An introduction to PET activity simulations and detector study

FLUKA Advanced Course and Workshop
18-22 November, NEA, Paris

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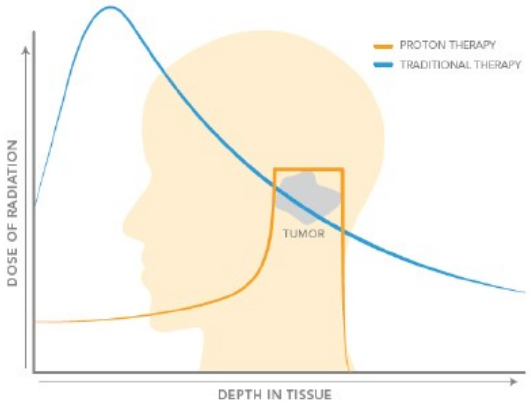
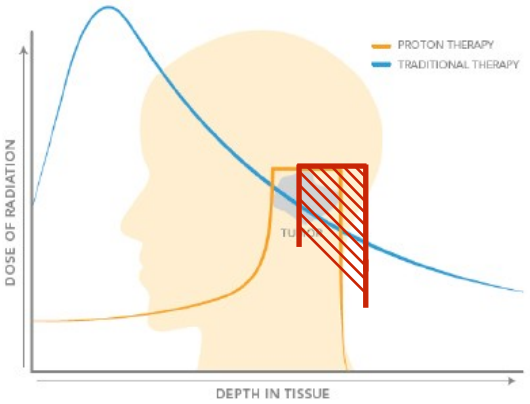
Why PET activity?

Proton treatment



$$-\frac{dE}{dx} = 4\pi N_A r_e^2 m_e c^2 \rho \frac{Z_t}{A_t}\frac{Z_p^2}{\beta^2}\left[ln(\frac{2m_e c^2\beta^2\gamma^2}{I}) - \beta^2 - \frac{\delta}{2} - \frac{C}{Z_t}\right]$$

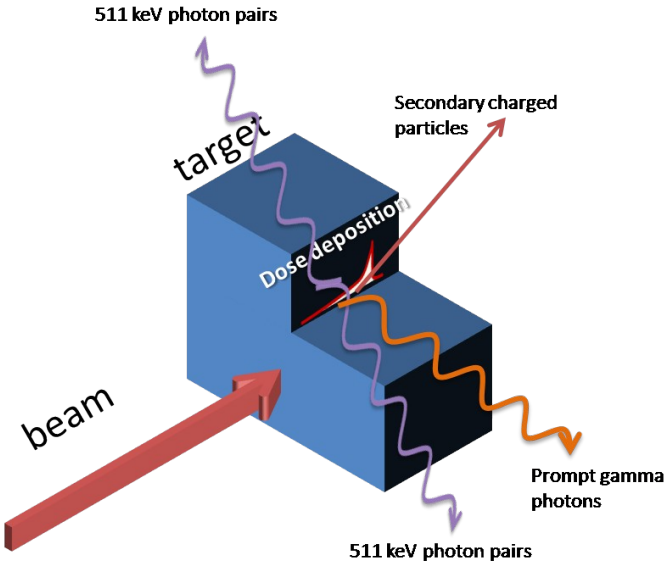


Dose uncertainties:

- Patient setup
- Anatomical changes
- Dose calculation

→ need of **particle range verification**

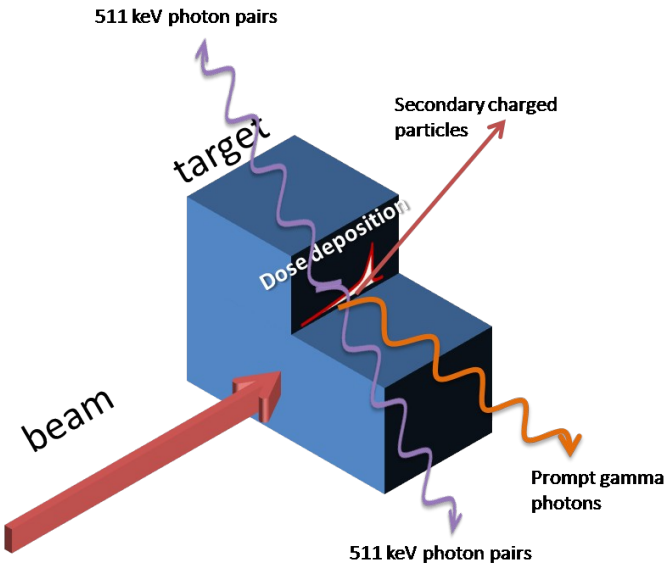
Why PET activity?



Particle range verification:

- Nuclear de-excitation → Gamma prompt
- Fragmentation → Charged particles
- β^+ isotopes → 511 keV annihilation photons

Why PET activity?



Particle range verification:

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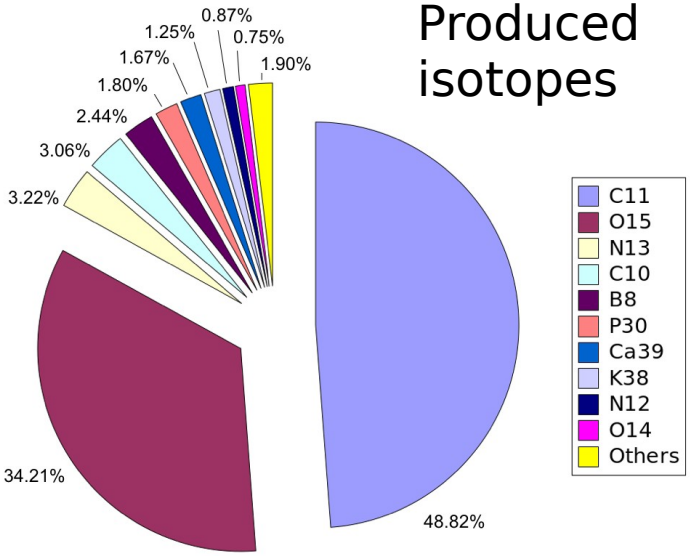
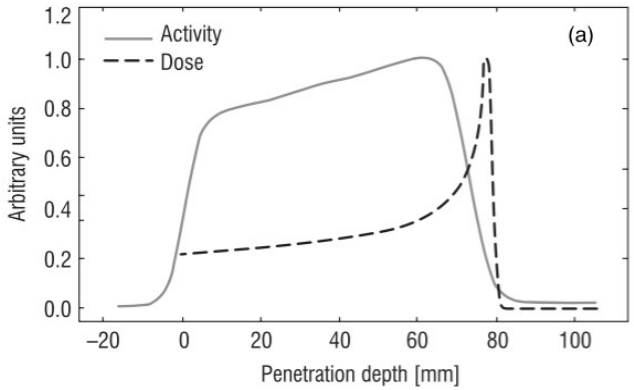


Isotope	$t_{1/2}$
^{10}C	19.3 s
^{11}C	20.28 min
^{14}O	70.59 ms
^{15}O	2.03 min
^{12}N	11.0 ms
^{13}N	9.96 min
^{8}B	770 ms
^{38}K	7.63 min
^{30}P	2.49 min
^{39}Ca	859 ms

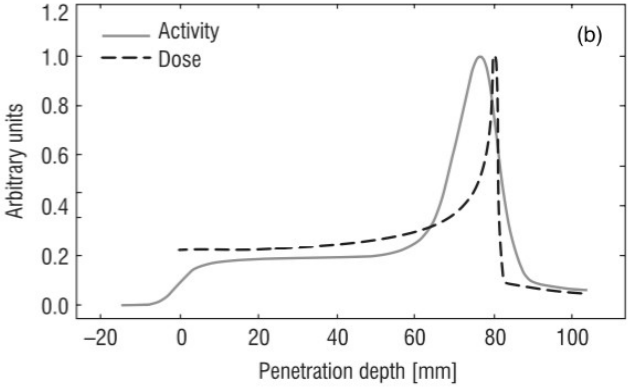
The INSIDE project

Short decay time: **online measurement** to minimize loss of signal and distribution washout (in-beam PET)

PROTONS



CARBON IONS



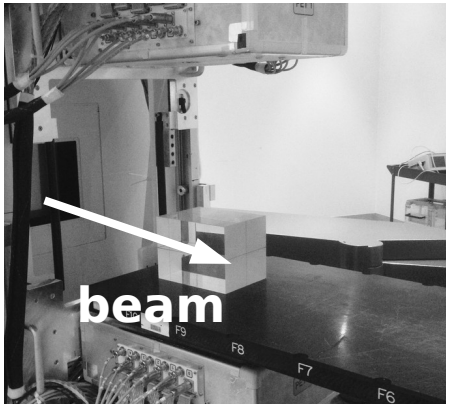
Enghardt W. et al. Radiother Oncol. 2014, 73.2:S96–98

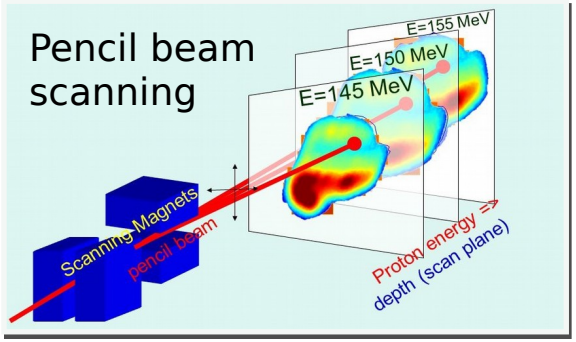
We measure the activity, not the dose (indirect comparison) → **need of an activity simulation**

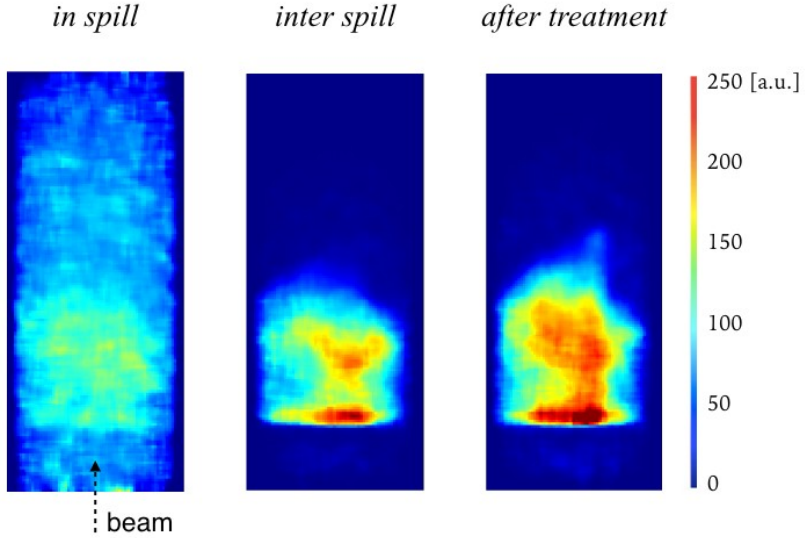
PET distribution: basic concepts

eg. treatment plan delivered on a PMMA phantom

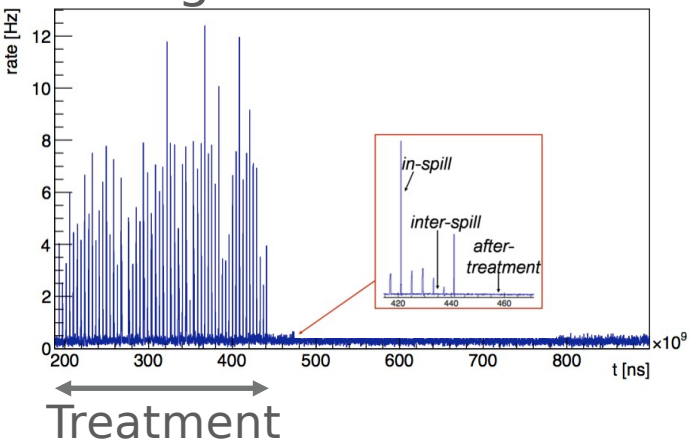
E=83-150 MeV, protons





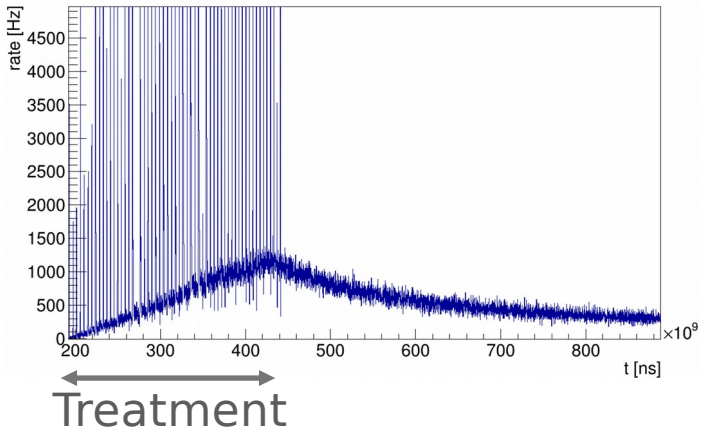


Single event rate



Treatment

Coincidence event rate



Treatment

Phantoms studies published in: V. Ferrero JINST 12(3), 2017; V. Ferrero et al, TRPMS 2(6), 2018; F. Pennazio et al., PMB 63, 2018.

The INSIDE PET simulation

Scanner geometry

Target model

Beam line characteristics

Treatment plan information

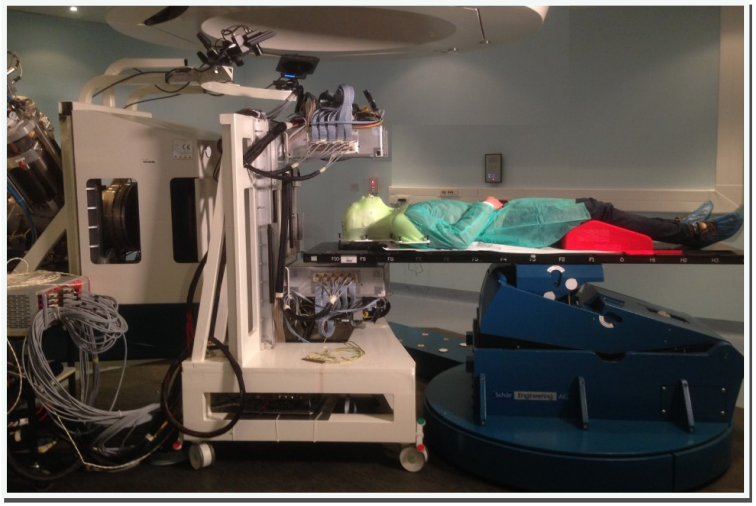
β^+ isotopes characteristics

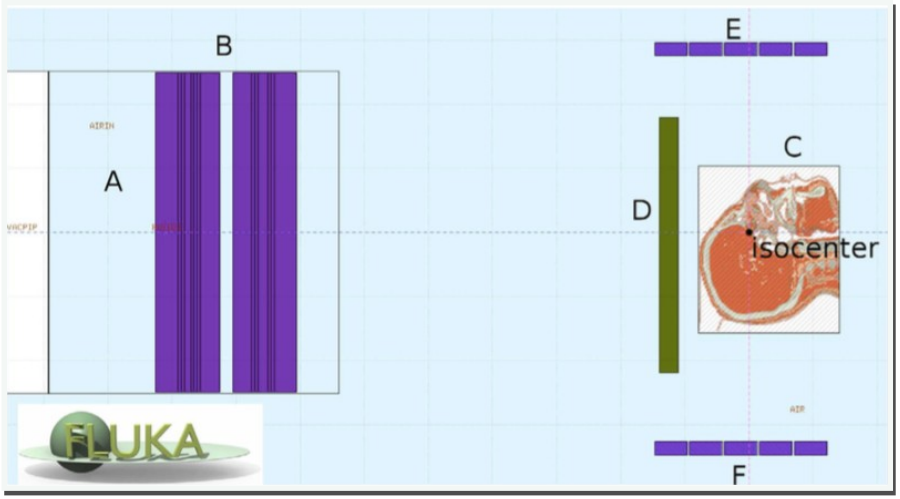
Two-step simulation

STEP 1 beam simulation	*Time-tagged activity scoring*	*STEP 2 PET simulation*	*Image reconstruction*
A fraction of primary hadrons is simulated (e.g. 1/100)	Isotope production map	All positrons are simulated (x100)	Same analysis chain as real data

The temporal and spatial structure of the beam are simulated

Isotopes decay is simulated





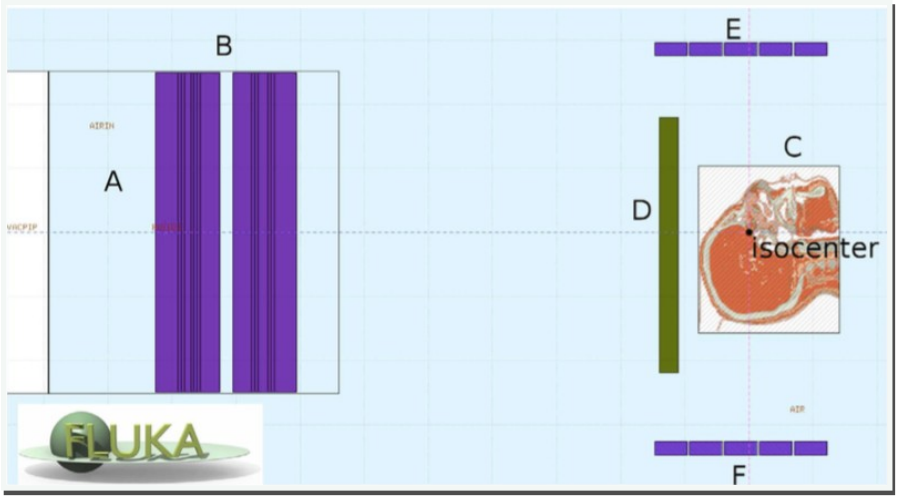
Pennazio et al. Acta Phys Pol A 127.5, 2015; E.Fiorina, V. Ferrero, et al. Phys Med 51, 2018.

The INSIDE PET simulation: step1

CNAO/INSIDE user ROUTINES (MGDRAW, SOURCE)

- Description of the **CNAO beam line** (particle, beam size)
- Description of the **treatment** (number of slices, energy, total particles/treatment, particle/spot, spot coordinates, delivery time)

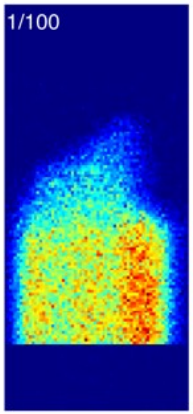
The treatment information are directly passed through the user ROUTINES



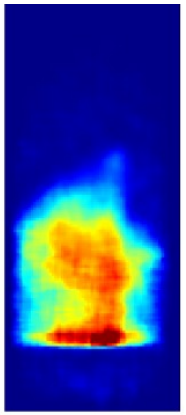
1/100 wrt total primaries is simulated for computational time issues (→ simuation is biased)

OUTPUT: fragmentation processes that result in the production of β+ isotopes are scored in the target (spatial and time coord)
Other process (neutron, prompt photons, charged fragments) are not taken into account

MC truth (step1 sim)



Exp data

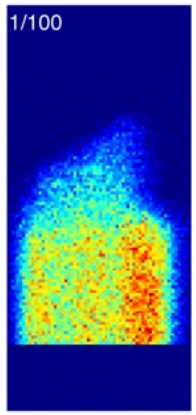


The INSIDE PET simulation: step2

CNAO/INSIDE user ROUTINES (MGDRAW, SOURCE, USRINI)

- **Step1 output** (i.e., isotope map distribution) as generator
- **All initial statistics** is accounted for (step1 output is read 100 times if 1/100 statistics was run in step1)
- Extraction of **decay events** over characteristics isotopes curve
- Simulation of **annihilation events** and scoring of 511 keV photons on the detector elements

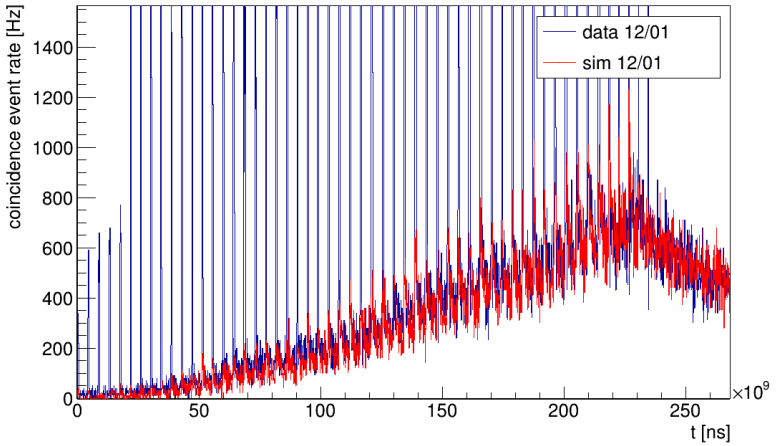
MC truth (step1 sim)



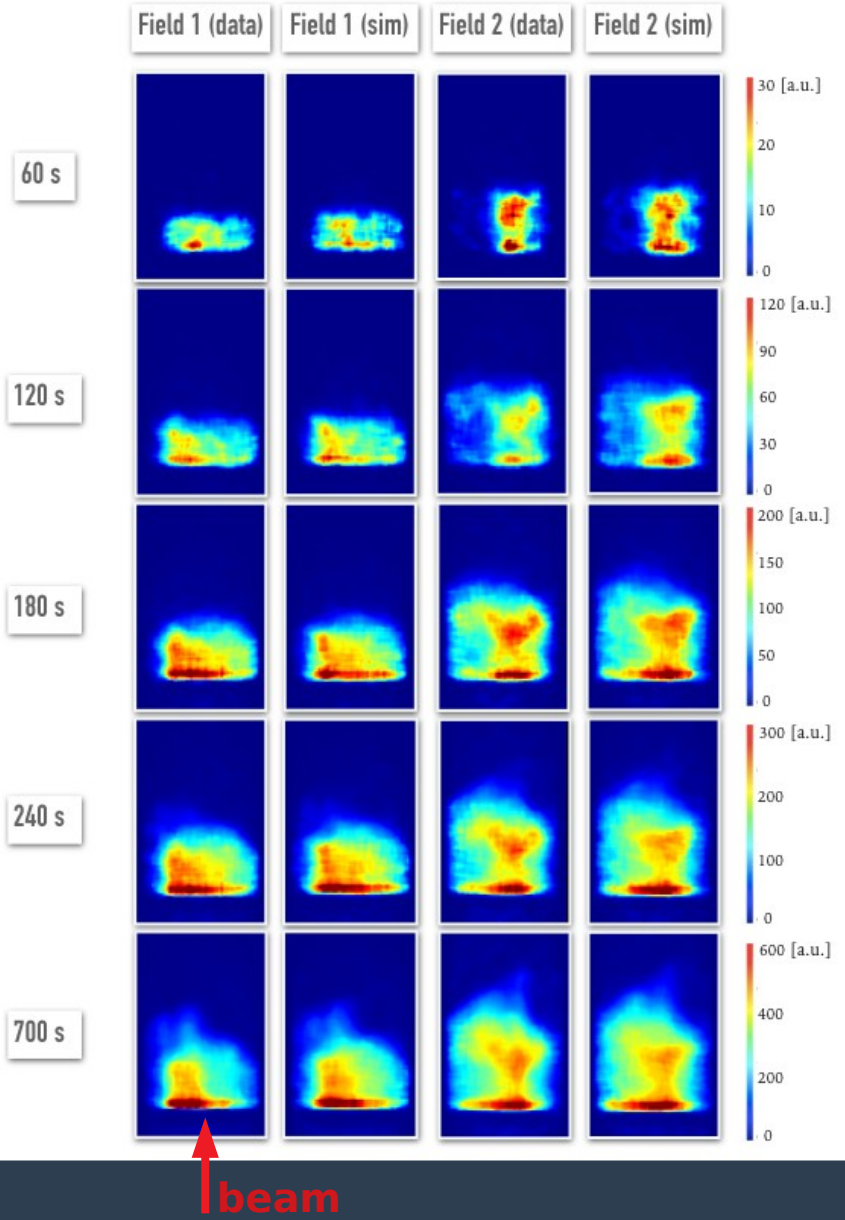
OUTPUT: file with single detected events

Simulated data is post-processed considering the detector experimental performances and a coincidence data filtering algorithm is applied

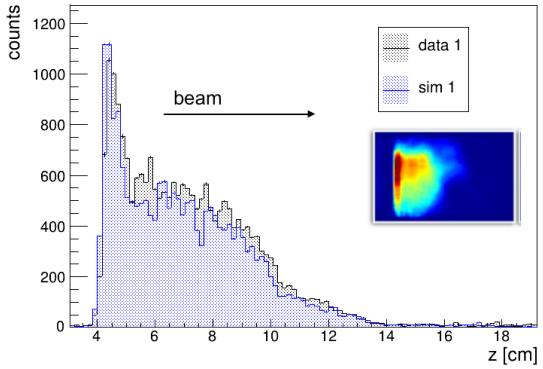
Coincidence event rate



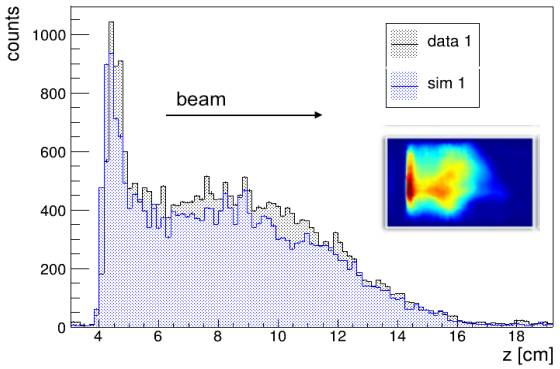
PET activity simulation



Field 1



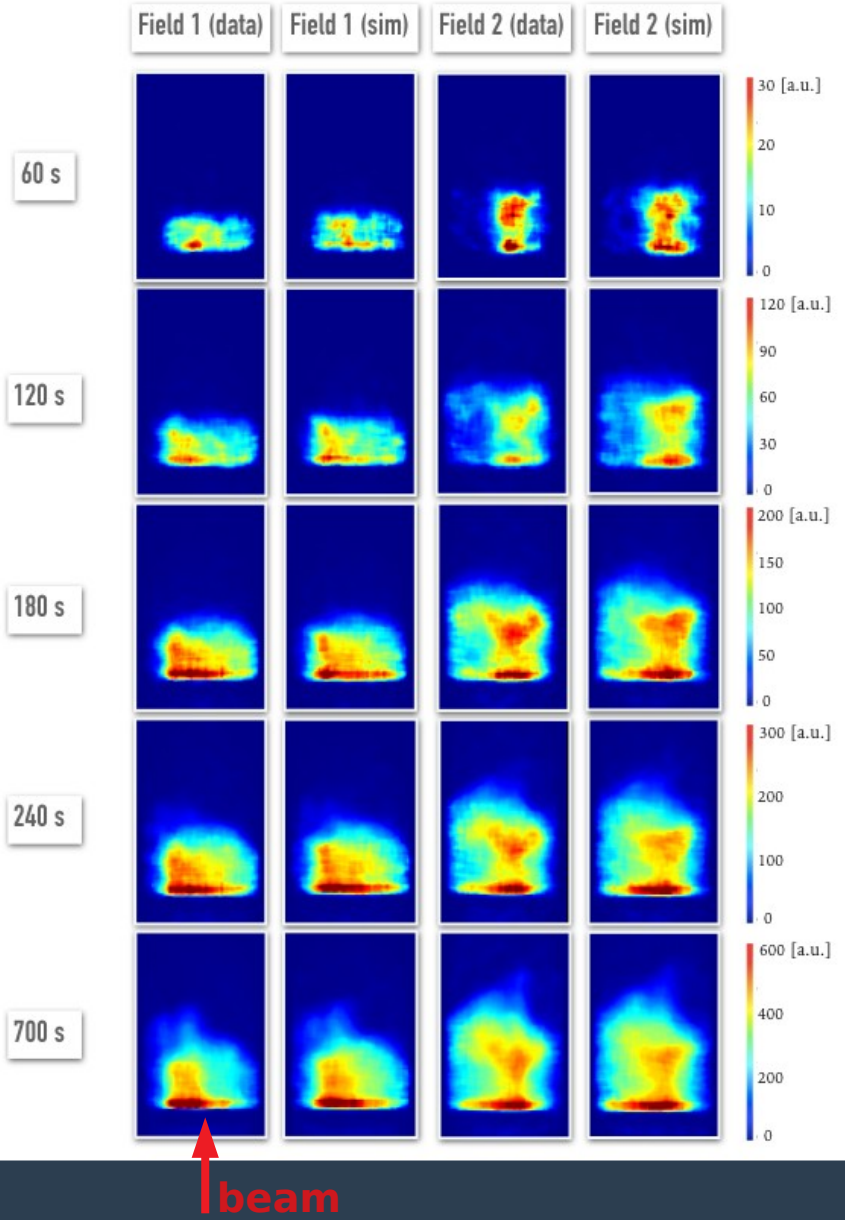
Field 2



	Field 1			
	data 1	sim 1	data 2	sim 2
Rising edge (mm)	44.5 ± 0.8	43.9 ± 0.6	44.5 ± 0.9	43.9 ± 0.6
Falling edge (mm)	97.2 ± 0.9	96.6 ± 0.9	97.7 ± 0.9	96.8 ± 0.9
Range (mm)	52.7 ± 1.2	52.7 ± 1.1	53.2 ± 1.3	52.9 ± 1.1

	Field 2			
	data 1	sim 1	data 2	sim 2
Rising edge (mm)	44.5 ± 0.9	43.9 ± 0.6	44.4 ± 0.9	43.9 ± 0.6
Falling edge (mm)	128.8 ± 0.8	123.4 ± 0.9	123.3 ± 0.9	123.9 ± 0.9
Range (mm)	79.3 ± 1.2	79.5 ± 1.1	78.9 ± 1.3	80.0 ± 1.1

PET activity simulation



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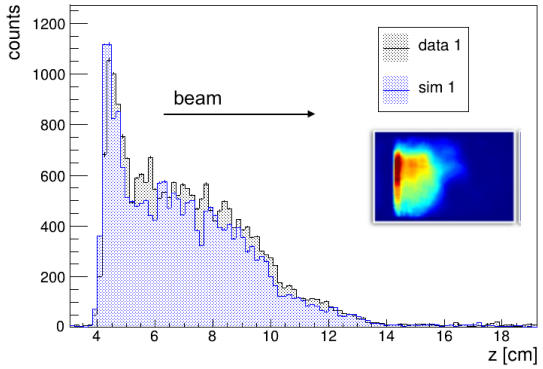
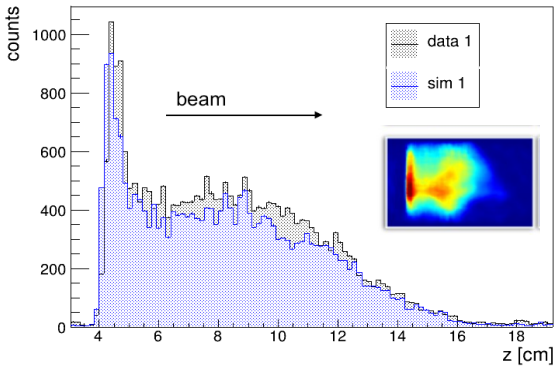


Field 2



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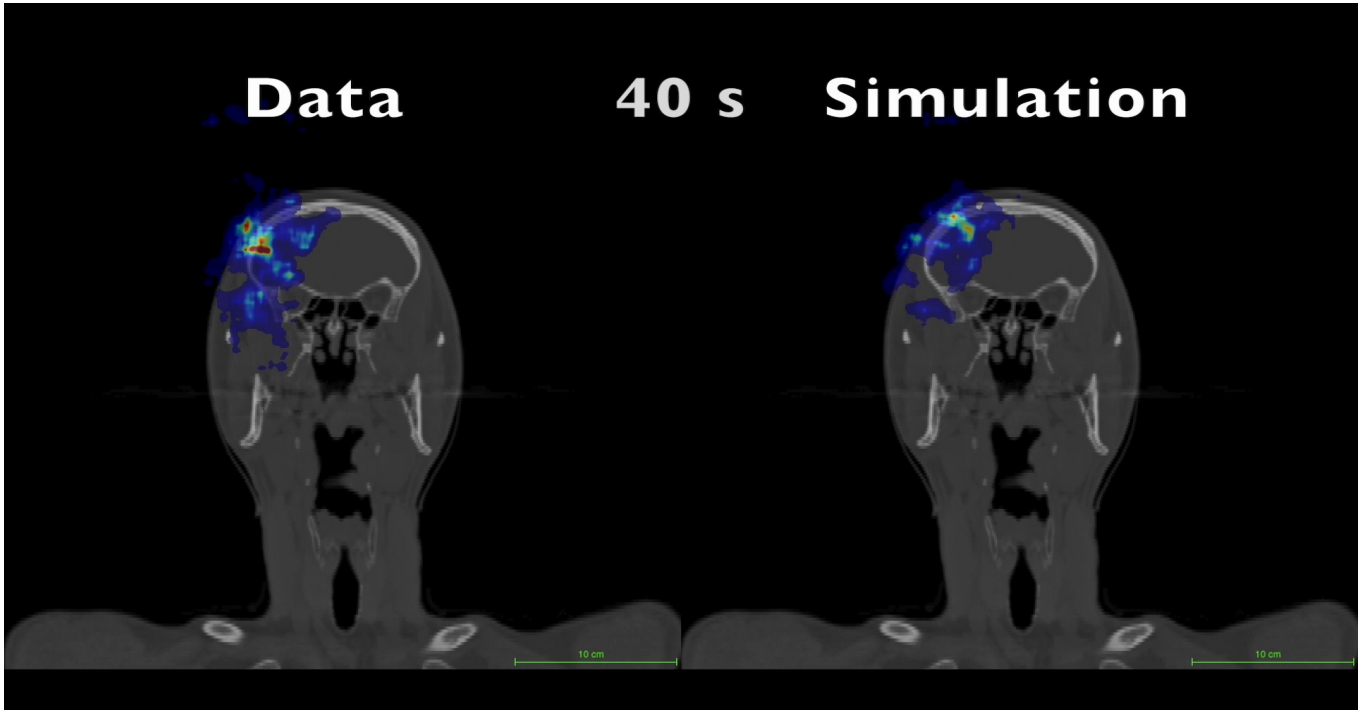
Range (mm)	52.7 ± 1.2	52.7 ± 1.1	53.2 ± 1.3	52.9 ± 1.1

Agreement:

- within **0.5 mm** between **experimental measurements**
- within **1 mm** between **experimental and simulated data**

The first in-vivo monitoring

The first in-vivo acquisition on Dec. 2015 showed the feasibility of using the INSIDE in-beam PET for range verification



Carcinoma of the lacrimal gland
$3.7\ 10^{10}$ protons
[66.3, 144.4] MeV/u
30 fractions, 2.2 GyE
Treatment time: 240 s

In-beam PET: no washout model is included

Results published in: V. Ferrero et al., Sci Rep 8.1, 2018; E.Fiorina, V. Ferrero, et al. Phys Med 51, 2018.

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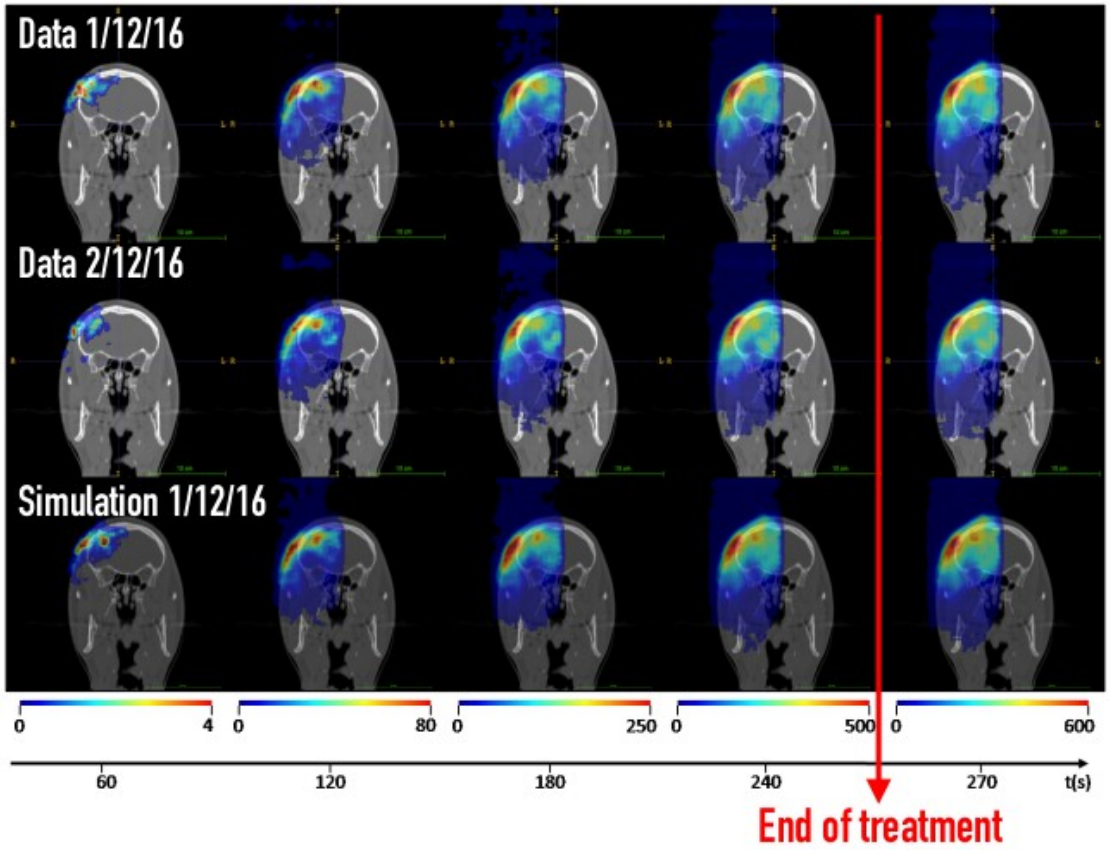

Carcinoma of the lacrimal gland
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Treatment time: 240 s

Agreement within **3 mm** before the treatment end, **FWHM ≤ 17.6 mm (data vs sim), 12.8 mm (data vs data)**

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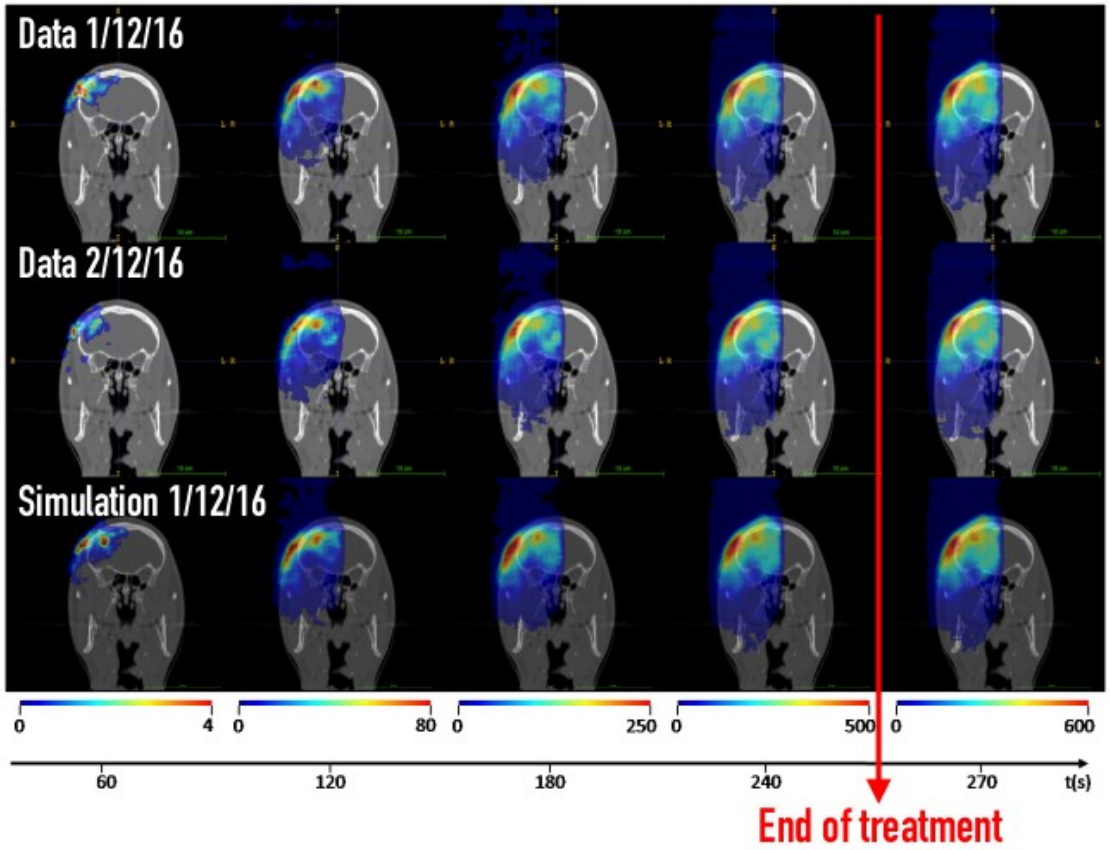

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How significant are these values?

Results published in: V. Ferrero et al., Sci Rep 8.1, 2018; E.Fiorina, V. Ferrero, et al. Phys Med 51, 2018.

The INSIDE clinical trial

Currently installed @ CNAO, Italy

The INSIDE clinical trial

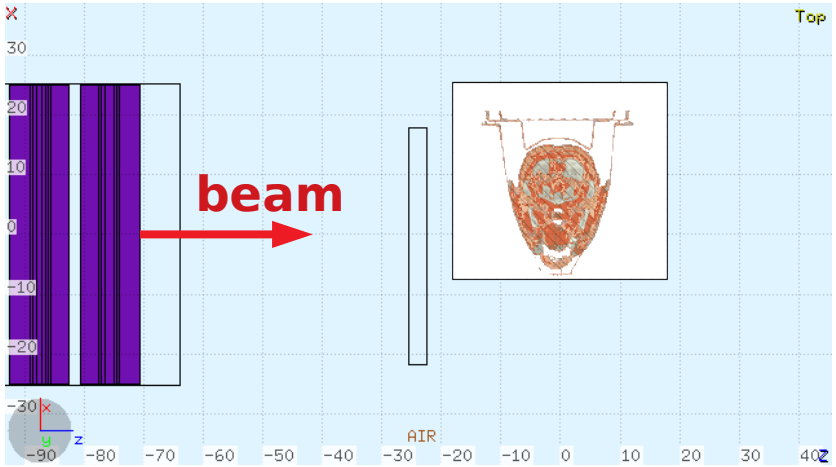
- Cohort of 20+20 patients
- Proton and carbon ion beams
- Different pathologies
- Study and optimize the INSIDE performances
- Find the clinically relevant tolerances
- Evaluate the benefits of the INSIDE system wrt the clinical routine

The INSIDE clinical trial started on Jul 19. Patients treated with both proton and carbon ion beams are being monitored

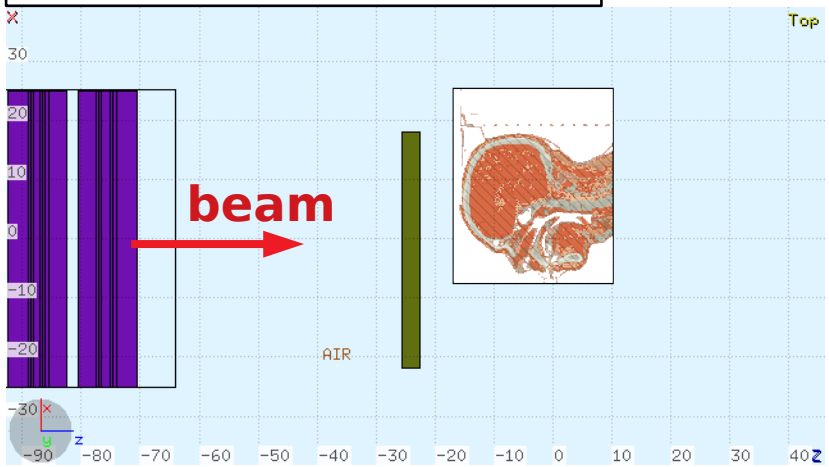
ClinicalTrials.gov ID: NCT03662373

The INSIDE clinical trial

Field 1: 0° IEC, no RS



Field 2: 270° IEC, RS

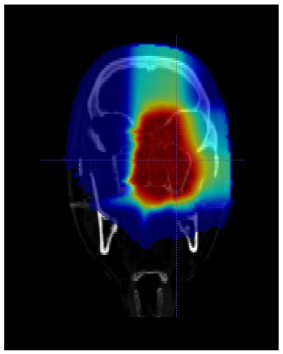


Squamocellular rhinopharynx carcinoma

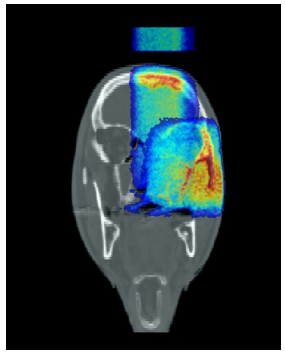
Patient treated with 2 fields (0° and 270° IEC)

27 sessions, D_{tot}=54 Gy

Planned dose



MC truth



The INSIDE clinical trial

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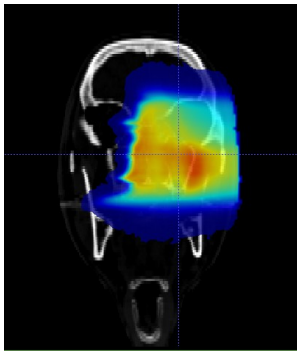
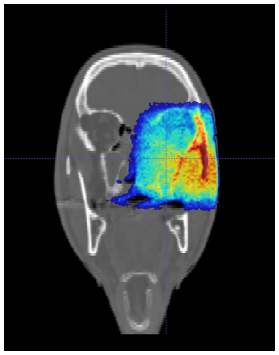
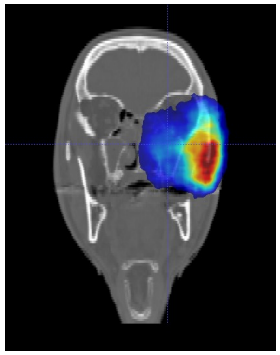


MC truth



step1

MC, reconstructed



step2

Squamocellular rhinopharynx carcinoma

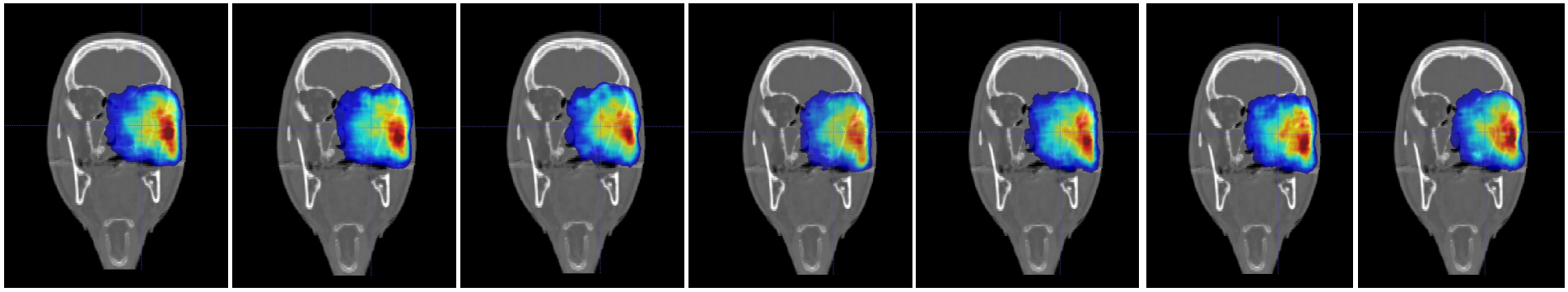
Patient treated with 2 fields (0° and 270° IEC)

27 sessions, D_{tot}=54 Gy

Field 1: 0° IEC, no RS

Exp data

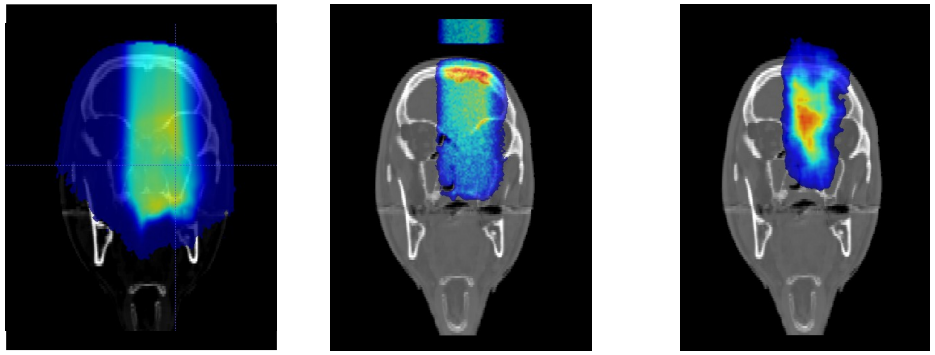
frac 16 *frac 17* *frac 22* *frac 23* *frac 24* *frac 25* *frac 27*



ClinicalTrials.gov ID: NCT03662373

The INSIDE clinical trial

Planned dose *MC truth* *MC, reconstructed*



step1 step2

Squamocellular rhinopharynx carcinoma

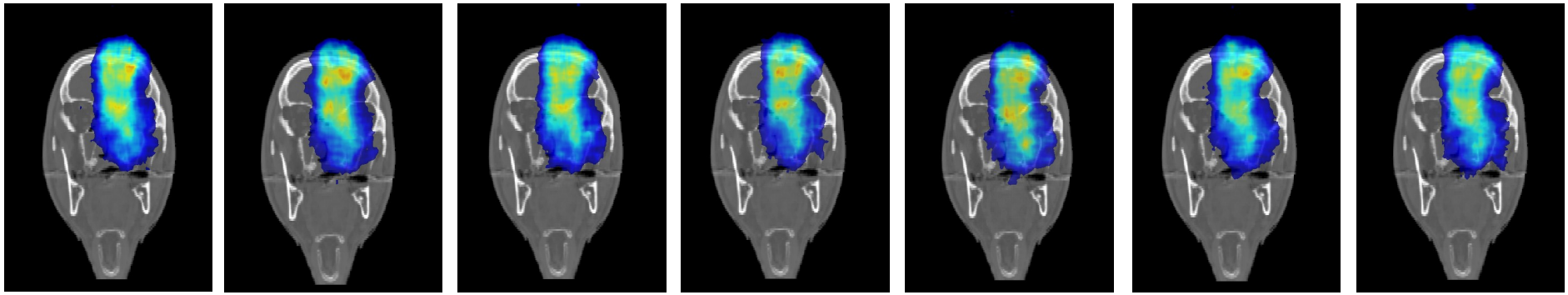
Patient treated with 2 fields (0° and 270° IEC)

27 sessions, D_{tot}=54 Gy

Field 2: 270° IEC, RS

frac 16 *frac 17* *frac 22* *frac 23* *frac 24* *frac 25* *frac 27*

Exp data



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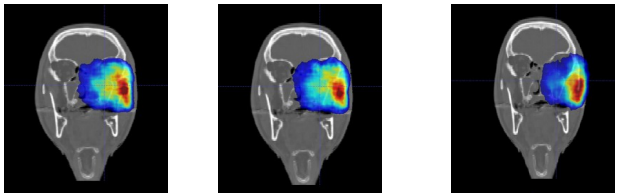
The INSIDE clinical trial

Field 1: 0° IEC, no RS

Image comparison	Range difference	Range difference FWHM	Pearson correlation coefficient
frac 16 vs 17	-0.68 mm	8.0 mm	0.96
frac 16 vs 22	0.83 mm	8.0 mm	0.95
frac 16 vs 23	-2 mm	9.6 mm	0.96
frac 16 vs 24	0.05 mm	11.2 mm	0.96
frac 16 vs 25	-0.62 mm	8.0 mm	0.95
frac 16 vs 27	-0.75 mm	8.0 mm	0.95

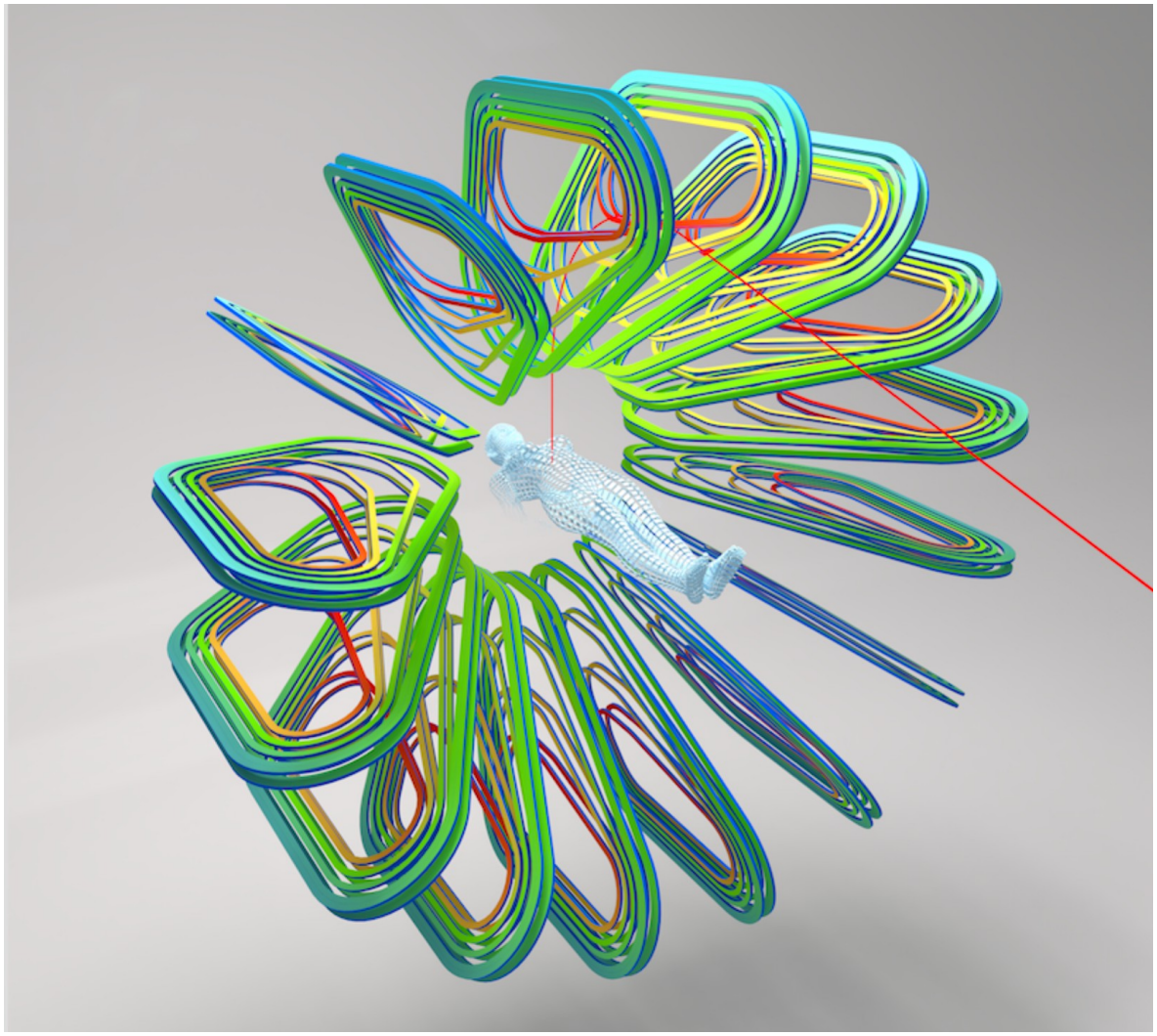
Image comparison	Range difference	Range difference FWHM	Pearson correlation coefficient
sim vs 16	-0.94 mm	6.4 mm	0.83
sim vs 17	-0.88 mm	8.0 mm	0.83
sim vs 22	-1.45 mm	9.6 mm	0.77
sim vs 23	-0.99 mm	6.4 mm	0.79
sim vs 24	-0.92 mm	9.6 mm	0.80
sim vs 25	-1.26 mm	4.8 mm	0.82
sim vs 27	-1.49 mm	11.2 mm	0.82

frac 16 *frac 17* *sim*



Analysis described in: V. Ferrero et al. TRMPS 2(6), 2018; E.Fiorina, V. Ferrero, et al. Phys Med 51, 2018.

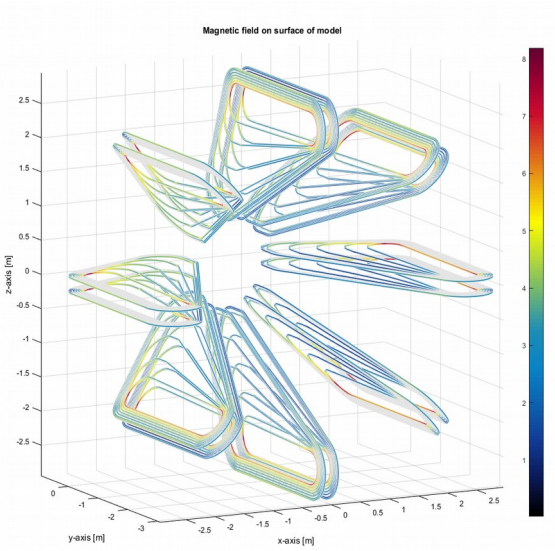
GaToroid: an idea for an integrated design



A Gantry and Apparatus for Focusing Beams of Charged Particles.
L. Bottura, European Patent Application EP 18173426.0, May 2018

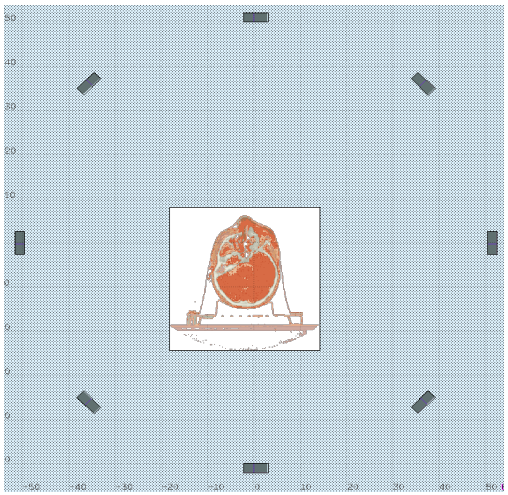
Static gantry: beam delivery at discrete angles without magnet rotation → steady-state configuration, superconducting magnets → reduction of size, weight and costs

GaToroid: an idea for an integrated design



Test geometry:

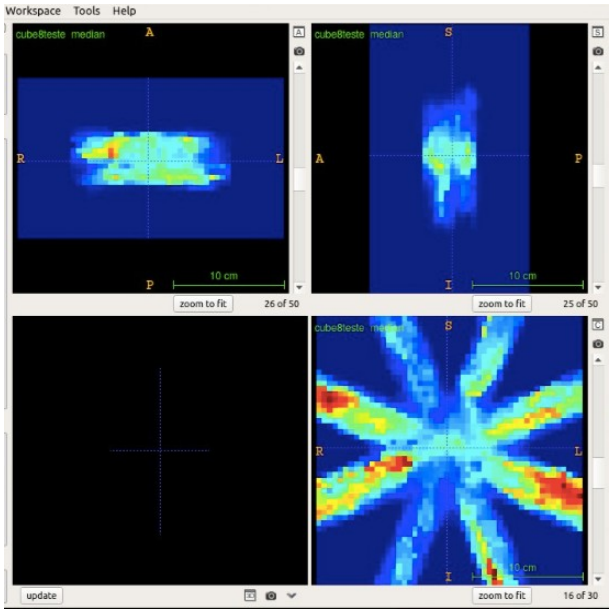
- 8 coils
- 100 cm bore



Test geometry:

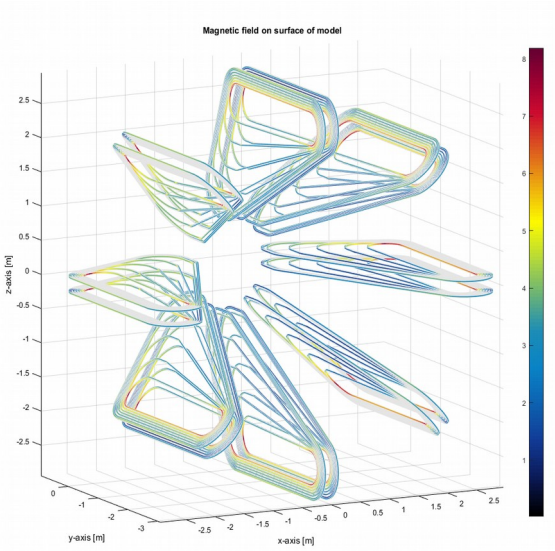
- 8 PET detector blocks
- 3 modules for each block (5x15 cm^2)
- 16x16 crystals (3.2 mm pitch) for each module

FLUKA simulation:
4.8x4.8x4.8 cm^3 activity cube



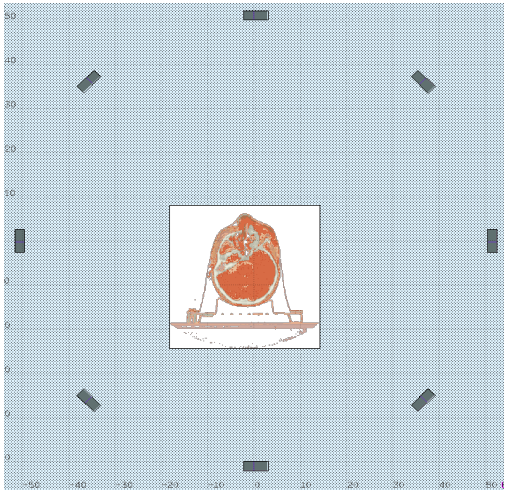
→ strong image artefacts!

GaToroid: an idea for an integrated design



Test geometry:

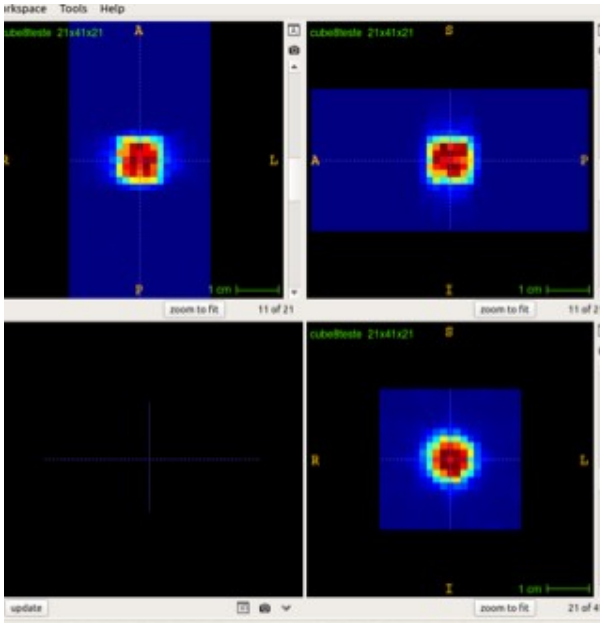
- 8 coils
- 100 cm bore



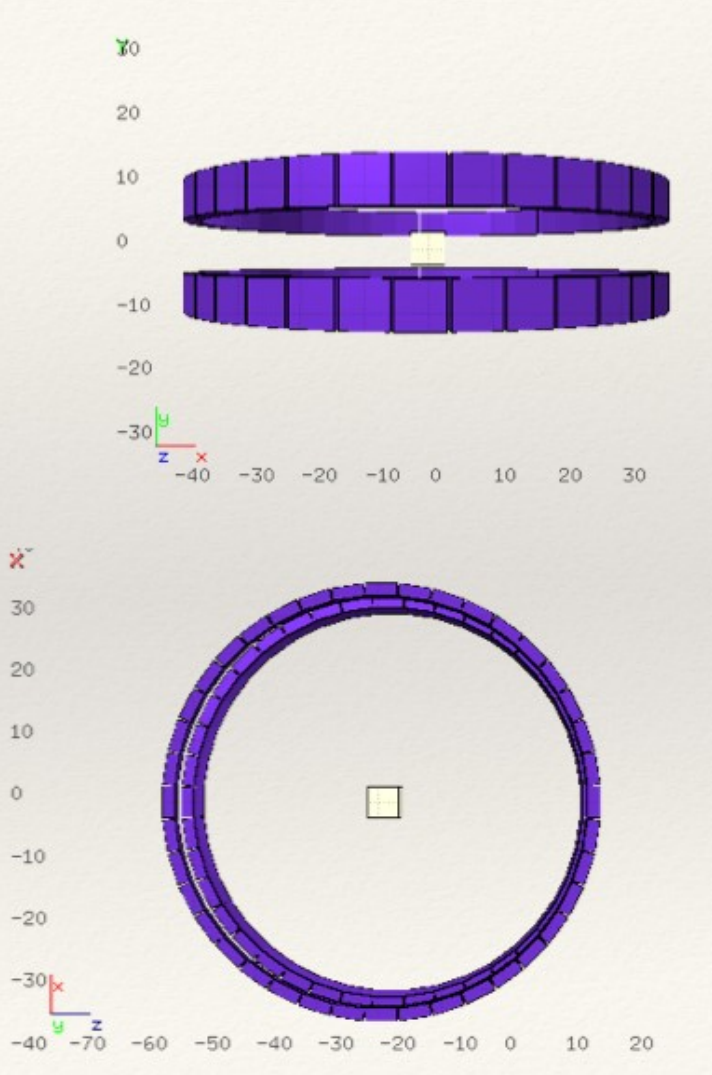
Test geometry:

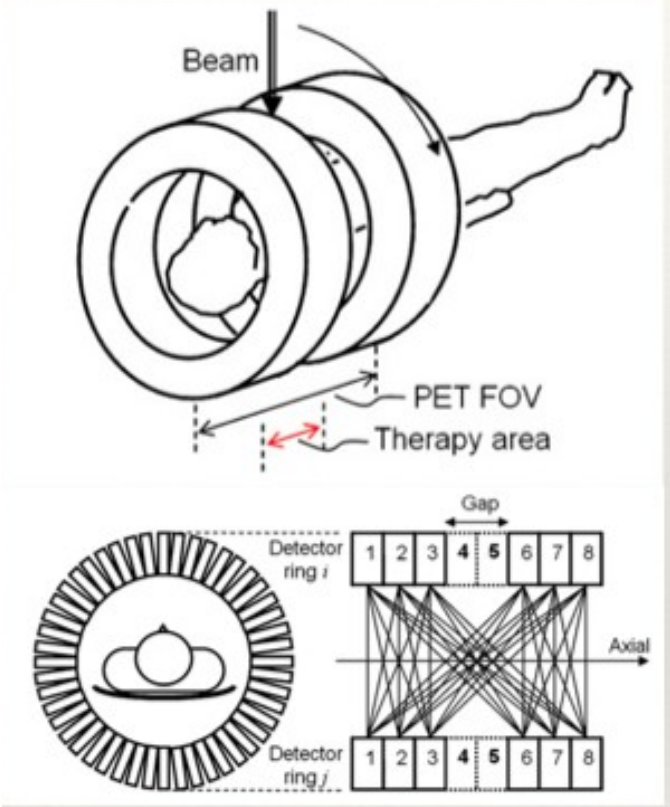
- 8 PET detector blocks
- 3 modules for each block (5x15 cm^2)
- 16x16 crystals (3.2 mm pitch) for each module

FLUKA simulation:
1 cm^3 activity cube



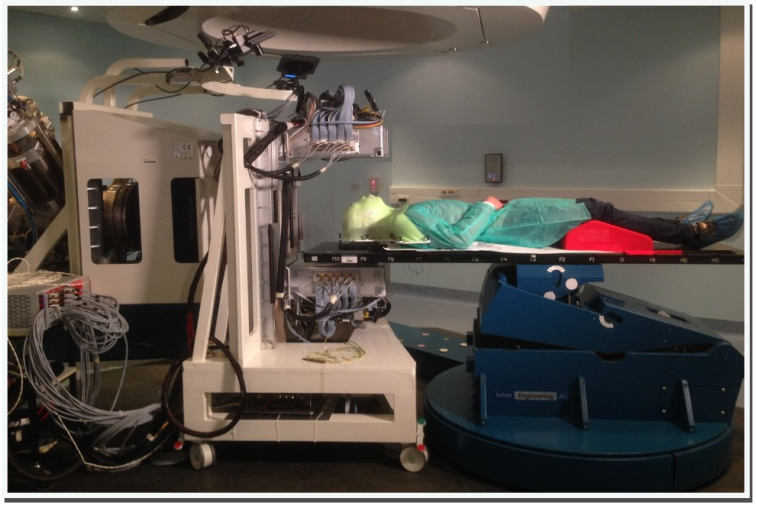
GaToroid: an idea for an integrated design



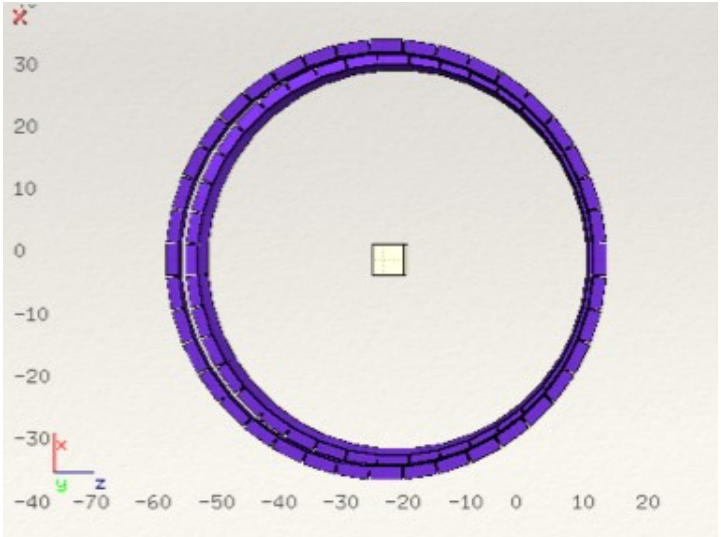


Repetition of the same detector block: LATTICE, ROT-DEFI

Conclusions



The INSIDE clinical trial: understand detector limits, sensitivity, impact on physicians
...with the aid of FLUKA



GaToroid: study and optimization for an integrated gantry geometry
...with the aid of FLUKA