Detectors for online monitoring of ion therapy and imaging

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Divonne les Bains, February 15, 2014

Problems raised in particle (i.e. proton and light ion) therapy

- particle range control
    - for a treatment fraction or
    - in real time
- in-vivo dosimetry
- beam monitoring (future accelerators)

33% of the voters of an AAPM poll in Aug. 2012 considered particle range uncertainties as the main obstacle for a wide application of particle therapy

ENVISION (2010-2014)
+ ENTERVISION (2011-2015)

Two CERN-coordinated European collaborative projects

Objectives:

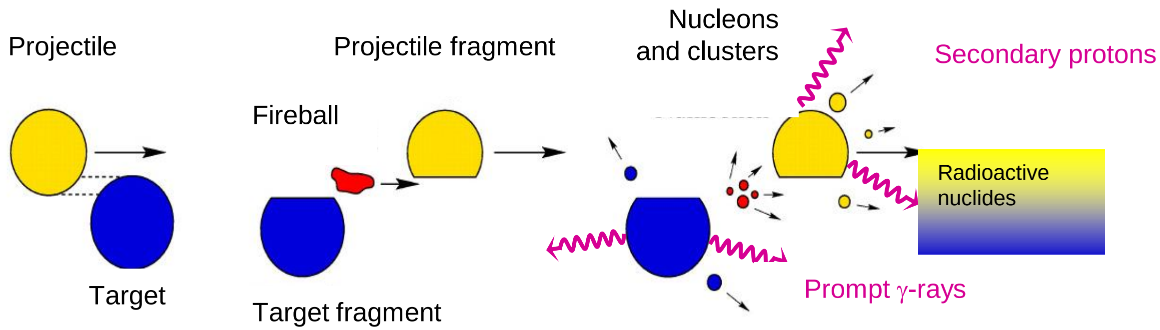
Real-time non invasive monitoring, quantitative imaging, precise determination of delivered dose. fast feedback for optimal treatment planning, real-time response to moving organs, simulation studies.

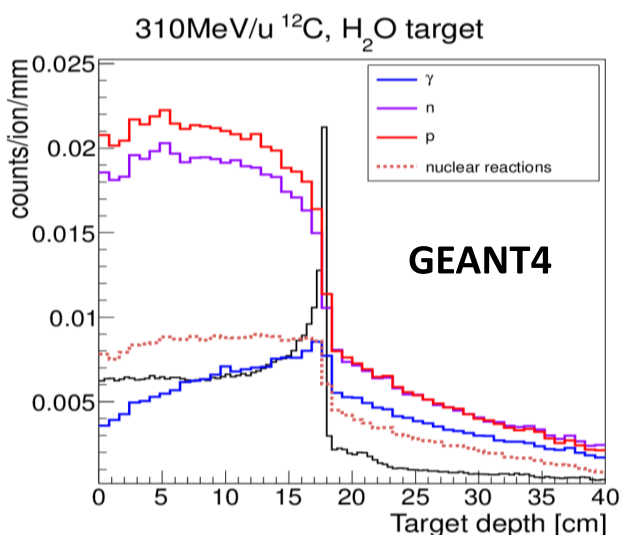
Imaging solutions: ToF-PET , Prompt radiations

Leading aspects

- Basic measurements and modelling
- Novel detectors/electronics developments
- Software (simulations, image reconstruction)
- Clinical constraints (moving organs)
- Clinical feedback and relevance
- Translationnal aspects
- Education and dissemination

Rationale: Secondary particle imaging





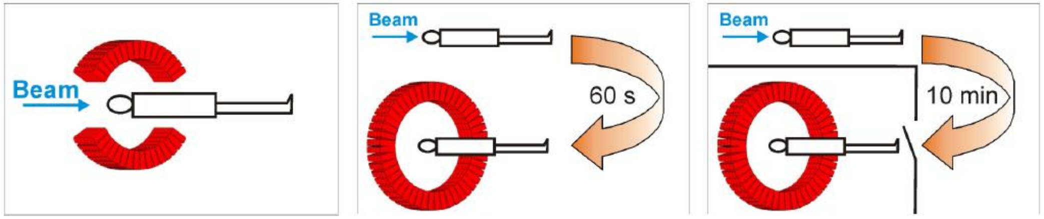
Production / projectile (15 cm range)		
	Protons	**Carbon ions**
Prompt-γ	**0.05**	**1**
β^+ emitters	**0.05**	**0.25**
Protons	**-**	**3**

	Protons	Carbon ions
Ions /treatment fraction	10^{11} - 10^{12}	10^{9} - 10^{10}
Ions/pencil spot	10^{8} (distal)	10^{5} - 10^{6}

(W. Enghardt)

Particle therapy positron emission tomography - PT-PET (I)

In-beam, in-room, off-line



Situation:

- Several applications since first clinical proof at the GSI facility
- Technologically well established imaging technique
- Can be implemented on the basis of mature and high quality PET components delivered by industry
- Because of the low number of installations in therapy, industry is not willing to perform R&D for in-beam scanners (i.e. integration into a therapeutic beam line)

Problems:

- Degradation of dose-activity-correlation by metabolism increasing from in-beam via in-room to off-line PT-PET
- Low counting statistics
- Missing real time capability

(W. Enghardt)

Particle therapy positron emission tomography - PT-PET (II)

Research needed:

- Very fast detectors and acquisition systems of
    - system, not detector time resolution well below 100 ps (FWHM)

  for
    - direct time-of-flight reconstruction and real time in-beam PT-PET

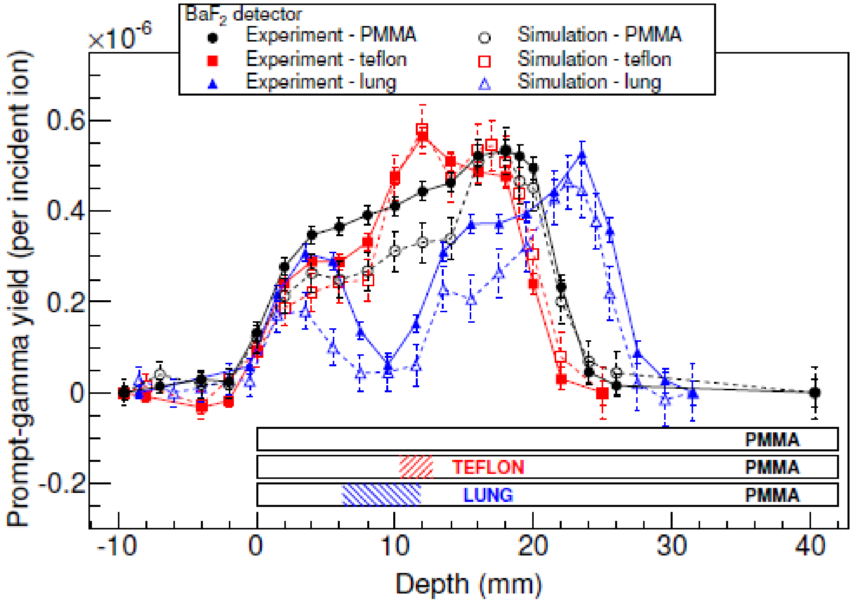
Explicitely, no PT-PET research is needed on:

- PET detectors with comparable properties as those being commercially available
- Improving a factor of 2 or 3 in time resolution, we need a factor of >10
- Organic scintillators, RPC and other low atomic number, low density detectors

Either there is to expect a breakthrough, or the PT-PET community should buy their detectors (tomographs) from companies

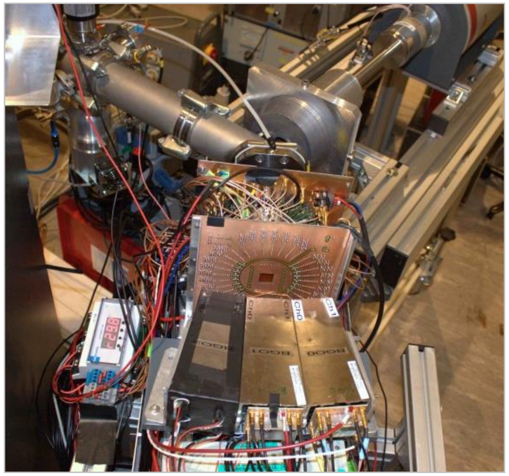
Prompt gamma imaging

- Collimated gamma cameras
  - reach real size prototypes
  - millimetric resolution on range variation
    - Pencil beam scale for protons
    - Energy slice scale for carbon ions
  - TOF : better sensitivity (lower background)
    - Mandatory for C ions



Pinto et al. *submitted to Appl. Phys. Lett.*

- Compton cameras
  - Small size prototypes
  - Further developments are ongoing
    - Fortuitous coincidence issue

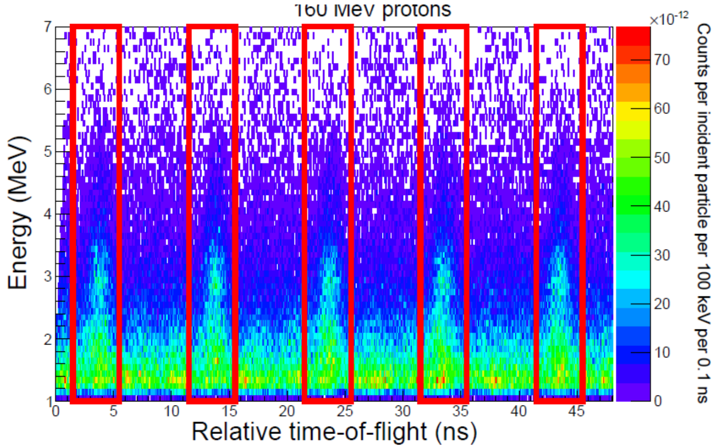


Dresden Compton camera

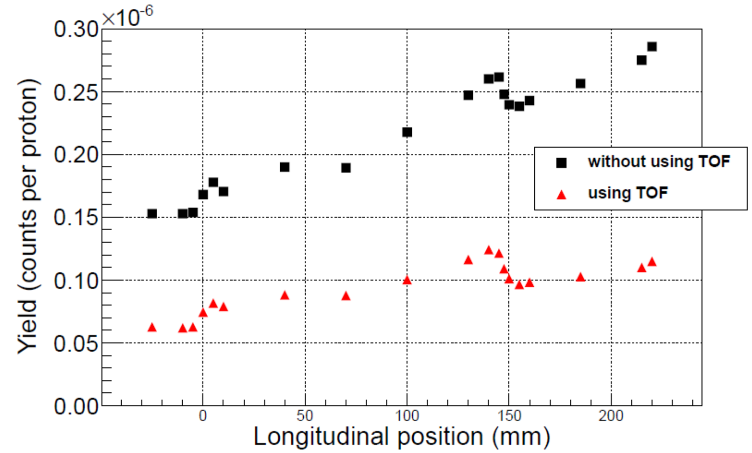
Prompt gamma imaging

- Beam time structure issue

  IBA C230, 160 MeV protons



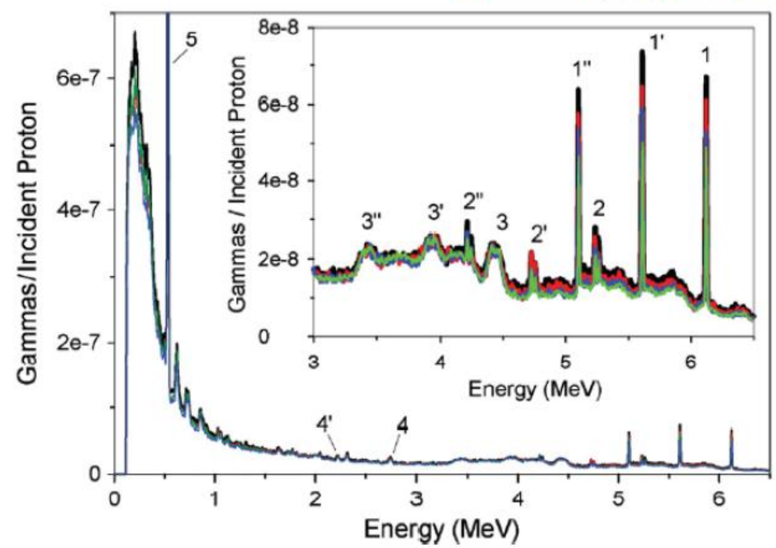
F. Roellinghoff , PMB 2013



  Synchrotrons: beam pulses ~20 ns

  Ion per ion difficult at 10^8 pps

Polf *et al.*, PMB 2013



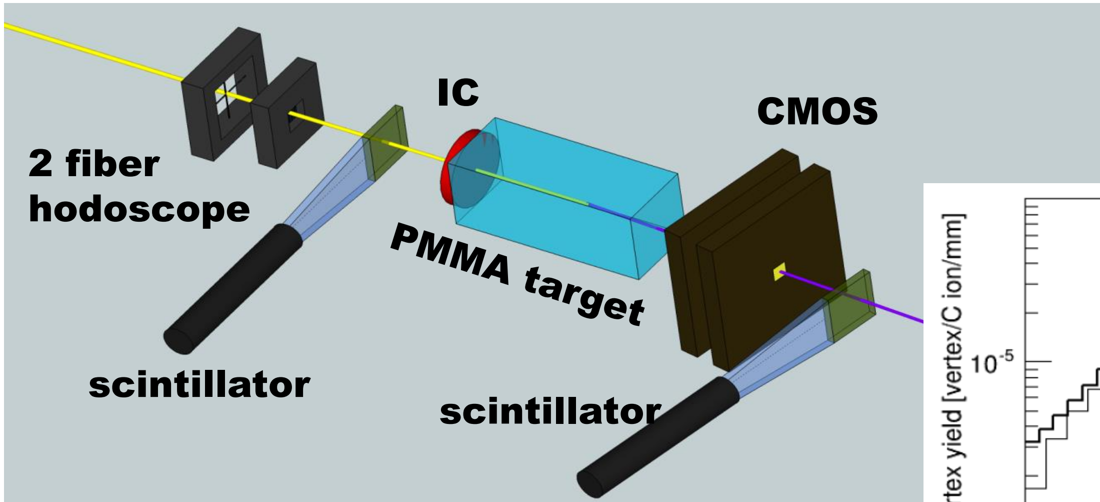
- Energy issue

  Chemical composition information

  Localization?

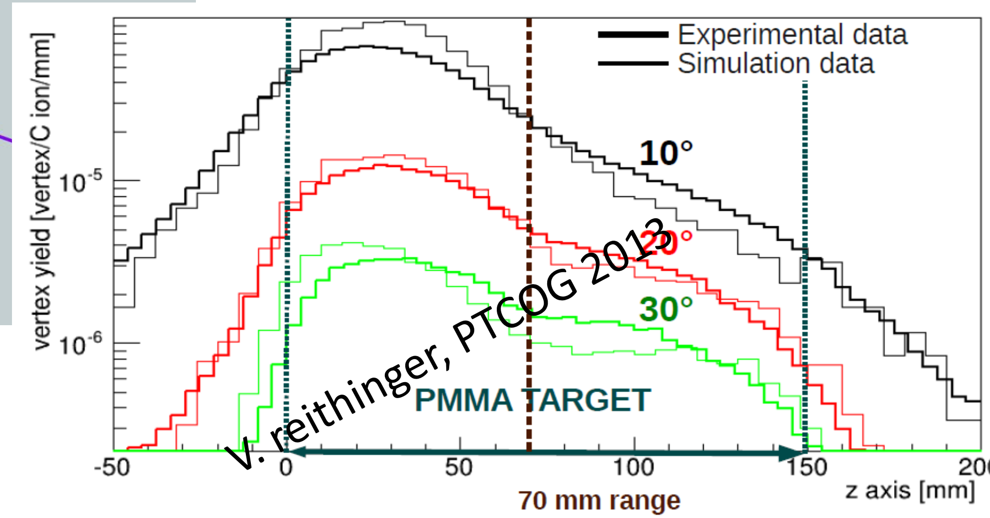
Secondary proton imaging for range verification

Millimetric resolution of range variations in homogenous targets at pencil beam scale (simulations and experience)



^{12}C beam [310-395 MeV/u]

Si-CMOS pixel tracker, 2 × 2 cm², 50 µm thick



TERA: Large Acceptance tracker (GEM) + proton range (plastic scintillator stack) : PRR30 under test

30 × 30 cm², high rate (~ 10^6 s^{-1})

Patient dependent calibration (multiple scattering)

(W. Enghardt, K. Parodi)

Other methods of particle range assessment

Acoustic signals

- Several experimental attempts since 1979
- Potential for clinical application unclear

→ Proof of principle at therapeutic beams with different time characteristics

Radiation induced MRI visible signal

- MR visible signals shown for
  - vertebral bone marrow
  - liver (contrast agent based)
- Time dependence of MR signal appearance under investigation

→ Feasibility of transfer to other organs and tissues

→ Identification of dose sensitive MRI contrast agents (vision)

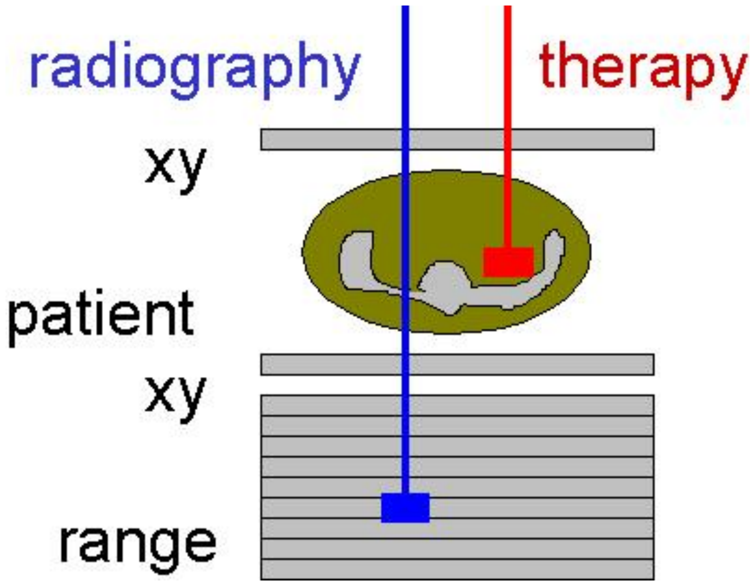
In-room scanners with molecular imaging capabilities

→ Visualisation of biomarkers for biologically-adapted radiotherapy

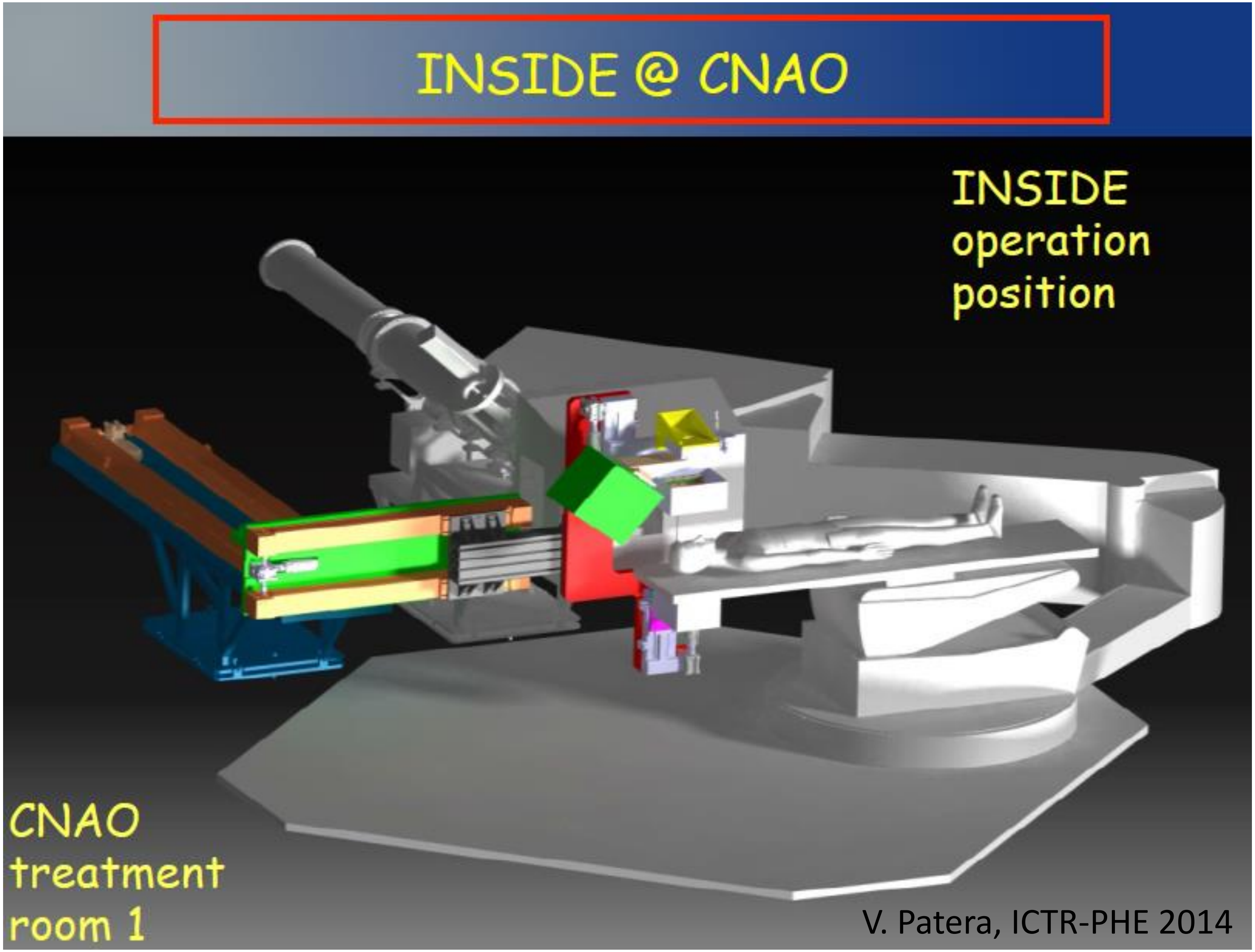
K. Parodi et al. ICTR-PHE 2014, M.F. Gensheimer et al. IJROBP 2010; C. Richter et al. to be published

Particle radiography

- Direct measurement of dE/dx
  - TPS verification in-beam
- Several prototypes or projects in Europe (PSI, TERA, Firenze, HIT-Munich...)
- Requires high energy protons or light ions
- Lower dose than X-rays?
- Modelling and experiments are neccesary



Multimodal solutions



Novel in-beam monitors

- Next generation accelerators (laser, DWA, synchrocyclotron)
  - High instantaneous dose rate
- Mixed fields of different ions
  - Variable LET
- Faster beam scanning
  - Fast readout
- Therapeutic and transmission/absorption verification
  - Large dynamic range

→ New solutions should be envisaged (GEM, diamond…)
Radiation hardness, stability, cost…

Measurement of nuclear data

- **Range verification** by means of secondary radiations requires scalable knowledge of production cross sections
- **In-vivo dosimetry** requires precise calculations from treatment planning
  - Monte-Carlo simulations based on measured or modelled cross sections
  - Feasibility of yield based simulation proven for PT-PET

→ Measurements at LEIR for more accurate Monte Carlo simulations :

- PT-PET: β^+-activity yield as a function of: $(A, Z)_{\text{target}}$, $E_{\text{projectile}}$, Range
- PGI: γ-ray emission density as function of: $(A, Z)_{\text{target}}$, $E_{\text{projectile}}$, Range, E_γ
- IVI: p,d,t,He production yields as function of: $(A, Z)_{\text{target}}$, $E_{\text{projectile}}$, Range, E, angle

- Low statistical error (< 1%)
- Dedicated apparatus at a flexible beam of high availability

Requirements for LEIR experiments

Close to clinical beams – and beyond

- Beam intensities: 1pA to 10nA (clinical dose rates)
- Beam energies: above 250 MeV protons?
- Beam time structure:
  - Cyclotron like (1ns pulse every 10-1000 ns)
  - Synchrotron like (20-50 ns pulse microstructure)
- Pencil beam scanning and passive beam delivery?
- Robotic patient positioning system

In the more general field of imaging

- Novel PET technology
- Sub-10 ps electronics
- Digital DAQ based on modern FPGAs for high granularity high connectivity system
- Computing networks for parametric images strategy and biomarkers mining
- New Imaging methodology (e.g., Photoacustic, Cerenkov,..)
- Hybrid imaging methodology
- Very fast detectors for synchrotron radiation biological applications, e.g., dynamic unfolding of proteins and protein crystallography
- and more

Simulations and image processing

It is absolutely mandatory that software and hardware scientists work together.

There is no real/effective detector for medical imaging if there has not been a simulation/design, construction and testing, data acquisition and reconstruction of the images.

CERN has the unique opportunity to provide an environment where these two communities have been for a long time and still are working strictly and productively together, e.g. ATLAS, CMS.

(A. Del Guerra)

Questions

- Should online control adapt to the treatment modality, or should the treatment adapt to the control?
- Which strategy (strategies) to be envisaged?
  - CERN driven research?
  - International collaboration on a single device?
  - Open platform to external users?