Neutron doses to patients and staff around proton therapy installations

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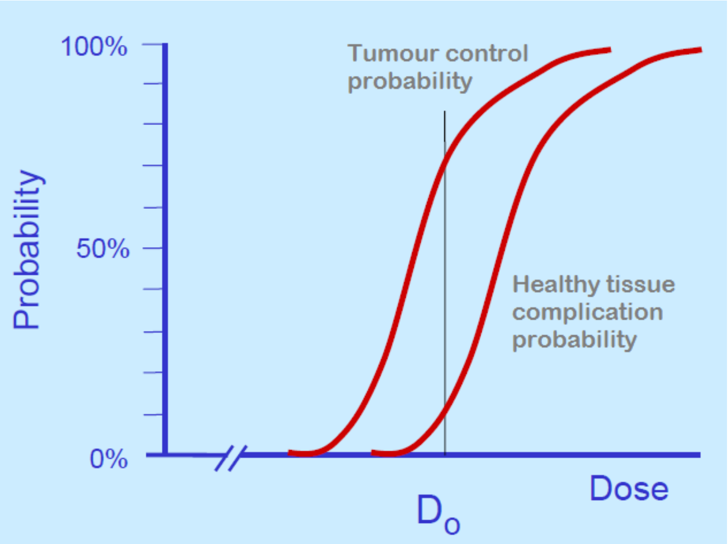
Content

- Proton therapy
- Neutron dosimetry
- Patient radiation protection
- Staff radiation protection

Proton therapy

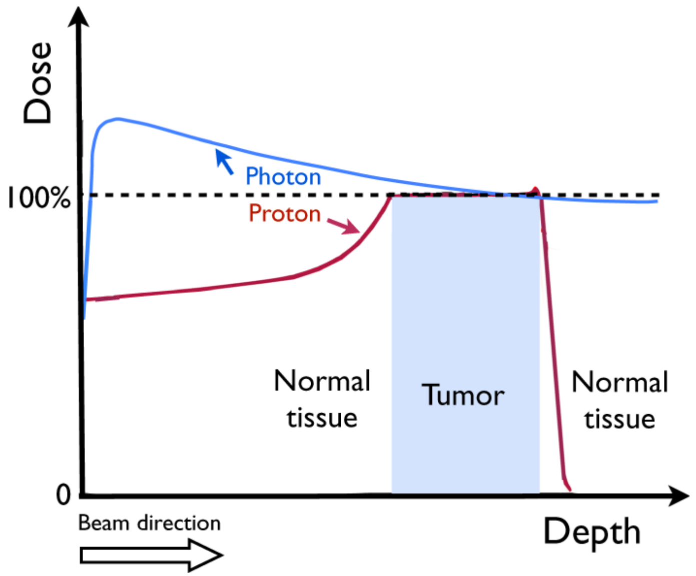
Radiotherapy

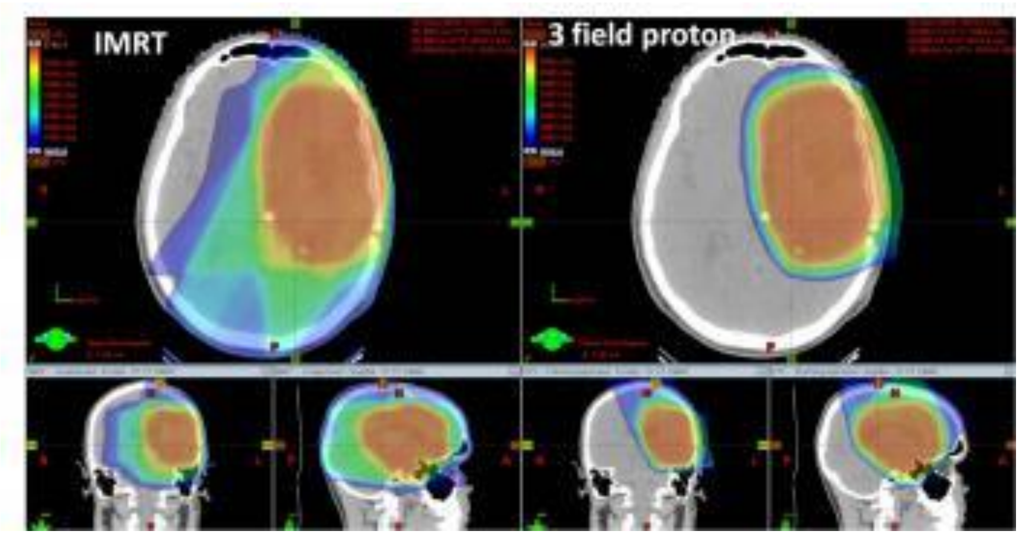
- Over 14 million cancer diagnoses per year
- In ¼ of cases radiotherapy is used
- Challenge is maximizing tumour damage, while sparing healthy tissues to minimize secondary cancer risk



Proton therapy

- Localized energy deposition at a tuneable depth
- Beneficial for deep tumours, tumours surrounded by radiosensitive organs and certain tumours in children
- Over 70 active facilities and over 200.000 patients treated





Proton therapy in Belgium

- 1st Belgian proton therapy facility built in Leuven
- First patient end 2019

UZ LEUVEN

KU LEUVEN

Université catholique de Louvain UCL

Cliniques universitaires SAINT-LUC UCL BRUXELLES

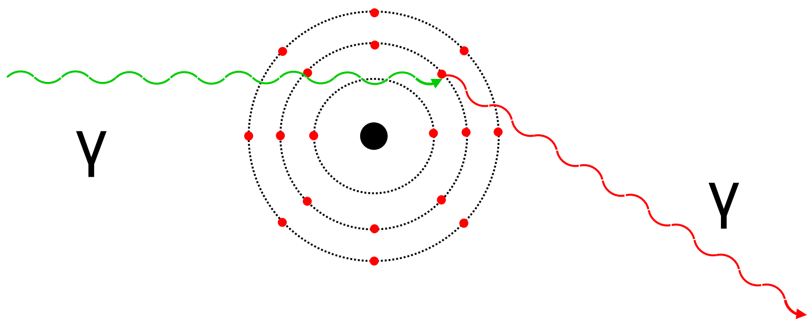
Neutrons in proton therapy

- Protons interacting with beamline or patient create secondary radiation
- Secondary radiation is dominated by neutrons
  - High-energy neutrons created by intra-nuclear cascades
    - Energy up to maximum proton energy
  - Fast neutrons evaporated by excited nuclei
    - Energy of the order of a few MeV
  - Thermal neutrons by slowing down during collisions
    - Energy around 0.025 eV
- Neutrons are radiation protection issue
  - Out-of-field doses in patients leading to secondary cancer risk
  - Staff exposure

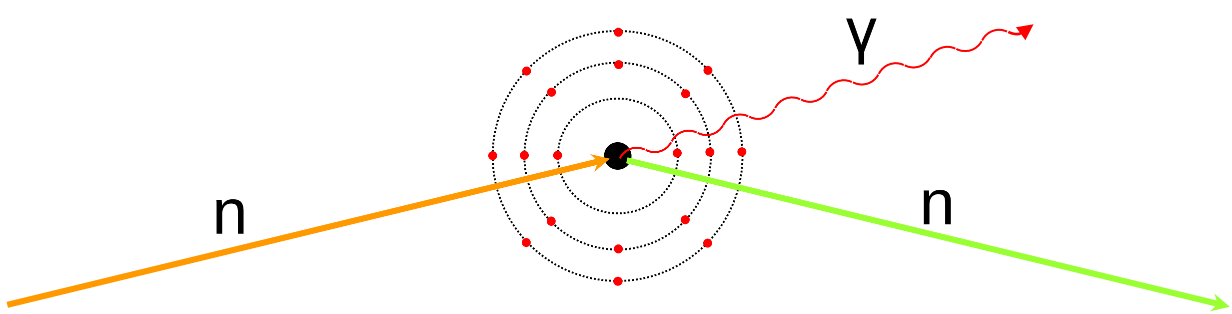
Neutron dosimetry

Neutron interaction with matter

- Photons (gamma rays and x-rays) interact with orbital electrons in the atom.



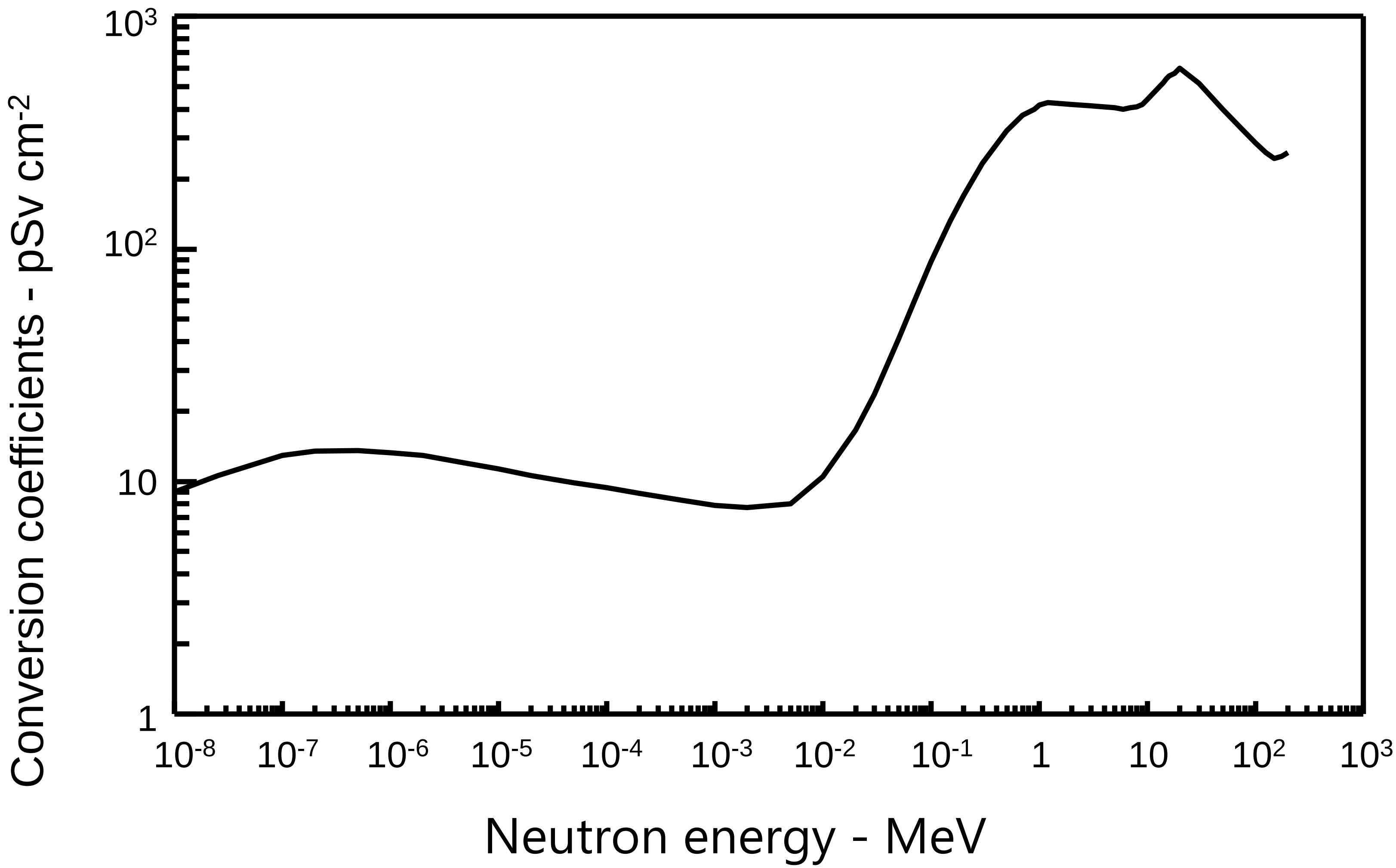
- Neutrons interact with the atom nucleus.



Why is personal neutron dosimetry so difficult?

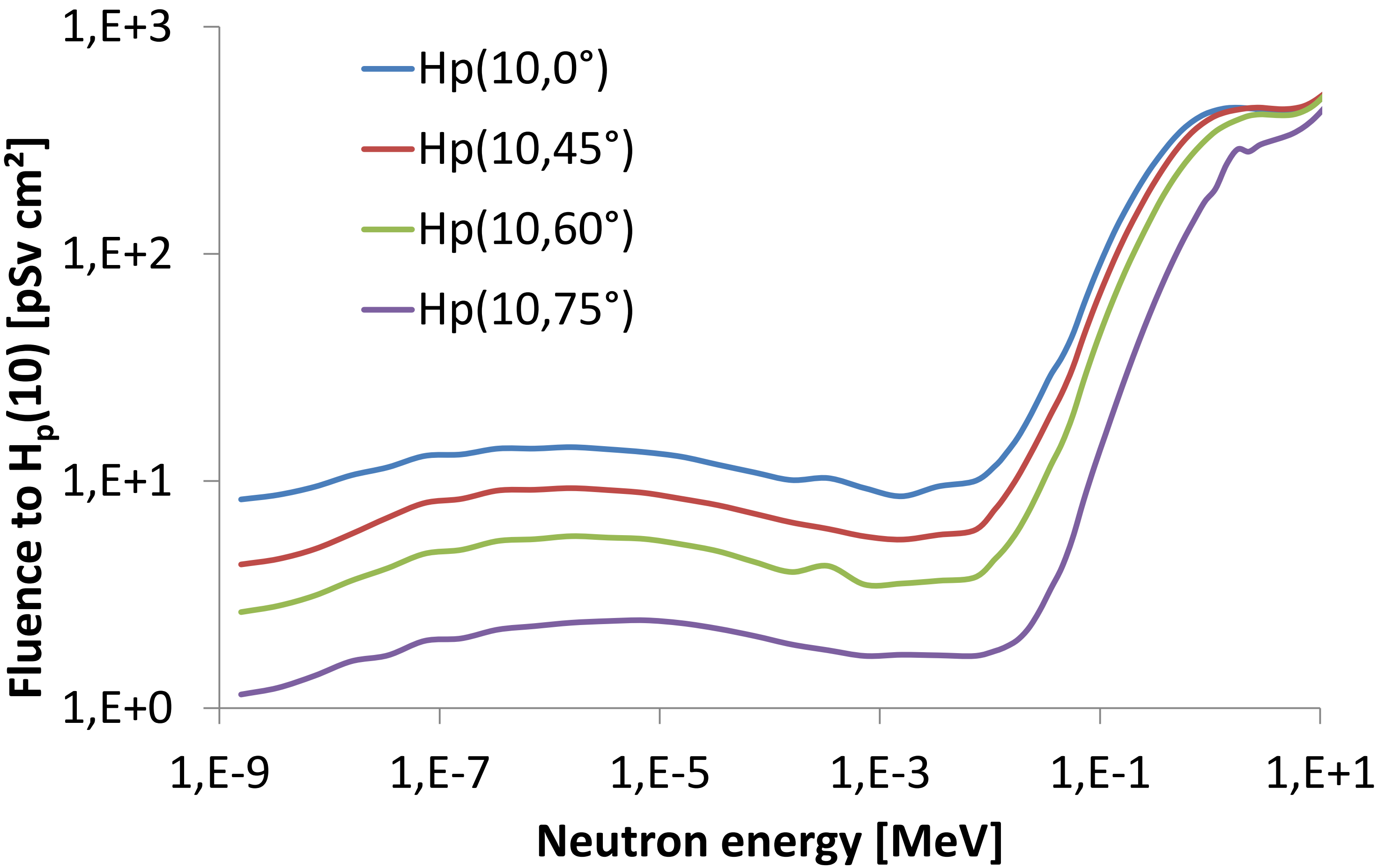
- Neutrons always together with (mostly strong) gamma fields
- Large energy range: 9 orders of magnitude
  - Thermal 0.025 eV to 100s of MeV
- Need to measure dose equivalent:
  - weighting factor dependent on neutron energy
  - e.g. fast neutron much more harmfull than thermal neutron (per deposited energy)
- Easy detection of thermal neutrons, but
  - Least harmfull
  - Original neutrons are fast

Neutron dose conversion coefficients for Ambient Dose Equivalent, H*(10)



Personal neutron dosimeters

- Personal dose depends strongly on neutron energy and angle

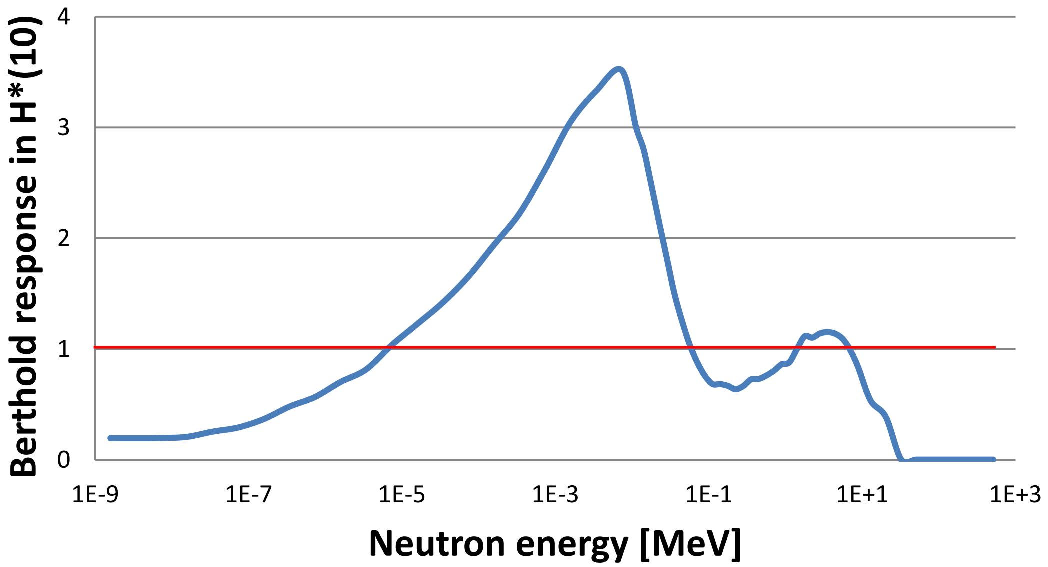


Field instrument properties

- Designed to measure ambient dose equivalent.
- Better sensitivity = lower detection levels.
- Better dose equivalent response than personal dosimeters.
- Heavier than personal dosimeters.
- Isotropic response for H*(10).
- Constructed with a central thermal-neutron detector, surrounded by a hydrogenous moderator (CH2) to thermalize the neutrons
- Generally rely on capture reactions: e.g. $^{10}B(n,\alpha)^{7}Li$ or $^{3}He(n,p)^{3}H$

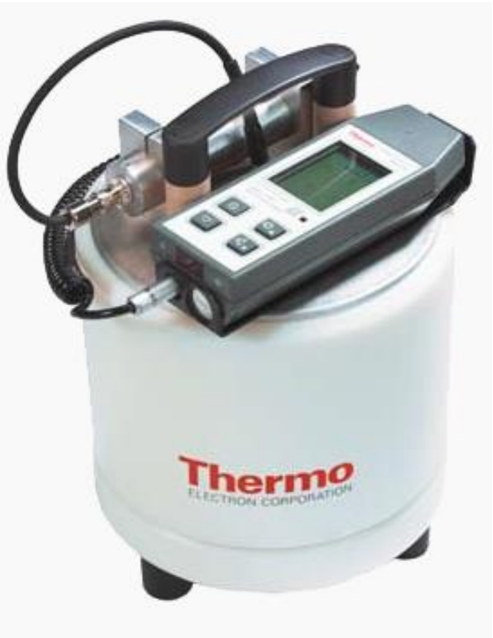
Ambient neutron monitors

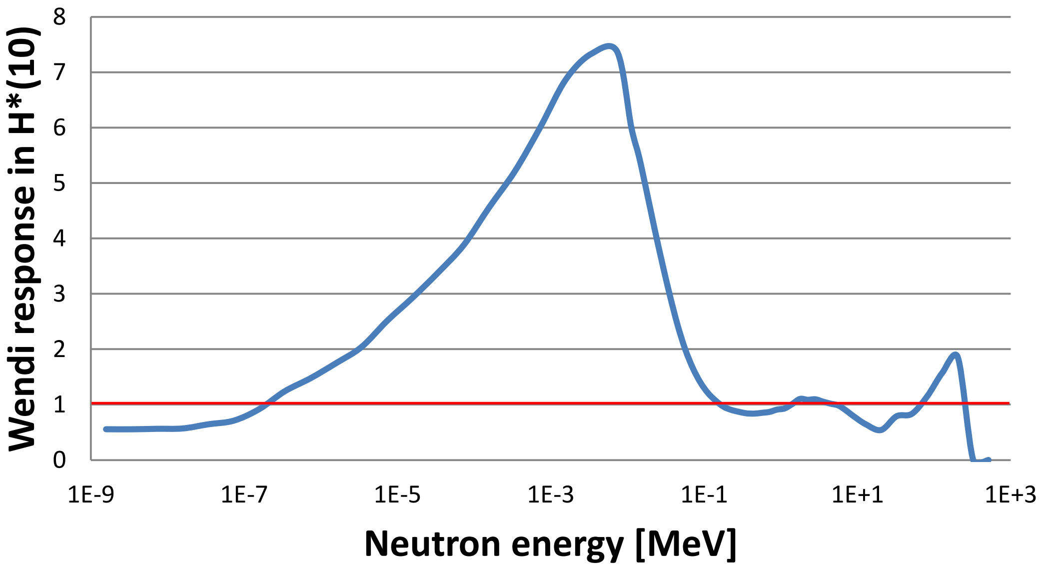
- Berthold LB 6411
- ^{3}He proportional counter for detection of thermal neutrons
- Polyethylene moderator to thermalize fast neutrons
- Under-response for high energy neutrons



Ambient neutron monitors

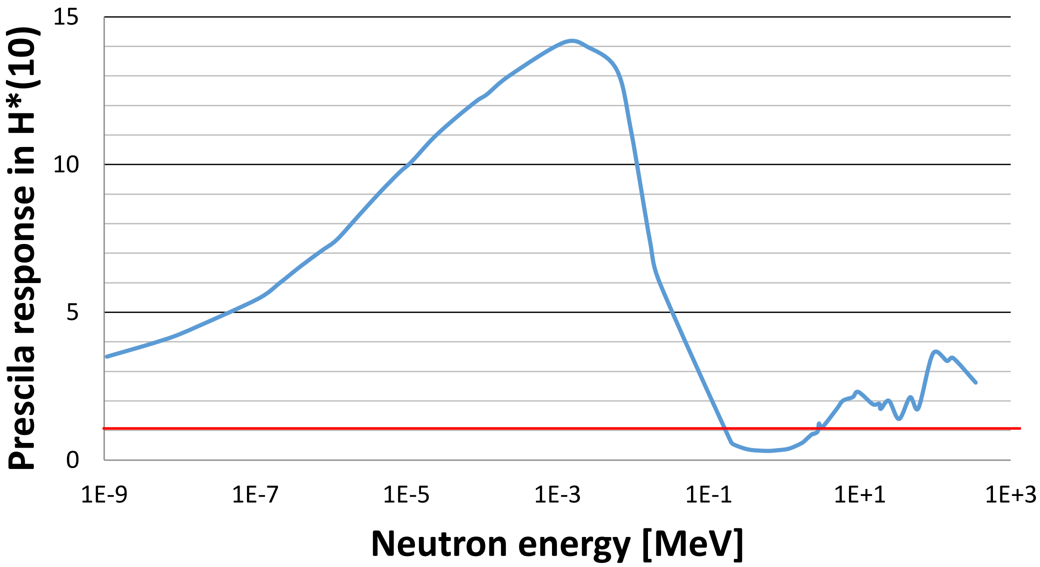
- Thermo Scientific Wendi-2
- ^{3}He proportional counter for detection of thermal neutrons
- Polyethylene moderator to thermalize fast neutrons
- Tungsten shell for detecting high energy neutrons



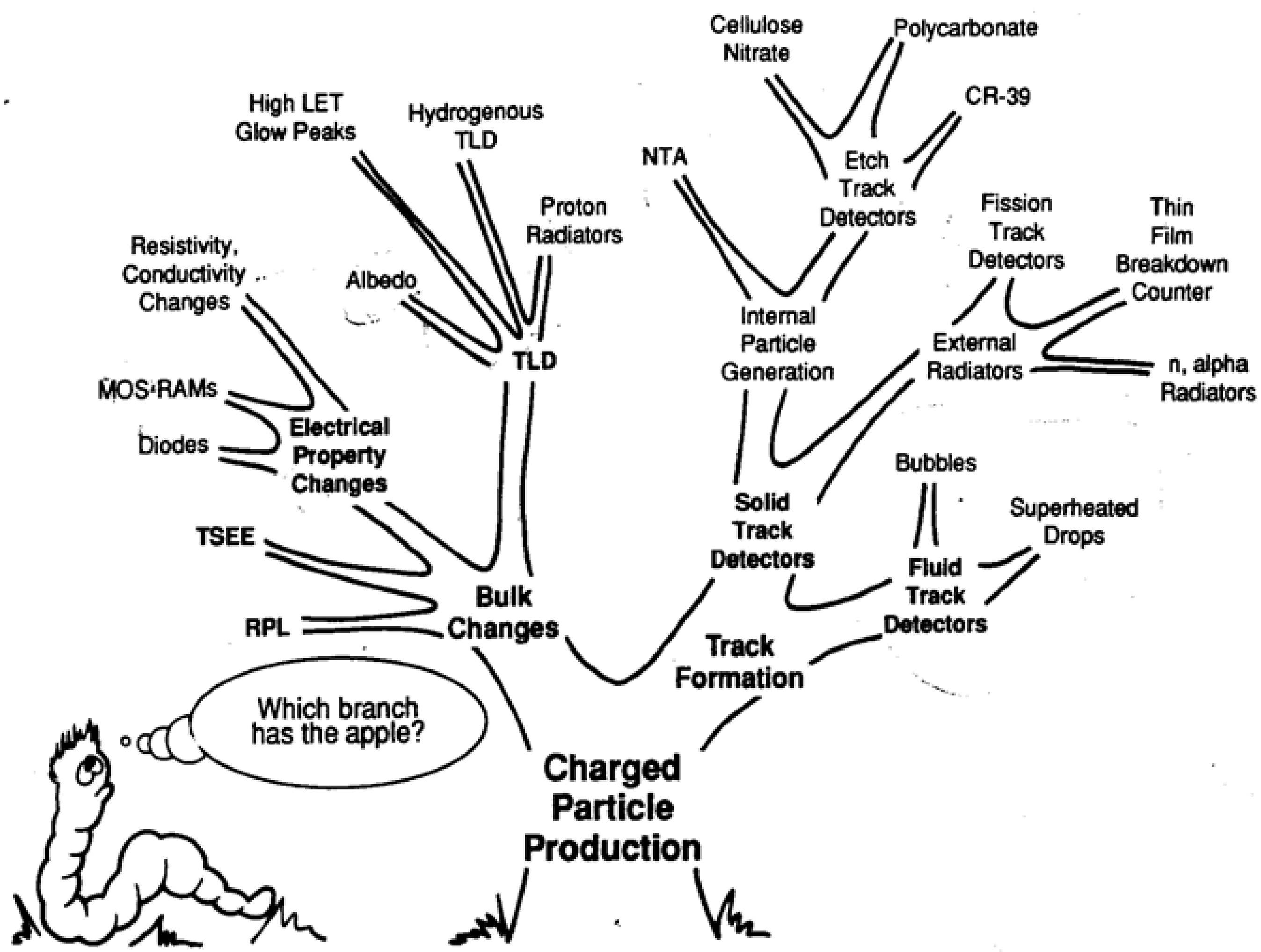


Ambient neutron monitors

- Ludlum Model 42-41L PRESCILA
- Proton recoil ZnS(Ag) scintillator
- Scintillators for thermal and fast + high energy neutrons



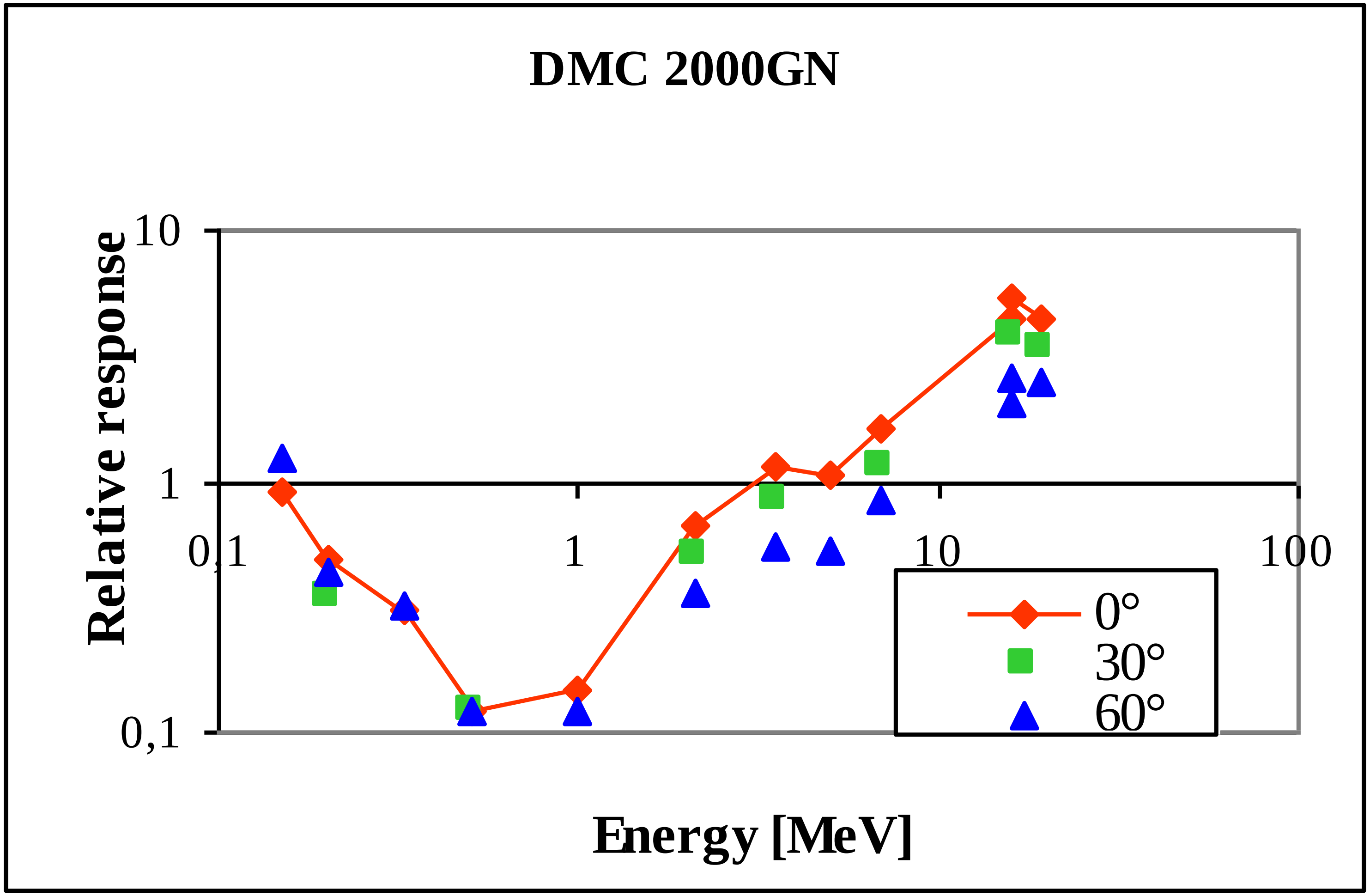
Different types of neutron dosemeters



Active Personal neutron dosimeters

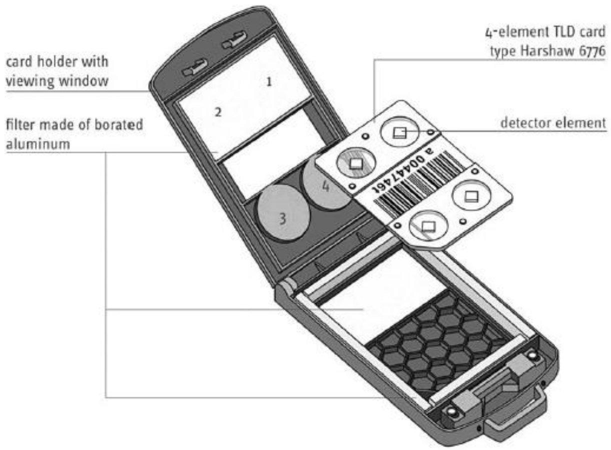
- Thermo Scientific EPD-N2 or DMC GN
- Active electronic dosimeter with 3 Si diodes
  - With hydrogen rich convertor for fast + high energy neutrons
  - With ^{6}Li convertor for thermal neutrons
  - Without convertor for photons
- Large over- or underestimations possible for some energies

Similar behaviour Thermo and MGPi detector



Personal neutron dosimeters

- Albedo dosimeter
- Passive dosimeter with 2 pairs of LiF thermoluminescent detectors
  - Combination of ^{6}LiF and ^{7}LiF 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



Personal neutron dosimeters

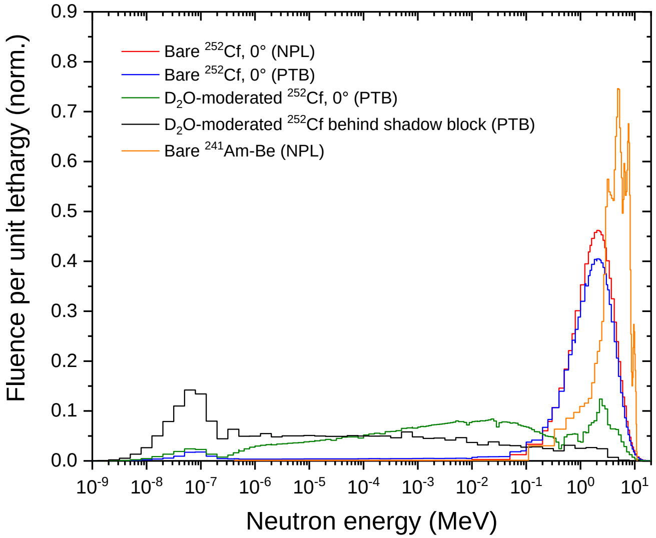
- (Landauer) track etch detector
- Passive dosimeter with special polymer (CR-39)
  - Recoil protons create broken polymer chains
  - Tracks can be visualized under microscope by chemical etching
- Relatively good energy response

Scope of IC2017n

Country	Number of participating system per country
Germany (1), Italy (1)	4
France, United Kingdom	3
Austria, Belgium, Czech Republic, Japan, Switzerland, United States (1)	2
Brazil, Finland, India, Poland, Romania, The Netherlands, Turkey	1

EURADOS

IC2017n Irradiation fields



IC2017n

No.	Radiation quality	$H_p(10)$ (mSv)
1	Bare ^{252}Cf source at 0°	0.3 1.5 12
2	Bare ^{252}Cf & ^{137}Cs sources at 0° [$H_p(10)$ photons = 1 mSv]	1.5
3	Bare ^{252}Cf source at 45°	1.5
4	D_2O-moderated ^{252}Cf source at 0°	1.2
5	D_2O-moderated ^{252}Cf source behind shadow block	1.0
6	Bare ^{241}Am-Be at 0°	1.5

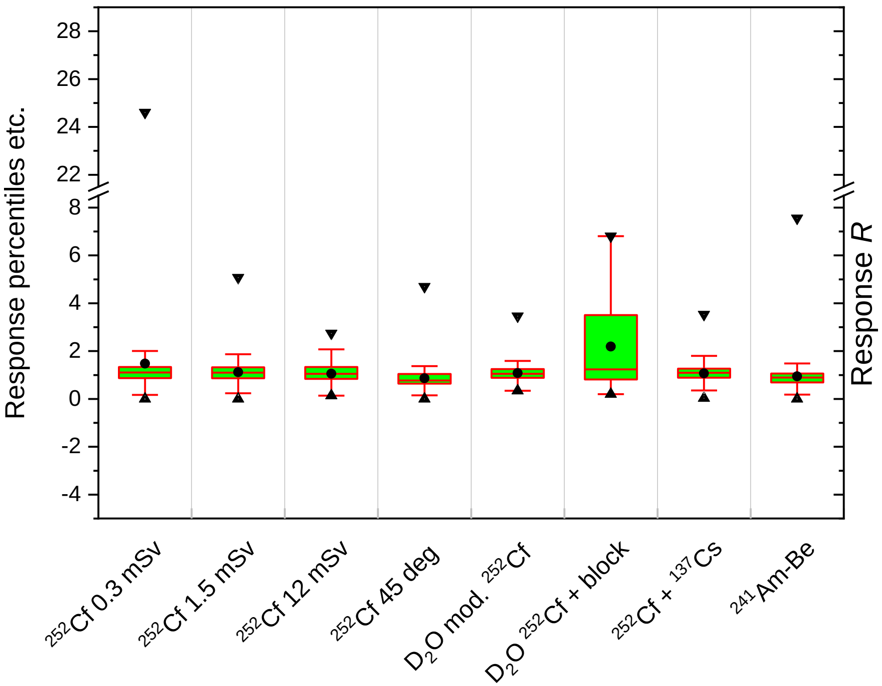
EURADOS

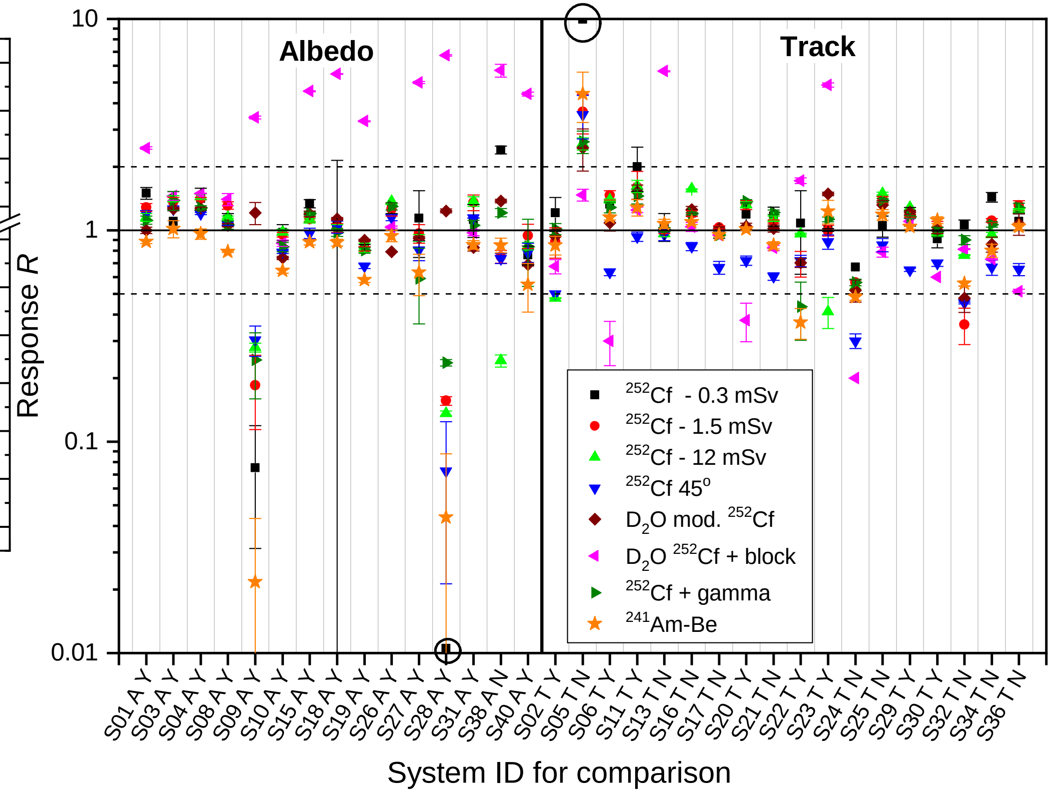
Categories of Dosemeter

- 33 dosemeter systems from 32 individual monitoring services
  - 18 track systems
    - 7 etched track detectors for fast neutrons with thermal neutron TLD
    - 7 etched track detectors for fast neutrons with thermal neutron converters
    - 3 etched track detectors for fast neutrons without evidence of thermal sensor
    - 1 fission track detector
  - 15 albedo systems
    - 10 TLD with boron-loaded shield
    - 3 TLD with cadmium shield
    - 1 OSLD
    - 1 TLD lacking information on shielding against direct thermal neutrons
  - No electronic dosemeters

EURADOS

Dosemeter Response - summary





EURADOS

Conclusions

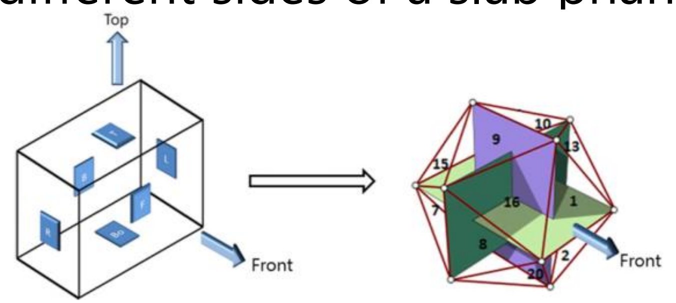
- Applying approval criterion and performance limits of ISO 14146:2018
  - 9 (out of 15) albedo passed with not more than two outliers
  - 12 (out of 18) track systems passed with not more than two outliers
- Albedo systems for D_2O-moderated ^{252}Cf source behind shadow block over-responded due to nearly isotropic distribution and very soft field
- Some albedo systems responded within performance limits because of improved side shielding or correction based on ratio of readings behind front and albedo window
- Track detectors tend to underestimate low-energy neutrons at high angles of incidence

EURADOS

Personal neutron dosimeters

- Workplace specific correction factor by field characterization
  - Assessment of neutron energy spectrum with Bonner spheres

  - Assessment of neutron directional distribution with personal dosimeters on different sides of a slab phantom

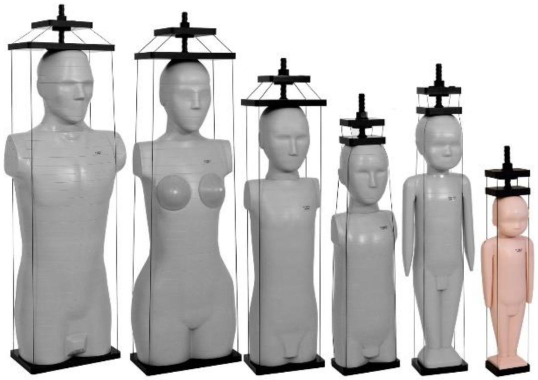


  - Calculation of reference Hp(10) value and comparison with personal dosimeter measurement to determine appropriate correction factor

Patient radiation protection

Organ dose assessment

- Physical anthropomorphic phantoms of different sex and age



- Compact passive detectors for in-phantom measurements

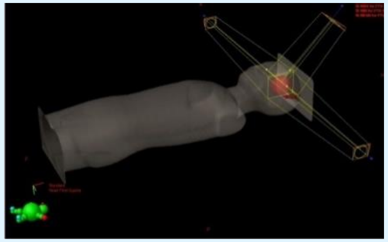
Bubble detectors

Track etch detectors

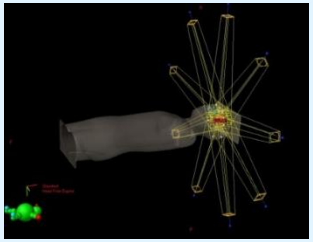
Thermoluminescent detectors

Brain irradiation measurements

- **Brain irradiation**
  - Spherical tumor
    - r=3 cm
    - Dose per fraction to the tumor 2 Gy
  - Out-of-field organ doses
  - 5 year and 10 year old phantoms

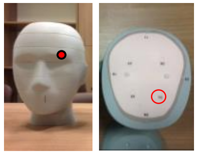


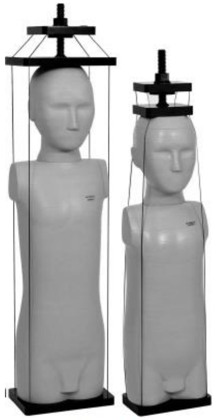
3D-CRT (Varian)



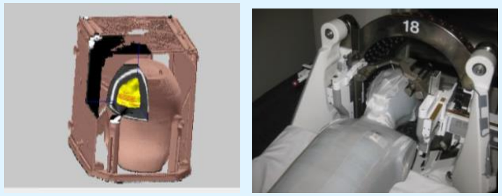
IMRT (Varian)

- 3D-CRT (Krakow 2013)
  - Varian Clinac 2300, Centre of Oncology Krakow
  - 3 non-coplanar beams (6MV) 336MU
  - Dynamic and mechanical wedge
- IMRT (Krakow 2013)
  - Varian Clinac 2300, Centre of Oncology Krakow
  - 9 coplanar beams (6MV) 443MU
- GammaKnife (Zagreb 2014)
  - Leksell GK, University Hospital Zagreb
  - Co-60 sources
  - Usually small tumours
- Proton therapy (Krakow 2014)
  - Proteus 235 (IBA), Cyclotron Centre Bronowice in Krakow
  - Spot scanning (70-140 MeV)

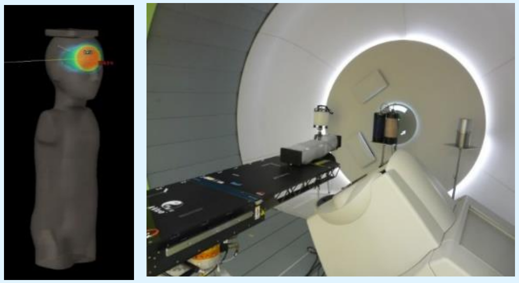




10-year old 5-year old

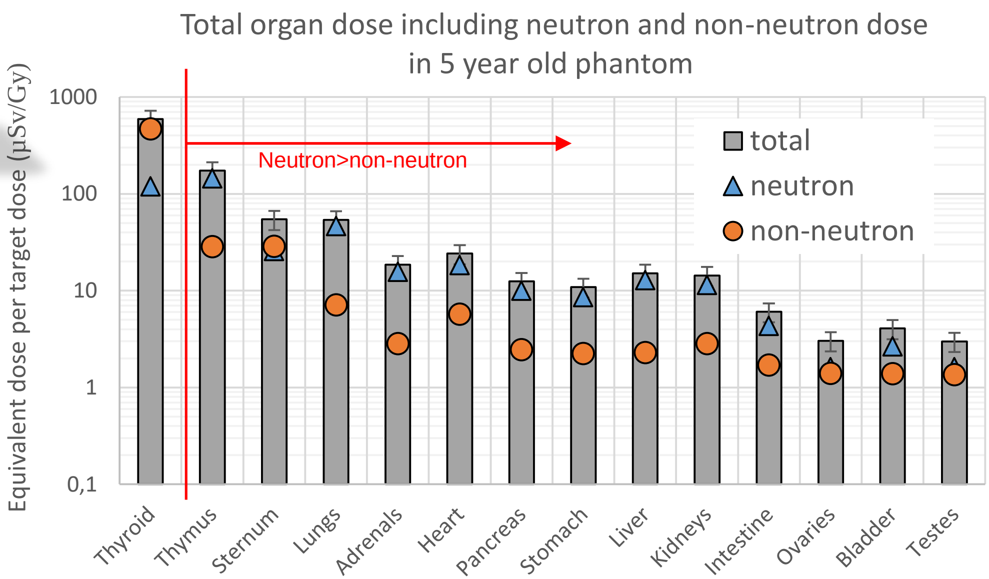


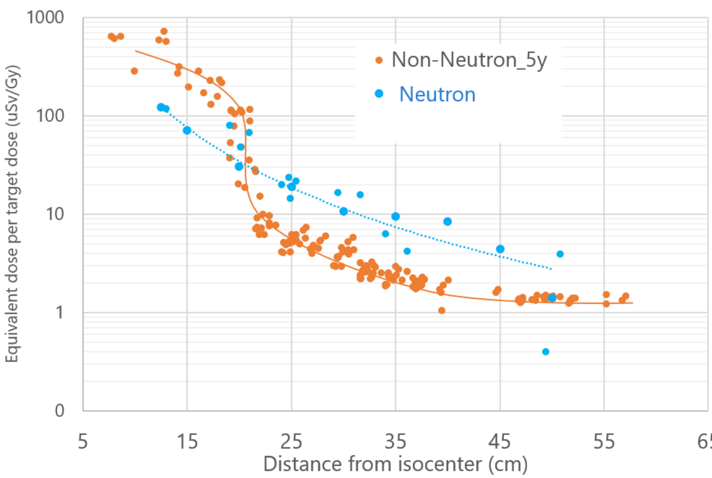
Leksell **Gamma Knife**



Proton therapy (IBA, Proteus C-235)

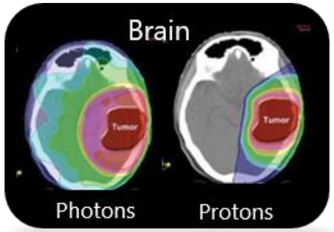
Brain irradiation measurements in proton therapy





- Neutron doses are lower than non-neutron doses close to the target, while the neutron dose becomes larger than non-neutron dose further away from the target
- In proton therapy the out-of-field doses range from 0.6 mSv/Gy in thyroid to <0.01 mSv/Gy in intestines, ovaries, bladder and testes

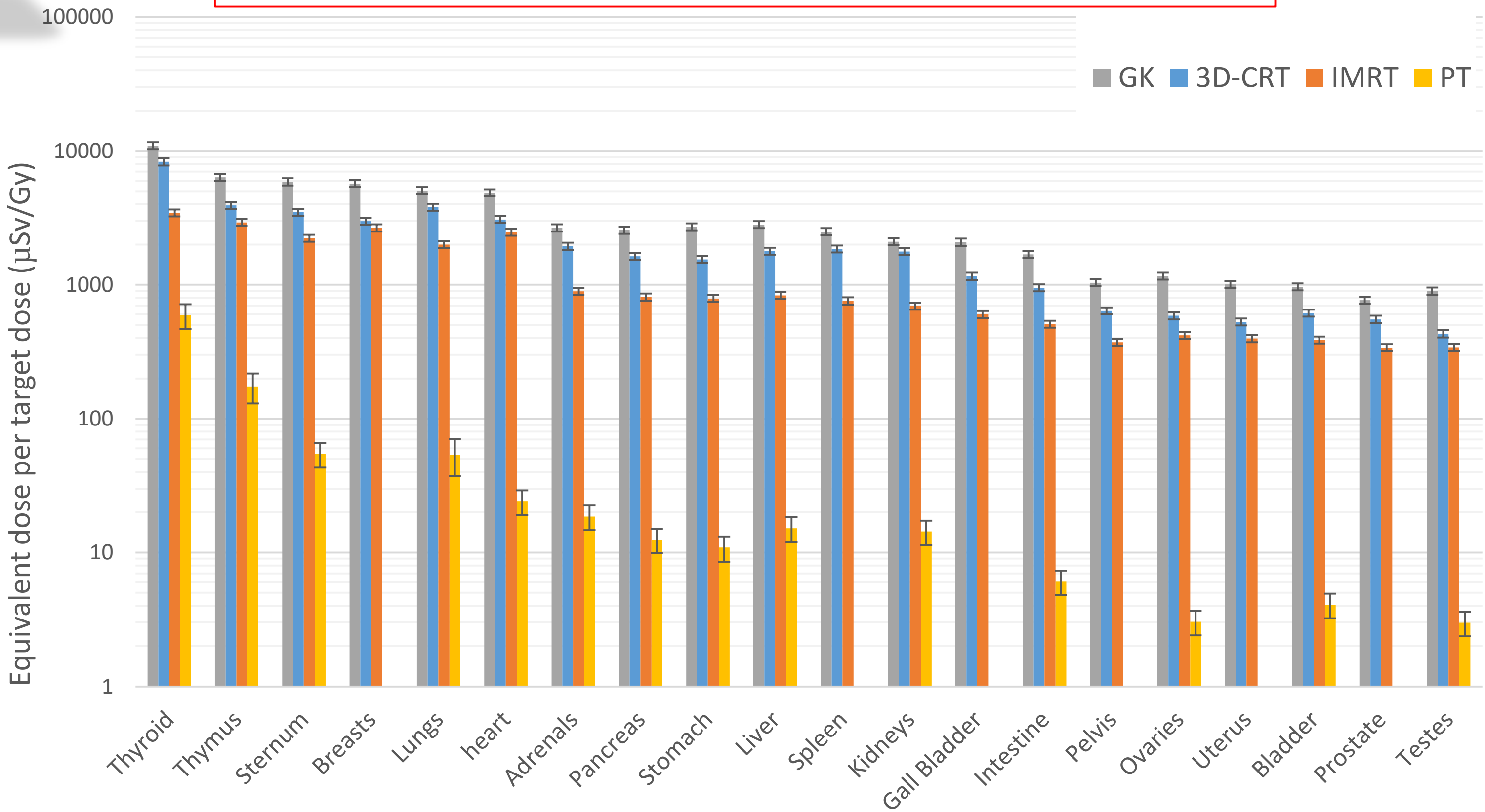
Brain irradiation measurements: Protons vs photons



→ Protons result in lower out of field doses than photons

- One order of magnitude close to the brain
- More than two order of magnitude further away from the brain
- Measurements during craniospinal irradiations show even two to three orders of magnitude lower out-of-field doses for protons in comparison with photons

5-year old

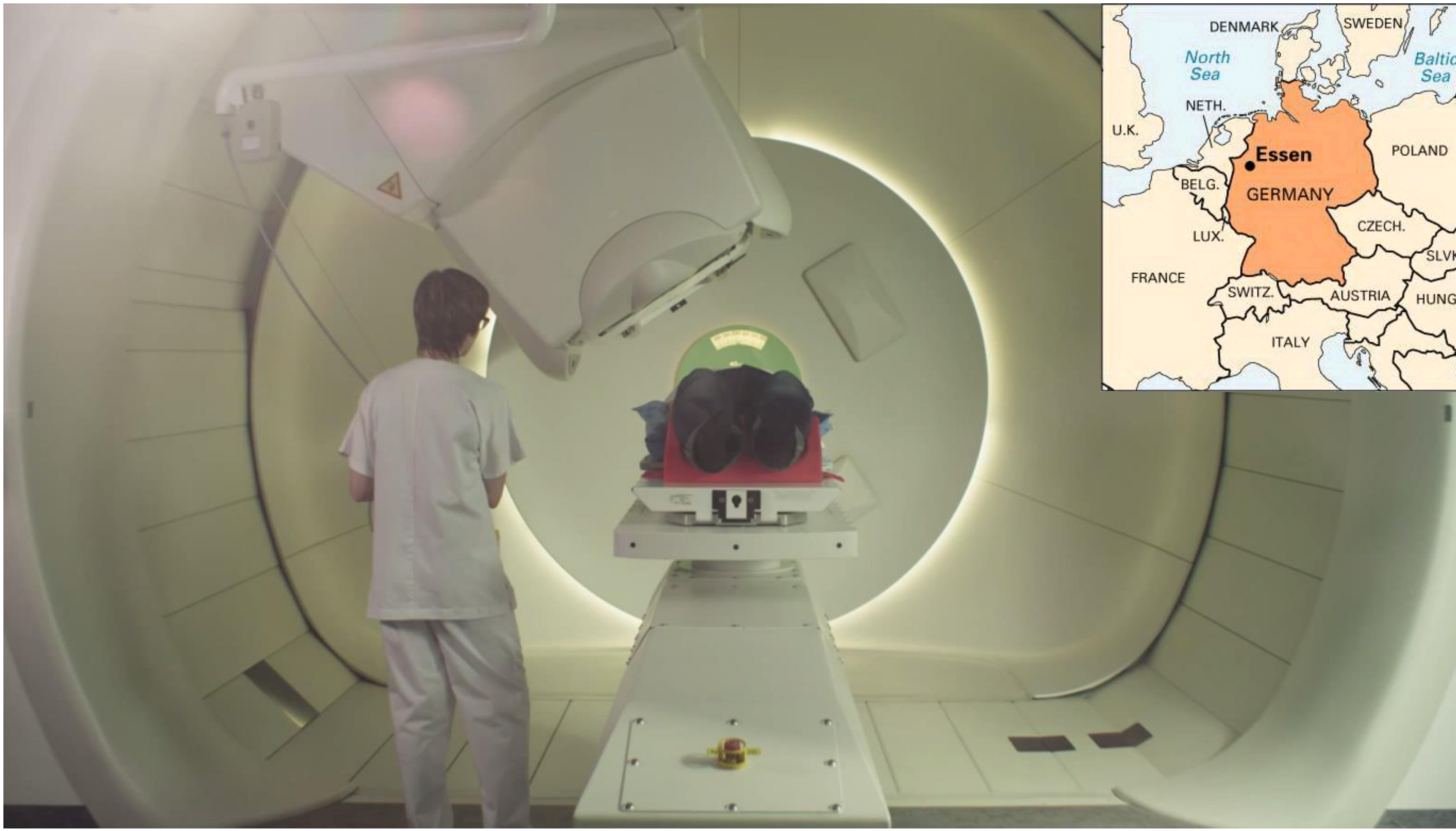


Patient radiation protection in proton therapy

- Out-of-field doses are 1-3 orders of magnitude lower than in photon therapy
- Further away from the target, neutron doses are dominant for the out-of-field doses
- Further research required to limit neutron doses and thus secondary cancer risk even more

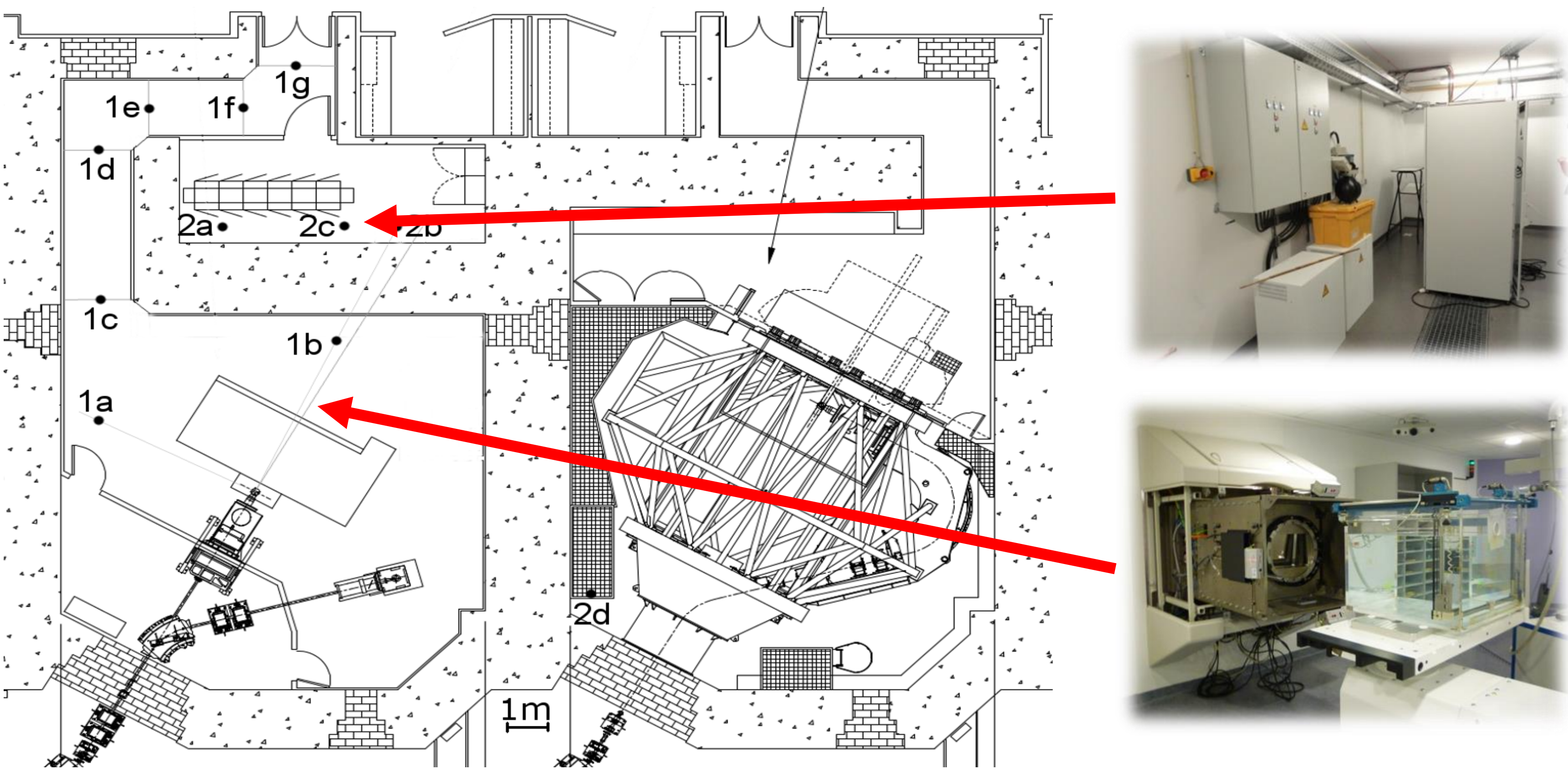
Staff radiation protection

Westdeutsches Protonentherapiezentrum Essen



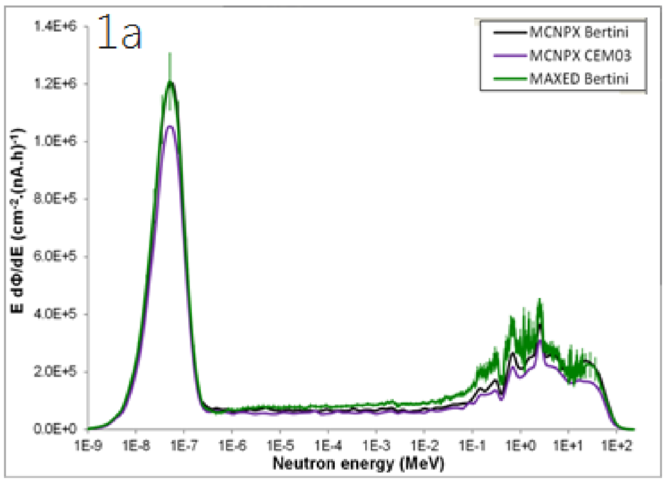
Westdeutsches Protonentherapiezentrum Essen

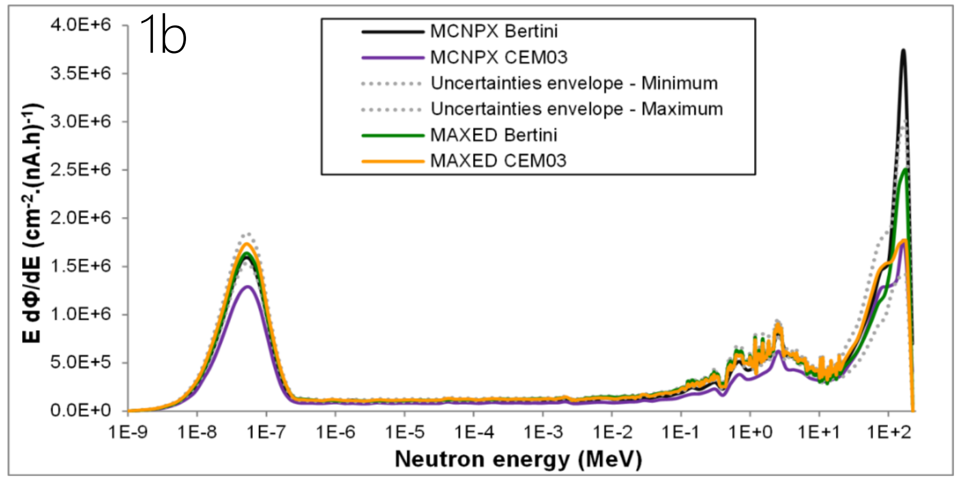
- Neutron field characterization at different locations inside treatment room and adjacent technical rooms

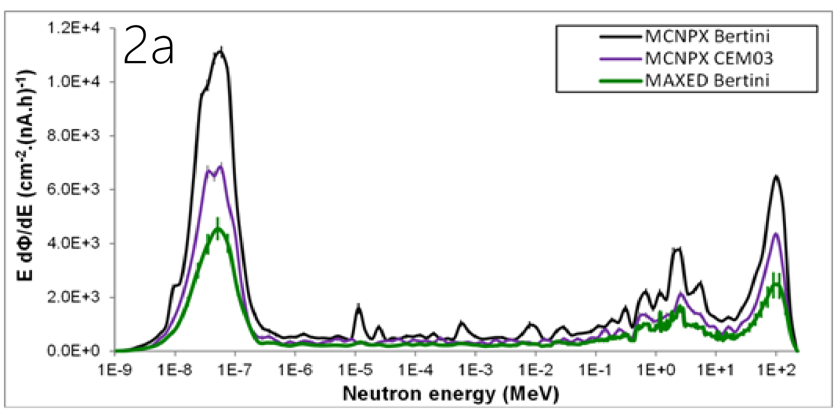


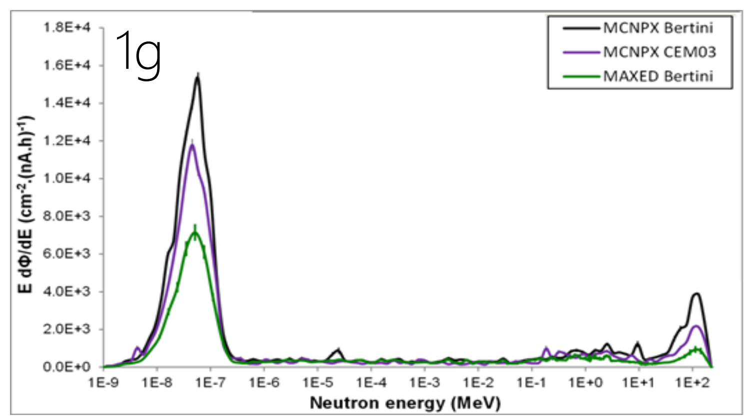
Westdeutsches Protonentherapiezentrum Essen

- Thermal, fast and high energy neutrons with different contributions depending on the location









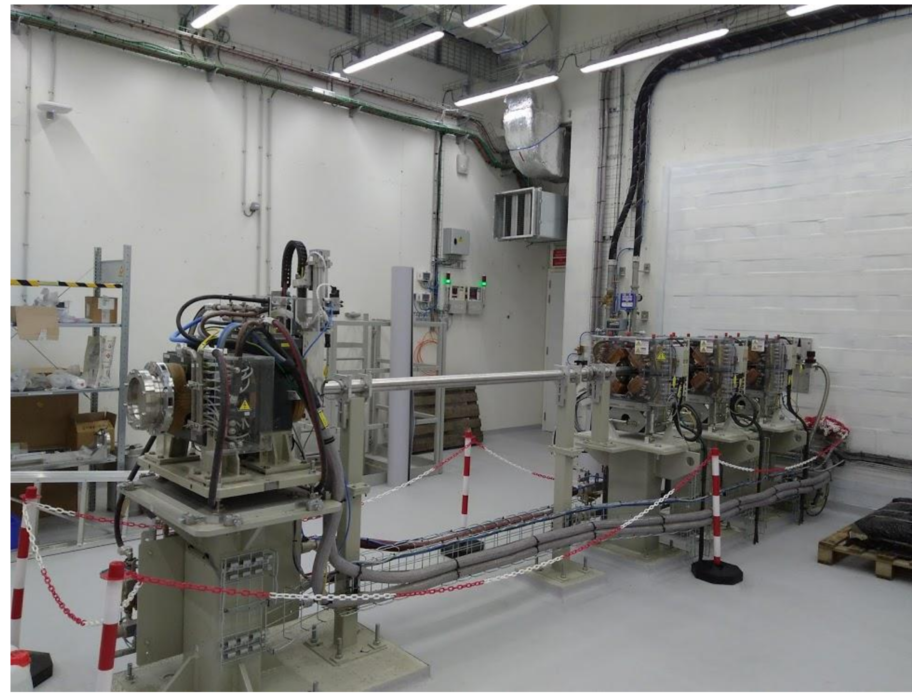
Westdeutsches Protonentherapiezentrum Essen

- Correction factors for electronic dosimeters up to a factor 16
- Smaller corrections for track etch and especially bubble detectors

$\frac{H_p(10)_{meas}}{H_p(10)_{ref}}$	**1a**	**1b**	**2a**	**2c**
EPD-N2	3.2	16	8.0	-
DMC 2000 GN	3.2	11	7.2	-
Bubble	1.2	-	-	1.1
Landauer CR39	0.5	0.6	-	-

Proton therapy facility UZ Leuven

Proton therapy treatment room



Proton therapy research beamline

Staff radiation protection in proton therapy

- Sufficient neutron shielding is required for cyclotron bunker and treatment room to limit staff doses
- Shielding design should be based on Monte Carlo radiation transport simulations
- Validation of shielding and estimation of staff doses by measurements with portable neutron and gamma monitors
- Fixed ambient neutron and gamma monitors can be installed for monitoring dose rates at critical locations, also important for gamma radiation due to activation
- If staff can receive significant neutrons doses, personal neutron dosimeters should be used
- Ambient neutron monitors and personal neutron dosimeters should be able to measure high energy neutrons, preferably a field specific correction factor should be applied