Développement de caméras gamma (Compton et collimatée) pour le contrôle de l'hadronthérapie

É. Testa on behalf of the CLaRyS collaboration

Journée GDR-MI2B – ARCHADE, November 10, 2020

Ion-range uncertainties and current treatment plans

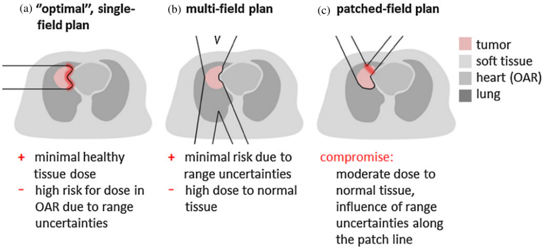
Sources of uncertainties in particle therapy (PT)

Independent of dose calculation	**Dependent** of dose calculation
– Organ motion	– Dose calculation approximations
– Setup and patient variations	– Biological considerations

Limitations of current treatment plans

- Large margins around the PTV: $\sim$ 1 cm for ranges of 20 cm
- "Non-optimal" field plans

$\Rightarrow$ Ballistic properties of ions not fully exploited

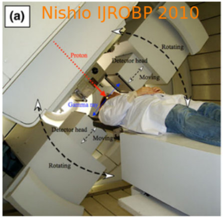


Knopf PMB 2013

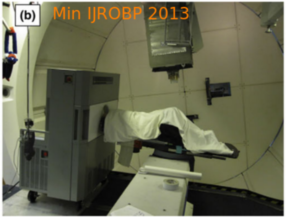
Range verification in PT: first developments (PET)

PET

- Principle: Correlation between dose and nuclear reaction distributions (e.g. β^+ emitters and prompt gammas)
- Main difficulties: Low statistics (orders of magnitude $<$ regular PET)
- First attempts: Pioneering clinical investigation (LBNL, Maccabee PMB 1969)
- Then developments leading to clinical studies



Just after treatment



few minutes after...

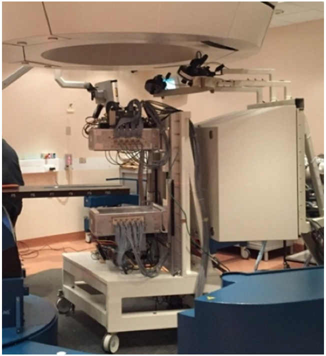
a few minutes after...

Main conclusions (Parodi MP 2018)

- "Limitations due to the adoption of suboptimal instrumentation for the sake of fast clinical translation" (high costs and small market of ion therapy)

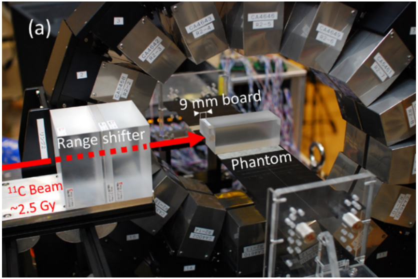
Range verification in PT: Examples of new developments (PET)

INSIDE project



Bisogni JMI 2017

OpenPET (NIRS et al.)



Tashima PMB 2016

Main improvements

- "DOI" PET detectors (exploitation of oblique lines), in-beam acquisitions, fast reconstruction (tens of seconds)

Range verification in PT: Prompt Gammas (PG)

Current modalities

- Main: PET and Prompt Gamma (PG)
- But also: Bremsstrahlung, ionoacoustic waves and post-treatment MR images
- Combination of several modalities considered (e.g. PET and PG, Parodi NIMA 2016)

PET vs PG

- Production rates: very similar

	PET	PG
Pros	- Mature technology - "Natural electronic collimation"	- Direct Emission (⇒ Real-time)
Cons	- Washout - Delayed emission	- Neutron background - High energy gammas

PG detection modalities

PG modalities

PG	Imaging systems			Non-imaging systems		
features	Physical collimation	Electronic collimation	TIARA	PG Timing (PGT)	PG Peak Integral (PGPI)	PG Spectroscopy (PGS)
Position	✓	✓	✓			
Energy	(✓)	(✓)	(✓)	(✓)	(✓)	✓
TOF	(✓)	(✓)	✓	✓	✓	(✓)

adapted from Krimmer NIMA 2018

- CLaRyS collaboration: collimated and Compton cameras, PGPI and TIARA

Main respective advantages

- Imaging systems ⇒ Direct measurement
- "Non-imaging" systems ⇒ Light devices
- TIARA: Direct measurement + light device but need for reduced beam intensity for optimal performances

PG detection: state of the art

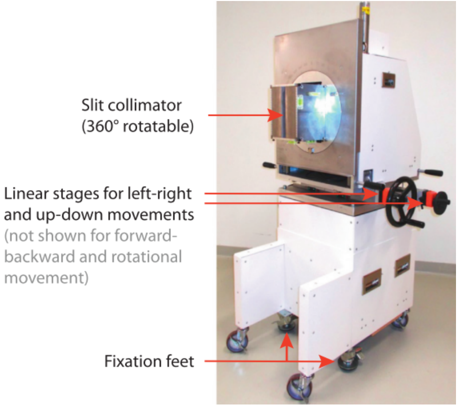
Typical precision on Bragg position

- A few mm (σ) for 10^8 incident protons (large beam spot)
- At the moment, similar precision with all modalities in homogeneous targets

IBA prototype

- Knife-edge slit camera (KES)
- Tested during treatments with passive and active beam delivery

⇒ Millimetric precision achieved with large spots or “spot grouping”



Richter RO 2015

The CLaRyS collaboration

4 labs

- 3 IN2P3 labs: CPPM, IP2I, LPSC + CREATIS (Biomedical imaging lab in Lyon)

Objectives

- **C**ontrôle en **L**igne de l'h**a**dronthérapie par détection de **R**ayonnements **S**econdaires

Current projects

- Gamedi: collimated and Compton cameras with TOF
- CLaRyS-UFT (on-going "Physique Cancer" project): TOF-Compton camera with ultra fast timing (mainly)
- PGPI: PG counting in a few detectors around the patient
- TIARA (starting "Physique Cancer" project): PG emission vertex reconstruction by means of TOF

Strengths

- Synergy between the projects
- Same acquisition system (AMC40 board, μTCA standard)
- Common Monte Carlo simulations tools (Geant4, GATE)

The Gamedi projet of the CLaRyS collaboration

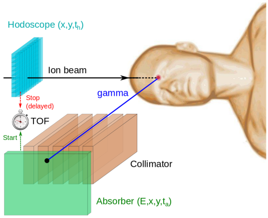
The Gamedi project: **Gam**ma cameras for **medi**cal applications

- Multi parallel-slit camera (MPS) + Compton camera(CC)
- Compton camera also considered for nuclear imaging (diagnotics)

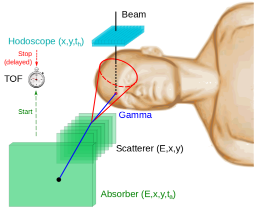
Positioning wrt state of the art

- MPS:
  - Similar efficiency as the one of KES but measurement of the whole PG profile
  - Background reduction with TOF
- CC
  - Hodoscope: Line-cone reconstruction + TOF
  - Perspectives of UFT (talk of S. Marcatili)
  - Use of relatively thick silicon detectors (2 mm)
  - Perspective of detection efficiency enhancement (factor ~50 wrt collimated cameras)

Multi parallel-slit cam.



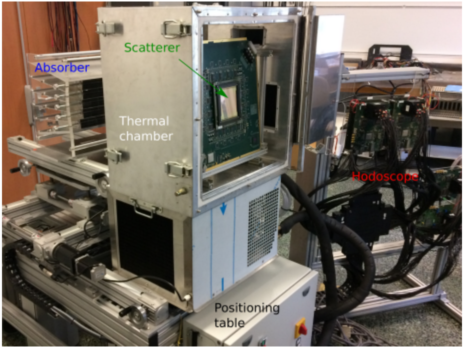
Compton camera



The Gamedi projet of the CLaRyS collaboration

Demonstrators

- Common beam hodoscope (scintillating fibers) and absorber (BGO)
- Common acquisition system and software
- Scatterer of the CC: 7 double sided silicon detectors
- Collimator of the MPS: Tungsten alloy



Current status

- "Small hodoscope" and absorber characterized (lab+in-beam tests)
- Planned for 2021: CC scatterer firmware + integration in the CLaRyS acquisition

The Gamedi projet: “Small hodoscope” characterization

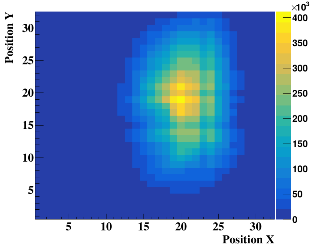
Experimental setup

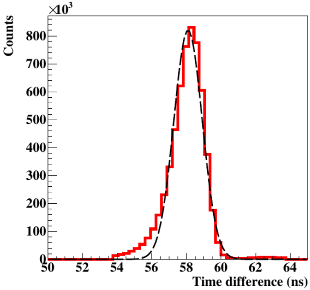
- 65 MeV proton beam (CAL, Nice)

Performances

Specification	Characterization
90% detection efficiency with AND on both planes	! (75%) $\sim$ 90% with OR
Timing resolution $<$ 2ns	✓
Counting rate capabilities: 100 MHz	✗ (10 MHz)
Radiation hardness: $>$ 1000 clinical irradiations	✓

- Lack of performance: ground fluctuations in the ASIC
- Perspectives: ASIC upgrade $\Rightarrow$ Specifications fulfilled





Allegrini submitted to JINST

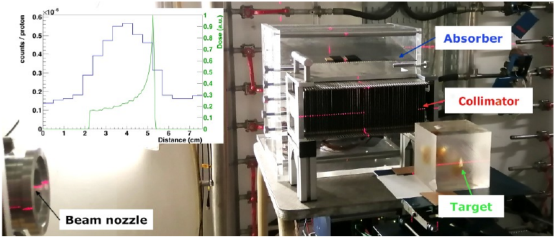
The Gamedi projet: First PG profile with a "small absorber"

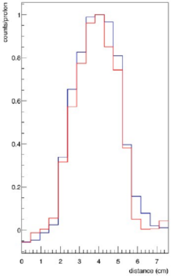
Experimental setup

- 65 MeV proton beam (Centre Antoine Lacassagne, Nice) ⇒ 30 mm range in the PMMA target
- Beam intensity: ∼ nA (clinical beam intensities)

Results

- PG profile in very good agreement with Geant4 simulations
- Large dead time of absorber front-end electronics (LPC Clermont): ∼ 1 μs





Left: Experimental setup. Inset: Measured PG profile and simulated dose profile. Right: Measured (blue) and simulated (red) PG profiles (after normalization)

Conclusion

The CLaRyS collaboration

- Strong collaboration (CPPM, IP2I, LPSC + CREATIS) addressing the challenge of *in vivo* ion-range verification with complementary approaches
- Instrumentation, MC simulations and image reconstruction (CC, TIARA)

The Gamedi project

- Gamma cameras coupled to beam hodoscope (collimated and Compton cameras)
- Positioning wrt the state of the art
  - MPS: measurement of the whole PG profile + TOF
  - CC: Line-cone reconstruction + TOF + UFT perspectives (talks of M.-L. Gallin-Martel and S. Marcatili)

Research perspectives in ARCHADE

- The performances of ion-range verification prototypes have to be assessed with many clinical conditions
- Investigation of PG detection with various beam types (p, alpha, carbon, etc.) and adapted to beam time-structure and intensities
- Investigation of multi-modalities

⇒ Need for beam time!