3-Dimensional Scintillation Dosimetry for Small Irradiation Fields Control in Protontherapy

E. Mainguy[1], J-M . Fontbonne[2], A-M . Frelin[1], D . Lebhertz[3], C . Moignier[3], J . Thariat[2,3], A . Vela[3]

[1]*Grand Accélérateur National d'Ions Lourds (GANIL), CEA/DRF CNRS/IN2P3, 14076 Caen, France*

[2]*LPCC - Laboratoire de physique corpusculaire de Caen, 14000 Caen, France*

[3]*CLCC François Baclesse, 14000 Caen, France*

Le projet PMRT est financé par

Cancer treatment and Radiation therapy

~ 399 000 new cancer cases in France in 2017

~ 213 000 patients/year treated by radiotherapy

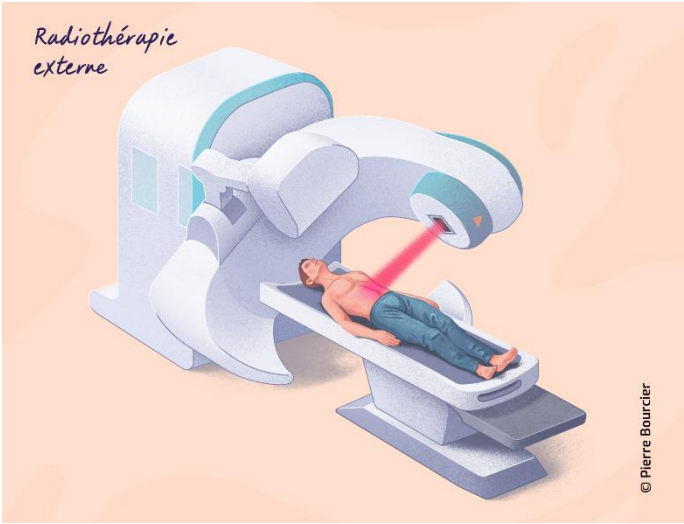


Image credit: INCa web site

Dose deposition by ionizing radiations

Tumor sterilization

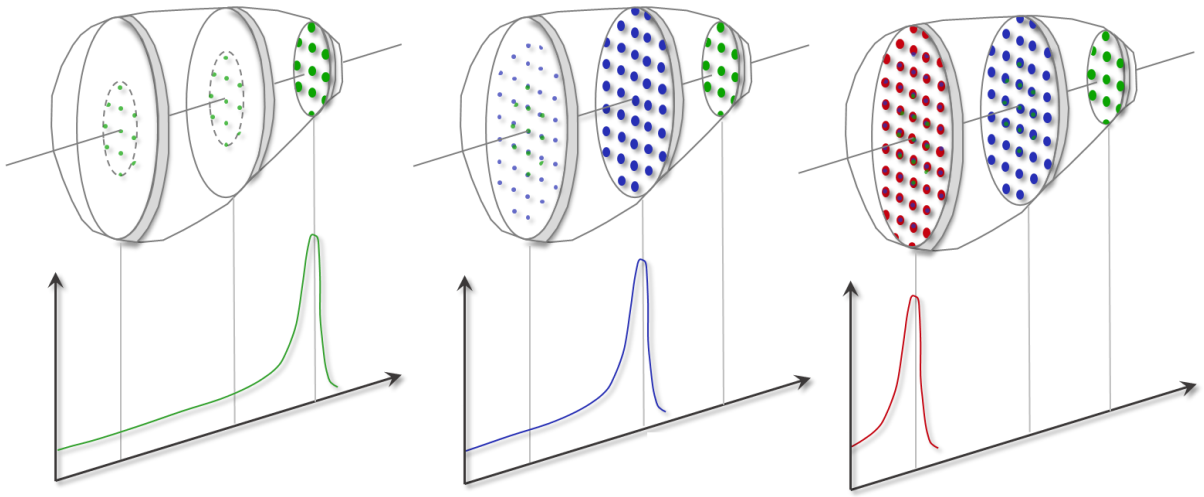
Complications on healthy tissues

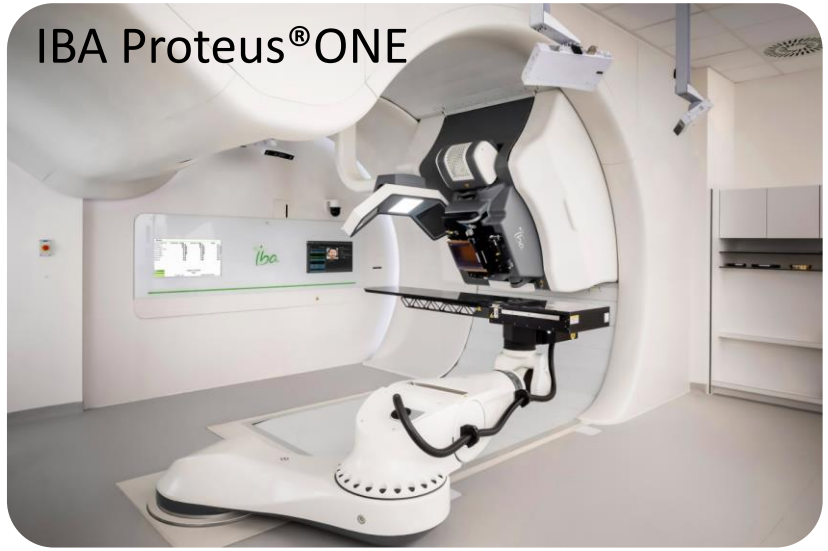
Necessity of **dose conformation** to the target volume

Development of advanced treatments

Proton therapy

Treatment planning and delivery in pencil beam scanning (PBS)





MC based **Treatment Planning System**

Calculation of the **number of beams**, **energy** (E), **position** (X,Y), **dose delivered** by each beam

to achieve dose constraints (high dose in the tumor, low dose in organ at risks)

- **Beam frequency = 1 kHz**
- Pulse = 7 µs
- Maximum energy = 230 MeV

- Gantry 220°
- Treatment table: 6 degrees of freedom

Treatment control in proton therapy

Case of the small tumors (< 27 cm^3)

Under $3 \times 3 \times 3$ cm^3 :

- Treatment Planning System uncertainties

  ⇨ 3D dose verifications

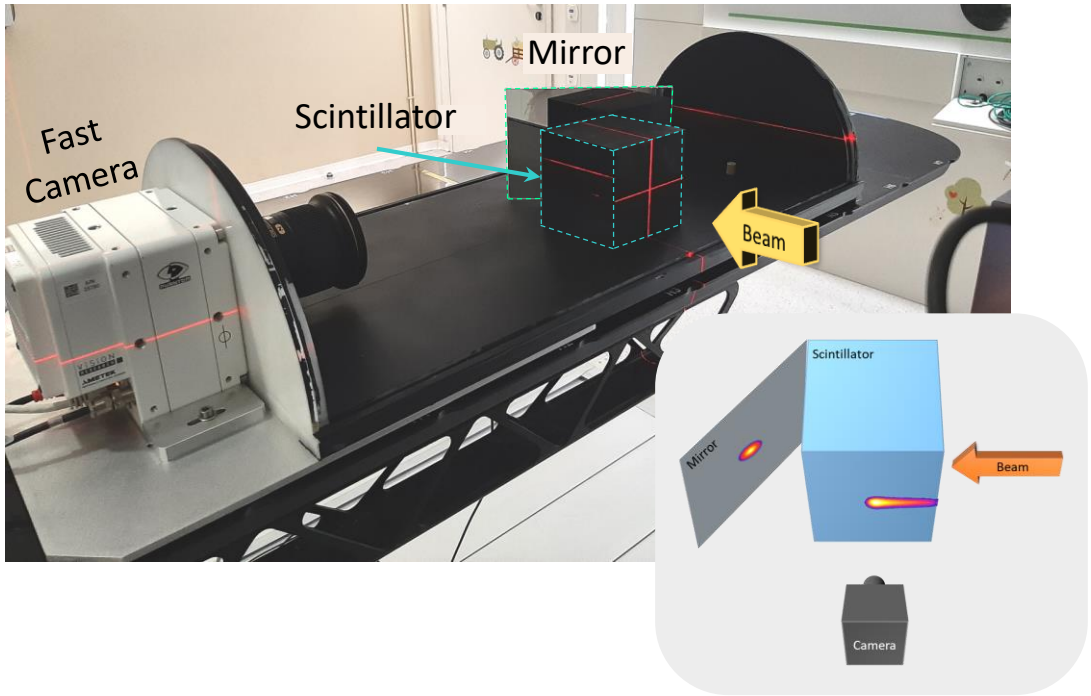
- Control detectors → 2D measurements (time consuming) and/or inadequate spatial resolution

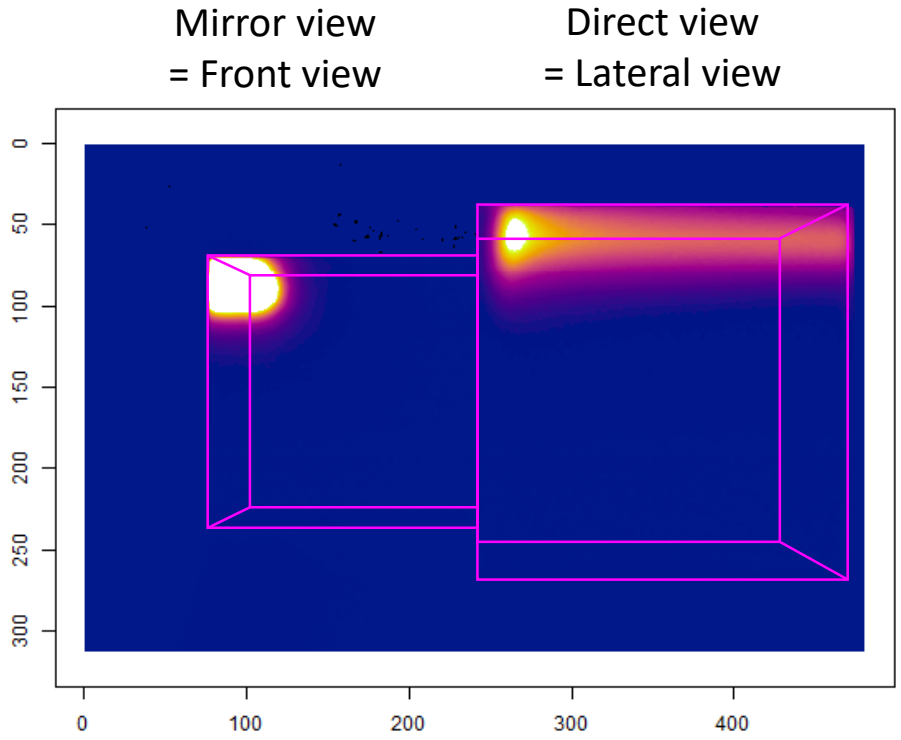
⇨ Need of a new proton therapy dosimeter

- 3D measurements
- Spatial resolution < 1 mm
- 2 % uncertainty on the dose delivered by the treatment

Development of a proton therapy dosimeter

Experimental setup



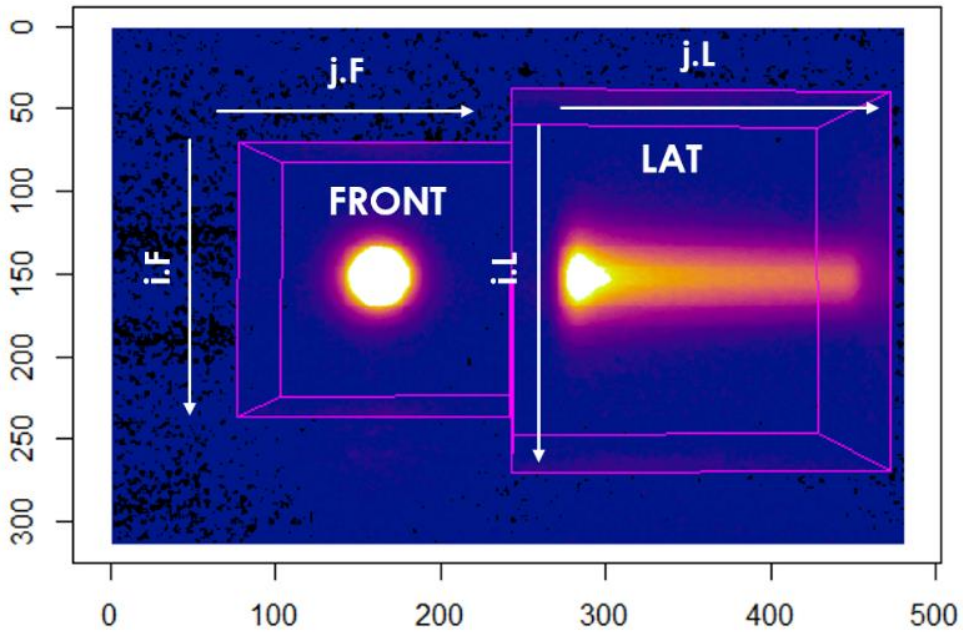


$10 \times 10 \times 10$ cm^3 BC412 plastic scintillator
Ultra fast camera: up to 5200 fps @ 1200×800 px
Synchronized to the beam (delivered at 1 kHz)
← logical signal provided by the Proteus®ONE

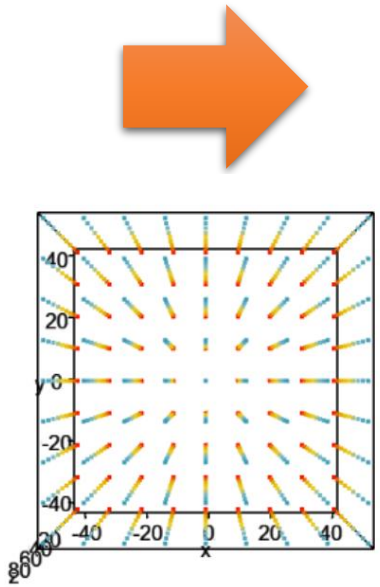
Recording of each beam
2 operating modes:
⇨ **Measurement/control of each beam characteristics**
⇨ **3D dose distribution of the entire treatment**

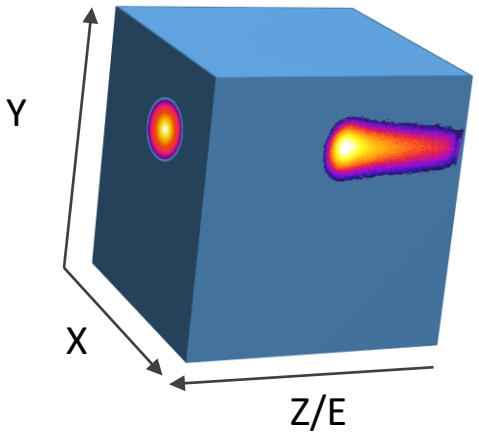
Development of a proton therapy dosimeter

Spatial calibration



Calibration





Intensity of the **0.1% most intense pixels** (in gray levels) in the Front and Lateral views
Corresponding **positions** (i, j) (in pixels)

≈ Bragg peak in both views

Reference irradiation:

$9 \times 9 \times 9$ beams
distributed in the sc. Volume
Same dose for each beam

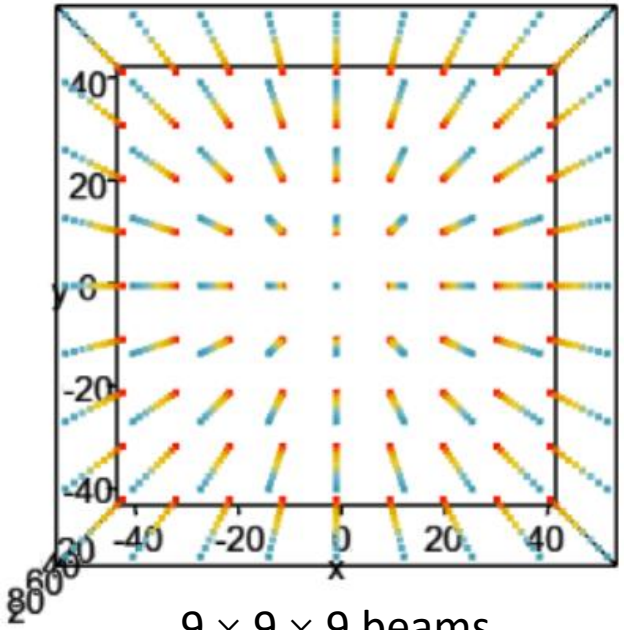
Beam characteristics:

- Position (X, Y)
- Depth / Energy
- Delivered dose

Measurement of beam characteristics

Performances evaluation – Repeatability measurements

10 repetitions of the **reference irradiation**



$9 \times 9 \times 9$ beams distributed in the sc. Volume
Same dose for each beam

→ **Standard deviation** for **each** beam characteristics: position, depth and delivered dose

$$\sigma_X,\ \sigma_Y,\ \sigma_Z,\ \sigma_D/D$$

Repeatability at ≠ delivered doses: **0.02**, **0.1** and **1** Monitor Unit (MU)*

smallest programmable dose	*representative of treatment doses*	*High dose Good S/N ratio*

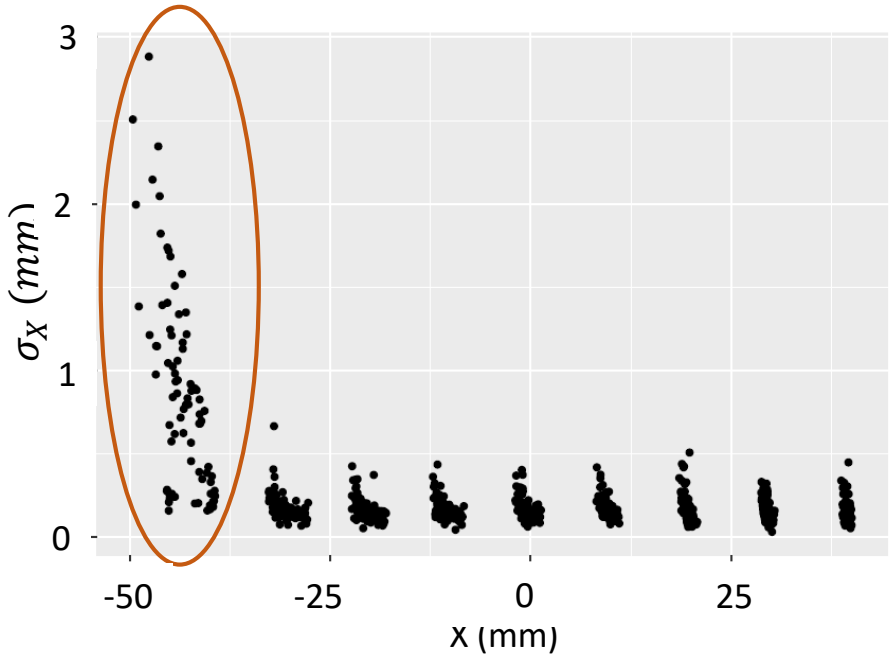
** A monitor unit (MU) is a measure of machine output from a clinical accelerator for radiation therapy. By convention, one monitor unit equals 1 cGy of absorbed dose in water under specific calibration conditions.*

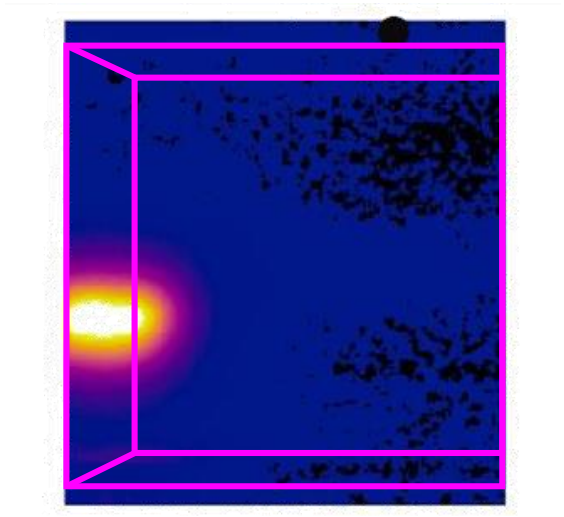
Measurement of beam characteristics

Performances evaluation – Repeatability measurements

First analysis: Increased dispersion for the **81 leftmost beams**

Exp result: std dev. on X at 0.1 MU





Combined effects:

- Optical perspective and reflections (← **dosimetry system**)
- Delivered beam position uncertainty (← **irradiation system**)

Not representative of the detector response (especially for irradiation fields < 3 × 3 cm²)

→ Exclusion from the results of the 81 leftmost beams in this study

Measurement of beam characteristics

Performances evaluation – Repeatability measurements

Average value and **standard deviation** of the variations for the 648 remaining beams → In agreement with objectives (1 mm, 2 %)

	1 MU	0.1 MU	0.02 MU
σ_X (µm)	103 ± 44	169 ± 75	342 ± 293
σ_Y (µm)	96 ± 35	152 ± 42	341 ± 122
σ_Z (µm)	**42 ± 19**	**75 ± 28**	**176 ± 91**
σ_D/D (%)	0.30 ± 0.17	0.77 ± 0.26	2.44 ± 0.89

$\sigma_X, \sigma_Y > \sigma_Z$

↑

Proteus®ONE beam positioning uncertainty

detector performance ~ σ_Z < **300 µm**

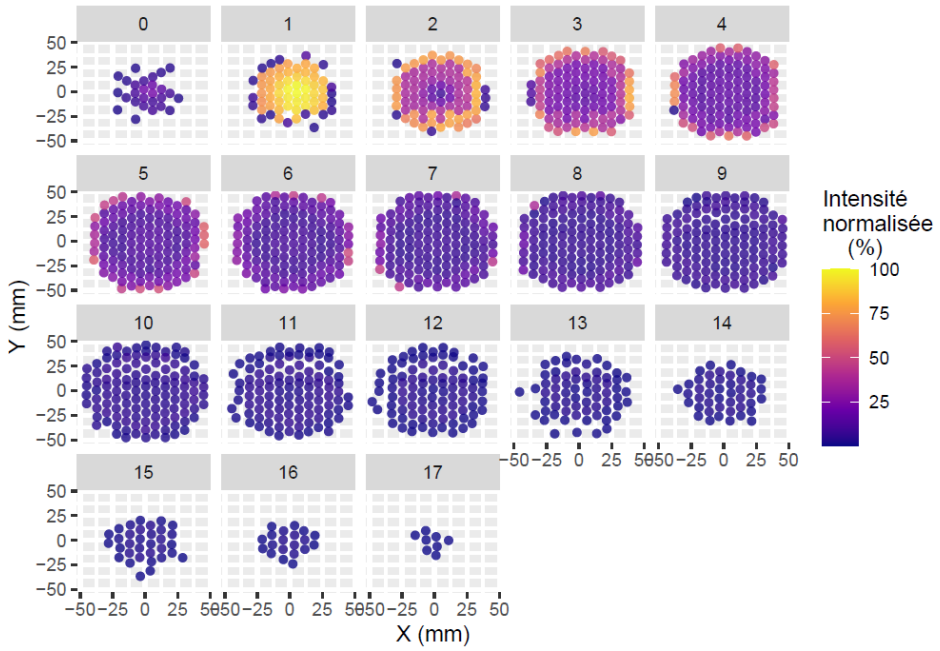
Very low dose beams
→ small fraction of the whole treatment

Expected improvement ← calib. / Dk signal subtraction / img analysis

Measurement of beam characteristics

Verification of the characteristics of planned beams

Treatment planning of an homogeneous dose distribution of 0.8 Gy in a sphere of 8 cm ∅ located inside the scintillator cube



~ 1 800 beams divided into 18 energy layers,

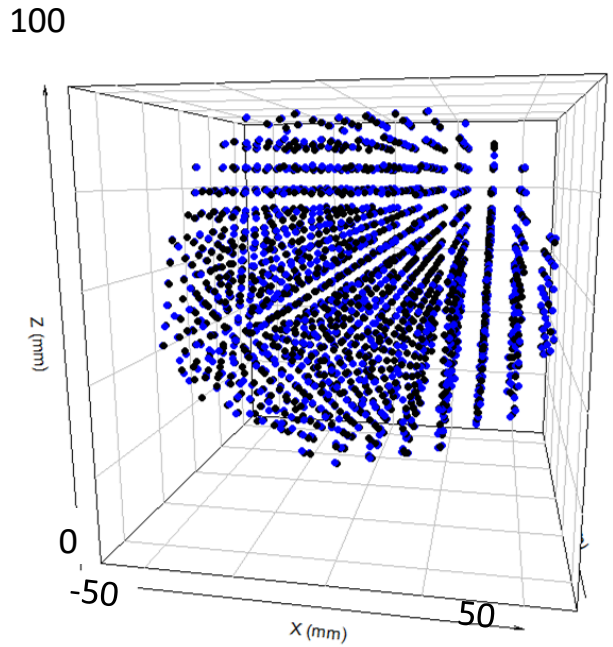
0.02 < D < ~1 MU

Agreement between planned and delivered beams ?

Measurement of beam characteristics

Verification of the characteristics of planned beams

Comparison between planned and measured beam characteristics:



$$d = \sqrt{\underbrace{\left(X_{meas} - X_{plan}\right)^2 + \left(Y_{meas} - Y_{plan}\right)^2}_{\text{position}} + \underbrace{\left(Z_{meas} - Z_{plan}\right)^2}_{\text{depth}}}$$ **for each beam**

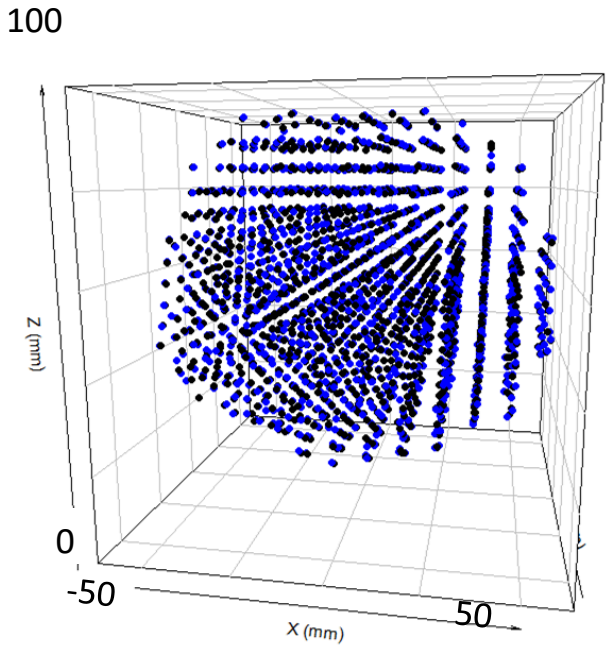
$$\Delta D = D_{meas} - D_{plan}$$ **for each beam**

$$\left(\frac{\Delta D}{D}\right)_{treatment} = \frac{D_{meas} - D_{plan}}{D_{plan}}$$ **for the whole treatment**

Measurement of beam characteristics

Verification of the characteristics of planned beams

Averaged distance and dose difference over the 1 800 beams



$$\bar{d} = (\mathbf{375} \pm 408)\ \mu m$$

$$\overline{\Delta D} = (\mathbf{-3.37} \pm 5.47).10^{-3}\ MU$$

$$\left(\frac{\Delta D}{D}\right)_{treatment} = -1.54\ \%$$

Biases correction:

- Leftmost beams treatment
- Overfitting calibration ?
- Significant contribution of beams with D < 0.1 MU
  - → Dark subtraction
  - → Images analysis

Differences in treatment tolerance (1 mm, 2 %)

Conclusion and perspectives

Development of a new dosimetry system for proton therapy

- Very promising results:
  - Spatial resolution < 300 µm
  - Dose uncertainty < 3.4 % (beam by beam)
- Ongoing improvement image treatment and analysis
  - Dark subtraction
  - Image analysis → Better position and light intensity measurement
  - Calibration
- Toward 3D dosimetry
  - Scintillation quenching correction
  - Optical effects specific correction
  - Pencil beam characterization
  - …

Thank you for your attention