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Commissioning of operational radiation protection in Compact Proton Therapy Centers (CPTC) with small accelerators

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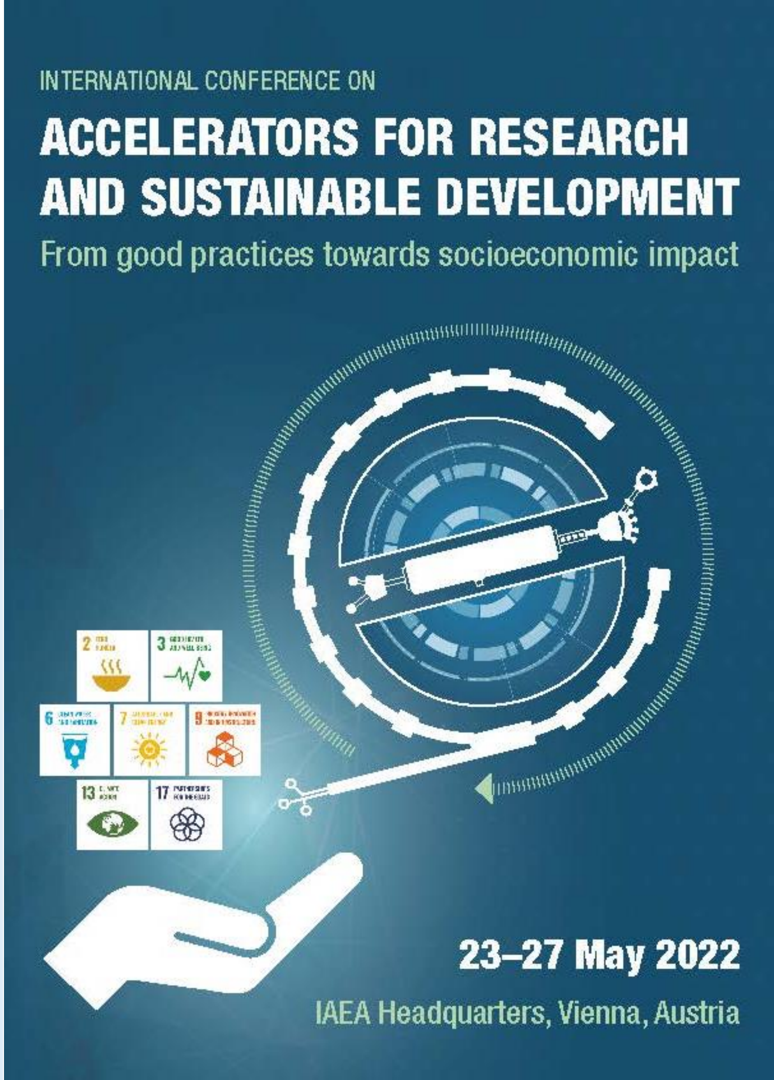
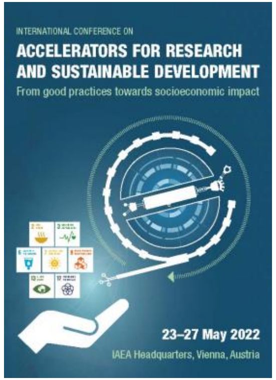




Faculty Disclosure

X	No, nothing to disclose
	Yes, please specify:

Company Name	*Honoraria/ Expenses*	*Consulting/ Advisory Board*	*Funded Research*	*Royalties/ Patent*	*Stock Options*	*Ownership/ Equity Position*	*Employee*	*Other (please specify)*

Scope

Purpose

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

Research activities and main results

The ten recommendations

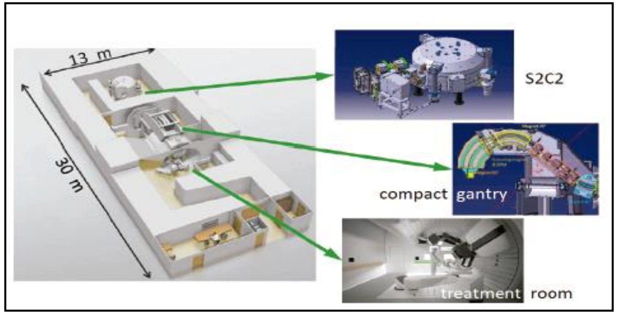
Summary

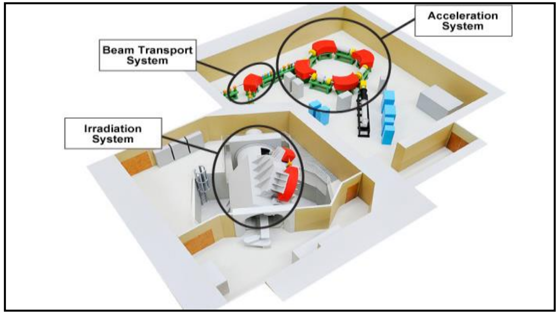
¡¡¡ This presentation is about Radiation Protection!!!!

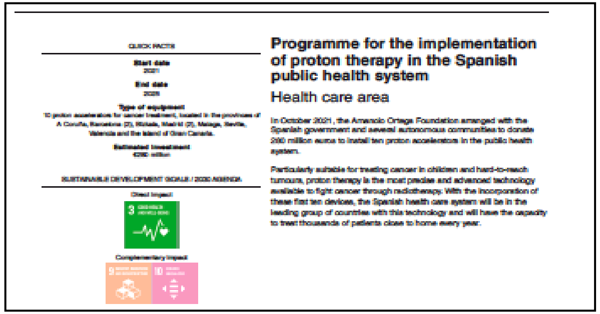
The advent of Protontherapy in Spain

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

Typical size MPTC (4 rooms) > 3000 m^2







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**

2017/18→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**

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…)

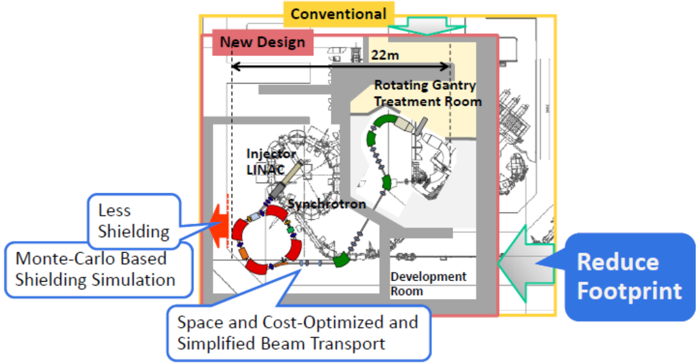
Compact proton therapy centers: CPTC (small size, 1 or 2 treatment rooms)

Study of several aspects of operational radiation protection focused in CPTC

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))

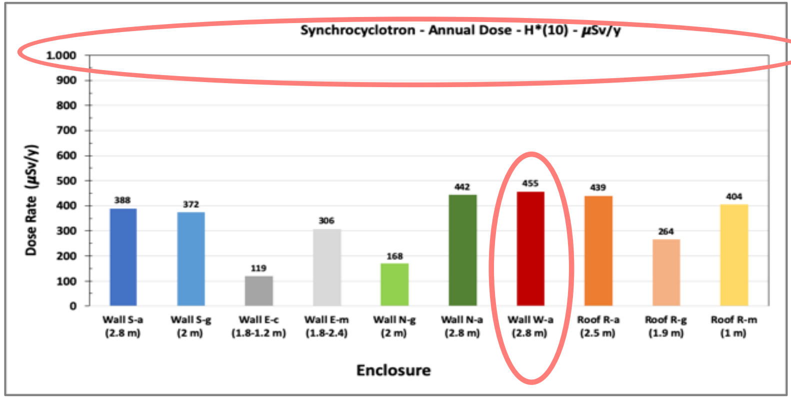
MCNP6 PHITS GEANT4

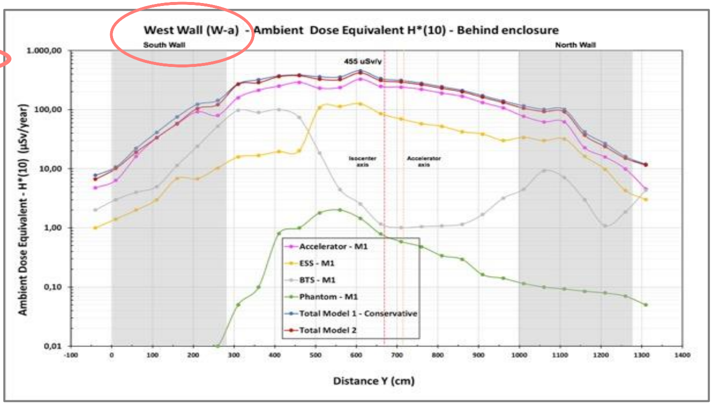
Assumptions and uncertainties (conservatives, 20y)

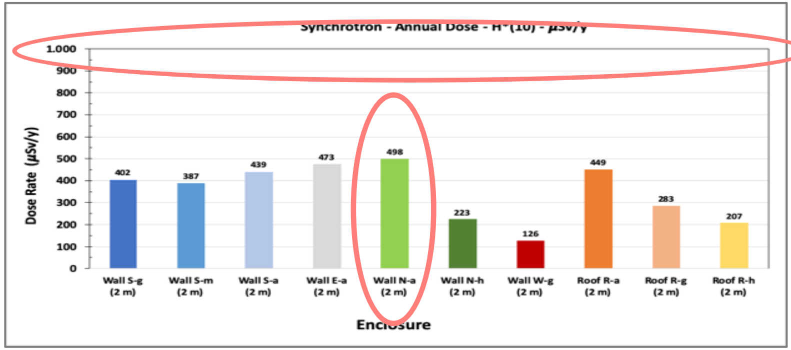
Compositions (nuclides) - Interactions – **Workload → <u>Delivery mode</u>**

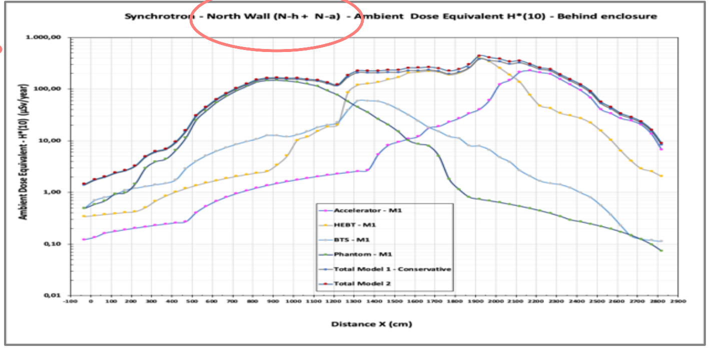
Design barriers and shielding against neutron and gamma radiation

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 m² footprint
2.8 m thickness in main barriers

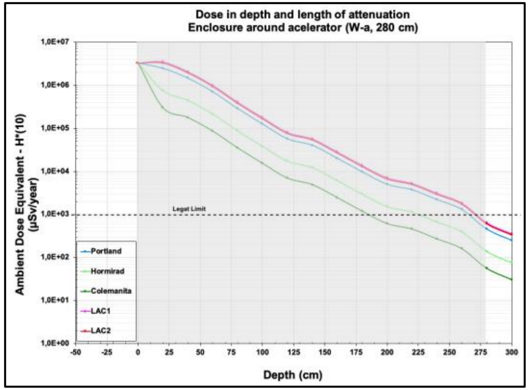
Synchrotron
One treatment room expandable
800 m² footprint
2 m thickness in main barriers

Intercomparing CPTC: synchrocyclotron vs. synchrotron

Expansion to new types of centers planned for the Public System

Study of different materials in barriers

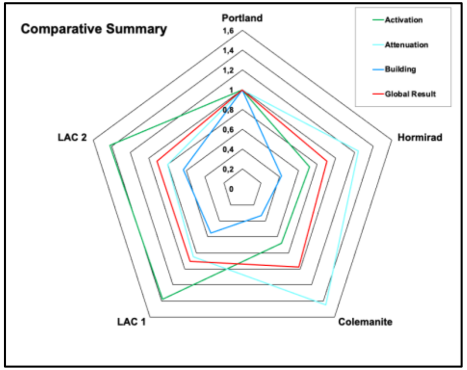
Attenuation plots with different types of concrete



Attenuation is essential but not enough

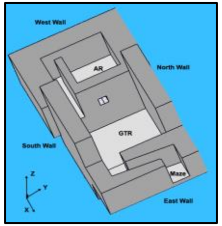
Radionuclide	Reaction channel	$T_{1/2}$
^{152}Eu	$^{151}Eu\ (n,\gamma)\ ^{152}Eu$	13.33 y
^{154}Eu	$^{153}Eu\ (n,\gamma)\ ^{154}Eu$	8.8 y
^{134}Cs	$^{133}Cs\ (n,\gamma)\ ^{134}Cs$ $^{134}Ba\ (n,p)\ ^{134}Cs$	2.06 y
^{60}Co	$^{59}Co\ (n,\gamma)\ ^{60}Co$	5.3 y
^{46}Sc	$^{45}Sc\ (n,\gamma)\ ^{46}Sc$	83 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

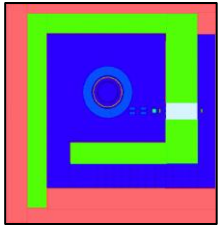
Comparative of several materials (concretes)



	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

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

Long-lives isotopes
yielded directly with protons

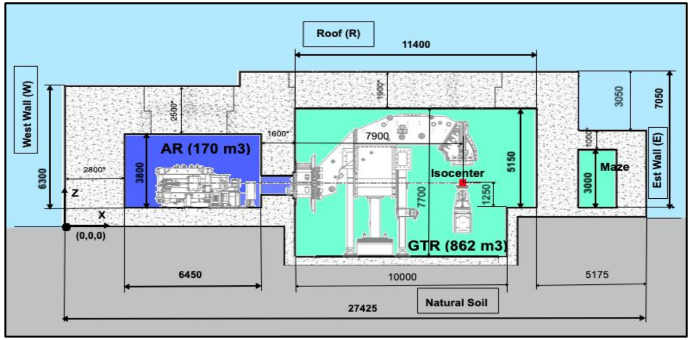
Isotopes	Half-life
^{60}Co	5.3 years
^{57}Co	271 days
^{58}Co	70 days
^{54}Mn	312 days
^{65}Zn	244 days
^{22}Na	2.6 years

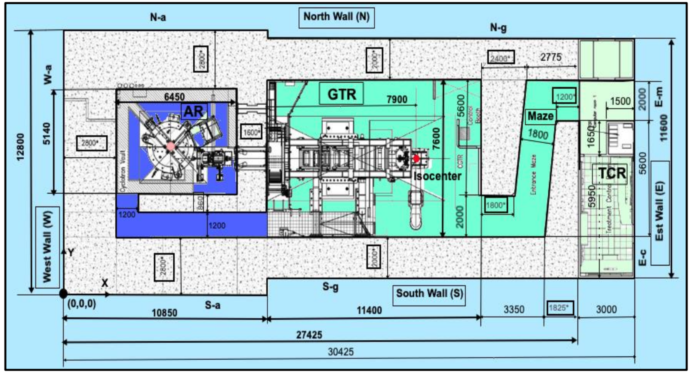
Many equipment and elements
of the facility with natural Cu

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 (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

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

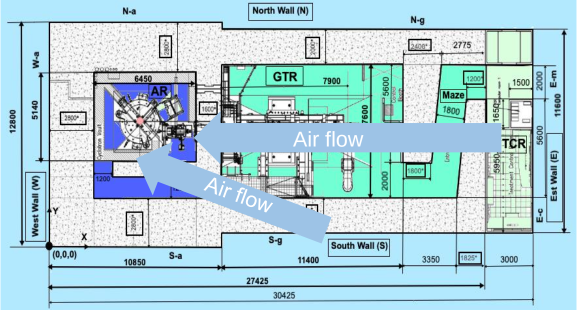
Air renewals rate

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

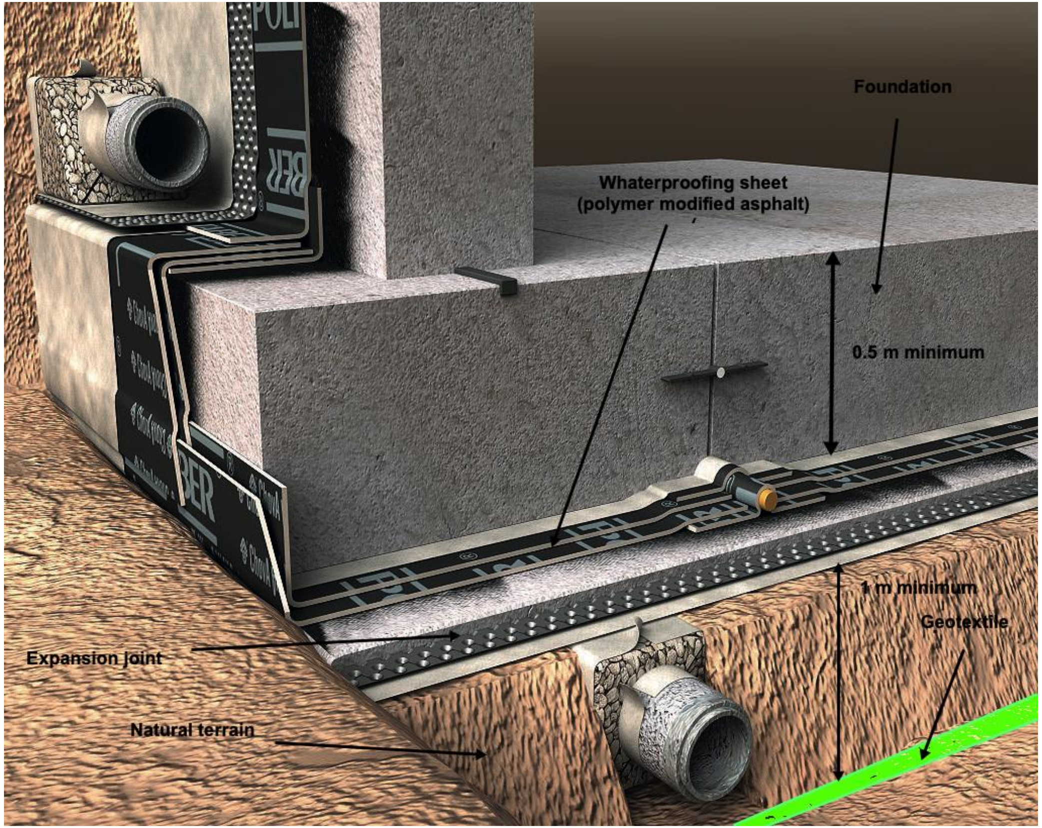
Differential pressure between maze/treatment room (10/15 Pa) and accelerator room (< -40 Pa)

Continuous readout and checking of pressures in rooms

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

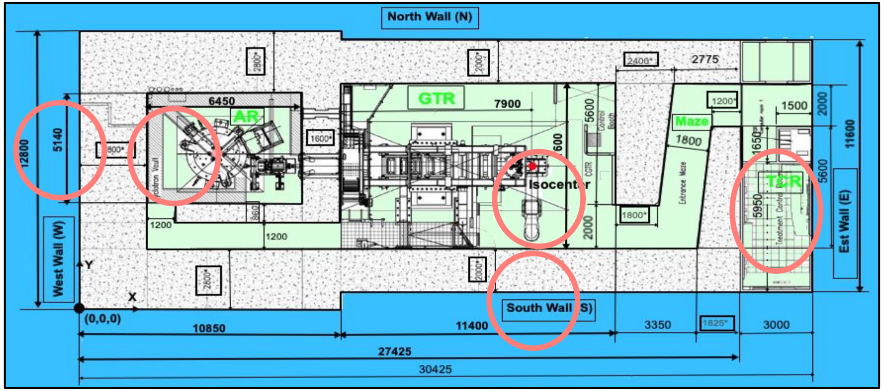


Assessment of personal dosemeters for proton centers (Monte Carlo)

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

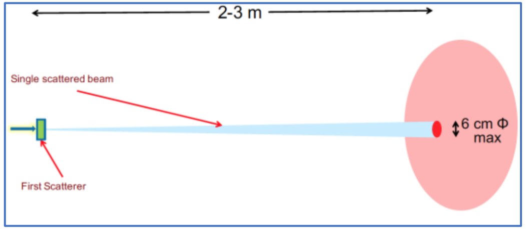
Garcia-Fernandez et. al., ISSSD XX 2020

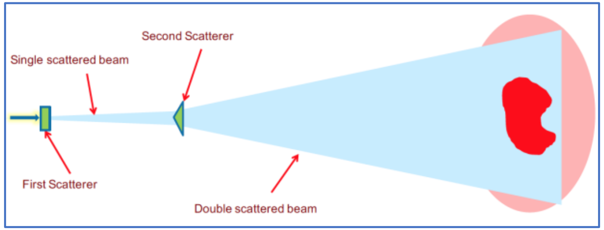
$H_p(10)_{cal}/H_p(10)_{ref}$	W-a inside	W-a outside	S-g inside	S-g outside	TCR
Active - DLD	8.4	8.9	3.2	4.7	9.6
Pasive - Albedo	2.7	1.5	1.2	1.8	1.3
Pasive – Track	0.7	2.9	0.8	1.6	2.4

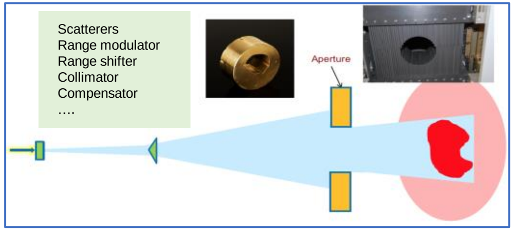
Selection of personal neutron dosemeter most suitable for CPTC

Impact of new developments (Evolution of delivery Methods)

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

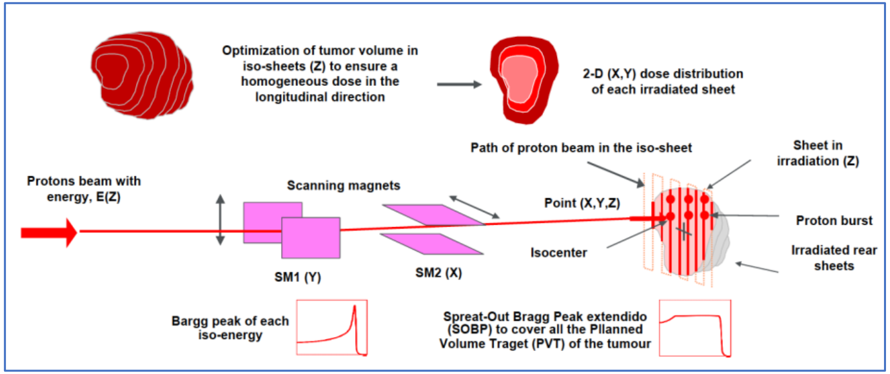


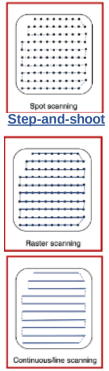




PT.2 → Active methods → Pencil Beam Scanning (PBS) → IMPT *(Intensity modulated proton therapy)*

Basic workload





PT.3 → In-development methods

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

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

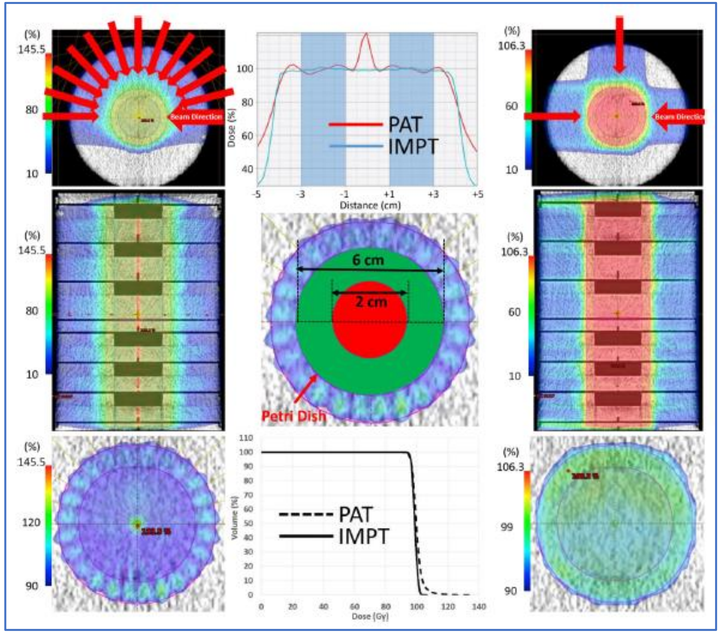
Impact of new delivery techniques on RP

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

PMAT (experimental)

Proton Monoenergetic Arc Therapy (Dr. Carabe- Fernandez)

Dosimetric plans PMAT/IMPT



6 Gy

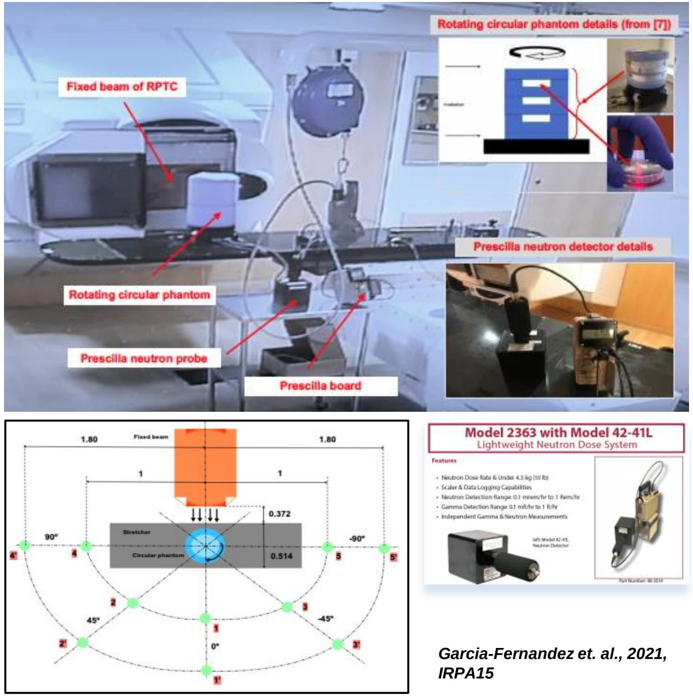
IMPT
SOBP
141.7 – 89.5 MeV

PMAT
Monoenergetic
117.5 MeV

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

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

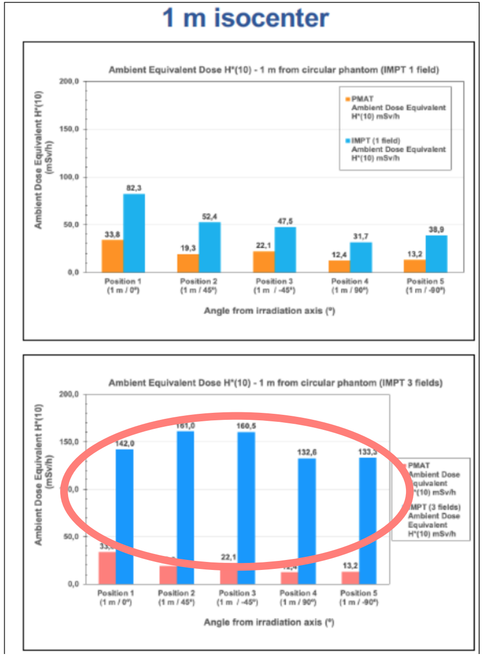
Set-up for experimental measurements, H*(10)

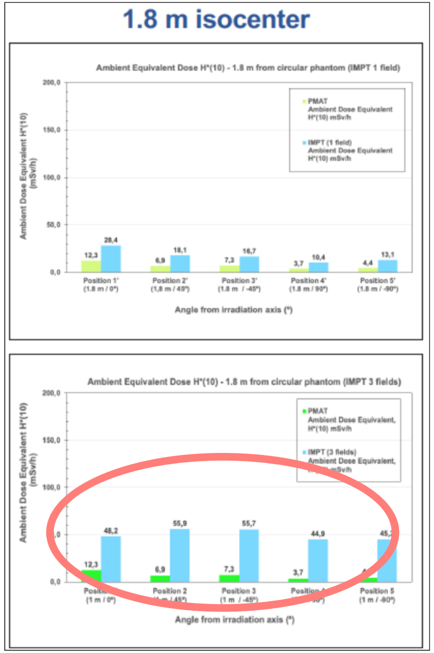


Garcia-Fernandez et. al., 2021, IRPA15

Impact of PMAT on RP

Experimental results, H*(10)





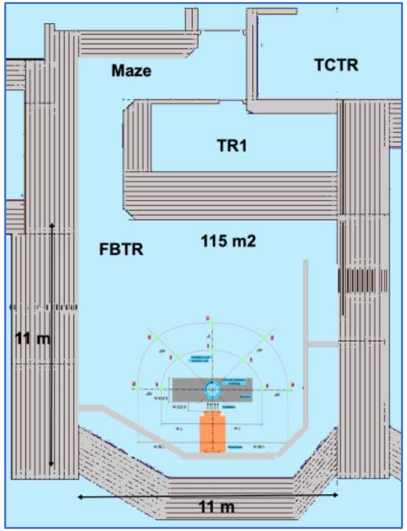
Garcia-Fernandez et. al., 2021, IRPA15

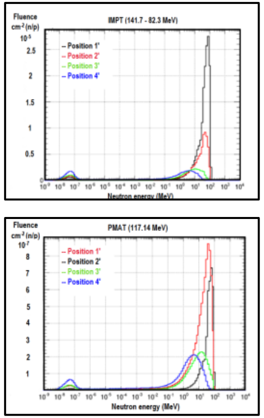
PMAT could have a non-negligible reduction of secondary neutrons, with a direct positive impact on operational radiation protection.

This is an experimental mode of Proton Arc Therapy not commercial

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%

International Conference on Accelerators for Research and Sustainable Development #Accelerators2022 23–27 May 2022 IAEA, Vienna, Austria

Impact of Pr-FLASH on RP

Some (relevant) uncertainties at this stage (linked with RP)

Pr-FLASH involve two main methods (transmission or Bragg-Peak) with specific features

Different dose per pulses (papers with rates from 10 Gy/s to 300 Gy/s). **Pulsed Neutron Fields (PNF)**

Number of treatments to be performed with each mode: FLASH, PMAT, IMPT, others

How and where the beam will be stopped with transmission Pr-FLASH?

How the beam will be conformed with Bragg-Peak Pr-FLASH?

Instantaneous Dose Rate (IDR) limits in some national regulations
(critical place: Treatment Control Room, occupancy factor T=1)

Challenges

Difficult to quantify the impact in new PTC (disruptive)
(but that will be very relevant)
Adapting existing facilities
Verification and measurements

…significance increase in neutron.

Jolly et al., 2020, Physica Medica, 78:71-82

…neutron dose and radiation shielding should be carefully considered.

Zou et al., 2021, Radiotherapy and Oncology, 155:212-218

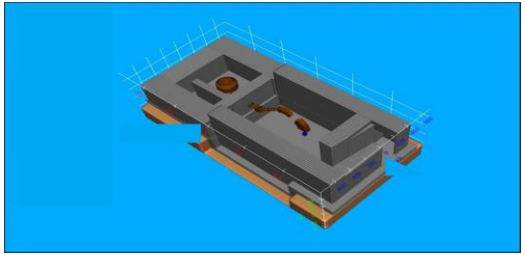
Some alternatives

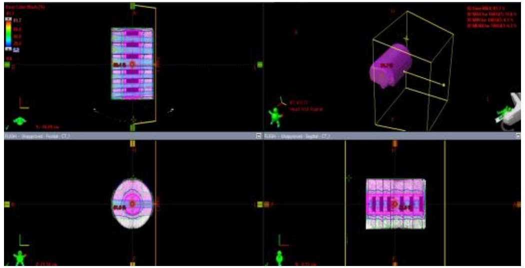
Parametric workload
Monte Carlo workload

Gupta et. al., POP04, PTCOG 2020 online

Simulations with Monte Carlo

CPTC (synchrocyclotron)





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)

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

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

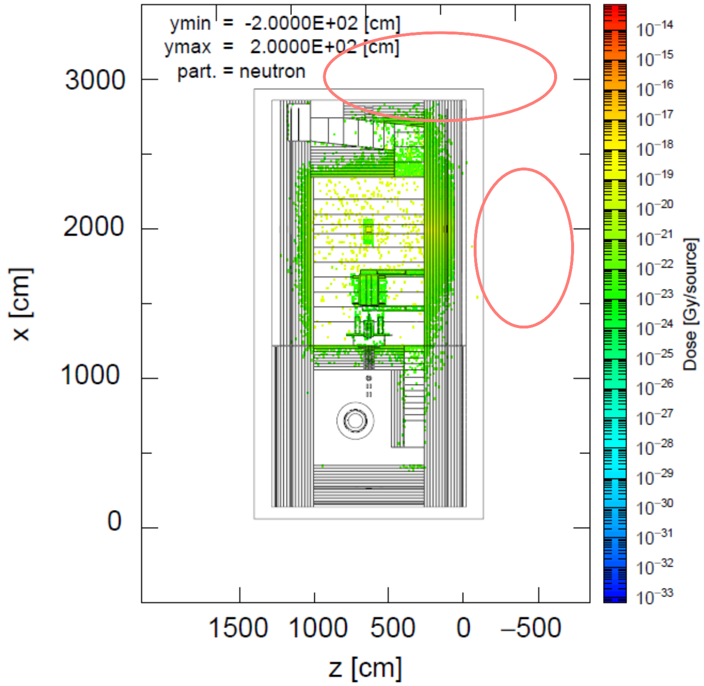
IMPT
5.1 uSv/h (baseline 1)

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

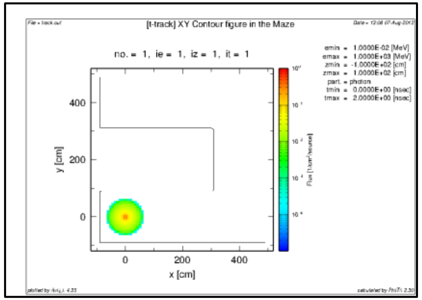


Garcia-Fernandez et. al., 2022, Radiation physics and chemistry, under review

Dead time of radiation monitors

(5-10 microsecond)

Underestimations

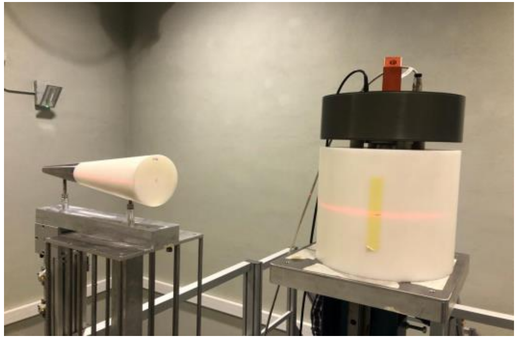


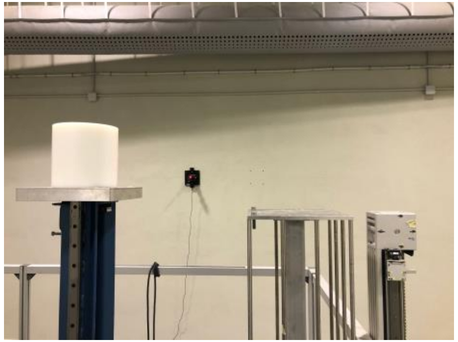
PHITS, 2021, tutorial

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



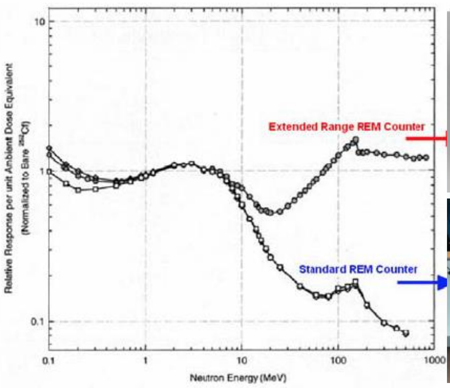


Extended-range rem-meters
Characterizing response of devices

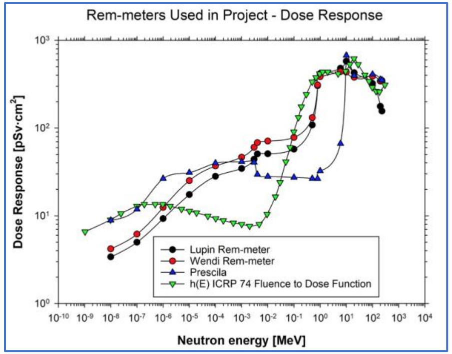
To carry out experimental measurements inside treatment rooms is necessary extended-range rem-meters (PNF with some new delivery methods)

Outdoor is possible use conventional devices

actives



wendi **prescila**



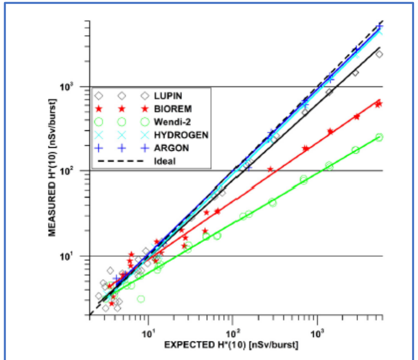


Fig. 7. Response of the detectors in position 1. The dotted line is the bisector of the first quadrant, representing the ideal linear behaviour. The uncertainties are not shown for clarity.

lupin

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

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

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

ALARA (as low as reasonably achievable)

Assumptions should be *conservative but realistic* (and based on updated information)

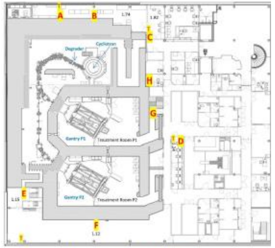


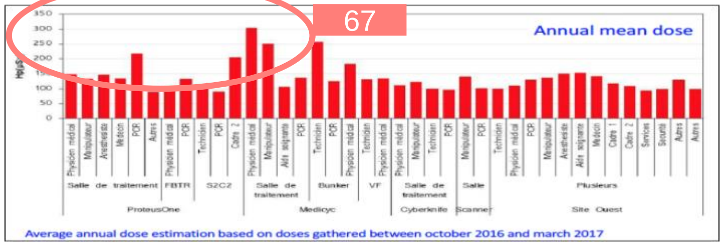
Figure 2. Lay-out of the facility
A...G are the measurement locations.
'T' indicates positions of TLD detectors in the building

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	0,000122	9
D	6	0,0013	0,000167	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

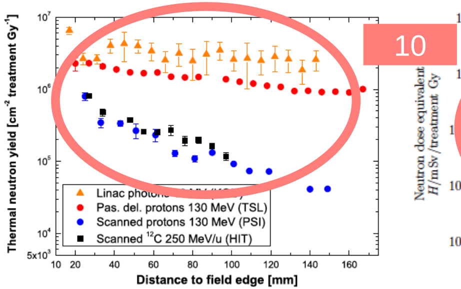


Herault et. al., Radiation Protection in PT in 1er Int. course on PT, Institute Curie, Paris, 2018

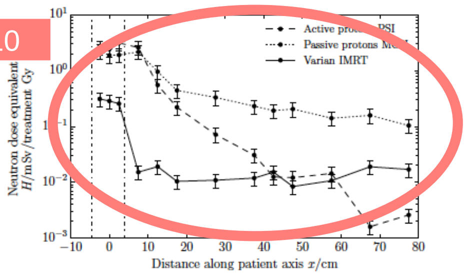
Assumptions are not forever but almost (20 years)

Some improvements mitigate significantly the *impact of neutrons* in PT facilities

Reducing *neutronic burden (PBS)*

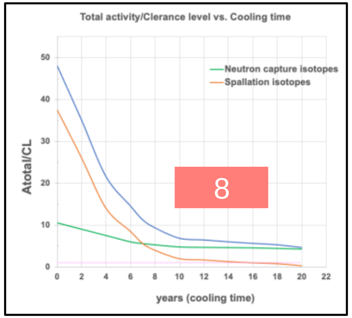


Kaderka et. al., 2012, Phys. Med. Biol. 57 5959



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

Using concretes with low impurities (Eu)



Garcia-Fernandez et. al., 2021, IRPA15

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. 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.

Thank you for your attention

Muchas gracias

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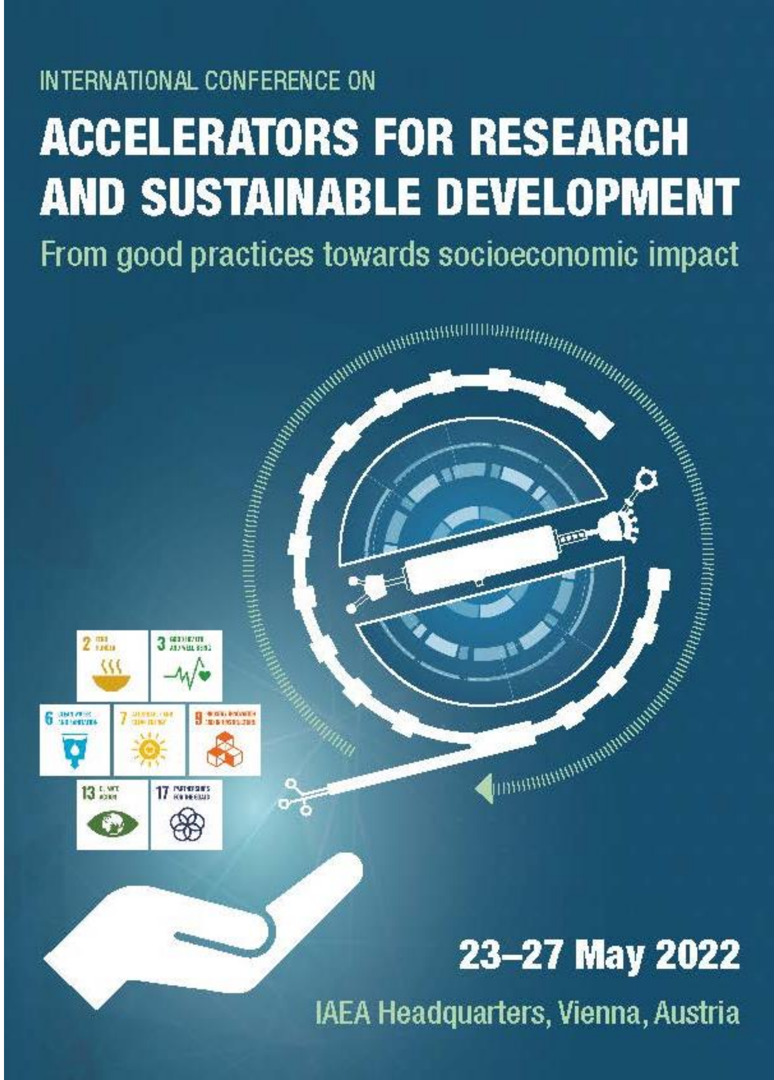
Arturo Pérez Mulas (CSN)
Marisa Tormo (CSN)

Alejandro Mazal (QuirónSalud)
Juan Castro (QuirónSalud)
Juan Antonio Vera (QuirónSalud)

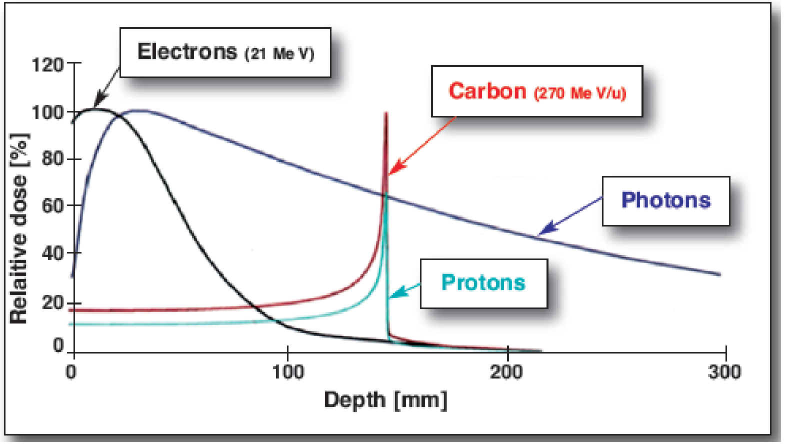
Josep M. Martí (CUN)

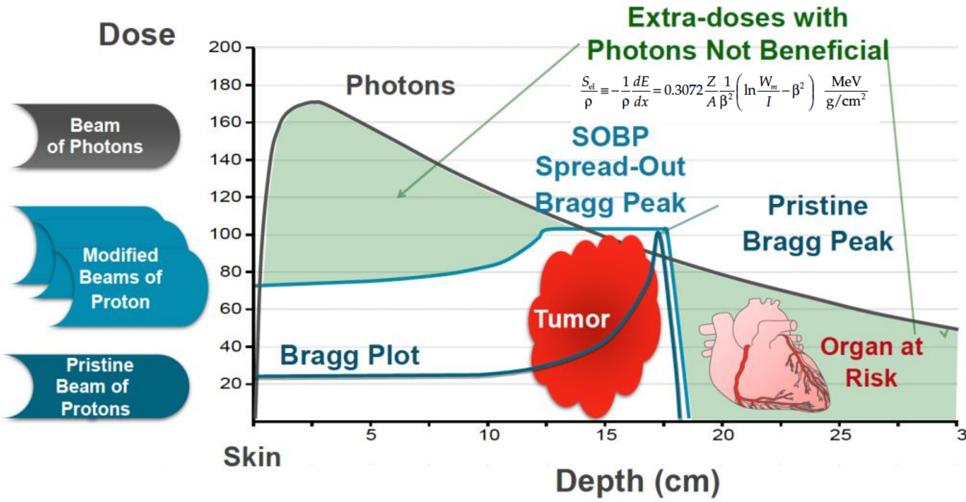
Eduardo Fuentes (Bioterra)

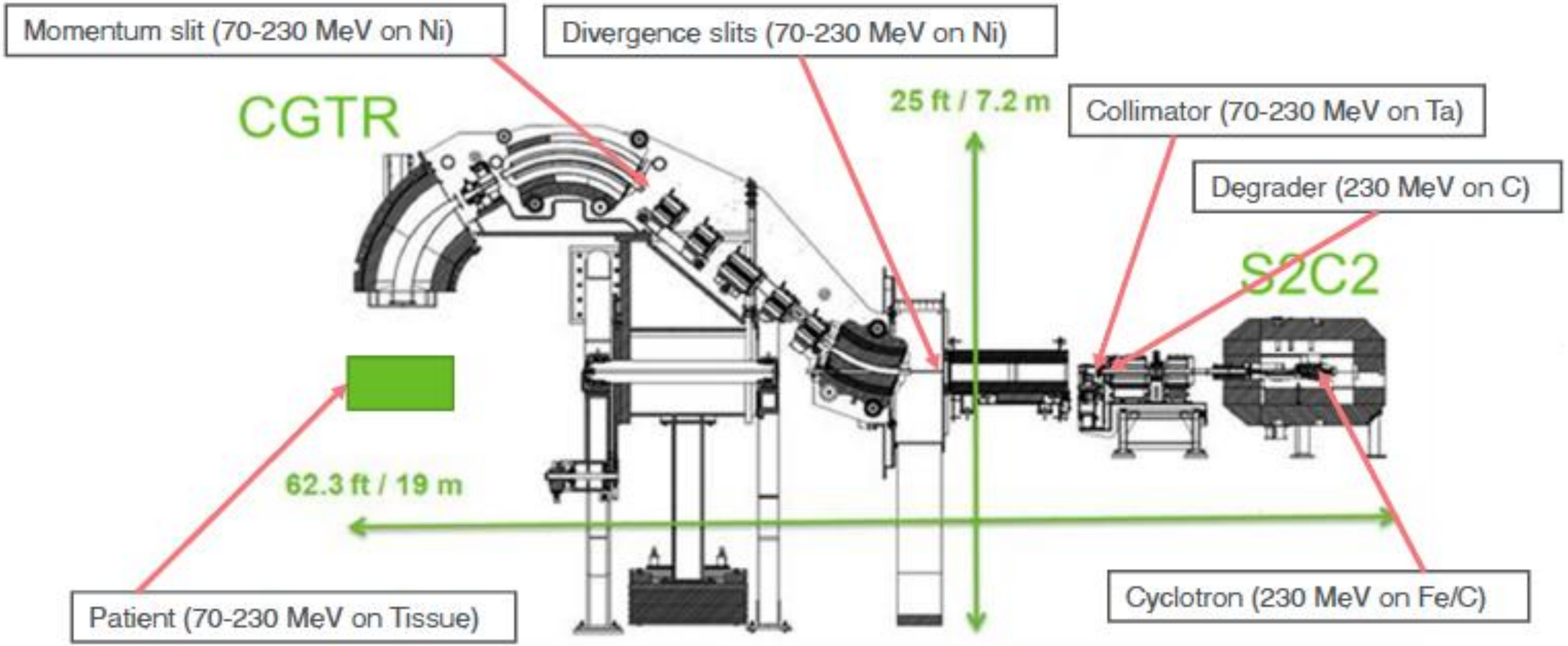
Ricardo Otero (IBA-Spain)



- Proton therapy (PT): External radiation therapy with accelerated proton beams at kinetic energies between 70 and 230 MeV.
- Advantages: Dosimetric improvements in the treatment of certain types of tumors and clinical cases due to the proton dose deposition curve.
- Beneficial for deep tumours, tumours surrounded by radiosensitive organs and certain tumours in children
- Over 100 active facilities and over 250.000 patients treated. PT in Spain: First center Dec-19, second Apr-20, third forecast 2022.

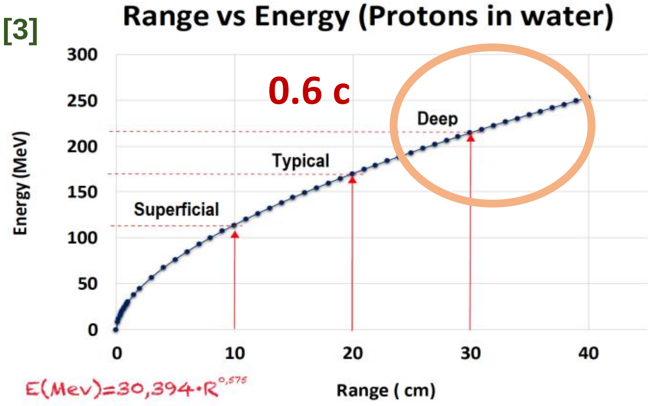






Momentum slit (70-230 MeV on Ni)
Divergence slits (70-230 MeV on Ni)
CGTR
25 ft / 7.2 m
Collimator (70-230 MeV on Ta)
Degrader (230 MeV on C)
S2C2
62.3 ft / 19 m
Patient (70-230 MeV on Tissue)
Cyclotron (230 MeV on Fe/C)

[3]

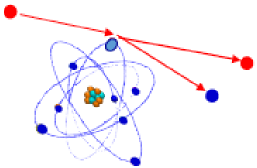


$E(Mev)=30{,}394\cdot R^{0{,}575}$

1) Stopping (Inelastic) [3]

Ionization

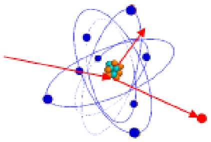
Dose in tumour



2) Scattering (Elastic)

Nuclear Coulomb Scattering (MCS)

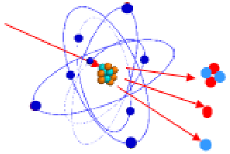
Lateral penumbra

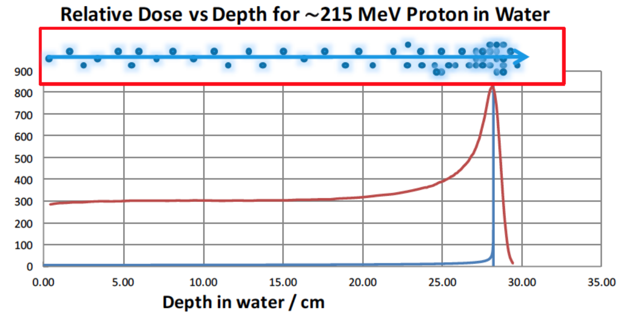


3) Nuclear In.)

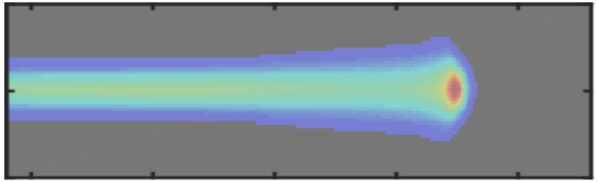
Nuclear reaction (Spa

PR)

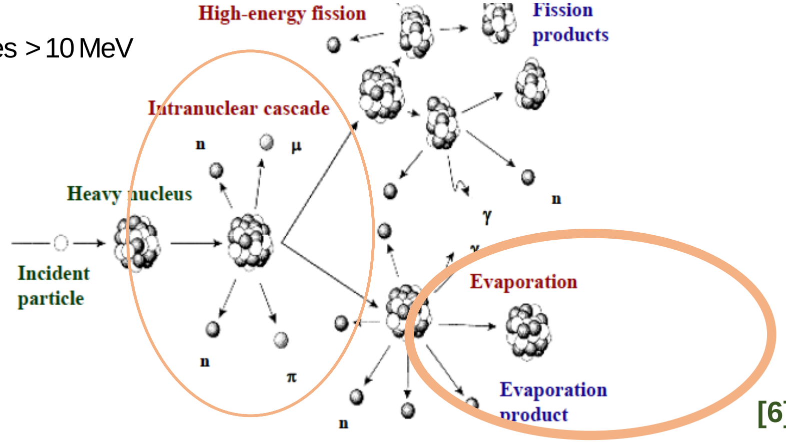




[5]



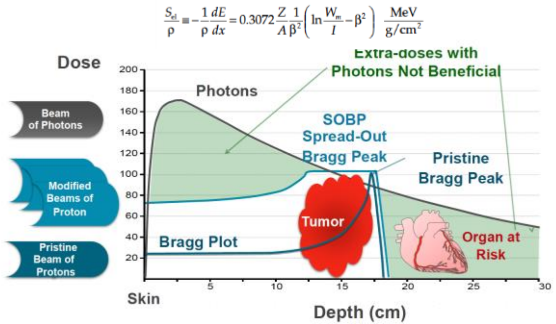
1/3 neutrones > 10 MeV



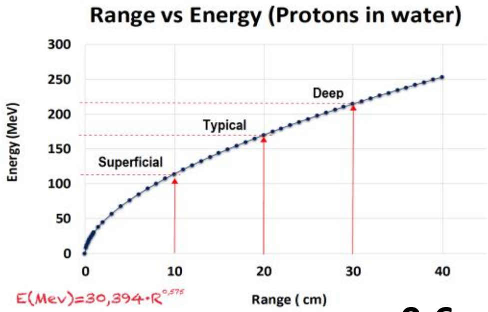
[6]

Impact in neutrón dosimetry: Ambient and personal

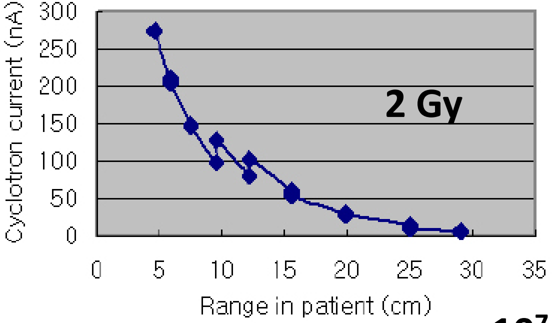
1.2 Sources of radiation p → n (+ gamma)



[8]



[9]



0.6 c

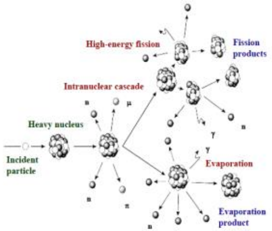
10^7 p

Nuclear interactions of protons → Spallation Process: INC + EV [10]

I.S. → Dose

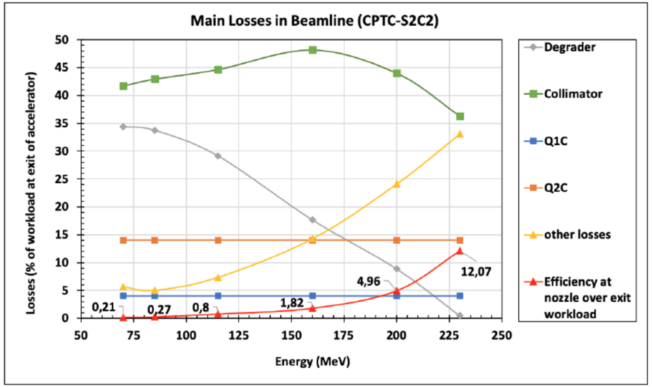
M.C.S. (E.S.) → Lateral Penumbra

1% - 20 MeV

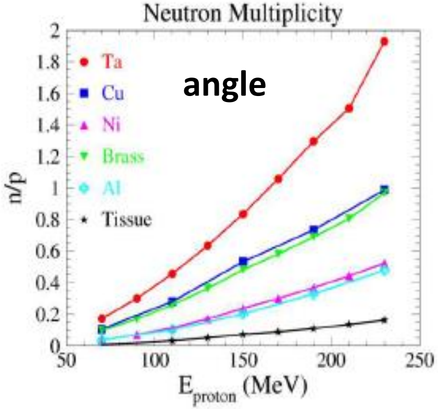


Changes in beam

Main Interaction of Proton in Facility		
Component	Energy (MeV)	Material
Cyclotron	230	Fe, C
Degrader	230	C
Collimator	70 -230	Ta
Divergence Slits	70-230	Ni
Momentum Slit	70 - 230	Ni
Patient	70 - 230	Tissue

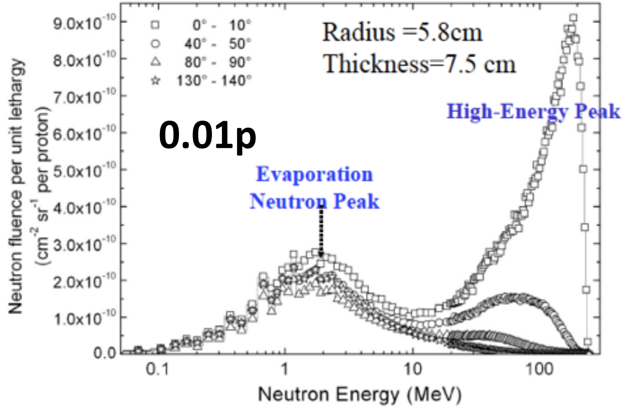


Energy (MeV)	70	85	115	160	200	230
Efficiency (%)	0,2	0,3	0,8	1,8	5	12



Proton interactions → Neutron Field

Lethargy = u = ln(E_0/E)   du = dE/E   E x dN/dE = dN/du



[14, Adapted from Agosteo]

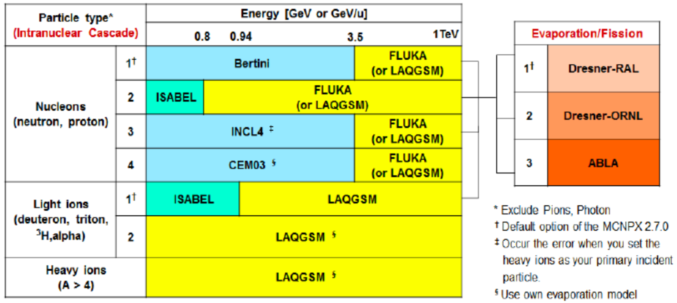
Neutrons interactions → impact in facility

Scattering

Absorption

1. Secondary dose inside TR (unwanted)
2. Ambient dose outside TR → shielding
3. Activation in walls and enclosures
4. Skyshine
5. Water and water table activation
6. Activation components and others

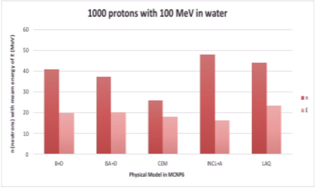
Nuclear Data and Physical Model

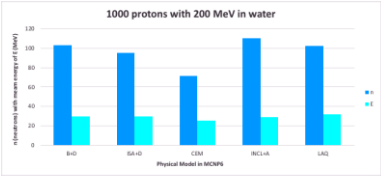


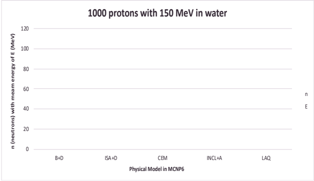
* Exclude Pions, Photon
† Default option of the MCNPX 2.7.0
‡ Occur the error when you set the heavy ions as your primary incident particle.
§ Use own evaporation model

[15, Lee]

Selection of Nuclear Data and Physic Model (E>150 MeV) in MCNP6 (Uncertainties)







[16, Adapted from Solc]

Indications	Min. Range (g/cm²)	Max. Range (g/cm²)	Tumor Volume (cm³)	Field Size (cm²)
Head & Neck	8	18	600	7.7 x 7.7
	2	12		7.7 x 7.7
Lung Tumor	8	20	810	7.9 x 7.9
	4	17		7.9 x 7.9
Pelvic Sarcoma	20	32	1218	10.1 x 10.1
	15	27		10.1 x 10.1
Pediatric	8	18	3460	18.6 x 18.6
	2	12		18.6 x 18.6
QA – low range	4	14	1000	10 x 10
QA – medium range	13	23	1000	10 x 10
QA – high range	22	32	1000	10 x 10

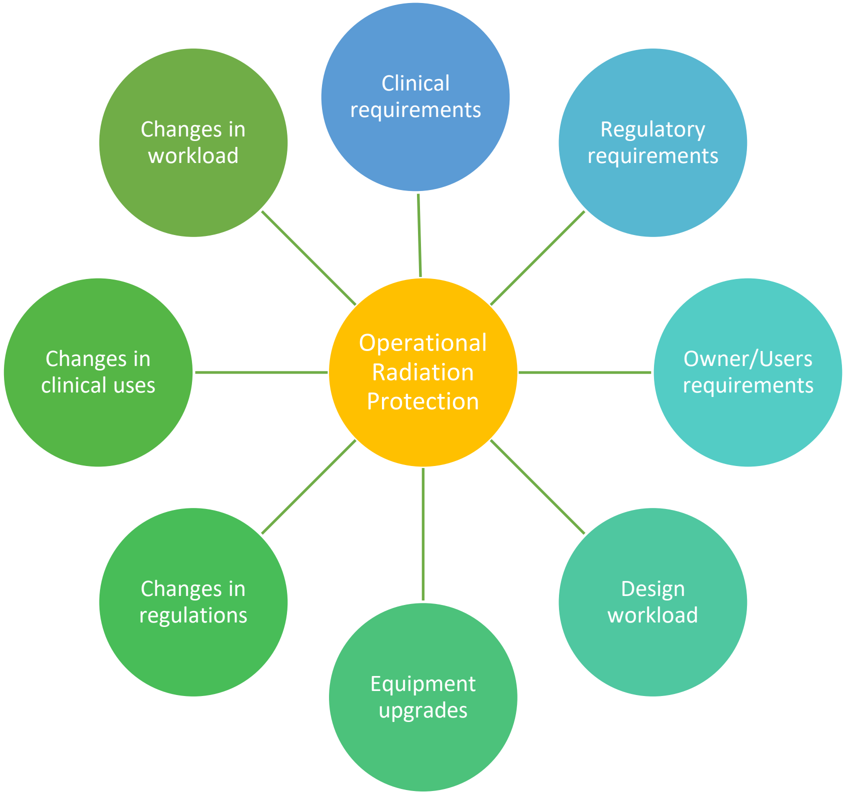
Indications	Dose for treatment (Gy)	Dose for QA (Gy)	Total dose (Gy)	# patient/year	Annual Dose at Isocenter (Gy)
Head & Neck	72	6	78	130.5 (30%)	10180
Lung Tumor	60	6	66	130.5 (30%)	8614
Pelvic Sarcoma	80	6	86	130.5 (30%)	11224
Pediatric	70	6	76	43.5 (10%)	3306
QA – low range			4*		1200
QA – medium range			4*		1200
QA – high range			4*		1200

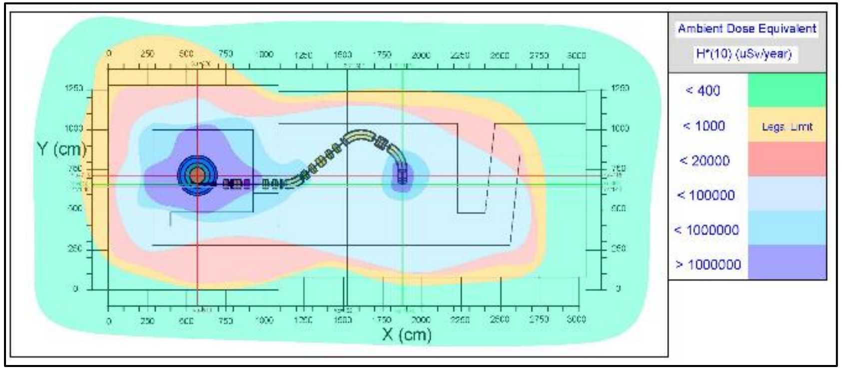
*Total dose per day

	Indications	Min. Range (g/cm²)	Max. Range (g/cm²)	Field size (cm²)	Annual Dose (Gy)	w(1Gy) (nA.s)	w_{iso} (nA.h)
Clinical Activities	Head & Neck	8	18	7.7 x 7.7	5090	7.29	10.31
		2	12	7.7 x 7.7	5090	6.27	8.87
	Lung Tumor	8	20	7.9 x 7.9	4307	8.39	10.04
		4	17	7.9 x 7.9	4307	8.36	10.01
	Sarcoma	20	32	10.1 x 10.1	5612	15.42	24.04
		15	27	10.1 x 10.1	5612	14.89	23.22
	Pediatric	8	18	18.6 x 18.6	1653	42.09	19.33
		2	12	18.6 x 18.6	1653	36.46	16.74
QA Activities	QA – low R	4	14	10 x 10	1200	12.04	4.013
	QA – medium R	13	23	10 x 10	1200	13.78	4.593
	QA – high R	22	32	10 x 10	1200	15.75	5.250

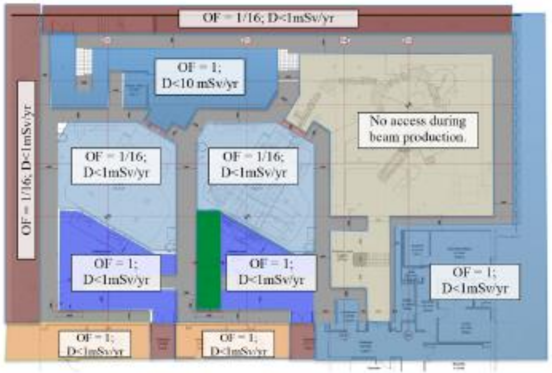
Sum = 136.42 nA.h

Clinical Indications	Max range (g/cm^2)	Max E range (MeV)	Average E (MeV)	Percentage
Head & Neck / ORL	18	160	145	18%
	12	130		
Lung / Breast Tumor	20	170	163	23%
	17	155		
Pancreas / Leaver	20	170	163	14%
	17	155		
CNS	18	160	145	20%
	12	130		
Pelvic Sarcoma (including Prostate)	32	225	203	8%
	22	180		
Pediatric	18	160	145	17%
	12	130		



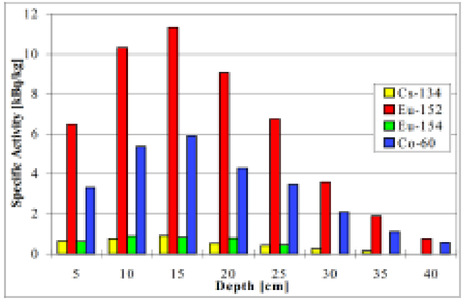


Garcia-Fernandez et. al., 2021, Applied Radiation and Isotopes, 169, 109279



Componentes principales (fracciones atómicas) y densidad					
Elemento	Portland (estándar)	Hormirad (hierro)	Colemanita (hidrógeno)	LAC1	LAC2
H	**0.1688**	0.1180	**0.8912**	0.0072	0.0075
C	0.0014	0.0016	0.0003	0.0891	0.0872
O	**0.5625**	**0.5292**	0.0732	**0.4777**	**0.4921**
Fe	0.0043	**0.2736**	5.0963E-5	0.0006	0.0006
Ca	0.0187	0.0309	0.0034	**0.4051**	**0.3405**
Si	0.2041	0.0263	0.0012	0.0124	0.0009
Mg	0.0014	0.0070	0.0006	0.0024	0.0016
Na	0.0118	0	0	0.0008	0.0008
B	0	0	**0.0297**	0	0
Densidad (g/cm3)	**2.30**	**4.10**	**2.12**	**2.18**	**2.20**

Componentes minoritarios e impurezas (fracciones atómicas)					
Elemento	Portland (estándar)	Hormirad (hierro)	Colemanita (hidrógeno)	LAC1	LAC2
Co (ppm)	**2.1900E+1**	**2.1900E+1**	**2.1900E+1**	**0.7500**	**0.2500**
Eu (ppm)	**1.0800**	**1.0800**	**1.0800**	**0.0230**	**0.0081**
Cs (ppm)	**3.2100**	**3.2100**	**3.2100**	**0.0520**	**0.0100**
Al	0.0214	0.0070	0.0003		
K	0.0057	0.0013	7.2813E-5		
Mn	0	0.0001	0		
Ti	0	0.0009	0		
V	0	0.0002	0		
S	0	0.0007	8.0682E-6		
P	0	0.0027	0		
Sr	0	0	4.1300E-5	0	0



Difficulties in personal neutron dosimetry

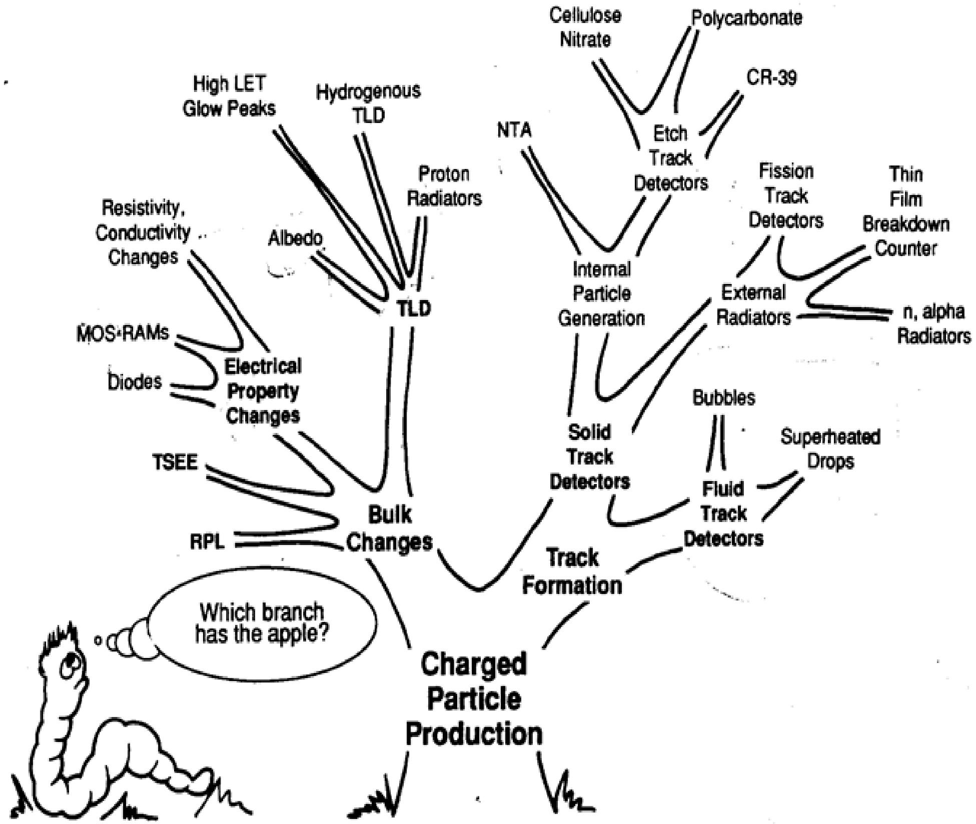
- Neutrons always together with (mostly strong) gamma fields

- Large energy range: 9 orders of magnitude
  - Thermal 0.025 eV to 100s 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, however
  - Least harmfull
  - Original neutrons are fast

IC2017n Irradiation fields



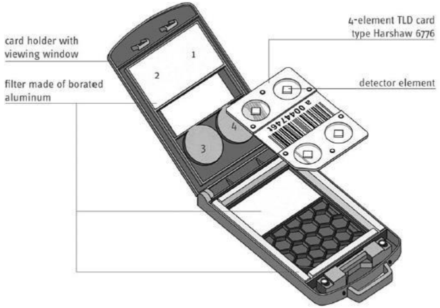
Dosemeter, active (DLD)

- Active electronic dosimeter with 3 Si diodes
  - With hydrogen rich convertor for fast + highenergy neutrons
  - With ^{6}Li convertor for thermal neutrons
  - Without convertor for photons

Dosemeters, Albedo (TLD)

- Passive dosimeter with 2 pairs of LiF thermoluminescent detectors
  - Combination of 6LiF and 7LiF to distinguish neutron and photons
  - One pair to measure incoming thermal neutrons
  - One pair to measure backscattered fast + high energy neutrons

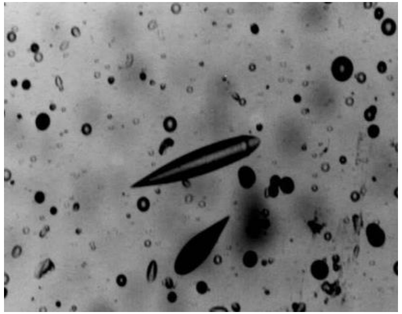
- Workplace specific empirical algorithm to combine 4 detectors



Dosemeters, Track etch

- Passive dosimeter with special polymer (CR-39, PADC)
  - Recoil protons create broken polymer chains
  - Tracks can be visualized under microscope by chemical etching

- Relatively good energy response



$$\Delta = \int_{E_{low}}^{E_{up}} \Phi_E(E)\ \delta_\Phi(E)\ dE$$

Theory (area magnitude)
Ambient Equivalent Dose

$$H^*(10) = \int h_\phi(E) \cdot \phi(E) \cdot dE$$

Reality (rem-meters)

$$R(E) = C \int r(E) \cdot \phi(E) \cdot dE$$

r(E) → absolute response (counts·cm²)

C → calibration factor (Sv/counts)

WENDI-II (He-3)

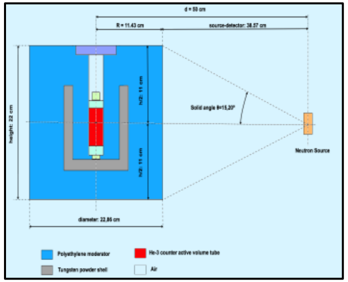
- Sensitivity

  $0.84 \left(\frac{cps}{\left(\frac{\mu Sv}{h}\right)}\right) Cf^{252}$
- Energy Range

  25 meV – 5 GeV
- Dose Range

  $0.01 \left(\frac{\mu Sv}{h}\right) - 100 \left(\frac{mSv}{h}\right)$
- Neutronic Field

  Continuos



LUPIN 5401 (BF_3)

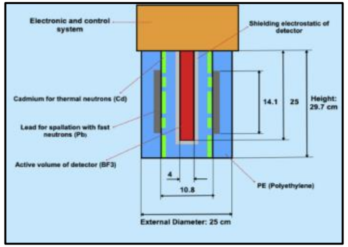
- Sensitivity

  $0.6 \left(\frac{cps}{\left(\frac{\mu Sv}{h}\right)}\right)\ Pu^{239}/Be^{9}$
- Energy Range

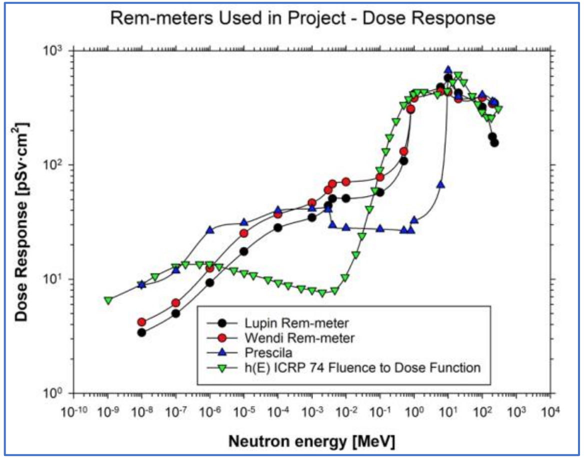
  25 meV – 5 GeV
- Dose Range

  $10 \left(\frac{nSv}{h}\right) - 100 \left(\frac{mSv}{h}\right) Cf^{252}$
- Neutron Field

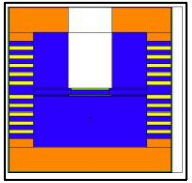
  Pulsed

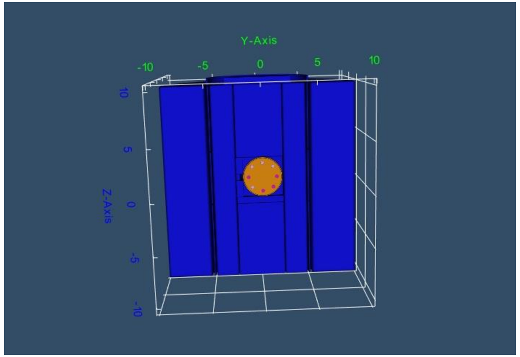


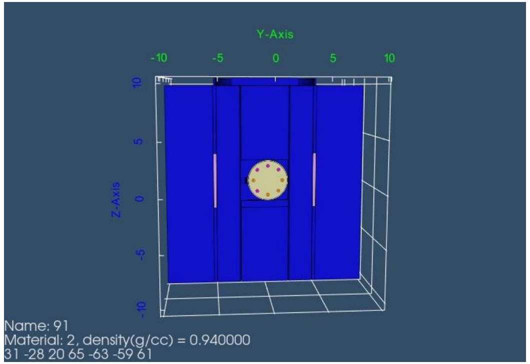
Garcia-Fernandez et. al., 2019, Applied Radiation and Isotopes, 152, 105-126

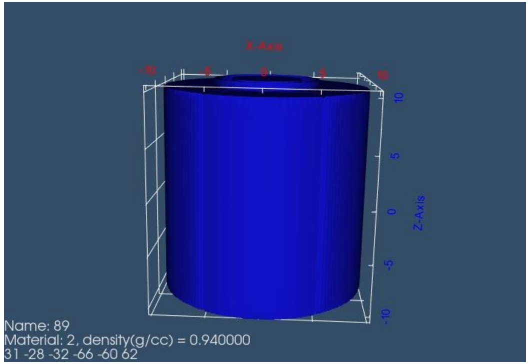


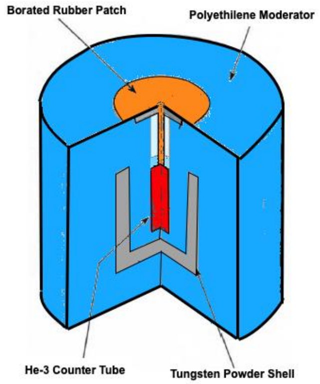
Prescila

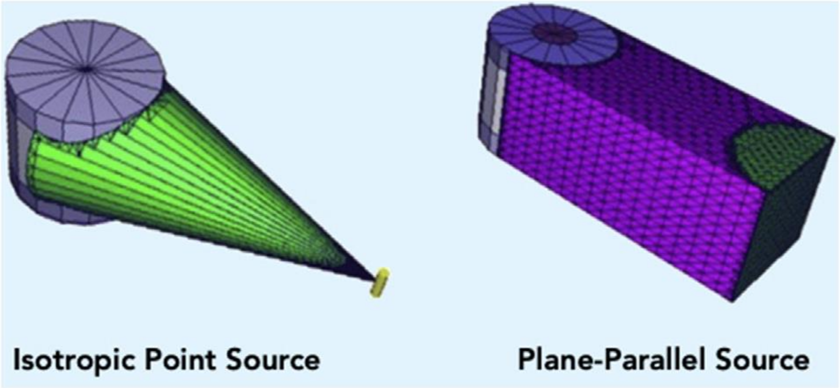


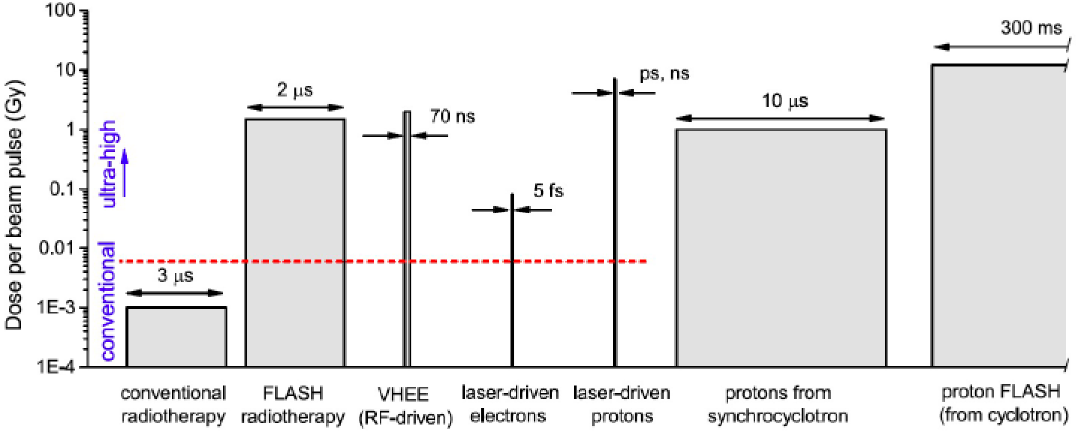

Y-Axis
Z-Axis


Y-Axis
Z-Axis
Name: 91
Material: 2, density(g/cc) = 0.940000
31 -28 20 65 -63 -59 61


X-Axis
Z-Axis
Name: 89
Material: 2, density(g/cc) = 0.940000
31 -28 -32 -66 -60 62

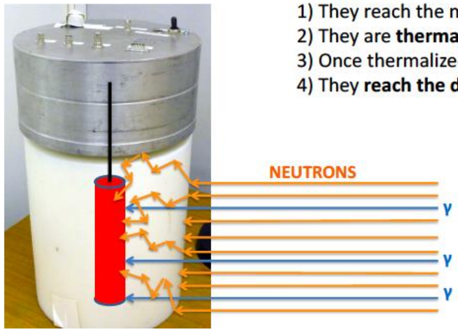

Borated Rubber Patch
Polyethilene Moderator
He-3 Counter Tube
Tungsten Powder Shell


Isotropic Point Source
Plane-Parallel Source



Detection of pulsed **neutron** fields shows an advantage, if compared to photons

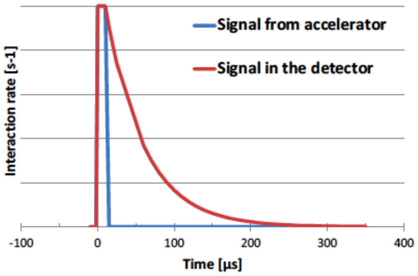
Neutron detection mechanism:
1) They reach the moderator surface
2) They are **thermalized** (scattering events)
3) Once thermalized they **diffuse**
4) They **reach the detector** (BF_3 or ^3He)



Photons do not need thermalization in order to be detected

Performances of detectors (rem counters) in pulsed neutron fields:

- **Dead time effects (↓)**
- **Neutrons thermalization and diffusion time (TDT) in the moderator (↑)**



Signal in the detector spread over several hundred µs, regardless of the original pulse width

↓

REDUCED UNDERESTIMATION

The reference quantity for dead time correction is the Dose Per Pulse (DPP)

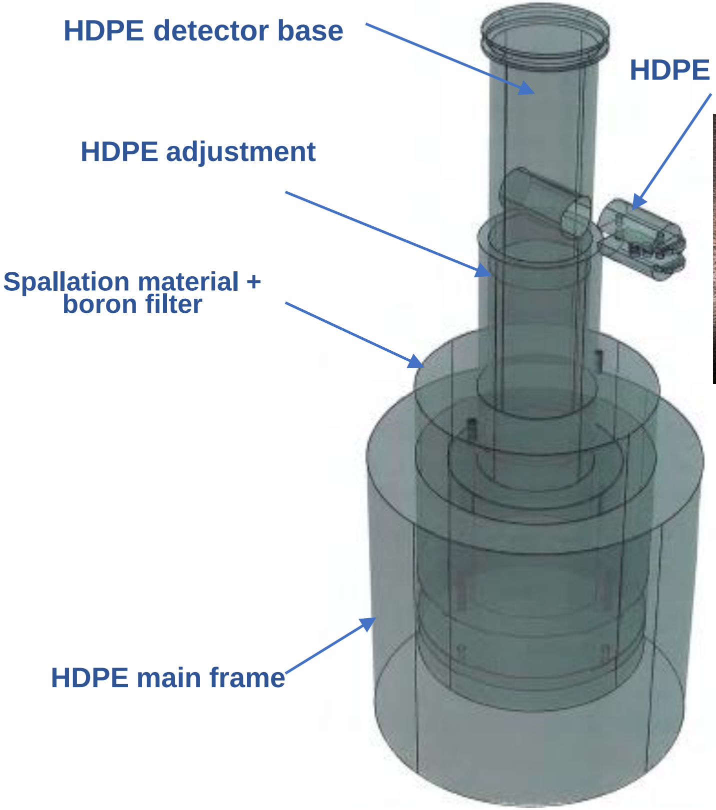
$$D_{meas} = \frac{D_{ref}}{1 + (D_{ref}/D_{half})}$$

D_{half} is the reference dose per pulse that causes an underestimation by a factor 2

The correction works on the single burst. To apply it the detector must resolve each burst

Instrument	Half response burst dose D_{half} [nSv]
LUPIN BF_3	1808
LUPIN ^3He	182
LB 6419	28
WENDI II	42
BIOREM	79
LB 6411	38
Studsvik 2202D	27
RadEye	25
Harwell N91	19
Linus	6
Cramal31	8
LIULIN	53

Caresana, M. et. al., 2022, Presentation at Neudos 14 (Krakow)



HDPE detector base
HDPE detectors frame
HDPE adjustment
Spallation material +
boron filter
HDPE main frame