BUNker SHIelding Monte Carlo Simulation of the HUMV Protontherapy Facility (BUNSHI)

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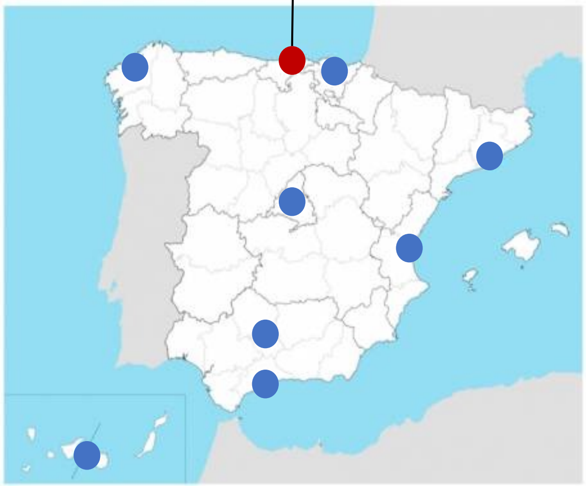
OUTLINE

- The HUMV Proton Therapy Project
- Motivation: Why to simulate the ambient dose and activation in a PT facility?
- The BUNSHI software package.
- Outcome: Annual ambient dose at the PT facility at the HUMV
- Future & Conclusion.

The HUMV Proton Therapy Project

Hospital universitario Marqués de Valdecilla (HUMV) in Santander



Technical challenges for FLASH proton therapy, Simon Jolly, Hywel Owen, Marco Schippers, Carsten Welsch,, Physica Medica, https://doi.org/10.1016/j.ejmp.2020.08.005.

Accelerator Type	Isochronous Cyclotron		Synchrocyclotron		Synchrotron	Linear Accelerator
Vendor	IBA	Varian	IBA	Mevion	Hitachi	AVO
System	C230	PROBEAM	S2C2	S250	ProBeam	LIGHT
Maximum Energy (MeV)	230	250	250	250	250	250
Minimum Energy (MeV)	70	70	70	70	70	37.5
Peak Current(μA)	0.3	0.8	~ 18	~ 7	4.8×10^{-3}	~ 40
Max Ave. Current (nA)	300	800	~ 130	~ 32	4.8	32
Accel. Frequency (MHz)	106.1	72.8	87.6–63.2	133–90	1.3–10	3,000
Repetition rate	CW	CW	1 kHz	500–750 Hz	CW	200 Hz
Treatment Pulse Length	>400 μs	>400 μs	7 μs	6 μs	0.5–5 s	4 μs
Bunch Length	~ 2 ns	~ 2 ns	~ 2 ns	~ 2 ns	~ 25–200 ns	~ 0.5 ns
Max Part. per Bunch/Pulse	100,000	70,000	8×10^8	4×10^8	1.5×10^{11}	10^{10}
Electric/Central Field	1.7 T	2.4 T	5.75 T	9 T	1.7 T	25 MV/m
References	[18,19]	[20,21]	[22]	[23–25]	[26–28]	[29,30]

FAO + Quirón

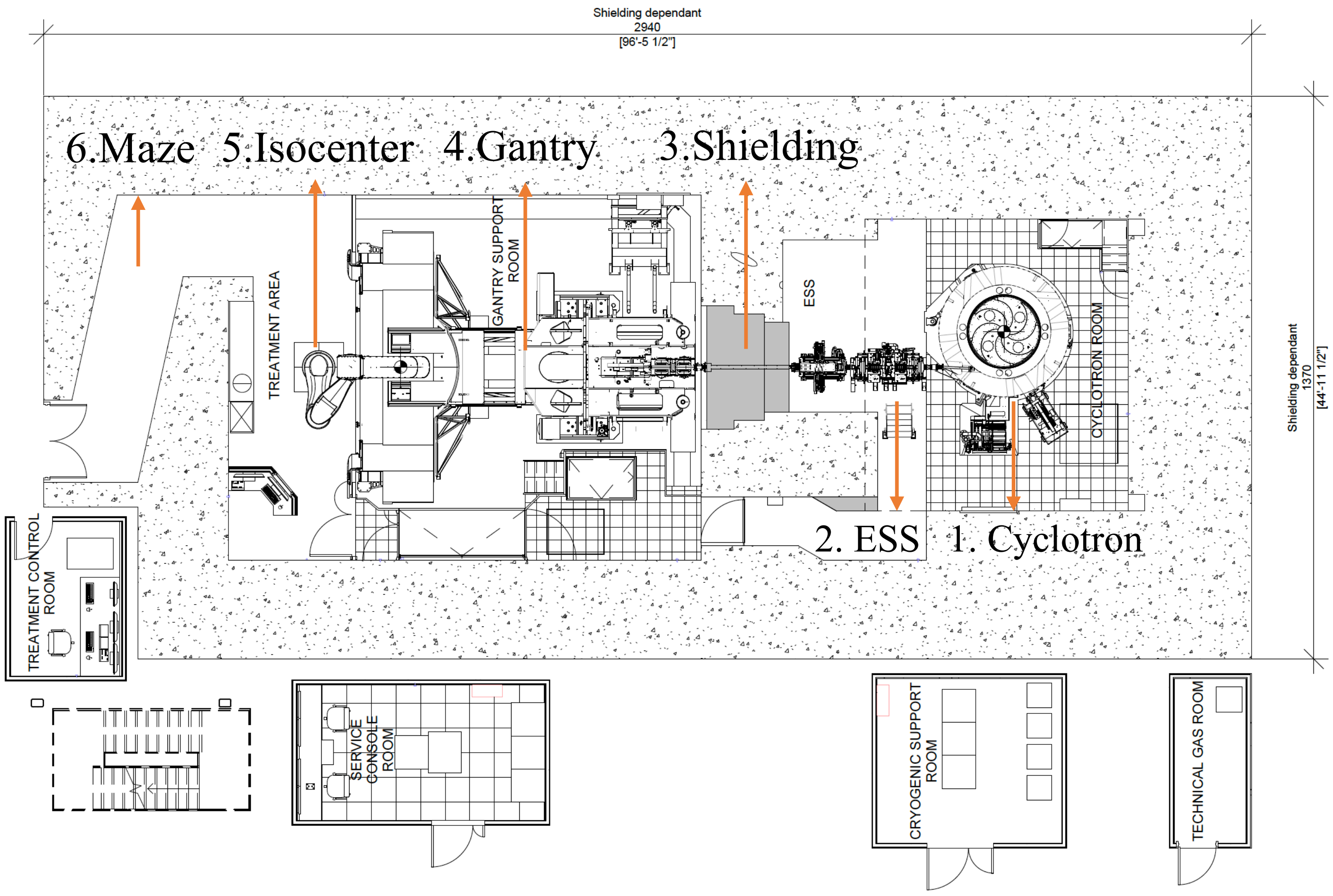
HUMV (Santander)

Clínica Navarra

- 10 IBA cyclotron machines in the public health care system in Spain + 1 at Quiron +1 Synchrotron machine at CN.
- Spain will become the country with more PT facilities *per capita*.
- Santander Machine is funded by the **Recovery assistance for cohesion and the territories of Europe (REACT-EU)**

VARIAN PRO BEAM 360

- Main accelerator elements:
  1. 250MeV Cyclotron.
  2. Energy Selection System (ESS): Degrader + Bending Magnets + Collimator Slit.
  3. Shielding: required to prevent secondary particles generated at the degrader from reaching the isocenter (patient).
  4. Gantry: 360^0 Rotation Gantry.
  5. Isocenter, i.e pacient/pahantom
  6. Exit Maze.
- First patient expected in mid 2025
- **Weekends dedicated to Research Activities**

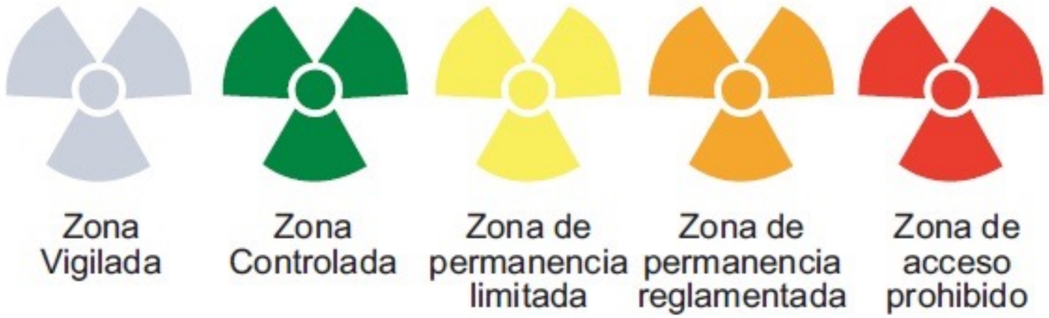


Why To Simulate a Bunker Shielding?

- **“Science” case:** The Spanish Nuclear Safety Council (CSN) demands to the preparation of a Radiation Protection (RP) report by an independent entity for the commissioning of the BEAMPRO250 cyclotron machine at Valdecilla Hospital.

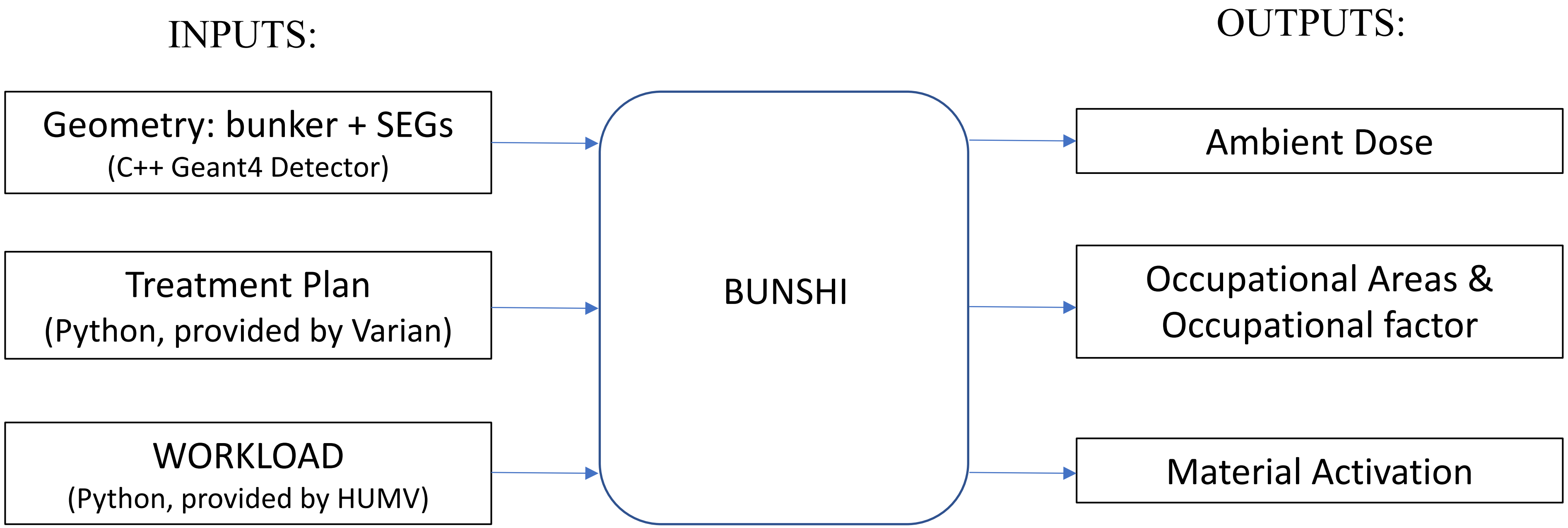
- The HUMV has signed a legal agreement with IFCA to develop a simulation tool to deliver:
  a) **Annual ambient dose $H^*(10)$ in the entire facility [bunker + adjacent rooms + surrounding soil].**
  b) **Identification of the occupational areas.**
  c) **Bunker activation for the entire life cycle [~30 years + dismantling].**
  d) **Potential civil engineering implications: wall thickness optimization, water pipe location (already pre-calculated by VARIAN).**

- Legal framework: 21/12/2022 BOE 21682.



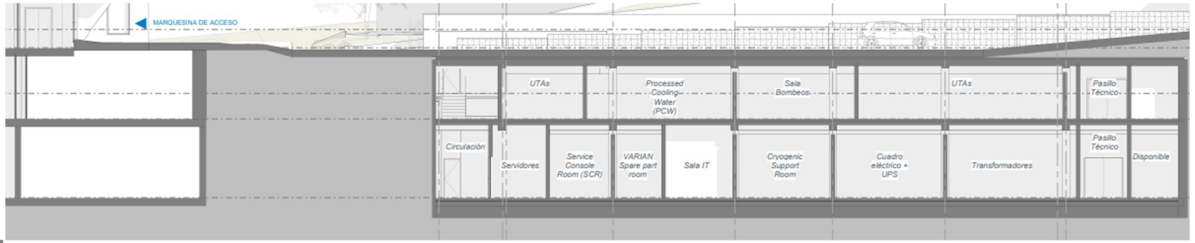
BUNker SHIelding Monte Carlo Package (BUNSHI)

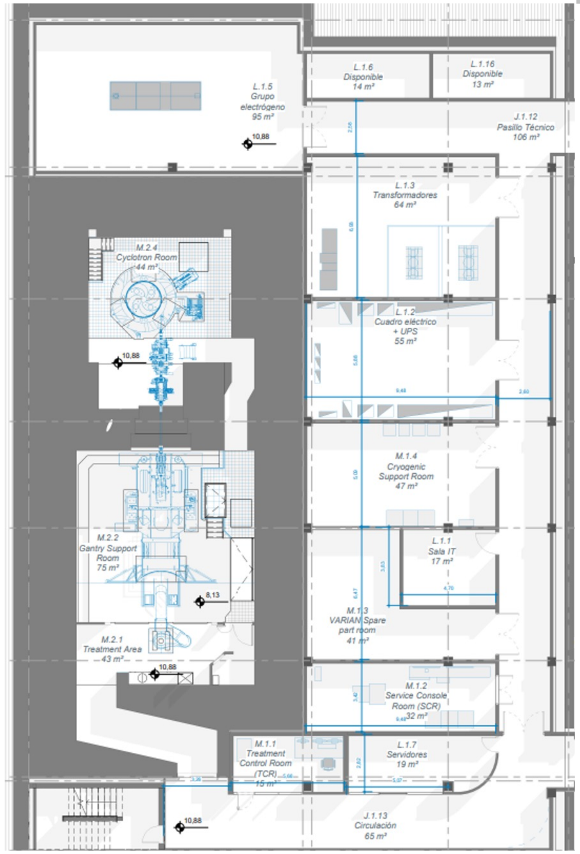
- State of the art for similar problems: FLUKA, NCPCM (CSN), Geant4 & others
- Selection of choice due to IFCA long-time expertise: **Geant4**
- Decoupled approach that works foe different facility geometries:

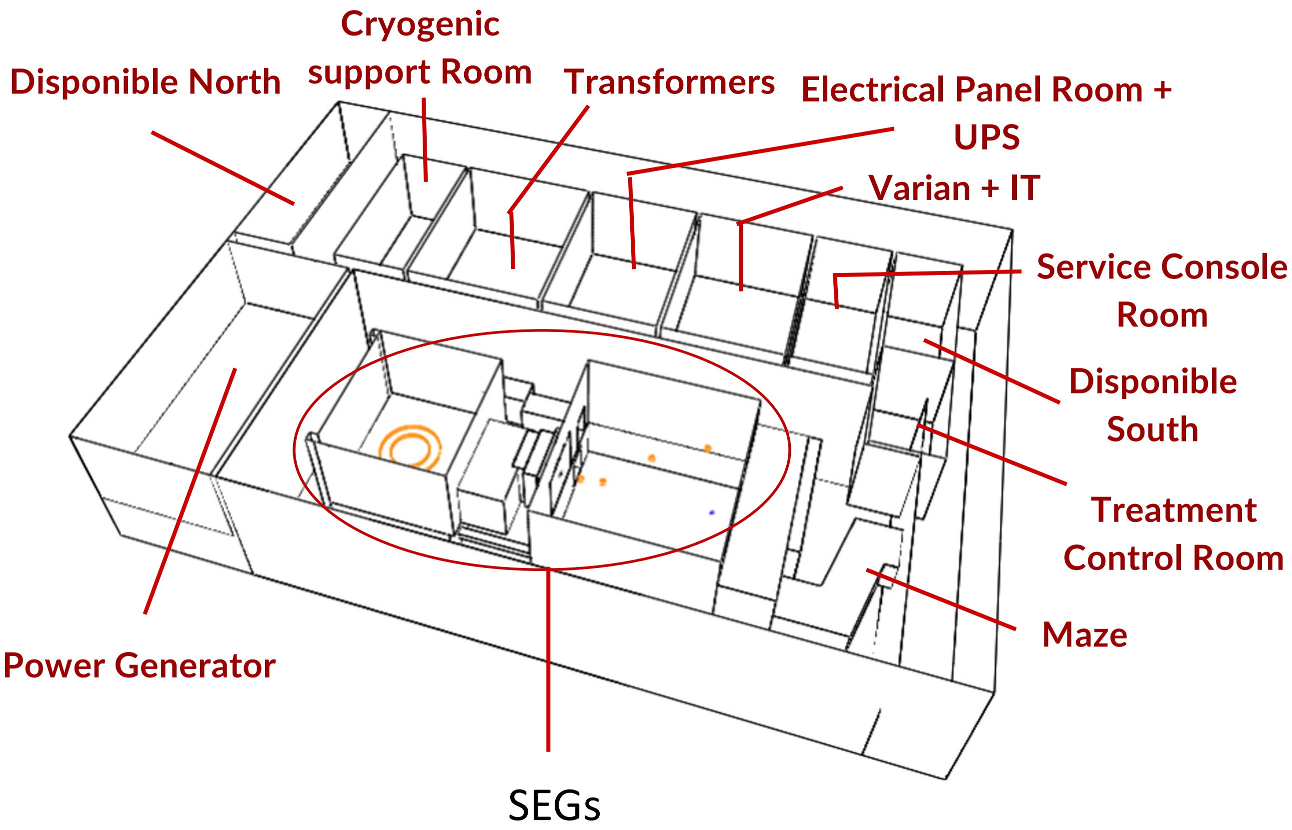


Geometry: bunker + SEGs
(C++ Geant4 Detector)

BUNSHI Geometry



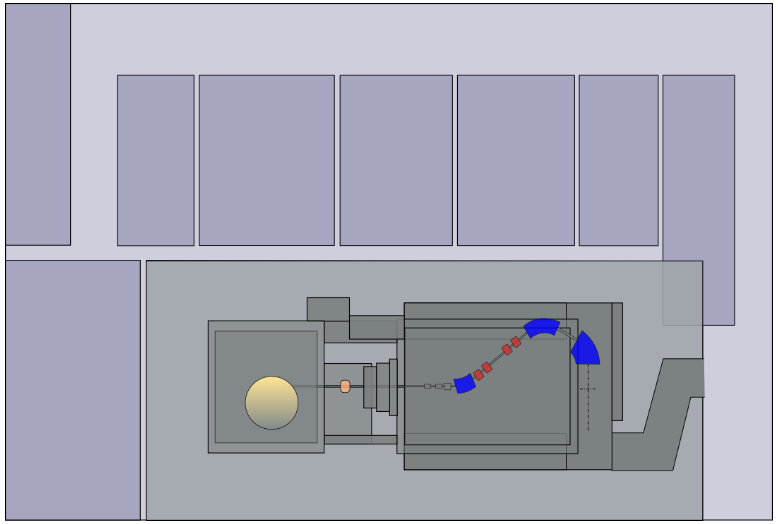




Geometry: bunker + SEGs
(C++ Geant4 Detector)

BUNSHI Geant4 Simulation

- **Secondary Element Generator (SEG):** Each of the 8 relevant accelerator elements is simulated as a material block.
- ***η***(*E*, θ, SEG) is the volumetric map of observables generated by the secondary particles in the geometry volume per incident proton for a SEG given a beam energy ***E*** and gantry angle θ (only if the SEG is in the gantry).
- It is calculated by simulating a 10^8 protons proton stream inciding perpendicularly to each SEG and then normalising it per a single proton.
- Total number of cases: 40 different energies E_i X 4 angles (0^0, 90^0, 180^0 & 270^0) X 8 SEG =1280 sims with 10^8 protons.



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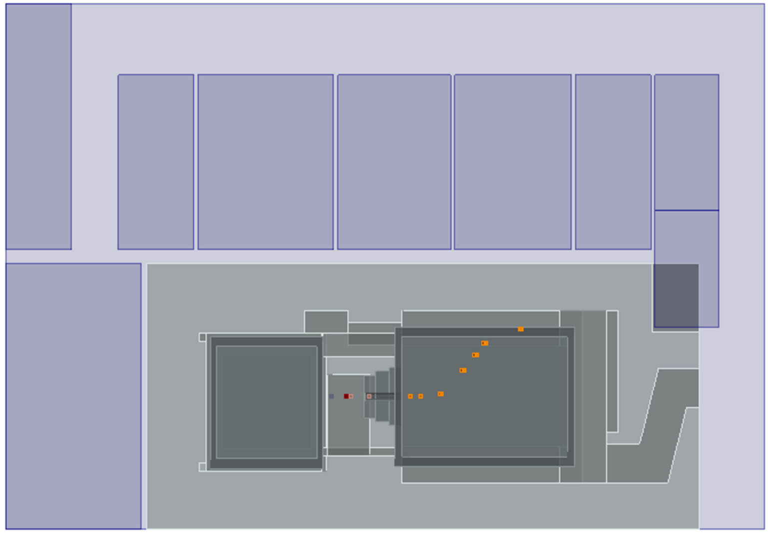


$$\eta(E_i, \text{cyclotron})$$
$$\eta(E_i, \text{degrader})$$
$$\eta(E_i, \text{collimator})$$
$$\ldots$$
$$\eta(E_i, \text{phantom})$$

Treatment Plan
(Python, provided by Varian)

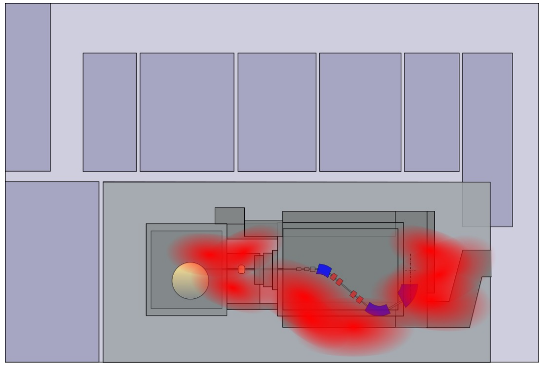
BUNSHI Dose Map Vector

- It considers the total dose deposited for an energy and gantry angle for a single proton at the isocentre.
- Example of a normalised Dose Map Vector H for an 80MeV proton beam with the gantry at 270^0:

$$H(80\mathrm{MeV}, 270^0) = 365 \times \eta(80\mathrm{MeV}, \mathrm{cyclotron}) + 219 \times \eta(80\mathrm{MeV}, \mathrm{degrader}) + \\ .. + 1 \times \eta(80\mathrm{MeV}, 270^0, \mathrm{phantom})$$

Clinical Energy — Degrader — Size Aperture — Cyclo Extracted → SEG list

E(MeV)	SEG-1	SEG-2	...	SEG-10
80	150.0	283.4		444.0
100	70.0	147.68		230.1
120	37.0	86.6		135.6
...	...	...		...
220	1.23	5.39		12.05

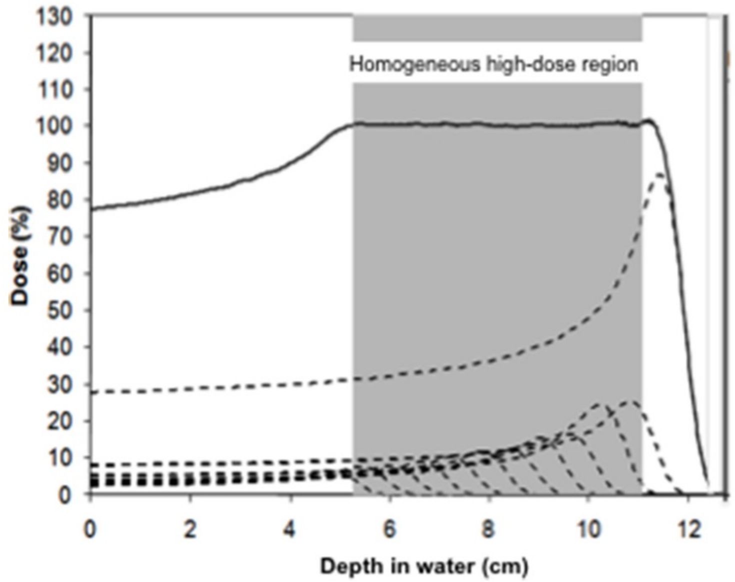


$$H(E_1, 270^0)$$

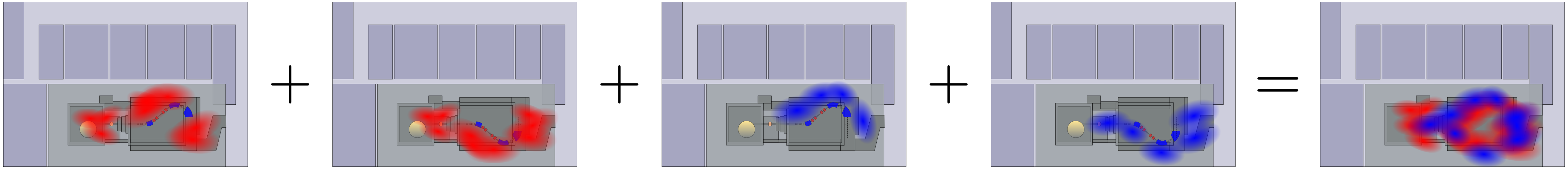
- Technical doc P00346 provided by VARIAN : It provides the particle losses at each SEG.
- Alternatively: it can be simulated with a beam transport software.

Treatment Plan
(Python, provided by Varian)

Dose Deposited per Treatment



- To simulate a treatment implies to recreate a SOBP from various angles.
- Therefore, the total dose of a cancer treatment can be expressed as a function of correctly weighted normalised dose map vectors.
- For instance, a treatment comprised by only 2 energies E_1 & E_2 and 2 angles 90^0 & 270^0:



$$\frac{w1}{2} \times H(E_1, 90^0) + \frac{w1}{2} \times H(E_1, 270^0) + \frac{w2}{2} \times H(E_2, 90^0) + \frac{w2}{2} \times H(E_2, 270^0) = \sum$$

WORKLOAD
(Python, provided by HUMV)

Total Annual Dose

- Create the **annual estimation,** by evaluating the annual estimation for each treatment and add them up:

$$H_{HUMV}^{year} = \sum_{t} H_t(year)$$

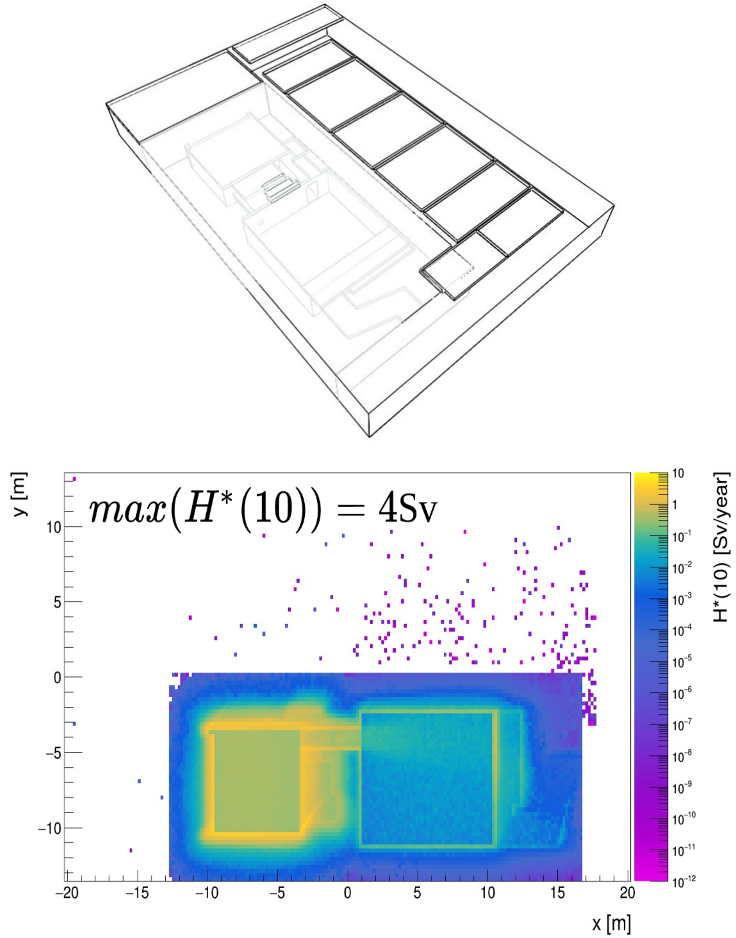
- *The ambient dose H*(10) (not background dose!) is particle and energy dependent. It is calculated using the factor tables to convert fluence to absorbed dose recommended by publications 116 & 144 of the ICRP-74 document.

Energy [MeV]	Protons incident on the patient
146,4	7,07E+11
142,4	2,42E+11
138,4	1,82E+11
134,7	1,34E+11
130,9	1,07E+11
127,2	8,89E+10
123,5	7,73E+10
119,9	6,66E+10
116,3	5,77E+10
112,8	5,17E+10
109,3	4,43E+10

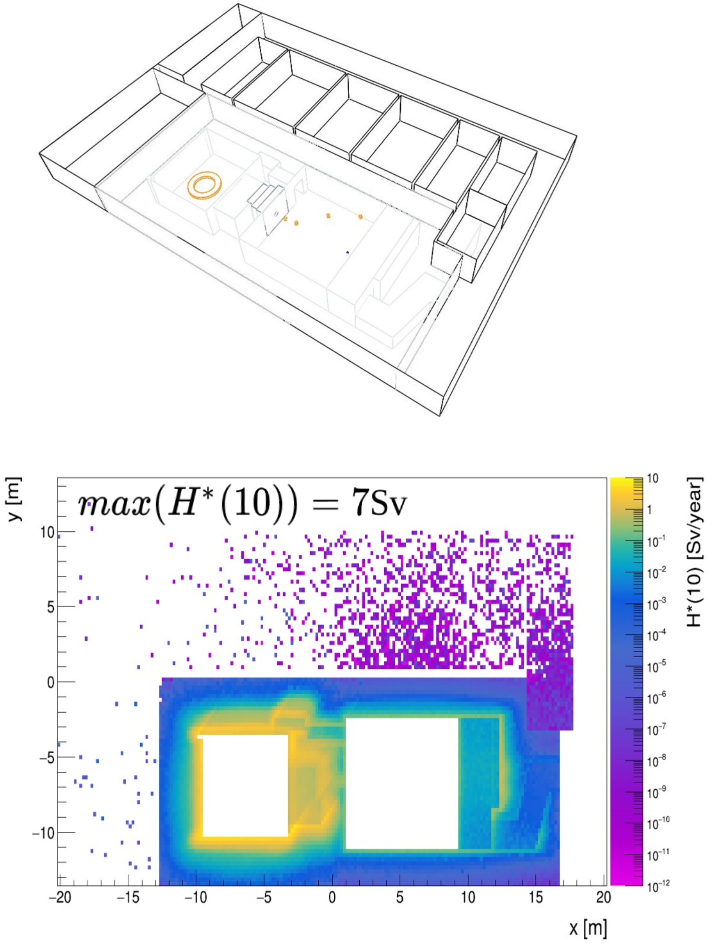
Modelo de carga de trabajo del centro Protonterapia del HUMV

Localizaciones de tratamiento	Dosis total de tratamiento	Número de fracciones	Volumen total de tratamiento	Profundidad estándar	Profundidad proximal estándar	Profundidad distal estándar	Número de incidencias de haz	Ángulo de incidencia de haz	Porcentaje de pacientes tratados	Número de pacientes por año
	Gy		cm^3	cm				°	%	
Cerebro / brain	60	30	300	8	3	12	2	isotrópico	30	120
SNC / pediatrics	60 / 40	30	1500 / 1000	8	3	12	2	0/180	15	60
Base de cráneo / skull_base	70	35	250 / 200	10	2	15	3	isotrópico	5	20
Cabeza y cuello / head_neck	70	35	1500	7	1	12	2	90/270	15	60
Tórax (pulmón) / lung	66 / 60	33	1000 / 2000	12	2	18	2	0/180	10	40
Metástasis / metastases	60 / 30	10	150 / 2000	5	2	15	1	isotrópico	5	20
Abdomen / rectum	54	28	1500 / 2500	20	5	32	3	isotrópico	5	20
Pelvis / rectum	70 / 54	30	1500 / 2500	20	5	32	3	0/90/270	10	40
Próstata / prostate	75	5	200	22	10	30	2	90/270	5	20
Suma									100 %	400

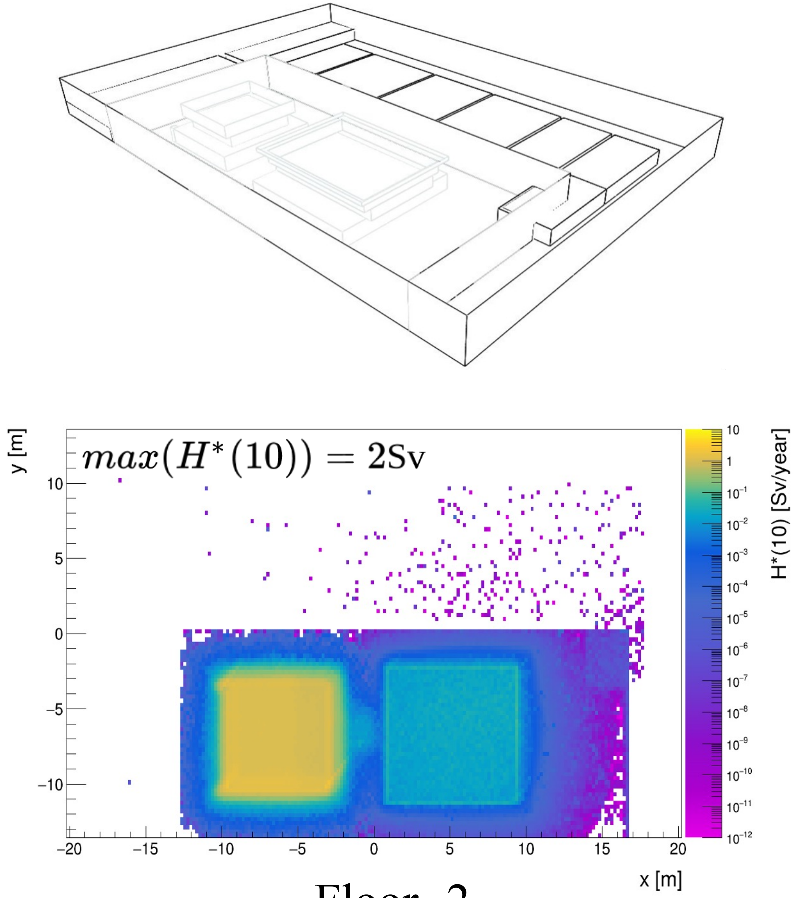
Output 1: Annual Ambient Dose



Floor -4

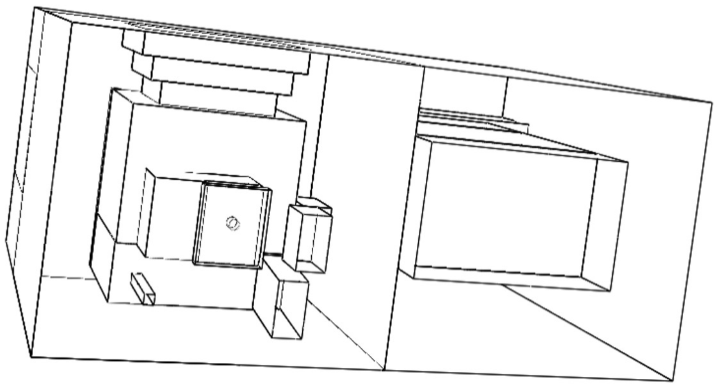


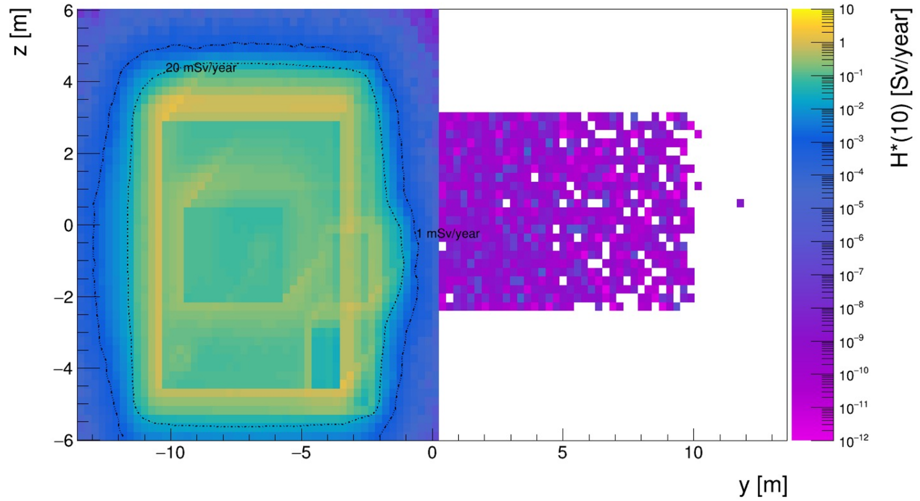
Floor -3

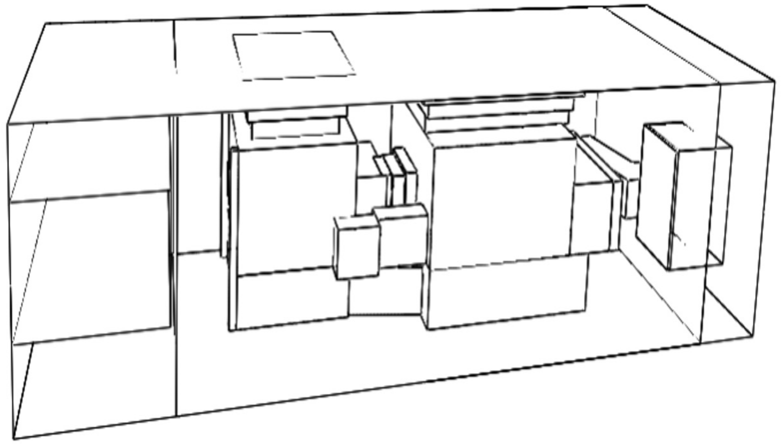


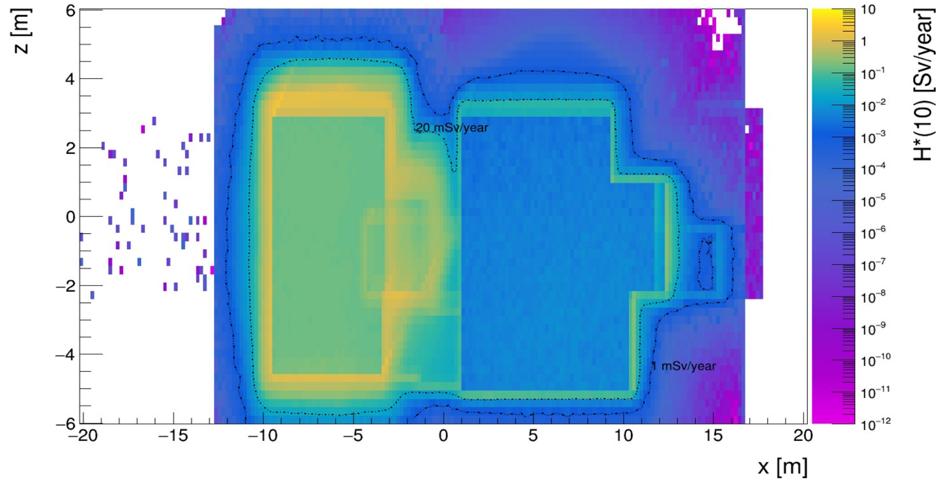
Floor -2

Output 2: Annual Ambient Dose





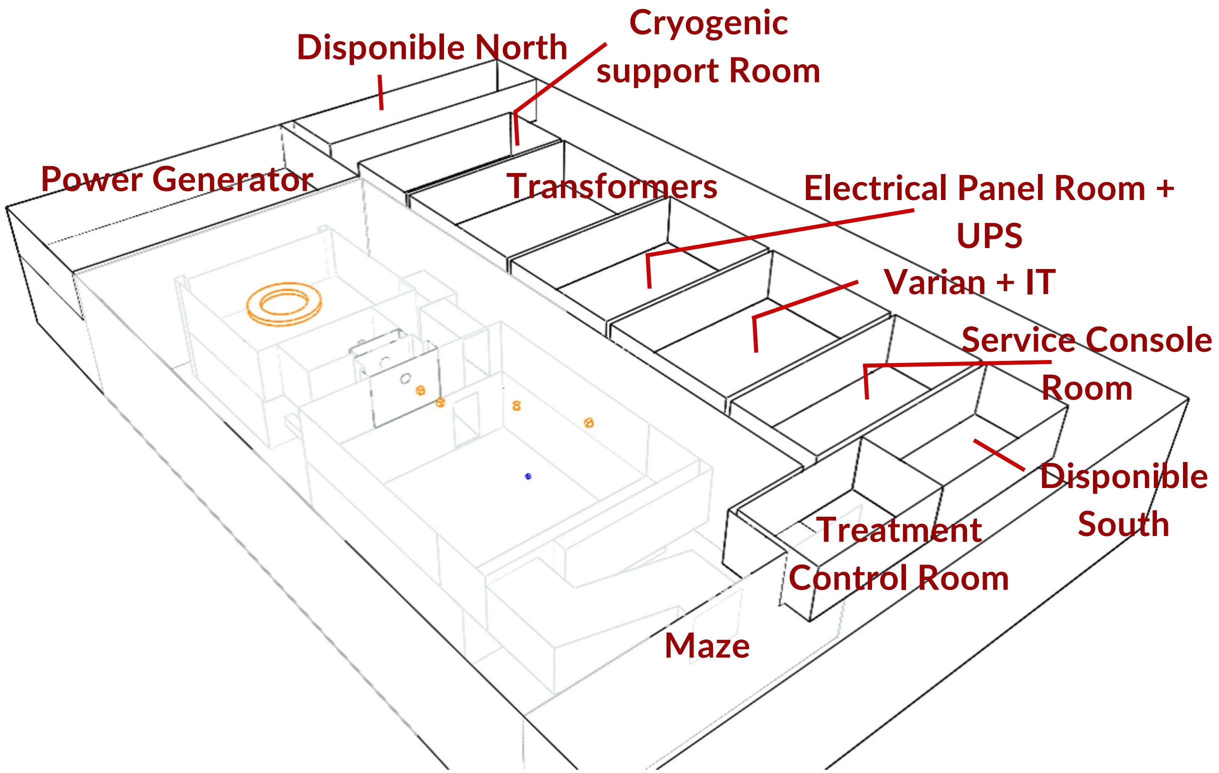




Forthcoming Tasks

- Calculation of the occupational factor in the highly-exposed rooms.
- Calculation of the activation of the bunker shielding for the entire facility life time (30 years) + dismantling.

Area	$H^*(10)$[mSv/year]
Power Generator	9.3 ± 0.7
Disponible North	0.53 ± 0.08
Cryogenic Support Room	0.085 ± 0.009
Transformers	5.3 ± 0.2
Electrical Panel Room	1.11 ± 0.03
VARIAN + IT	0.80 ± 0.01
Service Control Room	0.0240 ± 0.0005
Disponible South	9.0 ± 0.2
Treatment Control Room	5.39 ± 0.05
Maze	24.3 ± 0.3



Summary

- Successful delivery of:
  1. Ambient Dose $H^*(10)$ simulation of the HUMV PT simulation.
  2. Identification of the occupational areas (pending the occupational factor).
- Activation studies of the bunker shielding for the entire facility life time (30 years) + dismantling currently ongoing.
- **This is the first RP survey produced by IFCA and allowed us to develop a solid know-how technique easily transferable to other facilities.**
- Since 10 PT machines are on the way in Spain and it is a legal requirement, we raise the question:

IS ANYONE IN THE ROOM INTERESTED?

Valdecilla
Hospital Universitario Marqués de Valdecilla

IFCA

Thanks for your attention!

Alberto Arteche González
Instituto de Física de Cantabria (IFCA)

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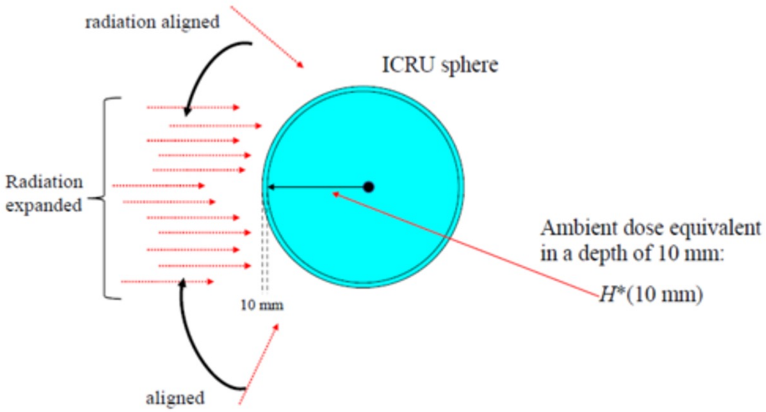
IFCA

Backup

Ambient Dose H*(10)



1. **Absorbed Dose:** energy lost per unit of mass
   a. Directly obtained from Geant4

1. **Ambient Dose:** operational magnitude for external exposition, H*(10)
   a. Equivalently, MC calculation of fluence within a volume [1] based on a Kellerner theorem [2], uses the track length of all particles entering the volume

$$H^*(10) = \sum \bar{\Phi}(E, \text{particle}) \cdot h_{10}(E, \text{particle})$$

   b. BOE: ICRP publications 116, 144 recommend use of ICRP-74 conversion factor tables to convert **fluence-to-absorbed dose**

[1] Fluence calculation methods in Monte Carlo dosimetry simulations, G. Hartmann, P. Andreo https://doi.org/10.1016/j.zemedi.2018.08.003
[2] Considerations on the Random Traversal of Convex Bodies and Solutions for General Cylinders, A. Kellerer, Rad. Research (1971) https://doi.org/10.2307/3573243

Total number of protons per year at isocenter

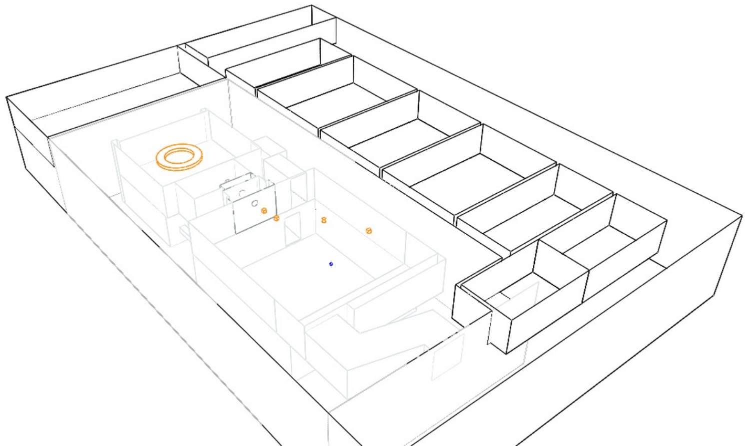
	Distal	Proximal	Num. Treatments
rain	2.1826×10^{14}	2.1600×10^{14}	120
Skull Base	4.3962×10^{13}	3.8550×10^{13}	20
Lung	1.9449×10^{14}	1.8781×10^{14}	40
Prostate	4.5740×10^{13}	3.6240×10^{13}	20
Head Neck	4.7436×10^{14}	4.7436×10^{14}	60
Metastases	1.2264×10^{13}	1.2264×10^{13}	20
Abdomen	1.4128×10^{14}	1.1627×10^{14}	20
Pelvis	4.7092×10^{14}	2.9842×10^{14}	40
SNC	1.6470×10^{14}	1.9278×10^{14}	60
Total	1.7659×10^{15}		

Simulation details

- Package **bunshi**, a Geant4 (v4.11) application for bunker shielding estimations
  a. Concrete (Portland): 2.35 gr/cm3
     i. Fraction of mass → H:0.01, C: 0.001, O: 0.529107, Na: 0.016, Mg: 0.002, Al: 0.033872, Si: 0.337021, K: 0.013, Ca: 0.044, Fe: 0.014
  b. High Density Concrete: 4.8 gr/cm3 (extracted from ?)
     i. Fraction of mass → H:0.0094, O: 0.3614, Na: 0.0136, Mg: 0.0222, Al: 0.0502, Si: 0.1875, K: 0.0065, Ca: 0.1374, Fe: 0.2083
  c. Physics list [1] (Hadrontherapy1)
  d. H*(10) for neutrons and photons
  e. Geometry: Bunker (SD), Rooms (SD), EGS

- Simulations ESS elements: cyclotron, degrader, apertures (CS, CA, CD)
  a. Cyclotron, degrader: 1E8 protons (at 250 MeV)
  b. 2 x 1e8 protons per EGS, energy
     i. Proximal energies

- Simulations Gantry elements: Quads, dipoles, phantom at isocenter
  a. 2 x 1E8 protons per EGS, energy (distal) and angle
     i. Distal energies
     ii. 4 angles (**0**, 90, 180, 270), used only 0 so far

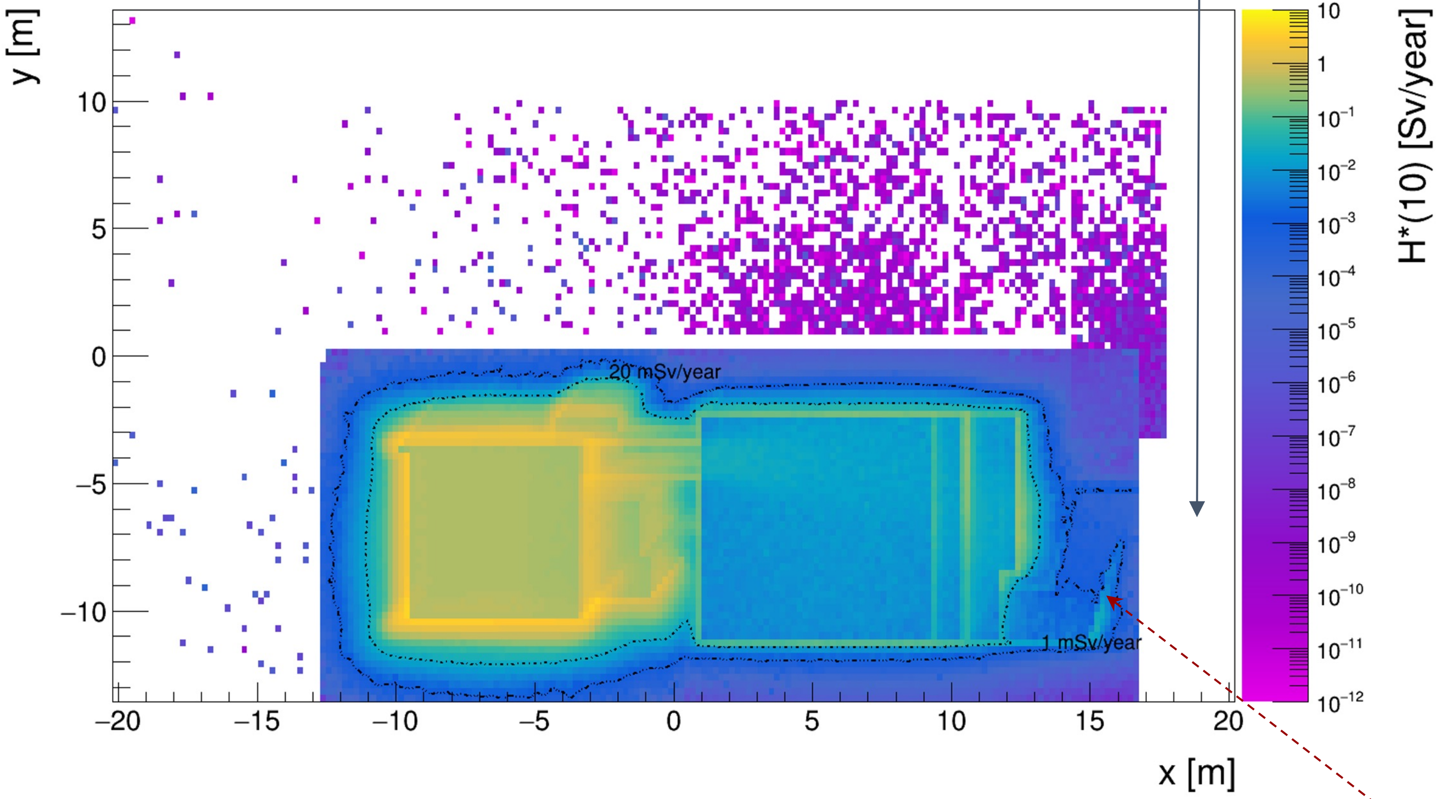


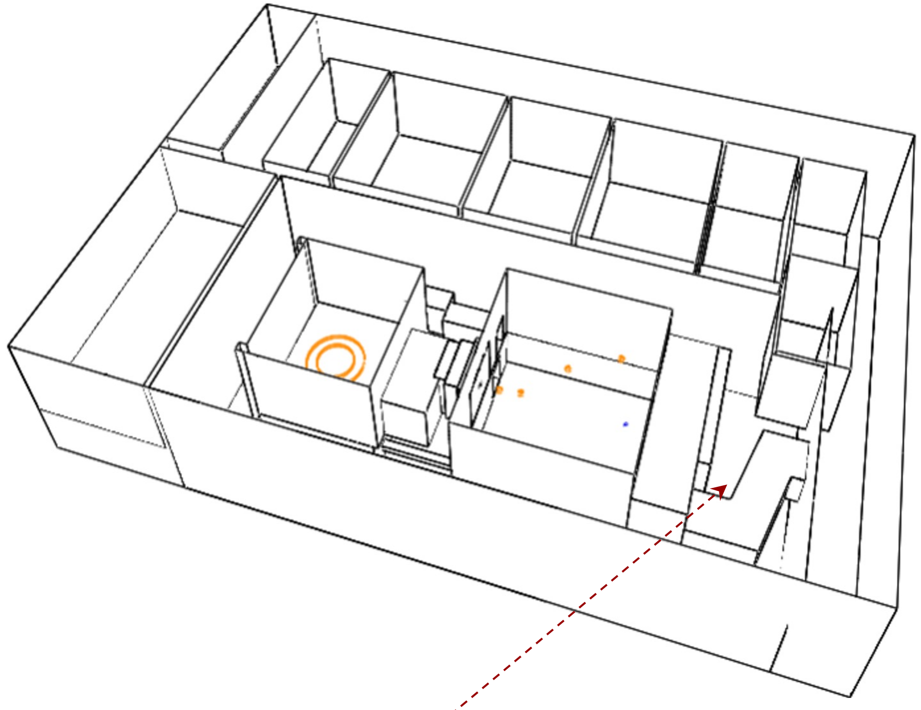
[1] Experimental validation of proton physics models of G4 for calculating stopping power ratio, R. Liu, X. Zhao, M. Medrano

Annual dose estimation: Walls

- Integrated all z

below uSv/year





West wall below 1 mSv/year

maze surroundings