Geant4 in Medical Physics

Joseph Perl
Stanford Linear Accelerator Center

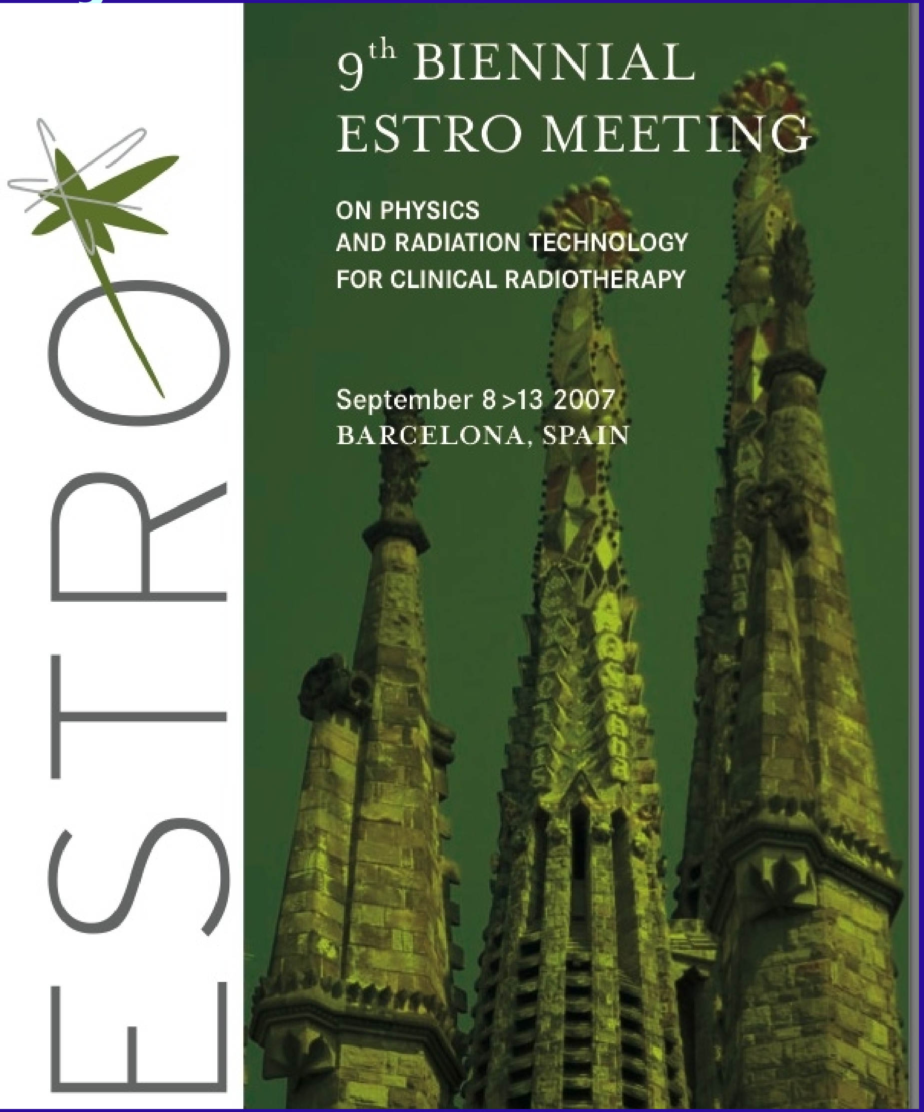
Geant4 Workshop

Hebden Bridge, UK

11 September 2007

Why is this man Speaking Today?

- My personal belief is that this talk would be better given by a senior medical physicist
- But most of that community is in Barcelona this week



Geant4 is Still a Newcomer

- Frank Verhaegen of McGill University writing in MedicalPhysicsWeb last year


GEANT4: a new giant in medical physics – MedicalPhysicsWeb

http://medicalphysicsweb.org/cws/article/opinion/25856

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LATEST TALKING POINT ARTICLES

- RTOG: a physics perspective
- The great IGRT debate
- Proton therapy: practice makes perfect
- Imaging and radiotherapy: getting closer all the time
- A virtual opportunity for interventional radiology

RELATED LINKS

- GEANT4 tutorial course, McGill University
- McGill Medical Physics Unit
- CR-UK Targeting and Imaging Group

RESTRICTED LINKS

- *Nucl. Instr. Meth. Phys. Res. A* **506** 250
- *Med. Phys.* **32** 1696

TALKING POINT

Sep 11, 2006

GEANT4: a new giant in medical physics

Have you ever seen the panic-stricken expression on the face of graduate students when you tell them they are expected to work with Monte Carlo particle-transport codes written in a language called FORTRAN? This is usually instantly followed by a suspicious gaze from the student, cataloguing you with the other dinosaurs in the local natural history museum.

Let's face it: young people entering the field of medical physics don't know FORTRAN and are not inclined to like FORTRAN, let alone its dialects that are used in some Monte Carlo codes for medical physics. Popular Monte Carlo codes in medical physics research - such as EGS, MCNP and PENELOPE - are all written in FORTRAN. This was the situation until recently. Enter GEANT4 (GEometry ANd Tracking; S Agostinelli *et al.* 2003), a fully object-oriented Monte Carlo "toolkit" (as the authors prefer to call it) written entirely in C++.

GEANT4, just like the older MCNP and EGS codes, was created for purposes outside the field of medical physics. The main players in its development are in the discipline of high-energy physics, combining the efforts of more than 100 workers from facilities such as CERN in Europe, KEK in Japan and SLAC in the US (where EGS was originally developed).

Model behaviour

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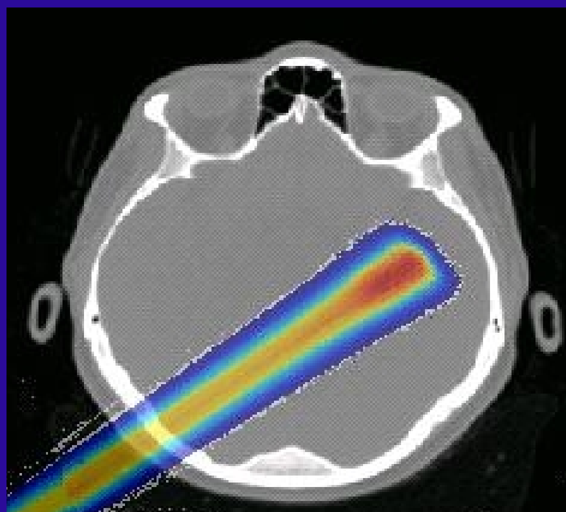
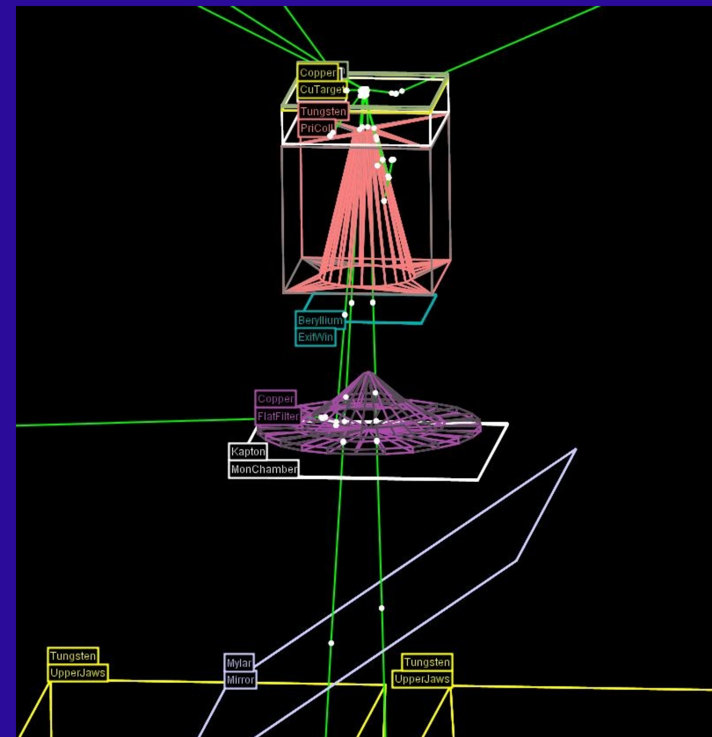
Uses of Monte Carlo within Med Phys

- Characterizing machines and sources
- Treatment planning
- Retrospective studies
- Imaging

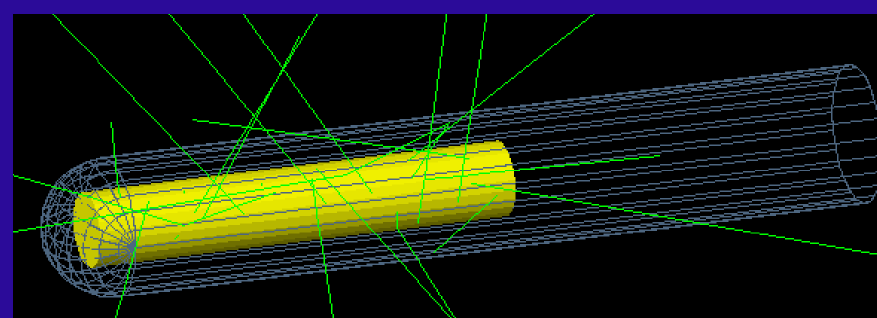
Characterizing machines and sources

- Beam Therapies





- Brachytherapy



Source: Emily Poon, Frank Verhaegen, McGill University

Example from ESTRO

DEVELOPMENT OF METHODS FOR THE DESIGN OF ELECTRON COLLECTION SYSTEMS FOR SCANNED THIN-TARGET BREMSSTRAHLUNG IMRT

R. Holmberg[1], B.Andreassen[1], A.Brahme[1]

[1] KAROLINSKA INSTITUTE, *Medical Radiation Physics, Stockholm, Sweden.*

Purpose/Objective

Driven by the need for more accurate and cost-effective therapeutic methods, IMRT is rapidly being deployed at radiation therapy departments. An efficient way of conducting IMRT is by using narrow scanned photon beams, produced from thin bremsstrahlung production targets. Thereby the photon penumbra and pencil beam half width are minimized, while the mean photon energy in the beam is increased, thus enhancing the quality of PET-CT dosimetry. This approach, however, imposes the additional problem of deflecting and stopping an intense stream of high-energy transmitted electrons. In this work, methods for resolving this problem was developed and applied to different treatment unit configurations.

Materials/Methods

To optimize the geometrical shape of the electron collector together with the scanning and purging magnetic fields, a composite framework, including CAD (Solid Edge 3D), electromagnetic field simulation (Opera 3D) and Monte Carlo simulation (GEANT4), has been set up. Codes have been developed to integrate the geometry from the CAD software as well as the magnetic fields from the electromagnetic design software in the Monte Carlo simulation,

Example from ESTRO

INVERSE TREATMENT PLANNING FOR THE MRI-ACCELERATOR BASED ON PRE-CALCULATED BEAMLET KERNELS

A. Raaijmakers[1], B.Hardemark[2], C.Raaijmakers[1], B.Raaymakers[1], J.Lagendijk[1]

[1] UMC Utrecht, *Radiation Oncology, Utrecht, Netherlands.*

[2] RaySearch Laboratories, *Stockholm, Sweden.*

Purpose/Objective

At the UMC Utrecht, in cooperation with Elekta and Philips Medical Systems, we are developing a combined 1.5 T MRI-6 MV linear accelerator system. The design is such that the patient will be irradiated in the presence of a magnetic field. This will influence the dose distribution: The build-up distance is reduced and the penumbra becomes asymmetrical. The dose in front of tissue-air boundaries is increased by electrons being forced back into the tissue due to the Lorentz Force. This will be referred to as 'electron return effect' (ERE). The dose increase in front of air cavities can be counterbalanced with the dose decrease behind air cavities if

Example from ESTRO

DESIGN AND EVALUATION OF AN HDR SKIN APPLICATOR WITH FLATTENING FILTER

J. Pérez-Calatayud[1], D.Granero[1], J.Gimeno[1], V.González[1], F.Ballester[2], E.Casal[3], M.Pujades[4], R.van der Laarse[5], V.Crispín[6]

[1] La Fe University Hospital, *Radiation Oncology Department, Valencia, Spain.*

[2] University of Valencia-IFIC, *Department of Atomic, Molecular and Nuclear Physics, Valencia, Spain.*

[3] University of Valencia-IFIC, *Department of Atomic, Molecular and Nuclear Physics and IFIC, Valencia, Spain .*

[4] University of Valencia, *Department of Atomic, Molecular and Nuclear Physics and IFIC, Valencia, Spain .*

[5] Nucletron BV, *Veenedaal, The Netherlands.*

[6] Fundación IVO, *Radiotherapy, Valencia, Spain.*

Purpose/Objective

The purpose of this study is: (I) To design flattening filters for the Leipzig applicators (Nucletron). These tungsten filters aim to flatten the heterogeneous dose distribution. (II) To manufacture prototypes of these new Leipzig + filters. (III) To estimate the dose rate distributions for these new applicators by means of the Monte Carlo method, (IV) To experimentally verify these distributions with a

Example from ESTRO

DOSIMETRY OF A NEW CO-60 SOURCE MODEL FOR HDR BRACHYTHERAPY

J. Gimeno[1], J.Pérez-Calatayud[1], D.Granero[1], V.González[1], F.Ballester[2], E.Casal[2], M.Pujades[3]

[1] LA FE UNIVERSITY HOSPITAL, *Radiation Oncology Department, Valencia, Spain.*

[2] UNIVERSITY OF VALENCIA-IFIC, *Department of Atomic, Molecular and Nuclear Physics, Valencia, Spain.*

[3] UNIVERSITY OF VALENCIA-CSIC, *Department of Atomic, Molecular and Nuclear Physics and IFIC, Valencia, Spain.*

Purpose/Objective

High dose rate (HDR) brachytherapy is a highly extended practice in clinical brachytherapy. Quality dose rate distribution datasets of the HDR sources used in a clinical treatment are required. Because of the different source designs, a specific dosimetry dataset is required for each source model. The purpose of this study is to obtain the dosimetric characteristics of a new Co-60 source used in brachytherapy and manufactured by BEBIG (Eckert & Ziegler BEBIG GmbH, Germany).

Materials/Methods

The Monte Carlo code GEANT4 has been used to obtain the dosimetric characteristics of the BEBIG Co-60 source following the AAPM recommendations for high energy sources. The physics "low energy" models of GEANT4 have been used. These physics models

Example from ESTRO

PHYSICAL ANALYSIS OF I-125 SEED USED FOR BRACHYTHERAPY– MODEL 6711 AND STM 1251; A GEANT4 STUDY

T. Hanada[1], S.Katsuta[1], A.Yorozu[1], T.Ohashi[1], T.Sato[2], T.Otsuka[1], R.Kikumura[1], K.Maruyama[3]

[1] NATIONAL HOSPITAL ORGANIZATION TOKYO MEDICAL CENTER, *Radiology, Tokyo, Japan.*

[2] THE CANCER INSTITUTE HOSPITAL OF JFCR, *Radiation Oncology, Tokyo, Japan.*

[3] KITASATO UNIVERSITY, *Graduate School of Medical Sciences, Sagamihara, Japan.*

Purpose/Objective

In Japan, 2 types of seed such as model 6711 and STM 1251 are provided. In these 2 seeds, internal components of seed designs are different, as a consequence of featuring the specific physical property. The purpose of this study is to analysis the difference of physical property in these 2 seeds. For this approach, energy spectra, radial dose function $g_L(r)$ and anisotropy function $F(r, \theta)$ were investigated.

Materials/Methods

In this work, particle transport simulations were performed with the Geant4 version 8.1 toolkit. The primary photon spectra were taken

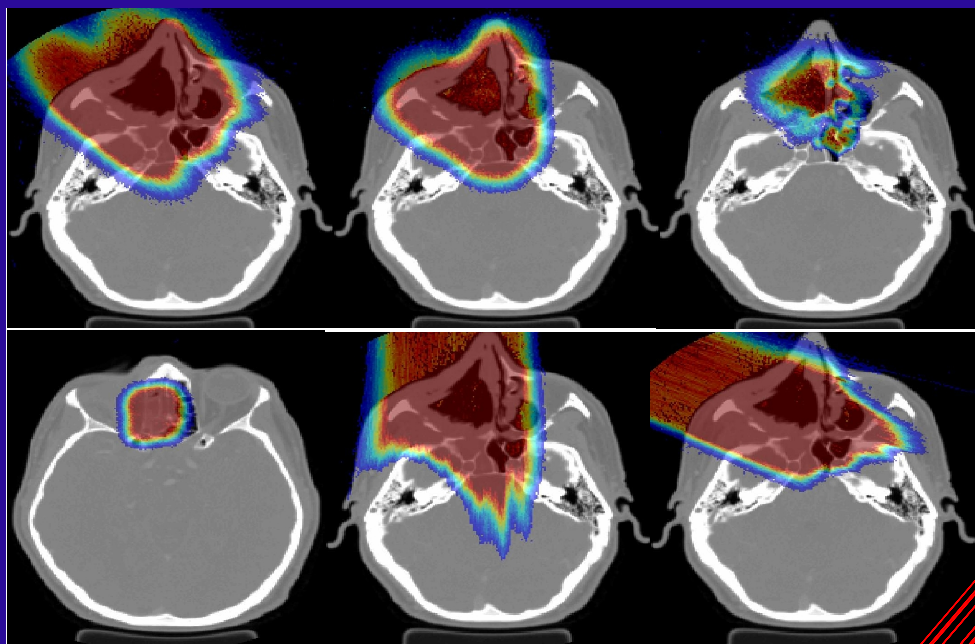
Talks Later Today

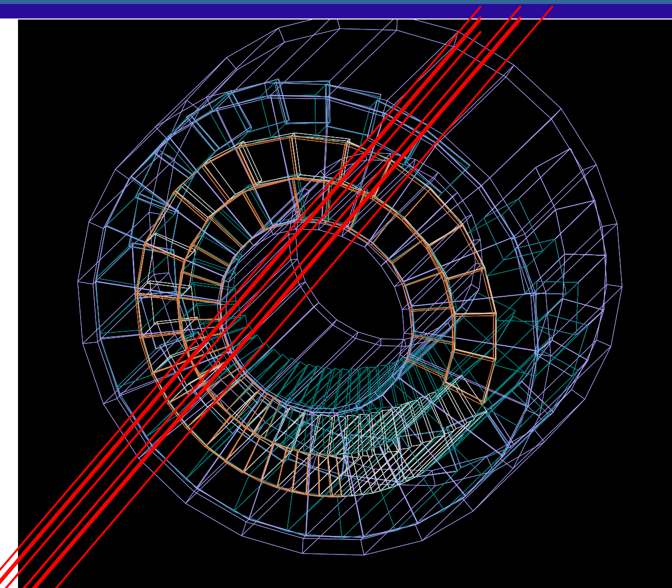
- **Validation of dose deposited for 125I brachytherapy sources (low-energy photons)**
  - by Lydia MAIGNE (LPC, Clermont Ferrand, France)
  - Thursday 14:00 - 14:20
- **Geant4 simulation of HIBMC facility using DICOM**
  - by Tomohiro Yamashita (Kobe University, Japan)
  - Thursday 16:30 - 16:50

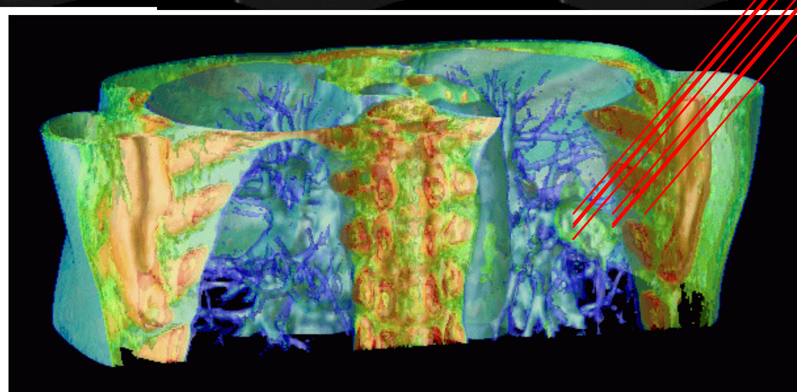
Treatment Planning

- Treatment sequence
  - 1) imaging
  - 2) planning
  - 3) simulation
  - repeat 2 and 3 as needed
  - mostly use parameterized models
  - might use parameterized for first iterations of 1 and 2 and then MC for validating the plan
  - Time available depends on the kind of therapy, from 20 min to one day.
- MC is superior to parameterized models in cases of heterogeneity:
  - tissue/air interface, such as lung
  - complicated tissue/bone interfaces such as in head and neck cases
  - near implants, such as treating prostate when also have artificial hip

GEANT4 based proton dose calculation in a clinical environment: technical aspects, strategies and challenges







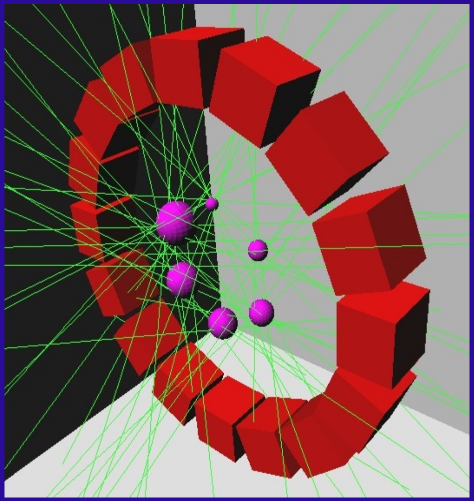
Harald Paganetti

MASSACHUSETTS GENERAL HOSPITAL

HARVARD MEDICAL SCHOOL

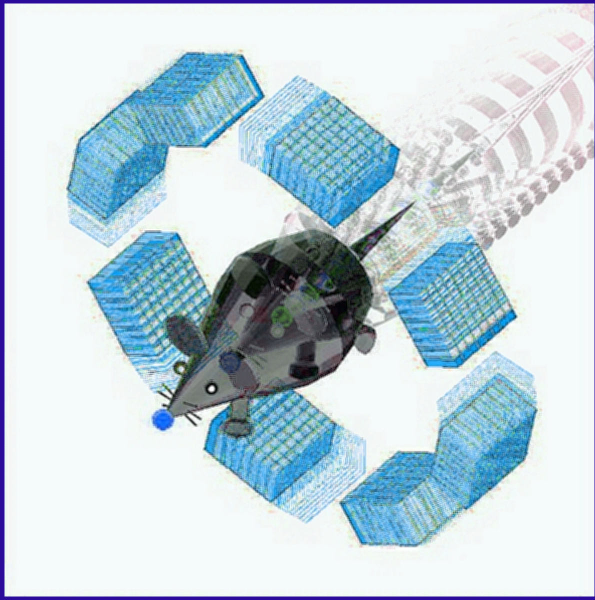
Retrospective Studies

- Similar to treatment planning, but done after the fact, to look at whether we believe the dose given was correct.
- Allows slow MC calculation to be used to validate the faster parameterized calculations that were used in treatment.
- May still be in time to affect decisions about how subsequent treatments (fractions) are given.



Source: Irene Buvat, INSERM/CHU

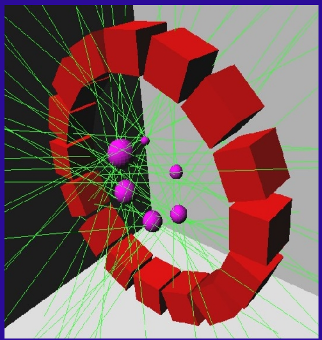
Imaging



- Many users use Geant4 for Imaging through a specific Geant4 application called GATE
  - See many talks in other sessions
- Other users build their own applications directly from Geant4

GATE : a simulation toolkit for emission tomography in nuclear medicine and molecular imaging

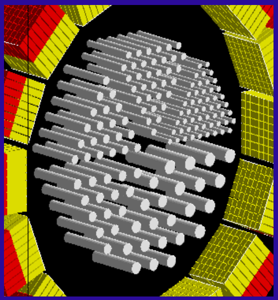
Team : I. Buvat , INSERM / CHU Pitié S., France and the GATE collaboration



Optimize detector design , assessing acquisitions…

Home made code available, from 1995 to 1999
After 1999, 8 home made codes and 7 publicly released.
Released in May 2004.

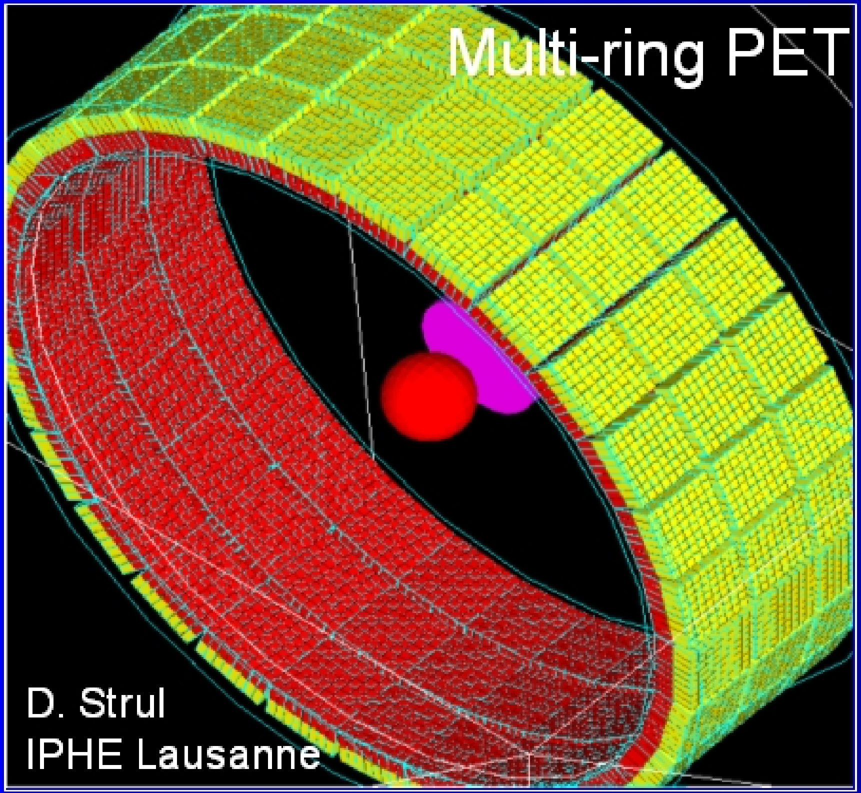
More than 400 users to the gate user mailing list

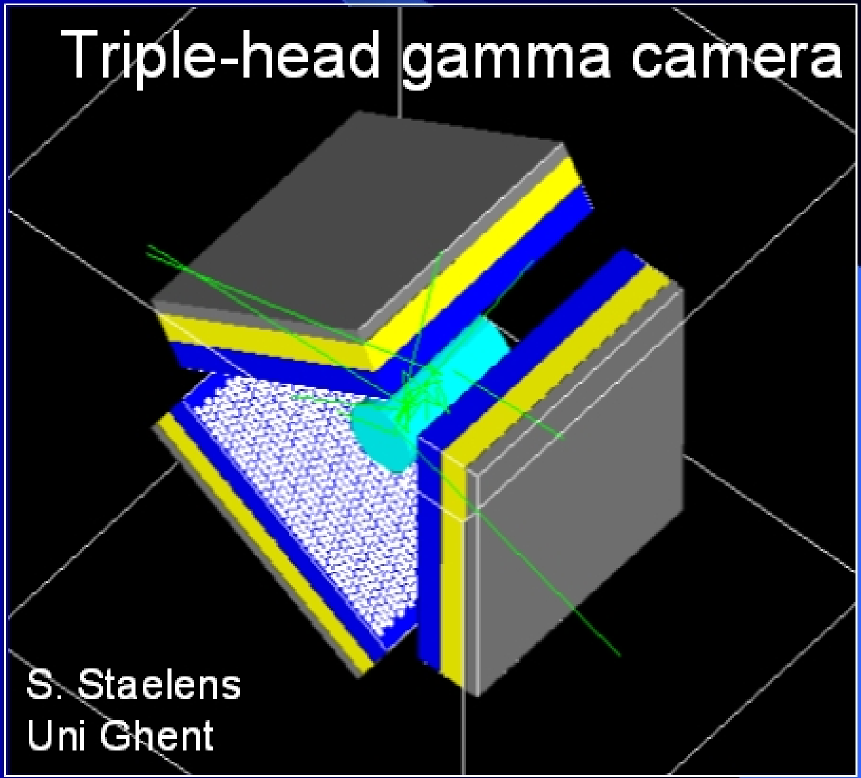


- Based on Geant4, written in C++, user-friendly (macros)
- Time dependence (source, detector) important for SPECT / PET imaging
- Realistic simulations of data acquisitions in time
- Modelling of detector response using digitization
- Use of decay module for source decay kinetics
- Voxelized or analytical phantoms
- Gate slow : emitting object large, voxelised maps, tracking slow through any border, low detection efficiency : high stat needed. Use accelerating methods : variance reduction technique, combine MC and non MC, parallel simulation

http://www.opengatecollaboration.org

Geometry examples of GATE applications





Example from ESTRO

MONTE CARLO CALCULATIONS OF POSITRON EMITTERS IN PROTON THERAPY

K. Parodi[1], A.Ferrari[2], F.Sommerer[2], T.Bortfeld[3], H.Paganetti[1]
[1] MASSACHUSETTS GENERAL HOSPITAL, *Boston, USA.*
[2] CERN, *Geneva, Switzerland.*
[3] MASSACHUSETTS GENERAL HOSPIAL, *Boston, USA.*

Clinical exploitation of the physical advantages of proton beams for improved conformation of the dose delivery can benefit from an in-vivo, non invasive verification of the applied treatment and, in particular, of the beam range in the patient. Since proton irradiation produces β^+-emitters like ^{11}C and ^{15}O, Positron Emission Tomography (PET) imaging during or shortly after treatment can

Talks Later Today

- **Deployment of GATE/G4 simulations on a grid arc**
  - Lydia Maigne (LPC, Clermont Ferrand, France)
  - Thursday 14:20 - 14:40
- **Simulating CT imaging with GATE**
  - Franca Cassol Brunner (CPPM Marseille, France)
  - Thursday 14:40 - 15:00
- **Overview of VR in GATE**
  - presenter TBA
  - Thursday 15:00 - 15:20

Why Do Medical Physicists Choose Geant4?

- Modern programming
- Flexible, Open, Free
- All particle
- Able to handle complex geometry
- Able to handle motion

Modern Programming

TALKING POINT

Sep 11, 2006

GEANT4: a new giant in medical physics

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MC code	Particle types	Class	Programming language
ETRAN/ITS	Photons, electrons	I	FORTRAN
MCNP	Photons, electrons, neutrons	I	FORTRAN
MCNPX	All particles	I	FORTRAN
EGS4	Photons, electrons	II	FORTRAN
EGSnrc	Photons, electrons	II	FORTRAN*
PENELOPE	Photons, electrons	II	FORTRAN
GEANT3	All particles	II	FORTRAN
GEANT4	All particles	II	C++

Table 3.1. General-purpose Monte

Source: Emily Poon, McGill University

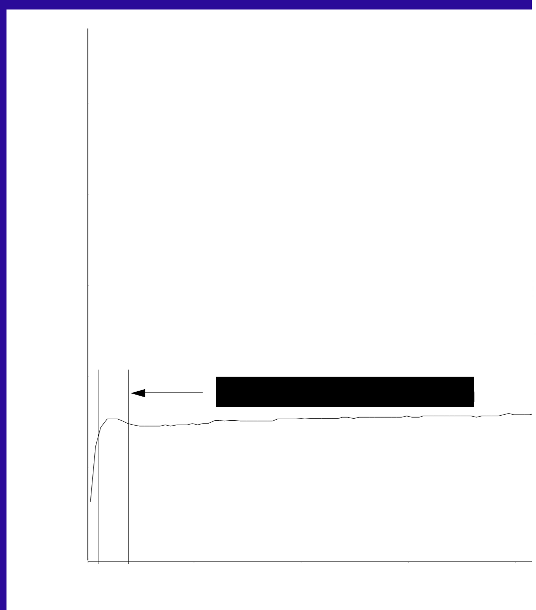
PENELOPE - are all written in FORTRAN. This was the situation until recently. Enter GEANT4 (GEometry ANd Tracking; S Agostinelli *et al.* 2003),

Flexible, Open, Free

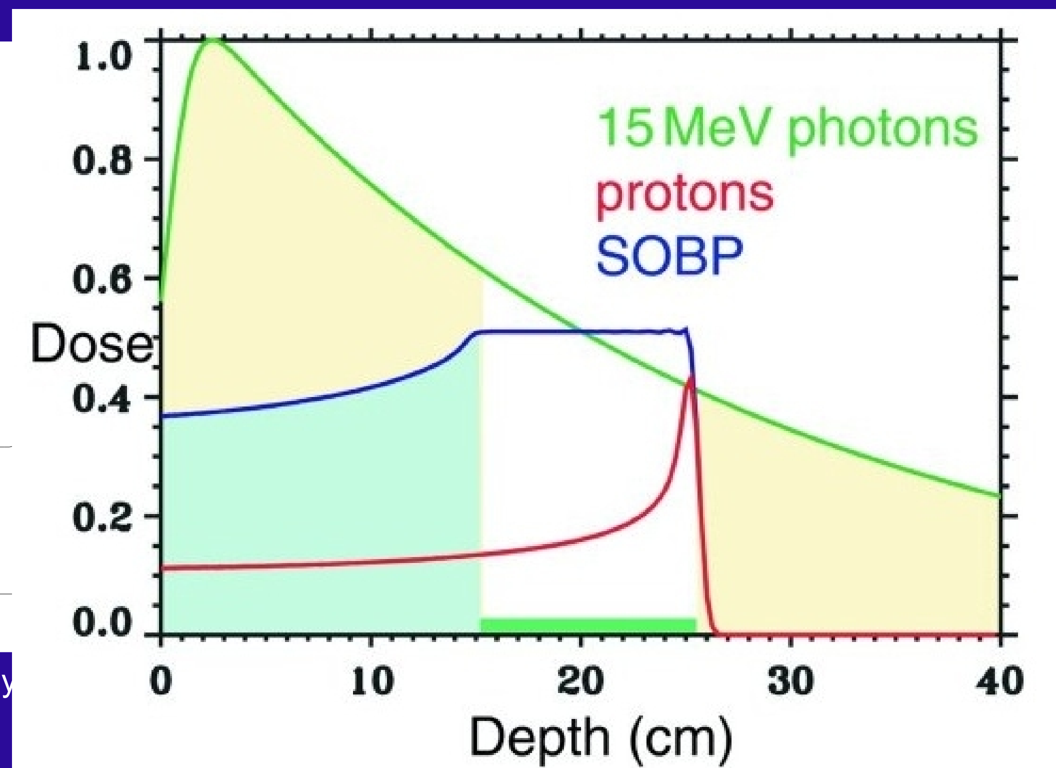
- Flexible - follows from good OO design
- Open - physicists like to have the ability to get in under the hood and make changes
- Free - not only free for user, but also freely available for redistribution (even for private companies to build Geant4 into their own systems)

All Particle

- Current “Gold Standard” in Med Phys, EGS, is only for electron and gamma
- Growth of Proton and Ion Therapy
  - Bragg Peak



Source: Dan Fry, Walter Reed Army



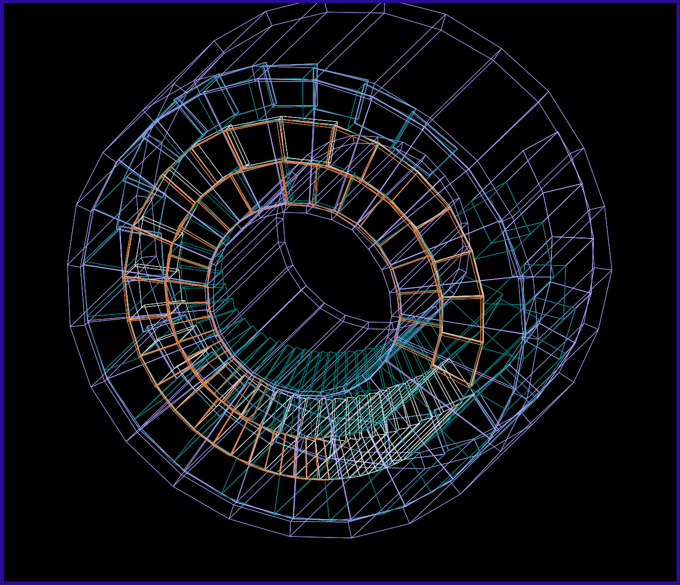
Source: E. Pedroni, Europhysics News (2000) Vol. 31 No. 6

Able to Handle Complex Geometry

- Geant4 offers by far the most flexible geometry description of any Monte Carlo
  - useful for modeling of brachytherapy seeds
  - useful for modeling of complex treatment head parts such as multileaf collimators

Able to Handle Motion

- Geant4 can model sources and geometries that are in motion
  - Rotating parts of proton IMRT machine
  - Dynamic multileaf collimators (MLCs)
  - Brachytherapy source moving through a catheter
  - Patient motion (respiration, etc.)



Source: Harald Paganetti, Harvard

Issues

- Accuracy
- Speed
- DICOM Compatibility
- Memory
- Volume Rendering
- Scoring
- Ease of Use

Accuracy

- Typically looking for 2 percent
- If 5 percent were good enough, would just use parameterized models

Speed

- Typically require millions of “histories” (medical physics term for “events”)
- Very serious issue for Treatment planning
- Less so, but still a barrier, in other uses
  - Characterizing machines and brachytherapy sources
  - Retrospective studies
  - Imaging
- Clusters of order of 10 machines typical
- Variance reduction (aka Event Biasing)

Speed - Voxel Navigation

- Voxel geometries lend themselves to faster navigation techniques than the standard Geant4 navigator
- Other codes more specialized for Med Phys have taken advantage of this for years
- Talk from Jan De Beenhouwer and Steven Staelens yesterday about how they did this in GATE.
- Talk by Pedro Arce on Friday

DICOM Compatibility

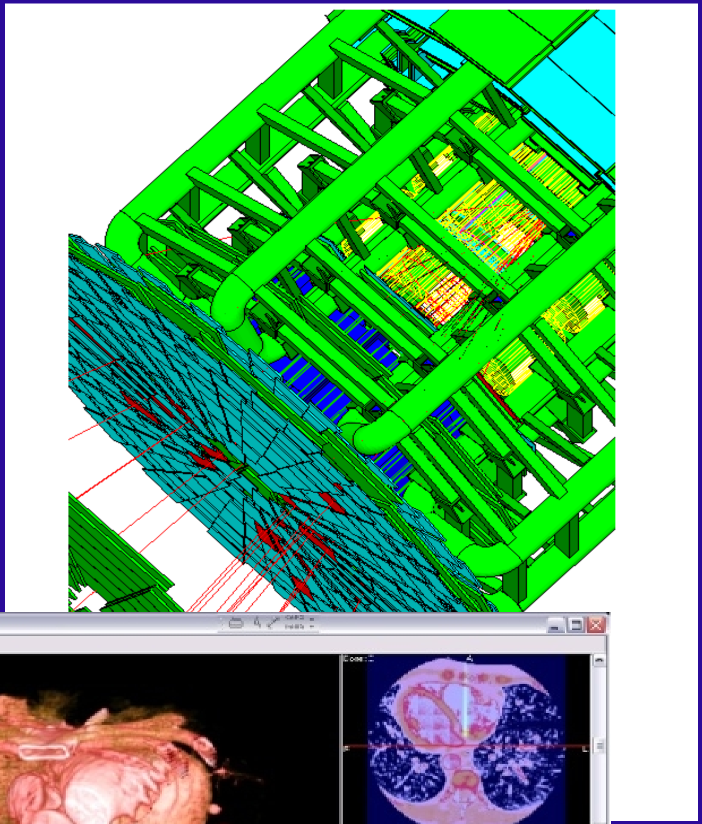
- Output of scans (CT, MRI, etc.) are in format called DICOM, basically a density (HUs)
  - Automated conversion to tissue type
  - Cutting edge technologies such as Dual Energy CT may give enhanced tissue type info
- DICOM may be annotated with treatment planning information (DICOM RT)

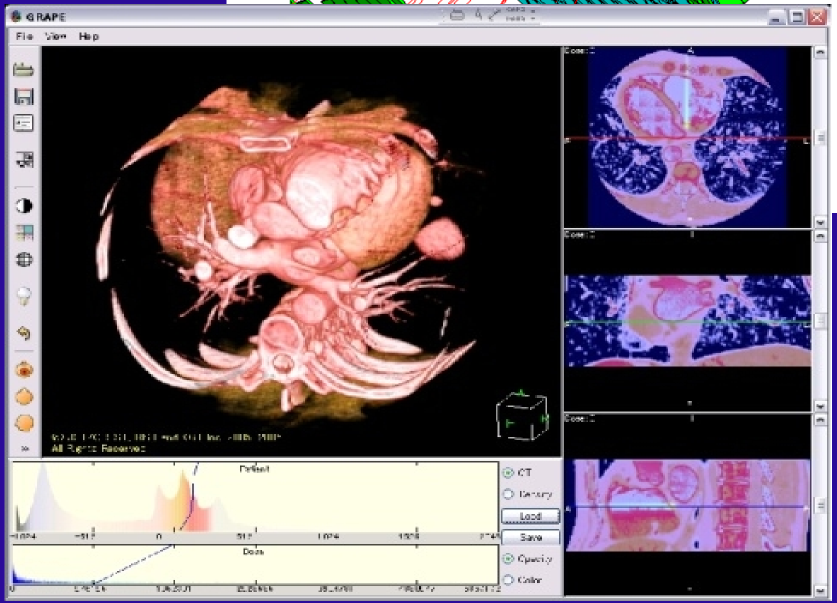
DICOM - Memory

- DICOM files have order of 4 Million voxels
  - e.g.
    - 50cm x 50cm x 25cm volume
    - 2mm x 2mm x 4mm slides
  - Even if DICOM density is approximated as a small number of materials, we require a large map to go from voxel to material
    - Parameterized materials would be helpful

Volume Rendering

- Visualization tools in Geant4 are aimed at complex hierarchical geometries
  - e.g., ATLAS detector
- Medical Physics has additional requirements
  - Representing voxel data from DICOM
  - Showing dose, etc in that data
  - Recent solutions from Japan:
    - GMocren





Scoring

- Hits versus Scoring
  - Original customers of Geant4, HEP, tended to have unique, cutting-edge, detectors. Wanted to model their own unique kinds of Hits.
  - Med Phys (perhaps exception of Imaging) use standard detectors already well characterized in published references
- Recent advances in Geant4
  - Ready-made scorers (Dose, Flux, etc., nicely filterable by particle type, etc.)
  - We will see this week a preview of scoring that can be done entirely from the command line (talk by Makoto Asai)

Ease of Use

- Other Medical Physics Monte Carlos are easier to use
  - Focused applications rather than general-purpose toolkits
  - EGSnrc, BEAMnrc, DOSXYZ
- Movement towards easier-to-use Geant4
  - GATE incorporates Geant4 into a more domain-specific application
  - Project in Japan to provide complete application for all Proton and Ion centers in Japan

Geant4 Medical Physics Communities

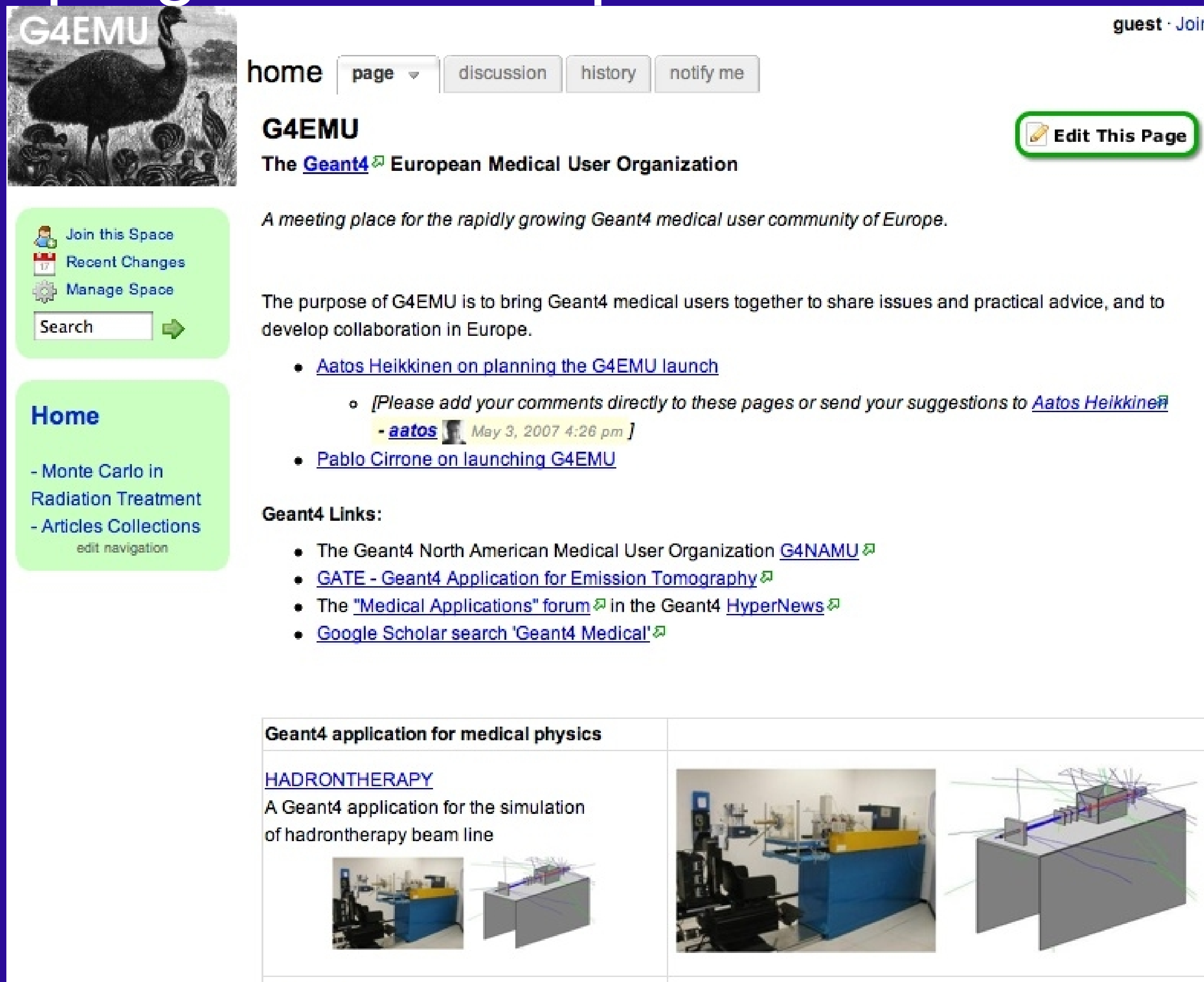
- Europe
- Japan
- North America

G4 Med Phys in Europe

- Wide range of applications
- Home of GATE
- Talks this afternoon, such as on activity of Italian group
- Some important recent meetings for this community:
  - First European Workshop on Monte Carlo Treatment Planning of the European Workgroup on MCTP
    - October 22 - 25, 2006, Gent, Belgium
    - Talks Online at: http://cdfc00.ugent.be/Ewg-mctp/
  - International Workshop on Monte Carlo Codes and 13th UK Monte Carlo User Group Meeting (MCNEG 2007)
    - March 26-27, 2007, NPL, Teddington, UK
  - 9th Biennial ESTRO Meeting on Physics and Radiation Technology for Clinical Radiotherapy
    - September 8-13, 2007, Barcelona, Spain

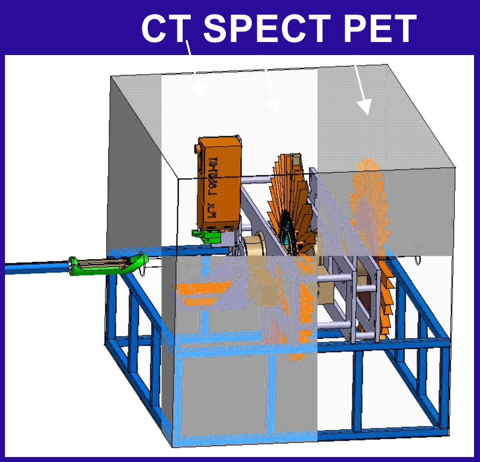
Geant4 European Medical User Organization

- http://g4emu.wikispaces.com



Multi modality imaging system dedicated to small animal

Team : D. Brasse *et al.*, ULP-IRES, France

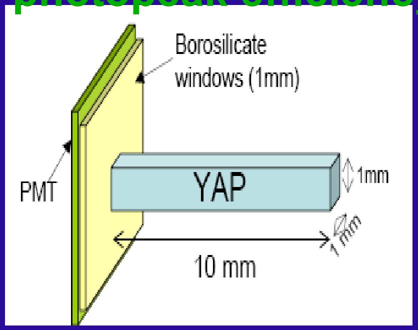


SPECT : Single Photon Emission Computed Tomography
PET : Positron Emission Tomography
CT : Computed Tomography

Anatomical + functional imaging

❶ Simulation of micro-SPECT with G4 & comparison with references : dx < 1 mm

- Scintillation Process
- Definition of the scintillator material (YAP) and optical properties of the medium
- Boundary Process (between YAP and Air): “Al coating” simulation
- Surface YAP - PMT window: two dielectric materials
- Comparison simu/exp in reas. agreement (Det/Emit) : pmt surf and edge effects
- Simulation of matrices of 64 crystals : energy distribution, photopeak efficiency…
- Shielding



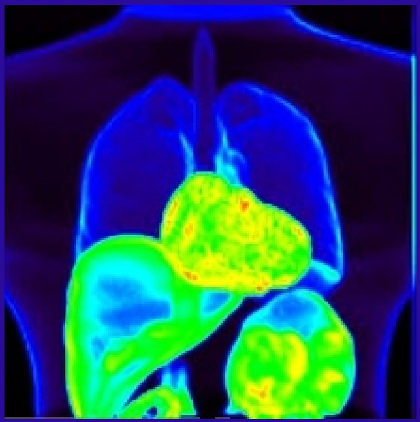
❷ Simulation of CT with G4 / MCNP4C / Semi-emp. model

- Good agreement above 13 keV in X-ray spectrum

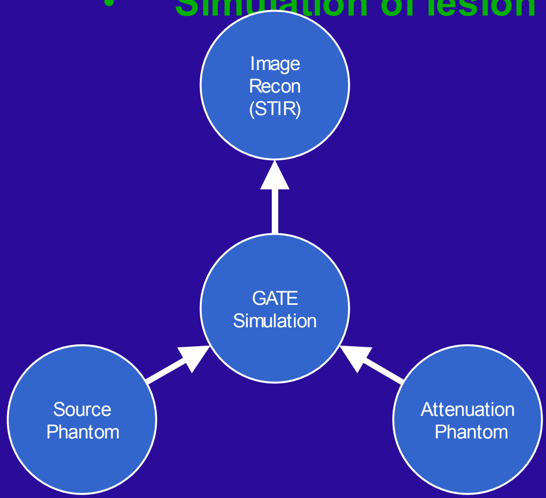
❸ Starting PET with GATE : geometry validated, physics…

Simulated PET acquisition of a respiratory and cardiac moved NCAT-human torso phantom using the GATE toolkit

Team : N. Lang *et al.*, UHM, Germany



- Realistic experiment PET/CT scanner
- GATE simulated PET scan
- Voxelized 3D-anatomy of human body
- Respiratory and cardiac motion implemented
- Emission and attenuation configuration
- Simulation of lesion or infarction

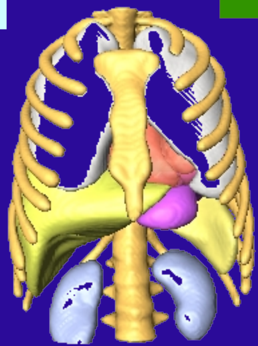


- Problem:
  - Image blurring during long scan times
  - Attenuation correction with static CT data produces artifacts in images
- Solution:
  - Gated listmode PET freezes motion
  - Use of software morphing (optical flow) to produce motion free images inheriting the full statistics

- Weeks of CPU-Time (2,4 GHz Xeon) needed for single image
- Attenuation increases CPU time by factor of 10 !
- Parallel cluster computing needed (not yet implemented in GATE)

Clear-PEM scanner for breast cancer imaging with Geant4

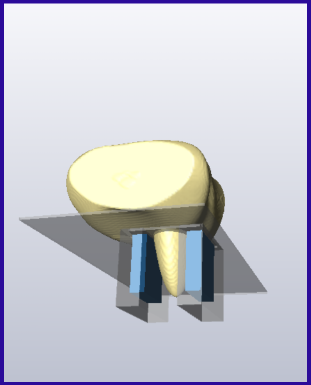
Team : A. Trindade *et al.*, LIP, Portugal



Geant4 toolkit is used for the simulation of the Clear-PEM scanner (dx < 5 mm & high sensitivity)

The developed simulation framework includes :

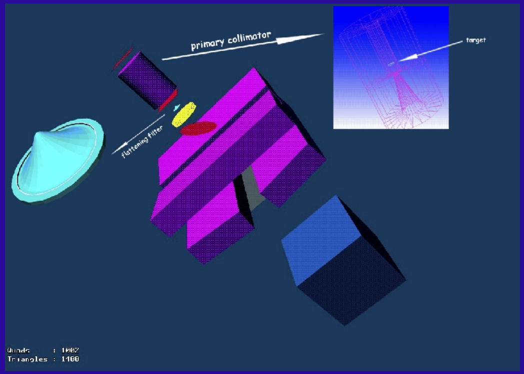
- **a patient model**
- **a detailed description of the detector geometry**
- **a C++ high-level simulator of the signal formation and data processing in the on-detector front-end and off-detector digital electronic systems was developed**



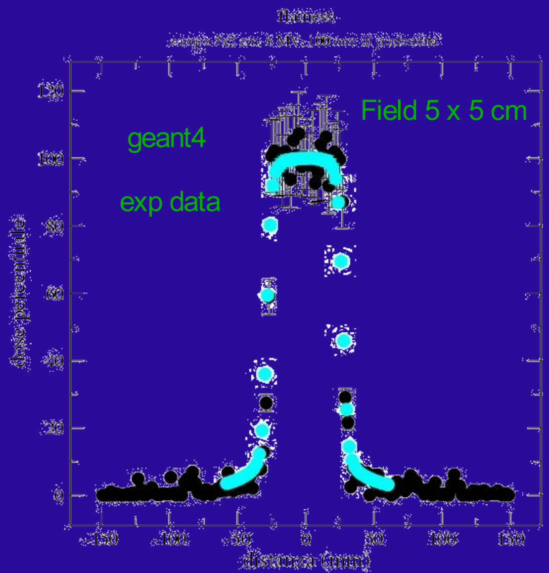
- The NURBS CArdiac Torso (NCAT) phantom was implemented in Geant4, as a voxelized geometry (class G4VPVParameterisation)
- A detailed description of the scanner geometry and material properties were implemented (~35000 solids)
- Several 5 min. acquisition exams were simulated with Geant4 to assess lesion visibility
- Computational resources: 70 d CPU (140 jobs), 236 GB, data production at CERN (LXBATCH), CASTOR storage

Medical accelerator for IMRT

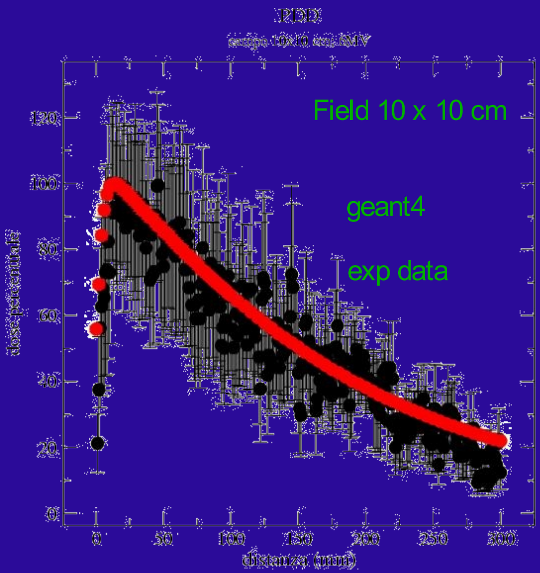
Team : F. Foppiano *et al.*, INFN Genova, Italy



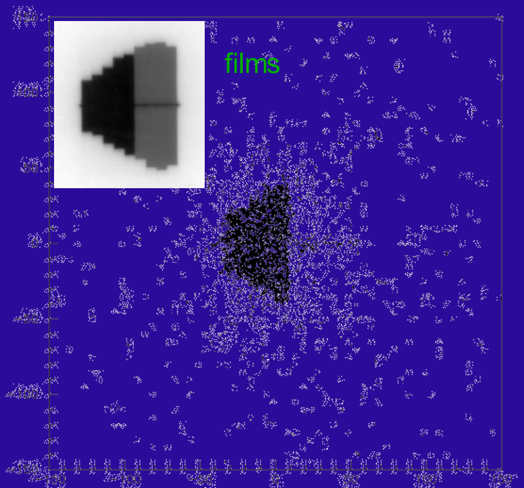
- Complex geometries
- Variety of physics processes – Low Energy Package
- Interactive facilities : visualization, analysis, UI



% dose at 100 mm depth in the phantom



% dose with respect to the depth in the phantom

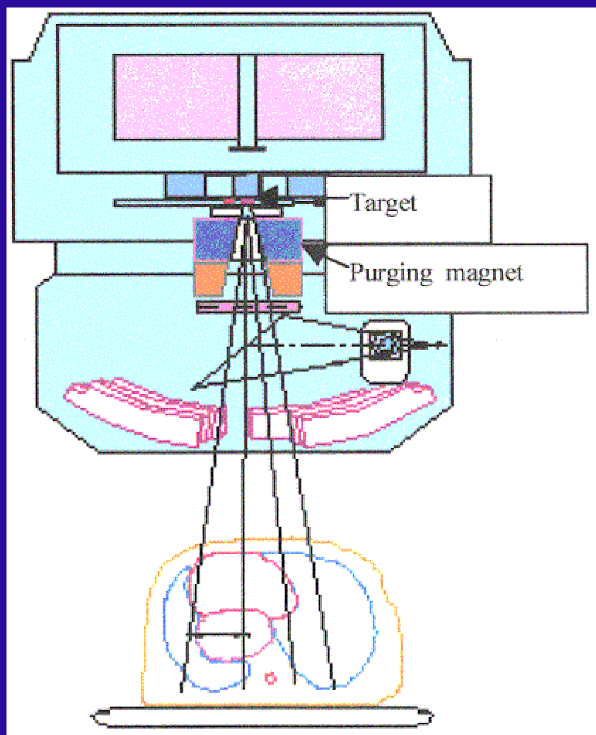


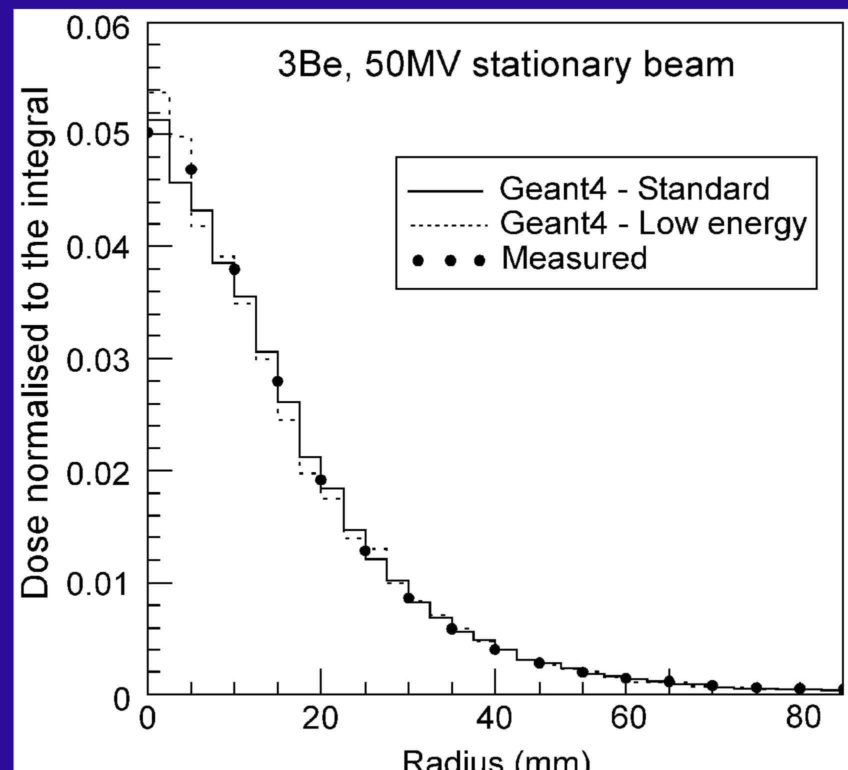
Treatment head simulation

Team : S. Larsson *et al.*, Karolinska U, Sweden

Bremsstrahlung validation: radial dose profile

- High energy electron beam, 50 MeV
- Target 3 mm Be





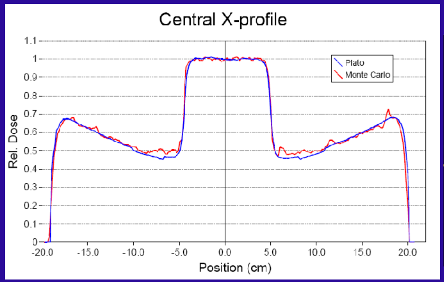
Accuracy in the **geometry** and **magnetic field** modeling

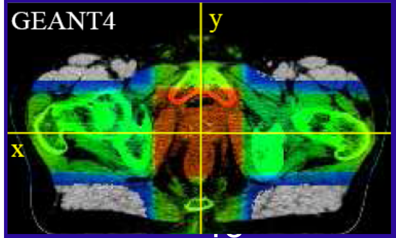
Simulations for the virtual prototyping of a radiotherapy MRI-linear accelerator system : linear accelerator output, CT-data implementation, dose deposition in the presence of a 1.5 T magnetic field

Team : A. Raaijmakers *et al.*, UMC Utrecht, The Netherlands

- **Simulation of a radiotherapy accelerator has been achieved**
- **CT-data implementation is working fine and is showing agreement with TPS PLATO**
- **Already, physicians come up with clinical cases of inhomogeneous target volumes in patients, where they want to know the dose distribution more accurately**
- **Need to validate the simulated dose distributions with linear accelerator in a magnetic field from MRI scanner (better dose control)**
- **Ionization chamber response in a magnetic field is still a problem**

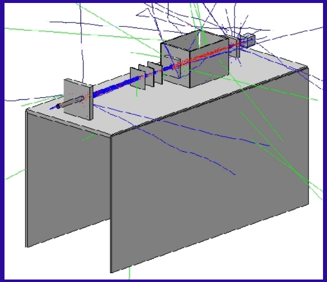
"GEANT4 is a very practical tool for our purposes, though there is room for some improvement (navigation, boundary crossing)"



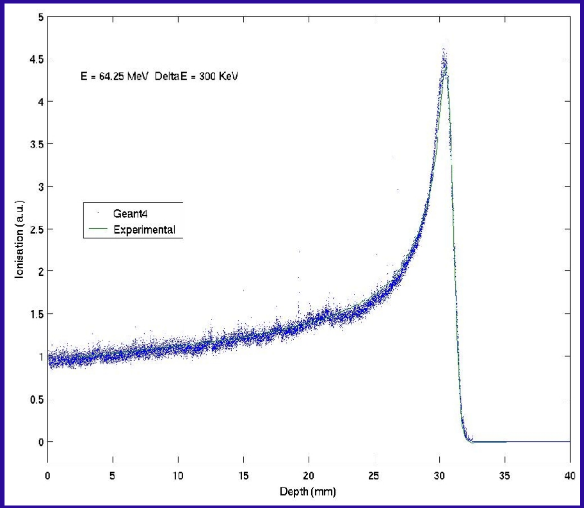


Hadrontherapy : proton beam line

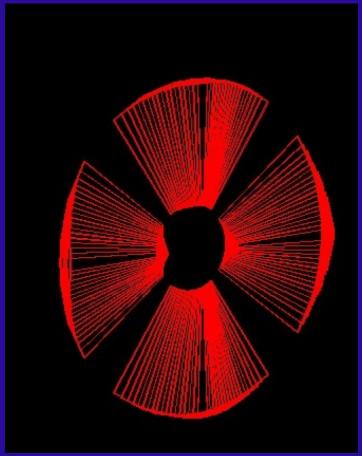
Team : P. Cirrone *et al.*, INFN Catana, Italy

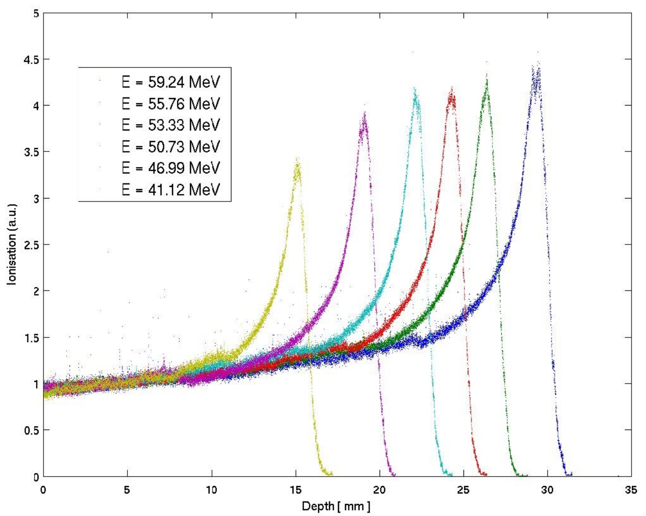


- Modeling of the Catana proton beam line
- **Electromagnetic** and **hadronic** interactions for protons, ions (and secondary particles)



agreement with data
better than 3%

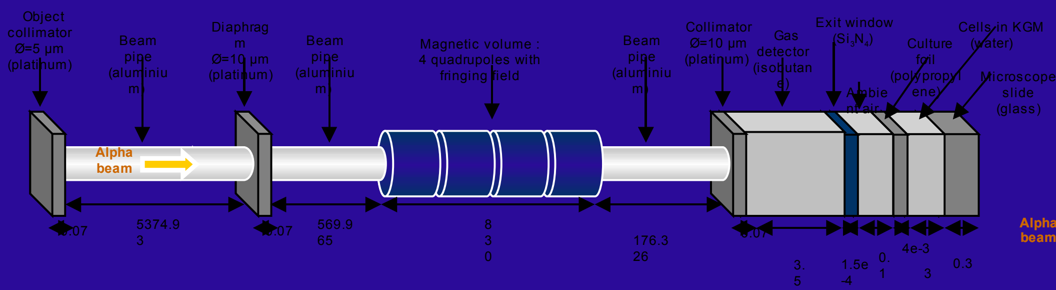


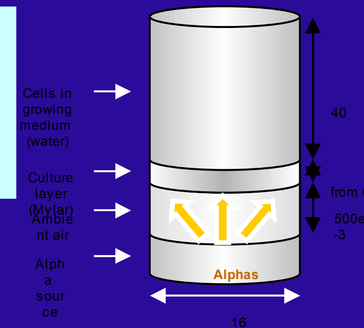


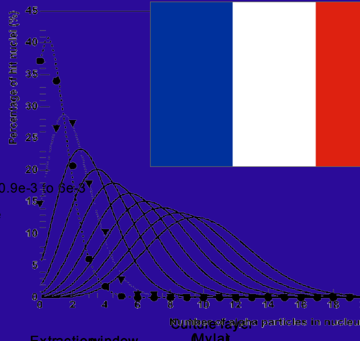
Modulator for hadrontherapy beam line

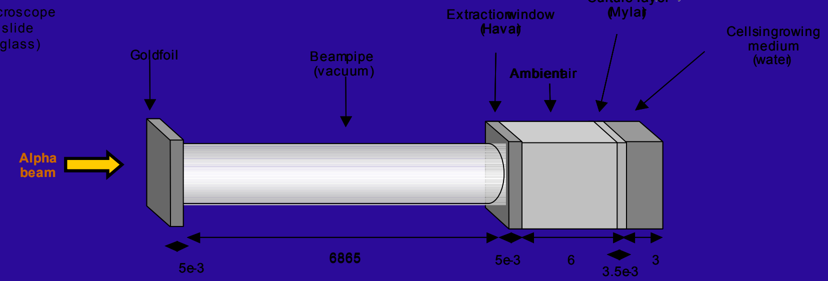
Microdosimetry at the cellular scale

Team : S. Incerti *et al.*, CENBG / IN2P3, France







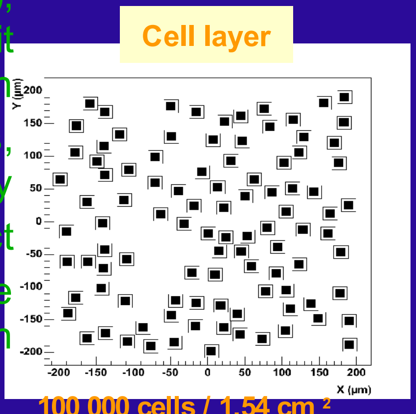


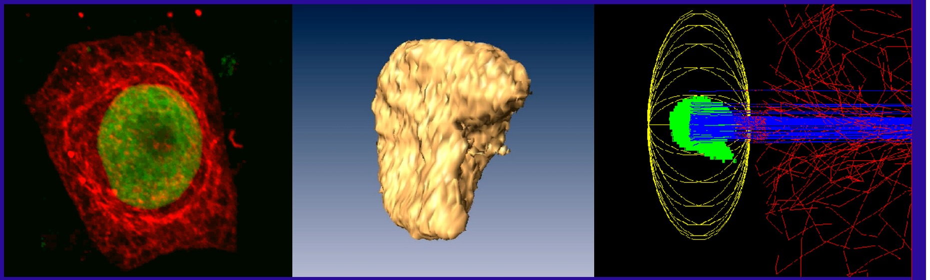
• Comparaison of **cellular irradiation setups** : microbeam (CENBG), classical macrobeam, electrodeposited sources of radioactive emitters : hit and dose distribution within cellular population

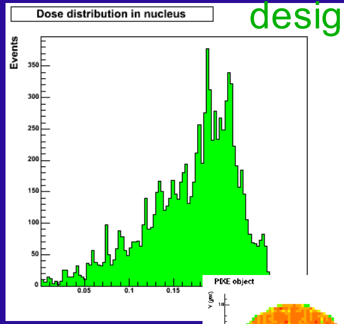
• Dévelopment of realistic **voxellized phantoms at the cell scale** : nucleus, cytoplasm, mitochondria from 3D confocal microscopy

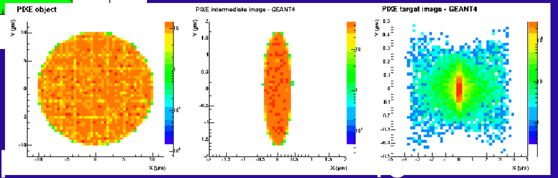
• **Geant4- DNA** project

• **Ray-tracing** in quadrupoles at the sub-micron scale for nanobeam line design









Anthropomorphic phantoms for dosimetry

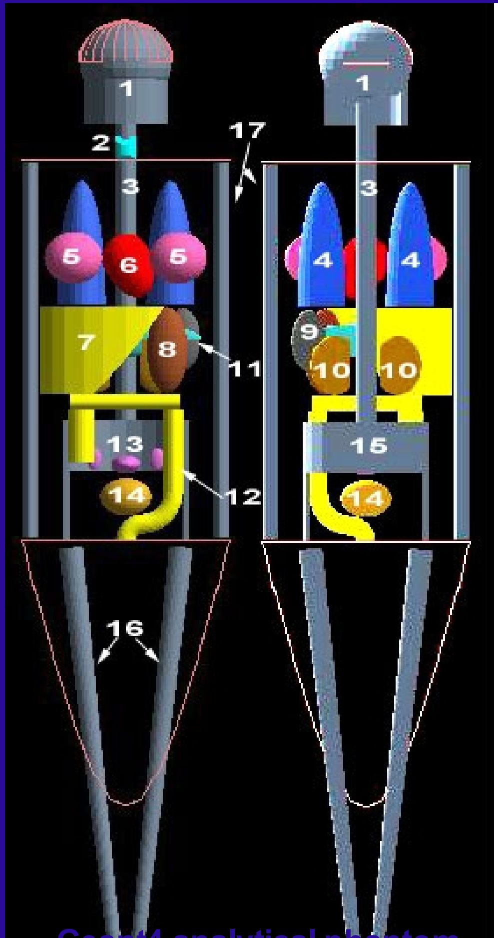
Team : M.G. Pia *et al.*, INFN Genova, Italy

Development of anthropomorphic phantom models for Geant4 : evaluate dose deposited in **critical organs** : radiation protection, total body irradiation…

Original approach

- **analytical and voxel** phantoms in the same simulation environment
- facilitated by the OO technology
- Male and Female

Application : **Total Body Irradiation** is used as a method of preparation for bone marrow transplantation for **leukemias** and **lymphomas**. Low dose TBI is sometimes used to treat disorders of the blood cells such as low grade lymphoma and does not require bone marrow transplant or stem cells. In TBI, the dose calculation is based on **dosimetry using a phantom**



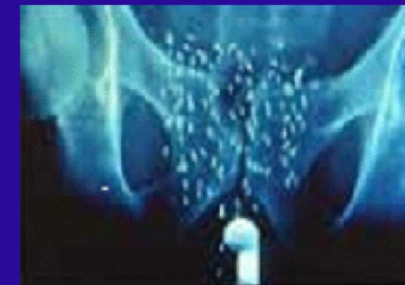
Geant4 analytical phantom
ORNL model, female

1 skull
2 thyroid
3 spine
4 lungs
5 breast
6 heart
7 liver
8 stomach
9 spleen
10 kidneys
11 pancreas
12 intestine
13 uterus and ovaries
14 bladder
15 womb
16 leg bones
17 arm bones

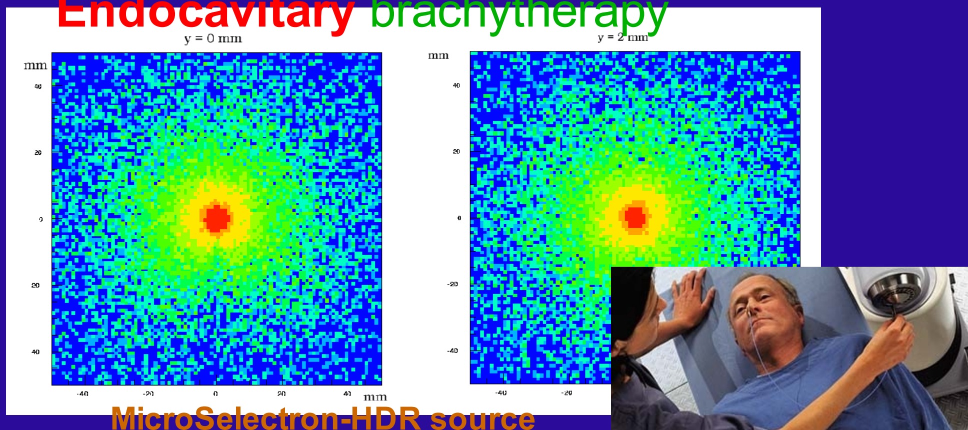
Brachytherapy

Team : S. Guatelli *et al.*, INFN + IST Genova, Italy

Dosimetry for all brachytherapy devices

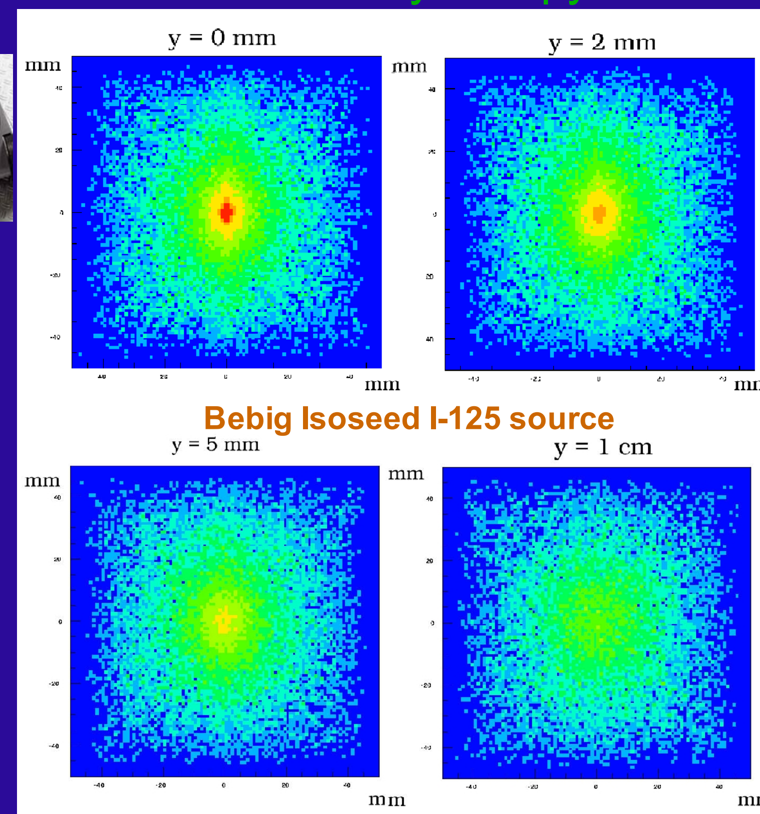


Dosimetry
Endocavitary brachytherapy



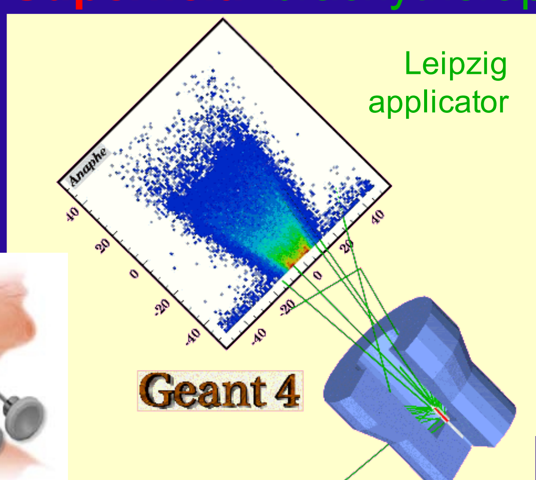
MicroSelectron-HDR source

Dosimetry
Interstitial brachytherapy



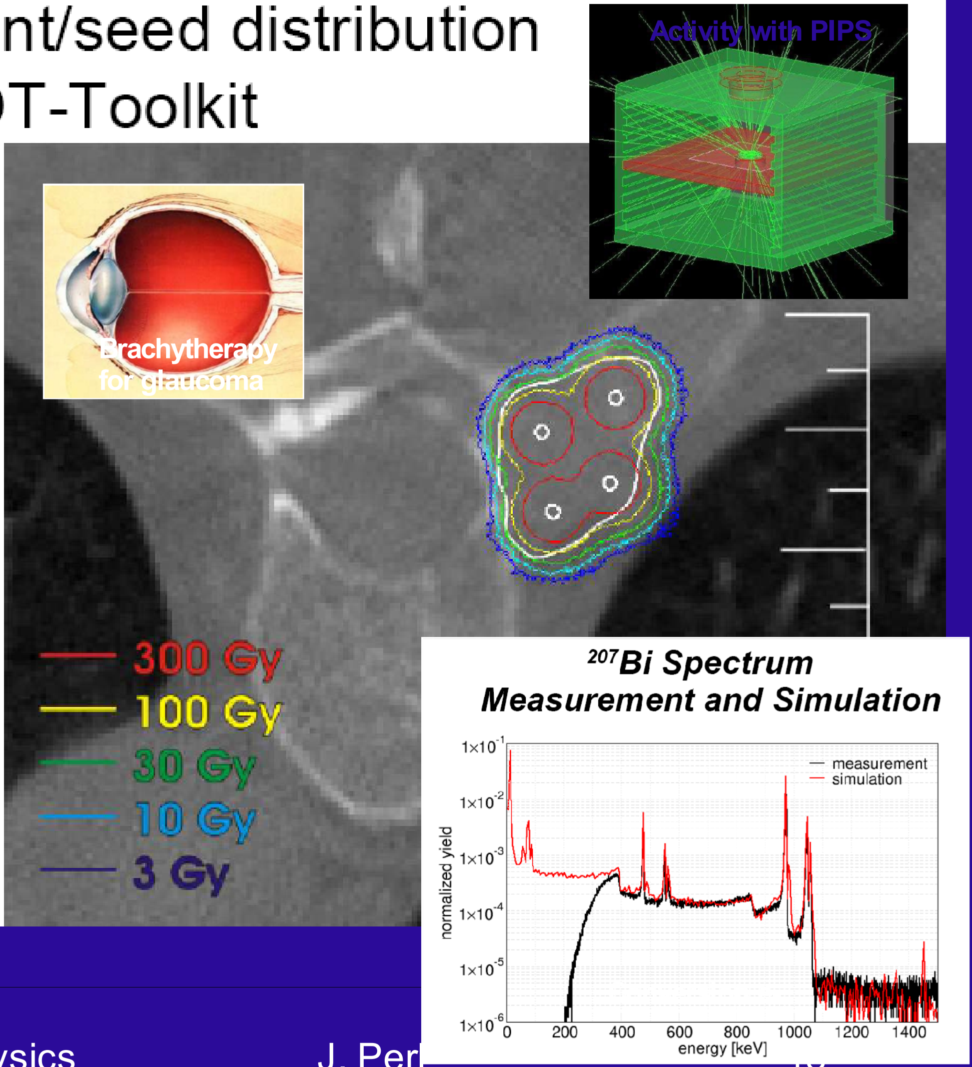
Bebig Isoseed I-125 source

Dosimetry
Superficial brachytherapy



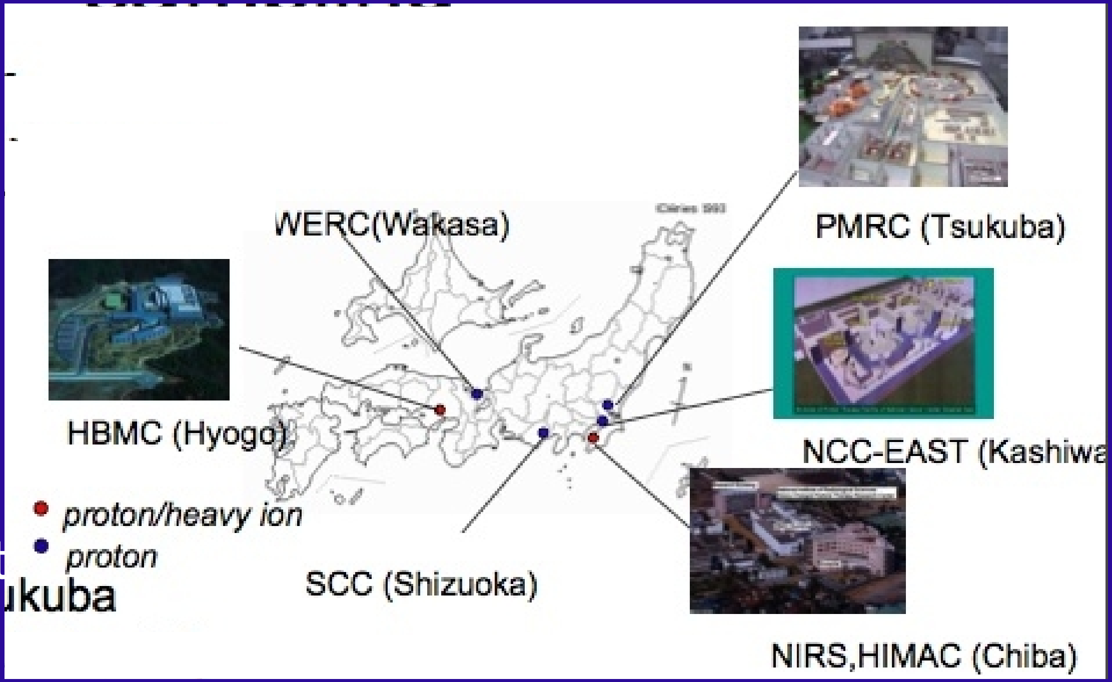
F. Foppiano, IST and Susanna Guatelli, INFN Genova

- Simulation on a 50 CPU Linux-Cluster using MPI
- Parallelisation by event/seed distribution
- Histogramming: ROOT-Toolkit
- Geant4 is used for:
  - Dose calculations
  - Helping to develop or calibrate detector systems
  - Future use
- Dose planning using CT-data
  - Dicom-library DCMTK
  - Clinical study
  - ^{32}P implants
  - Tumor therapy



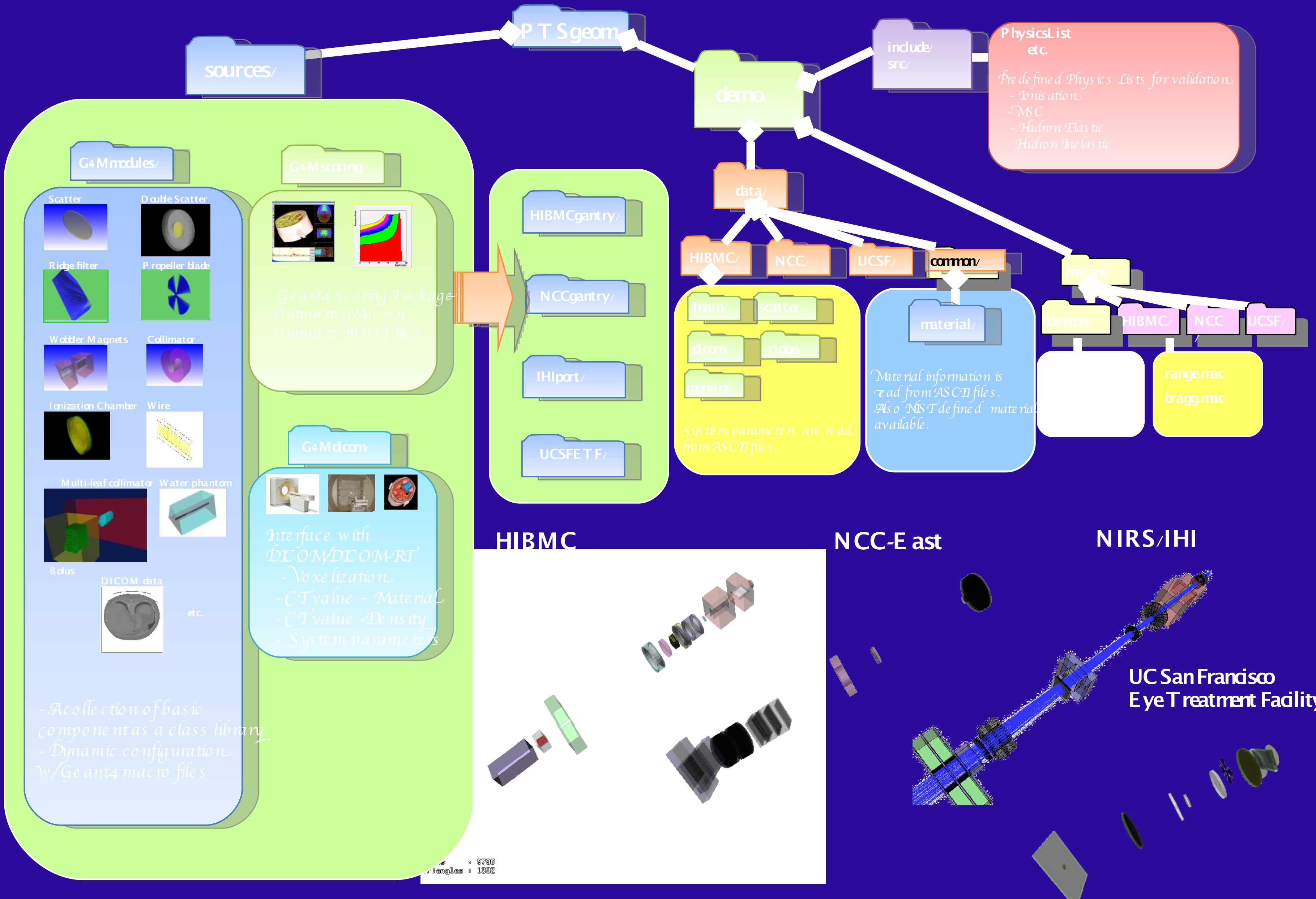
G4 Med Phys in Japan

- Large concentration of Proton and Ion therapy machines



- Major 5 yr research project led by Takashi Sasaki
  - http://g4med.kek.jp/
- Talk this afternoon by Tomohiro Yamashita
- The Japan-Taiwan Symposium on Simulation in Medicine
  - December 12 - 15, 2006, Tsukuba, Japan
  - http://www-conf.kek.jp/geant4/

Software Structure for Particle Therapy Simulation

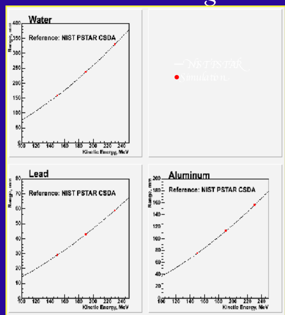


Validation Activities

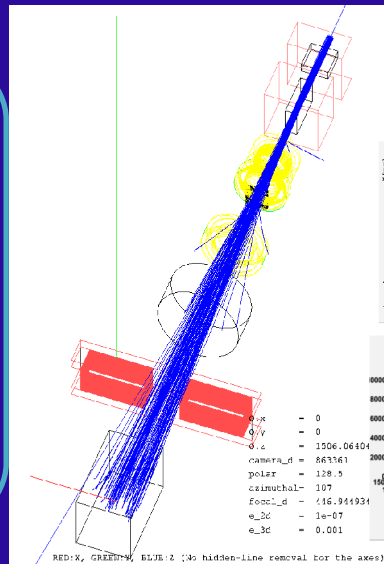
for Proton Therapy

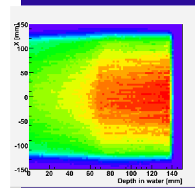
Material Properties

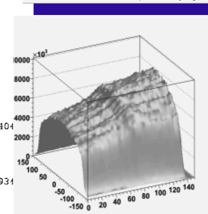
Proton range



Stopping Power/Range, checked with NIST data

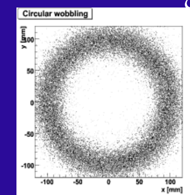




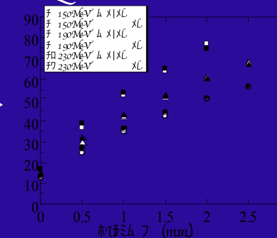


Beam Delivery system validation

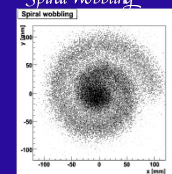
Wobbler Magnet



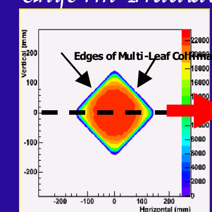
Lead Scatterer

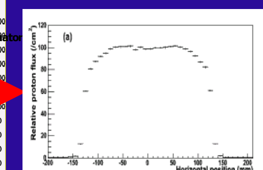


Wobbler demonstration: Spiral Wobbling



Uniform Irradiation Field

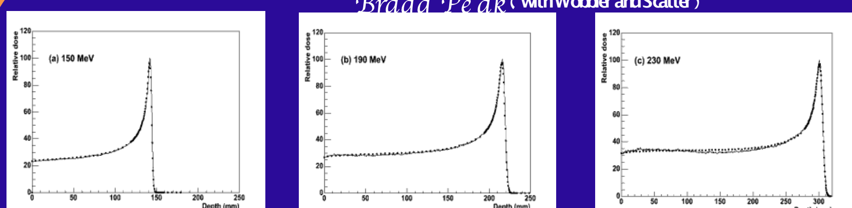




Depth-Dose distribution

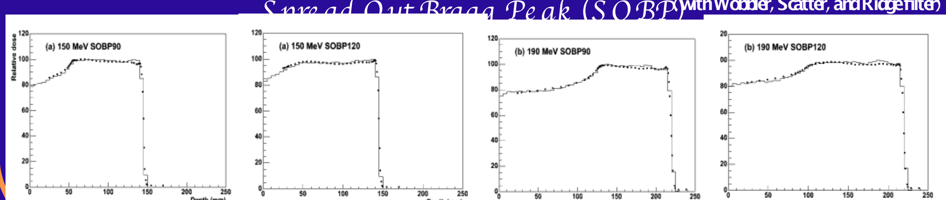
IEEE TNS V52, Issue 4, (2005) pp.896-901

Bragg Peak (with Wobbler and Scatter)



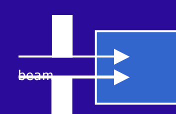
— Simulation
■ Measurement

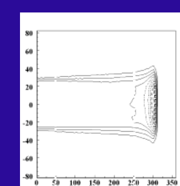
Spread Out Bragg Peak (SOBP) (with Wobbler, Scatter, and Ridge filter)

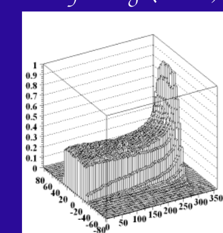


Nuclear Interaction Effect

by T. Akagi (HIBMC)

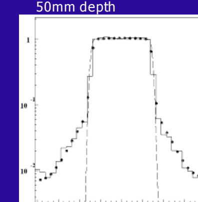




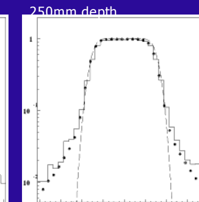


● : Measurements
— : TPS calculations
□ : G4 (histograms)

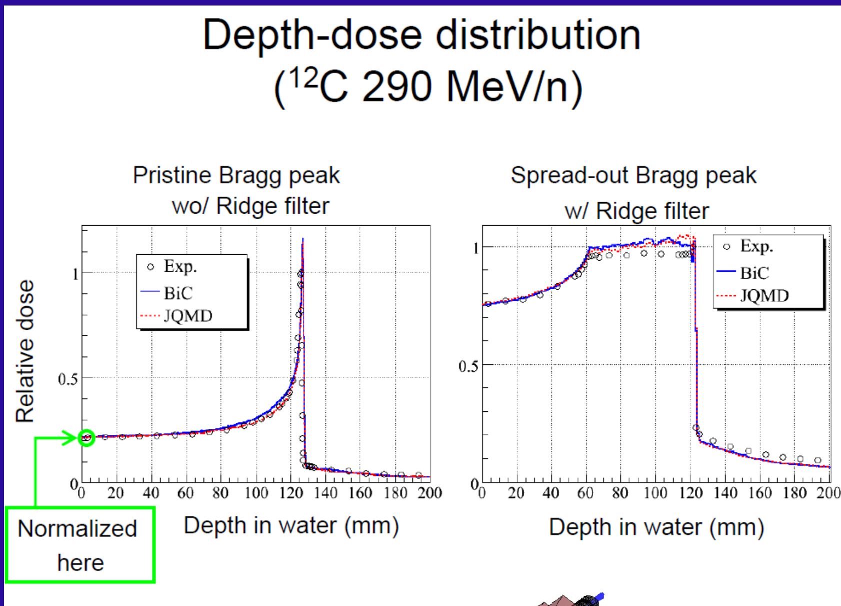
50mm depth

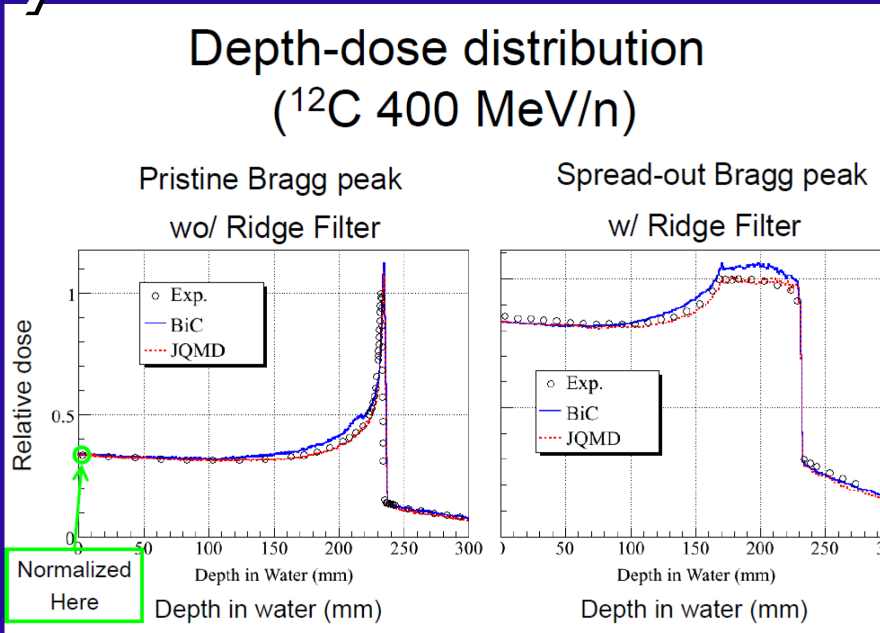


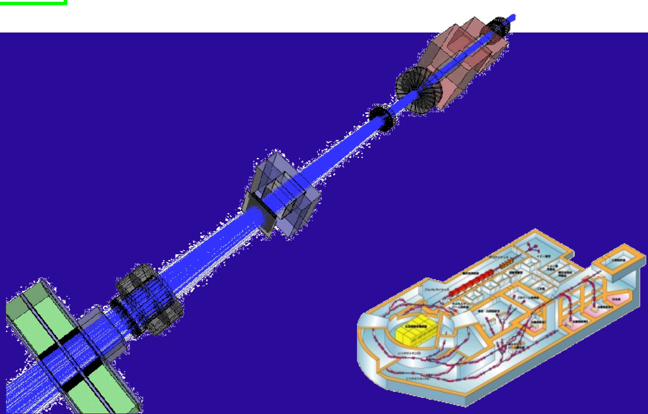
250mm depth

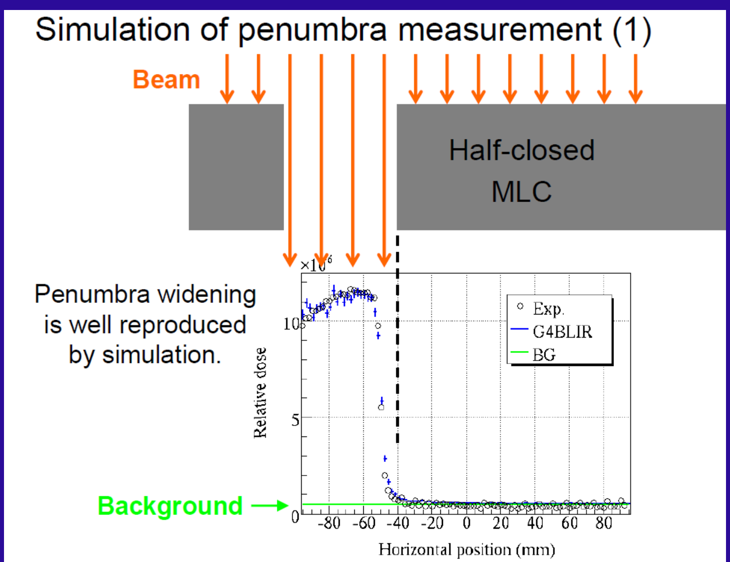


also for Carbon Therapy









NIRS /
The experimental beam line

gMocren : A Visualization Tool

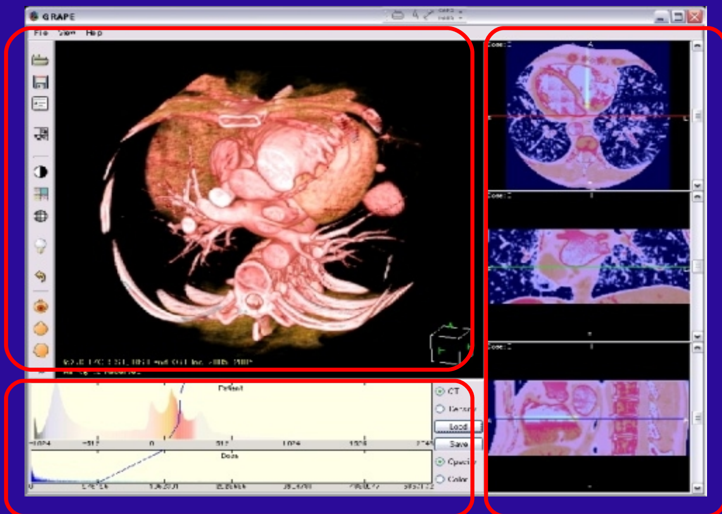
http://geant4.kek.jp/gMocren/

gMocren and utility softwares are freely available.

***Supported system*:**
- Windows 2k/XP or PC Linux OS
- Pentium 4 or faster
- more than 1 GB (recommend)

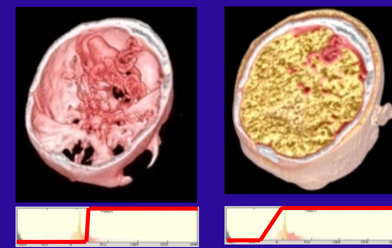
3D (ray casting)

2D (MPR)



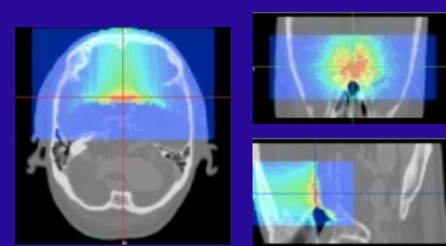
Opacity curve and color map editor

Opacity curve and color map editor

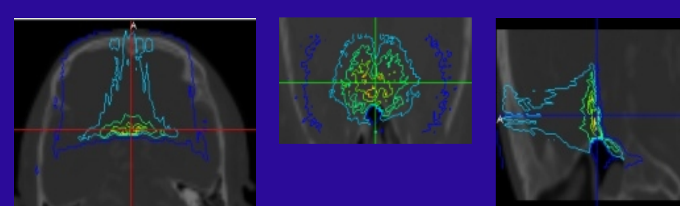


free hand or templates with WW&WL editing

Calculated dose distribution

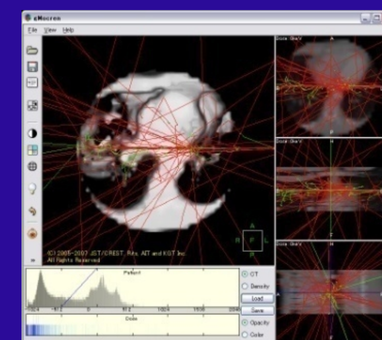


color mapping



contour plot

Particle trajectories

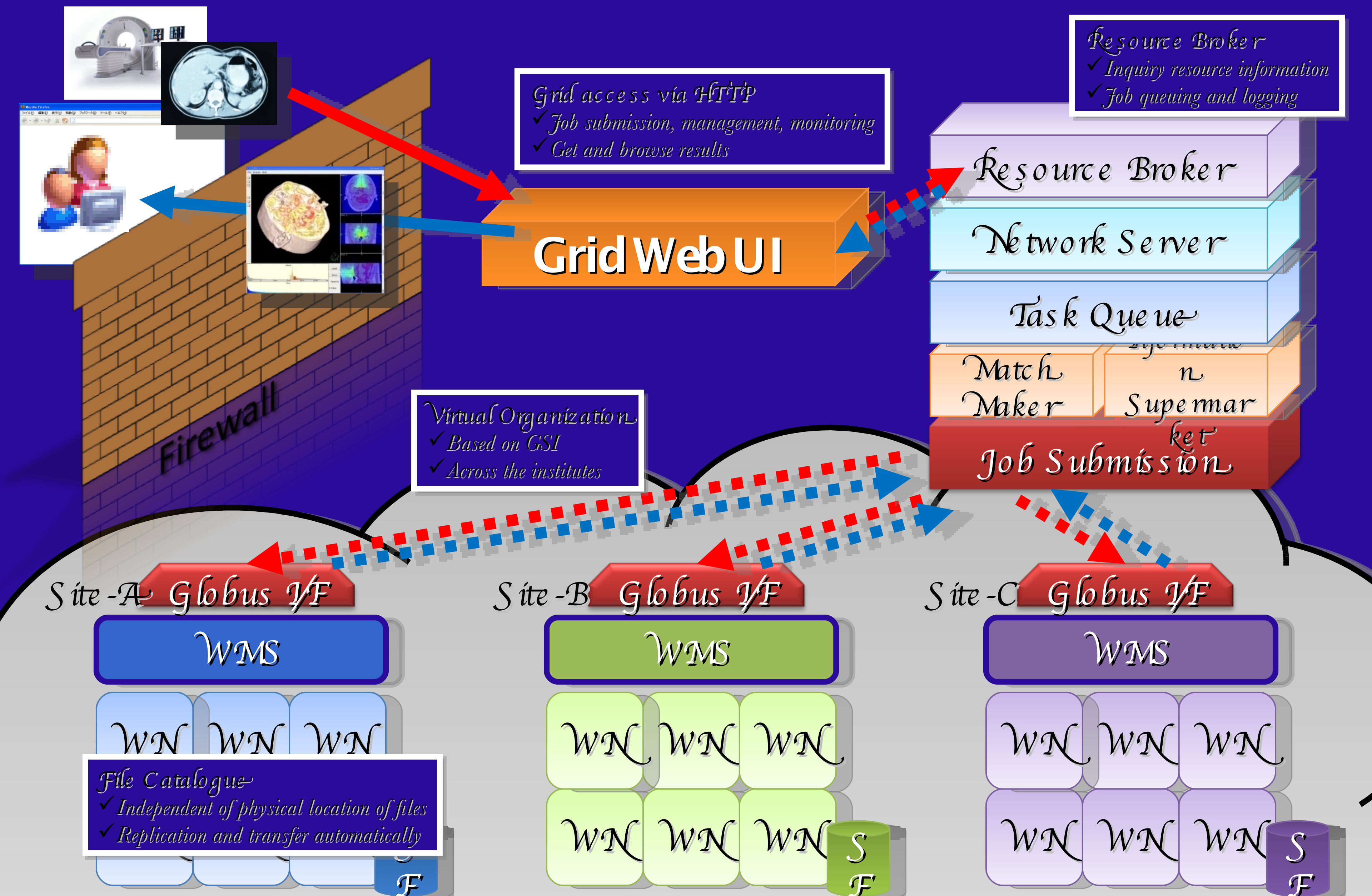


Trajectory information in the simulation is available.

***Functionality Requirements*:**

- To visualize
  - the modality image used by the simulation,
  - the calculated dose distribution and
  - the particle trajectories
  - in an agreeable speed
- Transfer function editor
- Multi-platform

GRID Deployment and Web UI Interface



G4 Med Phys in North America

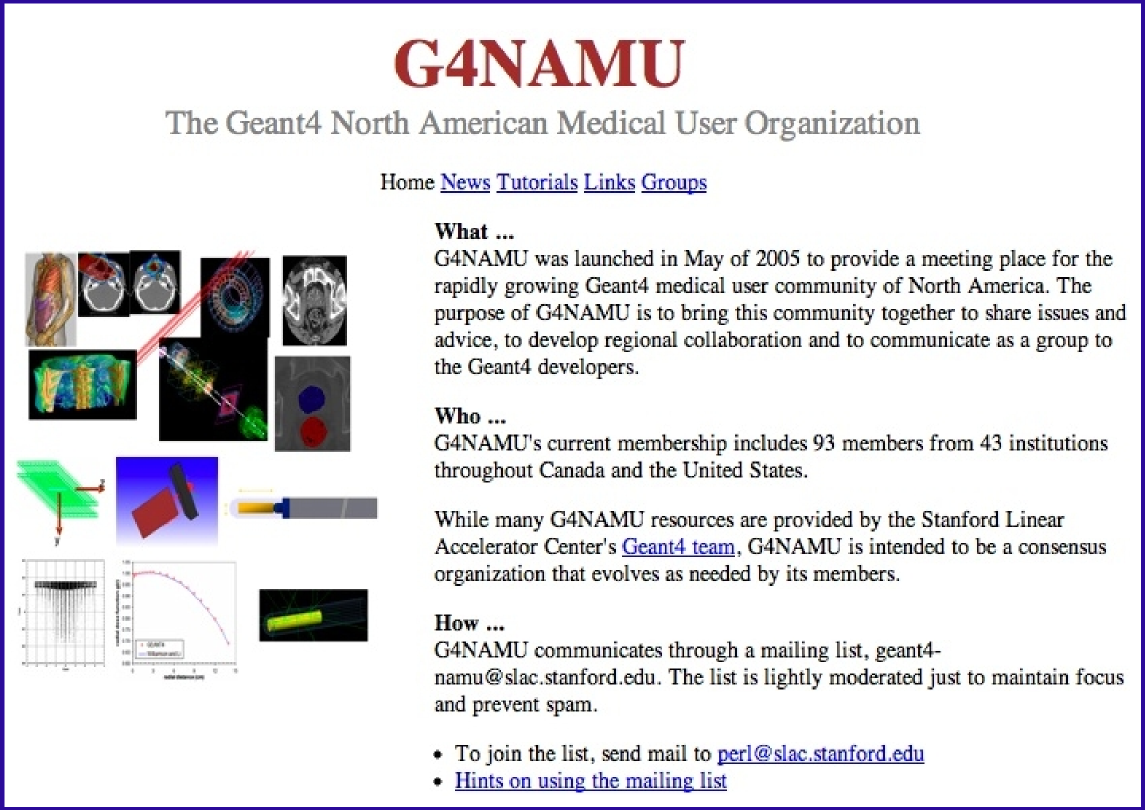
- Wide range of applications
- Some important recent meetings for this community:
  - Monte Carlo techniques in radiotherapy and verification :
    Third McGill International Workshop
    - May 28 - June 1, 2007, McGill University, Montreal, Canada
    - Talks Online at:
      http://www.medphys.mcgill.ca/~mcworkshop2007/talks/
  - XVth International Conference on the Use of Computers in Radiation Therapy (ICCR 2007)
    - June 4-7, 2007, Ontario, Canada
  - American Association of Physicists in Medicine (AAPM) 49th Annual Meeting
    - July 22-26, 2007, Minneapolis

Geant4 North American Medical Users Organization - G4NAMU

Launched in May of 2005 to provide a meeting place for the rapidly growing Geant4 medical user community of North America

- Bring this community together to share issues and advice, to develop regional collaboration and to communicate as a group to the Geant4 developers.

- Current membership includes 95 members from 44 institutions throughout Canada and the United States


G4NAMU

The Geant4 North American Medical User Organization

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What ...
G4NAMU was launched in May of 2005 to provide a meeting place for the rapidly growing Geant4 medical user community of North America. The purpose of G4NAMU is to bring this community together to share issues and advice, to develop regional collaboration and to communicate as a group to the Geant4 developers.

Who ...
G4NAMU's current membership includes 93 members from 43 institutions throughout Canada and the United States.

While many G4NAMU resources are provided by the Stanford Linear Accelerator Center's Geant4 team, G4NAMU is intended to be a consensus organization that evolves as needed by its members.

How ...
G4NAMU communicates through a mailing list, geant4-namu@slac.stanford.edu. The list is lightly moderated just to maintain focus and prevent spam.

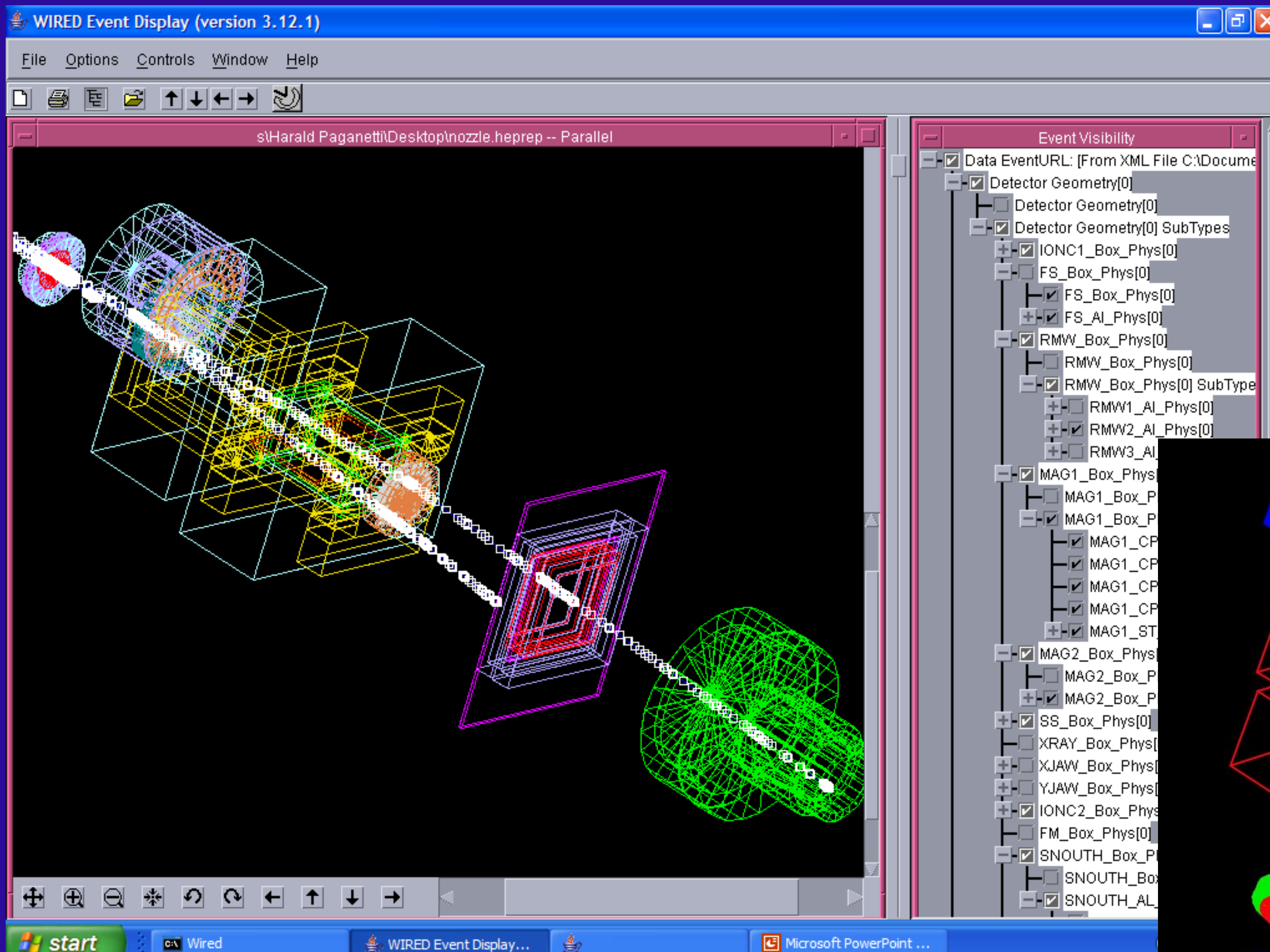
- To join the list, send mail to perl@slac.stanford.edu
- Hints on using the mailing list

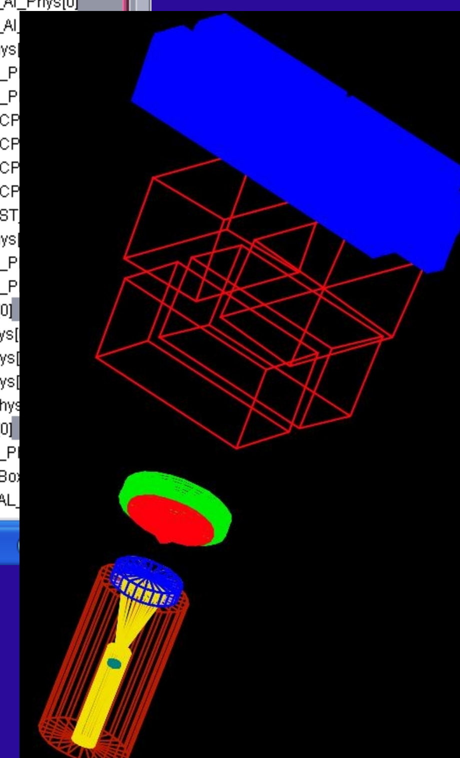
- http://geant4.slac.stanford.edu/g4namu/

Geant4-Related Talks and Posters at AAPM Annual Meeting 2007

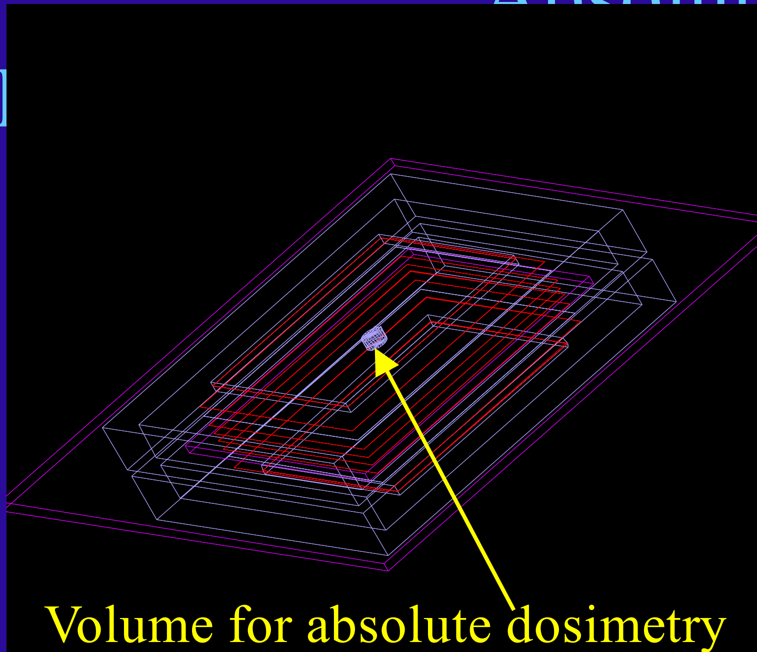
- Charara: Development of a Novel Detector for Measuring Proton Energy Spectra
- Z-Jarlskog: Simulation of Neutron Dose Exposure for Pediatric Proton Therapy Patients Using Whole-Body Age-Dependent Voxel Phantoms
- Sechopoulos: Radiation Dose to Tissues From Mammography
- Peterson: Variations in Scanned Beam Proton Therapy Doses Due to Random Magnetic Beam Steering Errors
- Archambault: Proton Dose Deposition in Water-Equivalent Plastic Scintillation Detectors
- Chen: Dose Saving and Scatter Reduction in Volume-Of-Interest (VOI) Cone Beam CT-a Monte Carlo Simulation Study with Geant4
- Ulmer: Analytical and Monte-Carlo (GEANT4) Calculations of Collimator Scatter of Proton Beams
- Faddegon: Comparison of Monte Carlo Simulation Results to An Experimental Thick-Target Bremsstrahlung Benchmark
- Clasie: Design of a Vacuum Chamber for a Universal Proton Therapy Nozzle
- Z-Jarlskog: Different Methods of Organ Equivalent Dose Scoring in Monte Carlo Neutron Dose Calculations
- Clasie: Optimization of the Beam Width in a Universal Proton Therapy Nozzle
- Tinslay: Verification of Bremsstrahlung Splitting in Geant4 for Radiotherapy Quality Beams
- Paganetti: The IAEA Initiative to Standardize Nuclear Data for Heavy Charged-Particle Radiotherapy

Beamline design and quality assurance
Paganetti et al., Harvard/Massachusetts General



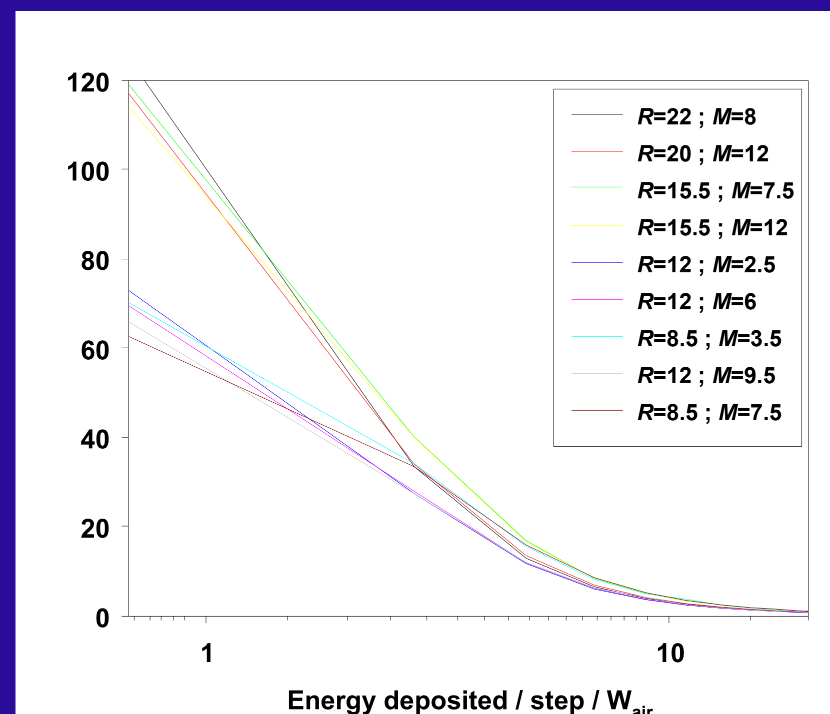


Absolute dosimetry
...rd/Massachusetts General

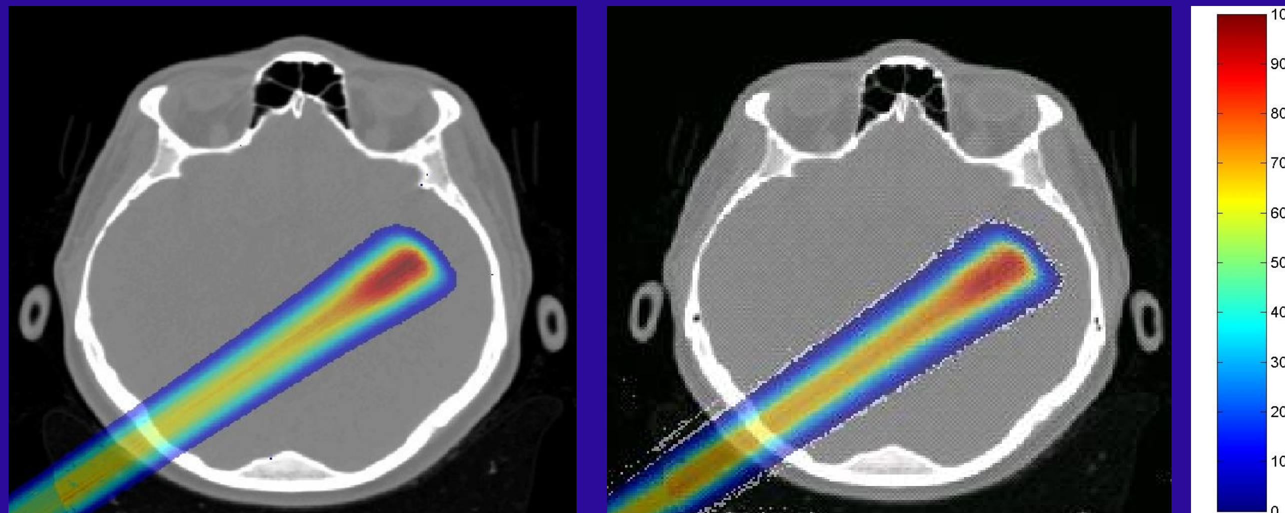


$$Output - Factor \quad @ \quad \frac{D_{cal}}{i_{ic}} \left(cGy / MU \right)$$

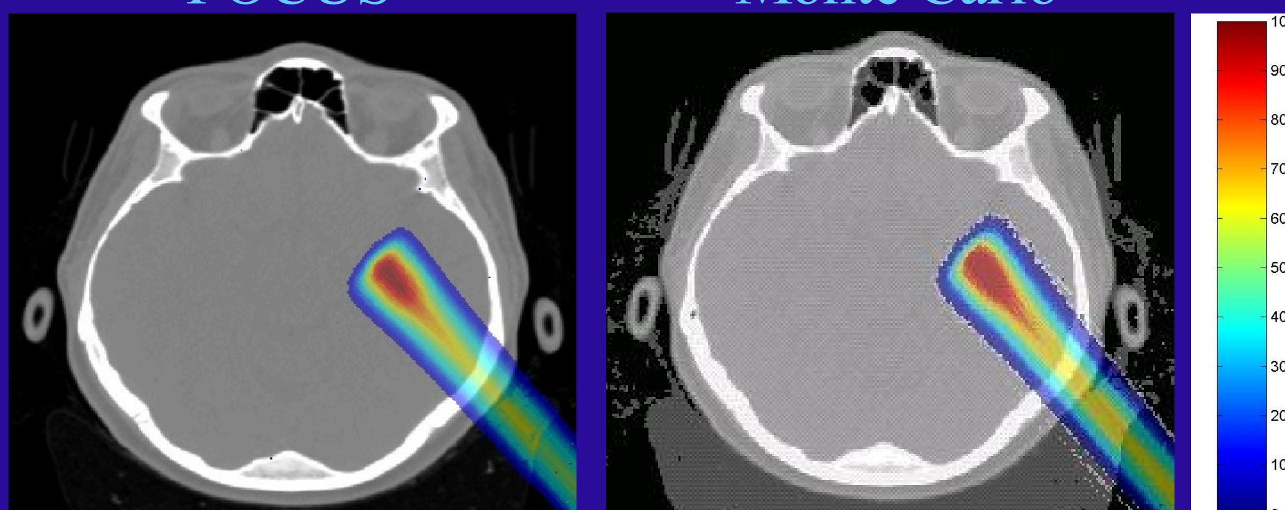
$$i_{ic} = \frac{e \; e_{ic}}{W_{air}} \int \int \left(\frac{dE}{dx} \right)_{air} p \; dx dF$$



Patient dose calculation
Paganetti et al., Harvard/Massachusetts General

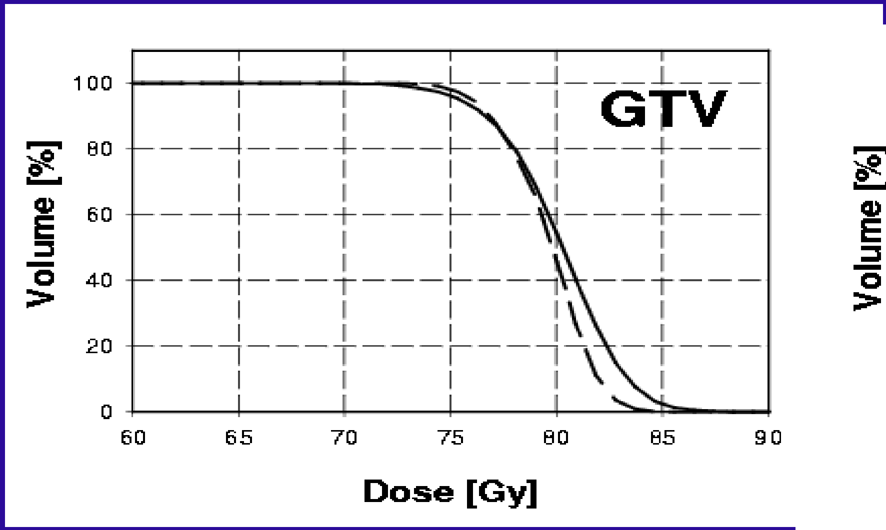


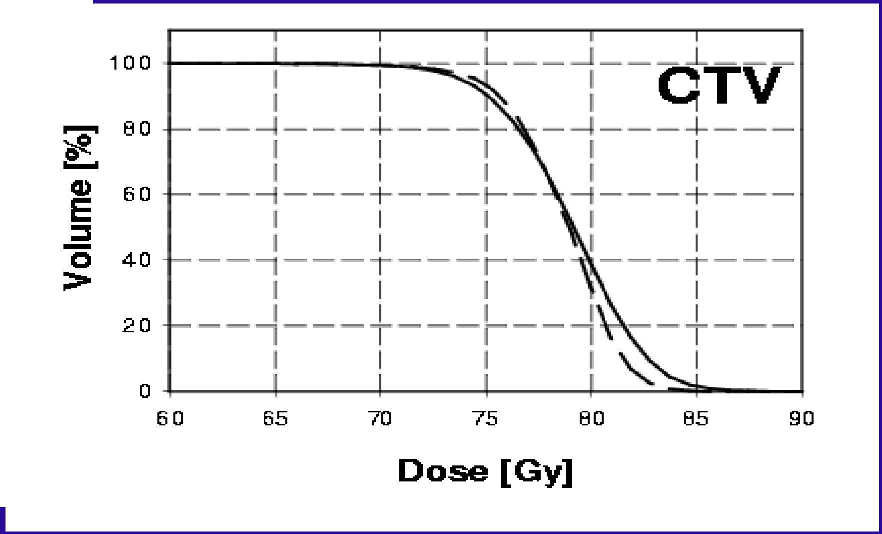
FOCUS Monte Carlo



FOCUS Monte Carlo

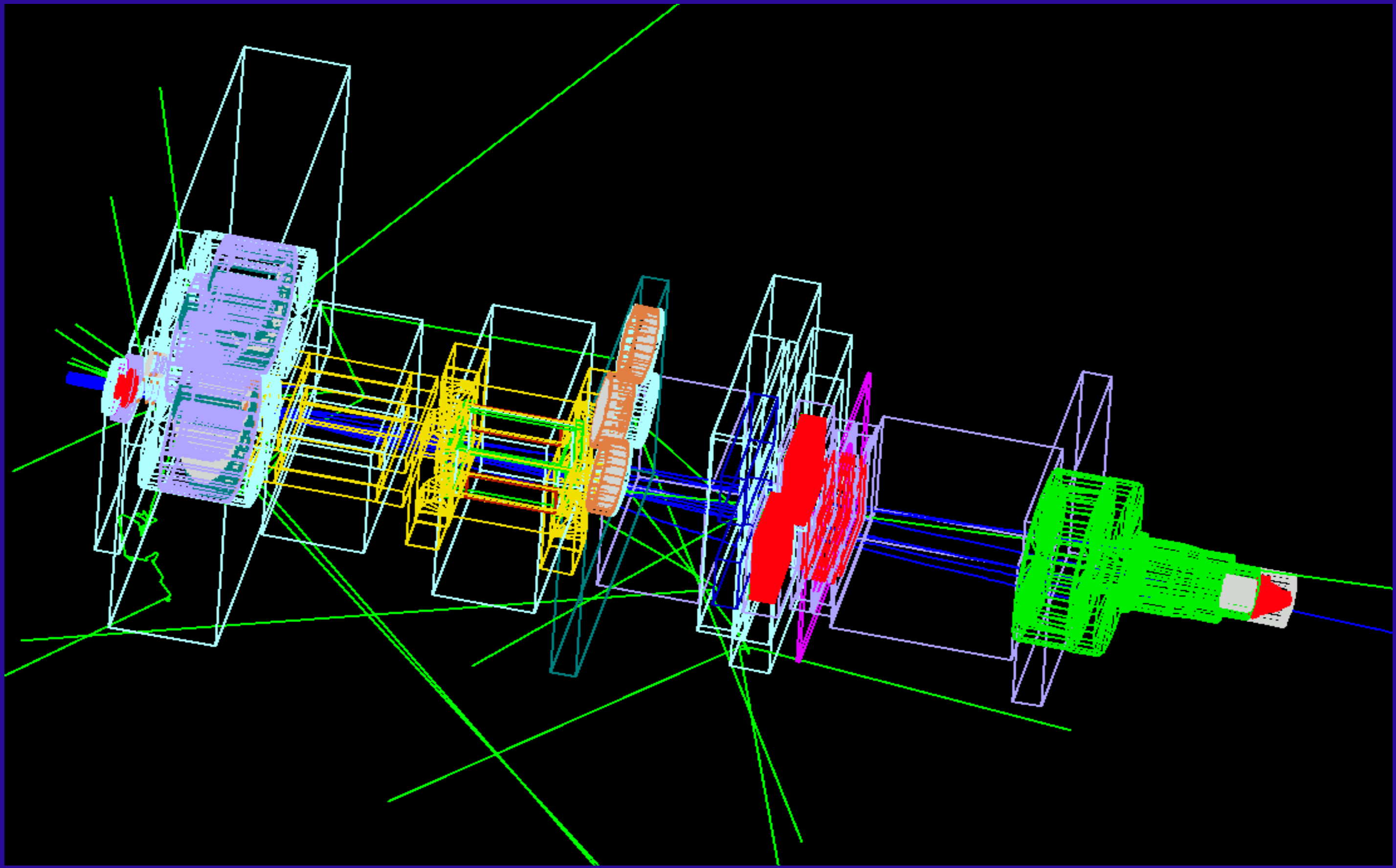
Time dependent simulations
Paganetti et al., Harvard/Massachusetts General



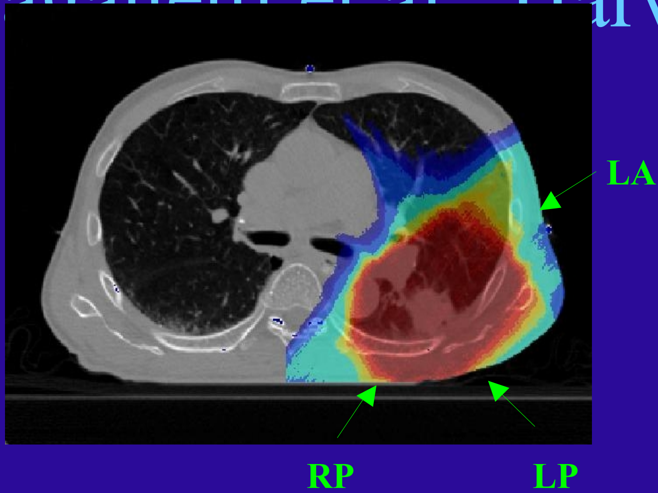


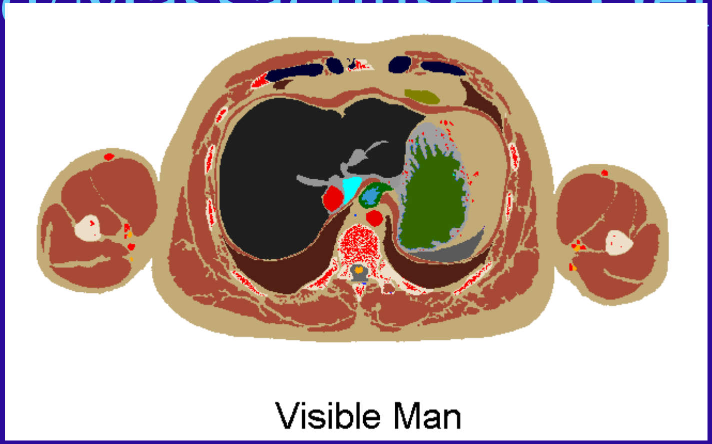
Solid lines: **Patient in inhale**
Dashed lines: **Considering the entire breathing phase**

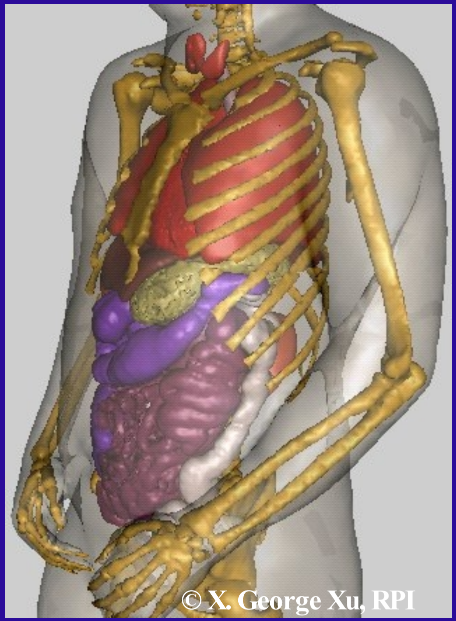
Radiation Protection
Paganetti et al., Harvard/Massachusetts General

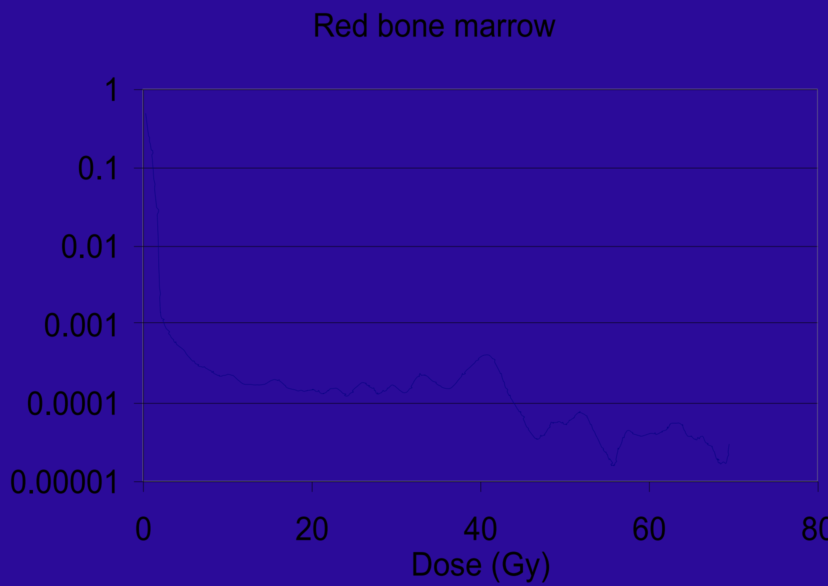


Radiation Risk
Paganetti et al., Harvard/Massachusetts General

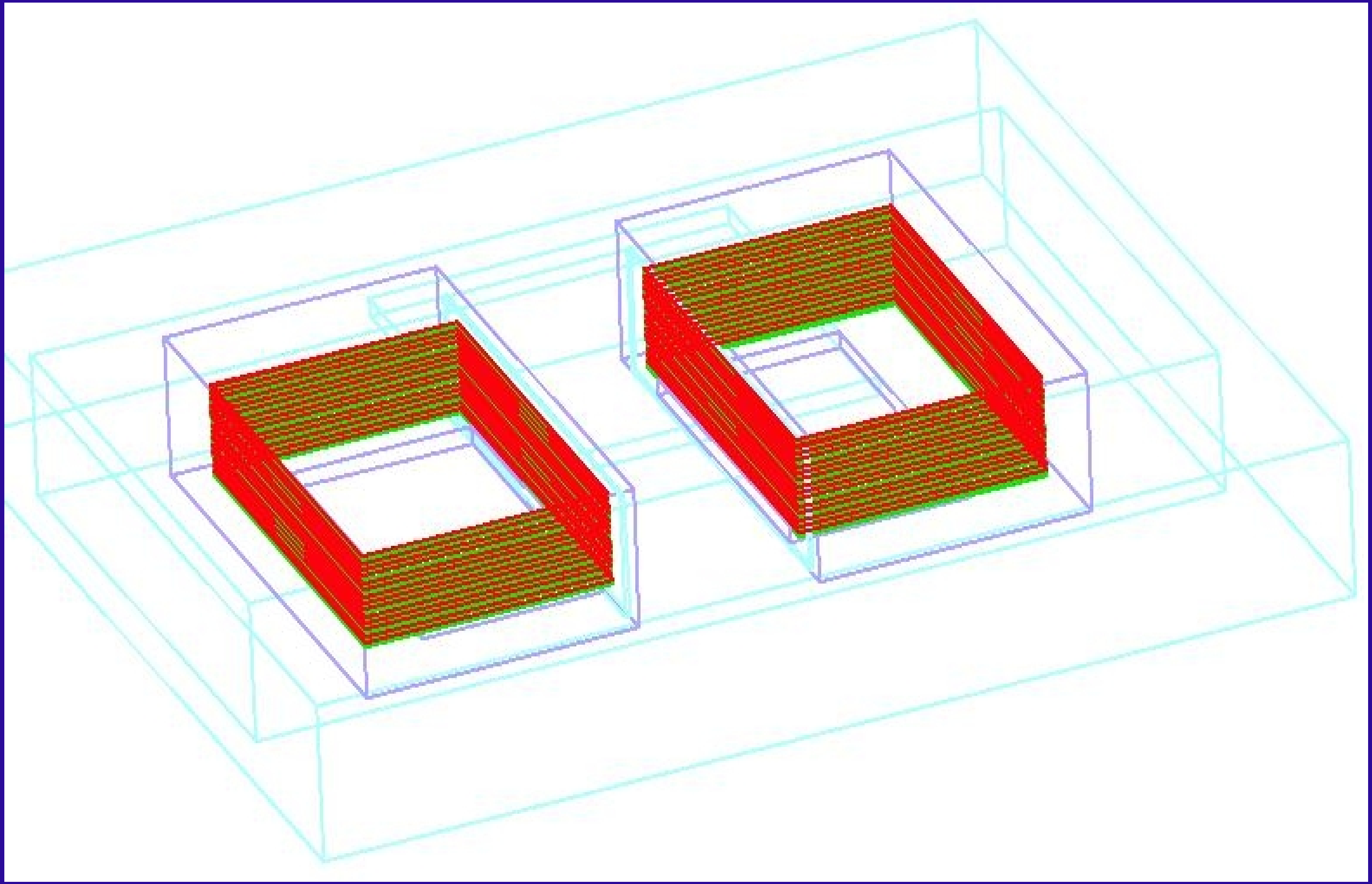






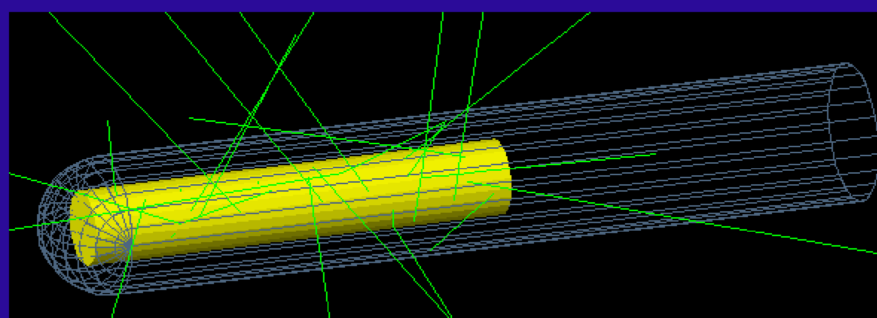


Detector Simulation
Paganetti et al., Harvard/Massachusetts General



Modeling of encapsulated ^{192}Ir source

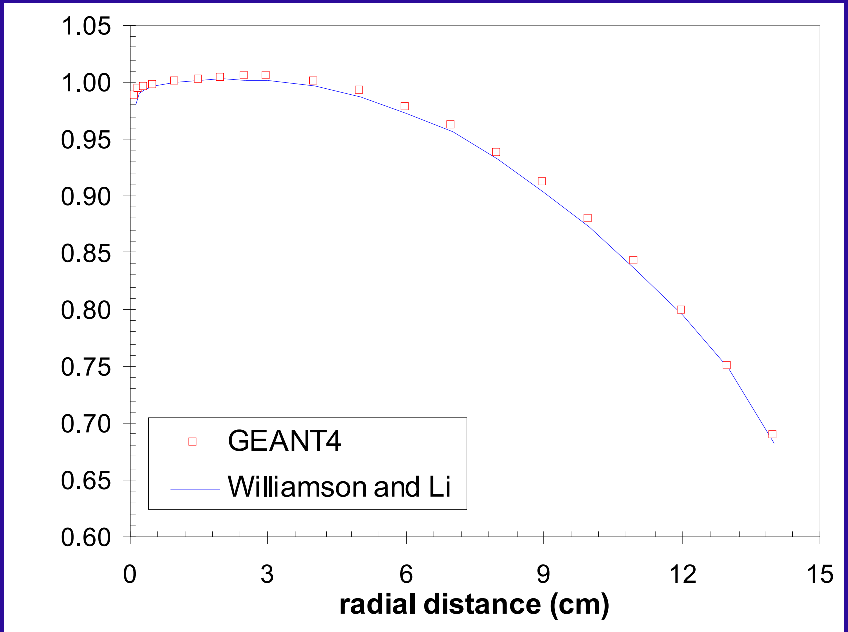
(Courtesy of McGill University)

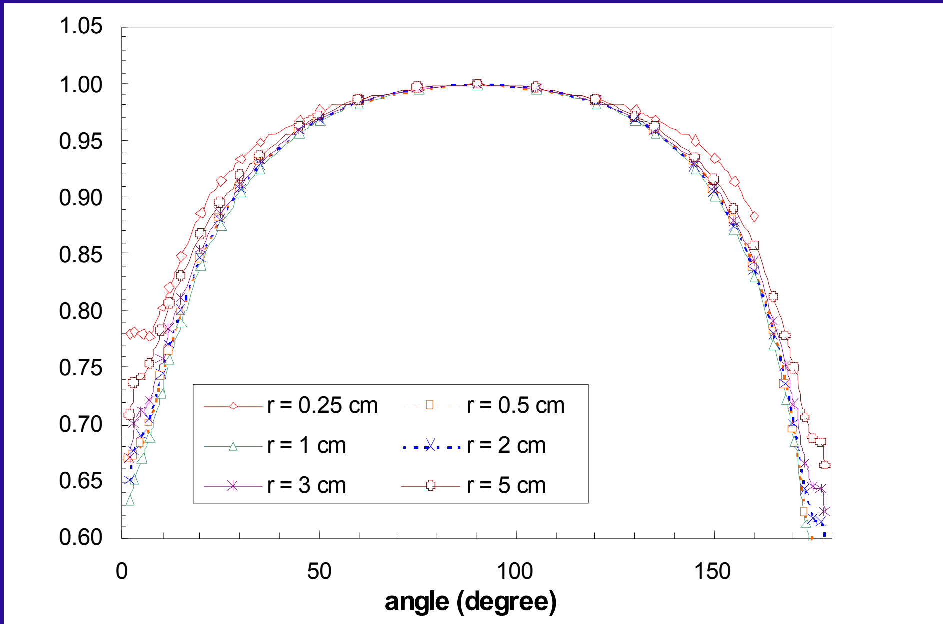


MicroSelectron Classic HDR source (part no. 080950)

Radial dose and anisotropy functions of encapsulated source

(Courtesy of McGill University)





Radial dose function

GEANT4:

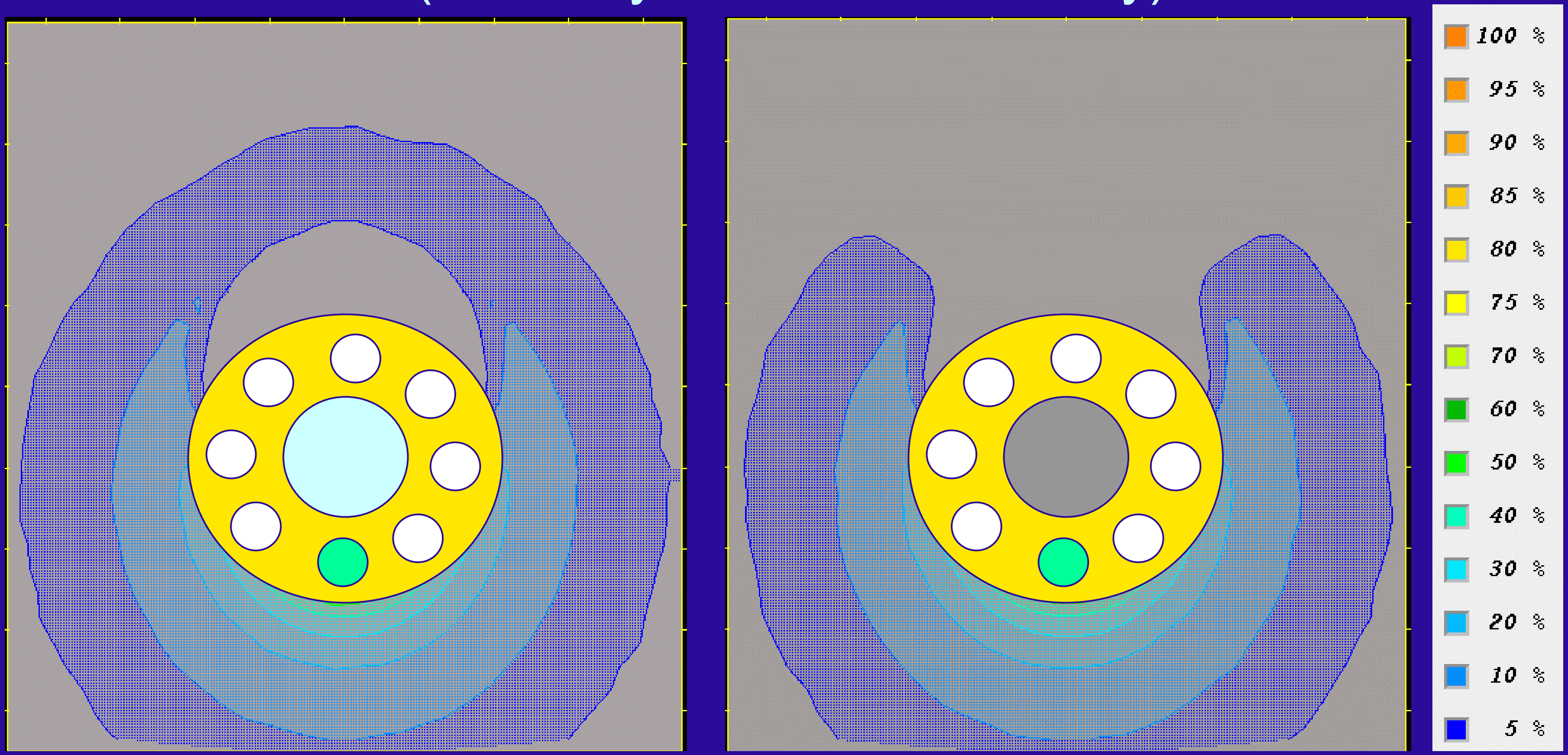
~0.4% higher than Williamson and Li

(Med. Phys. **22**, 809-819, 1995)

Anisotropy function

Isodose distributions

(Courtesy of McGill University)



Presence of lead shielding reduces the dose distribution in a lucite phantom by up to 20%, and it is confirmed by ion chamber measurements.

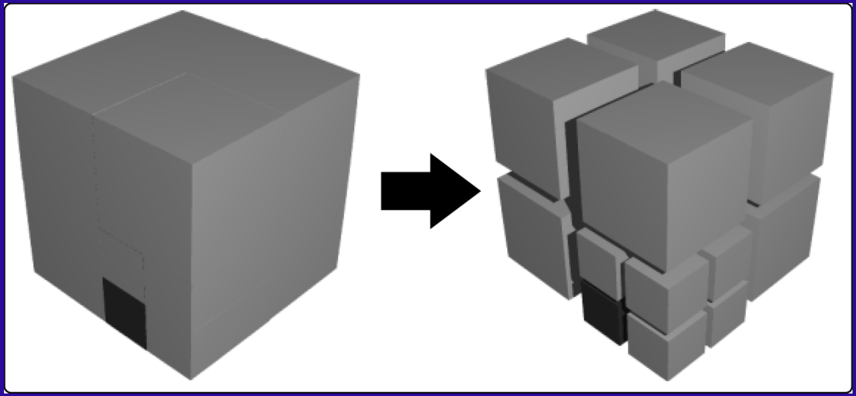
Octree geometry compression – DICOM images

UNIVERSITÉ LAVAL

Voxel-based geometry

Objectives:

- **Reduce the number of voxels**
- **Keep the critical information**

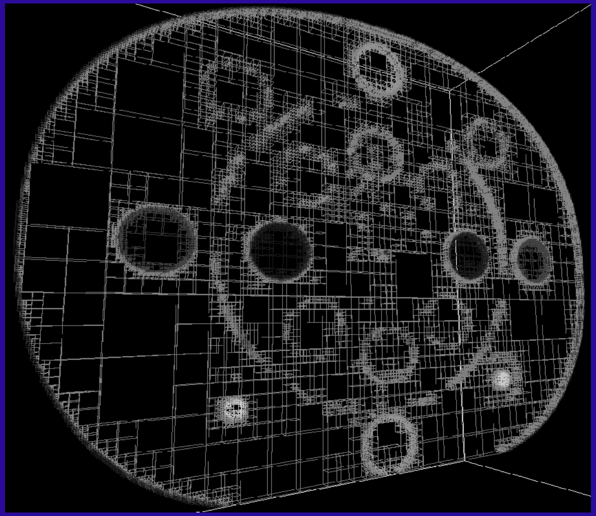


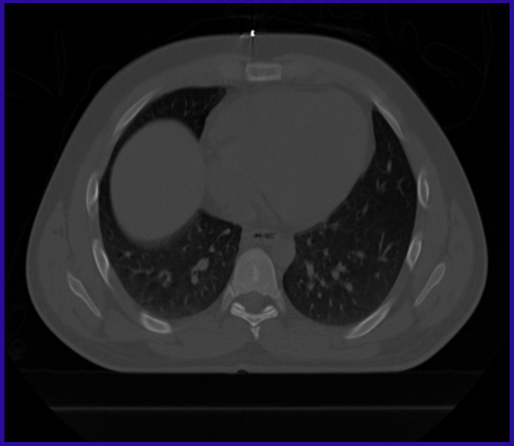
- **Indexing of the density distributions using a density gradient threshold:**
  - **High resolution kept only in heterogeneous area**
  - **Can easily reduce the number of voxels by 75%**
- **Does not affect dose distribution**

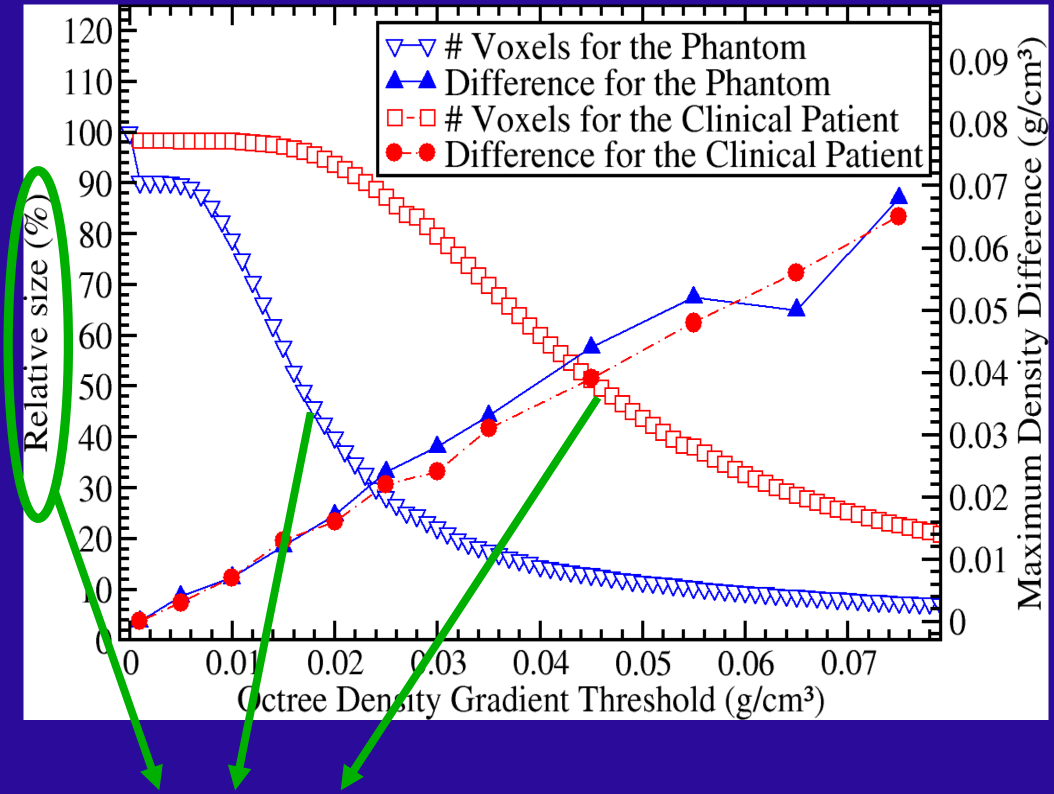
V. Hubert-Tremblay, MSc project

Octree geometry compression – DICOM images

Examples: CT phantom + thorax patient



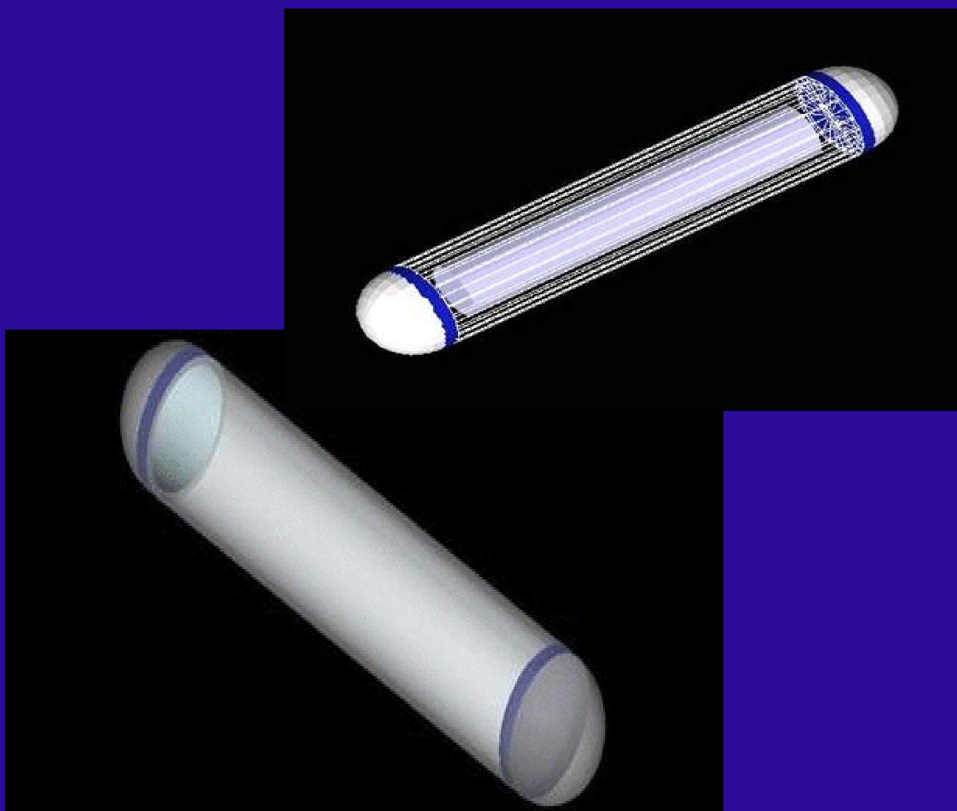


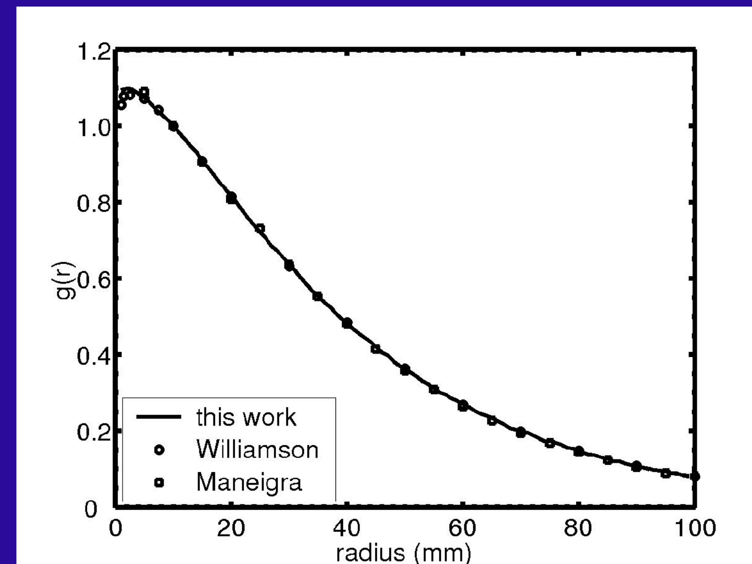


Voxel number v/s DGT

Prostate brachytherapy - LDR

LDR ^{125}I source, Amersham 6711





Validation of the model: radial dose fonction

J.-F. Carrier, Ph.D. project

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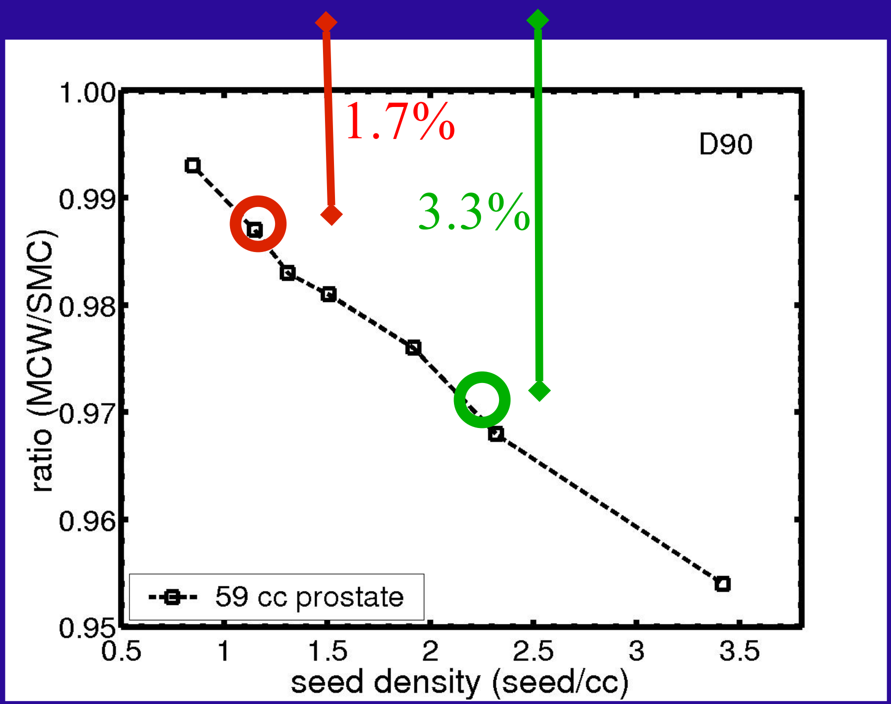
MC simulations on clinical treatment plans

1) Interseed attenuation



RED PLAN

- 77 seeds
- 0.6 mCi activity
- 1.7% of the D90 value is lost due to interseed attenuation

BLUE PLAN

- 137 seeds
- 0.3 mCi activity
- 3.3% of the D90 value is lost due to interseed attenuation

This interseed attenuation is not considered in TG43 (clinical) dose calculations

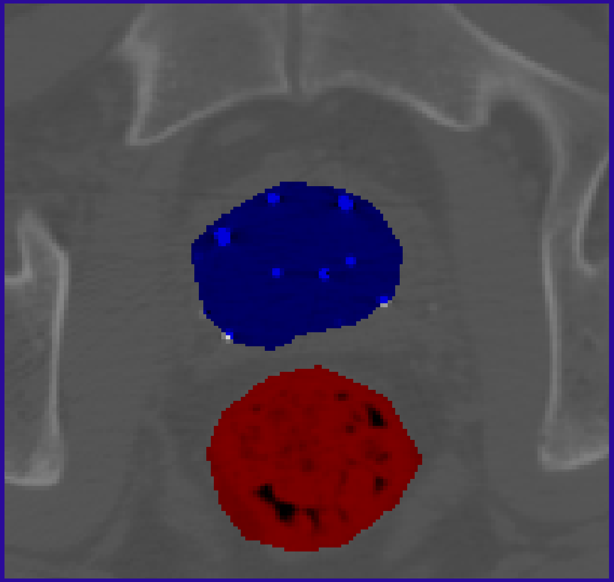
Prostate brachytherapy - LDR

MC simulations on clinical treatment plans

2) Medium composition: CT-based MC

CT image

G4 DICOM reader[1]
Organ contours
Seed positions



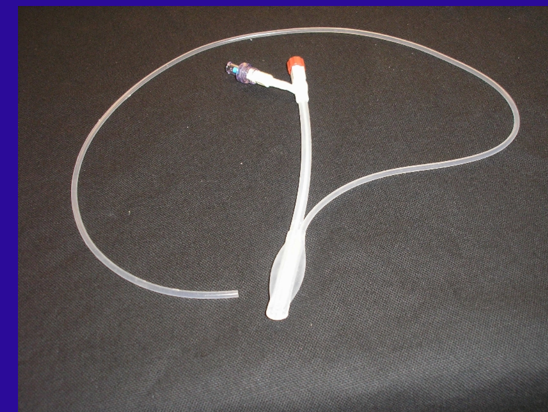
G4 geometry

D90: 5-7% differences between water MC and CT-based MC

[1] http://www.physmed.phy.ulaval.ca/phys_med/DICOM

Hampton University

(Collaboration: Proxima Therapeutics, dePaul)



Active Mammosite

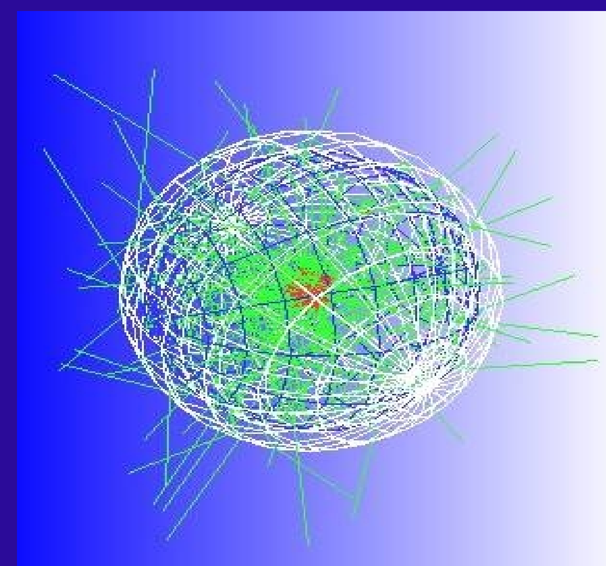
→ Absolute real-time position measurement (within ±1 mm)

→ Absolute real-time dose measurement

→ Modelization of the dose distribution using CT scan data & 4D phantom

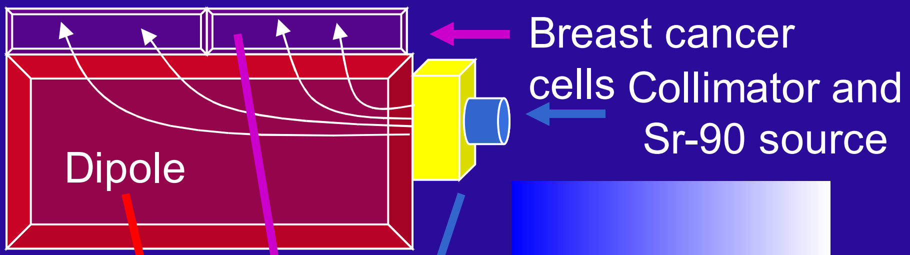
Jacquelyn Winston, M.Sc.: Detector

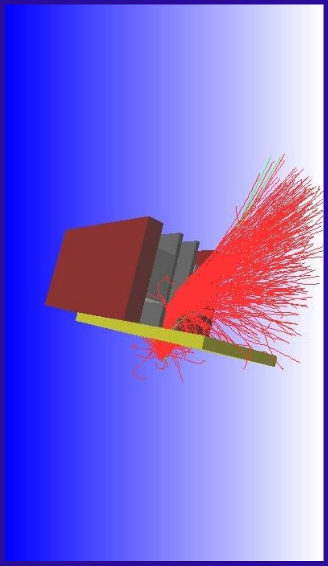
Rachel Black, Ph.D. : Detector, Geant4 & VTK

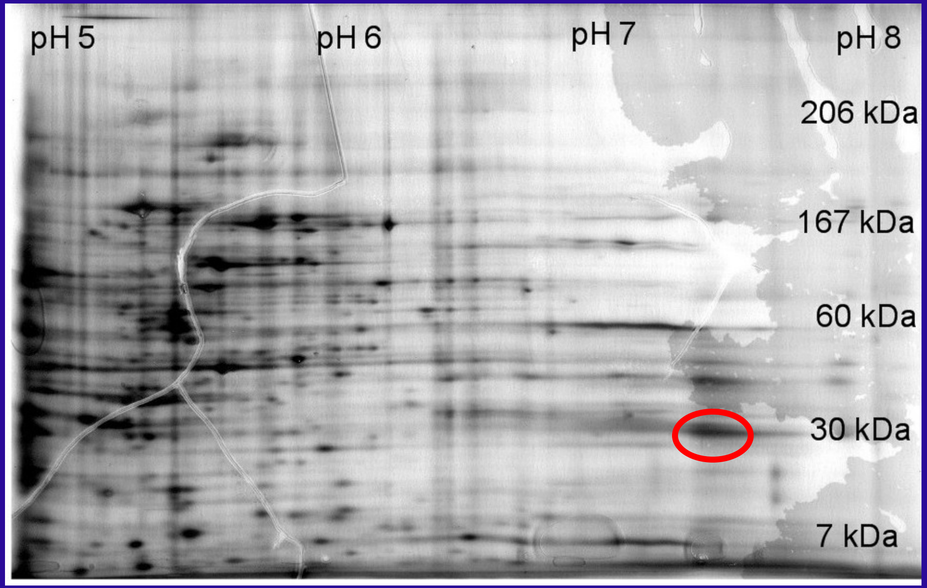


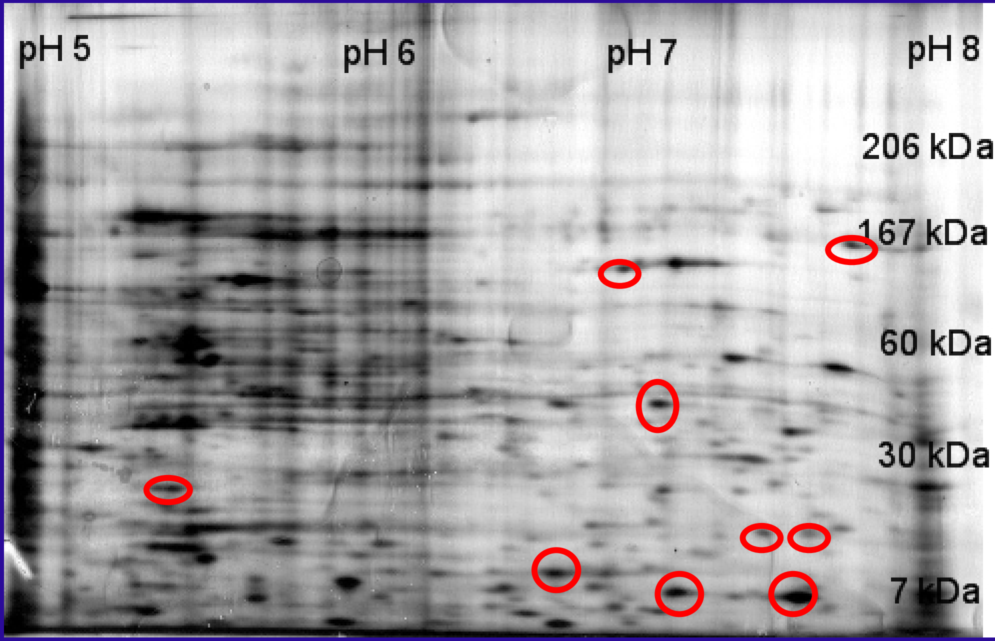
Hampton University

(Collaboration: Jefferson Lab, EVMS, ODU)





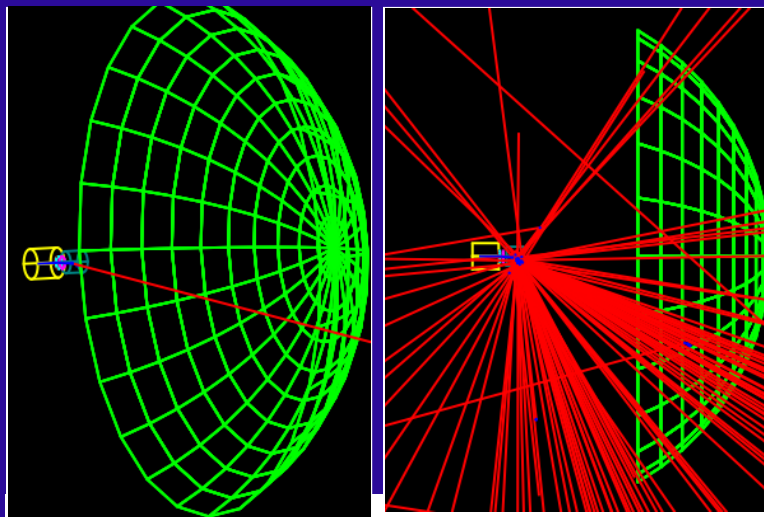




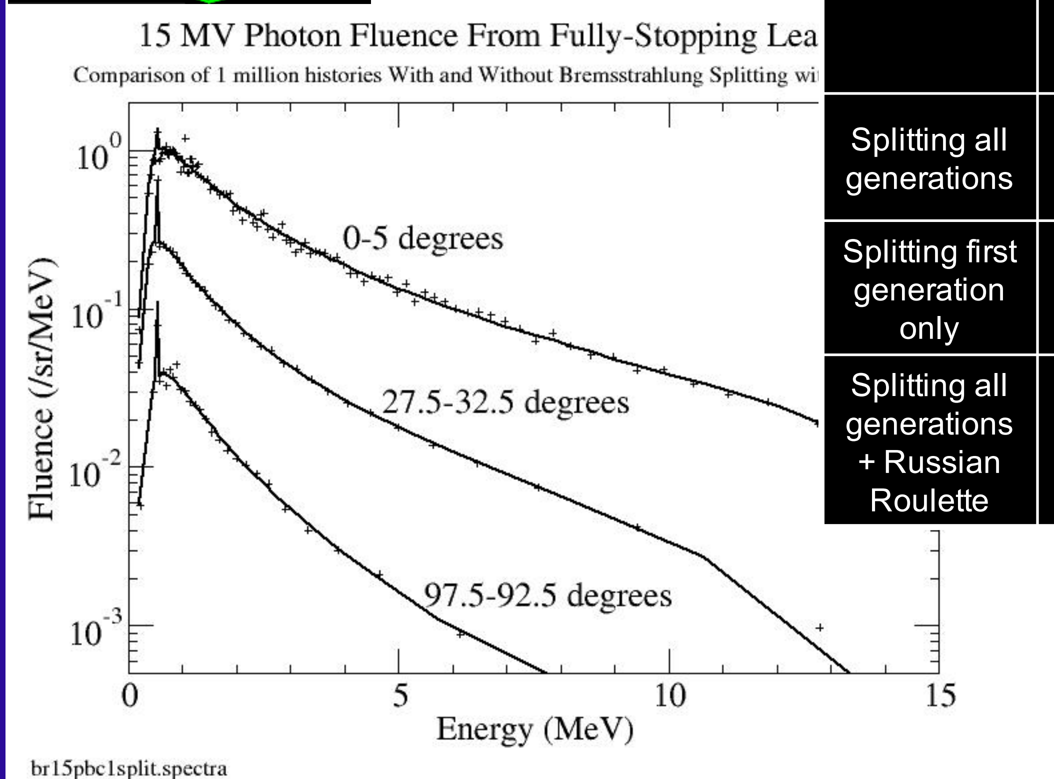
Monoenergetic Brachytherapy Sources

→ Energy dependence of irradiated breast cancer cells

Ariano Munden, M.Sc.

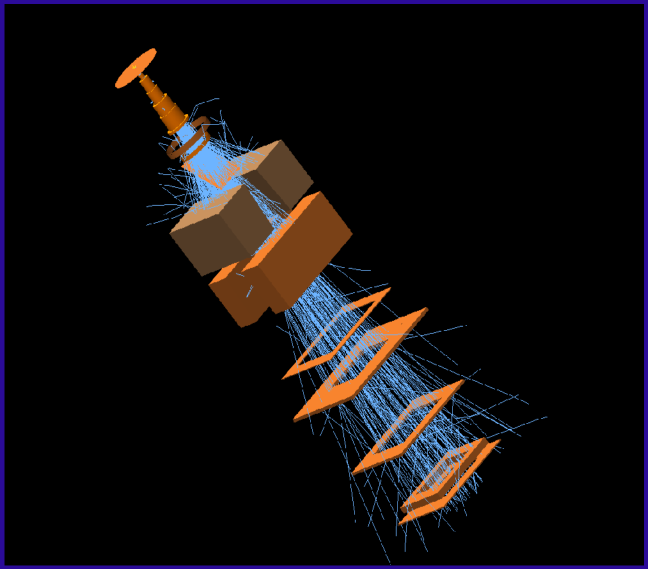


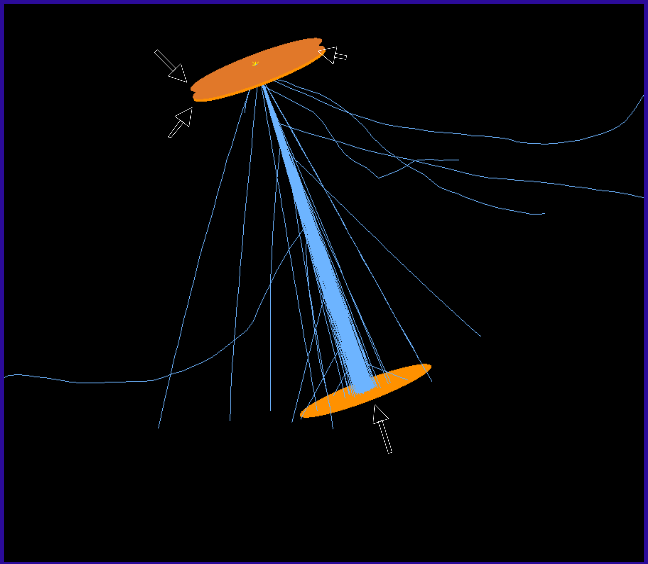
Tinslay et al, “Verification of bremsstrahlung splitting in Geant4 for radiotherapy quality beams,” SU-FF-T-447

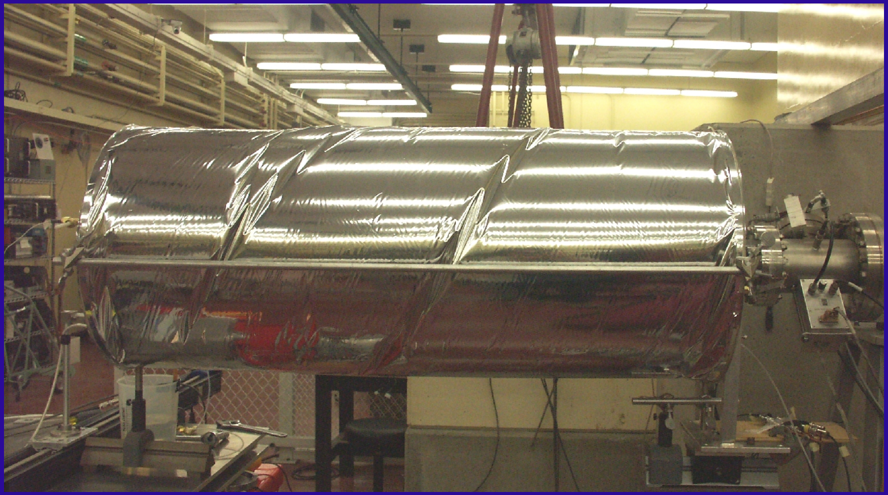


	Beryllium	Aluminum	Lead
Splitting all generations	8.8	3.4	0.1
Splitting first generation only	15.3	6.2	2.2
Splitting all generations + Russian Roulette	11.8	6.6	3.1

McDonald et al, “High precision data set for benchmarking of electron beam Monte Carlo,” SU-FF-T-241







Warning: Personal Opinion

- From here on, what I'll be saying is just my personal opinion, based on my own contacts with Med Phys users over the last three years.

Validation

- Must be led by Medical Physicists publishing in Medical Physics publications.
- Geant4 collaborators work well with this community, but Medical Physicists should be the lead authors on these papers.
  Their colleagues are professionally bound to listen to them, not to us.
- Radiation therapy machines are NOT turn-key operations. They must be and are continually maintained, calibrated and characterized by individual medical physicists who are ethically bound to check everything out themselves.
  The same is true for the Monte Carlo software that these medical physicists use.
- While many of my colleagues spend tremendous energies validating Geant4, the ultimate responsibility for such validation in Med Phys falls on the Medical Physicist.

Some Rocky History

- Conclusions from a highly cited early Paper by Emily Poon and Frank Verhaegen, “Accuracy of the photon and electron physics in GEANT4 for radiotherapy applications,” Med Phys. 32(6):1696-711, 2005.

> Although recommended for medical physics applications, the *Low-energy* model does not always give the best results. It is also considerably slower to run than the *Standard* model. Overall, GEANT4 is best-suited for applications where electron transport is not critical, in areas such as brachytherapy and megavoltage photon beam simulations.

And Recent Success

Monte Carlo Techniques in Radiotherapy delivery and verification:
Third McGill International Workshop
Montreal, May 29 - June 1, 2007

Comparison of Geant4 Results to EGSnrc and Measured Data in Large Field Electron Dose Distributions

Bruce Faddegon (UCSF), Joseph Perl (SLAC)
Jane Tinslay (SLAC), Makoto Asai (SLAC)

Central axis depth dose curves and dose profiles of 6-21 MeV Primus electron beams were measured for a 40x40 cm field and simulated in EGS4 in work presented at the First McGill International Workshop in 2004.

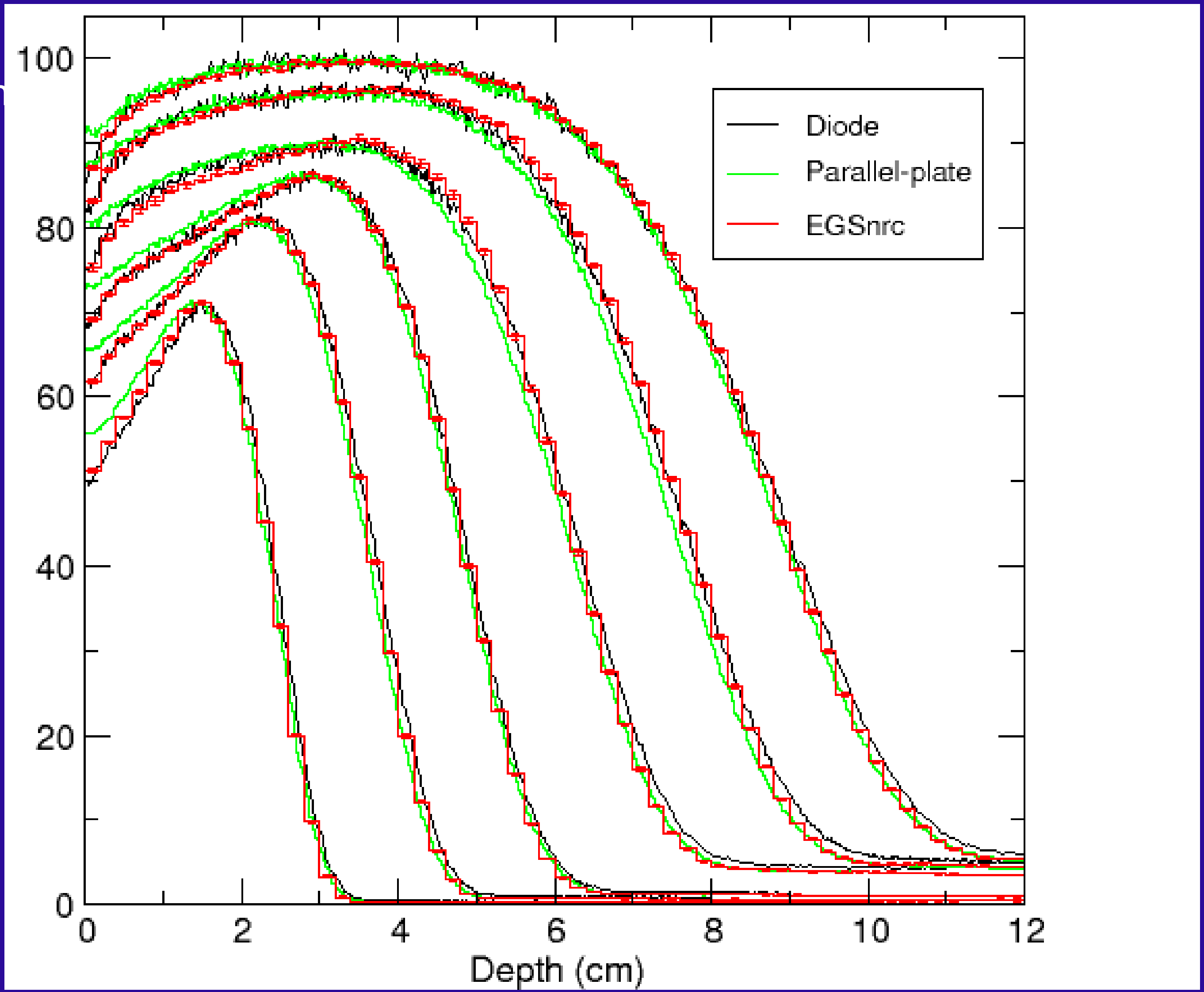
Those Monte Carlo treatment head and water phantom simulations have now been replicated with EGSnrc and the Geant4 Simulation Toolkit (version 8.2.p01).
In each case, as with the original EGS4 simulation, source and geometry have been adjusted to best match simulation results to measurement.

Geant4 simulations were also shown for case of using the exact same source and geometry parameters used in the EGSnrc simulations.

Work supported in part by the U.S. Department of Energy under contract number DE-AC02-76SF00515
and NIH R01 CA104777-01A2.

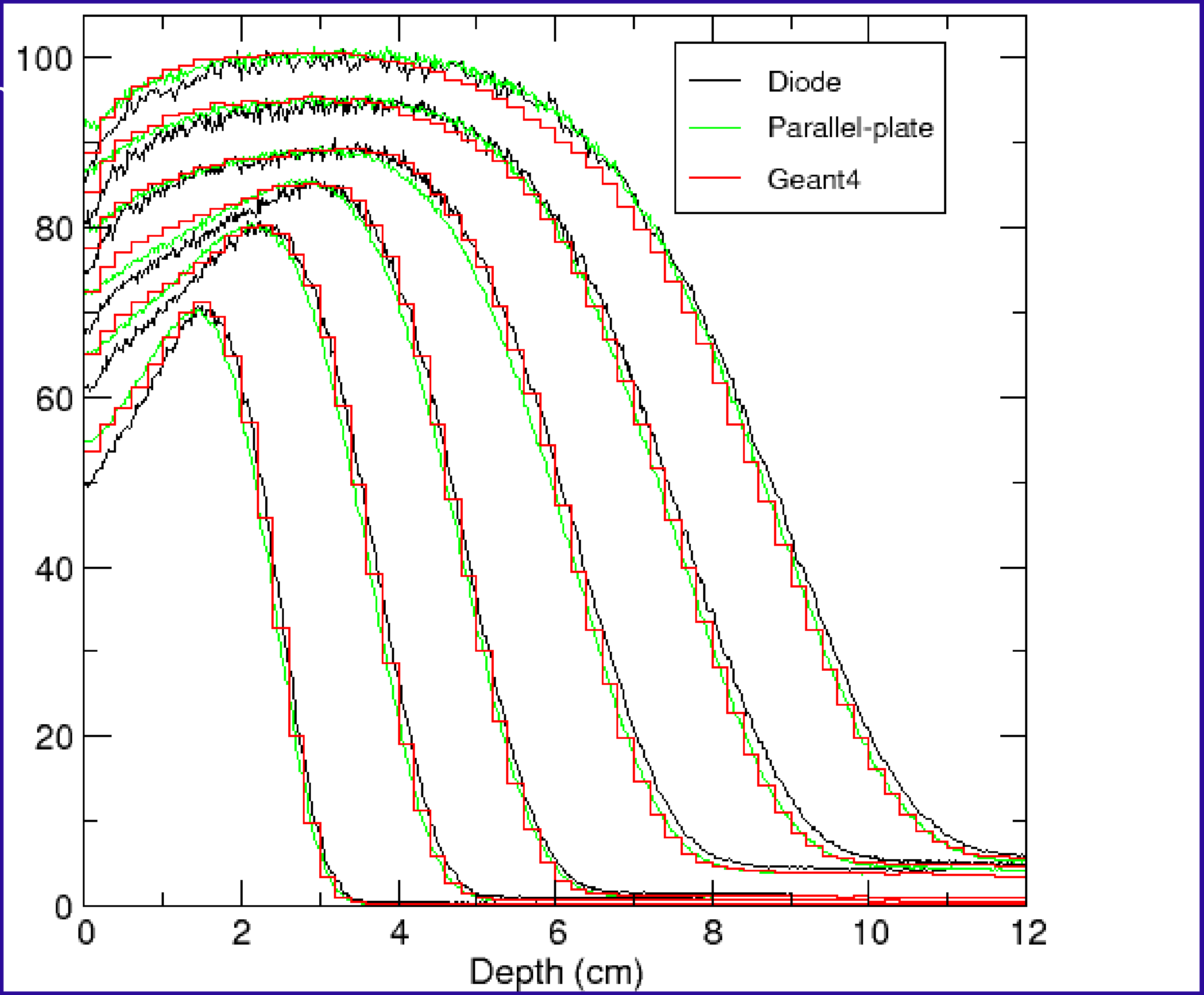
Results: EGSnrc vs Measurement

- EGSnrc gets to 2%/2mm agreement with measurement inside useful field
- 5%/5mm in penumbra and beyond
- bremsstrahlung (D_e/D_x) matched to better than 5%
- Better match to diode than parallel plate in build-up region.
- Diode over-responds in the brems region

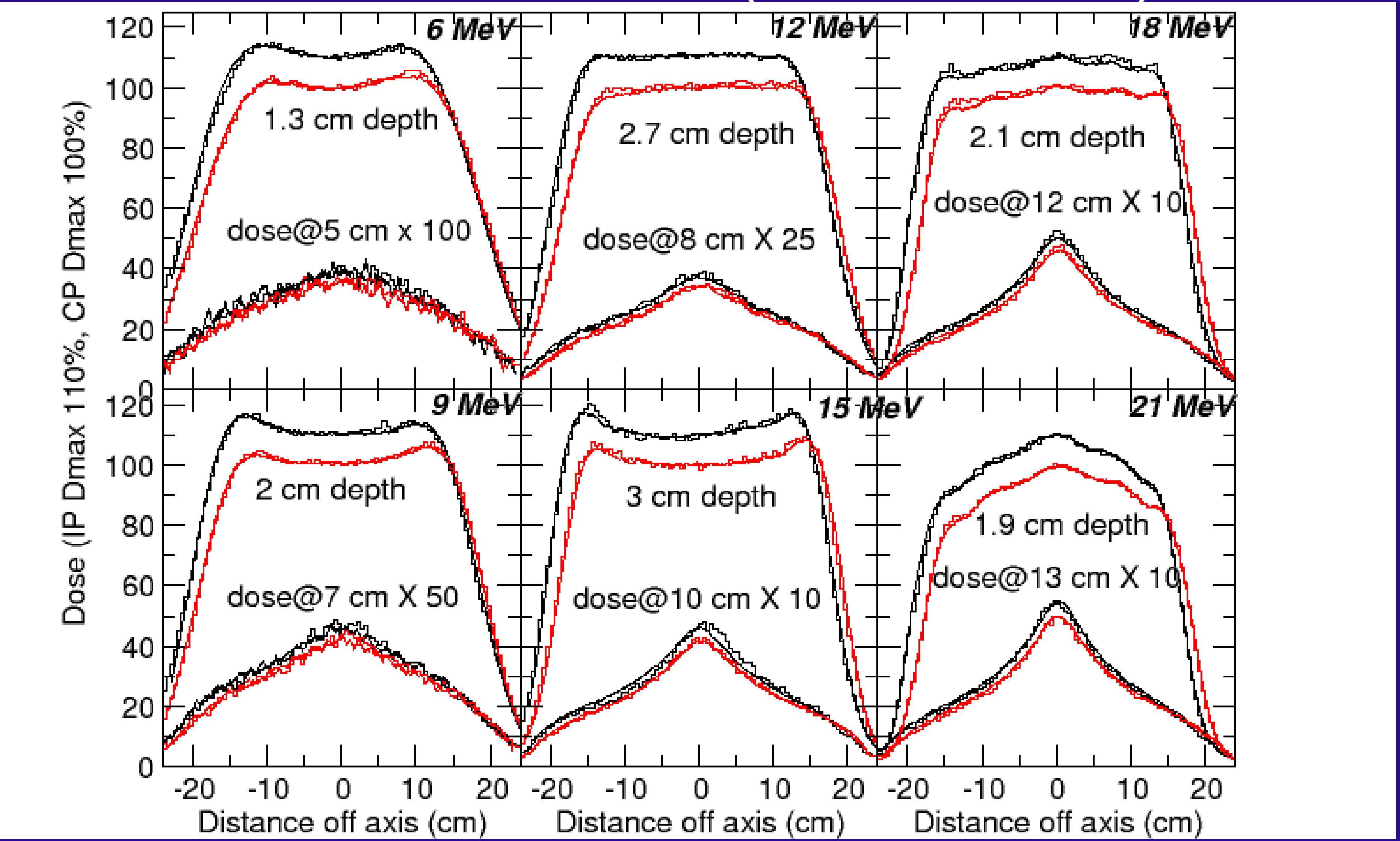


Results: Geant4 vs Measurement

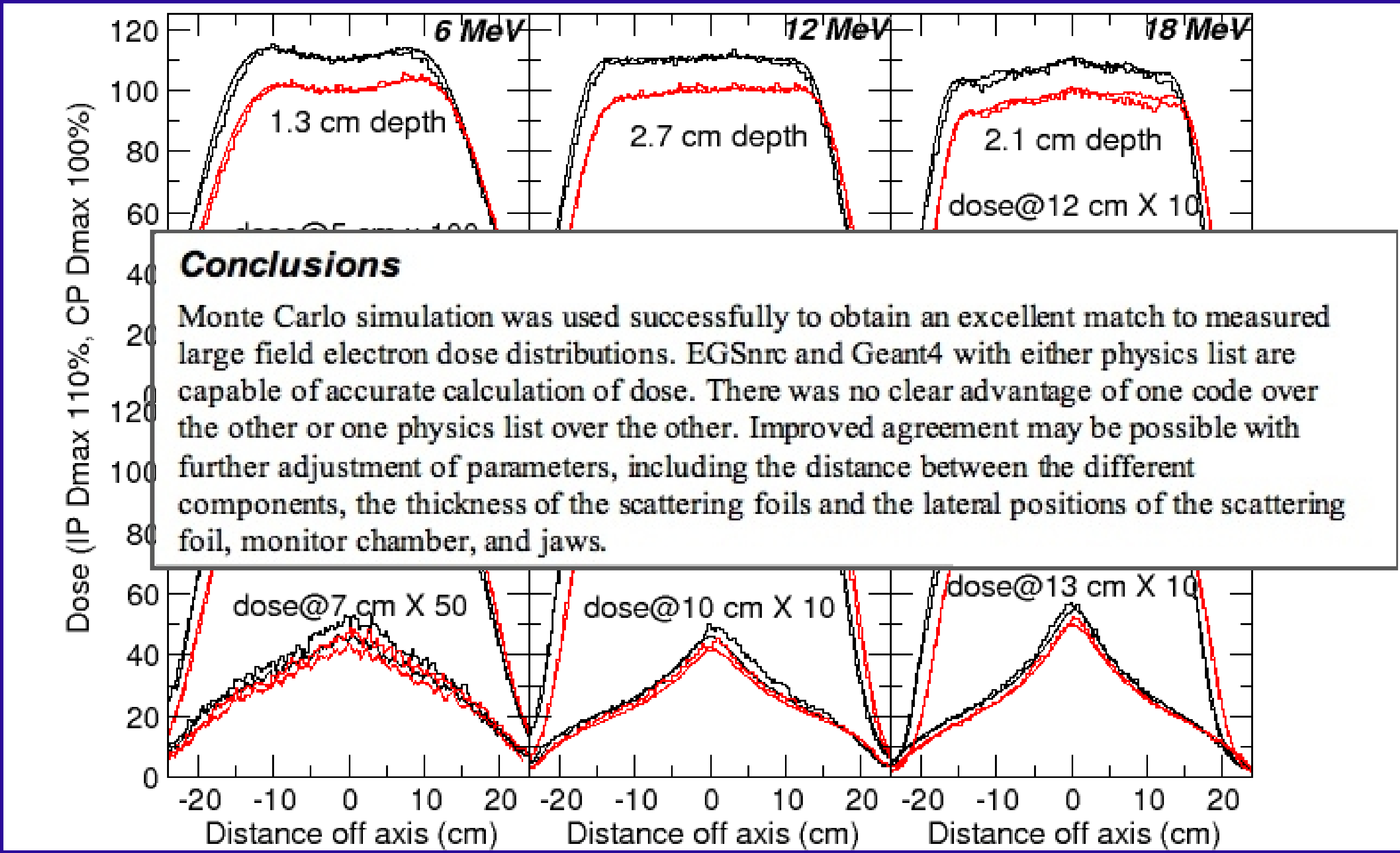
- Geant4 gets to 3%/2mm agreemen with measurement inside useful field
- 6%/6mm in penumbra and beyond
- bremsstrahlung (D_e/D_x) high by about 6%, but we are not finished tweaking
- Better match to parallel plate than diode in build-up region.



EGSnrc Results (most recent)



Results: Geant4 vs Measurement



Conclusions

Monte Carlo simulation was used successfully to obtain an excellent match to measured large field electron dose distributions. EGSnrc and Geant4 with either physics list are capable of accurate calculation of dose. There was no clear advantage of one code over the other or one physics list over the other. Improved agreement may be possible with further adjustment of parameters, including the distance between the different components, the thickness of the scattering foils and the lateral positions of the scattering foil, monitor chamber, and jaws.

And Recent Frustration

- Just last month at the annual meeting of the American Association of Physicists in Medicine, I had a conversation with a colleague who is frustrated with step size dependence of protons in recent releases

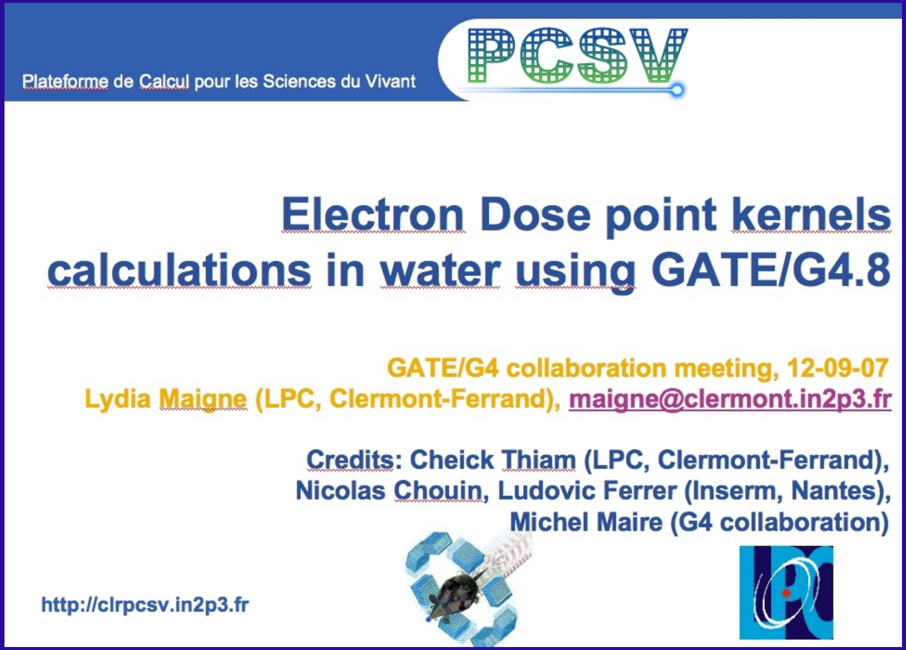
- My own work with colleague at UCSF also found confusing relationship between step size and accuracy (sign opposite of expected)

Why is Accuracy so Difficult?

- OK to have speed/accuracy trade off in step size and range cuts, our users understand this
  - but need to be linear
    - i.e., smaller step size or range cut = better accuracy
  - at all medical physics energies
    - e.g., electron beam, 6-21 MeV
    - proton beam, 160 MeV
  - and materials
    - huge range of atomic weights, from vacuum to plexiglass to water to tungsten (they'd probably use Neutronium if they could get it)
  - and particles
    - we're the place users come for an all-particle code
  - and need these to be consistently improving from one release to the next
- This is a very challenging requirement
  - both for writing the code
  - and for re-testing from one release to the next

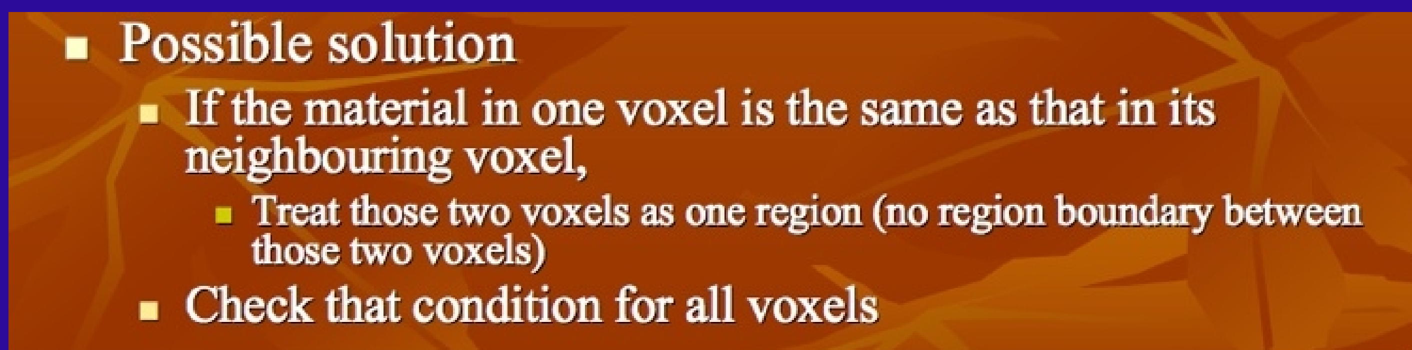
And Aside from Accuracy

- Clarity
  - We need to provide guidance on which EM options to use
    - processes
    - step Sizes
    - range Cuts
  - We heard this same thing from the Geant4 reviewers
  - We saw a talk in the GATE meeting just yesterday where a researcher had to spend a great deal of time to figure out these options



And Aside from Accuracy

- Speed
  - Slower than EGSnrc by factor of 2 to 10 depending who you talk to
    - Do we know that this is true?
    - If we are slower, do we know why?
    - Fermilab recently joined Geant4 collaboration and is contributing software engineering/profiling expertise
    - There are many areas where we know we can make improvements, given the manpower
      - Specialized navigators for Voxel geometries
      - Compressed voxel parameterization as in talk yesterday from Nicolas Karakatsanis, George Loudos, Arion Chatziioannou



      - Similar to OCTREE design by Vincent Hubert-Tremblay and Louis Archambault from Canada
      - And other ideas shown in fastGATE talk yesterday by Arion, George, Nicolas, Richard

Other Issues for Med Phys

- DICOM Compatibility
  - Much to be done to get to where the EGS community already is
    - Promising work coming out of Japan
- Memory
  - Not such a serious issue in all cases (depends on specific application)
    - Would help if we allowed materials to be parameterized by density, but this is not easy in Geant4 design
- Volume Rendering
  - Much to be done to get to where the EGS community already is
    - Promising work coming out of Japan
- Scoring
  - Good news here, rapidly approaching best functionality offered by other codes
    - Made possible by parallel worlds
- Ease of Use
  - Encourage communities to make their own applications
    - Such as GATE
    - Such as being done in Japan for their Proton machines
    - Is it time to start a GART collaboration (Geant4 Application for RadioTherapy)?

What would Help?

- Manpower
  - Especially in electromagnetics at Med Phys energies
  - In lieu of that, I've found it helpful to explain to our Med Phys colleagues that most of our funding comes from other problem domains such as HEP that concern themselves with very different energies (don't just assume the medical physicist knows how we're funded)
- Some movement in the right direction
  - SPACE - a more recent source of funding, has some promising overlap in energies with Med Phys
  - Beginnings of direct funding from Med Phys:
    - Major project in Japan
    - In US, at least getting some travel assistance from an NIH grant
- Parallels to EGS
  - The "Gold Standard" in medical physics Monte Carlo, EGSnrc, began as a tool for the HEP community (the EGS project at SLAC).
  - Now almost entirely funded for medical physics.

Critical Time Right Now

- Reminder: This is just my Personal Opinion, but I feel it strongly

- We are running out of time to get it right for Medical Physics
  - Remaining good will down to maybe one year or so

Ranking of Issues for Med Phys

Top Priorities (In This Order):

- Accuracy - with stability against step size and range cut variation
- Clarity - guidance on which EM options (processes, step sizes, range cuts)
- Speed

Less Critical:

- DICOM Compatibility
  - Our users are willing to bolt this stuff together themselves if need be (they’re used to doing things the hard way, even willing to use MORTRAN)
- Memory
  - Our users are willing to use the various available workarounds
- Volume Rendering
  - Our users are willing to do this part themselves by various complicated hacks
- Scoring
  - Recent improvements, and others almost ready, have essentially solved this
- Ease of Use
  - Our users are willing to do whatever it takes provided we give sufficient accuracy with clear recommendations on which EM options to use and acceptable speed

Now is the Time

- The Medical Physics community is paying attention to us Right Now.
- We need to pay attention to them Right Now.
- Coming back to Frank Verhaegen's piece in MedicalPhysicsWeb