CEIDEN
PLATAFORMA TECNOLÓGICA DE ENERGÍA NUCLEAR DE FISIÓN

CNA Centro Nacional de Aceleradores

Infraestructuras Científicas y Técnicas Singulares

REUNION DEL CEIDEN – GUN
CNA (Sevilla)
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Desarrollo de modelos y equipos para el estudio de la protección radiológica frente a neutrones en protonterapia y aceleradores

Gonzalo F. Garcia-Fernandez[1], Eduardo Gallego[1], Jose M. Gomez-Ros[2]

(gf.garcia@upm.com)

Contribucciones en diferentes áreas/momentos del proyecto

Alejandro Carabe-Fernandez[3], Alejandro Bertolet-Reina[4], Roberto Méndez[2], Ana Mª Romero[2], Hector R. Vega-Carrillo[5]

Karen A. Guzman-Garcia[5], Lenin E. Cevallo-Robalino[6], Alfredo Lorente Fillol[1], Sviatoslav Ibáñez[1]

Roberto García-Baonza[1], Sergio Rivera[2], Pablo Gracia Tolosana[1]

1 POLITÉCNICA – INDUSTRIALES ETSII | UPM

2 Ciemat – Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

3 HAMPTON UNIVERSITY PROTON THERAPY INSTITUTE

4 MGH MASSACHUSETTS GENERAL HOSPITAL

5 UNIVERSIDAD AUTÓNOMA DE ZACATECAS "FRANCISCO GARCÍA SALINAS"

6 UNIVERSIDAD POLITÉCNICA SALESIANA ECUADOR

Scope

Purpose and context

Operational Radiation Protection (RP) in compact proton therapy centers (CPTC)

Research activities and main results

The ten recommendations

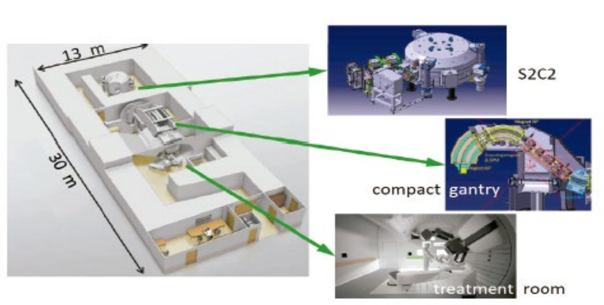
Summary

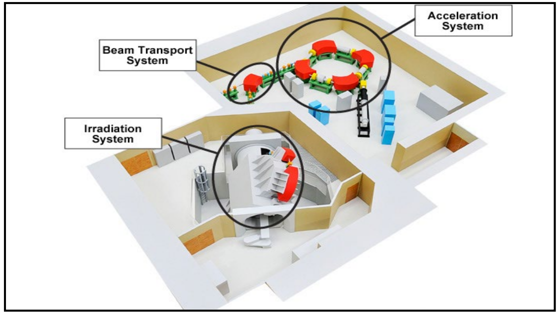
The advent of Protontherapy in Spain

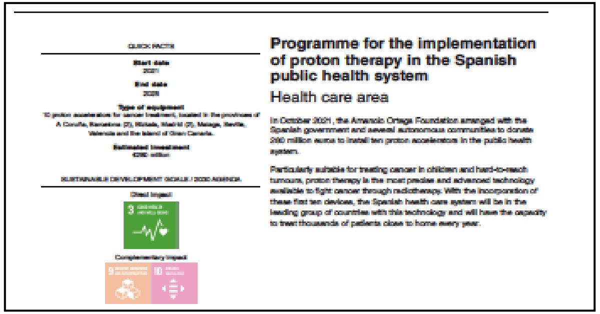
Number	Acelerator	Rooms	Footprint (Aprox)	Operation
1	**Synchrocyclotron**	1	360 m^2	Dec 2019
2	**Synchrotron**	1+(1)	800 m^2	March 2020


El Hospital Virtual Valdecilla formará a profesionales para aplicar la protonterapia antes de la puesta en marcha del equipo

Acelerator	Energy of Protons	Beam Delivery	Proton Field	Gantry Rotation
Synchrocyclotron	**Fixed (235 MeV)**	**PBS**	Continuous*	**220º**
Synchrotron	**Variable (70-230 MeV)**	**PBS**	Pulsed	**360º**






Programme for the implementation of proton therapy in the Spanish public health system

Health care area

2018→0 2020→ 2 (private) 2025?→ 13 (11 public) To infinity and beyond….

Origin and challenges of radioprotection in proton centers

Proton interactions → Neutron Fields
Neutron interactions → Impact in facility

Protons with energies between 70-230 MeV (intranuclear cascade + evaporation)

Neutrons interaction with matter

- Elastic scattering X (n,n) X
- Inelastic scattering X (n,n') X'
- Radiative capture $^{A}X\ (n,\gamma)\ ^{A+1}X$

For high-energy neutrons (> 8 MeV), reactions such as (n,2n) or (n,n+p) are possible

Each isotope exhibits its own cross section.

Neutron-induced activation processes

- Inelastic collisions (spallation processes)
- Neutron capture (n, γ)

Impact of neutrons in compact facilities

Material in walls What type of concrete is the best option for CPTC shielding and barriers → **Shielding, decommissioning and radioprotection**

- **Geometric and constructive factors**
- **New Materials**
- **New nuclear data libraries**

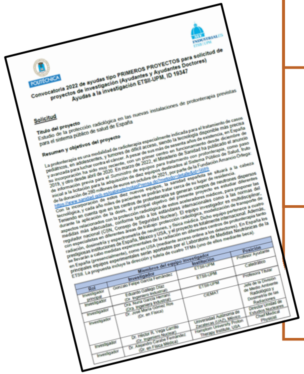
Elements of the facility (accelerator, beam components) → **Long term decommissioning, release strategy and personal radioprotection**

Air and water activation (cooling, others and ground water) → **Release strategy and personal radioprotection**

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



Parte 1 – Modelos de CPTC con MCNP6
1. Materiales y geometría
2. Fuentes de radiación
3. Carga de trabajo

Parte 2 – Medidas experimentales en CPTC
1. Caracterización de REM-metros y espectrómetros
2. Medidas experimentales en centros de protonterapia
3. Ampliación de monitores y sistemas de espectrometría

Parte 3 – Análisis de sensibilidad
1. Comparación de materiales y geometría
2. Comparación de Modelos físicos
3. Comparación de REM-metros y detectores

- **Proyecto de investigación**, colaboración empresa/organismo investigación: *Contribuciones a la protección radiológica operacional y dosimetría de neutrones en CPTC.*
- Primera etapa (financiación): 3 años (Feb. 2018 – Enero 2021) Investigación + Adquisión y ampliación de equipos
- 3 TFGs + 5 TFMs + 2 TDs
- Objetivos: **PT fuente continua de innovaciones. Impacto de los avances en PT en la PR de estos centros. Desarrollo de metodologías para analizar la protección radiológica operacional, dosimetría de neutrones, eficiencia de los blindajes, dosimetría personal.**

Purpose

Commissioning of proton centers: encompass radiation protection aspects

Operational radiation protection (RP): staff and general public. Shielding and barriers, activation, monitoring (personal dose, ambient equivalent dose…)

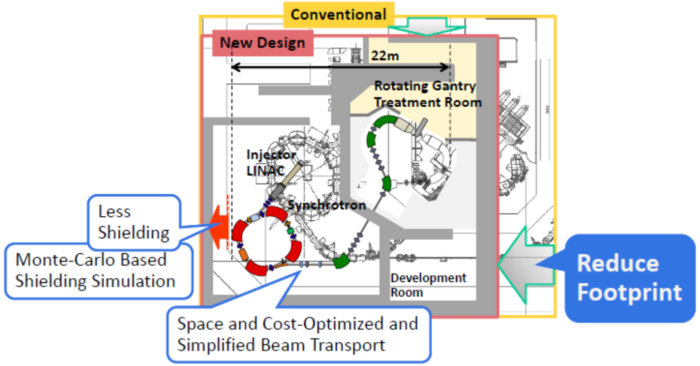
Compact proton therapy centers: CPTC (small size, 1 or 2 treatment rooms)

Impact of developments in proton therapy on operational radiation protection

Trends

1. **Compact and standard facilities**
2. **Small size accelerators**
3. **New delivery modes**
4. **Changes in regulations**

….



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)

- Factors of use and mix operation

    450 patients/year, 17.000 sessions, 2 Gy/patient

    Patient-case indications

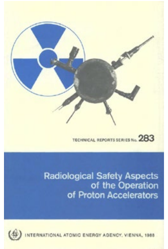
- Regulatory limits

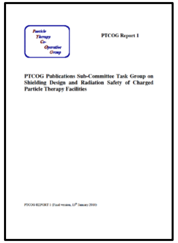
    General Public, 1 mSv/year (Spain)

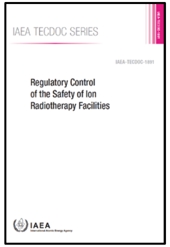
    Exposed workers, 20 mSv/year (Spain)

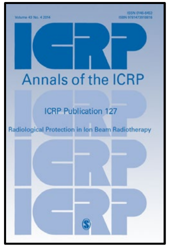
    Instantaneous dose rate, IDR, hourly: 10 uSv/h (Spain)

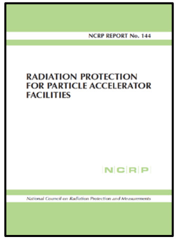
- Occupancy factors (T) → IAEA, 2006
- Types of beam: Clinic, Q&A, Maintenance
- Dose Rates: year, hour, instantaneous, facility
- Conservative magnitudes → Ambient Dose Equivalent, H*(10) (Hp*(10))









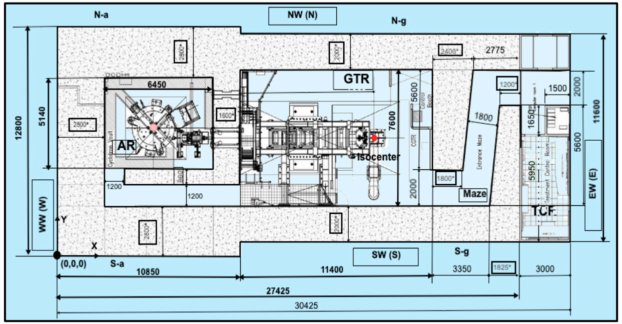


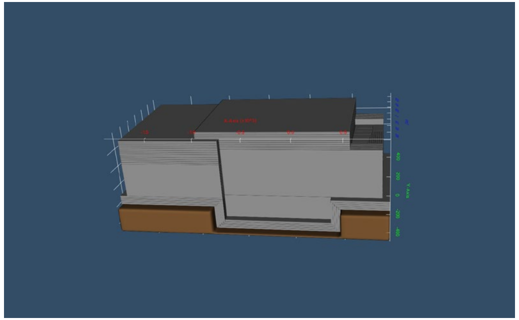
MCNP6 | PHITS Particle and Heavy Ion Transport code System | GEANT4

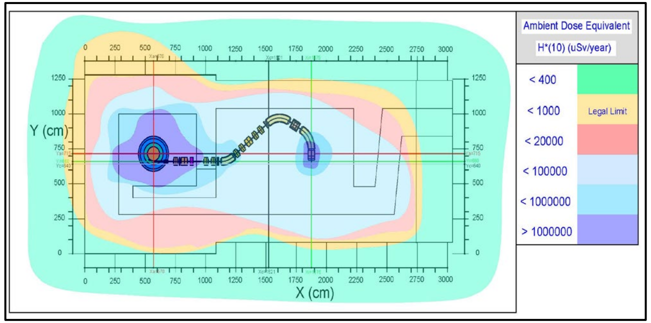
Assumptions and uncertainties (conservatives, 20y)

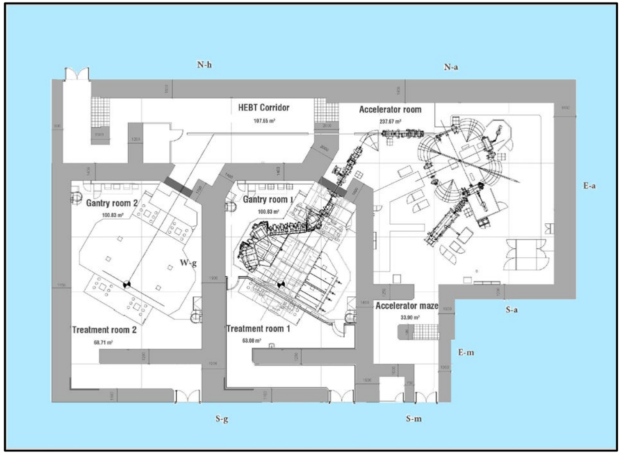
Compositions (nuclides) - Interactions – **Workload → <u>Delivery mode</u>**

Design barriers and shielding against neutron and gamma radiation







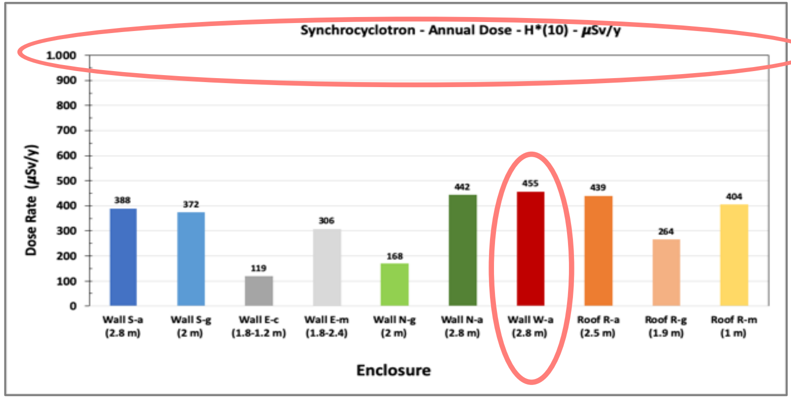


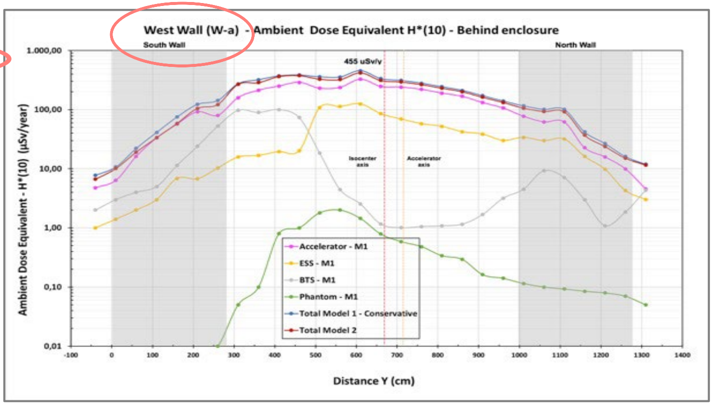
Main interaction of protons in Synchrocyclotron (SC)			
Element	**Energy (MeV)**	**% Losses**	**Material**
Accelerator (SC)	230	75%	Fe, Cu
Degrader (ESS)	230	25%	C
Collimator (ESS)	70 – 230	44%	Ta
Divergence Slits	70 – 230	5%	Ni
Divergence Momentum	70 – 230	1%	Ni
Patient-Phantom	70 – 230	100%	Tissue

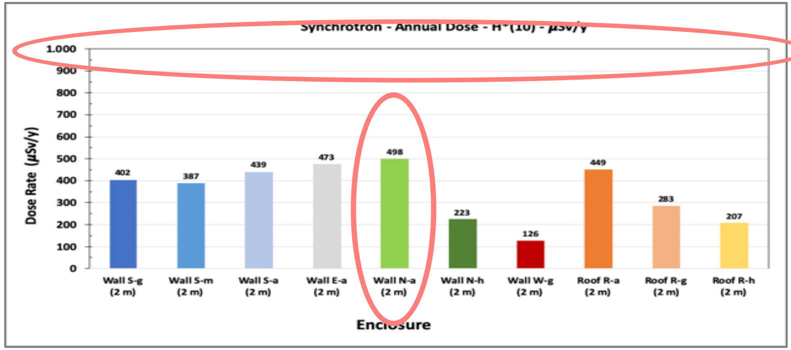
Main interaction of protons in Synchrotron (SC)			
Element	**Energy (MeV)**	**% Losses**	**Material**
Linac/Injection/LEBT	7.5	60%	Fe, Cu
Accelerator (S)	70 – 230	40%	Fe, Cu
HEBT	70 – 230	10%	Fe, Cu
Divergence Slits	70 – 230	5%	Ni
Divergence Momentum	70 – 230	1%	Ni
Patient-Phantom	70 – 230	100%	Tissue

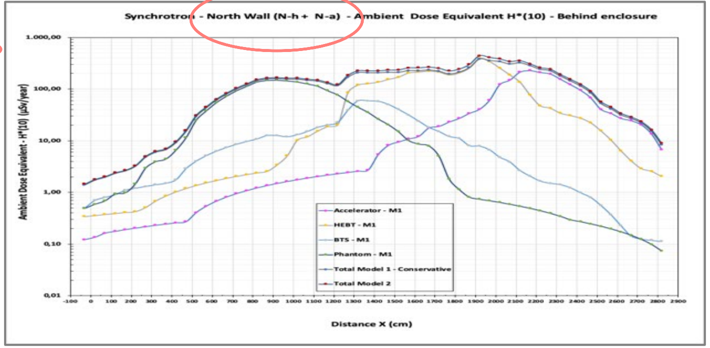
Design barriers and shielding against neutron and gamma radiation

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

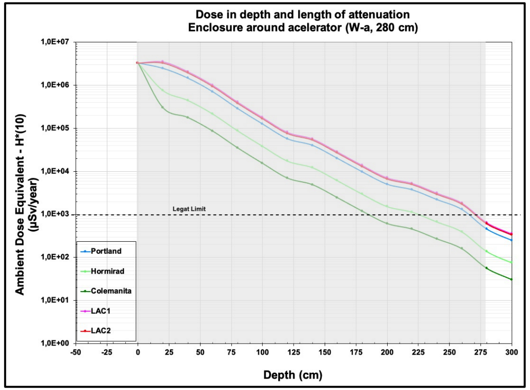
Synchrotron
One treatment room expandable
800 m^2 footprint
2 m thickness in main barriers

Intercomparing CPTC: synchrocyclotron vs. synchrotron

Expansion to new types of centers planned for the Public System

Study of different materials in barriers

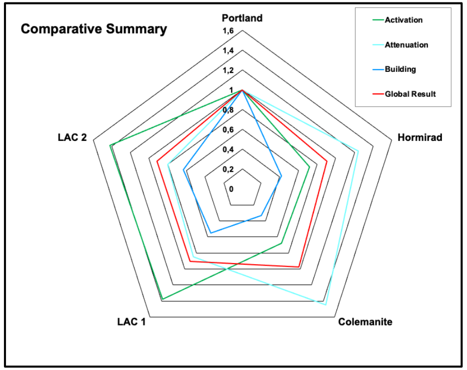
Attenuation plots with different types of concrete



Attenuation is essential but not enough

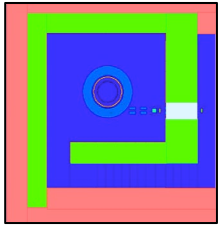
Radionuclide	Reaction channel	$T_{1/2}$
^{152}Eu	^{151}Eu (n,γ) ^{152}Eu	13.33 y
^{154}Eu	^{153}Eu (n,γ) ^{154}Eu	8.8 y
^{134}Cs	^{133}Cs (n,γ) ^{134}Cs ^{134}Ba (n,p) ^{134}Cs	2.06 y
^{60}Co	^{59}Co (n,γ) ^{60}Co	5.3 y
^{46}Sc	^{45}Sc (n,γ) ^{46}Sc	83 d
^{133}Ba	^{132}Ba (n,γ) ^{133}Ba	10.5 y
^{54}Mn	^{55}Mn (n,2n) ^{54}Mn ^{54}Fe (n,p) ^{54}Mn	312 d
^{22}Na	^{23}Na (n,2n) ^{22}Na ^{27}Al (n,2p4n) ^{22}Na	2.6 y
^{137}Cs	^{136}Ba (n,γ) ^{137m}Ba → ^{137}Cs ^{137}Ba (n,p) 137Cs	30 y

Comparative of several materials (concretes)



	Attenuation	Activation	Building	Global Result
Portland	1	1	1	1,00
Hormirad	1,24	0,72	0,42	0,91
Colemanite	1,45	0,68	0,33	0,98
LAC 1	0,85	1,38	0,55	0,91
LAC 2	0,8	1,42	0,63	0,91

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: $^{40}Ar(n,\gamma)^{41}Ar$ (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	$^{133}Cs(n,\gamma)^{134}Cs$	29
^{60}Co	5.3 year	$^{59}Co(n,\gamma)^{60}Co$ $^{60}Ni(n,p)^{60}Co$	37
^{59}Fe	44 days	$^{58}Fe(n,\gamma)^{59}Fe$	1.15
^{65}Zn	244 days	$^{64}Zn(n,\gamma)^{65}Zn$	0.78
^{54}Mn	312 days	$^{55}Mn(n,2n)^{54}Mn$ $^{54}Fe(n,p)^{54}Mn$	0.91 0.59
^{108}Ag	127 year	$^{107}Ag(n,\gamma)^{108}Ag$	36
^{110}Ag	249 days	$^{109}Ag(n,\gamma)^{110}Ag$	91
^{123}Sn	129 days	$^{122}Sn(n,\gamma)^{123}Sn$	0.15
^{125}Sn	9 days	$^{124}Sn(n,\gamma)^{125}Sn$	0.13
^{22}Na	2.6 year	$^{23}Na(n,2n)^{22}Na$ $^{27}Al(n,x)^{22}Na$	0.017 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

Impact of neutrons in the environment of compact facilities

Air and water activation (cooling, others and ground water) →

Release strategy and personal radioprotection

Materials in soil (characterizing the soil before building) →

Decommissioning and radioprotection

Elements of the facility (accelerator, beam components) →

Long term decommissioning, release strategy and personal radioprotection

$$\frac{\mathrm{d}N'}{\mathrm{d}t} = N\Phi\sigma - \lambda N'$$

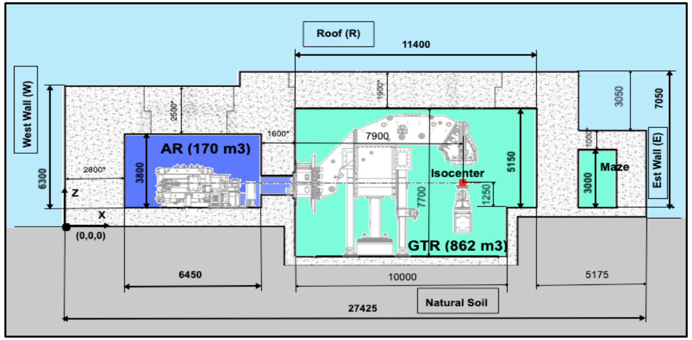
✓ Activity build-up during irradiation
- Number of target nuclei N
- Neutron flux Φ
- Reaction cross section σ

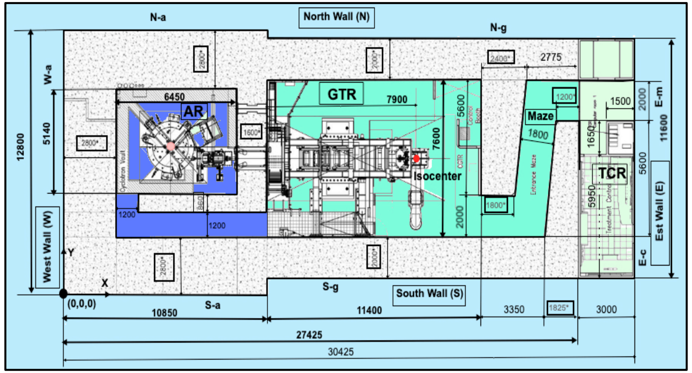
✓ And decay of the produced radionuclides
- Decay constant λ

$$\frac{\text{Reacciones}}{\text{Volumen}} = \int \varphi(E)\rho\sigma(E)dE$$

Air activation in CPTC (example)

Evaluation of effects





Monte Carlo methods

Yearly effective doses and activity concentration limits from activated air

- **Air renewal minimum: 6 CPH (each 10 minutes)**
- **No decay and no dilution considered (worst scenario**)

10^9 stories
Statistical uncertainty < 5%

Nuclear models (E>150 MeV)
INC → CEM03.03
EVM → GEM

Nuclear data:
ENDF/B (version VII.1)
JEFF (version 3.3),
TENDL 2017 and 2019

S(α,β) Model in PE and H
ENDF71SaB
(ENDF/B-VII.0)

Analytical methods

ICRP PUBLICATION 127 (2014)

AR = 33.8 Bq/m^3

GTR1 = 12.5 Bq/m^3

GTR2 = 48.7 Bq/m^3

Legal limit (IAEA) = 200 Bq/m^3

Analytical methods underestimate air activities in some nuclides (use of averaged cross sections)

Air activation in CPTC

Results: MC methods

Effective dose

$$E_{hora}\left(\frac{\mu Sv}{h}\right) = A_{sat}(i)\left(\frac{Bq}{m^3}\right)\cdot Res\left(\frac{m^3}{h}\right)\cdot \Gamma(i)\left(\frac{Sv}{bq}\right)\cdot 10^6$$

$$E_{Año}\left(\frac{\mu Sv}{año}\right) = E_{hora}\left(\frac{\mu Sv}{h}\right)\cdot 4800\, h/año$$

- Yearly effective doses and activity concentration limits from activated air
  - Air renewal 6 x per hour (10 minutes)
  - No decay and no dilution considered

Room	Nuclide	T1/2	Saturated Activity (Bq/m³)	e_{inh} (Sv/Bq)	Yearly Dose (µSv/y)	CA-20 mSv (Bq/m³)	CA-1 mSv (Bq/m³)
GTR	H-3	12.32 y	$2.59\ 10^{-5}$	$1.8\ 10^{-11}$	$2.69\ 10^{-6}$	$5\ 10^{9}$	$1.04\ 10^{8}$
	Be-7	53.22 d	$1.64\ 10^{-4}$	$4.6\ 10^{-11}$	$4.35\ 10^{-5}$	$5\ 10^{5}$	$1.04\ 10^{4}$
	C-11	20.39 min	$8.69\ 10^{-1}$	$3.2\ 10^{-12}$	$1.60\ 10^{-2}$	$2\ 10^{5}$	$4.17\ 10^{3}$
	N-13	9.965 min	6.09		NA	$7\ 10^{4}$	$1.46\ 10^{3}$
	O-15	122.24 sec	3.98		NA	$7\ 10^{4}$	$1.46\ 10^{3}$
	Ar-41	109.61 min	$5.35\ 10^{-1}$		NA	$5\ 10^{4}$	$1.04\ 10^{3}$
AR	H-3	12.32 y	$8.27\ 10^{-3}$	$1.8\ 10^{-11}$	$8.57\ 10^{-4}$	$5\ 10^{9}$	$1.04\ 10^{8}$
	Be-7	53.22 d	$7.04\ 10^{-2}$	$4.6\ 10^{-11}$	$1.87\ 10^{-2}$	$5\ 10^{5}$	$1.04\ 10^{4}$
	C-11	20.39 min	$3.80\ 10^{2}$	$3.2\ 10^{-12}$	$1.60\ 10^{-2}$	$2\ 10^{5}$	$4.17\ 10^{3}$
	N-13	9.965 min	$2.16\ 10^{3}$		NA	$7\ 10^{4}$	$1.46\ 10^{3}$
	O-15	122.24 sec	$1.60\ 10^{3}$		NA	$7\ 10^{4}$	$1.46\ 10^{3}$
	Ar-41	109.61 min	$8.91\ 10^{2}$		NA	$5\ 10^{4}$	$1.04\ 10^{3}$

Air activation in CPTC

Mitigation strategies for air activation

Ventilation requirements to prevent that the concentration of the radioactive gases (^{3}H, ^{15}O, ^{13}N, ^{41}Ar) and ozone produced during irradiation remain below the health safety limits and the legal radioactive atmospheric release criteria

Design of Ventilation System

General

Variable flow system ventilation. During irradiation, the ventilation System must be stopped, but once it is finished, post-irradiation air must be renewed as quickly as possible, considering the maximum speed recommended in ducts.

Decentralized ventilation circuits

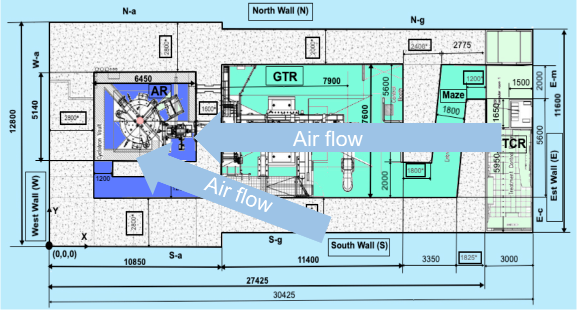
Air renewals rate

Cyclotron room, CPH = 10/hour

Treatment room, CPH = 10/hour

Technical part gantry (gantry pit) CPH = 6/hour

$$\lambda_{effective} = \lambda + r$$



Pressure cascade (avoid a flow of air from inside to outside of the bunker)

Underpressure inside the bunker

Differential pressure between maze/treatment room (10/15 Pa) and accelerator room (< -40 Pa)

Continuous readout and checking of pressures in rooms

Water activation in CPTC

Main results with MC

Isotope	MC Result (Bq/l)	Clearance Level, CL (IAEA, Bq/l)	Result/CL	Usual Range of Detection limit (Bq/l)
^{3}H	9.3	10^{5}	$9.3 \cdot 10^{-5}$	7 - 9
^{7}Be	7.7	10^{4}	$7.7 \cdot 10^{-4}$	5 - 7

Global activity in water
< 20 Bq/l

Σ Result/CL << 1

Self-shielding of water

Activation in metallic elements >> activation in water

Soil activation in CPTC

Location of center: check and remove

Radionuclide	Reaction channel	$T_{1/2}$
^{152}Eu	$^{151}Eu\ (n,\gamma)\ ^{152}Eu$	13.33 y
^{154}Eu	$^{153}Eu\ (n,\gamma)\ ^{154}Eu$	8.8 y
^{134}Cs	$^{133}Cs\ (n,\gamma)\ ^{134}Cs$ $^{134}Ba\ (n,p)\ ^{134}Cs$	2.06 y
^{60}Co	$^{59}Co\ (n,\gamma)\ ^{60}Co$	5.3 y
^{46}Sc	$^{45}Sc\ (n,\gamma)\ ^{46}Sc$	83 d
^{133}Ba	$^{132}Ba\ (n,\gamma)\ ^{133}Ba$	10.5 y
^{54}Mn	$^{55}Mn\ (n,2n)\ ^{54}Mn$ $^{54}Fe\ (n,p)\ ^{54}Mn$	312 d
^{22}Na	$^{23}Na\ (n,2n)\ ^{22}Na$ $^{27}Al\ (n,2p4n)\ ^{22}Na$	2.6 y
^{137}Cs	$^{136}Ba\ (n,\gamma)\ ^{137m}Ba \rightarrow\ ^{137}Cs$ $^{137}Ba\ (n,p)$ 137Cs	30 y

Depend on the specific location of each facility

Easy to mitigate in early stages

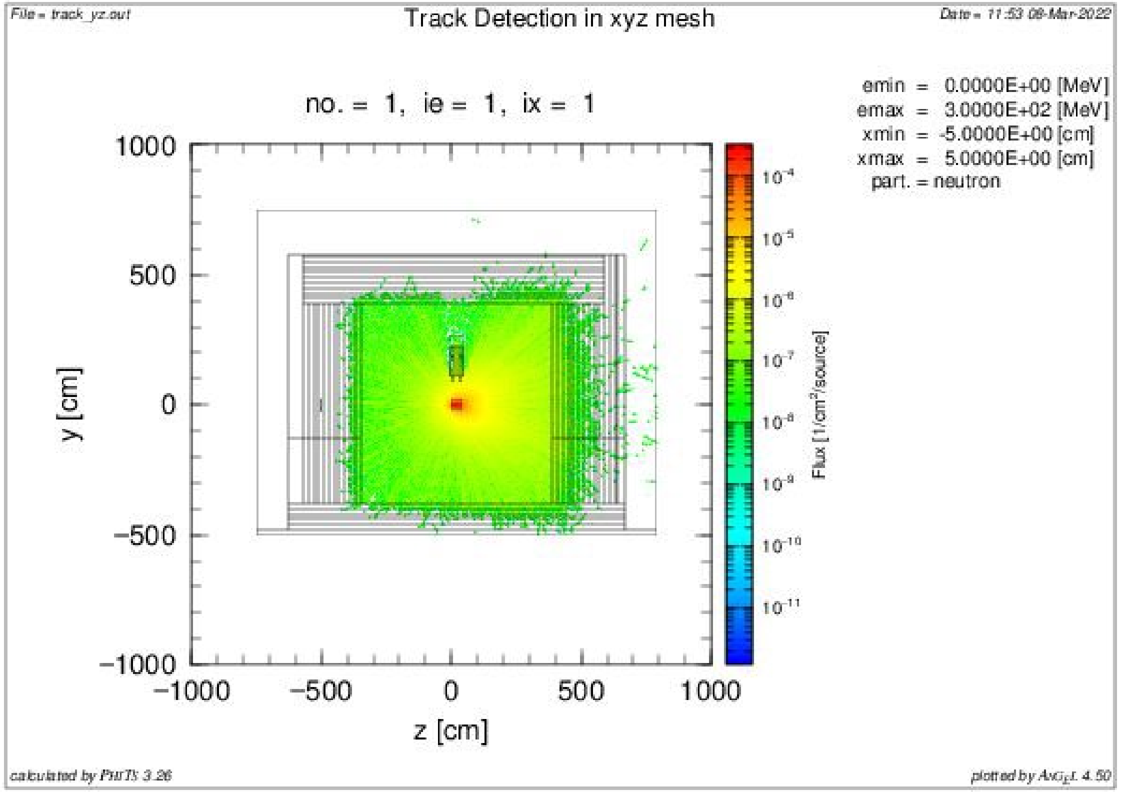
Soil characterisation, with gamma spectrometry, to know parents nuclides

Building material characterisation (cement. sand. gravel)

The main concern is the migration of radionuclides with ground water

Soil activation in CPTC

Results: MC methods



No activation with soil slabs:

> 75 cm (cyclotrons)

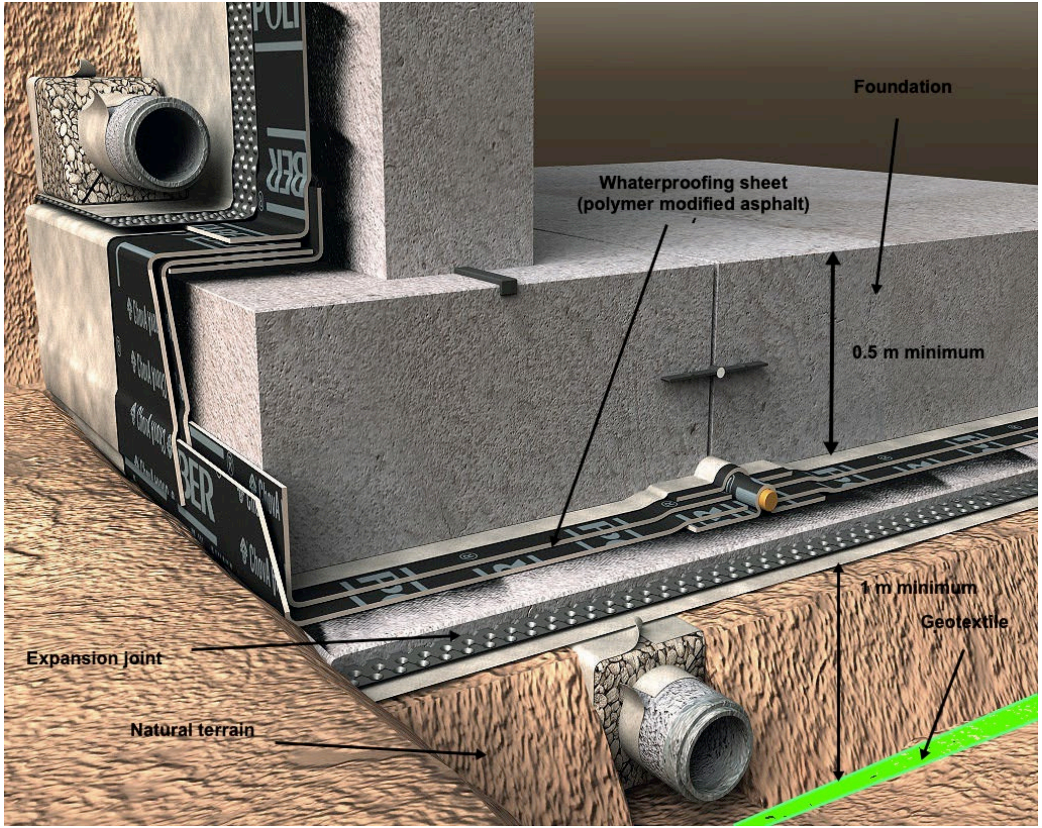
> 50 cm (synchrotrons)

Fiberglass recommended

Soil activation in CPTC

Mitigation strategies for soil activation

- Minimal slab thickness 50 cm
- Avoid water under the foundations slab
- Waterproofing sheet, expansion joint and geotextile under foundations to mitigate neutrons interactions with ground water and natural soil
- Soil characterisation with gamma spectrometry (substitution of upper layer)
- Building material characterisation (cement, sand, gravel, …) via gamma spectrometry

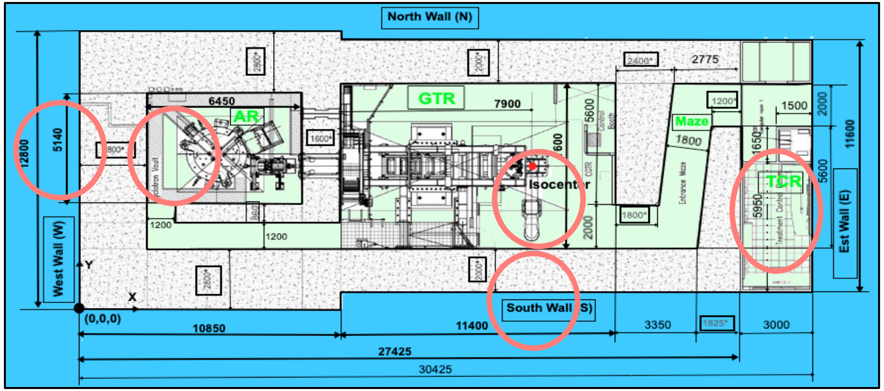


Assessment of personal dosemeters for proton centers (Monte Carlo)

Dosemeters, active (DLD)

Dosemeters, Passive, Albedo (TLD)

Dosemeters, Passive, Track etch (CR39)



- Correction factors for electronic dosimeters up to a factor 9
- Smaller corrections for track etch, and médium for albedo, depending ofnthe location

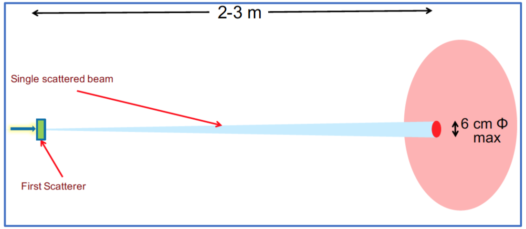
Garcia-Fernandez et. al., ISSSD XX 2020

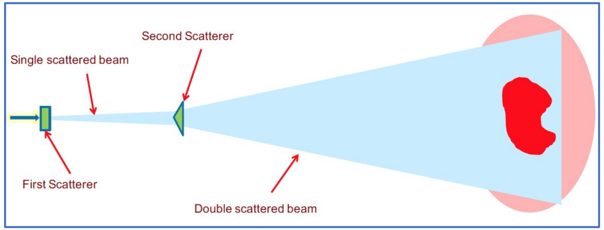
$H_p(10)_{cal}/H_p(10)_{ref}$	W-a inside	W-a outside	S-g inside	S-g outside	TCR
Active - DLD	8.4	8.9	3.2	4.7	9.6
Pasive - Albedo	2.7	1.5	1.2	1.8	1.3
Pasive – Track	0.7	2.9	0.8	1.6	2.4

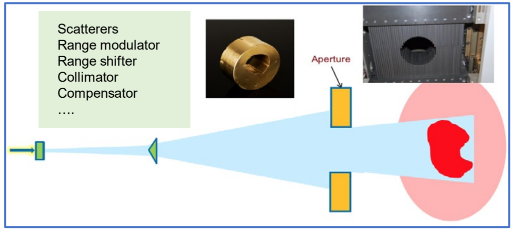
Selection of personal neutron dosemeter most suitable for CPTC

Impact of new developments (Evolution of delivery methods)

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

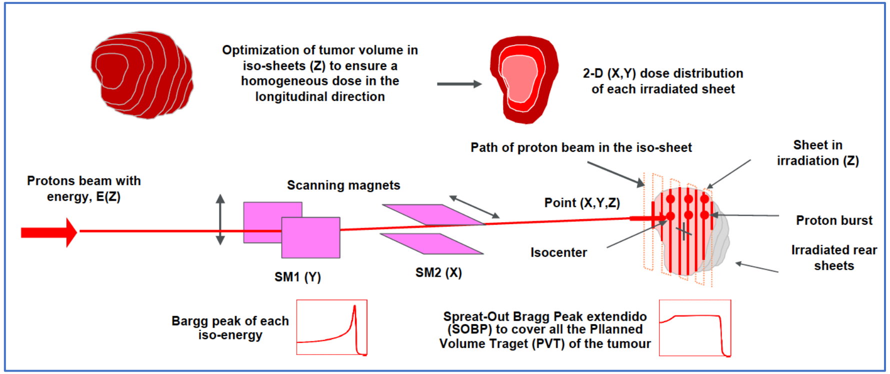


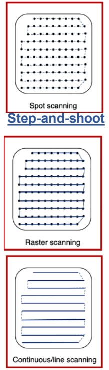




PT.2 → Active methods → Pencil Beam Scanning (PBS) → IMPT *(Intensity modulated proton therapy)*

Current Basic Workload





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

PT.3 → In-development methods

- Flash-therapy → Disruptive
- Mini-beams
- PMAT *(Proton monoenergetic arc therapy)* → Adaptative
- Blended modes (active+passive)

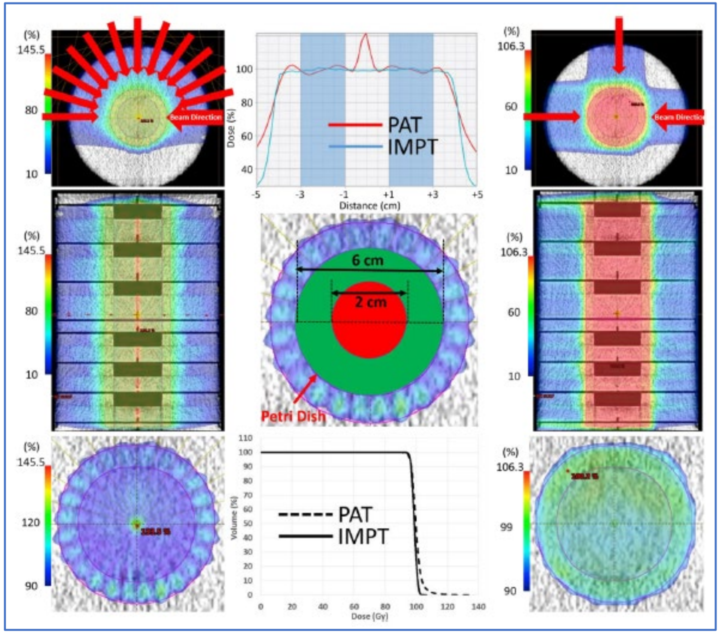
Impact of new delivery techniques on RP

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

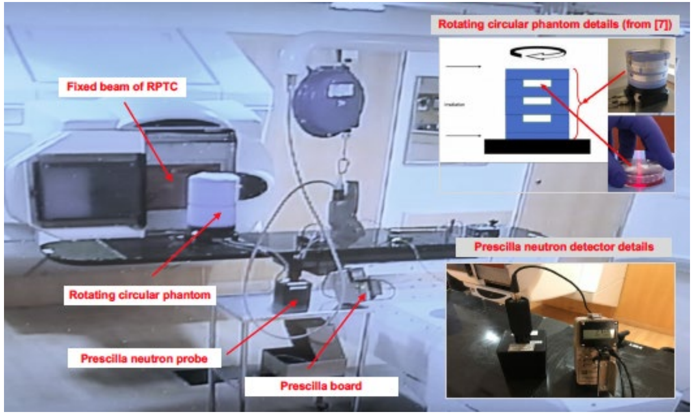
Which delivery method yields less secondary neutron dose, PMAT or IMPT?

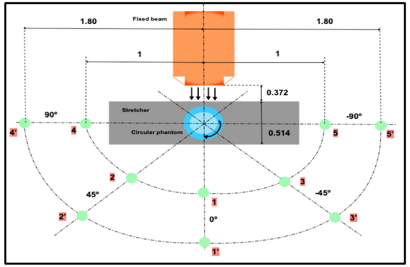
6 Gy

IMPT
SOBP
141.7 – 89.5 MeV

PMAT
Monoenergetic
117.5 MeV

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



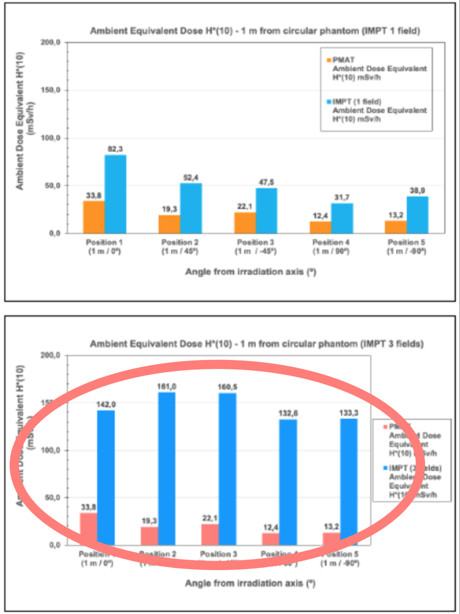


Garcia-Fernandez et. al., 2021, IRPA15

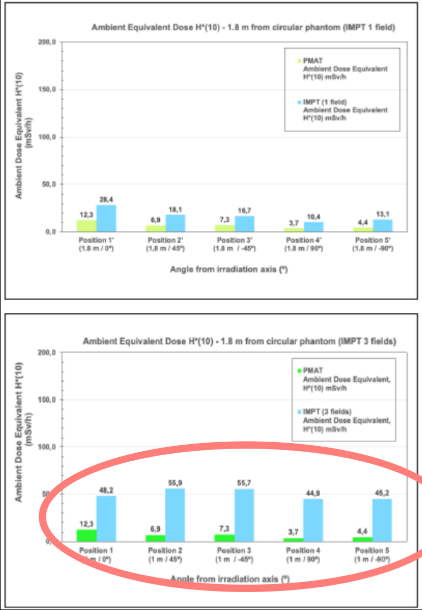
Impact of PMAT on RP

Experimental results, H*(10)

1 m isocenter



1.8 m isocenter



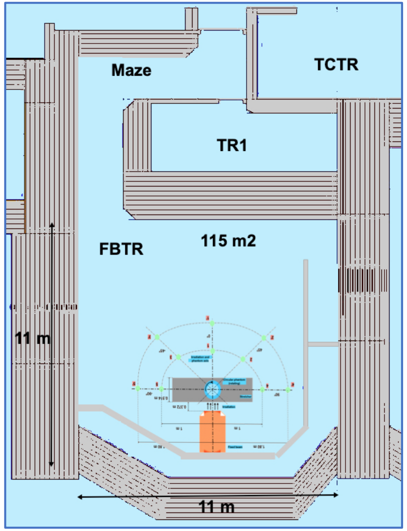
Garcia-Fernandez et. al., 2021, IRPA15

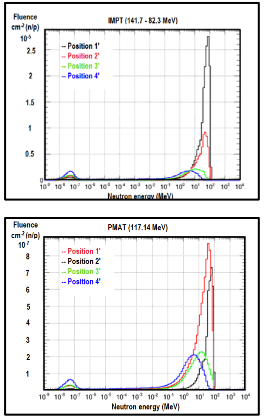
Biological improvement, based on enhanced biological impact (therapeutic index) better than based on increased conformity *Mazal et. al., 2021, Frontiers in Oncology, Volm. 10, article 613669*

PMAT could have a non-negligible reduction of secondary neutrons, with a direct positive impact on operational radiation protection.

Simulations with MCNP6.2/GEANT4

MPTC (isochronous cyclotron)





Garcia-Fernandez et. al., 2021, IRPA15

Position	Distance from source (cm)	MCNP6 WENDI-II Response (µSv/h)	MCNP6 Prescila Response (µSv/h)	MCNP6 H*(10) (µSv/h)	Experimental measurements With Prescila H*(10) (mSv/h)
1	100	89±4	86±4	88±3	82±7

Differences <10%

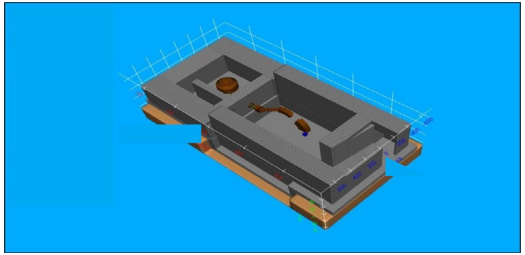
Some alternatives

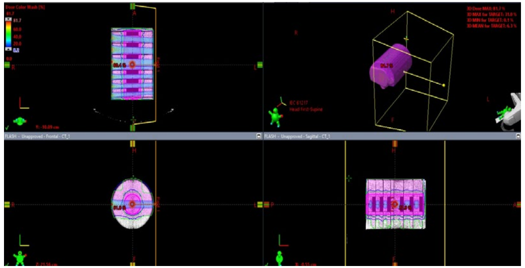
Parametric workload
Monte Carlo workload

Gupta et. al., POP04, PTCOG 2020 online

Simulations with Monte Carlo

CPTC (synchrocyclotron)





Garcia-Fernandez et. al., 2021, Applied Radiation and Isotopes, 169, 109279

Dose: 6 Gy

IMPT
SOBP
141.7 – 89.5 MeV

PMAT
Monoenergetic
117.5 MeV

Pr-FLASH
Transmission
210 MeV, 500 ms, 12 Gy/s
Stopped in water phantom
40x40x40 cm^3
(behind circular phantom)

Simple case with MCNP6.2® (Case 1)

10^9 stories
Statistical uncertainty < 5%

Nuclear models (E>150 MeV)
INC → CEM03.03
EVM → GEM

Nuclear data:
ENDF/B (version VII.1)
JEFF (version 3.3),
TENDL 2017 and 2019

S(α,β) Model in PE and H
ENDF71SaB
(ENDF/B-VII.0)

Hourly Dose Rate (HDR) uSv/h

Treatment Control Room (TCR)

Occupancy factor, T=1

IMPT
5.1 uSv/h (baseline 1)

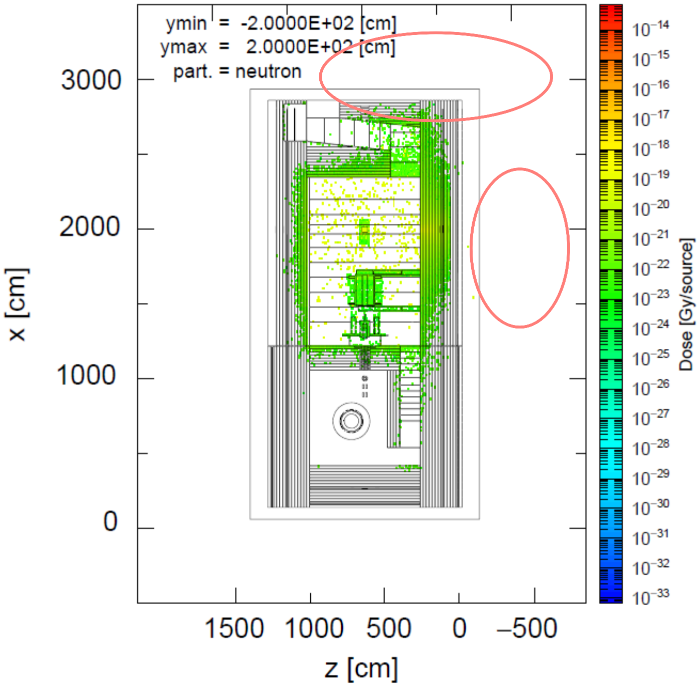
PMAT
2.3 uSv/h (0.45 under baseline)

Pr-FLASH
7.8 uSv/h (1.53 over baseline)

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

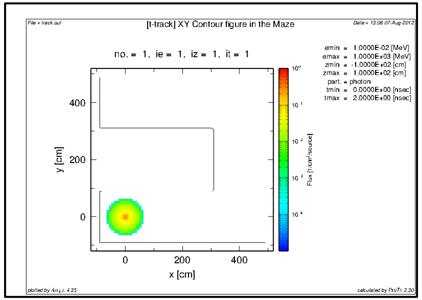


Garcia-Fernandez et. al., 2022, In Develpment

Dead time of radiation monitors

(5-10 microsecond)

Underestimations

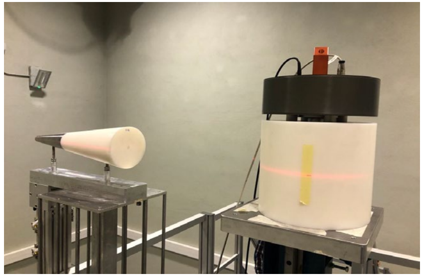


PHITS, 2021, tutorial

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

Wherever they come from, neutrons are a serious challenge in radioprotection

- Neutrons always together with (mostly strong) gamma fields

- Large energy range: nine orders of magnitude
    - Thermal 0.025 eV to hundred of MeV

- Need to measure dose equivalent
    - Weighting factor dependent on neutron energy
    - Fast neutron much more harmfull than thermal neutron (per deposited energy)

- Easy detection of thermal neutrons
    - Least harmfull
    - Original neutrons are fast

Vanhavere, P., Van Hoey, O., De Saint-Hubert, M.,
Neutron doses to patients and staff around proton therapy installations, SCK-CEN Presentation, Online 2019

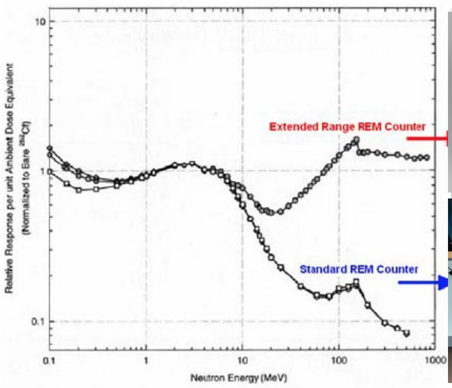
Extended-range rem-meters

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)

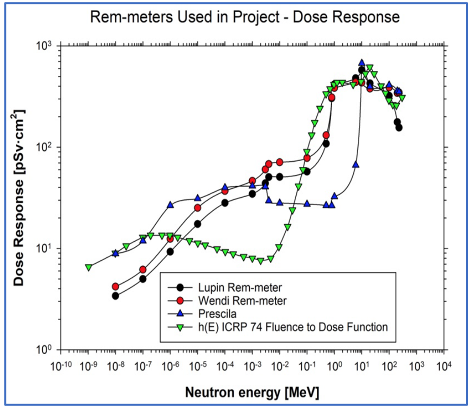
Outdoor is possible using conventional devices

actives



wendi

prescila



Garcia-Fernandez et. al., 2019, Applied Radiation and Isotopes, 152, 105-126

lupin

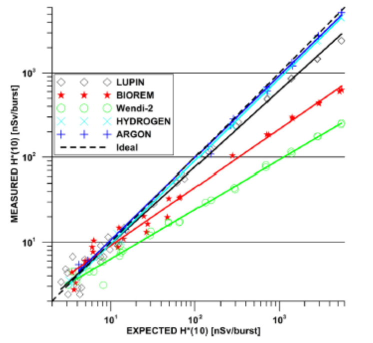


Fig. 7. Response of the detectors in position 1. The dotted line is the bisector of the first quadrant, representing the ideal linear behaviour. The uncertainties are not shown for clarity.

Dinar et. al., 2018, Radiation Measurements, 117, 24-34

Caresana et. al., 2014, NIM, 1737, 203-213

Manessi, G.P., 2015, DT, University of Liverpool

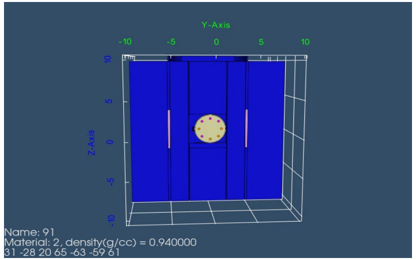
passives

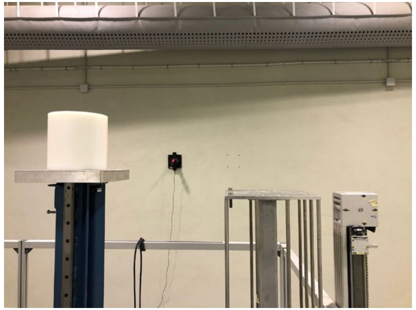
Always it is highly recommended to support measurements from active equipment with reliable data (passive monitors, Bonner spheres,…).

- No dead time
- Low sensitivity (increasing time of exposition)
- Insensitive to photons

Extended-Range Passive Neutron Monitor (ERPNM)

Calibration an assessment (Primer)





Simulations:
UPM
Roberto García-Baonza

Gamma calibration:
Ciemat (A. Romero)

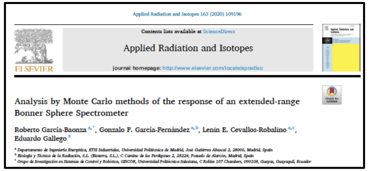
Neutron calibration:
Ciemat (R. Mendez)

Assessment:
CNA
(Carlos Guerrero
Begoña Fernández)

……

Another passive equipments/analysis at LMN-UPM

Extended Bonner Spheres Spectrometer


Applied Radiation and Isotopes 163 (2020) 109196

Contents lists available at ScienceDirect

Applied Radiation and Isotopes

journal homepage: http://www.elsevier.com/locate/apradiso

Analysis by Monte Carlo methods of the response of an extended-range Bonner Sphere Spectrometer

Roberto García-Baonza[a,*], Gonzalo F. García-Fernández[a,b], Lenin E. Cevallos-Robalino[a,c], Eduardo Gallego[a]

[a] Departamento de Ingeniería Energética, ETSI Industriales, Universidad Politécnica de Madrid, José Gutiérrez Abascal 2, 28006, Madrid, Spain
[b] Biología y Técnica de la Radiación, S.L. (Bioterra, S.L.), C Camino de los Perdigones 2, 28224, Pozuelo de Alarcón, Madrid, Spain
[c] Grupo de Investigación en Sistemas de Control y Robótica, GISCOR, Universidad Politécnica Salesiana, C Robles 107 Chambers, 090108, Guayas, Guayaquil, Ecuador

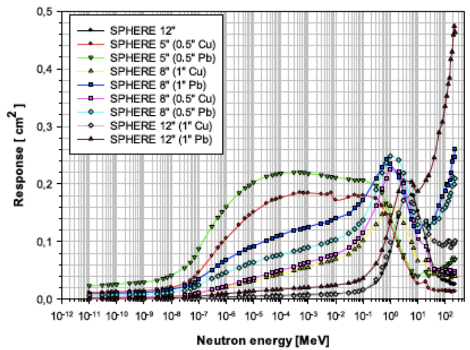
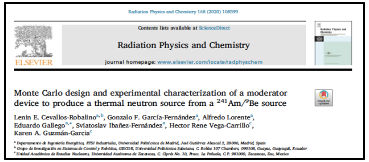


Fig. 3. Calculated response functions of the different spheres.

Thermal neutrons irradiation Facility (FANT)


Radiation Physics and Chemistry 168 (2020) 108599

Contents lists available at ScienceDirect

Radiation Physics and Chemistry

journal homepage: www.elsevier.com/locate/radphyschem

Monte Carlo design and experimental characterization of a moderator device to produce a thermal neutron source from a $^{241}Am/^{9}Be$ source

Lenin E. Cevallos-Robalino[a,b], Gonzalo F. García-Fernández[a], Alfredo Lorente[a], Eduardo Gallego[a,*], Sviatoslav Ibañez-Fernández[a], Hector Rene Vega-Carrillo[c], Karen A. Guzmán-Garcia[c]

[a] Departamento de Ingeniería Energética, ETSI Industriales, Universidad Politécnica de Madrid, José Gutiérrez Abascal 2, 28006, Madrid, Spain
[b] Grupo de Investigación en Sistemas de Control y Robótica, GISCOR, Universidad Politécnica Salesiana, C. Robles 107 Chambers, 090108, Guayas, Guayaquil, Ecuador
[c] Unidad Académica de Estudios Nucleares, Universidad Autónoma de Zacatecas, C. Ciprés No. 10, Fracc. La Peñuela, C.P. 981000, Zacatecas, Zac, Mexico

Based on concept of HOTNESS developed by Bedogni et. al.

Bedogni, R., Sacco, D., Gómez-Ros, J.M., Lorenzoli, M., Gentile, A., Buonomo, B., Pola, A., Introini, M.V., Bortot, D., Domingo, C., 2016. ETHERNES: a new design of radionuclide source-based thermal neutron facility with large homogeneity area. Appl. Radiat. Isot. 107, 171–176. https://doi.org/10.1016/j.apradiso.2015.10.016.

Bedogni, R., Sperduti, A., Pietropaolo, A., Pillon, M., Pola, A., Gómez-Ros, J.M., 2017. Experimental characterization of HOTNES: a new thermal neutron facility with large homogeneity area. Nucl. Instrum. Methods Phys. Res. 843, 18–21. https://doi.org/10.1016/j.nima.2016.10.056.

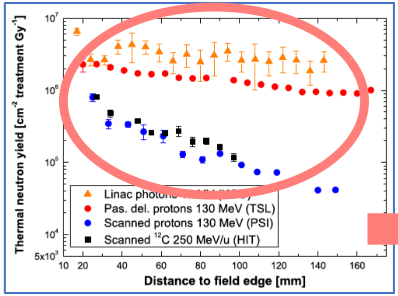
Estimation air activation with pasive methods

Based on sodium bicarbonate samples and the work of Vialle et al.

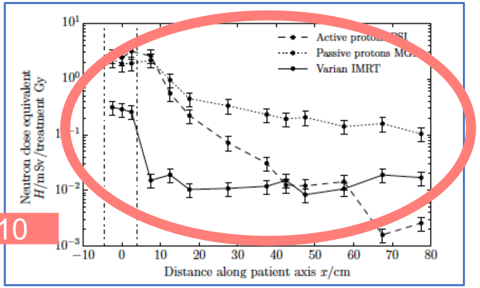
Verify assumptions and anticipate the impact of future developments

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

Reducing *neutronic burden (PBS)*

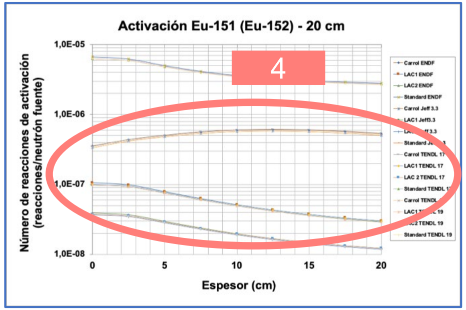


Kaderka et. al., 2012, Phys. Med. Biol. 57 5959



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

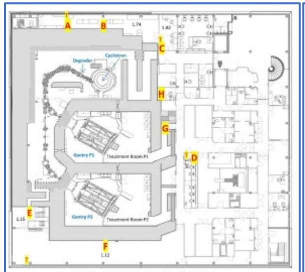


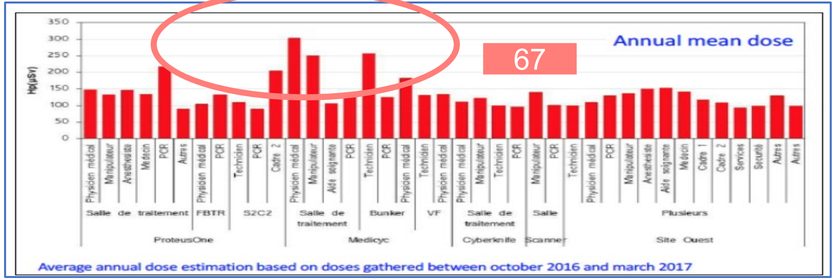
Figure 2. Lay-out of the facility
A…G are the measurement locations.
'T' indicates positions of TLD detectors in the building

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)

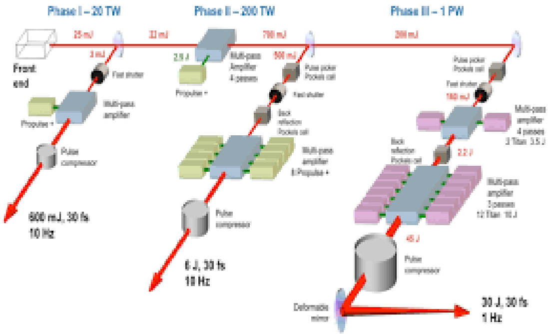
1. Select a suitable site and location for facility
2. Design barriers and shielding against neutron and gamma radiation
3. Use Monte Carlo simulations and check with analytical methods (or if you prefer, the opposite)
4. Choose appropriate materials in barriers
5. Review the impact of radiation on environment
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

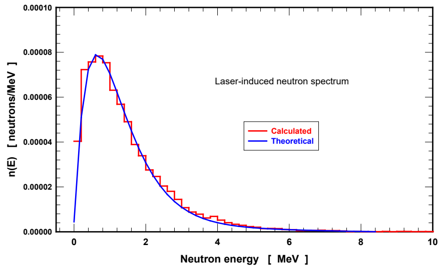
Contributions to the commissioning of operational radiation protection in CPTC

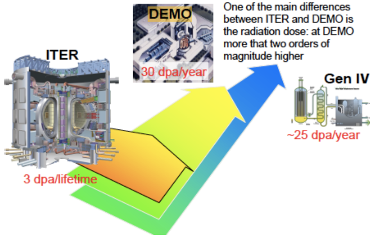
Another facilities with neutron worries

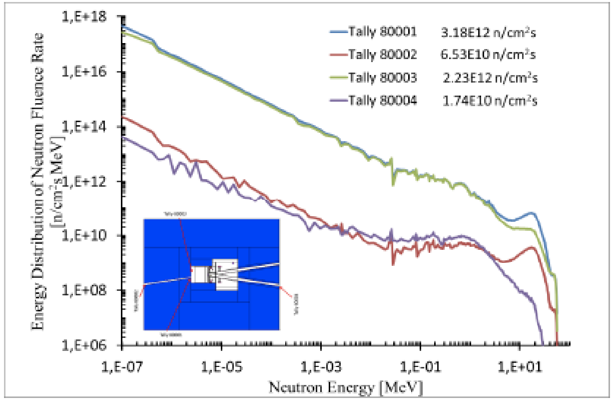
Physicists and engineers shall not live by protons alone….

CLPU CENTRO DE LÁSERES PULSADOS









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. Considering the permanent evolution in many aspects of proton therapy, international recommendations (ICRP Publication 127, IAEA TecDocs), should be periodically **updated and harmonized**.

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.

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Gonzalo García
Assistant professor and researcher
Universidad Politécnica de Madrid (UPM)
gf.garcia@upm.es