CEIDEN
PLATAFORMA TECNOLÓGICA DE ENERGÍA NUCLEAR DE FISIÓN

Hybrid Meeting (virtual & in-person)

Nuclear Databases for Nuclear Reactor Applications within the Spanish Nuclear Sector

September 20 (Tuesday), 2022. 09:00-13:00h

UPM activities with nuclear data (ND) in other applications

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CEIDEN
PLATAFORMA TECNOLÓGICA DE ENERGÍA NUCLEAR DE FISIÓN

POLITÉCNICA

Nfq

Hybrid Meeting (virtual & in-person) on
"Nuclear Databases for Nuclear Reactor Applications within the Spanish Nuclear Sector"

September 20 (Tuesday), 2022. 09:00-13:00h

UPM activities with nuclear data (ND) in other applications

Scope

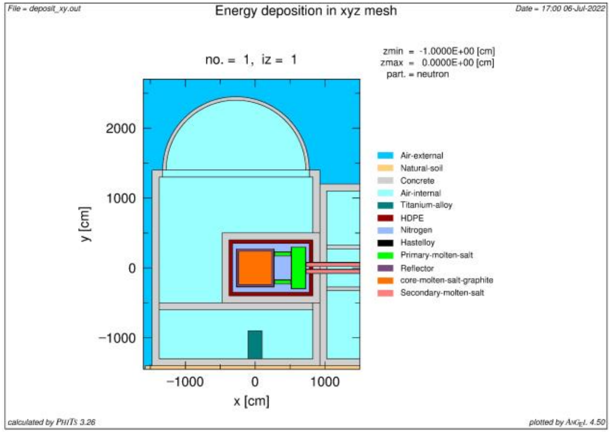
Purpose and context

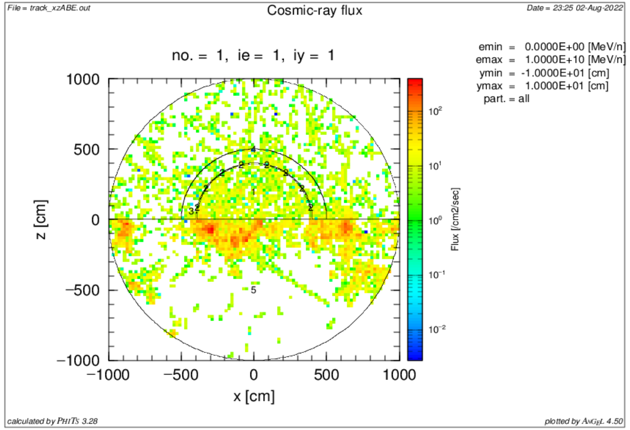
Research activities with ND, *the film*

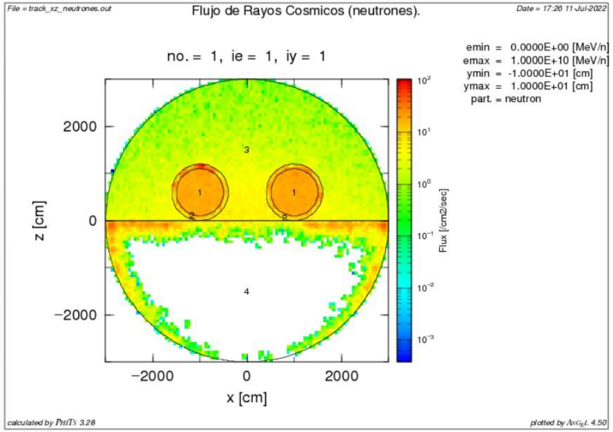
Health facilities (PT)
(The ten recommendations)

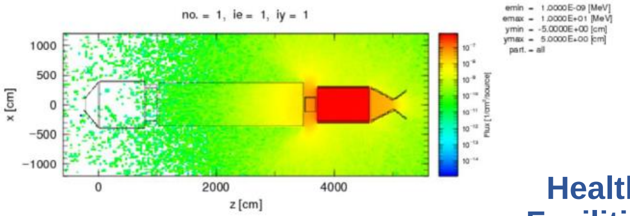
Summary

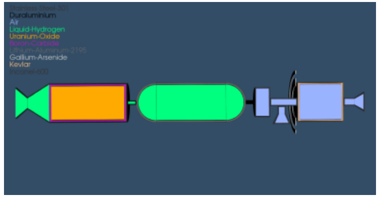
Other activities with Nuclear Data at UPM





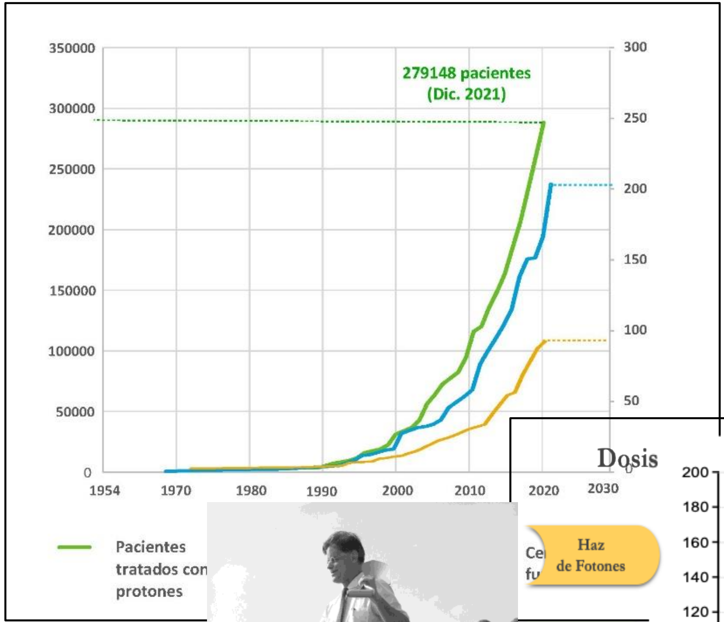


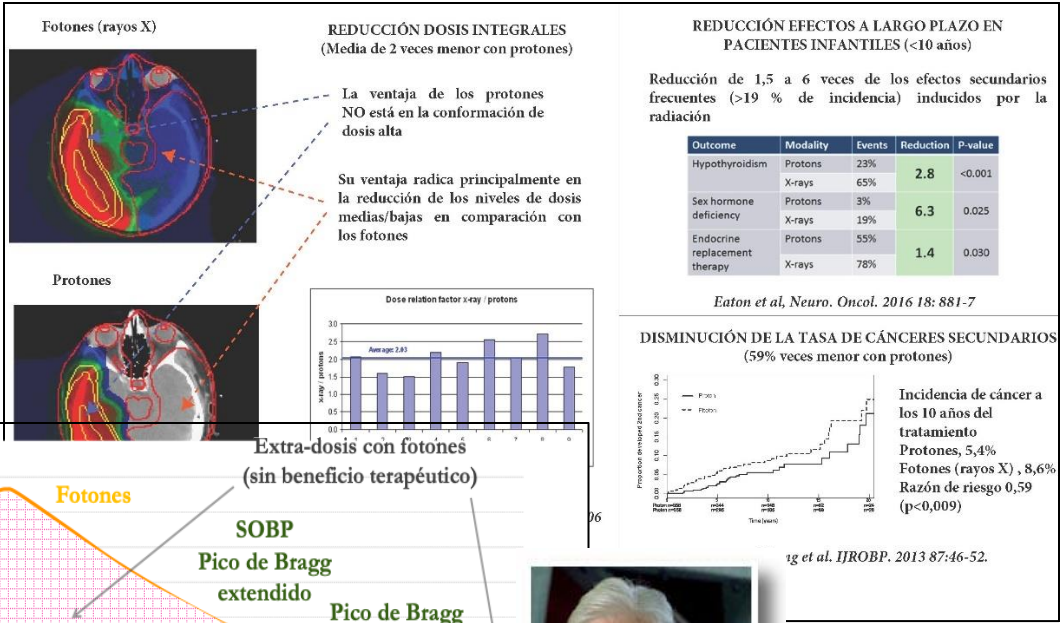




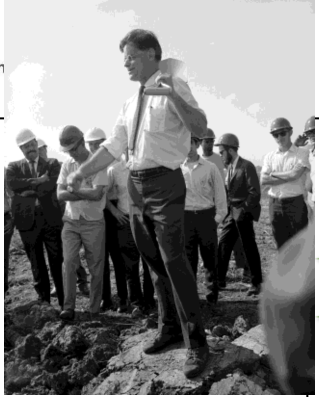
Health Facilities

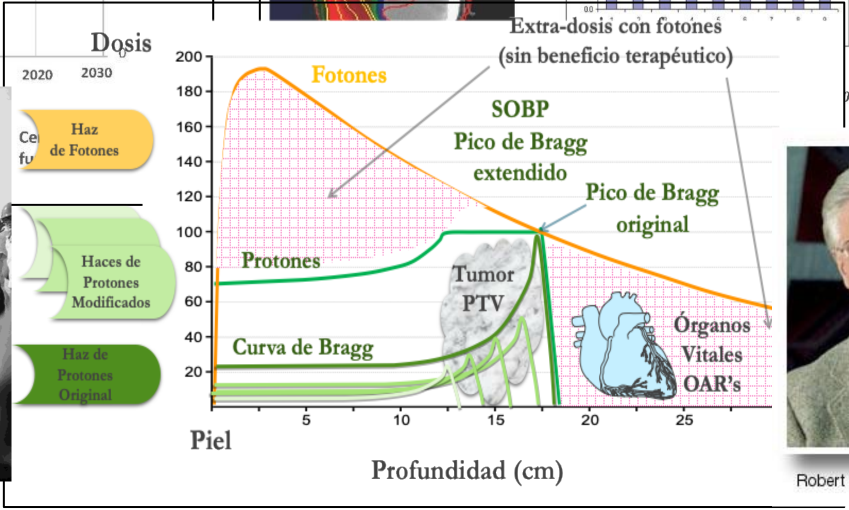
Proton therapy facilities

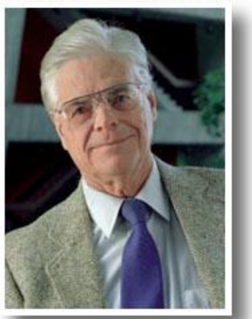




Outcome	Modality	Events	Reduction	P-value
Hypothyroidism	Protons	23%	2.8	<0.001
	X-rays	65%		
Sex hormone deficiency	Protons	3%	6.3	0.025
	X-rays	19%		
Endocrine replacement therapy	Protons	55%	1.4	0.030
	X-rays	78%		



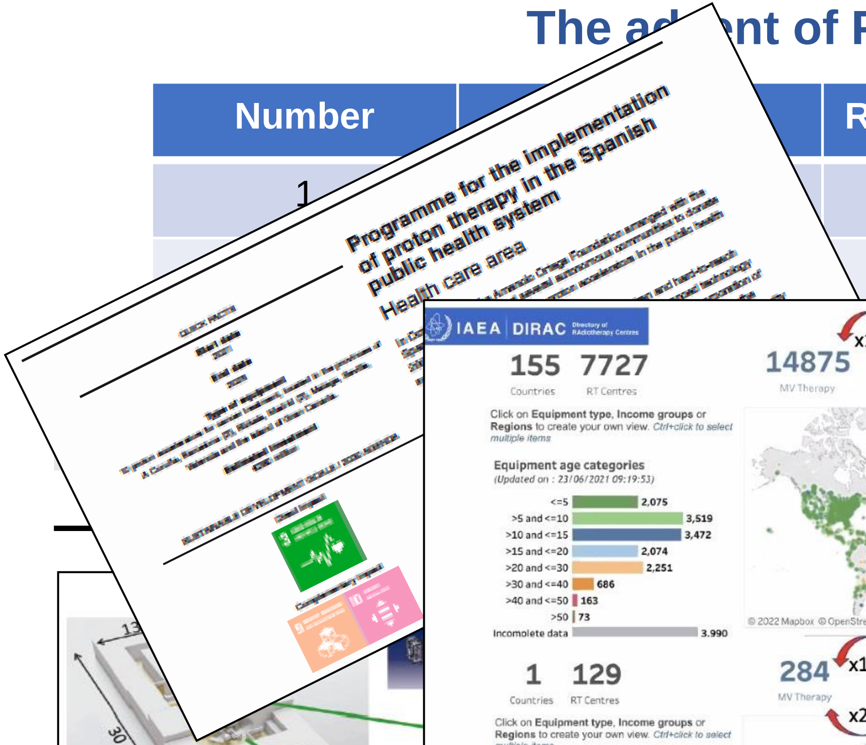


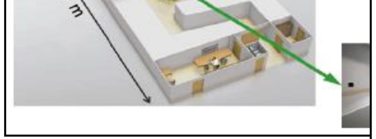

Robert Wilson

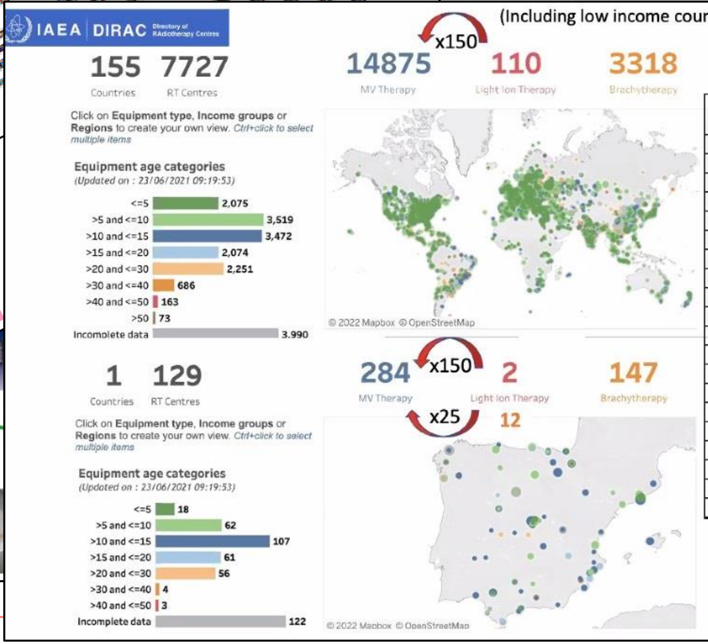
The advent of Protontherapy in Spain

Number		Rooms	Footprint (Aprox)	Operation
1		1	360 m²	Dec 2019
		1+(1)	800 m²	March 2020

Gantry Rotation
220º
360º

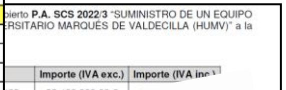


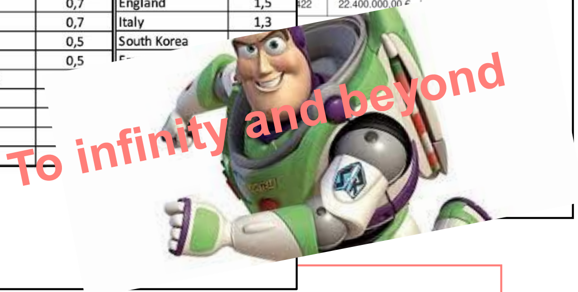




(AM from PTCOG 2020 w/Spain Projected to 12 centers)

Order	Country	Centers/ 10Mh	Country	Rooms/ 10Mh
1	Spain	2,6	Denmark	6,7
2	The Netherlands	1,8	Switzerland	5,7
3	Denmark	1,7	Czech Republic	3,6
4	Japan	1,4	The Netherlands	3,5
5	Switzerland	1,4	Austria	3,3
6	USA	1,1	Taiwan	3,3
7	Austria	1,1	USA	3,3
8	Sweden	1,0	Spain	2,6
9	Czech Republic	0,9	Japan	2,5
10	Belgium	0,8	Sweden	2,0
11	Taiwan	0,8	Germany	1,7
12	England	0,7	England	1,5
13	Germany	0,7	Italy	1,3
14	Italy	0,5	South Korea	
15	France	0,5	F	
16	South Korea			
17	Russia			
18	Poland			
19	China			
20	India			





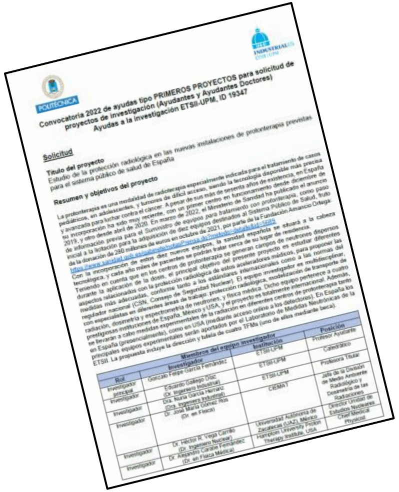
2018→0 2020→ 2 (private) + 1 Santander 2025?→ 13 (+10 public)

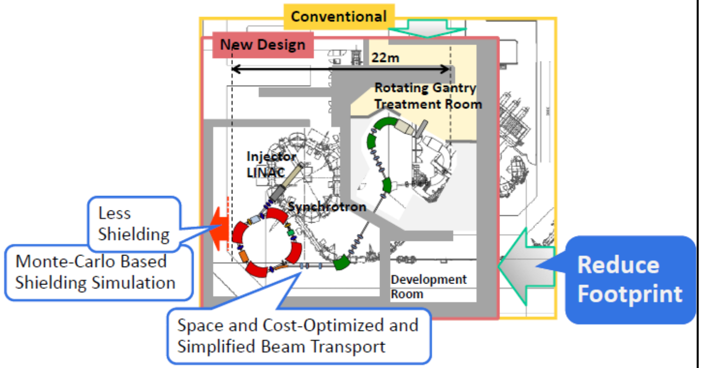
Dirección General de Investigación e Innovación
CONSEJERÍA DE EDUCACIÓN E INVESTIGACIÓN
Comunidad de Madrid

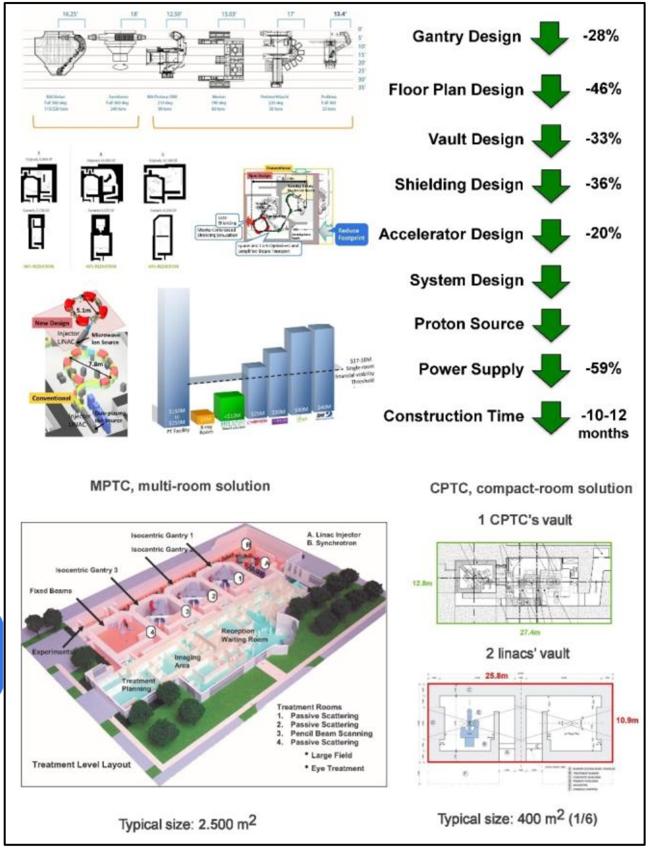
Research Project

Doctorado Industrial de la Comunidad de Madrid, nº IND2017/AMB-7797
UPM – Bioterra, SL

Contributions to the operational radiation protection in compact proton therapy centers (CPTC)

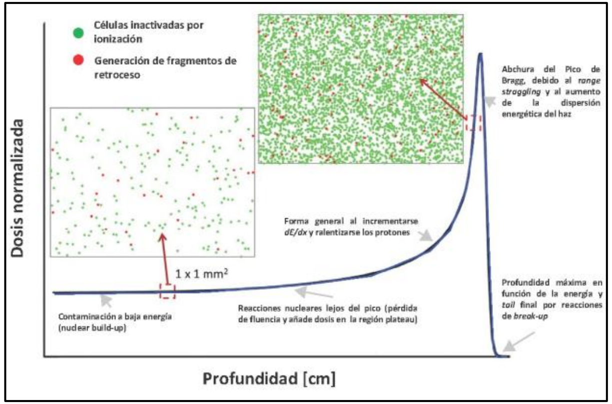


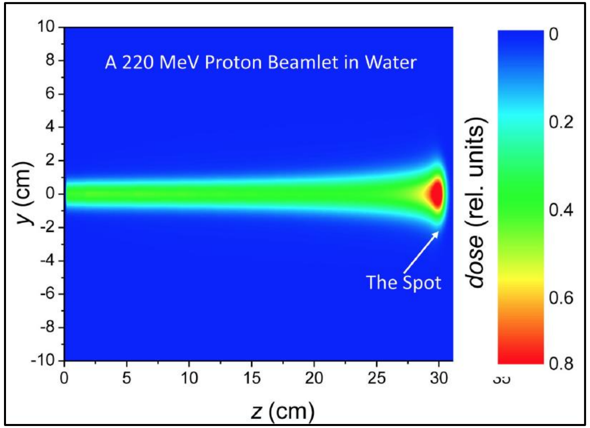


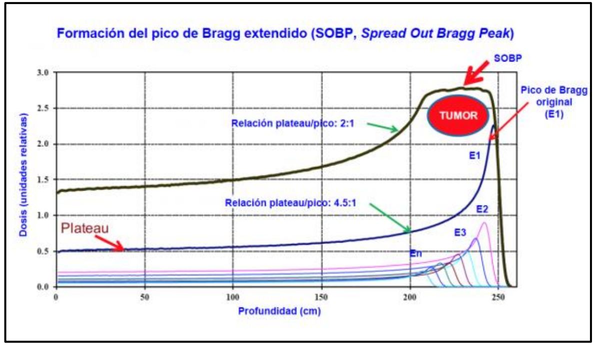


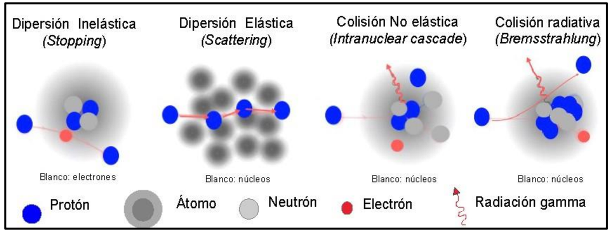
Physics, Nuclear Data and Nuclear Models in PT

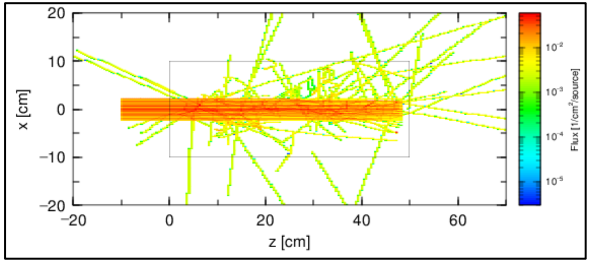
Proton interactions → Neutron Fields
Neutron interactions → Impact in facility

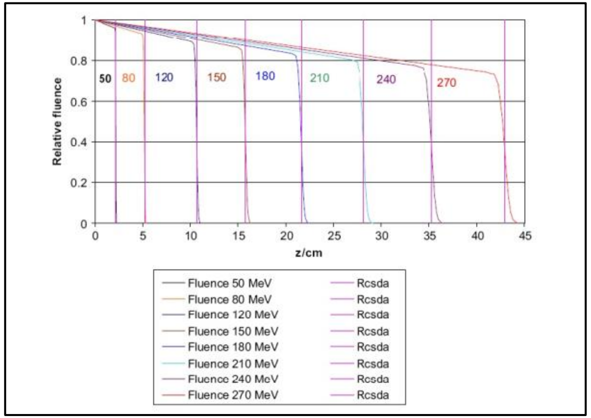






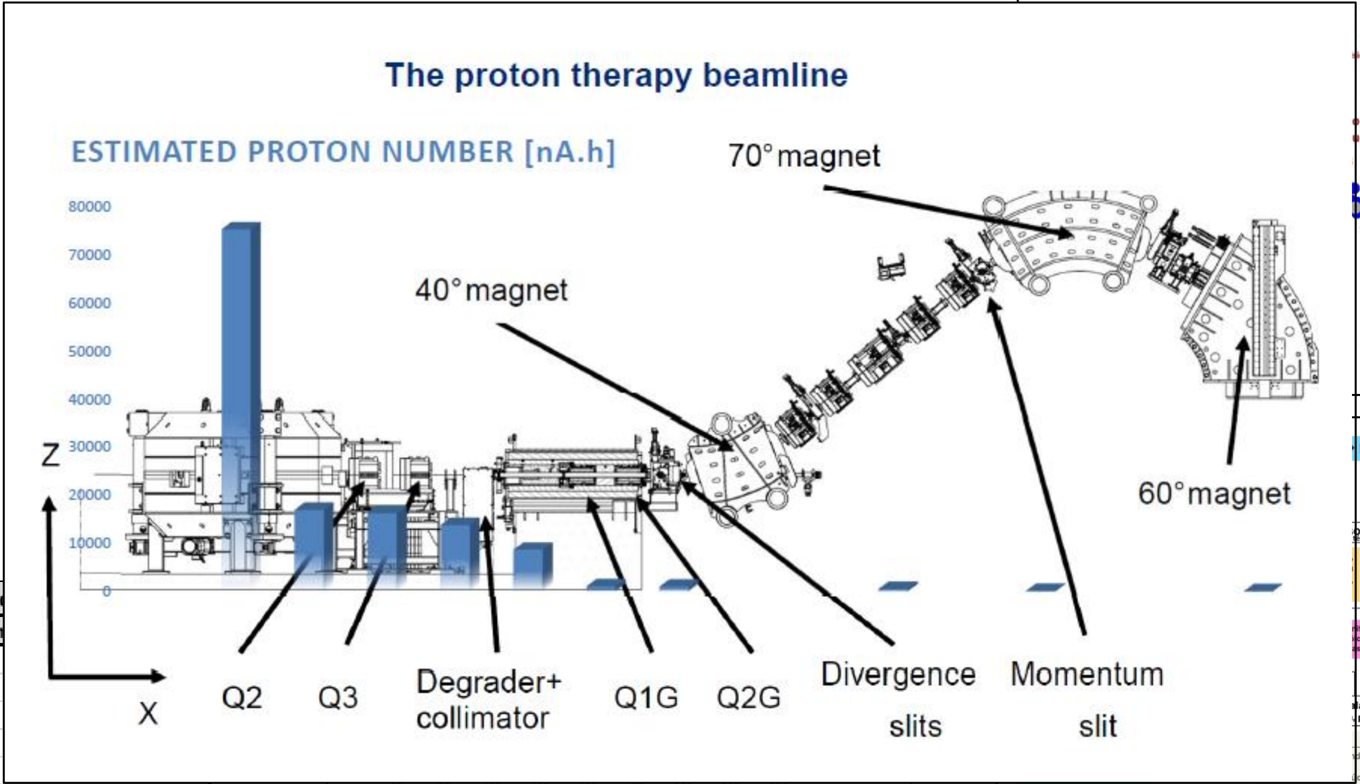


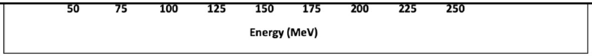


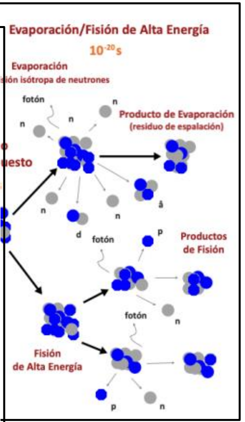


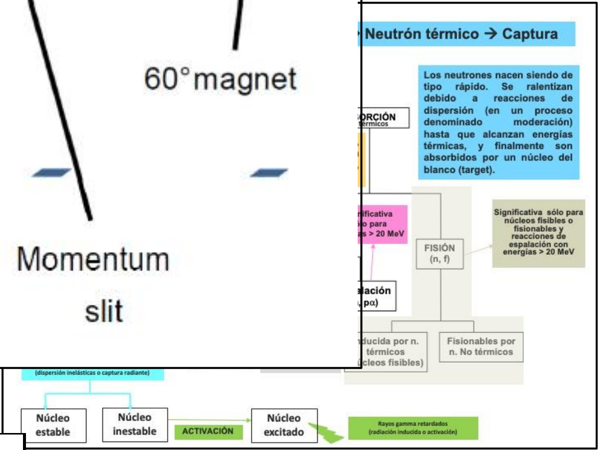
Neutron yielding and neutron transport

Main Interaction (		
Component	En	
Cyclotron		
Degrader		
Collimator		
Divergence Slits		
Momentum Slit		
Patient	70 - 230	Tissue







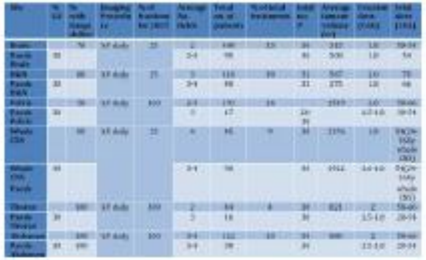


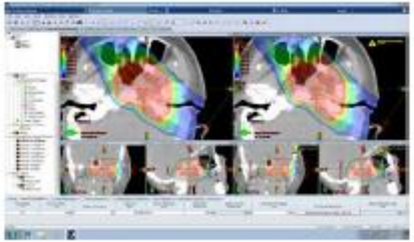
Energy (MeV)	70	85	115	160	200	230
Efficiency (%)	0,2	0,3	0,8	1,8	5	12

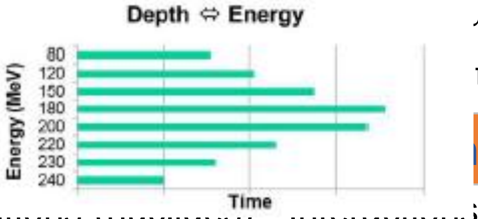
RP in proton centers: Starting Point

Workload (nA·h/year) → Estimation of Proton fields (annual dose) → Beam losses

COMPLEX INPUT: Number of patients x Number of Fields x Time per field x Current x Working days x (1h/60 min)



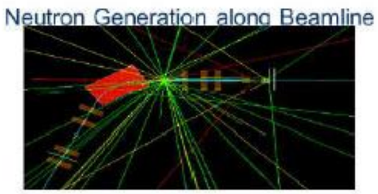


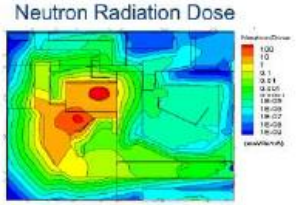


- Factor … , 2 Gy/patient
- Regula …)
  … pain)
  … rly: 10
- Occup … 5
- Types … nance
- Dose I … us, facility
- Conse … t Dose Equivalent, H*(10) (Hp*(10))

Ass … ities (conservatives, 20y)

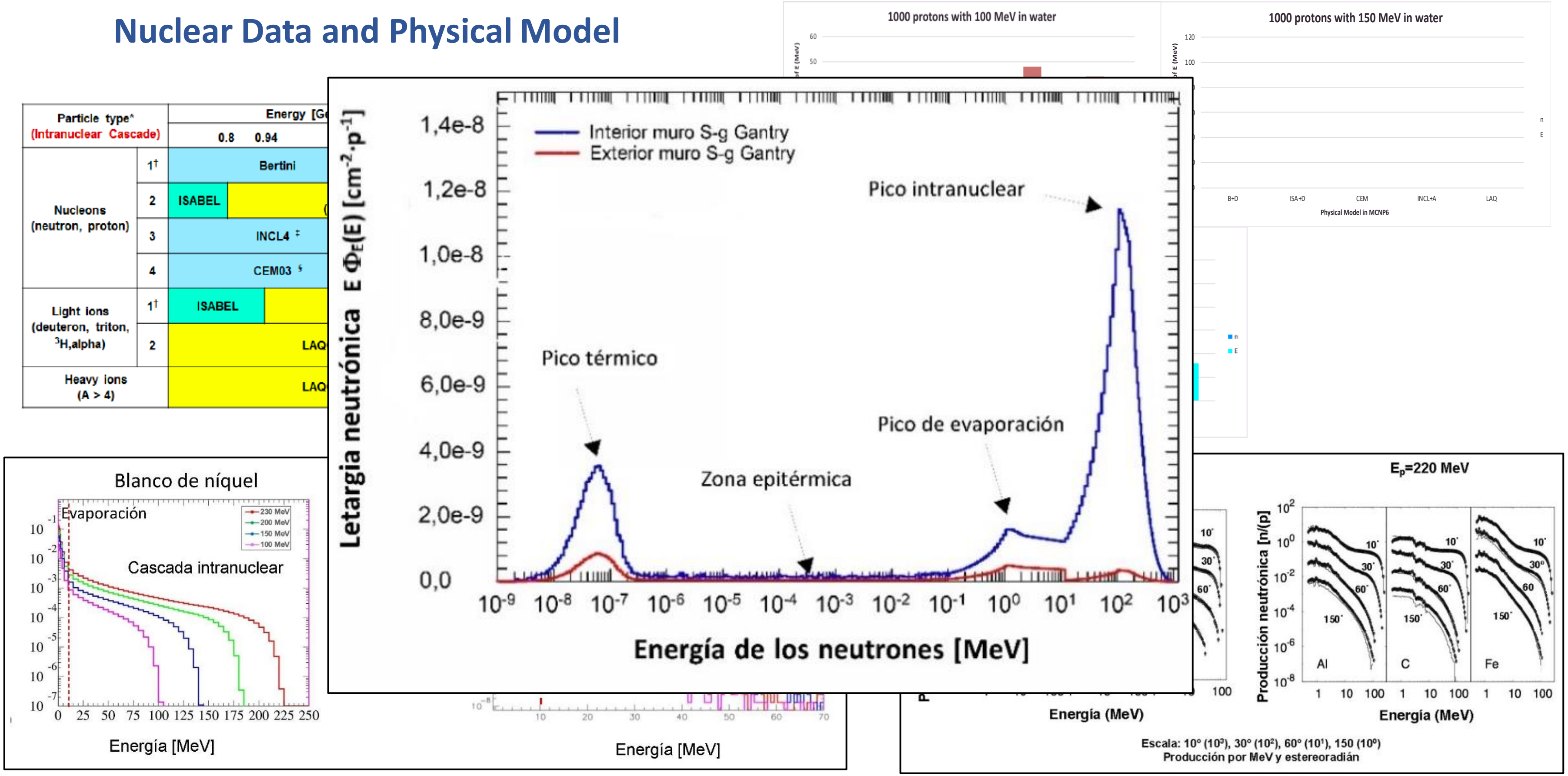
Compo… – **Workload → <u>Delivery mode</u>**





Neutron yielding and neutron transport

Nuclear Data and Physical Model



Verification of barriers and shielding against neutron and gamma radiation

Neutron Libraries for MCNP

MCNP6

- The MCNP6 data libraries are contained in the MCNP6 RSICC package.
- Continuous-energy neutron libraries for MCNP6:
  - endf71x/*/* ENDF/B-VII.1
  - endf70 a-k ENDF/B-VII.0

Older libraries, retained for historical reasons:

- t16_2003 preliminary ENDF/B-VII, for a few isotopes
- acti ENDF/B-VI.8
- endf66 ENDF/B-VI.6
- endf60 ENDF/B-VI.2
- endf62mt A multi-temperature Neutron Data Library
- ures ENDF/B-VI Neutron Library with Probability Tables
- endf6dn ENDF/B-VI Neutron Library with Delayed Neutron Tables
- newxs LANL based evaluations
- rmccs ENDF/B-V and LANL based evaluations
- rmccsa ENDF/B-V and LANL
- endf5p ENDF/B-V based
- endf5u ENDF/B-V based
- misc5xs Contains a number of previously released smaller libraries
- kidman Fission product evaluations
- 100xs LANL based
- endl92 1992 ENDL library from LLNL
- endl85 1985 ENDL library
- endf5mt Multi-temperature data previously released as eprixs and u600k

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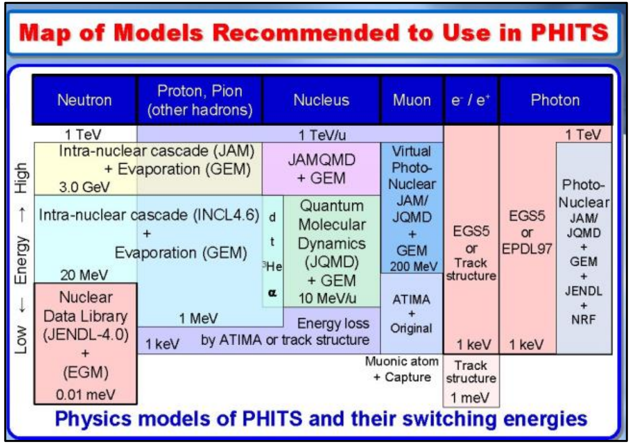

INC Model Options in MCNP6

MCNP6

Variable	Bertini	ISABEL	CEM (default)	INCL	LAQGSM
Lower Energy	20-150 MeV	20-150 MeV	~ 10 MeV	~ 100 MeV (not in MCNP: ~ 5 MeV/A)	~ 100 MeV/A (not in MCNP: ~a few MeV/A)
Upper Energy	3.5 GeV (nuc-nuc) 2.5 GeV (pion-nuc)	1 GeV	5 GeV	2 GeV (not in MCNP: ~ 15 GeV)	~ 1 TeV/A (not in MCNP: ~ 20-100 TeV)
Target Nuclei	All	All	A ≥ 4	All	All
Incident particles	h, n, pions	h, n, $\bar{h}$, $\bar{n}$ A ≤ 4, (not in MCNP: also A>4)	h, n, pions, γ	h, n, A ≤ 4 (not in MCNP: ~ A<16)	Almost all particles & ions

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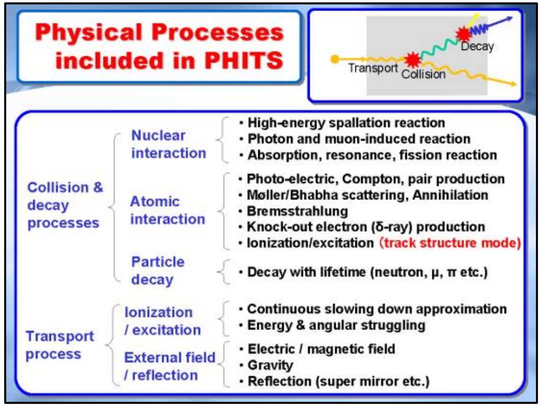
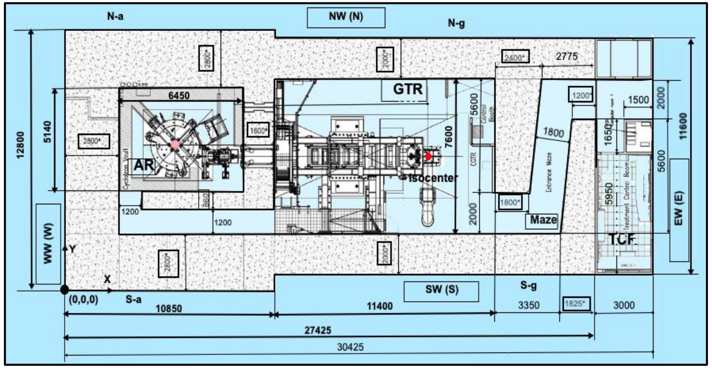
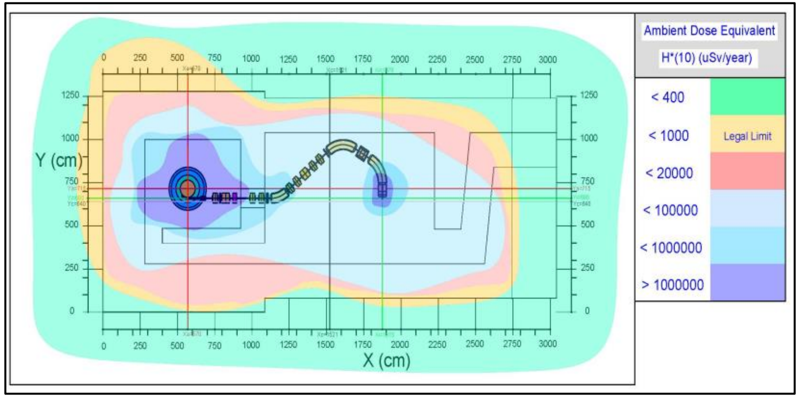
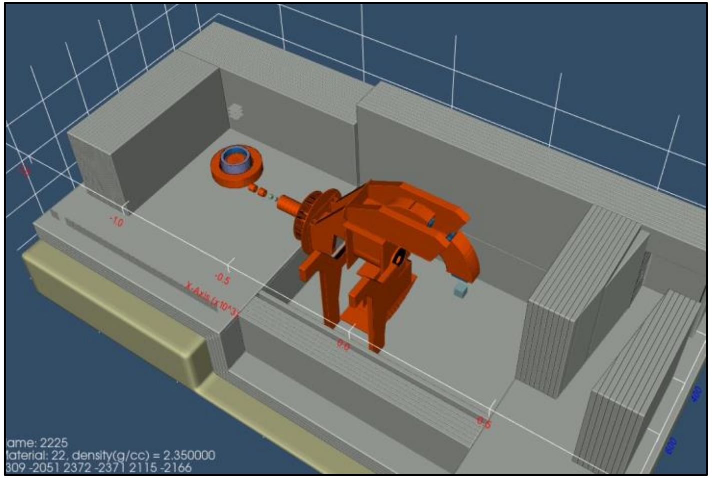
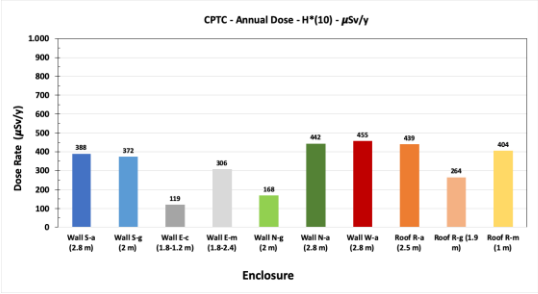


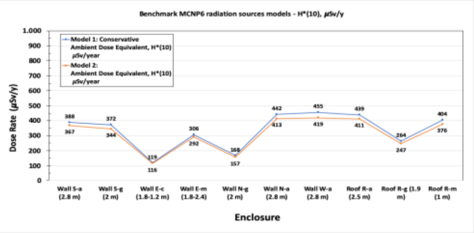
Verification of barriers and shielding against neutron and gamma radiation







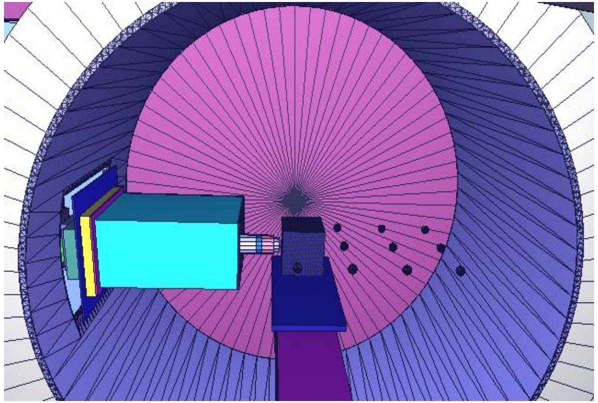


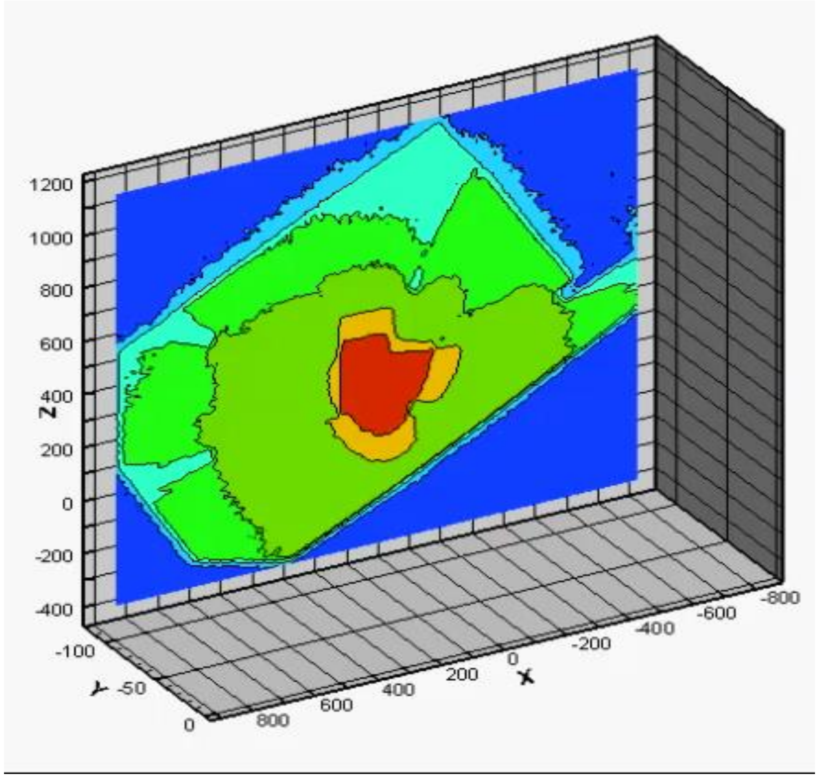


Máx.: 0.455 mSv/year

12-15% lower

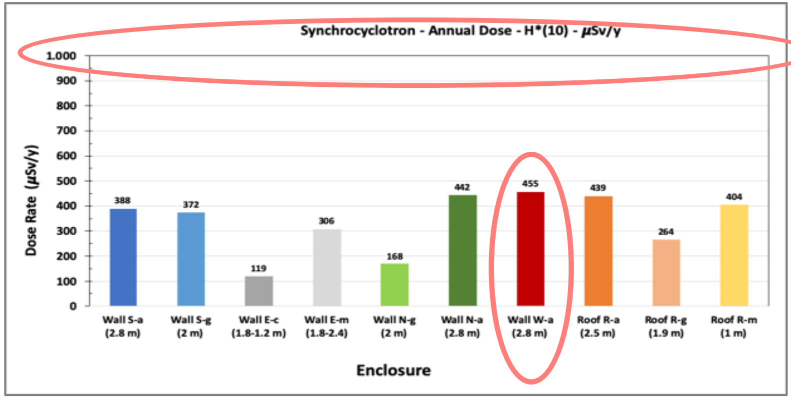
Isodose plots

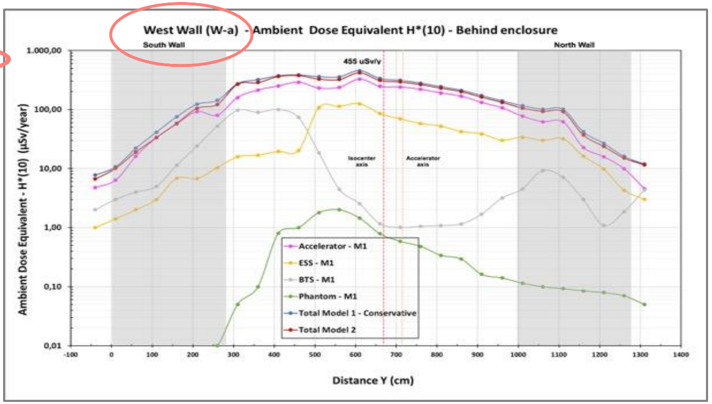


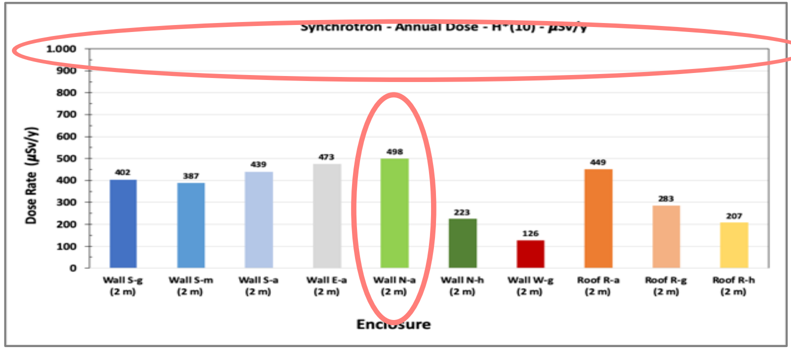


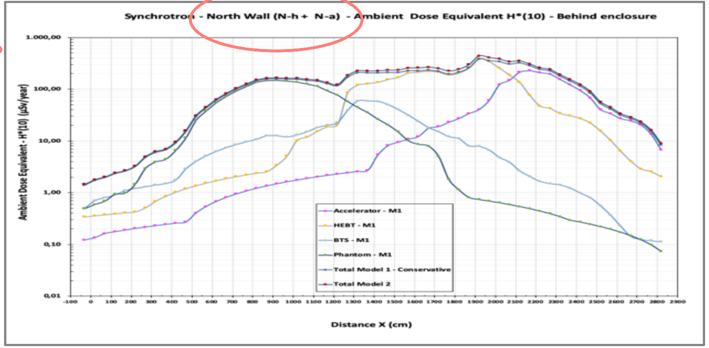
Verification of barriers and shielding against neutron and gamma radiation

Checking the shielding of compact centers









MC methods

Thickness proposed by vendors

Both facilities always below international legal limits (1 mSv, general public)

Synchrocyclotron
One treatment room
360 m^2 footprint
2.8 m thickness in main barriers

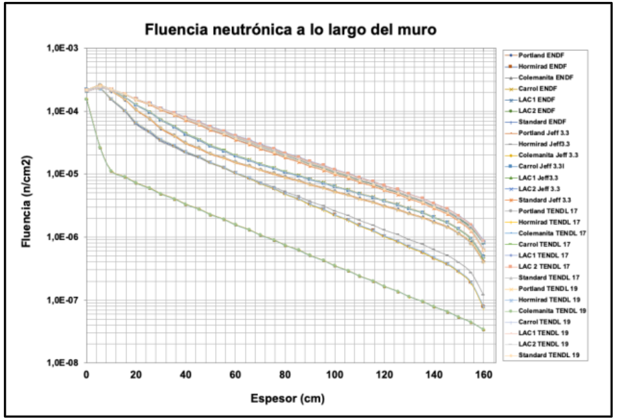
Synchrotron
One treatment room expandable
800 m^2 footprint
2 m thickness in main barriers

Intercomparing CPTC: synchrocyclotron vs. synchrotron

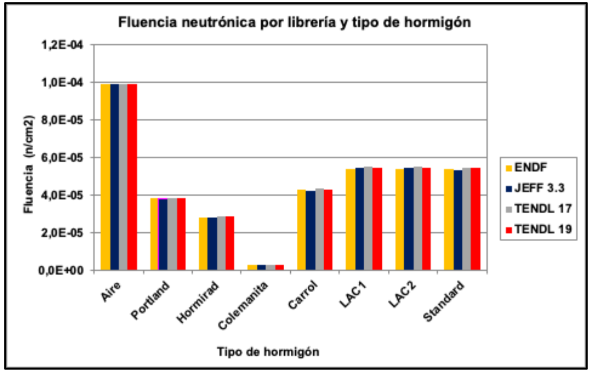
Expansion to new types of centers planned for the Public System

Study of different materials in barriers

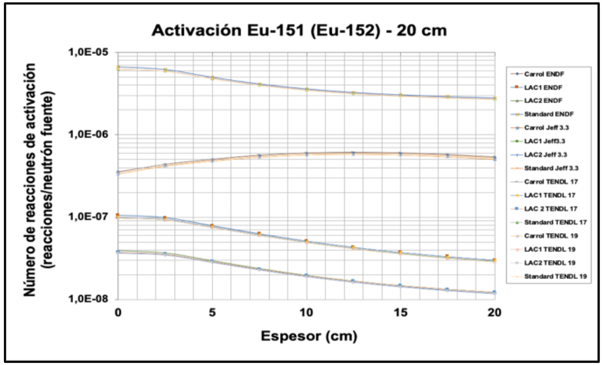
Attenuation plots with different types of concrete



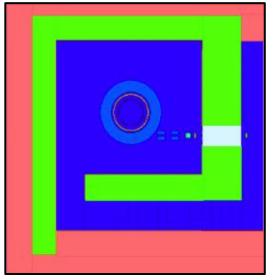
Attenuation is essential but not enough

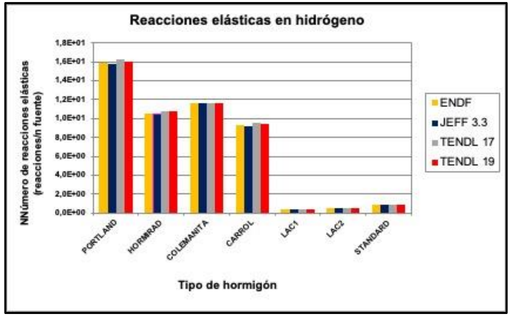


Comparative of several materials (concretes)



Different materials in different places and mix barriers





Compromise between attenuation, activation in components, and cost of building

Impact of radiation on environment inside and around CPTC

Air activation

Neutron capture in ^{40}Ar: ^{40}Ar(n,γ)^{41}Ar (Cross section ^{40}Ar, σ = 610 mb)
Spallation processes on ^{14}N and ^{16}O atoms, with neutrons above 20 MeV of energy
Air renewal rate, r (r > 6 RPH, $\lambda_{effective} = \lambda + r$), underpressure, treatment and humidity

Water activation + ground activation in soil

Spallation processes on O atoms, with neutrons above 20 MeV of energy
Productions of same radionuclides as air, except ^{41}Ar:
- Long-lived isotopes: ^{3}H and ^{7}Be
- Short-lived isotopes: ^{11}C, ^{13}N, ^{15}O, ^{14}O, ^{18}F

Spallation processes with high energy neutrons (En>20 MeV) in Oxygene (^{16}O)				
Target	**Reaction**	**Cross section (mb)**	**Nuclide yielded**	**Half-life**
^{16}O	^{16}O(n,x)^{3}H	30	^{3}H	12.3 y
^{16}O	^{16}O(n,x)^{7}Be	5	^{7}Be	53.3 d
^{16}O	^{16}O(n,x)^{11}C	5	^{11}C	20.4 m
^{16}O	^{16}O(n,x)^{13}N	9	^{13}N	1.18 m
^{16}O	^{16}O(n,x)^{15}O	40	^{15}O	2.04 m

Spallation processes with high energy neutrons (En>20 MeV) in Nitrogen (14N)				
Target	**Reaction**	**Cross section (mb)**	**Nuclide yielded**	**Half-life**
^{14}N	^{14}N(n,x)^{3}H	30	^{3}H	12.3 y
^{14}N	^{14}N(n,x)^{7}Be	10	^{7}Be	53.3 d
^{14}N	^{14}N(n,x)^{11}C	10	^{11}C	20.4 m
^{14}N	^{14}N(n,x)^{13}N	10	^{13}N	1.18 m

Metallic components activation (accelerator parts, beam line elements,…)

Spallation, (n,x), and neutron capture, (n,γ), processes

Long-lives isotopes
yielded directly with protons

Many equipment and elements
of the facility with natural Cu

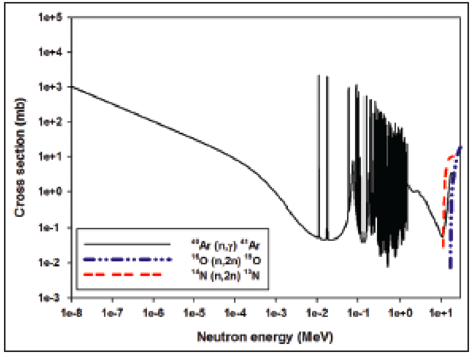
Nuclide	Half-life	Reaction	Cross section (barn)
^{134}Cs	2.06 year	^{133}Cs(n,γ)^{134}Cs	29
^{60}Co	5.3 year	^{59}Co(n,γ)^{60}Co	37
		^{60}Ni(n,p)^{60}Co	
^{59}Fe	44 days	^{58}Fe(n,γ)^{59}Fe	1.15
^{65}Zn	244 days	^{64}Zn(n,γ)^{65}Zn	0.78
^{54}Mn	312 days	^{55}Mn(n,2n)^{54}Mn	0.91
		^{54}Fe(n,p)^{54}Mn	0.59
^{108}Ag	127 year	^{107}Ag(n,γ)^{108}Ag	36
^{110}Ag	249 days	^{109}Ag(n,γ)^{110}Ag	91
^{123}Sn	129 days	^{122}Sn(n,γ)^{123}Sn	0.15
^{125}Sn	9 days	^{124}Sn(n,γ)^{125}Sn	0.13
^{22}Na	2.6 year	^{23}Na(n,2n)^{22}Na	0.017
		^{27}Al(n,x)^{22}Na	0.010

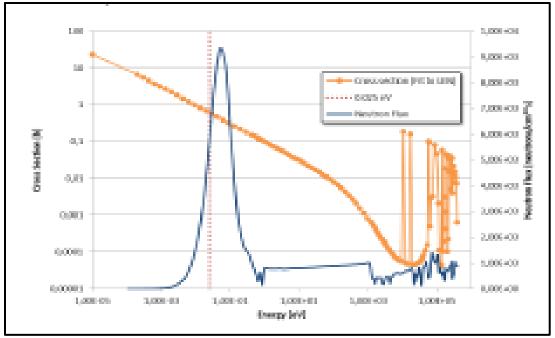
Isotopes	Half-life
^{60}Co	5.3 years
^{57}Co	271 days
^{58}Co	70 days
^{54}Mn	312 days
^{65}Zn	244 days
^{22}Na	2.6 years

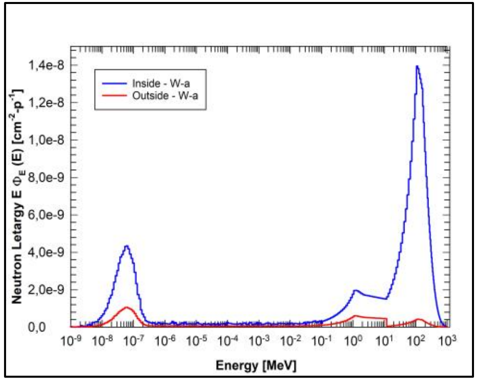
Parent	Reaction	Reaction Product	Half-life
^{63}Cu 69.17%	(n,γ)	^{64}Cu	12.7 hours
	(n,α)	^{60}Co	5.3 years
	(n,2n)	^{64}Cu	12.7 hours
^{65}Cu 30.83%	(n,p)	^{65}Ni	2.5 hours
	(p,n)	^{65}Zn	244 days

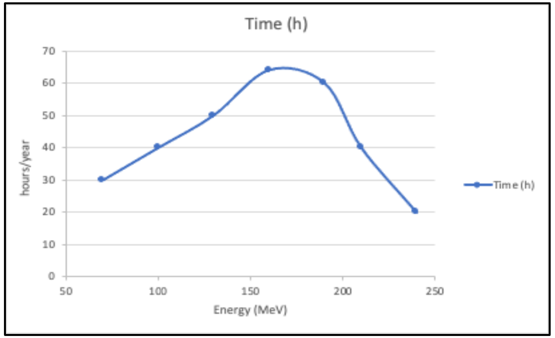
Air activation in CPTC

MC methods



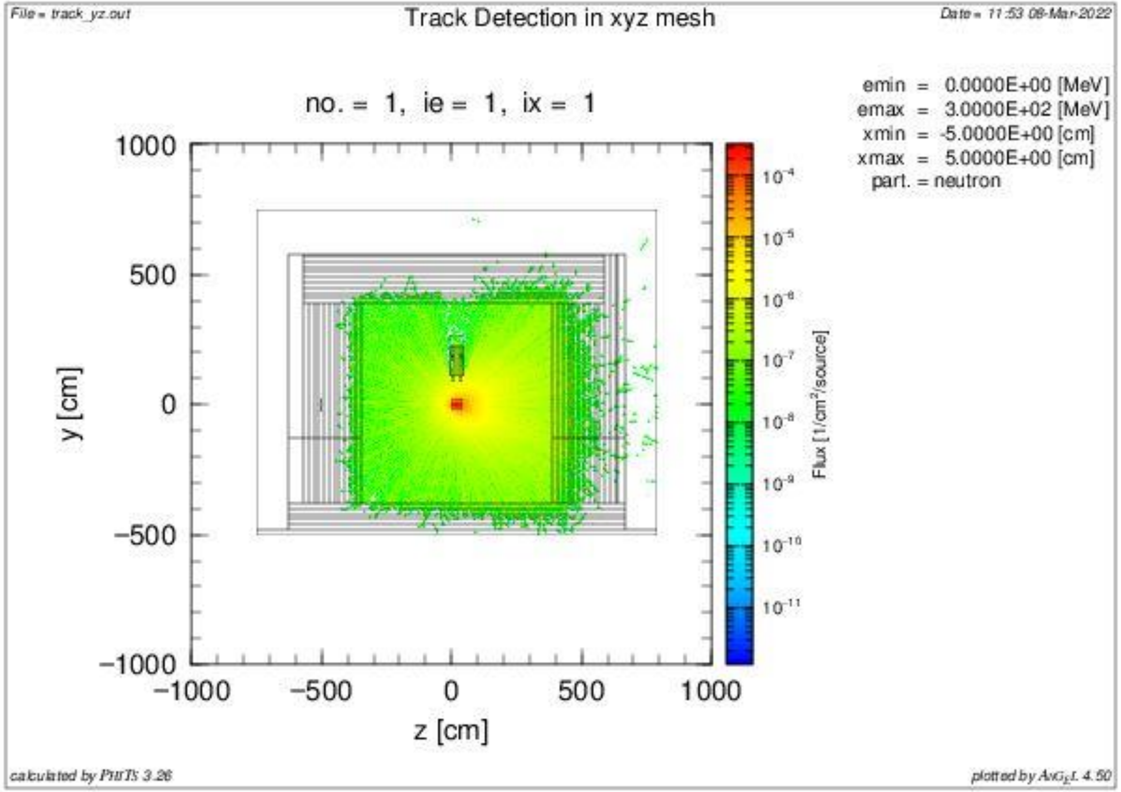


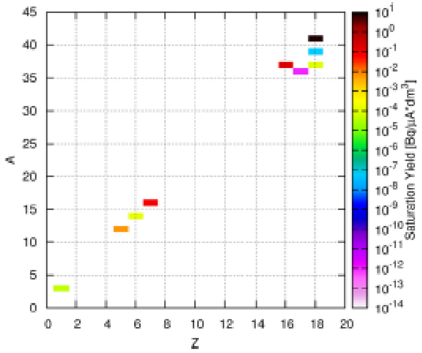




Soil activation in CPTC

Results: MC methods





No activation with soil slabs:

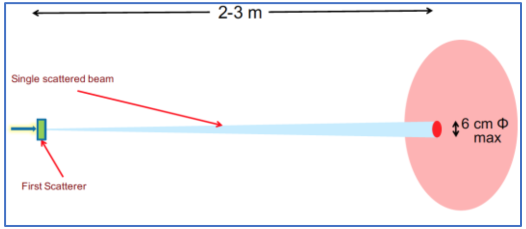
> 75 cm (cyclotrons)

> 50 cm (synchrotrons)

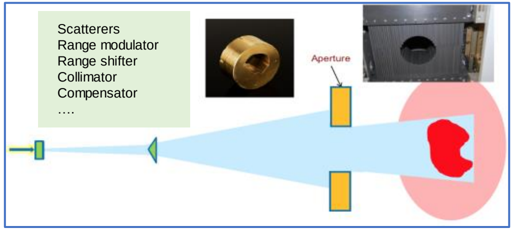
Fiberglass recommended

Impact of new developments (Evolution of delivery methods)

PT.1 → Passive methods → Scattering → High production of secondary neutrons

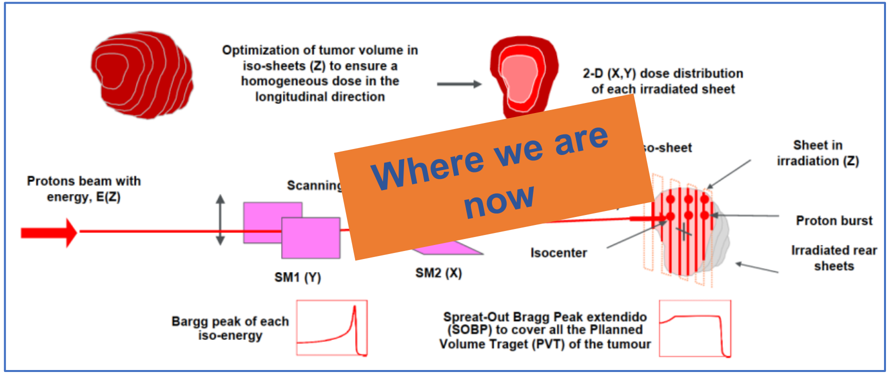


Where we come from

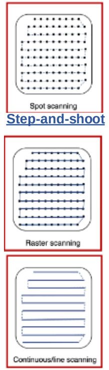


PT.2 → Active methods → Pencil Beam Scanning (PBS) → IMPT *(Intensity modulated proton therapy)*

Current Basic Workload



Where we are now



Yap et. al., 2021, Frontiers in Oncology, 11, 780025

PT.3 → In-development methods

- Flash-therapy → Disruptive
- Mini-beams
- PMAT … *ergetic arc therap*… ptative
- Blended modes (active+passive)

Where we are going

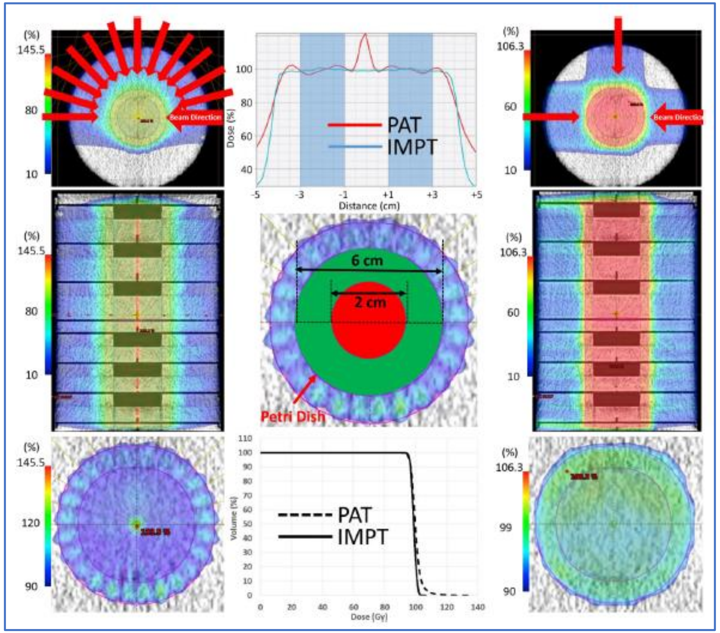
Impact of new delivery techniques on RP

New delivery modes: Special consideration (IAEA Tec-Doc 1891, 2020)

PMAT (Experimental)

Proton Monoenergetic Arc Therapy (Dr. Carabe- Fernandez)

Dosimetric plans PMAT/IMPT



Carabe-Fernández et al., 2020, Physics Medical and Biology, 65:165002

Bertolet and Carabe-Fernández, 2020, Physics Medical and Biology, 65:165006

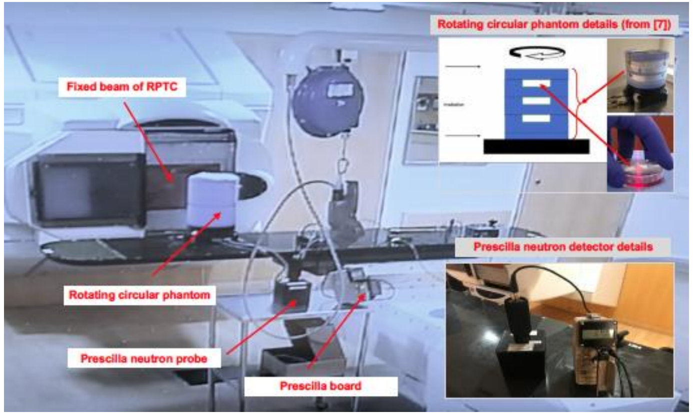
Which delivery method yields less secondary neutron dose, PMAT or IMPT?

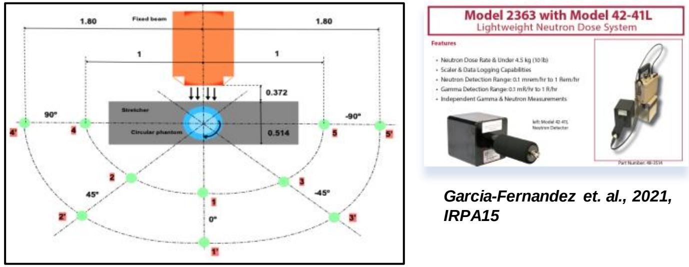
6 Gy

IMPT
SOBP
141.7 – 89.5 MeV

PMAT
Monoenergetic
117.5 MeV

Set-up for experimental measurements, H*(10)

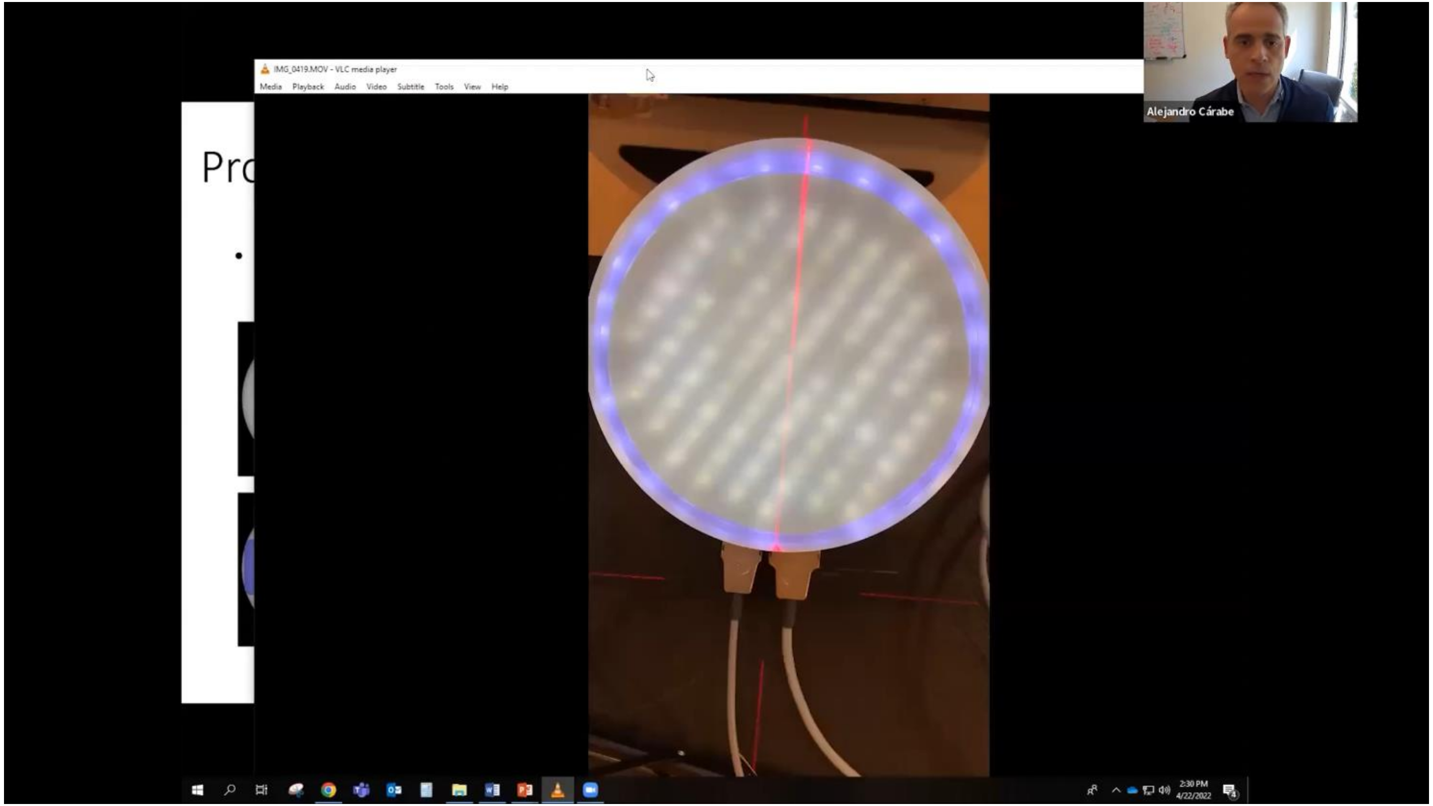




Garcia-Fernandez et. al., 2021, IRPA15

Radiation in action

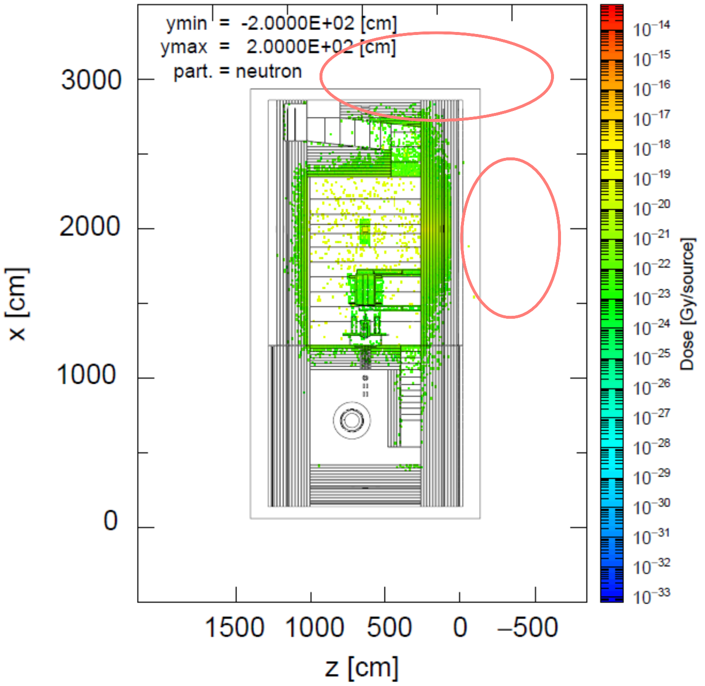
by Dr Carabe-Fernández



Case 2: Dose rate 25 Gy/s, transmission method, 230 MeV

IDR = 18 uSv/h > 10 uSv/h in some areas

IDR different in different countries

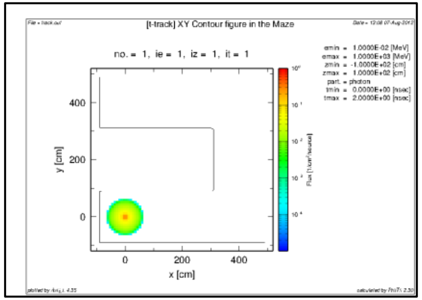


Garcia-Fernandez et. al., 2022, In Develpment

Dead time of radiation monitors

(5-10 microsecond)

Underestimations



PHITS, 2021, tutorial

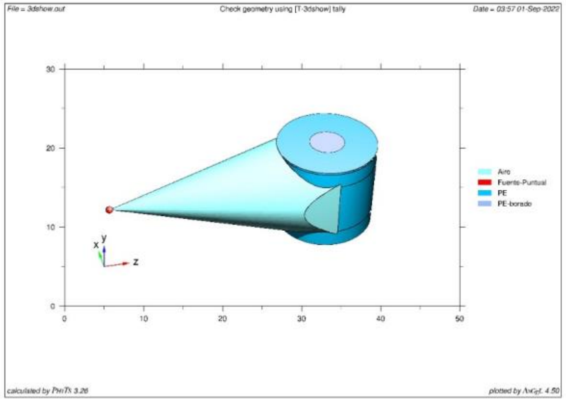
Another way to make more realistic assumptions

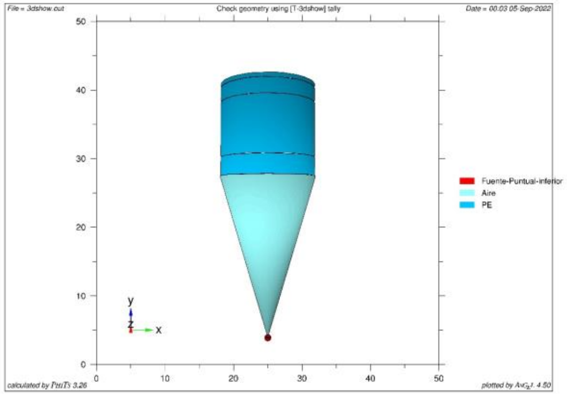
Experimental measurements to better assess the impact of new delivery techniques in development

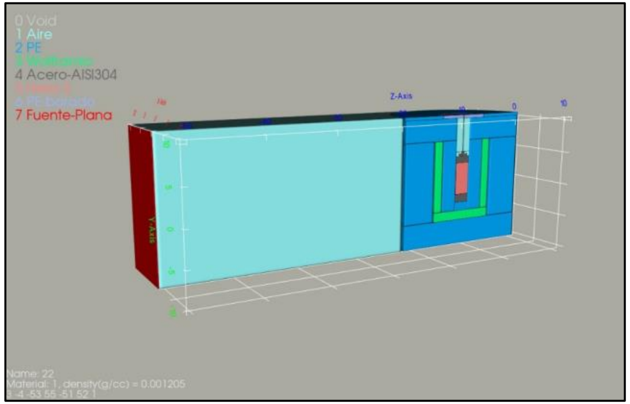
Carry-out of experimental measurements

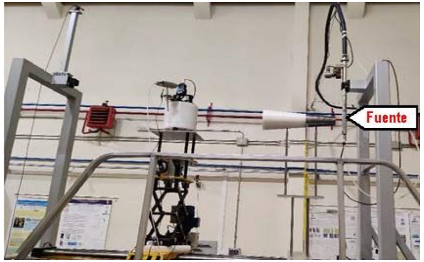
Another complementary way to make more realistic assumptions in workload

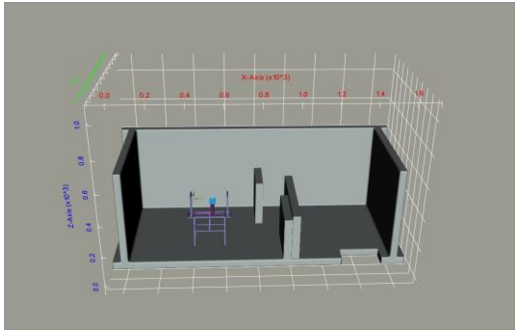
Carry-out of experimental measurements

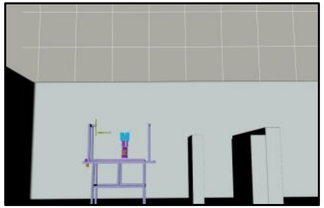












Another complementary way to make more realistic assumptions in workload

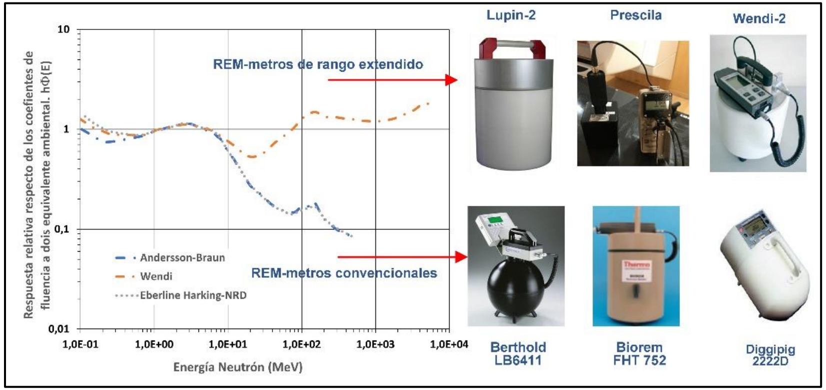
Extended-range rem-meters

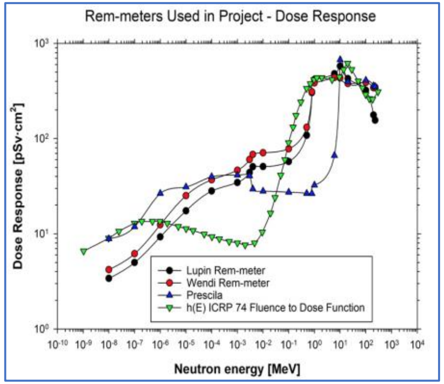
Selecting the right device for each application: Characterizing response of devices

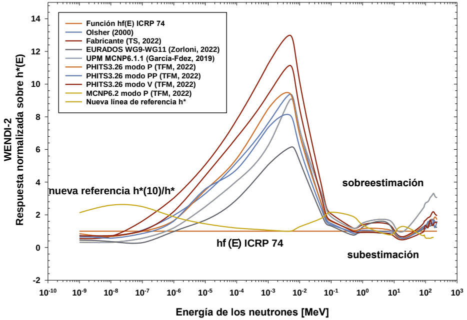
To carry out experimental measurements inside treatment rooms is necessary extended-range rem-meters (PNF with some new delivery methods)

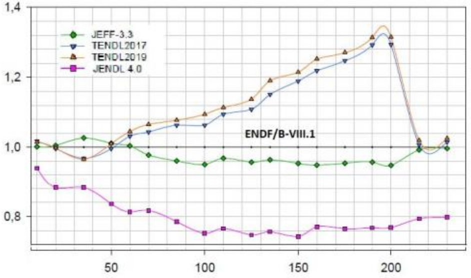
Outdoor is possible using conventional devices

actives





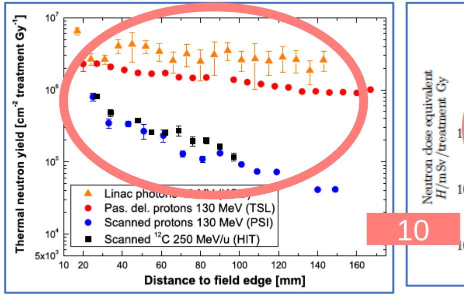




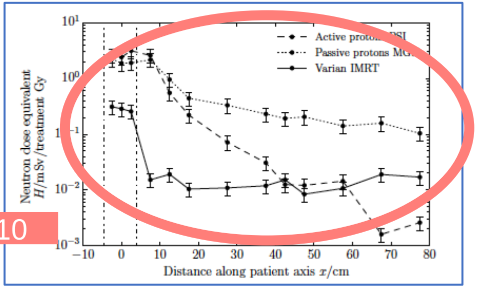
Verify assumptions and anticipate the impact of future developments

Developments could dramatically mitigate the effects of neutrons in proton therapy centers

Reducing *neutronic burden (PBS)*

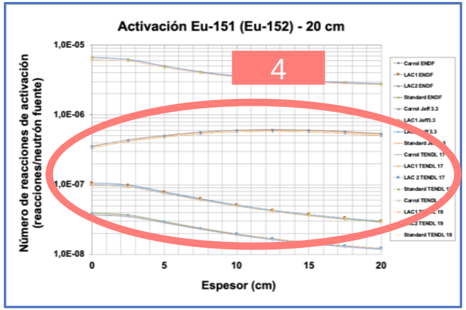


Kaderka et. al., 2012, Phys. Med. Biol. 57 5959



Hälg et. al., 2014, Phys. Med. Biol. 59 2457

Using concretes with low content in impurities (Eu for example)



Garcia-Fernandez et. al., 2021, IRPA15

Assumptions should be conservative but realistic, and based on updated information

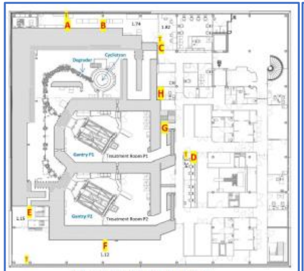


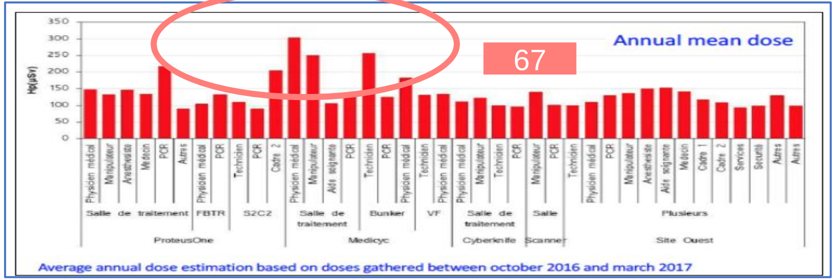
Figure 2. Lay-out of the facility
A…G are the measurement locations.
'T' indicates positions of TLD detectors in the building

Measurement Location	Simulation µSv/year	Simulation µSv/nAh	Measured Dose/nAh	Simulation/ Measurement
A	110	0,0229	0,000768	30
B	2	0,0004	0,000024	17
C	5	0,0010	0,00012	9
D	6	0,0013	0,00016	7
E	12	0,0025	0,000079	32
F	7	0,0015	0,000096	15
G	30	0,0063	0,00079	8
H	50	0,0104	0,0003	35

Table 1: comparison of MC-predicted and actual yearly dose levels at the locations shown in Figure 2.

7 - 35

Bolt et. al., PTC58-0127, PTCOG 2020 online



Herault et. al., Radiation Protection in PT in 1er Int. course on PT, Institute Curie, Paris, 2018

The Ten “Commandments” of RP in Compact Proton Therapy Centers (CPTC)

1. Select a suitable site and location for facility
2. Design barriers and shielding against neutron and gamma radiation
3. Use Monte Carlo simulations and check with analytical methods (or if you prefer, the opposite)
4. Choose appropriate materials in barriers
5. Review the impact of radiation on environment
6. Anticipate changes in assumptions and future developments
7. Place the right radiation monitor in the right place of the facility
8. Pick suitable personal dosemeters
9. Assume uncertainties but collect as much information as possible (soil, cement, concrete,…)
10. Carry out experimental measurements

Contributions to the commissioning of operational radiation protection in CPTC

Summary

1. The design of some **aspects of operational radiation protection was developed from 2018 until now**, within the research project Contributions to operational radiation protection and neutron dosimetry in compact proton therapy centers.

2. Currently, radiological protection in PTCs is carried out with **very conservative assumptions and high safety margins**, however, developments in proton therapy could have a huge impact in the operational radiation protection. Some developments could strongly change inputs in the workload and probably will rise the requirements.

3. The aim of this work was to present a commissioning process of the operational radiation protection of Compact Proton Centers, **summarized in ten main recommendations**, achieved in the activities mentioned above**, and lined up with requirements of Nuclear Authority (CSN)**. The goal of this process is to guarantee the compliance of dose limits for clinical and technical staff, and general public.

4. **Nuclear data are essential** for the comprehensive development of a research of this nature

The development of more efficient radiation protection measures could, significantly, optimize the thickness of the barriers, lowering the cost and size required to implement a proton therapy center, and in this way, the access to proton therapy could be easier for more countries and patients.

CEIDEN
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POLITÉCNICA

Nfq

Hybrid Meeting (virtual & in-person) on
"Nuclear Databases for Nuclear Reactor Applications within the Spanish Nuclear Sector"

September 20 (Tuesday), 2022. 09:00-13:00h

Thanks all the team

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Marisa Tormo (CSN)

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Juan Antonio Vera (QuirónSalud)

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