Simulation Activities at IBA

Frédéric Stichelbaut – 31/03/2014

Outline

- **Presentation of IBA activities**
- **Use of Monte Carlo simulation codes at IBA**
- **Research studies:**
  - Design of high-performance X-rays systems
  - Radiation protection studies
  - Secondary neutron doses
  - Monitoring of proton range inside Patient
- **Conclusions**

IBA in short

- Company formed in 1986 as spin-off of UCL and based in Louvain-La-Neuve, Belgium
- Employs ~ 1,000 people worldwide.
- Number one provider of integrated proton therapy solutions
  - More compact and targeted radiotherapy applications
- Synergistic businesses in dosimetry, medical and industrial accelerators

Proton Therapy

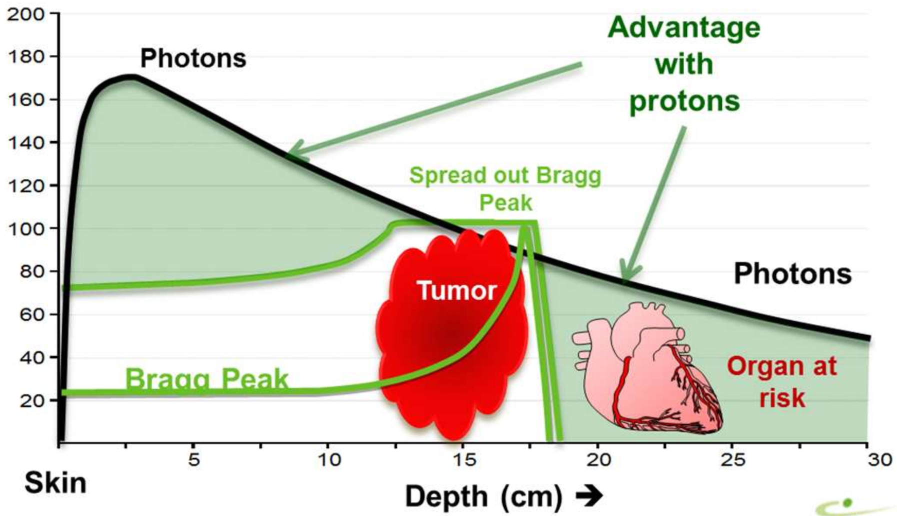
Next generation in targeted cancer treatment

Proton therapy vs. conventional radiotherapy

Case studies for efficacy and toxicity

Protons have a superior dose distribution

- Protons:
  - Deliver their maximum energy within a precisely controlled range
  - Deposit a high and conformal dose
  - Deposit very little entry dose
  - Deposit no exit dose



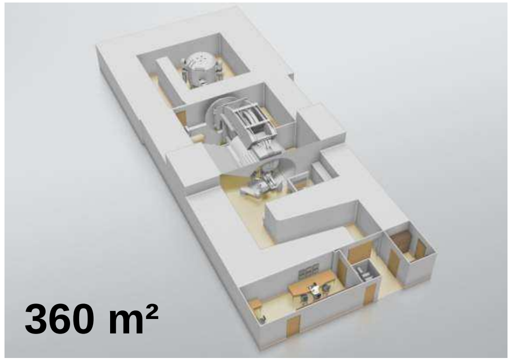
Clinical outcome and affordable

Multi-room to single-room solutions

Proteus®PLUS

1800 m^2

*Proteus®ONE**



***Proteus®ONE features PBS, Cone Beam CT and Compact gantry.**

**Subject to review by Competent Authorities (FDA, European Notified Bodies, et al.) before being put on the market.*

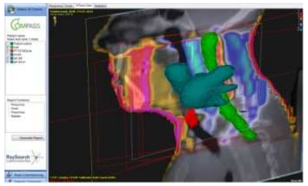
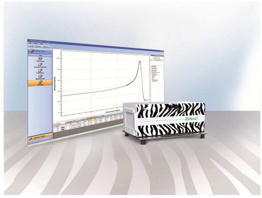
Global adoption of IBA proton therapy

26 IBA reference centers - 25,000 patients treated

IBA DOSIMETRY PRODUCTS

Radiation Therapy

Linac commissioning and quality assurance of machine and patient plan, for safer patient treatments.

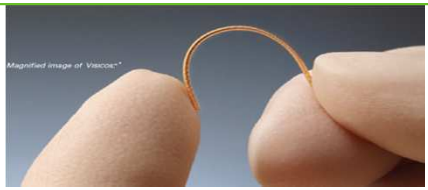




Medical Imaging

Full solution provider in quality control in diagnostics imaging, for better diagnosis.


Image Markers

Clear tumor localization, for higher targeting accuracy.



Quality Assurance & GMP

^{18}F-

+ other radioisotopes

^{18}FDG

+ other compounds

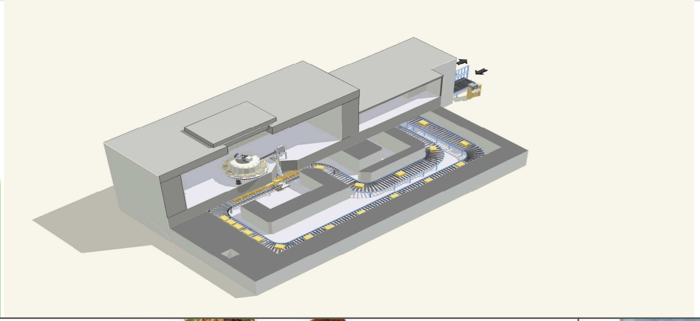
Quality control & sterility tests

MRI/PET or PET/CT

Injection & Diagnostic

IBA Industrial Accelerators

- Electron beams 3 to 10 MeV
- Beam power 35 kW to 700 kW (7 MeV/100 mA)
- E-beam or X-ray treatment modes
- Applications:
  - Medical device sterilization
  - Food pasteurization
  - Advanced material manufacturing (cables, tires, …)
- Installed base > 200 units



Monte Carlo Simulations at IBA (1)

- **IBA core business deals with the use of particle accelerators for medical/industrial applications**

  ➔ **MC transport codes are essential tools in many activities**

  - Radiation protection studies (shielding design, activation);
  - Accelerator physics (beam losses, beam line modeling);
  - Evaluation of radiation damages to electronic devices;
  - Development of new industrial applications (X-ray treatment mode);
  - Development of new processes for medical isotope production (accelerator-based ^{99}Mo production using lowly-enriched Uranium);
  - Medical physics:
    - Development of accelerator-based Boron neutron capture therapy (BNCT)
    - On-line monitoring of proton beam range inside patient (Prompt gamma, PET emission)
    - Study of secondary neutron doses delivered to patient during treatment

Monte Carlo Simulations at IBA (2)

- **Major used codes:**

  - **<u>MCNPX (Monte Carlo N-Particle eXtended)</u>**
    - Developed by Los Alamos National Lab. for Nuclear Physics
    - Transport of e^-,γ, n, h, light ions, heavy ions, µ, baryons, mesons (π, K, D).
    - Tracking from 1 keV (e,γ) up to a few GeV.
    - Transport of h, n based upon evaluated nuclear data up to 150 MeV, nuclear models (Bertini, INCL4, CEM03) above.
    - No access to code, work with text input files where geometry, particle sources and tallies are defined.

Monte Carlo Simulations at IBA (3)

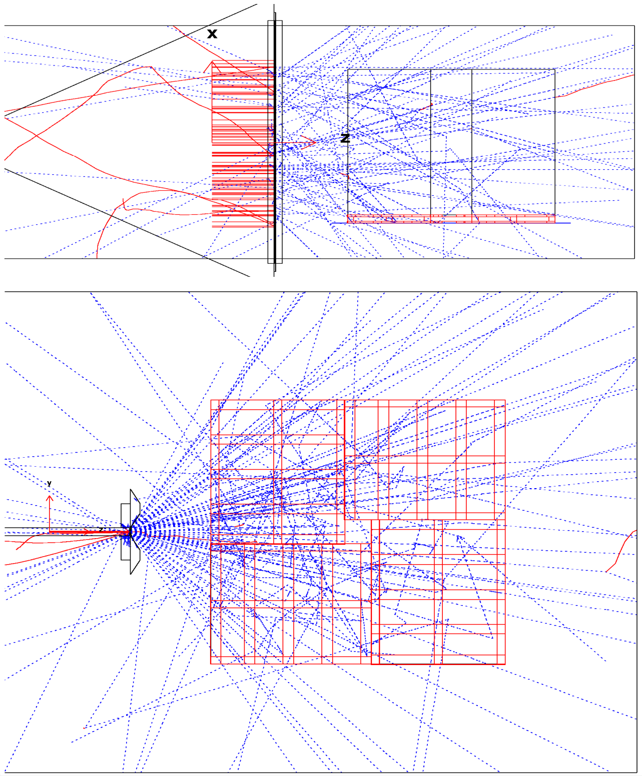
- **<u>PHITS (Particle and Heay Ion Transport code System)</u>**
  - Developed by JAEA, RIKEN for accelerator design, medical physics and cosmic-ray research
  - Transport of e^-,γ, n, h, light ions, heavy ions
  - Nucleon-nucleus and nucleus-nucleus interactions simulated by various models:
    - Bertini
    - INCL4.6
    - JQMD (Quantum Molecular Dynamics)
    - JAM (Jet AA Microscopic transport)

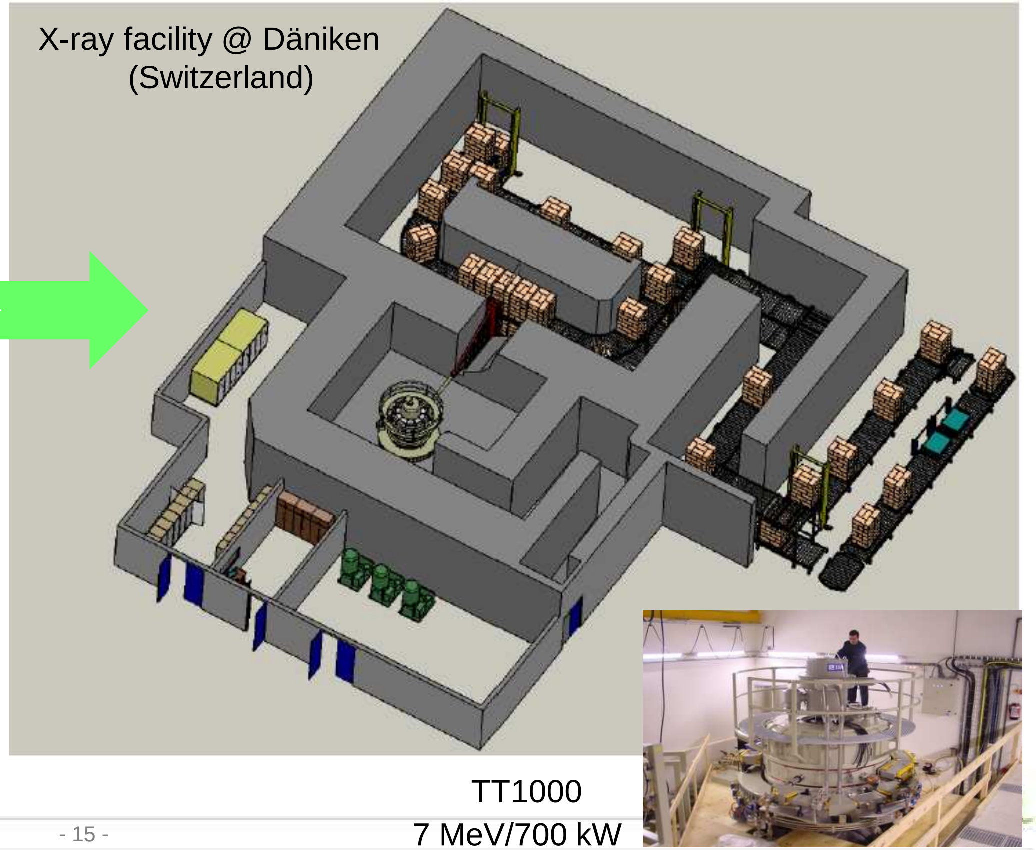
Monte Carlo Simulations at IBA (4)

- **FLUKA**
  - Developed by INFN and CERN
  - Transport of ~60 different particles from 1 keV up to PeV energies.
  - Hadron-induced nuclear interactions simulated by models such as PEANUT, RQMD or DPJMET depending upon hadron energy range.
- **GEANT3, GEANT4**
  - Developed by CERN, SLAC and other HEP Labs.
  - Transport of particles for energies from 250 eV to 1 TeV.
  - Simulation toolkit ➔ very powerful but also complex to master.

Design of High-Performance X-Ray Systems

GEANT3 Simulations





X-ray facility @ Däniken
(Switzerland)

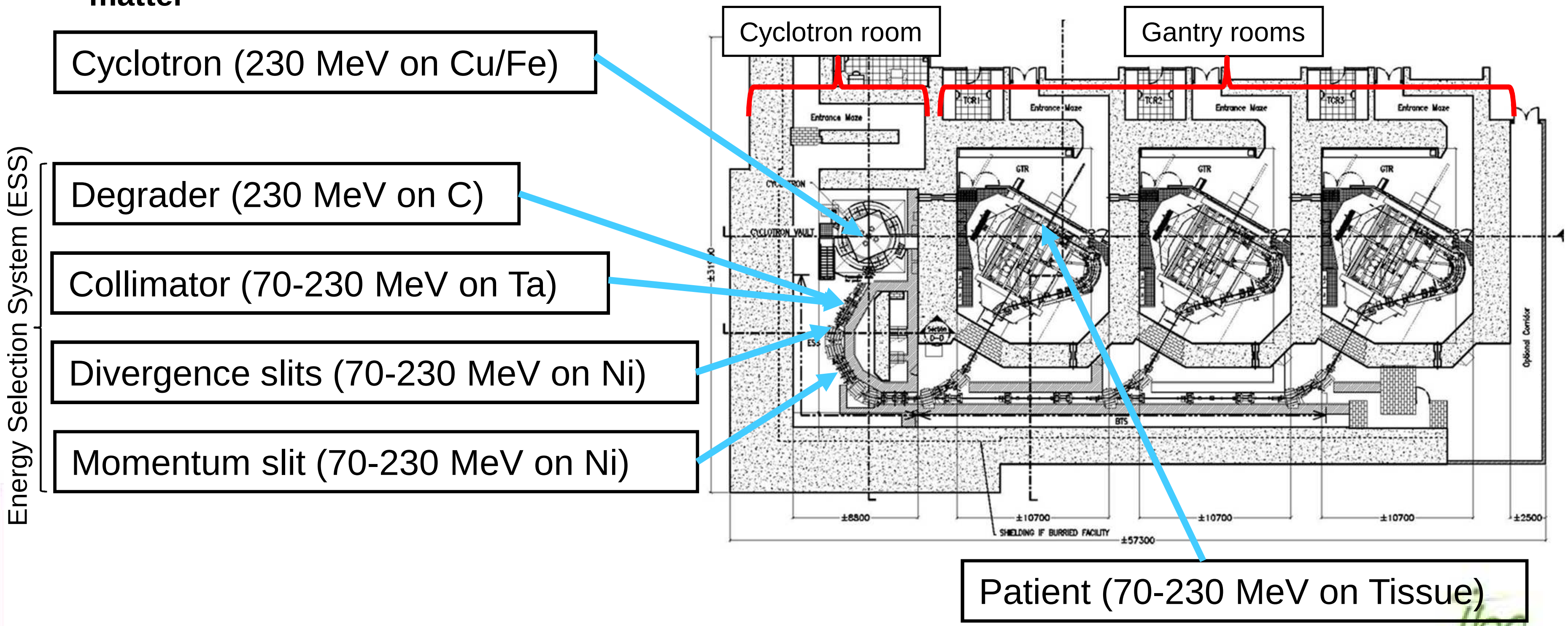
TT1000
7 MeV/700 kW

Radiation Protection Studies

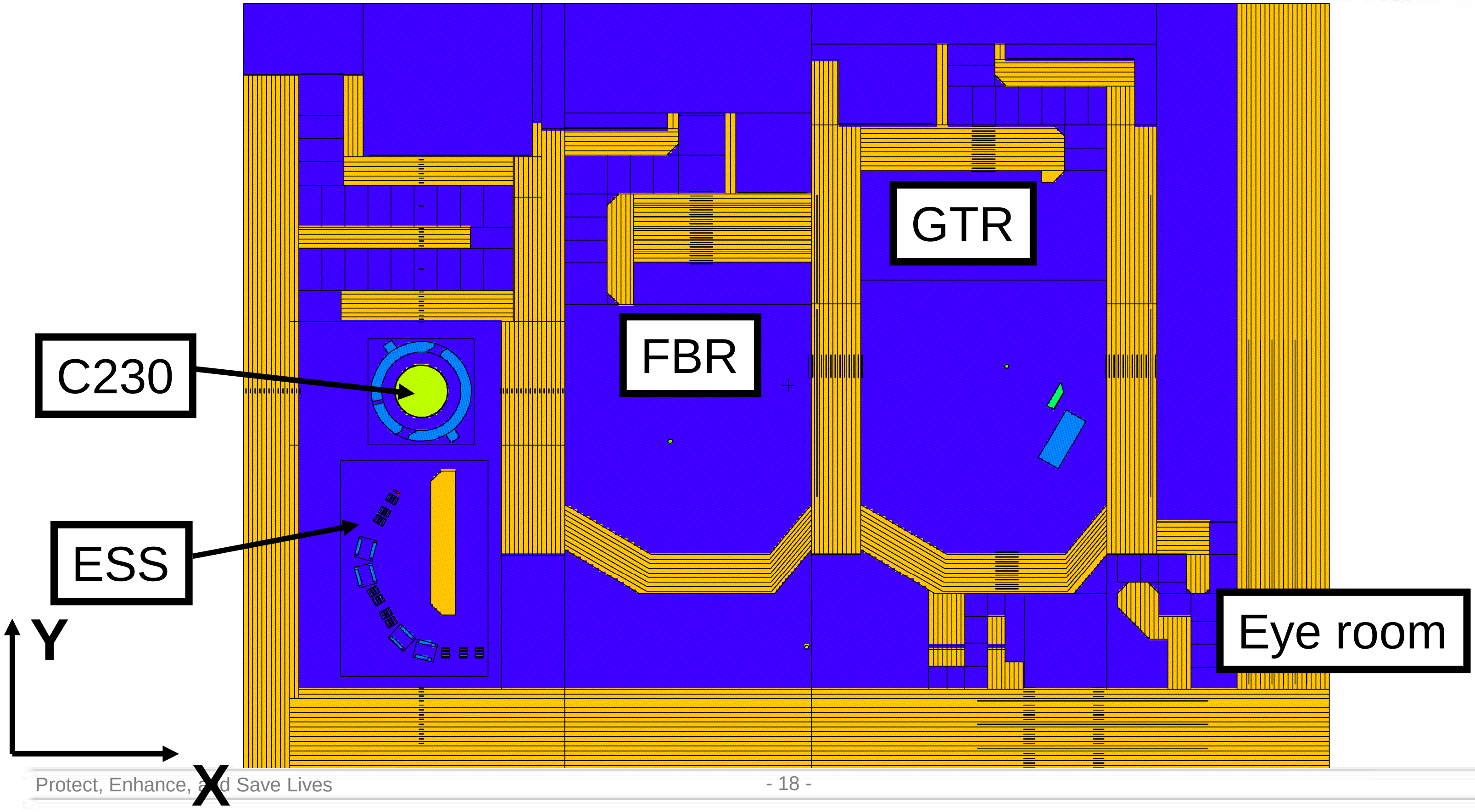
- **Proton beams interacting with matter generate complex fields of secondary neutrons and photons.**
- **MC transport codes are ideal tools to study these mixed fields for:**
  - Radiation protection for public and medical personnel;
  - Radiation protection for the patient himself;
  - Activation of equipment and environment (air, ground, concrete).
- **Shielding design for:**
  - PET cyclotrons: 11 MeV up to 70 MeV
  - Proton Therapy: 230 MeV proton beams
  - Hadron Therapy: 400 MeV/u ^{12}C beams.

Radiation Sources in Proton Therapy

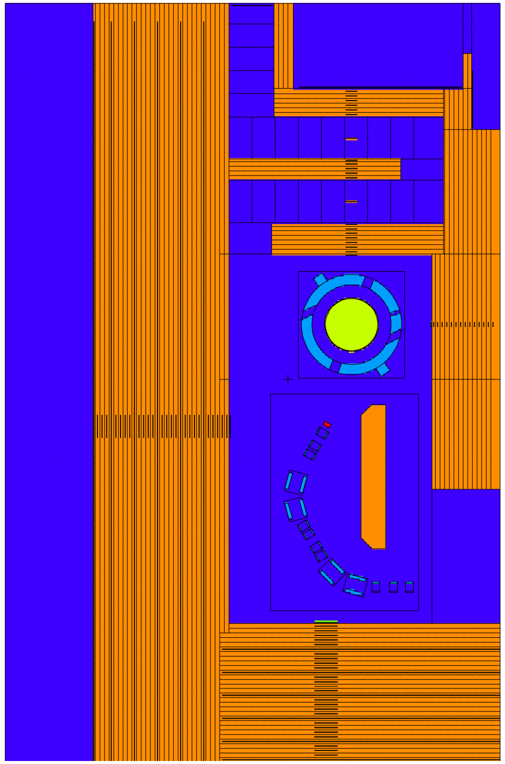
Neutrons and photons are produced at various locations along beam path when protons hit matter

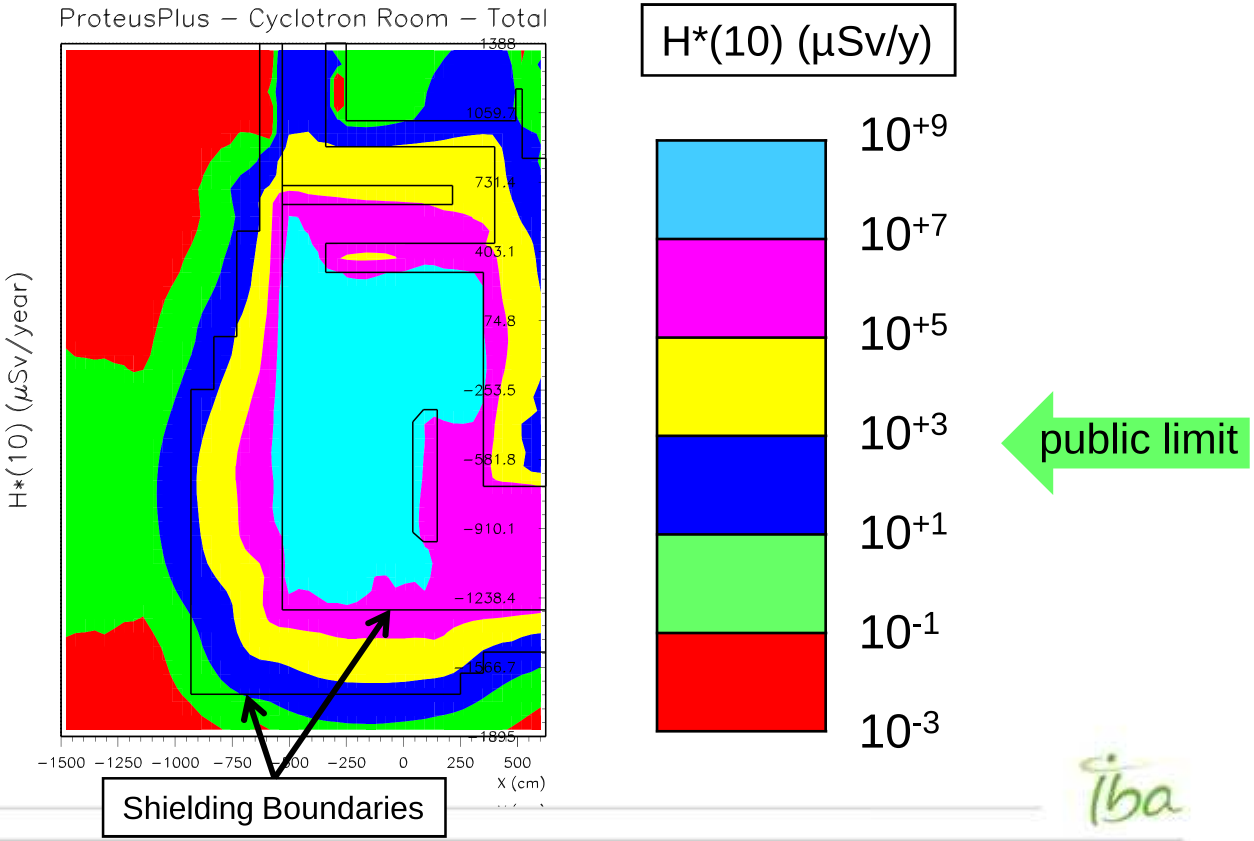


ProteusPLUS Modelling with MCNPX



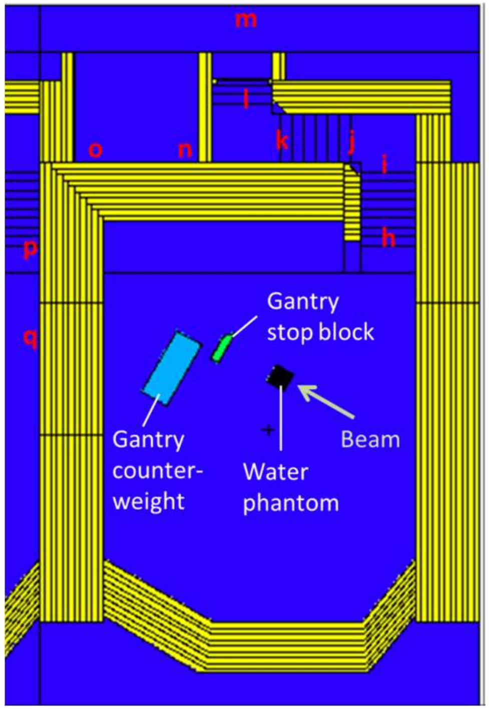
Cyclotron Room: Annual Dose Rates





MC Validation using WENDI-2 Neutron Detector

H*(10) measurements around GTR

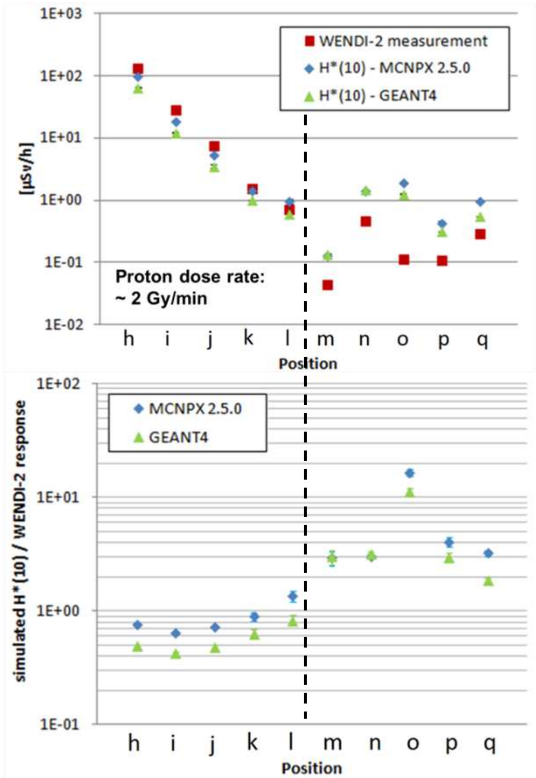


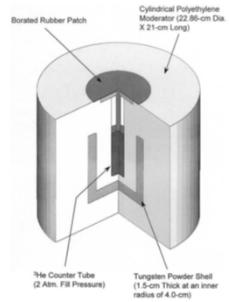
Ebeam = 227 MeV

Dose rate ~ 2 Gy/min

Measurements with WENDI-2

MC simulations:
- MCNPX
- GEANT4





MC/Data > 1

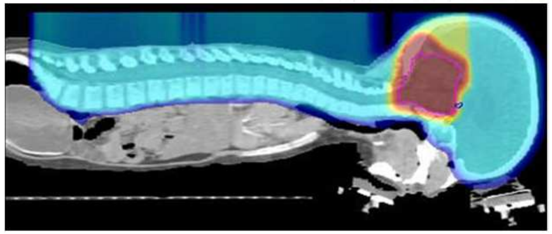
← 1

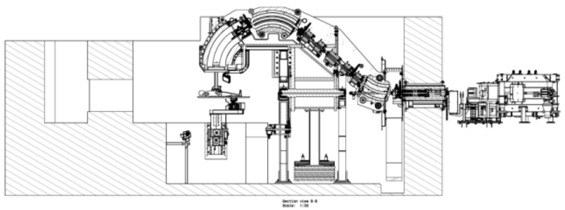
Activation Studies

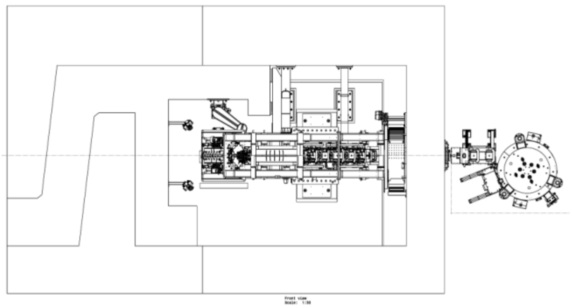
- **Neutron-induced activation processes:**
  - Inelastic collisions (spallation processes)
  - Neutron capture (n,γ)
- **MC codes are also very usefull for these activation studies:**
  - Air and cooling water activation ➔ release strategy.
  - Shielding concrete activation ➔ building decommissioning.
  - Activation of PT components (Cyclotron, magnets, beam shaping devices) ➔ personal radioprotection and long-term decommissioning.
- **Codes such as FLUKA and PHITS allow the prediction of the whole history, from nuclear reactions to specific activities or dose rates after some cooling period.**

Secondary Neutron Doses

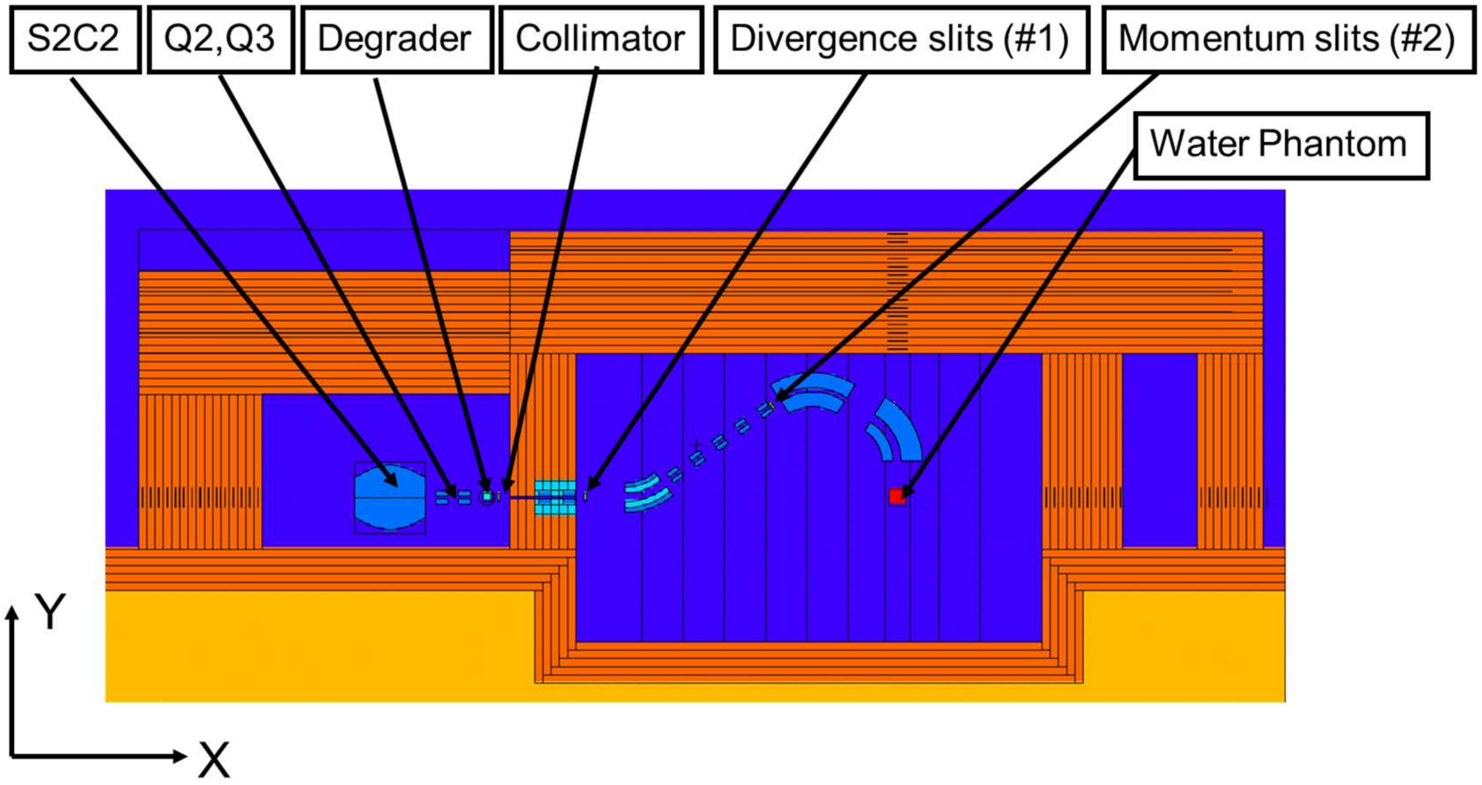
- Secondary neutrons generated by proton beams induce an additional dose to the patient distributed over the whole body ➔ risk of secondary cancer developed at a later stage.
- MCNPX study of secondary neutron doses to a patient treated for a medulloblastoma (spinal cord only).
- Compare two systems:
  - Pure PBS system (patient only)
  - ProteusONE solution with compact gantry
- Neutron doses computed in a 40x40x40 cm^3 water absorber ➔ evolution with depth.
- Neutron doses absorbed by organs using VIP-MAN anthropomorphic model
  ➔ compare risk of secondary cancer occurrence.





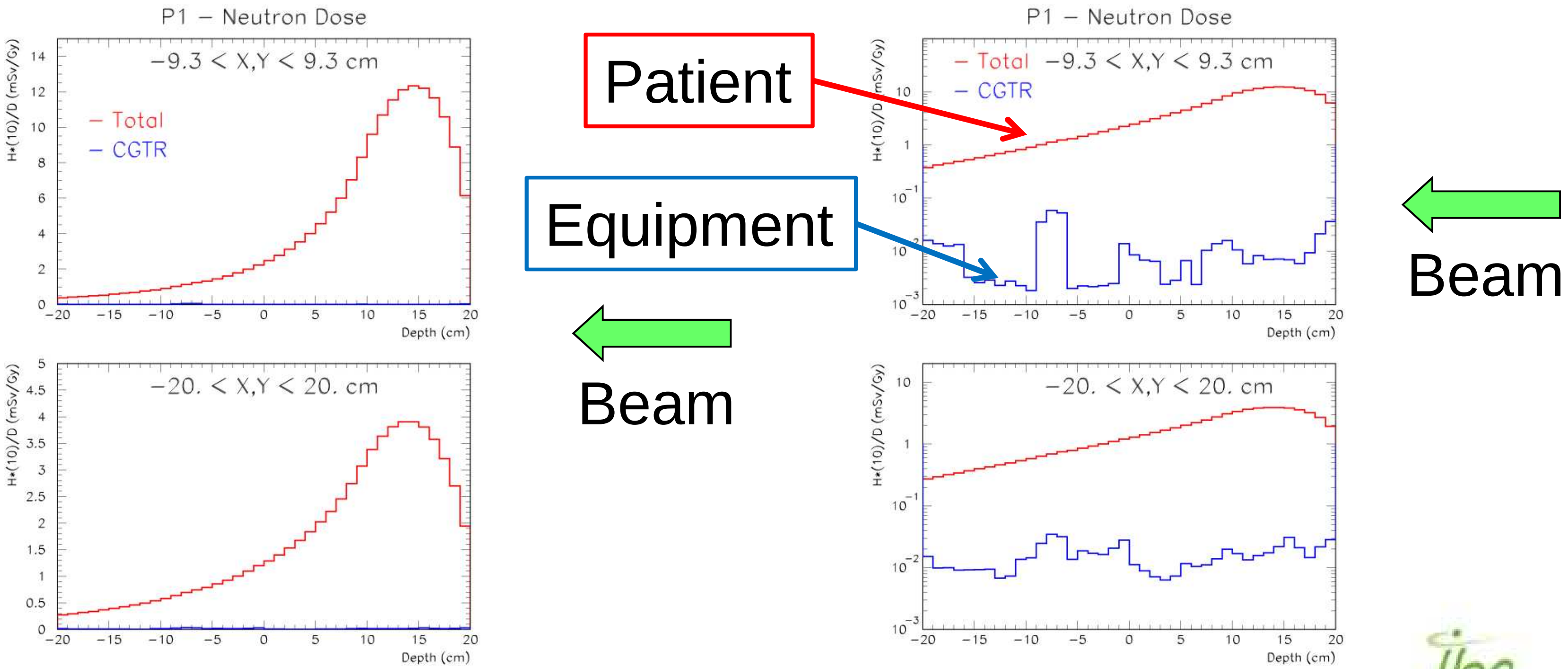


ProteusONE Modelling with MCNPX



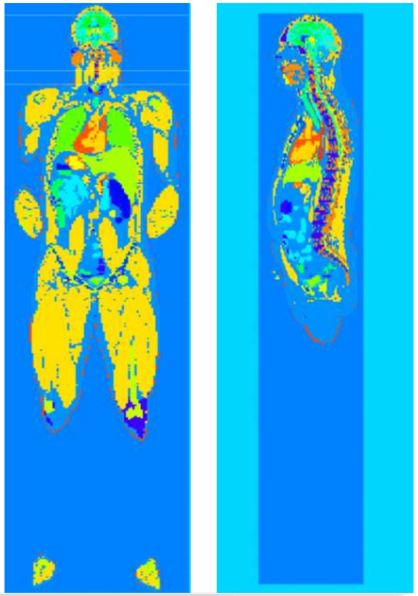
Neutron Doses in ProteusONE

Evolution of H*(10)/D along depth for different transversal field sizes



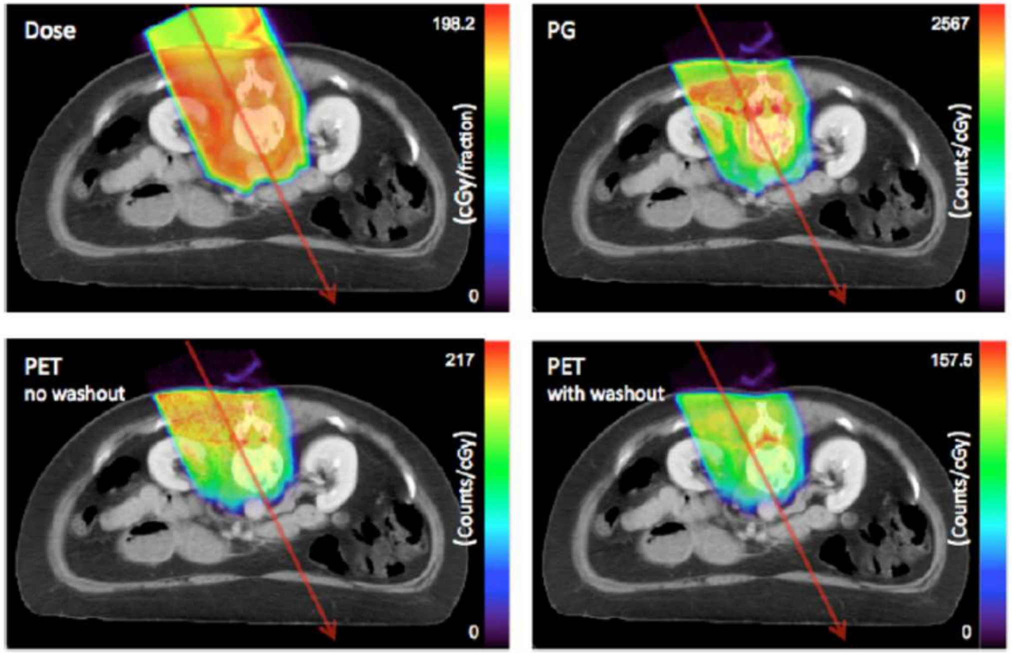
Effective Dose and Lifetime Risk of Second Cancer

- **Treatment done using VIP-MAN anthropomorphic model.**
- **Estimation of effective dose received by a patient and lifetime risk of second cancer based upon ICRP 103 publication.**
- **For the effective dose, we obtain:**
  - In PBS mode: E/D = 1.173 mSv/Gy
  - In P1 mode: E/D = 1.178 mSv/Gy (+0.4%)
- **Considering a total therapeutic dose of 36 Gy delivered to the patient, the lifetime risk of second cancer is:**
  - In PBS mode: R = 0.433%
  - In P1 mode: R = 0.439% (+1.4%)



Proton Range Monitoring inside Patient

- **To improve PT precision, we need to better monitor the proton range inside the patient:**
  - Production of PET isotopes in patient:
    - ^{11}C ($T_{½}$ = 20.39 min)
    - ^{15}O ($T_{½}$ = 2.03 min)
    - ^{13}N ($T_{½}$ = 9.97 min)
    - ^{30}P ($T_{½}$ = 2.50 min)
    - ^{38}K($T_{½}$ = 7.63 min)
  - Production of prompt γ by excited nuclei along the beam path.
- **A lot of MC studies to study the feasability of these two techniques.**



M. Moteabbed et al., PMB **56** (2011) 1063.

PET Isotope Production

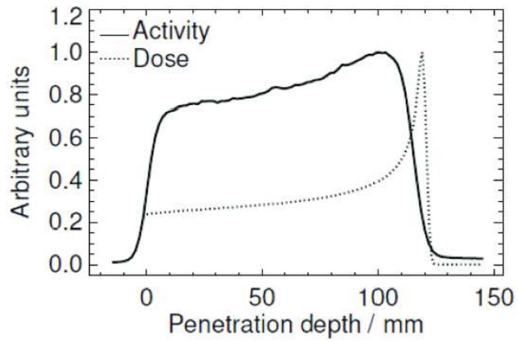
- This method heavily rely upon MC simulations to predict the β+ activity distribution inside the patient and compare to PET-CT measurements.
- Recent comparison of ^{11}C and ^{15}O production in water and PMMA using 4 MC codes: GEANT4, FLUKA, MCNPX, PHITS.

IOP PUBLISHING PHYSICS IN MEDICINE AND BIOLOGY
Phys. Med. Biol. 57 (2012) 1659–1673 doi:10.1088/0031-9155/57/6/1659

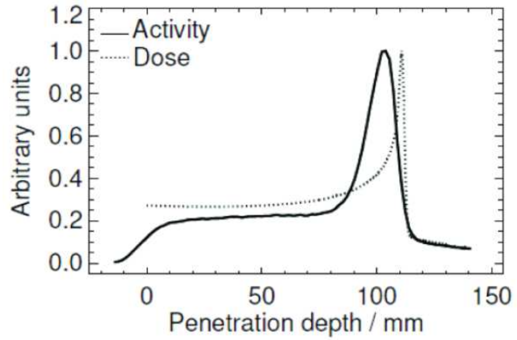
Monte Carlo calculations of positron emitter yields in proton radiotherapy

E Seravalli[1], C Robert[2,9], J Bauer[3,9], F Stichelbaut[4,9], C Kurz[3,9], J Smeets[5], C Van Ngoc Ty[6], D R Schaart[7], I Buvat[2], K Parodi[3] and F Verhaegen[1,8,10]

[1] Department of Radiation Oncology (MAASTRO), University Medical Centre Maastricht, Maastricht, The Netherlands
[2] IMNC—UMR 8165 CNRS, Universités Paris 7 et Paris 11, Bât 440, Orsay, France
[3] Heidelberg Ion Beam Therapy Centre and Department of Radiation Oncology, Heidelberg University, Clinic, Heidelberg, Germany
[4] IBA, Louvain-la-Neuve, Belgium
[5] Service de Métrologie Nucléaire, Université Libre de Bruxelles
[6] CEA-SHFJ, Orsay, France
[7] Delft University of Technology, Delft, The Netherlands
[8] Department of Oncology, McGill University, Montréal, Québec H3G 1A4, Canada



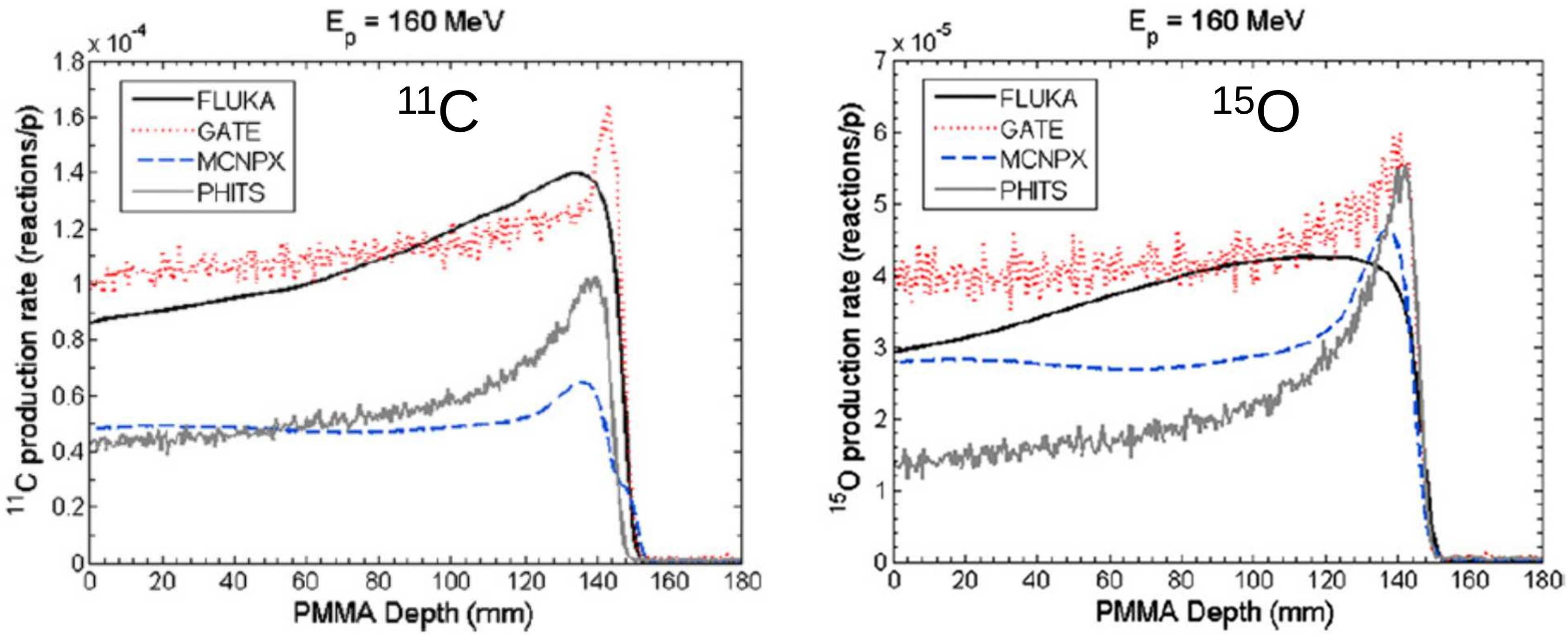
140 MeV ^{1}He



260 MeV/u ^{12}C

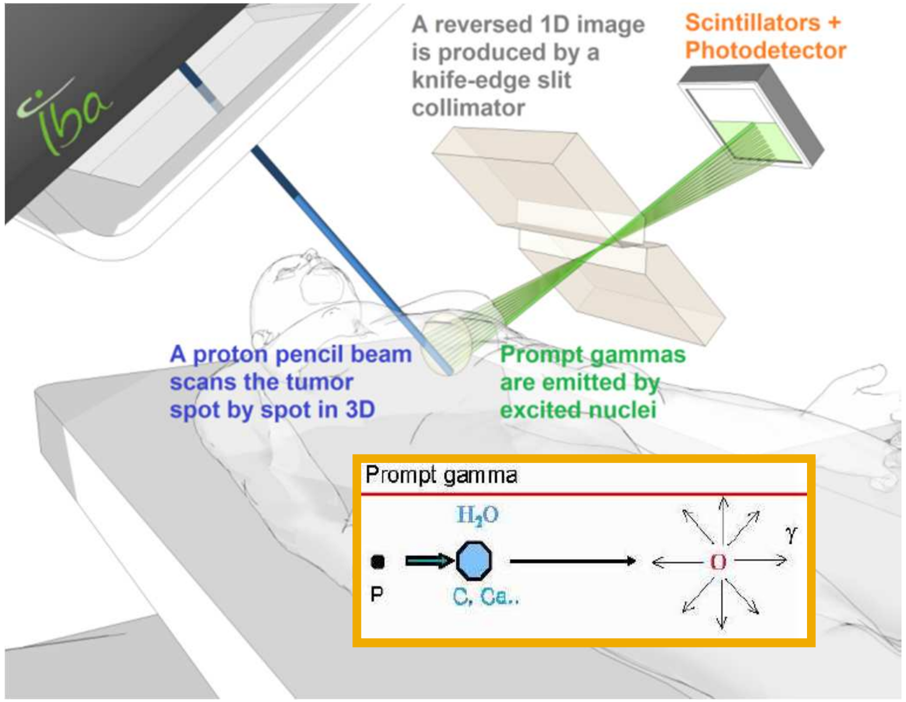
K. Parodi thesis, 2004.

PET Isotope Production



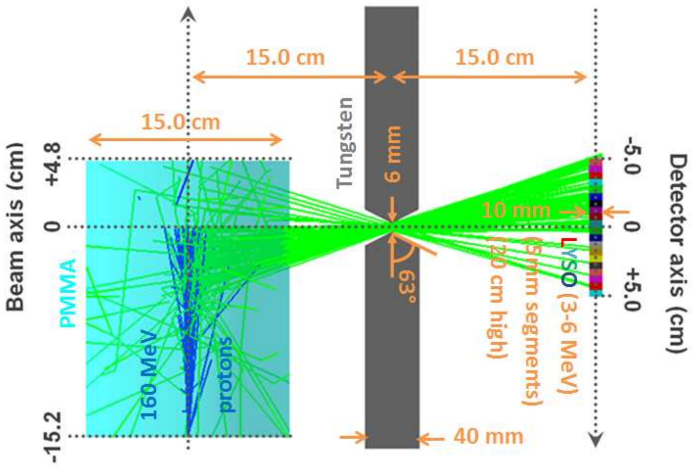
(E. Seravalli et al., PMB **57** (2012) 1659)

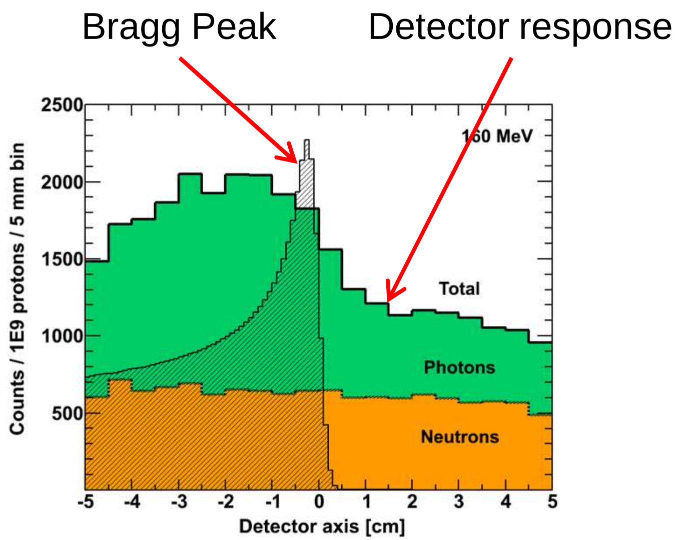
Slit Camera Concept for Proton Therapy



- Measurement of the position at which the proton beam stops in the patient in PBS mode
- Real-time verification with an accuracy < 5 mm for a selection of critical spots
- Points of attention: simplicity, low-dose sensitivity, cost effectiveness

Slit Camera Collimator Design

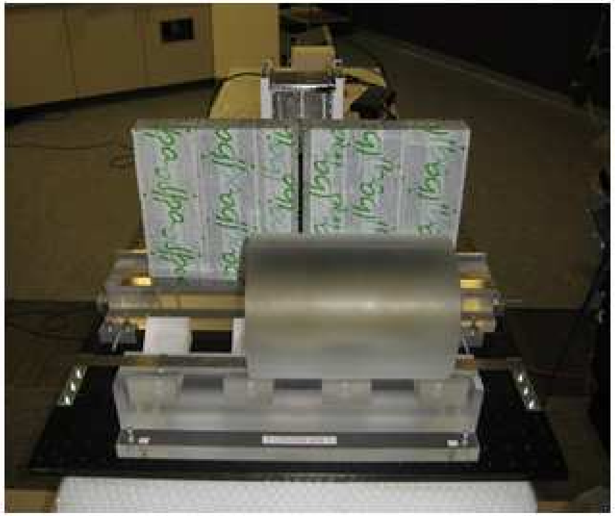


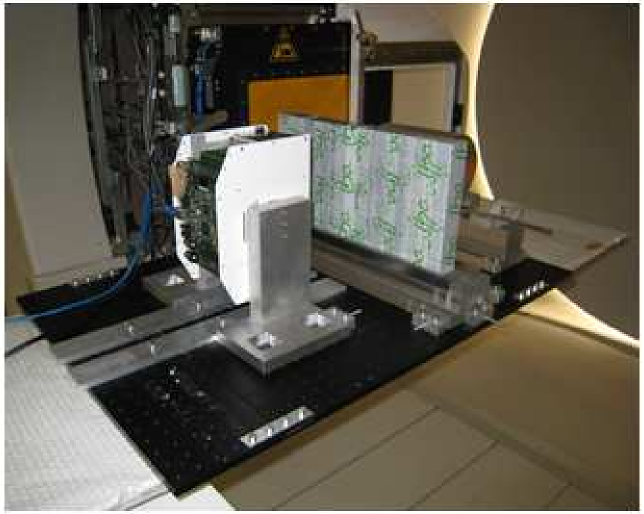


- Optimization by means of MCNPX simulations
- Moderate collimation ➔ Low spatial resolution but High counting statistics
- Detector design in collaboration XGLab and Politecnico di Milano

First Beam Tests with Full FOV

Perali, Celani et al. IEEE NSS/MIC 2013

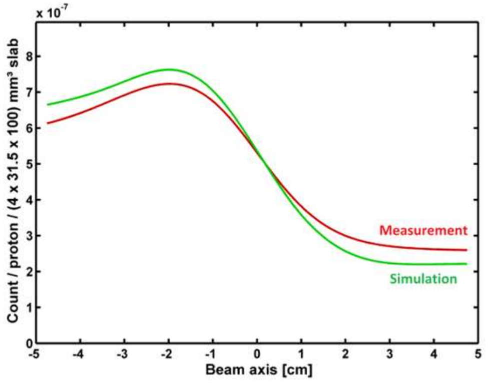




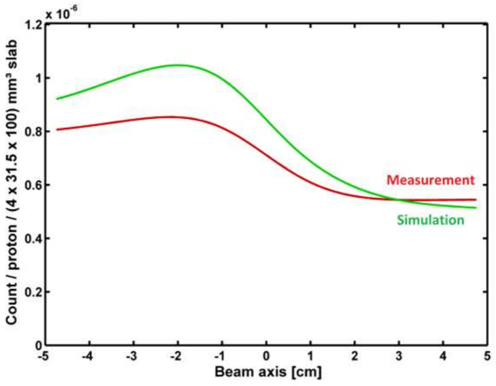
First Beam Tests with Full FOV

Detection profiles of the Bragg peak at different beam energies

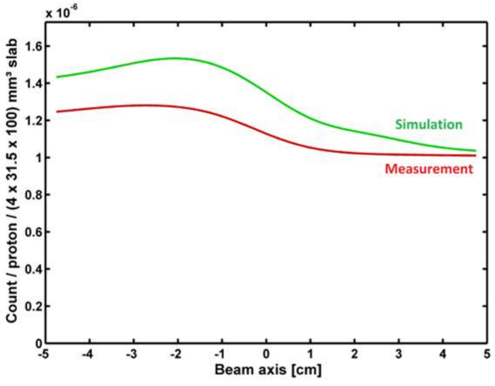
100 MeV



160 MeV



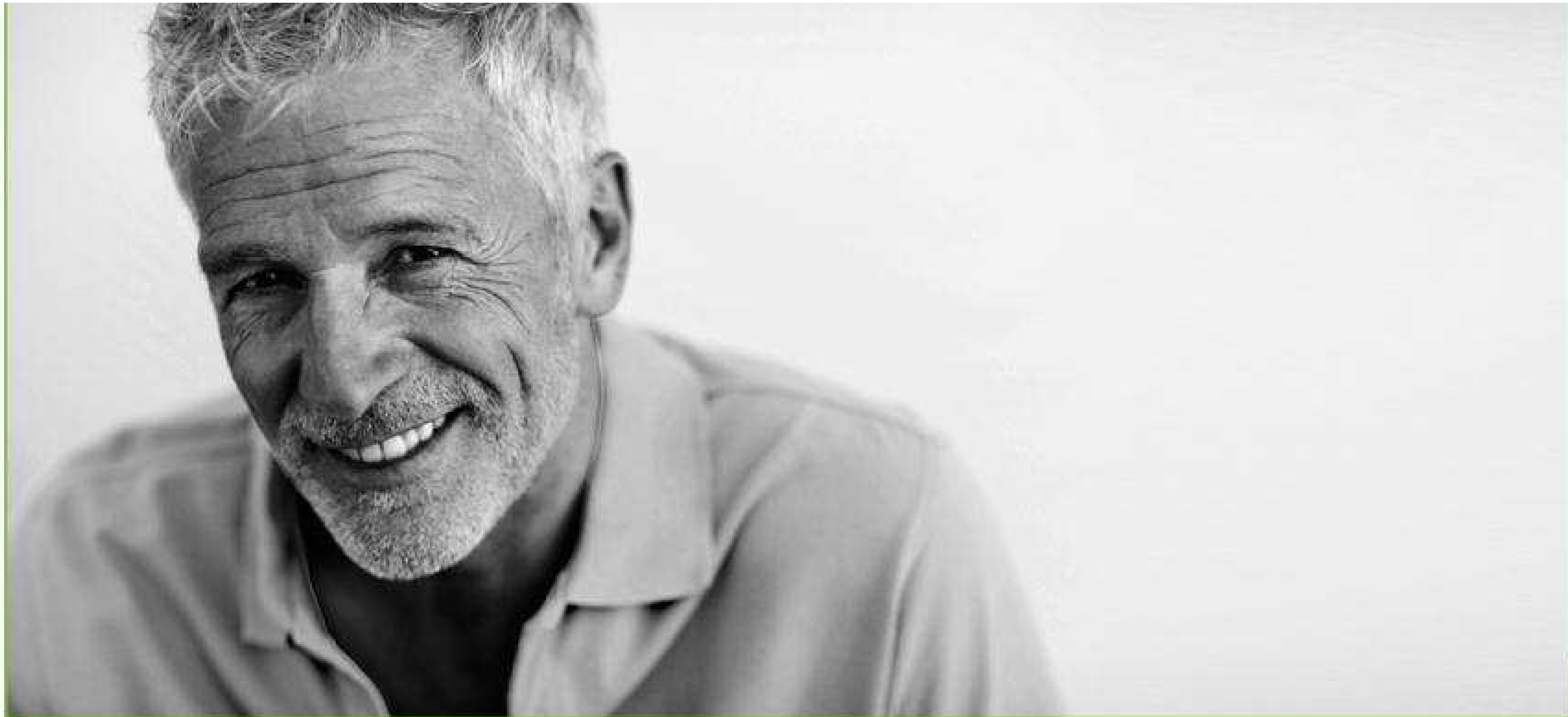
230 MeV



- Measurements with the prototype are in rather good agreement with MCNPX simulations
- Possible to measure proton range with a 4 mm accuracy (2σ) using ~ 10^8 protons (=1 pencil beam).

Conclusions

- The IBA Company core business is the development of particle accelerators for medical (diagnostic, therapy) and industrial applications.
- To understand the interactions of our beams with the patients or the products, we heavily rely on Monte Carlo transport codes such as MCNPX, PHITS, FLUKA or GEANT4.
- We work on a lot of different applications in the medium-energy range up to 250 MeV.
- E-mail: FST@IBA.BE



Thank you