Developments and simulation around a detector dedicated to the quality assurance in radiation therapy

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Outline

Introduction to the scientific background

→ Quality assurance in radiation therapy and bi-dimensional detectors

Simulation around the detector

→ Linac simulation and input parameters determination

Developments around the detector

→ New prototype and electronics calibration

Conclusion and perspectives

Scientific background

Scientific background

Cancer treatment, the situation in France

In 2015, the French National Cancer Institute (*INCa*) lists :

- **385 000** new cancer diagnosed
  - → About 1/2 of the cancers are « cured »

Treatment statistics in 2014

- About **1.200 million patients** hospitalized
- Represents approximately **15 billion € expense** to handle cancer patients : 5% of this budget for radiotherapy
- **About 1/2** of the patients treated with radiations
  - → Huge improvements in the treatment methods but increase of the complexity

Medical linear accelerator (Linac)

Several incidents involving a patient in radiation therapy occur every year

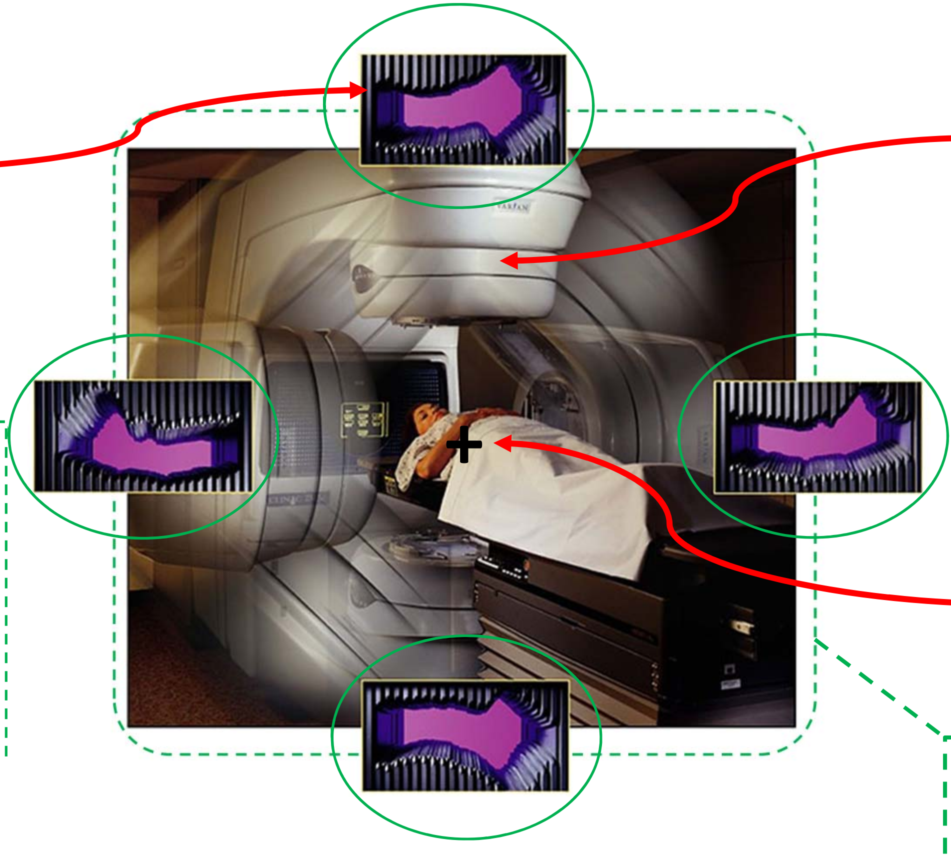
- **5 severe incidents** in 2015, **4** in 2014 (*source : ASN*)
- Nevertheless, fewer and fewer compared to the past decades…
  - → More and more constraining quality assurance procedures adopted in radiation therapy services

Scientific background

To understand, how a radiation therapy session looks like…

Multi-Leaf collimator (MLC)

Rotating Linac's head of treatment



Usually:
1 treatment (60-70 Gy)
=
30-35 sessions (once a day, 5 times a week) of 2 Gy

1 Gy = 1 J/kg

+ Linac isocenter (rotation center of the head)

4 different beam entry points, with different beam shapes

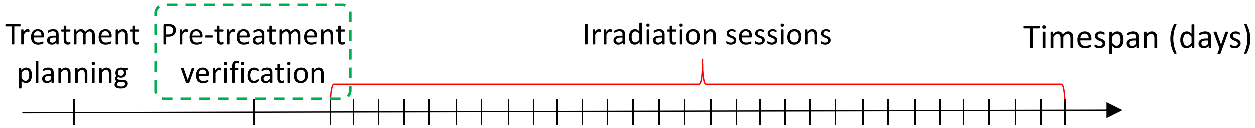
Complex MLC leaves movements, errors are possible
→ Need for efficient tools to control the quality of treatments

Scientific background

Quality assurance (QA) : how the medical physicist prevents errors

Pre-treatment verification

- With **dedicated device or radiochromic films**
- **Drawback**: only once before ALL the irradiation sessions



QA 2D detector with phantom

DIV for head&neck cancer treatment

"In-vivo" dosimetry (DIV)

- With **point-like diode dosimeters**, placed on the patient's skin
- **Drawback**: point-like detector ≠ 2D information, once per treatment…

Electronic Portal Imaging Device (EPID)

- Originally dedicated to **patient repositioning**
- **Drawback**: Distinction between the possible irradiation error and the patient's contribution? Impossible

Deployed EPID on a Linac

→ In any case, not efficient enough to prevent every possible error…

→ Challenge: control the beam during each irradiation session

Scientific background

2D upstream detectors : toward a better quality assurance

The idea? Use of a bi-dimensional transmission-type detector

- Operate **during** irradiation session ✓
- Give **2D information** ✓
- Located upstream of the patient ✓

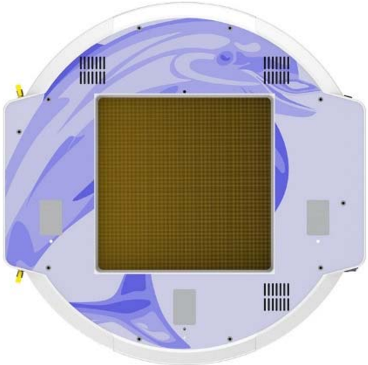
Specifications?

→ Low and homogeneous beam attenuation
→ Lightweight
→ Wide enough to cover the whole beam
→ With embedded fast readout electronics

Some detectors have already been released

Detector PTW David

→ *Good reconstruction of the shape of the beam*
→ *Poor in-beam fluence information*



Detector IBA Dolphin

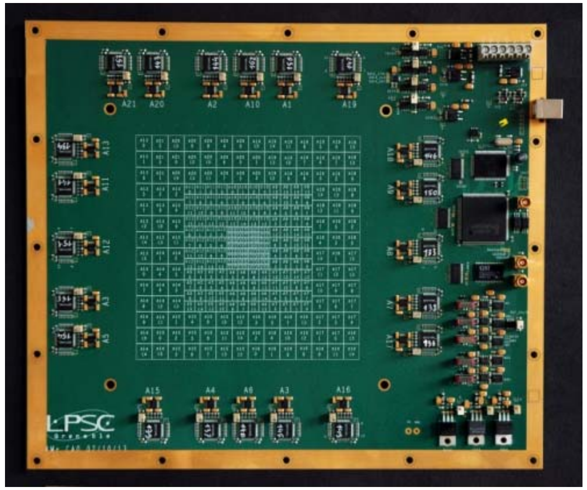
→ *Good reconstruction of the overall photon fluence*
→ *Non-homogeneous beam attenuation*

Scientific background

LPSC's contribution: TraDeRa *(Transparent Detector for Radiotherapy)*

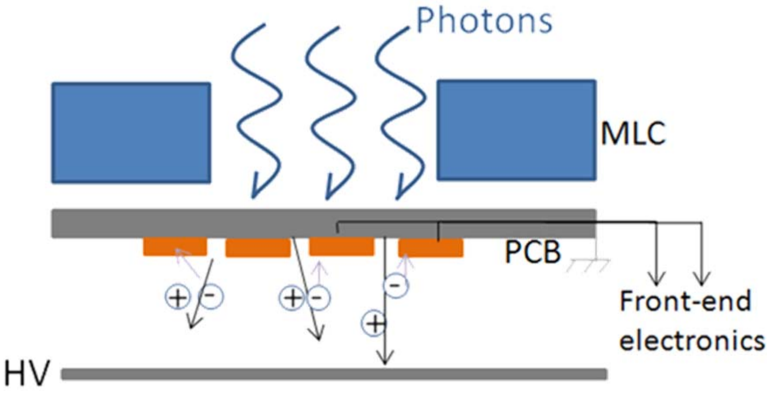
Description

- 2D array of 324 ionization chambers
- **Different sizes of electrodes** (pixels)
- **20x20 cm² coverage**
- **High speed data collection** thanks to in-house designed embedded electronics
- Measured homogeneous attenuation of approx. 2%

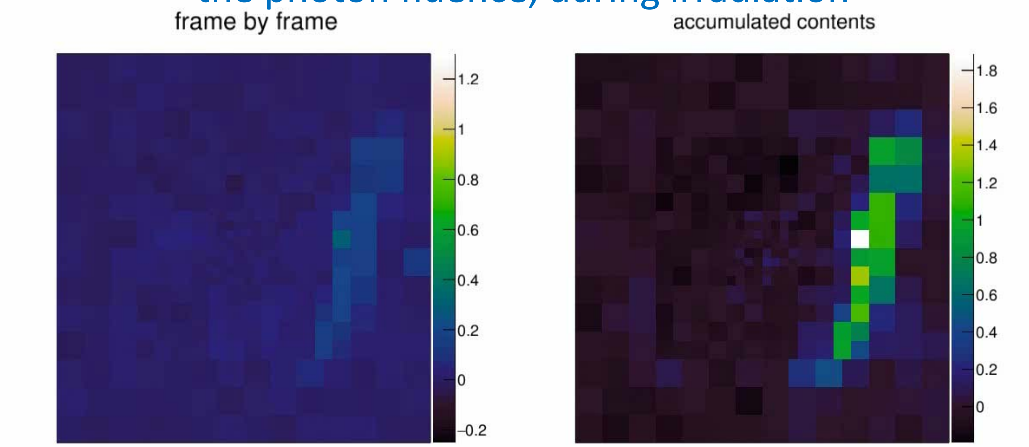


TraDeRa's printed circuit board (PCB)

Detection process



Can provide a complete 2D signal map of the photon fluence, during irradiation



Simulation around the detector

Monte Carlo simulation around TraDeRa
Why is that necessary?

Main objective: Dose reconstruction in a **water tank** (reference model for the patient) from the signal map given by TraDeRa (not trivial)

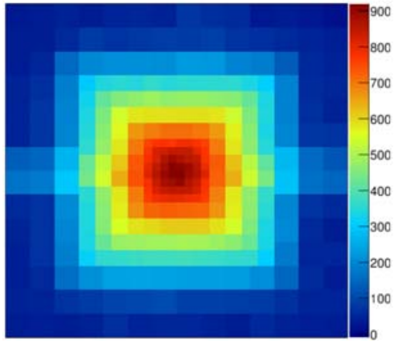
Impossibility to perform an absolute dose calibration of TraDeRa

Absolute dose = Physical dose that can be measured by a calibrated punctual ionization chamber

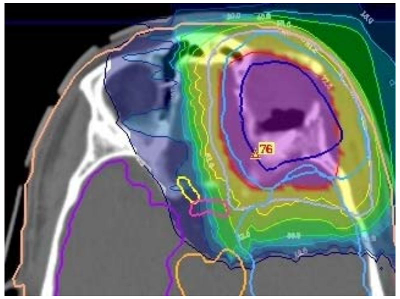
- Due to **its size:** Bragg-Gray cavity theory respected only if:
  → small enough to not perturb the beam
  → energy deposited only by electron passing through the cavity
- Due to the **contaminant electrons** coming from the Linac head (about 13% of the signal)

→ Relative dose calibration? How?

Relative dose = dose normalized to the absolute dose



Signal to dose?



Solution? Monte Carlo simulation (PENELOPE, *Salvat et al.*)

- Associate a **3D dose matrix in water/patient** with the **deposited energy in the TraDeRa air active volume**
- **Comparison with real measurements under Linac**

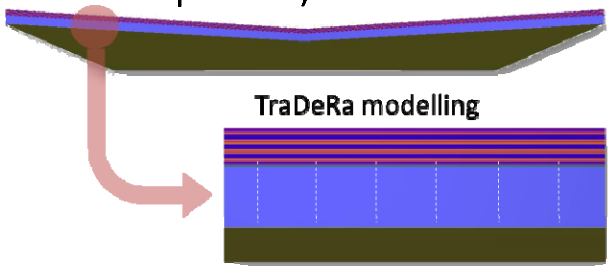
→ To do so, necessity to reproduce a reference Linac…

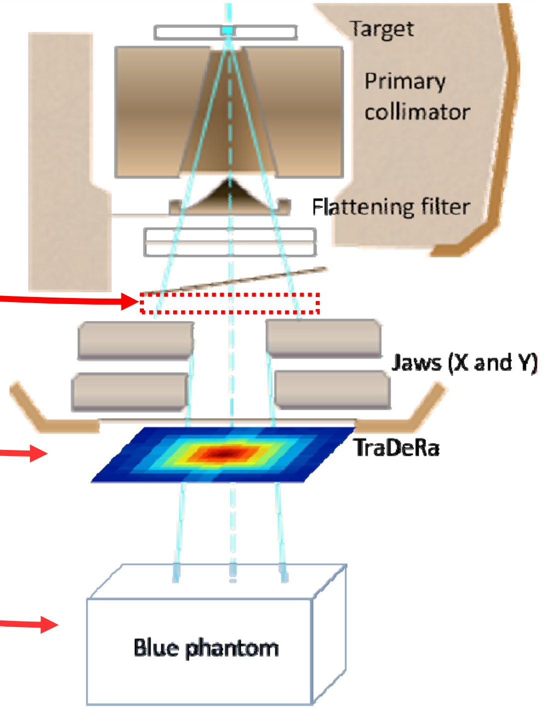
Monte Carlo simulation around TraDeRa

Geometry and simulation setup

Simulation setup

- **Clinac 2100** (different field sizes, 6MV mode)
  → **Phase space file (PSF)**
- **TraDeRa**
- 50x50x50 cm^3 **water tank**
  (mimic the patient)





Simulation specification

- Sending of $\mathbf{6 \times 10^8}$ **primary electrons** through the target
  → Represents approx. **8.3 CPU years** (25 days on 100 CPU)
  → Mandatory to achieve a good level of precision (about 2% in the field)
- **Hardwork** on simulation optimization to keep a good simulation efficiency
  → Especially in the target and the water tank
  → Use of various variance reduction techniques

→ How to correctly reproduce a reference Linac then… ?

Monte Carlo simulation around TraDeRa

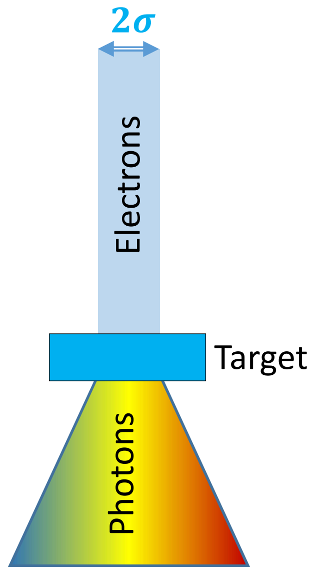
The importance of the simulation input parameters

Two parameters of importance to match with a reference accelerator beam (Clinac 2100 @ Grenoble Public Hospital (CHUG))

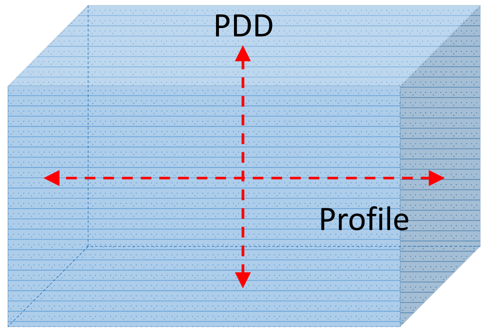
- **Electron beam energy** delivered by the acceleration structure (E)
- **Focal spot size** on the target (σ)

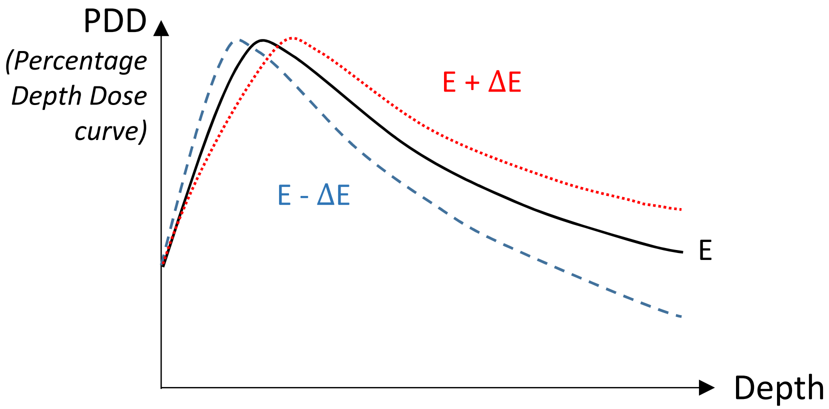
Objective: to get an accurate enough simulation **to compare with measurements** (square-shaped fields of different sizes)

→ Unique set of parameters for each Linac (typically : E ∈ [5.85 ; 6.25] MeV for the 6MV mode and σ ∈ [0.2 ; 1.5] mm)

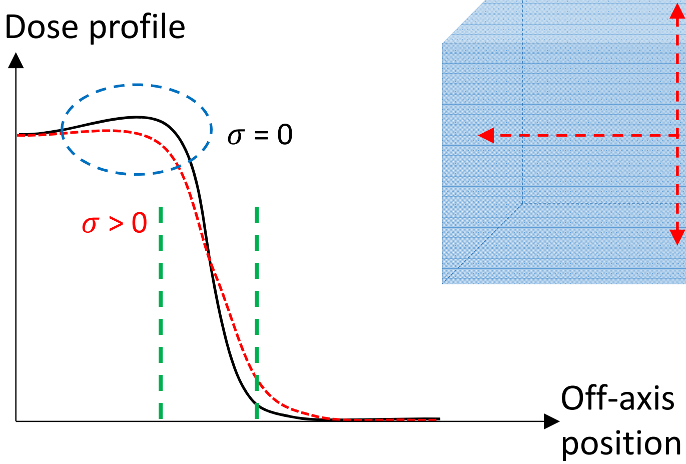


Each parameter will influence an observable in the water tank





Different D_{max} and shapes



Different horns and penumbra

Monte Carlo simulation around TraDeRa

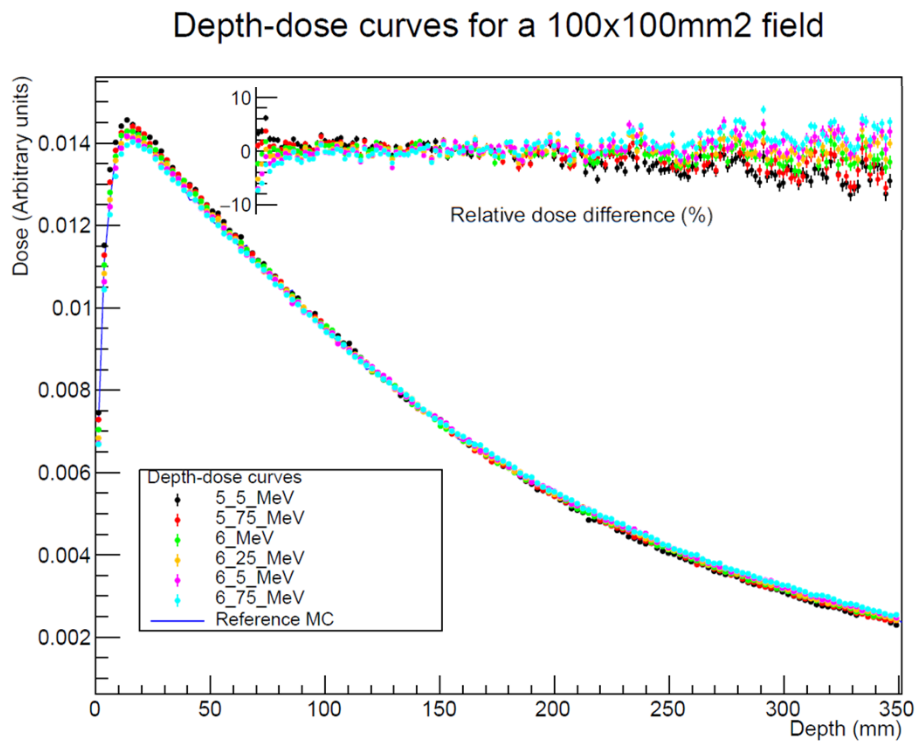
MC/measurements comparison method (example for energy)

Problem: Common tests used in medical physics (e.g.:gamma index) do **not consider MC statistical uncertainty**

Objective: New comparison method including MC statistical uncertainty in the MC/measurements PDDs comparison?

→ Based on the ranking of compatibility level between each MC energy point and measurements

→ Can provide within minutes the parameters of a given accelerator

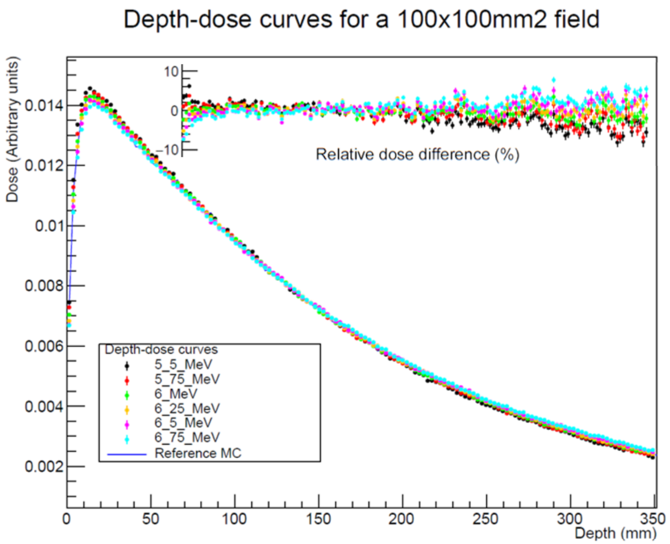


Data processing required:

- Data binning constrained by the number of measurement points
- **Normalization to the integral** of dose along the range of measurement points

Monte Carlo simulation around TraDeRa
MC/measurements comparison method

The method I built? (For energy determination)



For a given energy j : $S_j = \sum_{i=1}^{N_{bin}} (D^i_{meas} - D^i_{MC_j})^2$

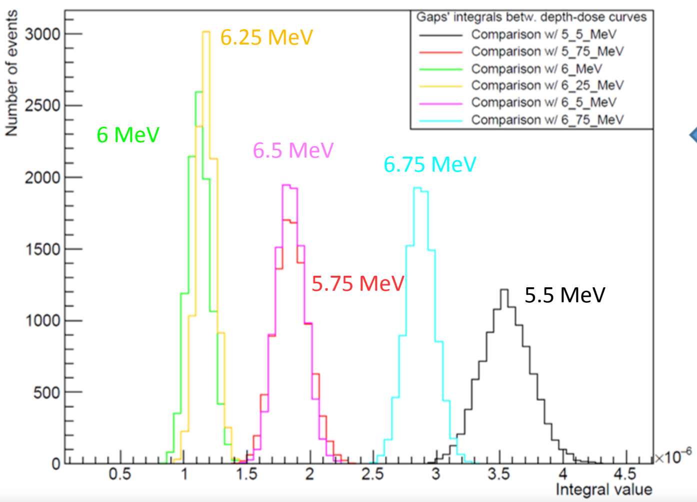
D^i_{meas} : measured dose @ depth given by the bin i

$D^i_{MC_j}$: randomized MC dose for the same depth (Gaussian distribution centered on the value given by simulation, with the standard deviation also given by the simulation)

1 value of the compatibility test

Repeat the same randomization procedure a large number of time

Do this for all the MC energy points



→The lower the value of the test, the more compatible the sets

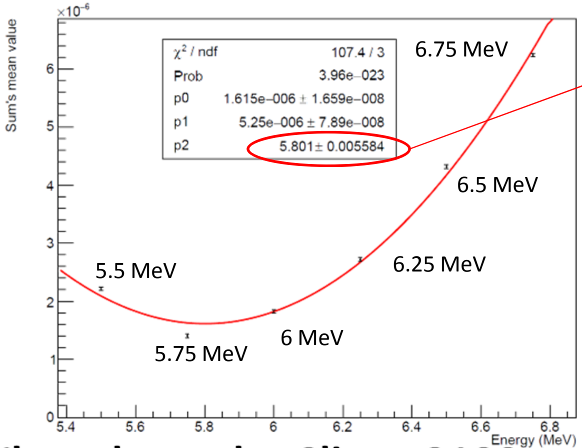
→Fit distributions means estimators with a polynomial of degree 2 to determine the optimal value (next slide)

Monte Carlo simulation around TraDeRa

Validation (MC/MC agreement) and CHUG Clinac 2100 energy determination

2 MC/MC agreements: 5.7915 and 6.1591 MeV

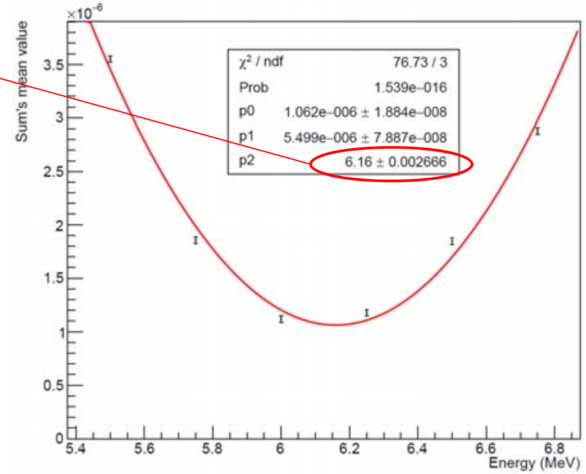
- Simulation with « weird » values of primary electrons energy to get the sensitivity of my method



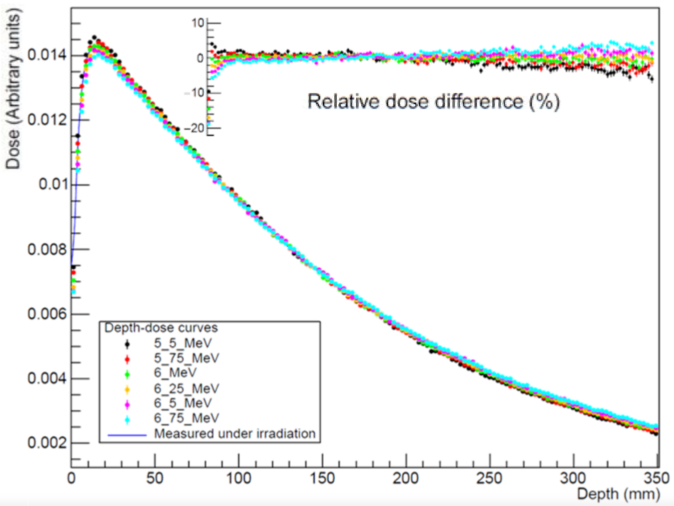
5.80 MeV 6.16 MeV

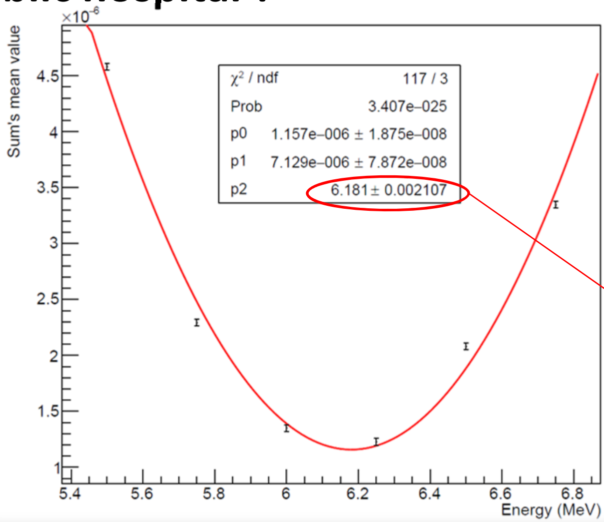
(at least 10 keV precision)

→ The method seems to be very sensitive and the number of simulation points is high enough



What about the Clinac 2100 at the Public hospital ?





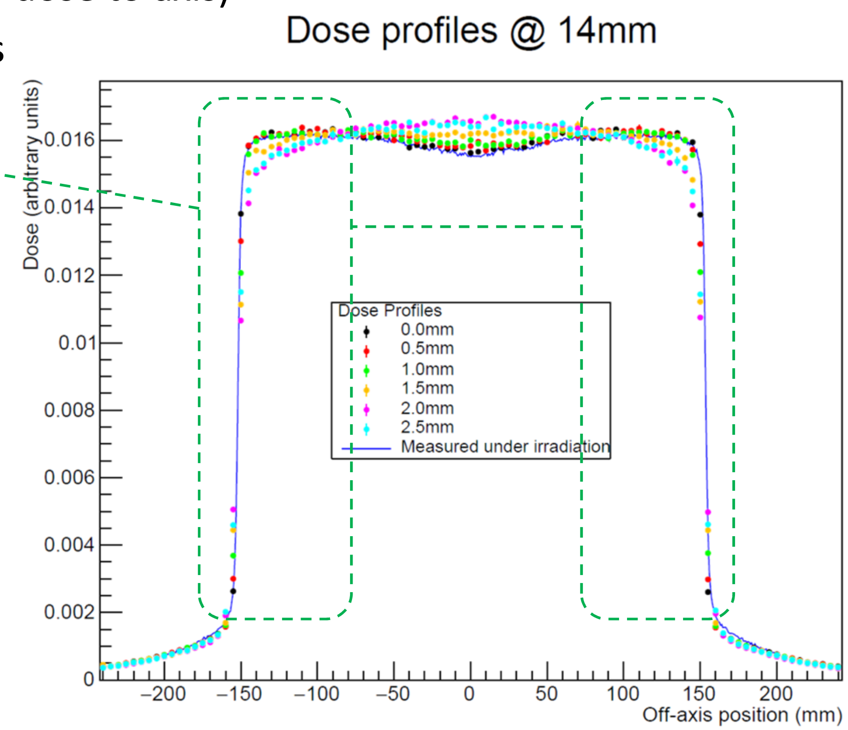
Comparison with the depth-dose curve measured under irradiation, in a blue phantom, at the Grenoble public Hospital

6.18 MeV

Monte Carlo simulation around TraDeRa
MC/measurements comparison method

For the focal spot size: same principle, a few differences

- A few more points to be simulated
- Use of dose profiles at different depths in the water tank (14, 50, 100 and 200 mm)
- **Normalization remains to be tested** (integral or dose to axis)
- Method won't be focused on the whole profiles
  → Focused on horns and penumbra
  → slight differences of shape here



Work in progress…

Monte Carlo simulation around TraDeRa
What to do with this simulation?

Main use: for my own purposes

→ **Huge simulation** with both input parameters corresponding to the Clinac @CHUG

- Quantify the **"cross-talk"** between one chamber and its neighbors
- Link between a pixel's response and the dose deposition
- Comparison of **more complex plans** with my simulation
- **Association of a 3D dose matrix with a given detector's simulated response** and comparison with the true response

→ Next steps of my simulations

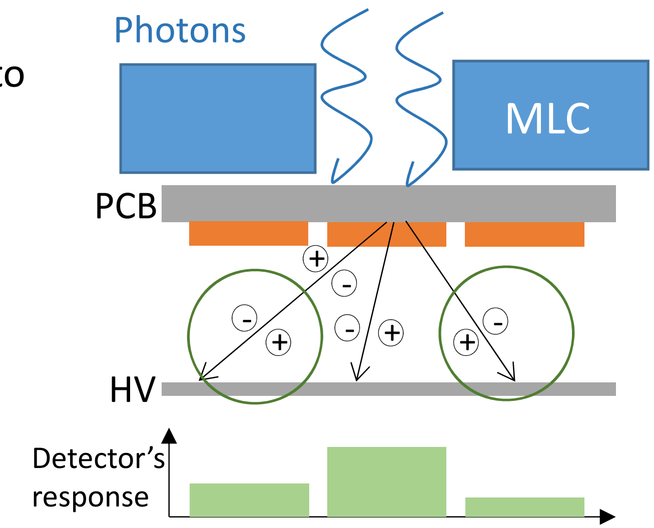


Illustration of the cross-talk

Other use: for clinical purposes

→ Determine the electrons beam parameters of **other medical accelerators**

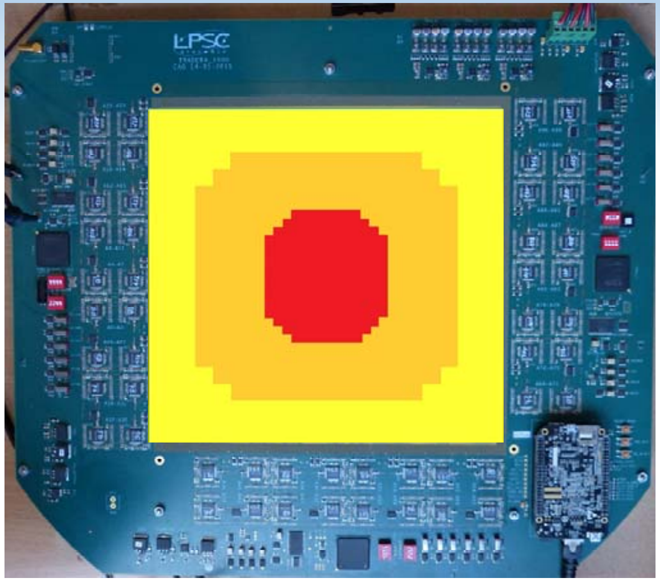
- Information locked by medical linear accelerator manufacturers
- Will fit for any Clinac 2100 (and other accelerators with different geometries)

Radiotherapy service	Linac's primary electrons energy
Centre Léon Bérard (Lyon)	6.09 +/- 0,01 MeV
CH Métropole Savoie (Chambéry)	6.20 +/- 0,02 MeV

Developments around the detector

Developments around TraDeRa

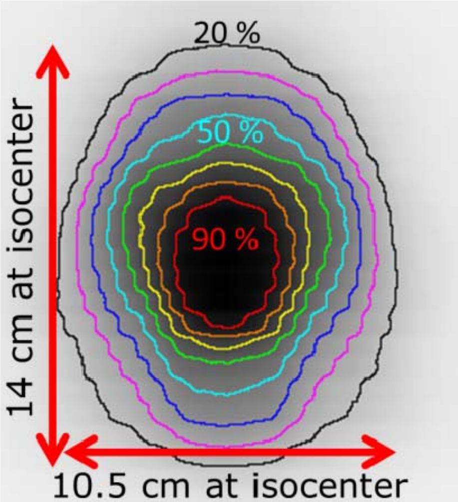
The last prototype: TraDeRa 1600



Printed circuit board of TraDeRa 1600

New features

- **1600 ionization chambers**
- Coverage of **40x40 cm²** fields (maximum field size available)
- **New electrodes layout** (my contribution to this prototype)



Superposition of EPID images from approx. 200 patients' treatments and 20 different locations (CHU Grenoble)

Optimized layout

→ Challenge: with a **limited number of electrodes**, provide **as much information as possible**

- Different layout from the square-shaped areas of the previous prototype
- Small electrodes **full coverage** of 50% iso-exposure area
- Medium electrodes coverage of nearly the whole 20% iso-exposure area
  - → Much bigger area covered by small electrodes
  - → Waiting for tests under irradiation

Developments around TraDeRa
Electronics calibration with a high dose rate source

Encountered issue: Each readout circuit of each electrode induces a different electronic gain

→ Necessity to calibrate this gain

Idea: homogeneously irradiate the whole active area of the detector

But, with a Linac…

→ **Flatness** only achievable at **a certain distance d_{ref}** (medium dependent)

→ Detector located at a distance << d_{ref} (under the Linac head, approx. 35 cm higher)

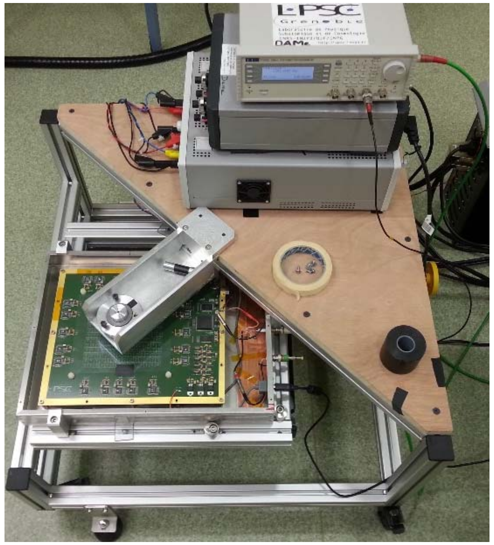
→ Necessary to use another source of photons, with an equivalent energy and high enough flux

Solution: use of an high dose rate (HDR) curietherapy ^{60}Co source

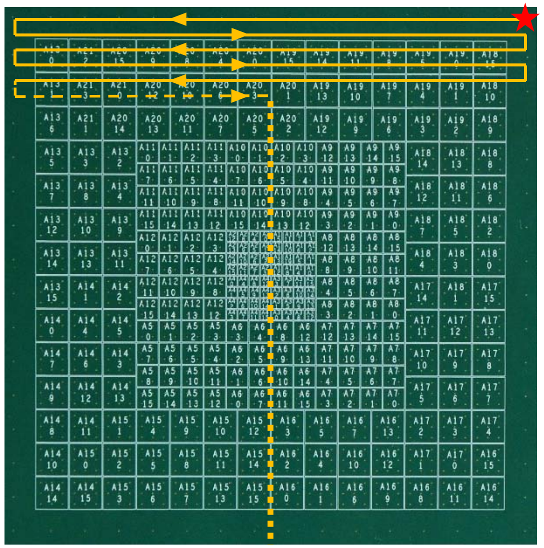
- Used to treat prostate, uterus or breast cancer
- Activity: approx**. 1.5Ci** (= 7.4×10^{10} Bq)
- Treatment currently proposed in the radiotherapy service of the CHUG

Developments around TraDeRa
Electronics calibration with a high dose rate source

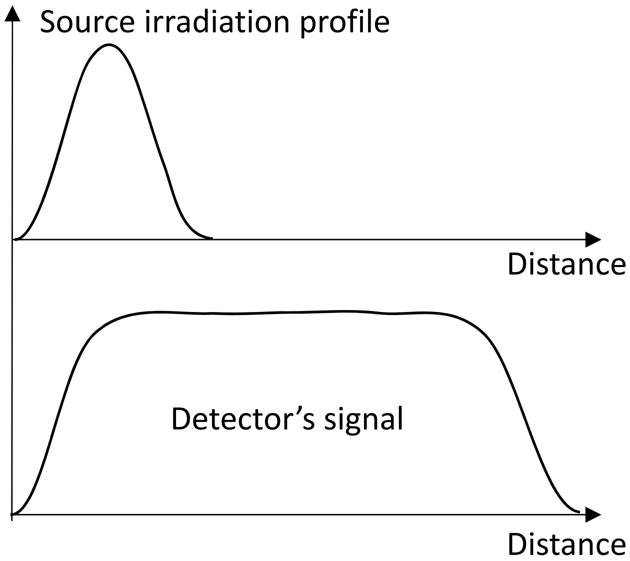
Scan the source over the detector, **to mimic an homogeneous irradiation as seen by the detector**



Micrometric displacement table and source support Design: J. Menu



Source trajectory over the detector



Profile of the source and detector's signal while scanning

Developments around TraDeRa

Electronics calibration with a high dose rate source

Preliminary experiment march 2016 @ CHUG: tested parameters

- **Source-detector distance:** from 1.25 to 2 cm
- **Scan velocity:** from 2.5 to 10 mm/s
- **Pitch:** from to 1 to 5 mm

  → Analysis in progress, further experiment coming in a few days to perform a slow scan of source on the detector

My contribution to this experiment

- **Table control software:** upgrade of the existing version of control software

  → Adaptive algorithm to perform of full scan of the detector, no matter the position of it

  → Keyboard control

  → Quality assessment of the table/software
- **Experiment preparation and data acquisition**

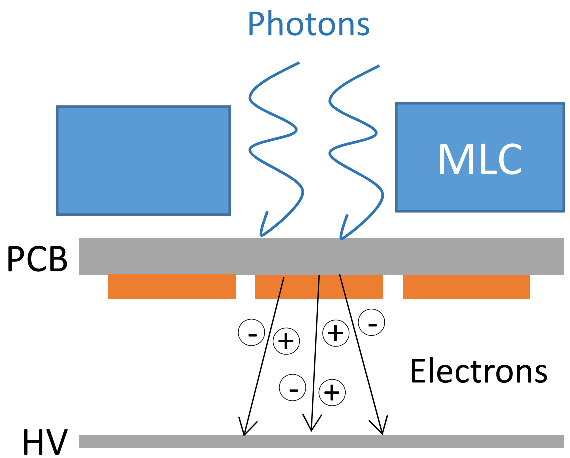
Conclusion & perspectives

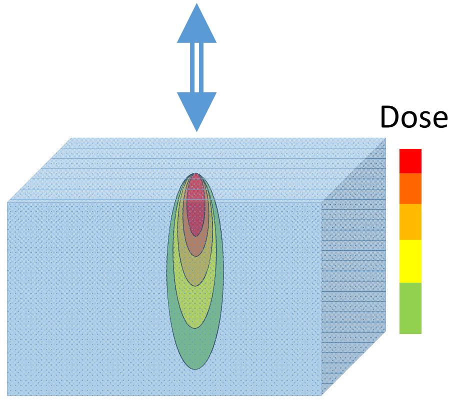
Simulation input parameters determination: in progress

- Comparison method is **robust**
- Primary electrons **energy** has been **determined**
- **Focal spot size** of the electron beam on the target **to be determined**

→ Will give an accurate modelling of the Clinac 2100 at the Grenoble hospital to perform the detector dose calibration

→ The method could be applied to any other clinical accelerators





Further simulation studies and detector developments:

- Pixels cross-talk study by simulation
- Association of one pixel response to the dose distribution in the water tank
- Complex plans comparisons between measurements and simulation
- Electronics gain calibration with High Dose Rate cobalt source in progress
- **1600 channels prototype** remains to be tested under irradiation

→ Next objectives of my thesis

Thank you for your attention