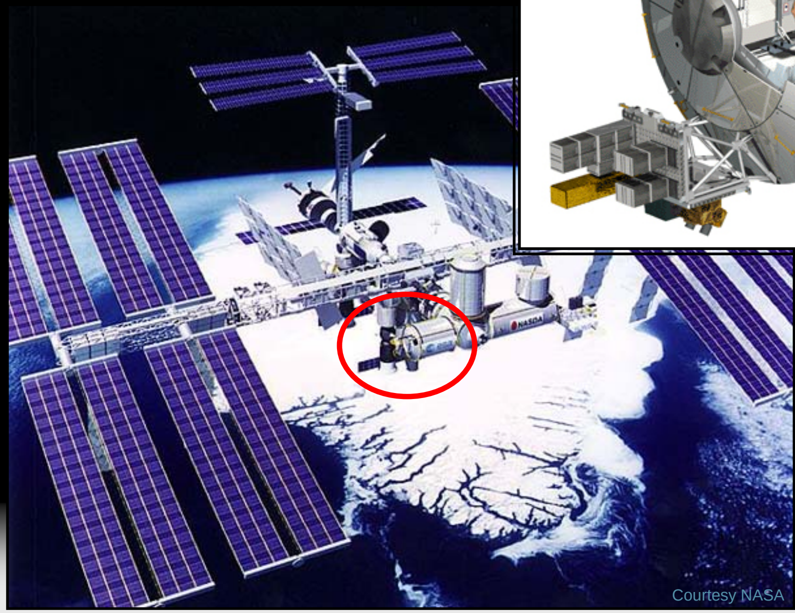
GOAL

Accurate Monte Carlo calculations (Geant4) of the radiation fields and doses to astronauts inside the European Columbus module of the International Space Station.

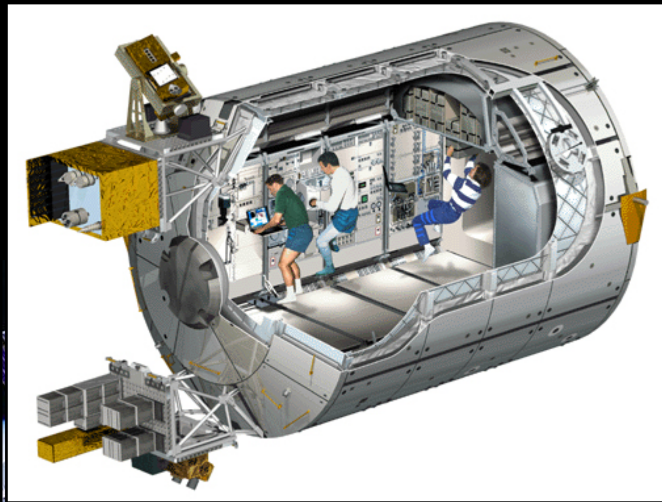
INCIDENT RADIATION

- Trapped protons
- Galactic cosmic rays
- Solar particle events
- Earth albedo neutrons



Courtesy NASA

ISS AND COLUMBUS

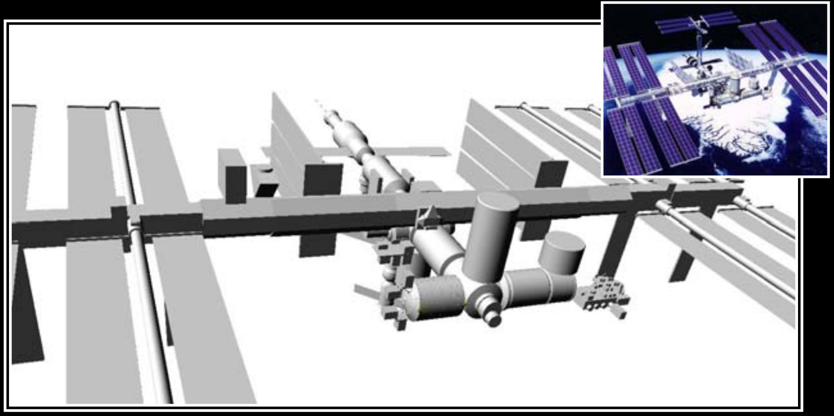


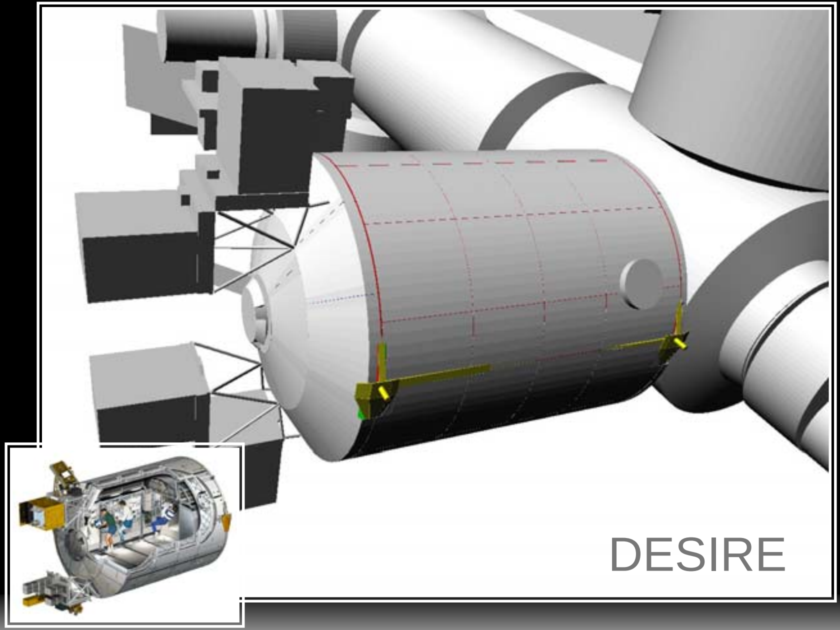
Courtesy ESA

- Circular orbit
- 400 km altitude
- 51.6º inclination
- 370 tons (14A)
- 110 by 75 m

GEANT4 GEOMETRY

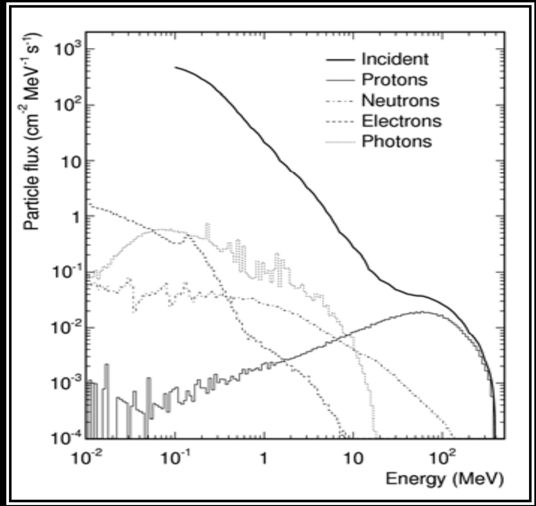
- ISS configuration 14A, 400 volumes
- Columbus, 800 volumes





CALCULATED DOSE RATES INSIDE COLUMBUS

- Spherical water phantom
  radius 0.5 m
- Trapped protons: 2.0 μGy/h
  SPENVIS, AP8-min
- GCR protons: 3.3 μGy/h
  CREME96, solar minimum



Example spectra of penetrating trapped protons and secondary particles.

Courtesy: T. Ersmark, KTH Stockholm

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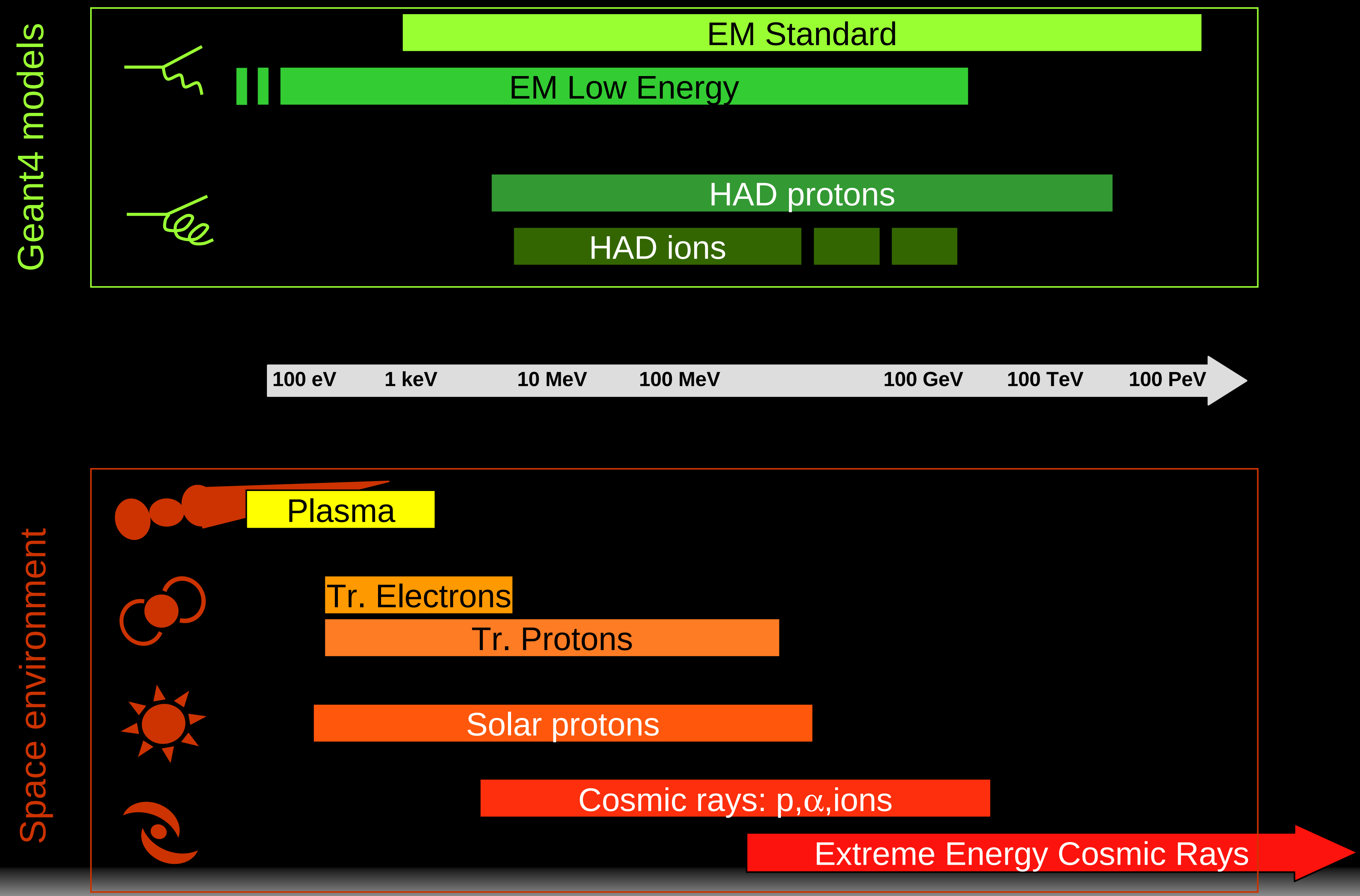
Space environment and Physics models



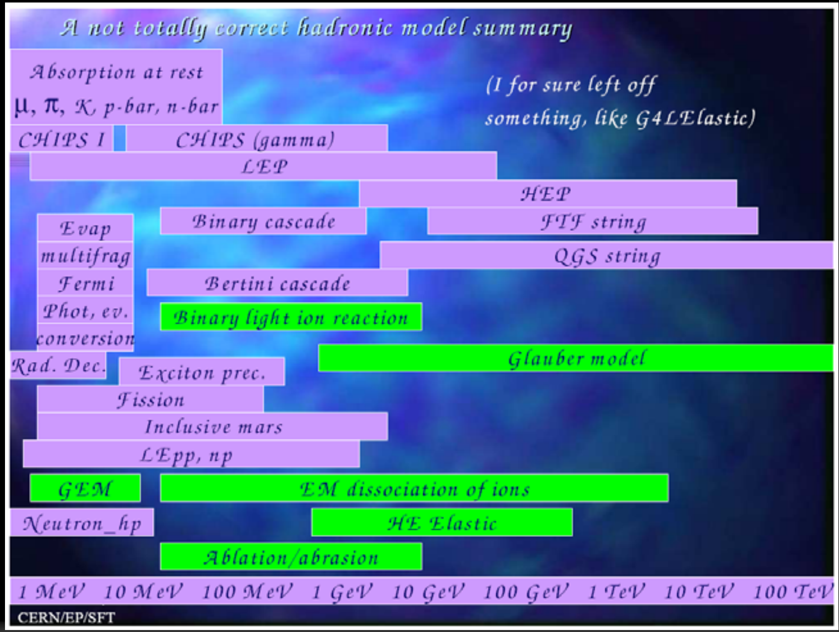
Physics developments

Low energy EM

- Models for photons, electrons, hadrons and ions to extend the coverage of electromagnetic interactions
  - photons and electrons down to 250 / 100 eV
  - protons, ions and antiprotons down to < 1 keV
- Specialised models taking into account photon polarisation
- Applications from high energy physics experiments to space science and astrophysics to the medical field

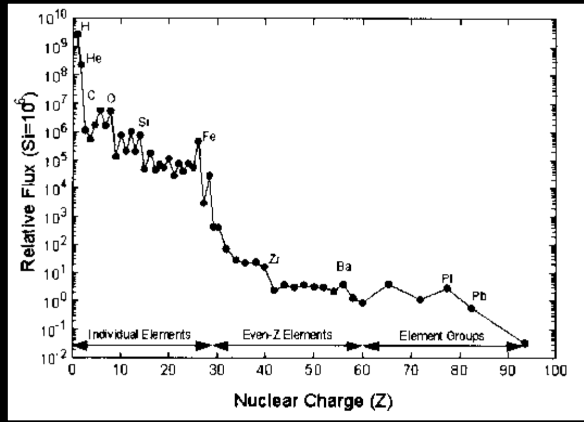
Hadronics

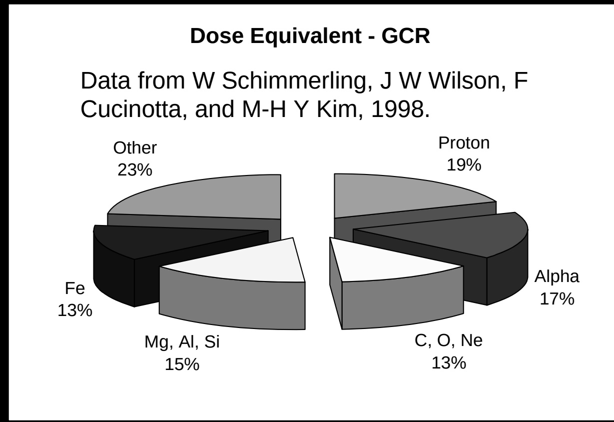
- Dose contribution typically 20-30%
- Important for background rate on science data analysis
- Recent new models
- See talk on Geant4 Hadronic Physics
- Ion importance: see next slide



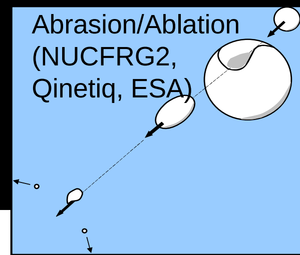
Physics developments

Ions

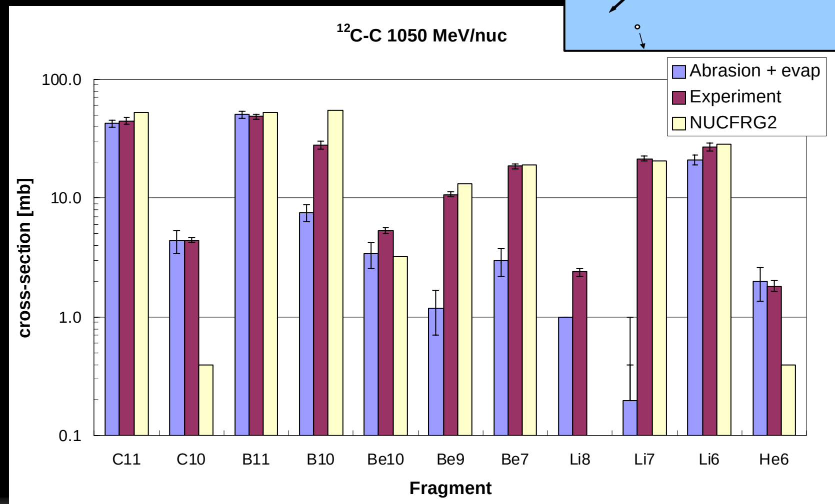




- Recent new models
  - EM: new ionisation model based on effective charge
  - Light Ion Binary Cascade
    - <~ 10 GeV/n
  - Abration / Ablation (Wilson)
    - P.Truscott, ESA – IONMARSE contract
  - New nuclear-nuclear cross section classes
    - P.Truscott



- Coming
  - Ion Quark Gluon String model
    - higher Z, higher Energy (<~ 100 GeV/n)



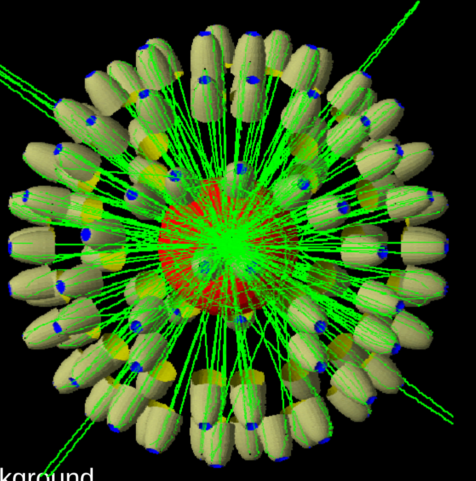
- Important for SEE studies, biological effects

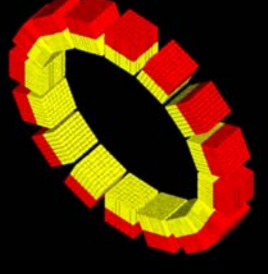
Physics development
Radioactive decay

- Complete radioactive decay chains
  - Emission of α, $\beta^{\pm}$, n, γ– and X-rays
  - Based on ENSDF data
  - Variance reduction techniques

- Medical applications
  - PET/SPECT, …
    - GATE,…

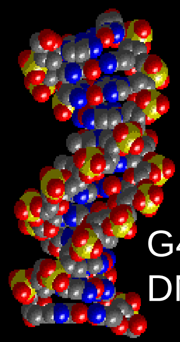
- Other fields
  - Underground experiments
    - Neutrino, Dark Matter, …
  - Space applications
    - Long term radioactivity contributor to background levels in γ- and X-ray instruments
    - Low background detectors
      - Integral,…





Geant4 DNA

- Damage mechanisms
- Interactions of Radiation with Biological Systems at the Cellular and DNA Level



G4 DNA

- Geant4 extension to simulate electromagnetic interactions in liquid water down to ~7.5 eV
  - e^-, p, H, He
- Validation : two independent computations performed by LPC Clermont & CENBG from litterature

e^- Total cross section	Energy deposit	Rutherford + screening factor		No models
e^- Angular distribution		Brenner	Emfietzoglou	
p energy distribution		Analytical	Tabulated	
e^-, H, He, He^+, He^{++} energy distribution		Tabulated		

Conclusions

- Geant4 simulations of radiotherapy and functional imaging are generally more precise than “standard” commercial tools

- There have been extensive validations and applications of Geant4-based tools for radiotherapy and functional imaging

- Synergies with space activities are useful to address critical areas of improvement
  - Interfaces
  - Physics model extensions

- Some issues still exist, which prevent tools based on advanced, precise MC codes (such as Geant4) from becoming part of the official protocols for treatment planning or image reconstruction. These include
  - Official validation
  - Friendliness of User Interfaces
  - Computation speed

- On-going activities are addressing these open issues. Work includes:
  - CAD model interface
  - Deployment on the GRID