HSE

Occupational Health & Safety
and Environmental Protection unit

CONSIGLIO NAZIONALE
DEGLI INGEGNERI

WEBINAR (modalità on line)
Giovedì 16 dicembre 2021, ore 15.00 - 18.00
Radioprotezione in campo medico: tecniche e pratiche per l'ingegneria biomedica in ambito diagnostico e terapeutico

Radiation protection at medical particle accelerators

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CERN

Outline of the lecture

- Particle accelerators in medicine
- Radionuclide production
- Radiation therapy
  - Conventional radiation therapy
  - Particle (hadron) therapy
- Principles of radiation protection
  - Justification, optimization and dose limitation
  - Radiological quantities and units
  - Protection means
  - Instrumentation
- Radiation shielding of radiation therapy accelerators
- CERN technology transfer in health and safety

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Particle accelerators worldwide

Three main applications: 1) Scientific research 2) Industrial uses 3) Medical applications

Accelerators	1968 [1]	1970 [2]	1989 [3]	1994 [4, 5]	1998 [6–8]	2000 [9, 10]	2004 [11, 12]	2007 [13, 14]	2009 [15, 16]	2012 [17, 18]	2014 forecast
Industrial accelerators,	~2000	~2700	>4000	>4500	~7500	~8500	>8500	~17 900	22 500	25 300	27 000
including											
Electron accelerators rated to energies in excess of 300 keV			~650	1500	1500	1500	>1500	2700	2750	~5000	~5000
Electron accelerators rated to energies below 300 keV			>350	>1000				4500	7000	7500	~8000
Ion implanters and accelerators for ion analysis			~3000	>2000	~6000	~7000	>7000	~9700	~10 000	~11 300	~12 000
Neutron generators								~1000	~2000	~2000	~2000
Accelerators in science				~1000	~1200	~1200	~1200	~1200	~1200	~1200	~1200
Accelerators in medcine,		306	>2500	~4200	~4700	~5200	~8500	~9650	~11 600	~13 000	~14 000
including											
Electron accelerators			~2500	~4000	~4500	~5000	~7500	~9000	>11 000	~12 000	~13 000
Proton and ion accelerators (radiotherapy) [19]			11	17	20	20	25	29	32	39	~59
Production of radioisotopes for medicine				~200	~200	~200	~260	>550	>600	~1000	~1100
Total	~2000	~3000	>6500	>9700	>13 500	>15 000	>18 000	~27 500	~30 000	~39 500	41 000

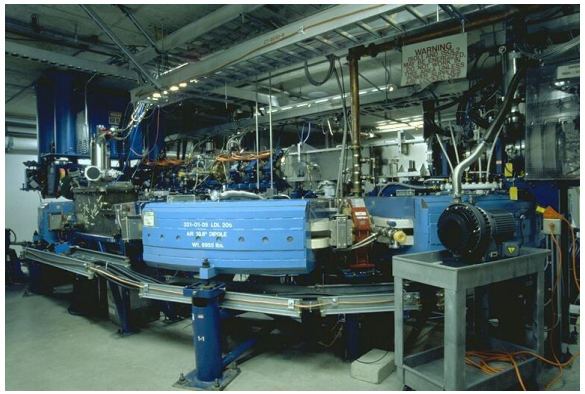
A. P. Chernyaev and S. M. Varzar, Particle Accelerators in Modern World, Physics of Atomic Nuclei, 2014, Vol. 77, No. 10, pp. 1203–1215.

Three classes of medical accelerators

- Production of radionuclides with (low-energy) cyclotrons
  - Imaging (PET and SPECT)
  - Therapy
- Electron linacs for conventional radiation therapy, including advanced modalities
- Medium-energy cyclotrons and synchrotrons for hadron therapy with protons (250 MeV) or light ion beams (400 MeV/u ^{12}C-ions)
  - Accelerators and beam delivery
  - New concepts


IBA Cyclone 30 XP


www.varian.com



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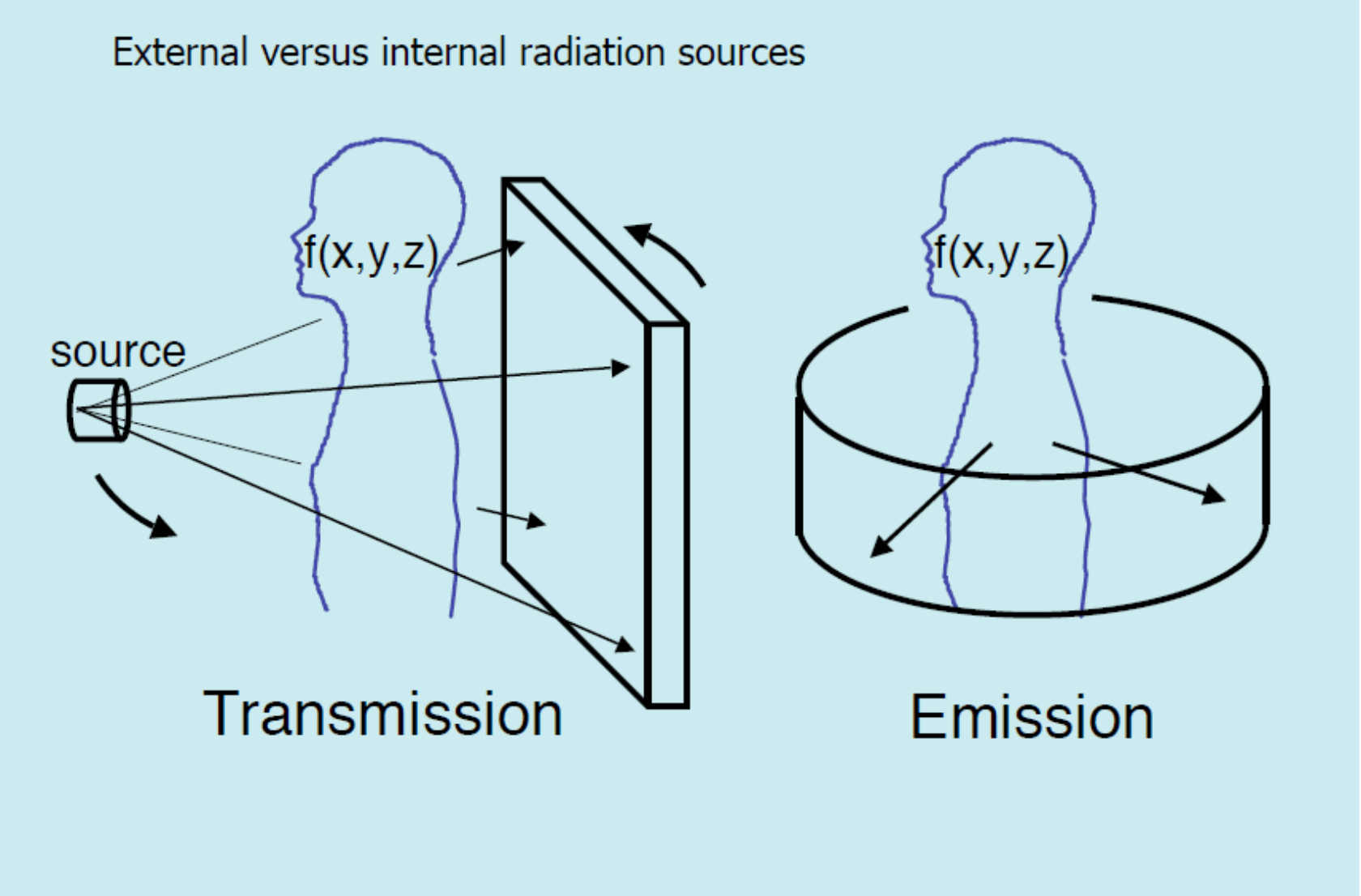
Emission versus transmission imaging



Radionuclide production

The use of radionuclides in the physical and biological sciences can be broken down into three categories:

- Radiotracers
- Imaging (95% of medical uses)
  SPECT (^{99m}Tc, ^{201}Tl, ^{123}I)
  PET (^{11}C, ^{13}N, ^{15}O, ^{18}F)
- Therapy (5% of medical uses)
  Brachytherapy (^{103}Pd)
  Targeted therapy (^{211}At, ^{213}Bi)

Relevant physical parameters (function of the application)

- Type of emission (α, β^+, β^-, γ)
- Energy of emission
- Half-life
- Radiation dose (essentially determined by the parameters above)

Production of radionuclides for medical imaging and therapy

All radionuclides commonly administered to patients in nuclear medicine are *artificially* produced

Three production routes:

- (n, γ) reactions (**nuclear reactor**): the resulting nuclide has the same chemical properties as those of the target nuclide
- Fission (**nuclear reactor**) followed by separation
- Charged particle induced reaction (**cyclotron**): the resulting nucleus is usually that of a different element

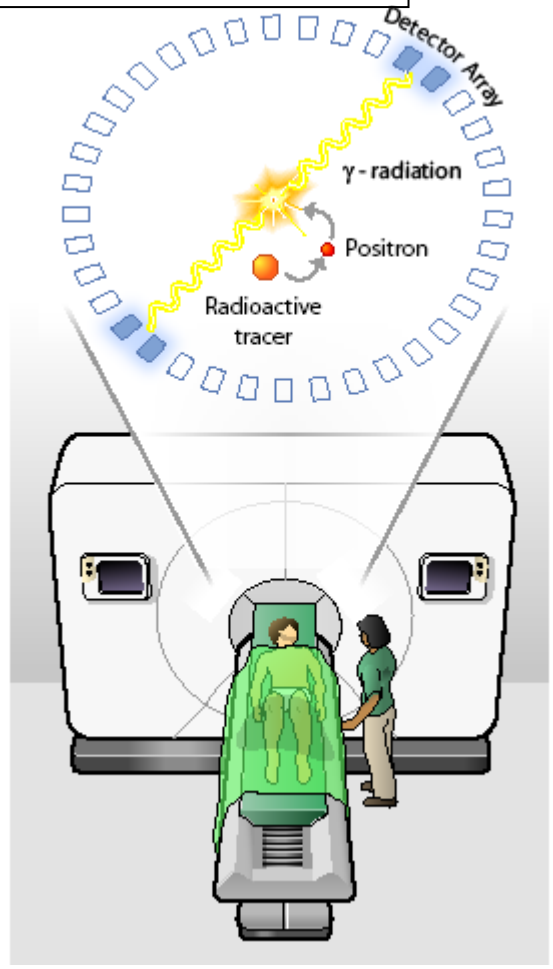
Positron Emission Tomography (PET)

ISOTOPES	Half-Life	
11-C	20.4 min,	“natural”
13-N	10.0 min	“natural”
15-O	2.0 min	“natural”
18-F	109.8 min	“pseudo-natural”

Cyclotron

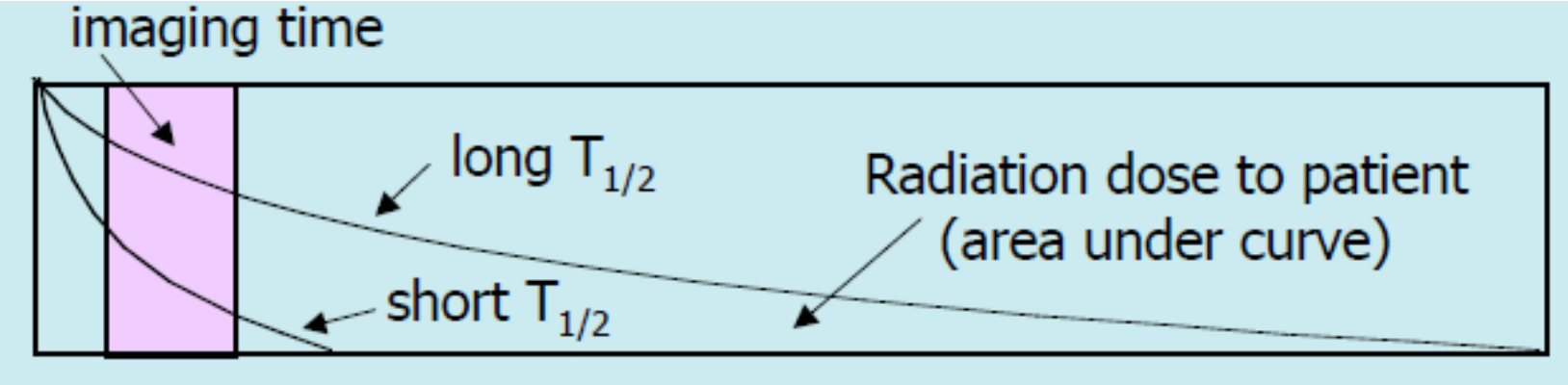
Radiochemistry

PET camera



The “ideal” diagnostics radiopharmaceutical

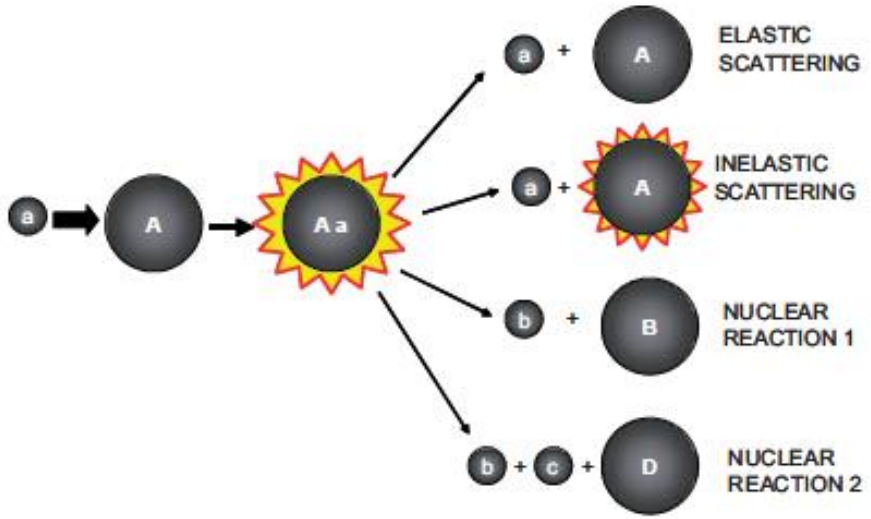
a) Be readily available at a low cost
b) Be a pure gamma emitter, i.e., have no particle emission such as alphas and betas (these particles contribute radiation dose to the patient while not providing any diagnostic information)
c) Have a short effective biological half-life (so that it is eliminated from the body as quickly as possible)
d) Have a high target to non-target ratio so that the resulting image has a high contrast (the object has much more activity than the background)
e) Follow or be trapped by the metabolic process of interest



$$A(t) = A(0)e^{-t(\ln(2)/T_{1/2})}$$

The essential steps in accelerator radionuclide production

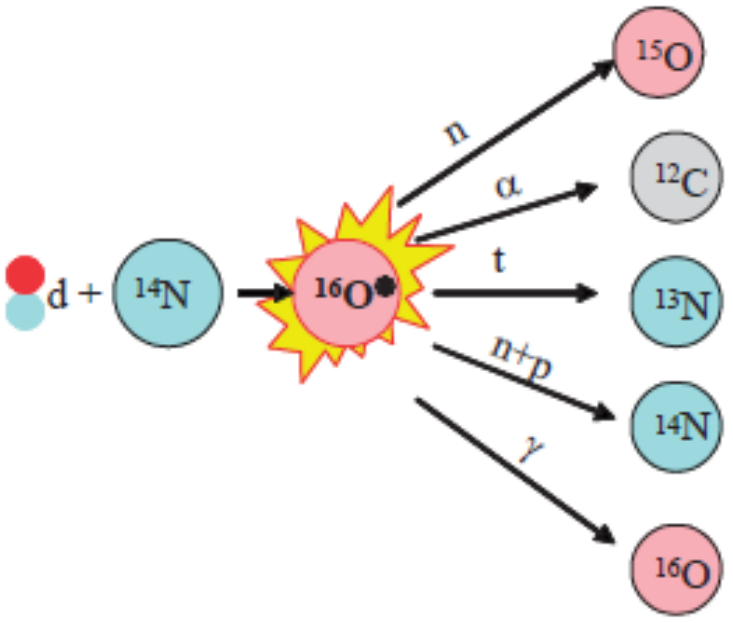
1. Acceleration of charged particles in a cyclotron
2. Beam transport (*or not*) to the irradiation station via a transfer line
3. Irradiation of target (solid, liquid, gas) – *internal or external*
4. Nuclear reaction occurring in the target (e.g. $^{A}X_{Z}(p,n)^{A}y_{Z+1}$)
5. Target processing and material recovering
6. Labeling of radiopharmaceuticals and quality control



a = bombarding particle
b, c = emitted particles
A, B, D = nuclei

Example: d + ^{14}N ⟶ ^{16}O*

Q values and thresholds of nuclear decomposition for the reaction of a deuteron with a ^{14}N nucleus after forming the compound nucleus ^{16}O



	Q value	Threshold
^{15}O	5.1 MeV	0 MeV
^{12}C	13.6 MeV	0 MeV
^{13}N	-4.3 MeV	4.9 MeV
^{14}N	-2.2 MeV	2.5 MeV
^{16}O	20.7 MeV	0 MeV

Nuclear reactions employed to produce PET isotopes

Radionuclide	Half-life	Reaction	Energy (MeV)
^{11}C	20.3 min	$^{14}N(p,\alpha)$ $^{11}B(p,n)$	11–19 10
^{13}N	9.97 min	$^{16}O(p,\alpha)$ $^{13}C(p,n)$	19 11
^{15}O	2.03 min	$^{15}N(p,n)$ $^{14}N(d,2n)$ $^{16}O(p,pn)$	11 6 > 26
^{18}F	110 min	**$^{18}O(p,n)$** ⟸ $^{20}Ne(d,\alpha)$ $^{nat}Ne(p,X)$	11-17 8-14 40

Shielding of PET cyclotrons

- Cyclotron self-shielding versus room shielding
- Low energy but high-intensity beam (several tens of µA): activation of components by protons and neutrons

Shielding of PET cyclotrons

CTI RDS-111

Inner shield ≈ 30 cm thick high-density core cast out of a mixture of lead, epoxy, and boron carbide.

Outer shield ≈ 70 cm thick made of polyethylene and boron carbide loaded concrete.

Cyclotron – 10 tons
Shields – 27 tons
Cabinets – 1.5 tons
Total – 38.5 tons

CTI RDS-Eclipse

Inner shield ≈ 25 cm thick high-density core cast out of a mixture of lead, epoxy, and boron carbide.

Outer shield ≈ 76 cm thick made of polyethylene and boron carbide loaded concrete.

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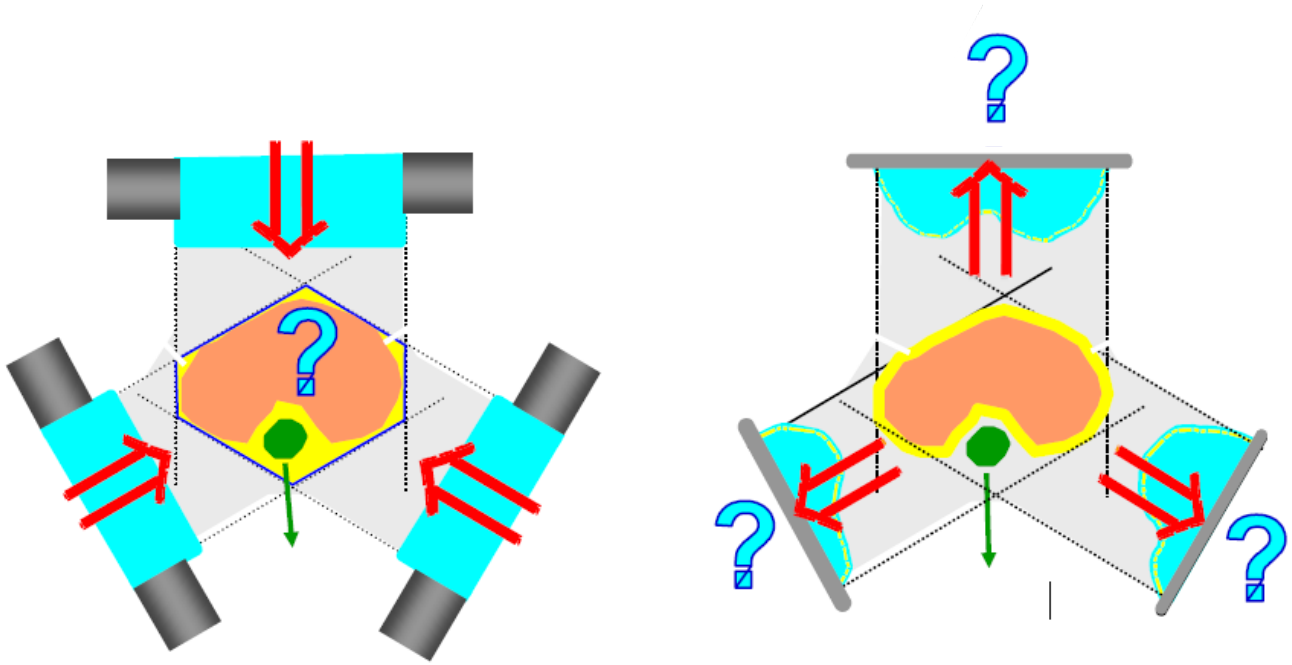
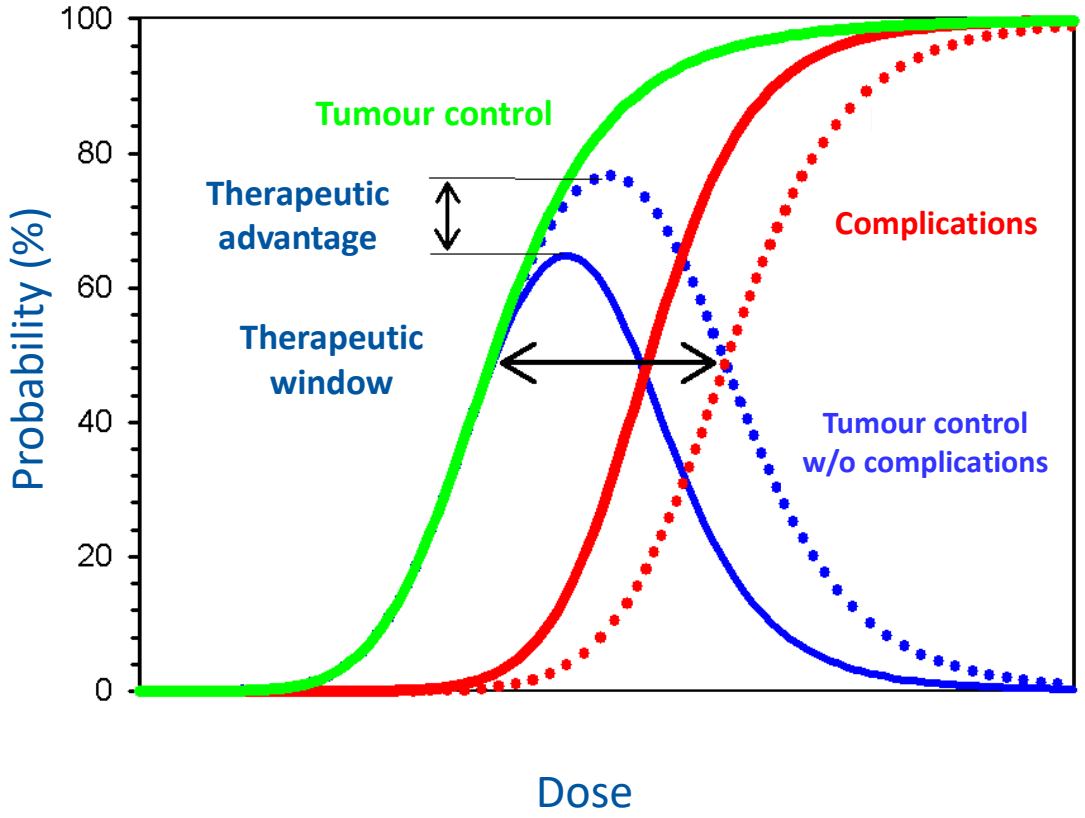
Treatment planning and dose delivery to tumour volume

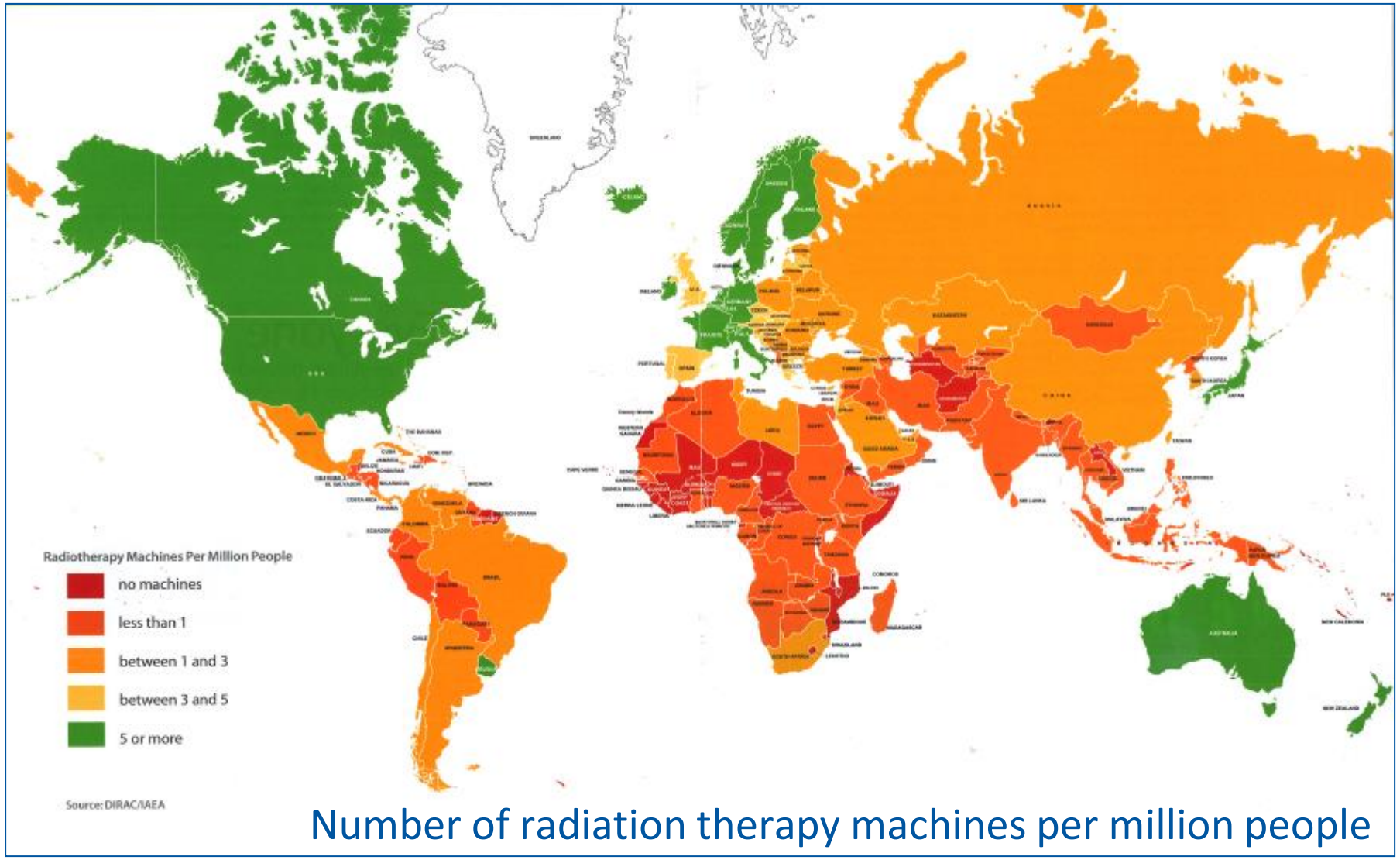
Treatment planning and dose delivery



Tumour control and therapeutic window

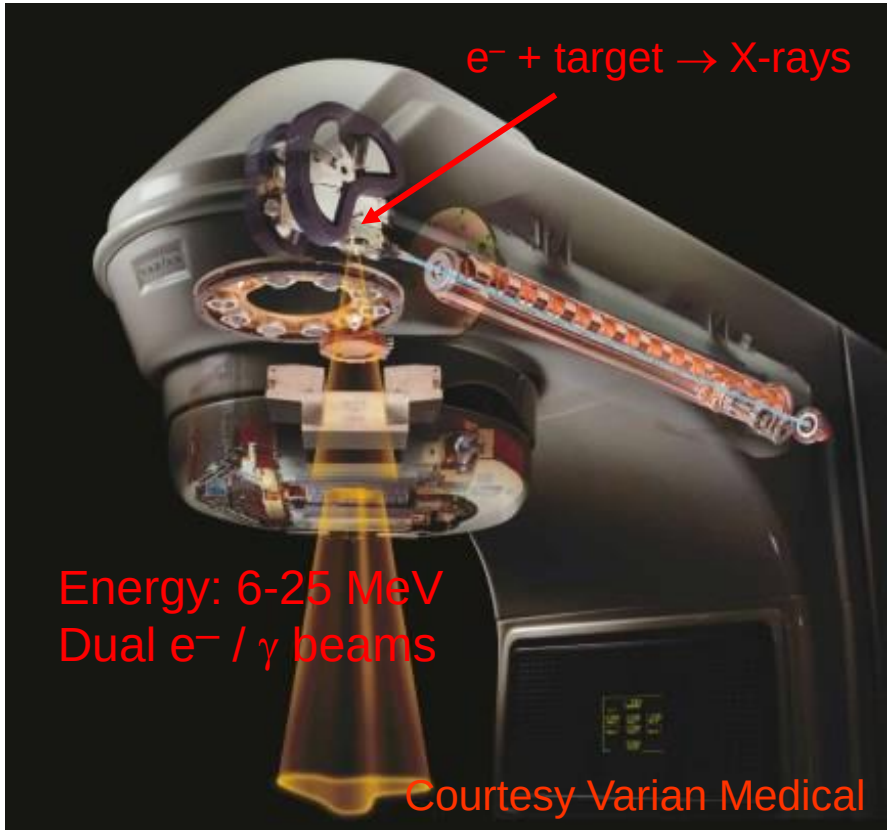


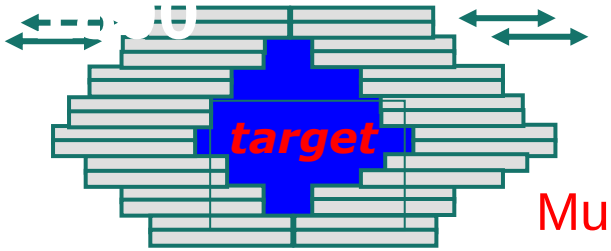
Availability of radiation therapy worldwide



Number of radiation therapy machines per million people

Electron linear accelerator



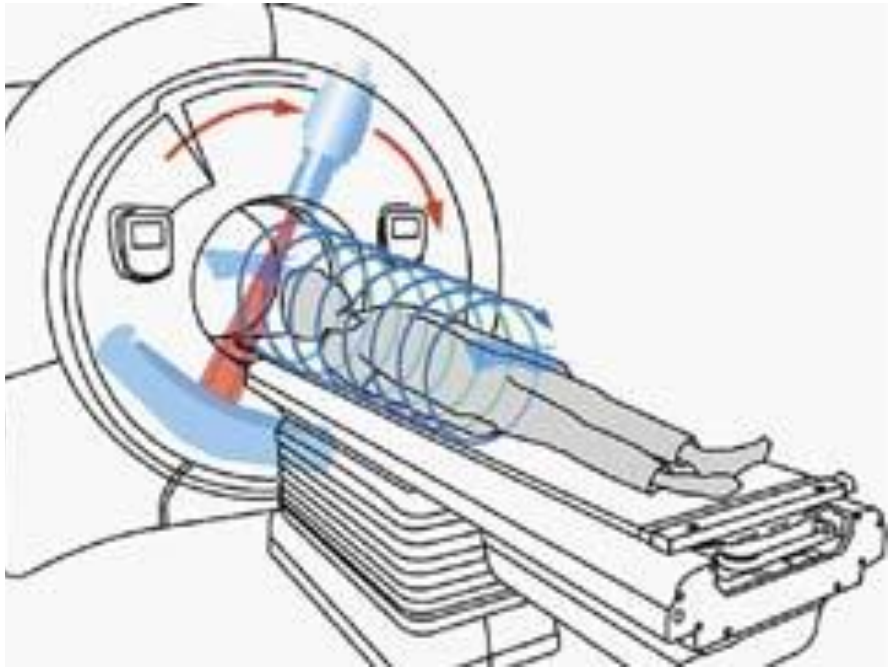


Multi-leaf collimator

Helical tomotherapy

Accuray Radixact®

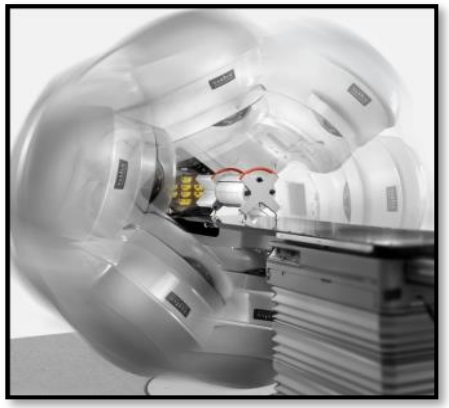
www.tomotherapy.com

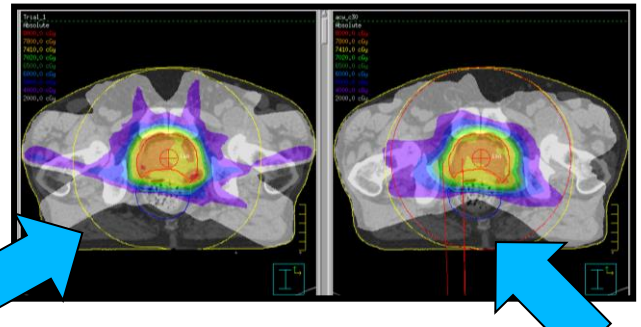


- Integrated CT guidance
  - Integrated CT scanner allowing efficient 3D CT imaging for ensuring the accuracy of treatment
- A binary multi-leaf collimator (MLC) for beam shaping and modulation
- A ring gantry design enabling TomoHelical delivery
  - As the ring gantry rotates in simultaneous motion to the couch, **helical fan-beam IMRT** is continuously delivered from all angles around the patient
- Very large volumes can be treated in a single set-up

Volumetric Modulated “ARC” Radiation Therapy

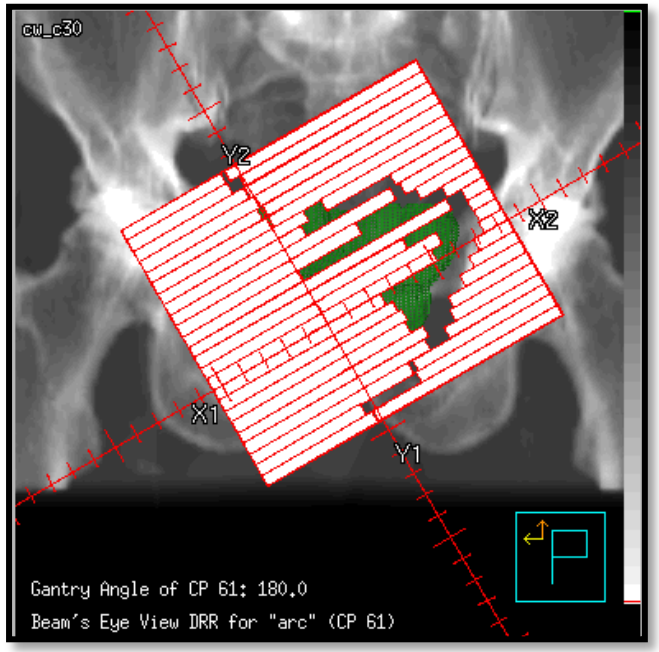
Rotate linac gantry while modulating the beam





Fixed 6 or so gantry angles

VMAT



Name-Prof Peter Metcalfe
BSOC lecture 08

University of Wollongong

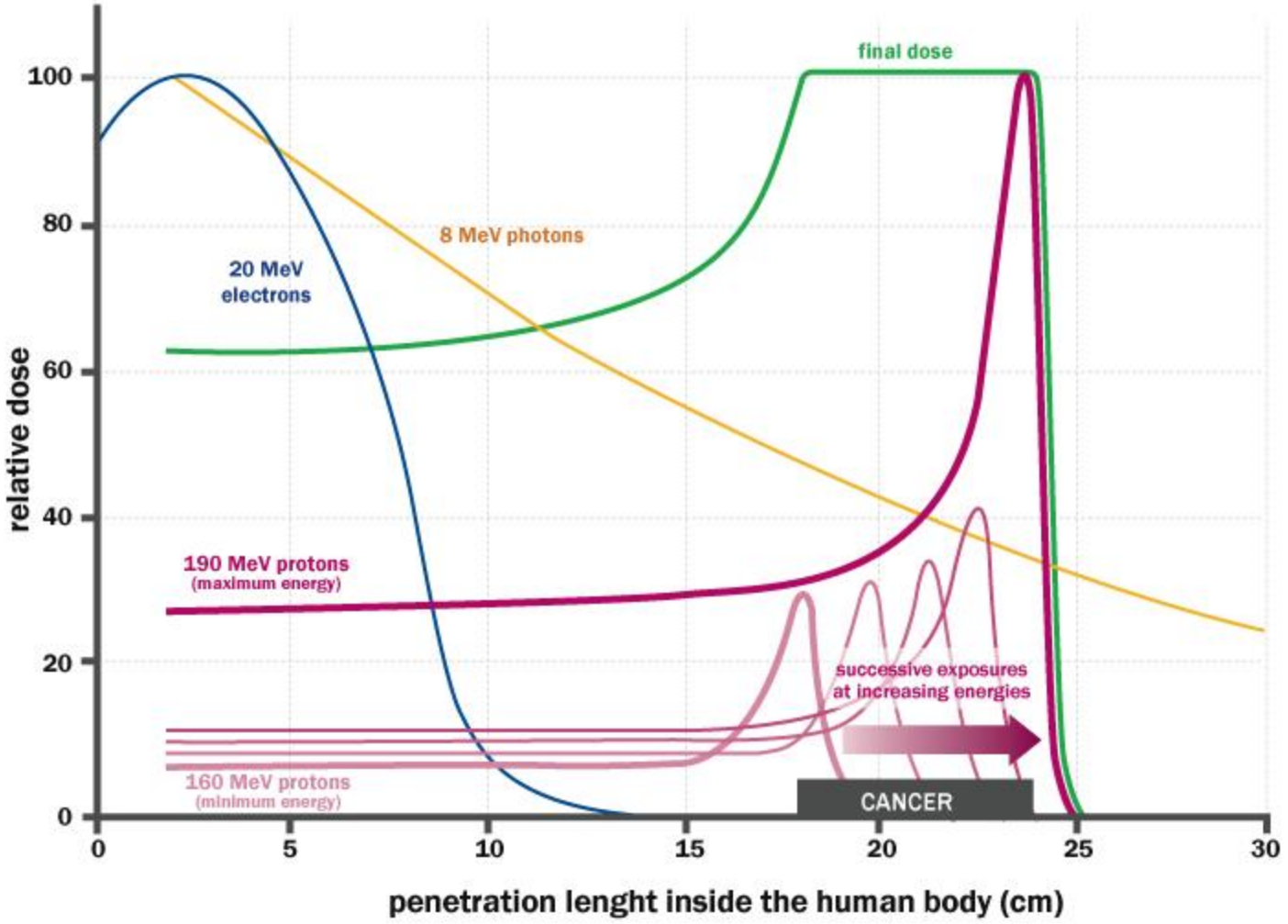
Accuray CyberKnife® S7™

- Robotic Platform
- Dose Minimization To Organs At Risk
- Moving or Stationary Targets
- Flexible Dose Sculpting
- Fast Treatment Planning
- Fast Treatment Delivery
- Quick Installation

Intra-Operative Radiation Therapy (IORT)

- Small electron linac
- Energy 6 – 12 MeV
- Treatment with electrons only
- Single irradiation
- Various models (Sordina in Italy)

Particle therapy (hadron therapy)

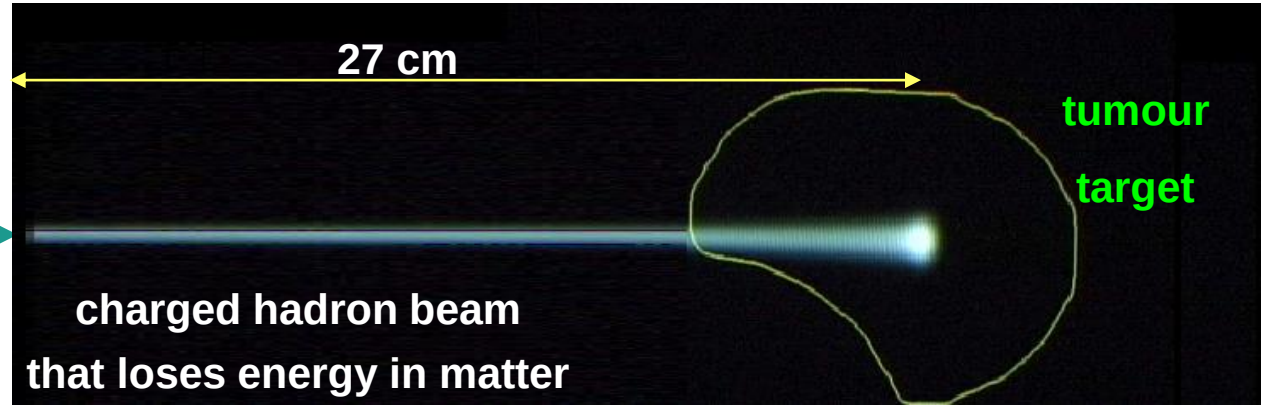


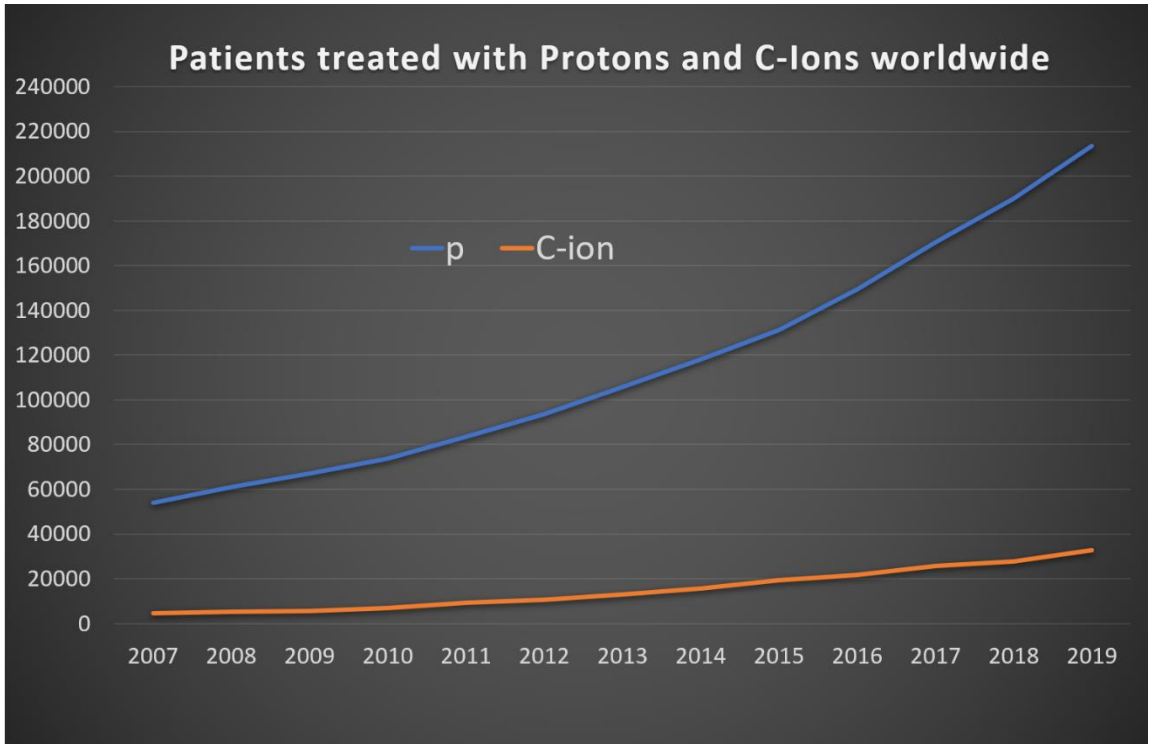
Courtesy INFN, Italy

Particle therapy (hadron therapy)

200 MeV protons

4800 MeV carbon ions

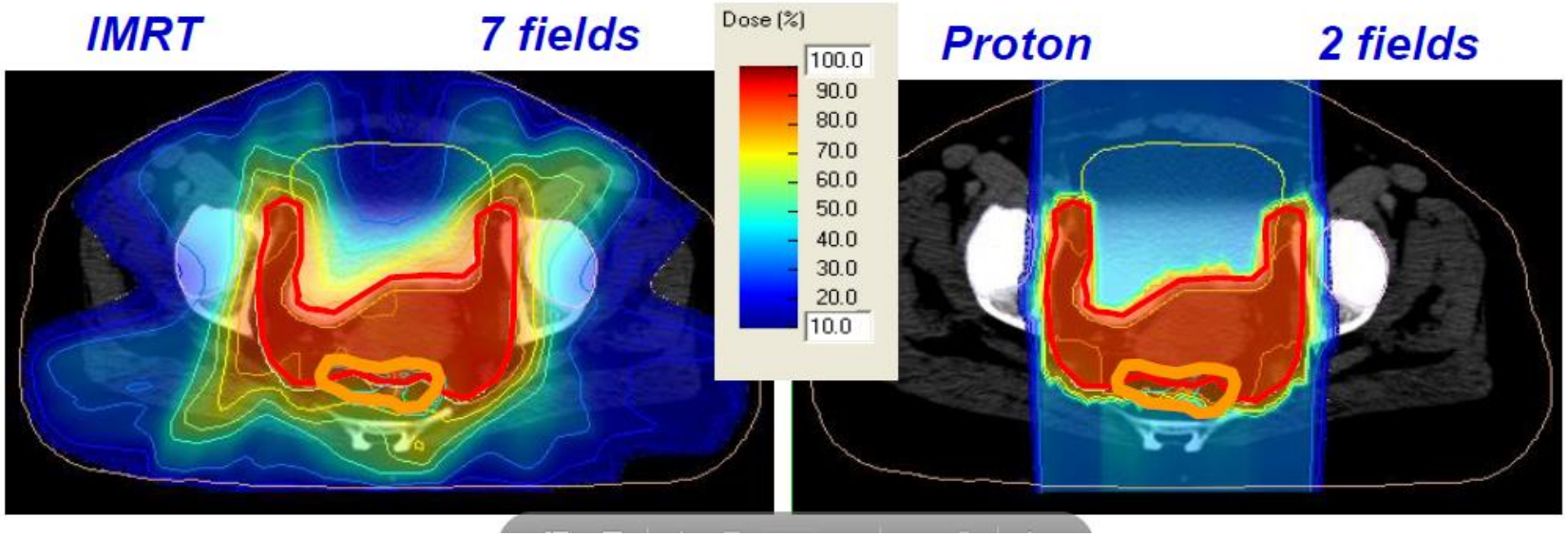




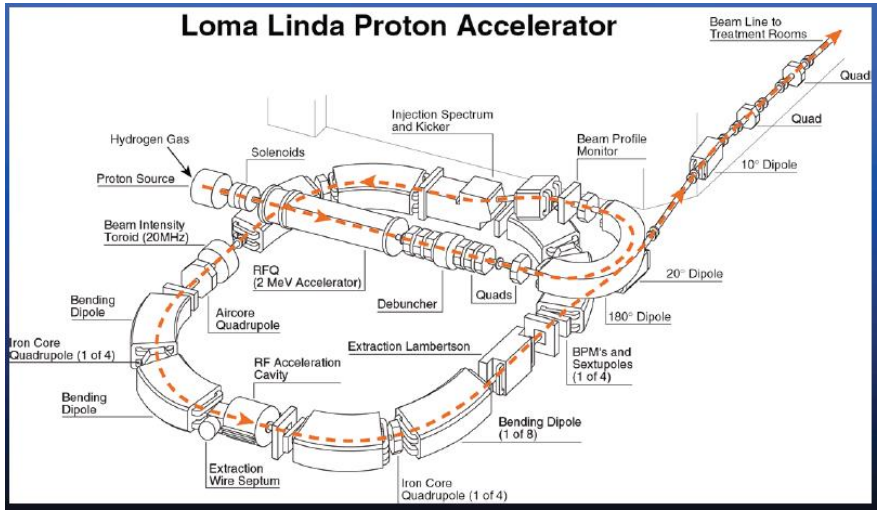
www.ptcog.ch

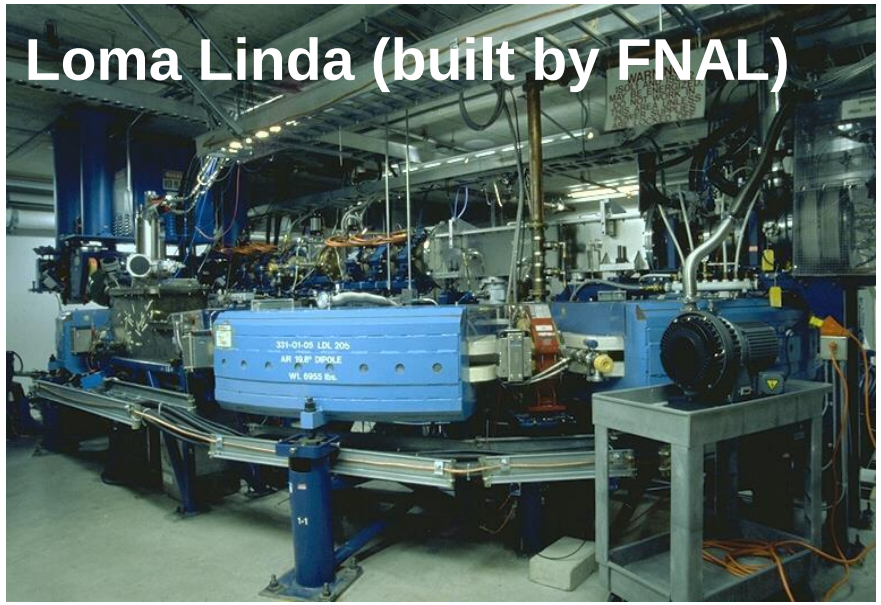
Treatment planning

- *Ion beam therapy is more conformal than photon beam RT*
- *Sharper dose fall off*
- *Range of ions much more influenced by tissue heterogeneities than photon beams with direct impact on TCP and NTCP*
- *Image guidance is necessary for ion beam therapy*



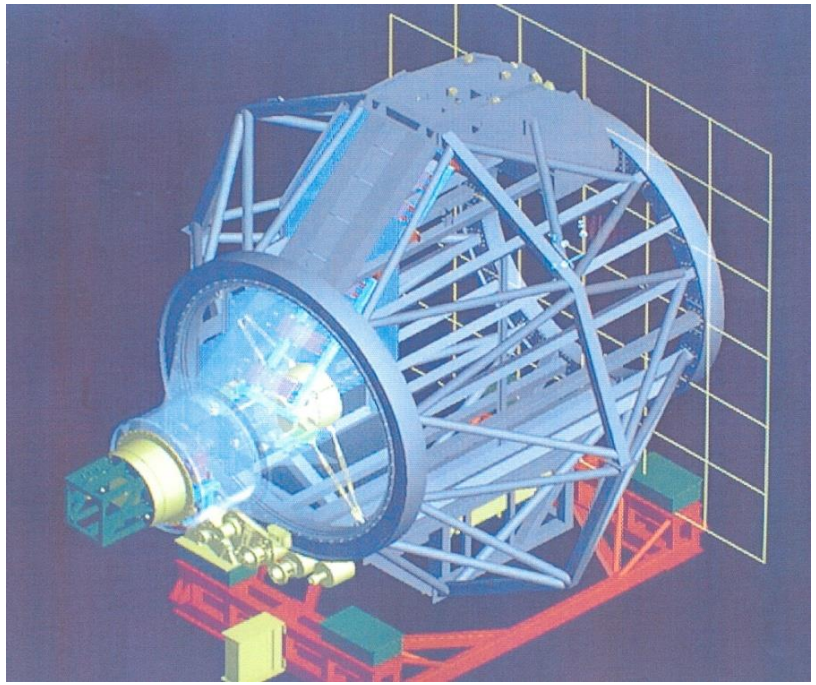
Cyclotrons and synchrotrons for proton therapy





Accel-Varian
(superconducting)

The IBA proton gantry



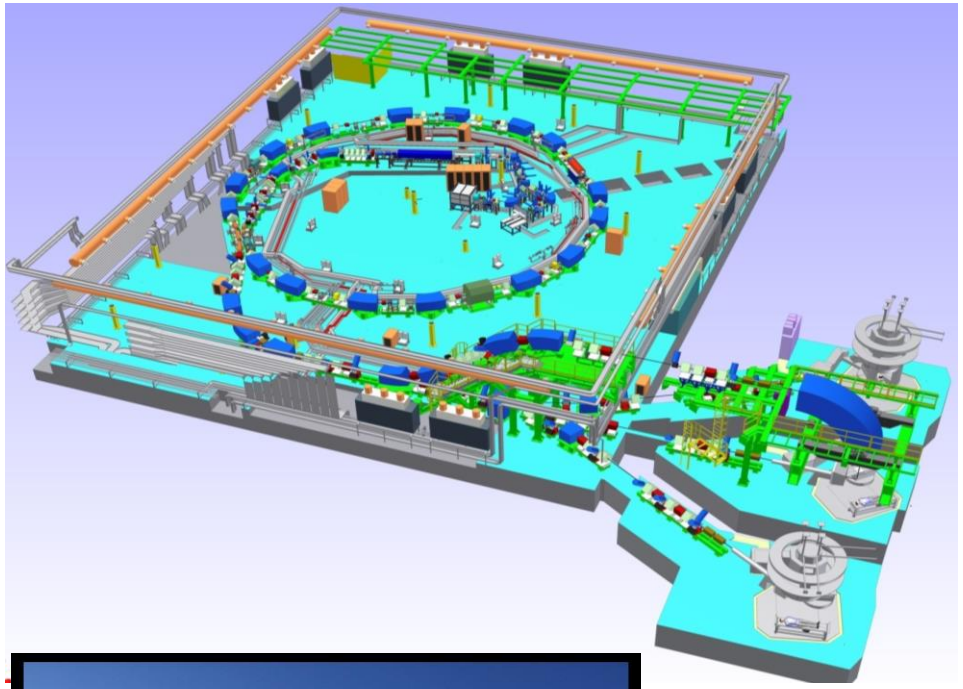
A gantry is a massive structure (≈10 m diameter, ≈200 ton weight) that allows directing the beam to the tumour from any direction. It carries

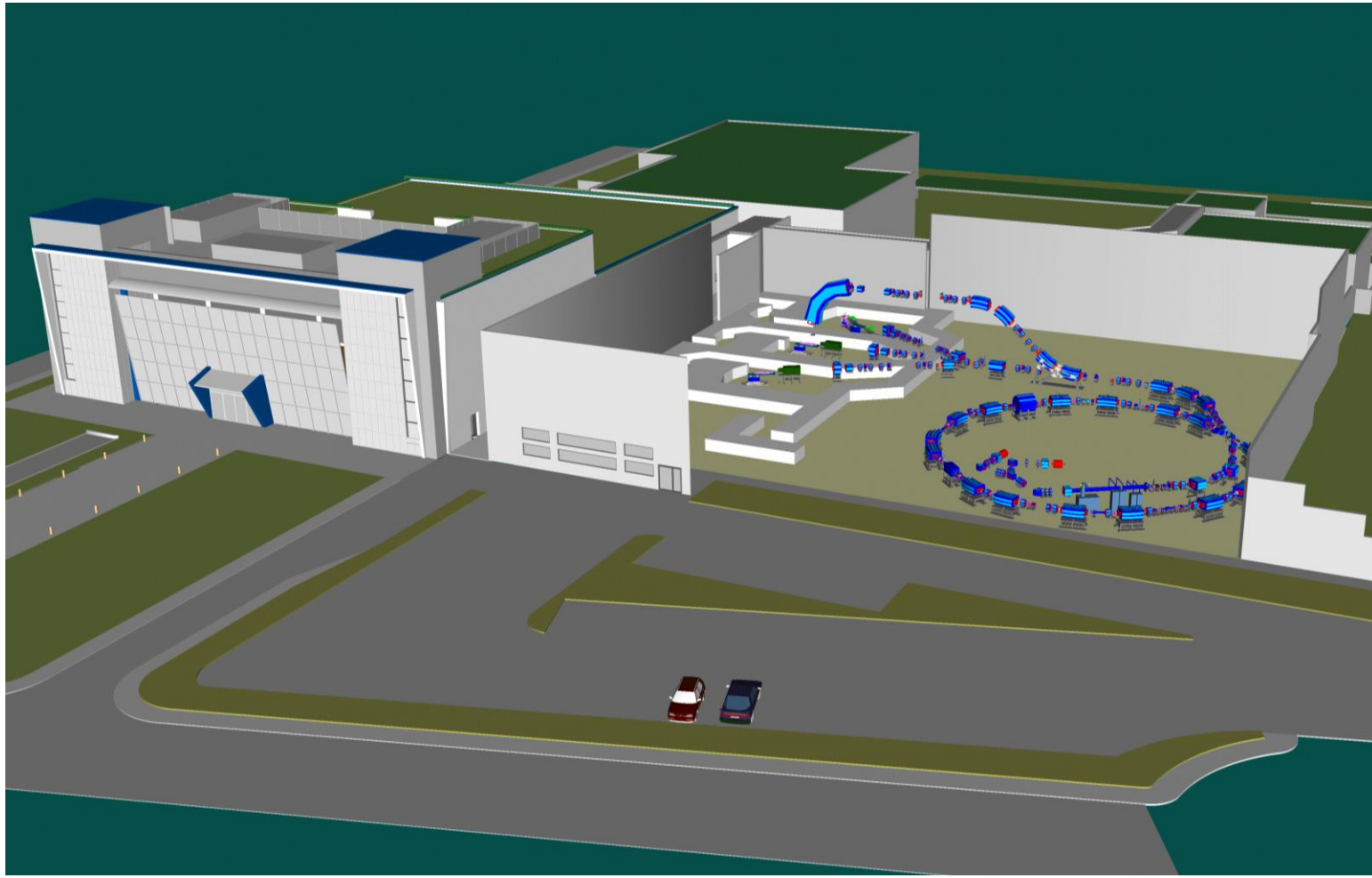
- the final section of the beam line
- the beam spreading ‘nozzle’
- the proton ‘snout’ which carries the aperture and range compensator

What it looks like to the patient:
gantry room at the Midwest Proton Radiotherapy Institute (MPRI)
(modified IBA gantry)

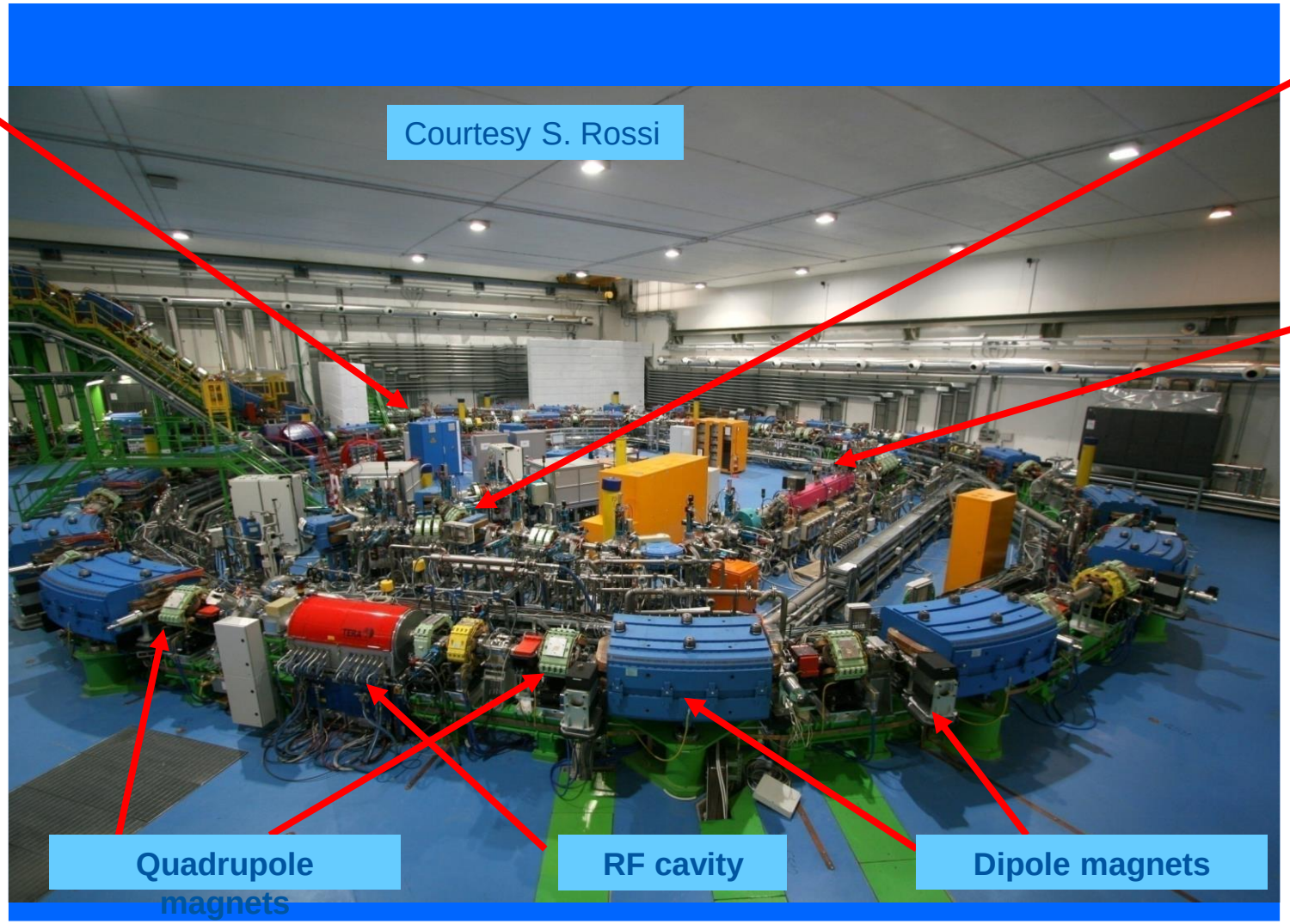
Adapted from B. Gottschalk

National Centre for Oncological Hadrontherapy (CNAO), Italy



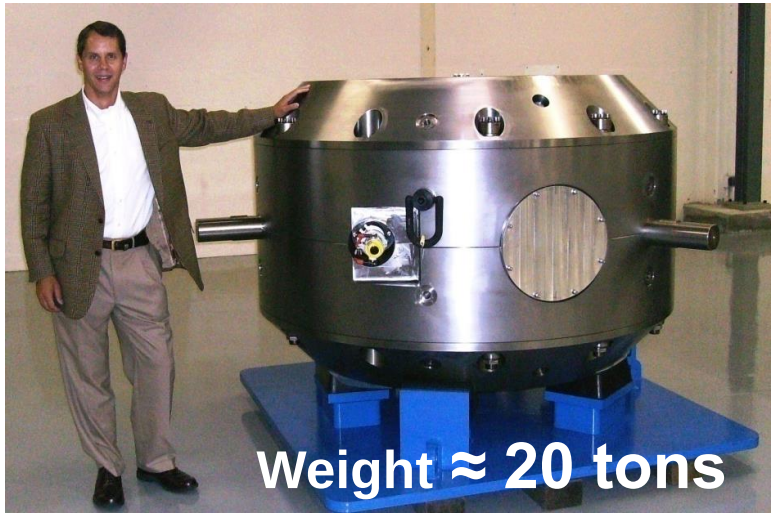


National Centre for Oncological Hadrontherapy (CNAO), Italy

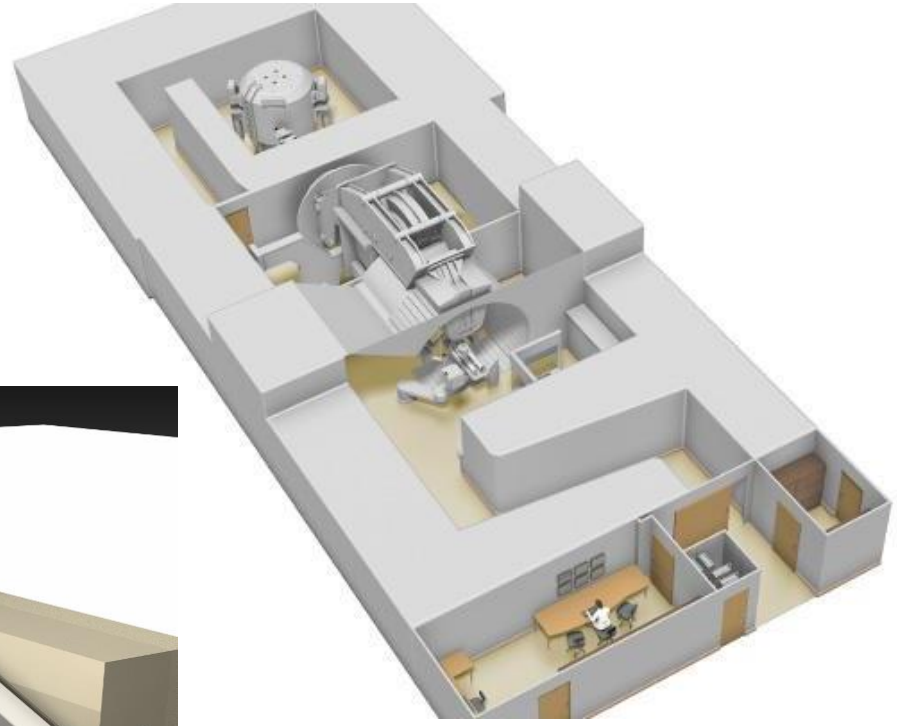


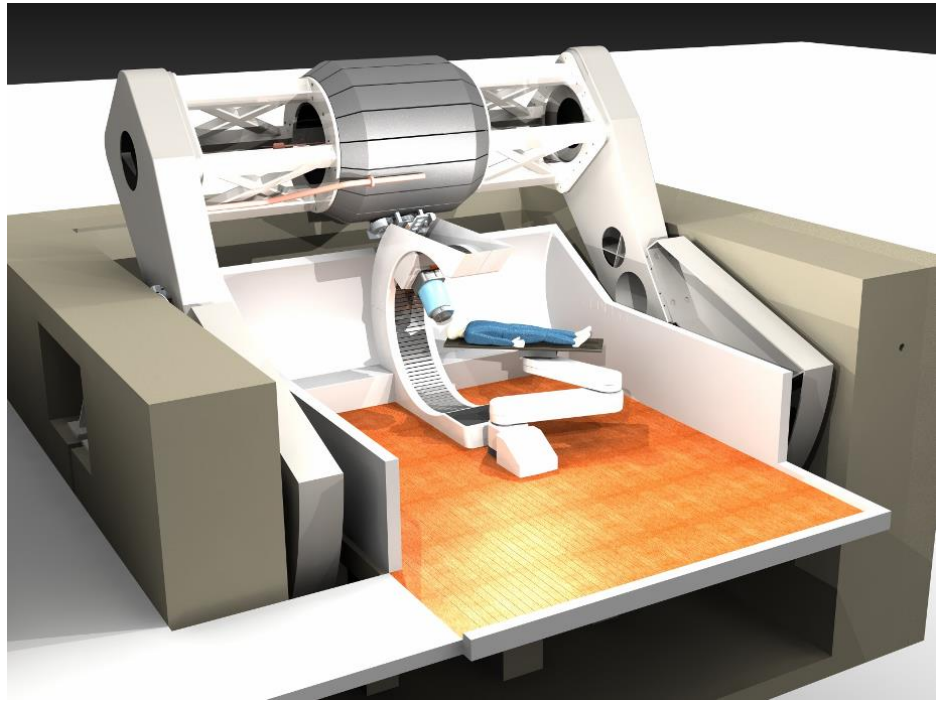
National Centre for Oncological Hadrontherapy (CNAO), Italy

Single room facilities



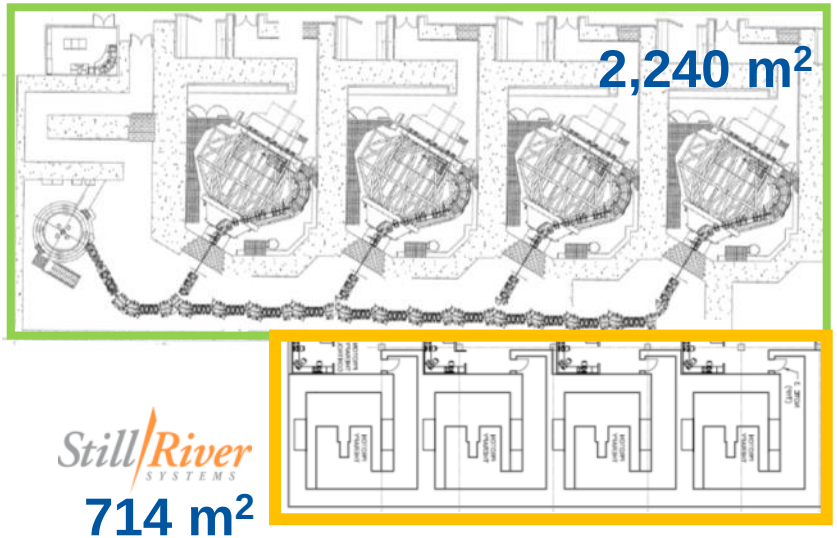
IBA Proteus Nano

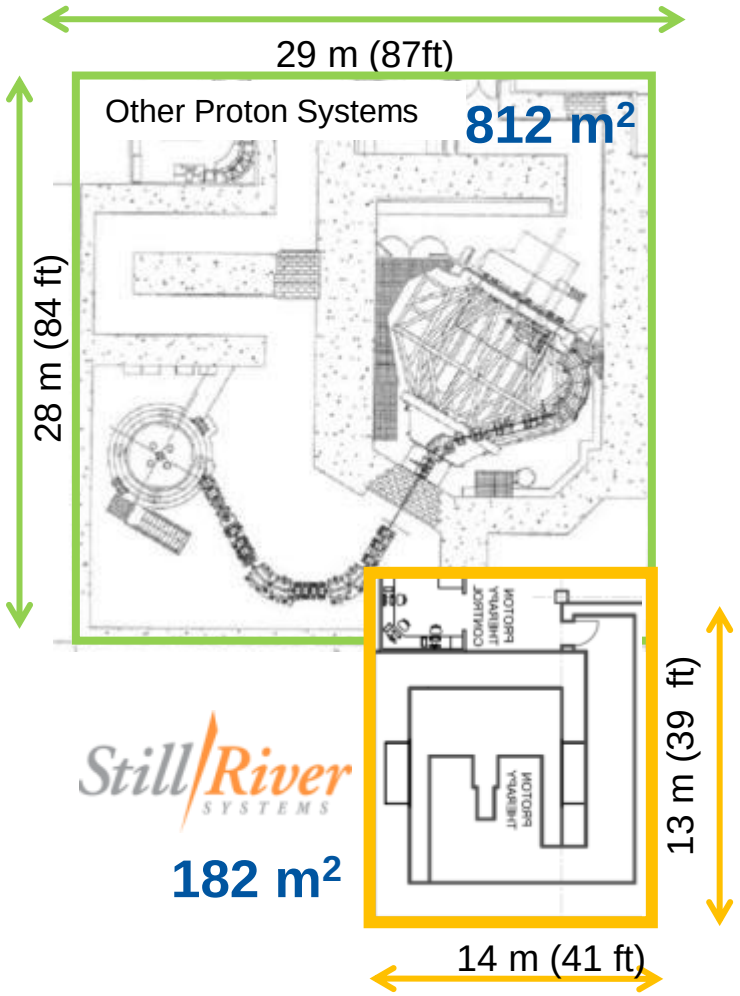




Mevion Medical Systems

Multi-room versus single-room facilities





Advantages of single-room facility:

- ✓ **Modularity**
- ✓ **Reliability / back-up**
- ✓ **PT treatment available at more hospitals**
- ✓ **Cost**

Courtesy L. Bouchet, *Still River Systems* (now *Mevion*)

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General principles of radiation protection

1) Justification

any exposure of persons to ionizing radiation has to be justified

2) Limitation

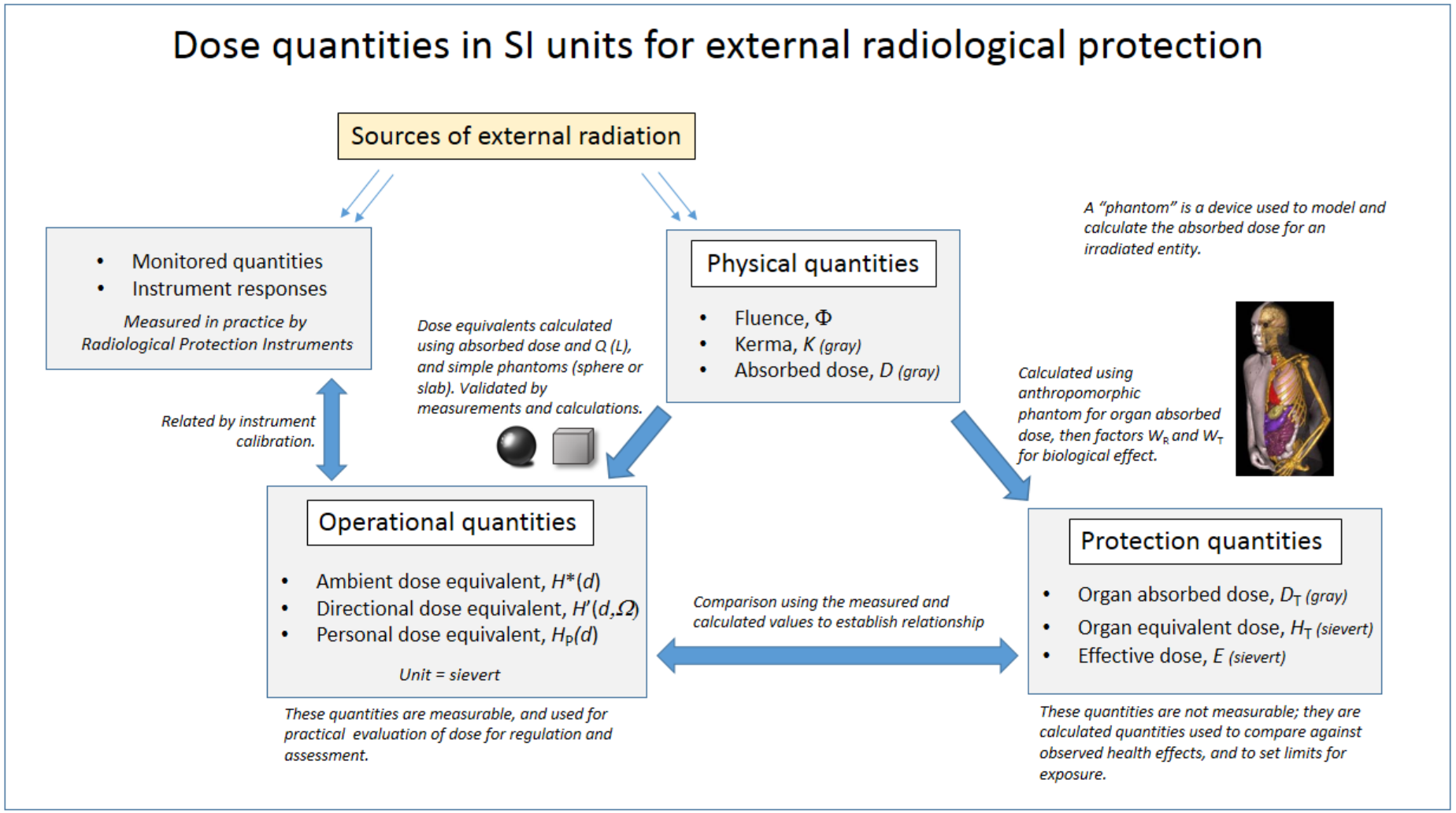
the personal doses have to be kept below the legal limits

3) Optimization

the personal doses and collective doses have to be kept As Low As Reasonably Achievable (**ALARA**) – including social and economical factors into account

Physical, protection and operational quantities

International Commission on Radiological Protection



Source: Wikipedia

Radiological quantities and units

Absorbed Dose D: energy absorbed per mass

Unit: Gy

1 Gy = 1 J/kg

(1 Gy = 100 rad)

$$D = \frac{1}{m}\int EdV$$

Equivalent Dose H: absorbed dose of organs weighted by the radiation weighting factor w_R of radiation R:

Unit: Sv (1 Sv = 100 rem)

$$H_T = \sum_R w_R D_{T,R}$$

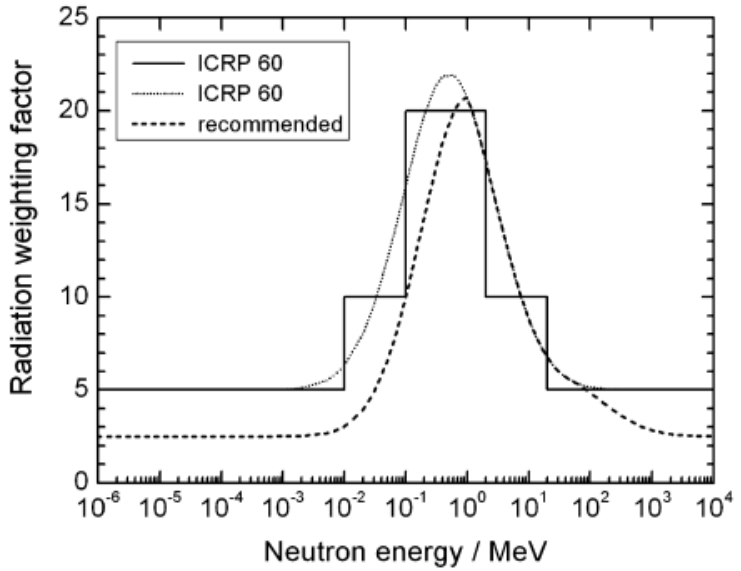
Effective dose E: Sum of all equivalent doses weighted with the weighting factor w_T for tissue T

Unit: Sv (1 Sv = 100 rem)

$$E = \sum_T w_T H_T = \sum_T w_T \sum_R w_R D_{T,R}$$

Radiation weighting factors, W_R

Type and energy of radiation R	w_R
Photons, all energies	1
Electrons and muons, all energies	1
Protons and charged pions	2
Alpha particles, fission fragments, heavy ions	20
Neutrons	$w_R = \begin{cases} 2.5 + 18.2\, e^{-[\ln(E_n)]^2/6}, & E_n < 1 \text{ MeV} \\ 5.0 + 17.0\, e^{-[\ln(2E_n)]^2/6}, & 1 \text{ MeV} \leqslant E_n \leqslant 50 \text{ MeV} \\ 2.5 + 3.25\, e^{-[\ln(0.04E_n)]^2/6}, & E_n > 50 \text{ MeV} \end{cases}$



Tissue sensitivity and tissue weighting factors, W_T

Organ / tissue	No of tissues	W_T	Total contribution
Bone-marrow, colon, lung, breast, stomach, remainder tissues	6	0.12	0.72
Gonads	1	0.08	0.08
Bladder, esophagus, liver, thyroid	4	0.04	0.16
Bone surface, brain, salivary glands, skin	4	0.01	0.04

The tissue weighting factors are sex- and age-averaged values for all organs and tissues

Operational quantities

- **Quantities on which limits are based** (effective dose, organ equivalent dose) are not measurable
- So **operational quantities** are defined
  - measurable quantities
  - quantities which are representative of the quantities on which limits are based (where possible overestimating these)
- **For external exposure:**
  - ambient dose: **H*(10)**
  - personal dose: **$H_p(10)$** and **$H_p(0,07)$**
- **For internal exposure** (after an intake):
  - committed effective dose (over 50 years): **E(50)**

Radiological risks

External radiation source → external exposure

Contamination → Surface

Contamination → Volumetric (air)

Internal radiation source → internal exposure

Classification of radiation areas and workers

- Person **occupationally exposed** to radiation (> 1 mSv/y)
  - Category **A** workers: > 6 mSv/y
  - Category **B** workers: < 6 mSv/y
- **Supervised area**: area with dose > 1 mSv/y

  (accessible to categories A and B workers)
- **Controlled area**: area with dose > 6 mSv/y

  (accessible to categories A workers, and with limited stay to category B workers)
- Exposure situations:
  - **risk of external exposure only** (sealed radioactive sources, radiation generators, for example X-ray tube)
  - **risk of internal and external exposure** (use of unsealed radioactive sources)

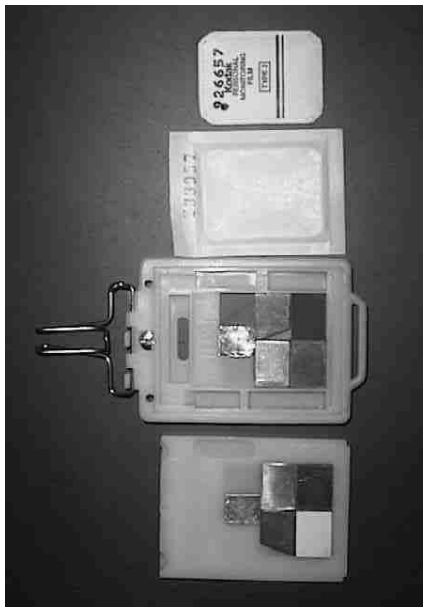
Monitoring of external exposure

- **Wearing a personal dosimeter** on the chest or at the waist
  - monthly measurement (at least)
  - delayed information (depends on dosimeter)
  - measurement threshold ~0.1 mSv/month
- **Wearing an electronic dosimeter**
  - instantaneous information
  - possibility to setting a dose or dose rate alarm
- **Wearing an extremity dosimeter**
  - In the case of specific hand exposure risk (handling of radioactive substances)

Operational quantities and dose limits

- **The dosimeter is calibrated to measure:**
  - **$H_p(10)$:** personal equivalent dose at a depth of 10 mm in the chest
  - **$H_p(0.07)$:** personal equivalent dose at a depth of 0.07 mm in the chest
- **At low measured doses** (less than the limits) it is assumed that:
  - the effective dose and the equivalent dose to each organ is equal to $H_p(10)$;
  - the equivalent dose to the skin is equal to $H_p(0.07)$;
- **At high measured doses** (exceeding the limits),
  - an investigation is undertaken (**dosimetric reconstruction**) in order to determine the effective dose and the equivalent doses to the organs which were actually received.

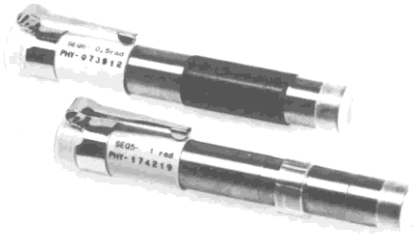
Personal dosimetry for monitoring external exposure

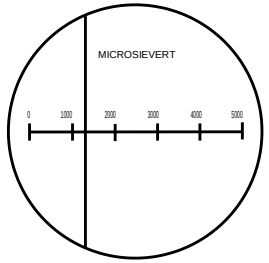


Kodak film badge

Personal dosimeter: "Legal dose"

RADOS DIS





Operational dosimeter DMC:
“Operational dose”

Finger dosimeter

Quartz-fiber dosimeter (ionisation chamber and electroscope)

Operational dosimetry at CERN

- Obligation to wear an operational dosimeter in a controlled area
- Continuous $\beta\gamma$-dose measurement
- Instrument: DMC
- Display of Hp(10) (resolution of 1 µSv)
- Dose alarm at 2 mSv
- Dose rate alarm at 2 mSv/h
- Audible detection signal (« bip »)
- Record the dose before and after the operation

Contamination

- **Internal** (+ **external**) exposure: the incorporated radionuclides irradiate the organs and tissues to which they attach
- Exposure lasts until the complete elimination of the radionuclides by radioactive decay and biological metabolism

Internal exposure can occur by:

- ingestion

- inhalation

- skin

Monitoring of internal exposure

- Determination of the activity taken into the body and calculation of the **committed effective dose** with a standard model
- **Measurements to determine the activity taken into the body:**
  - direct measurement of the radiation emitted by the person using a thyroid monitor, a lung monitor or a whole body monitor (WBC, whole body counter)
  - measurement of the activity in the excreta (urine, faeces)
- **Two stages strategy:**
  - screening measurement (with a simple laboratory instrument)
  - If a threshold is exceeded, actual measurement of the intake

Operational quantities and dose limits

- **Operational quantity**: committed effective dose E_{50}
- For radionuclides with **short half-life**, the dose is received in the days following the intake;
- For radionuclides with a **long half-life** (strontium-90, actinides), the dose is received over many years following the intake;
- **The committed dose** is attributed to the period of intake;
- Dose is calculated using standard metabolic models;
- If dose limits are exceeded an **investigation is undertaken** (dosimetric reconstruction) to determine the committed dose; an adaptation of the model may be necessary.

Personal protection equipment against contamination

For low level contamination / low risk

« Tyvek » overall
(synthetic paper)

Rubber gloves

generally completed by overshoes

mask or respirator

DLgs n. 101 del 31 luglio 2020 (in vigore dal 27 agosto 2020)

(recepimento della Direttiva Europea 1013/59 EURATOM)

- Introduzione del lavoratore esterno e sua protezione
- Introduzione della formazione per Dirigenti e Preposti ogni 3 anni
- Formazione per i lavoratori ogni 3 anni
- Introduzione e chiarimento sui vincoli di dose (fra cui vincoli di dose per una data sorgente in una esposizione pianificata)
- Ottimizzazione
- Revisione del limite di dose per il cristallino
- Revisione del livello di riferimento per il radon negli ambienti di lavoro (passa da 500 a 300 Bq/m^3)
- L'Esperto Qualificato diventa Esperto di Radioprotezione
- Obbligo di aggiornamento professionale per gli Esperti di Radioprotezione (ora 20 ore/anno, in futuro 100 ore/anno)
- Protezione operativa degli individui della popolazione
- La sorveglianza sanitaria solo a cura del Medico Autorizzato (scompare la figura del medico competente).
- Introduzione dell'esperto di radioprotezione III grado sanitario.
- Gestione integrate delle sorgenti naturali (NORM)
- Ridefinizione dei clearance and exemption levels
- Introduzione e avvio del database STRIMS (Sistema per la tracciabilità dei rifiuti e dei materiali radioattivi e delle sorgenti di radiazioni ionizzanti) presso ISIN (Ispettorato Nazionale per la sicurezza Nucleare e la Radioprotezione).
- Introduzione dell'archivio nazionale dei lavoratori esposti (non ancora operativo)

Courtesy Adolfo Esposito, INFN LNF

Outline of the lecture

- Particle accelerators in medicine
- Radionuclide production
- Radiation therapy
  - Conventional radiation therapy
  - Particle (hadron) therapy
- Principles of radiation protection
  - Justification, optimization and dose limitation
  - Radiological quantities and units
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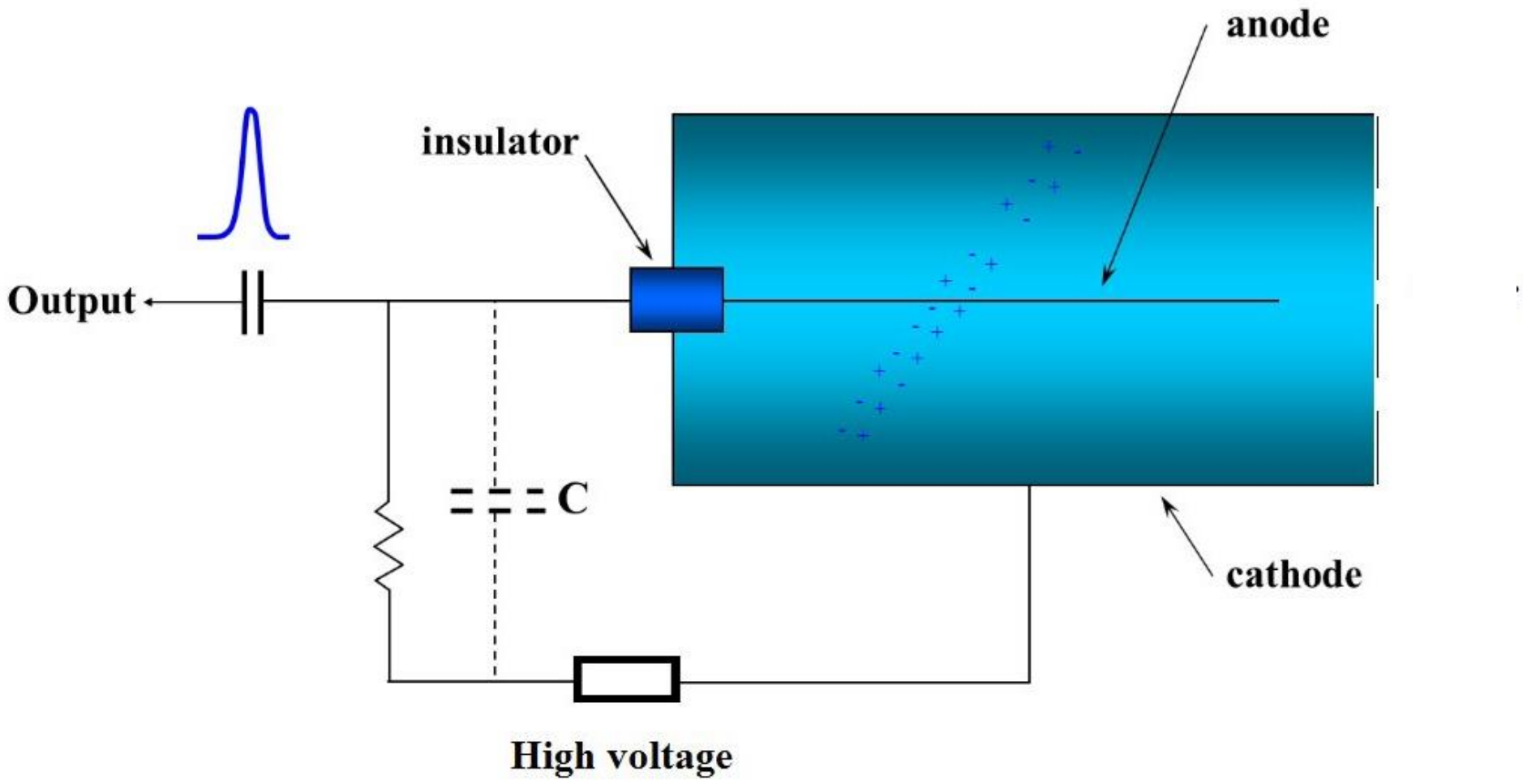
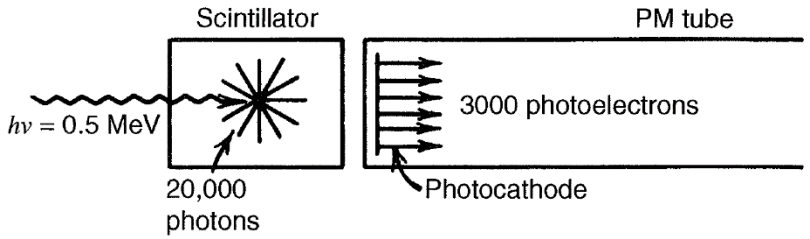
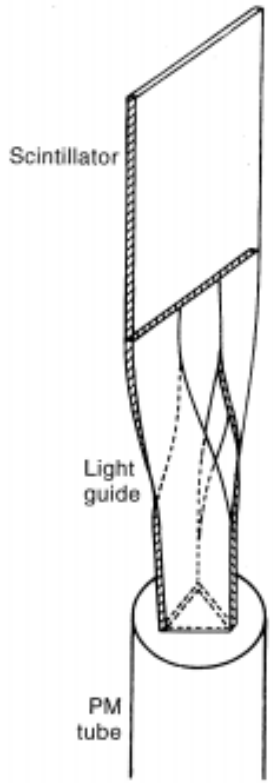
  - Instrumentation
- Radiation shielding of radiation therapy accelerators
- CERN technology transfer in health and safety

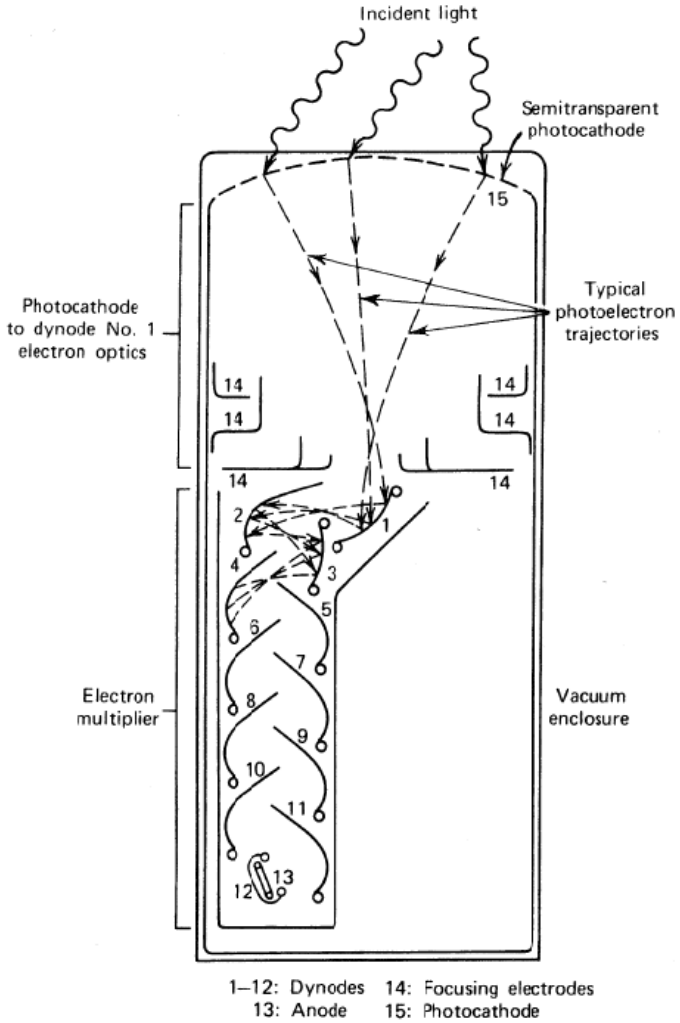
Ionization chamber



Scintillating crystal coupled to a PMT







From Glenn F. Knoll, Radiation Detection and Measurement

AUTOMESS dose rate meter 6150 AD6

AD17 external probe

Detector: Geiger Müller counter
Range: 0.5 µSv/h – 10 mSv/h
Energy range: 60 keV – 1.3 MeV
Dimensions: 130 mm x 80 mm x 29 mm
Alimentation: 9 V standard battery

ADK surface contamination meter for α, β and γ radiation
Detector: sealed proportional counter
Active surface 100 cm^2

Contamination monitors

APA

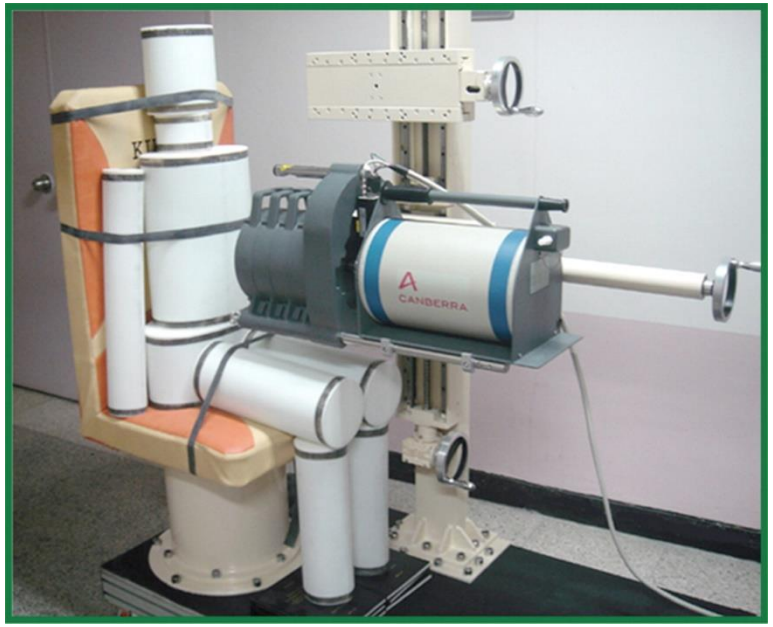
CMS2000

Air contamination monitors

Hand and foot monitor

ABPM203M

Whole body counting



Slow neutron detection

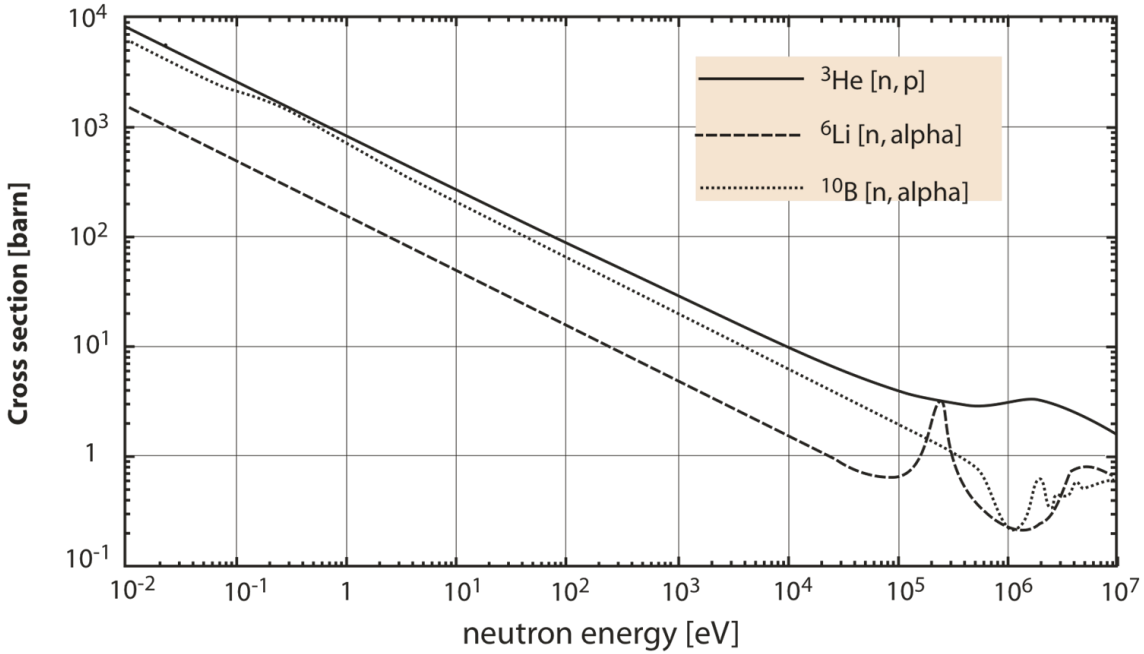
Some elements have a very large cross section for slow neutrons and can be exploited for neutron detection

1) Boron $^{10}B + n \rightarrow {}^{7}Li + \alpha$ Q = 2.793 MeV
   $^{10}B + n \rightarrow {}^{7}Li^{*} + \alpha$ Q = 2.310 MeV

2) Lithium $^{6}Li + n \rightarrow {}^{3}H + \alpha$ Q = 4.78 MeV

3) ^{3}He $^{3}He + n \rightarrow {}^{3}H + p$ Q = 764 keV

Mean free path of thermal neutrons
- in ^{3}He gas ≈ 7 cm
- in solid ^{10}B ≈ 70 µm

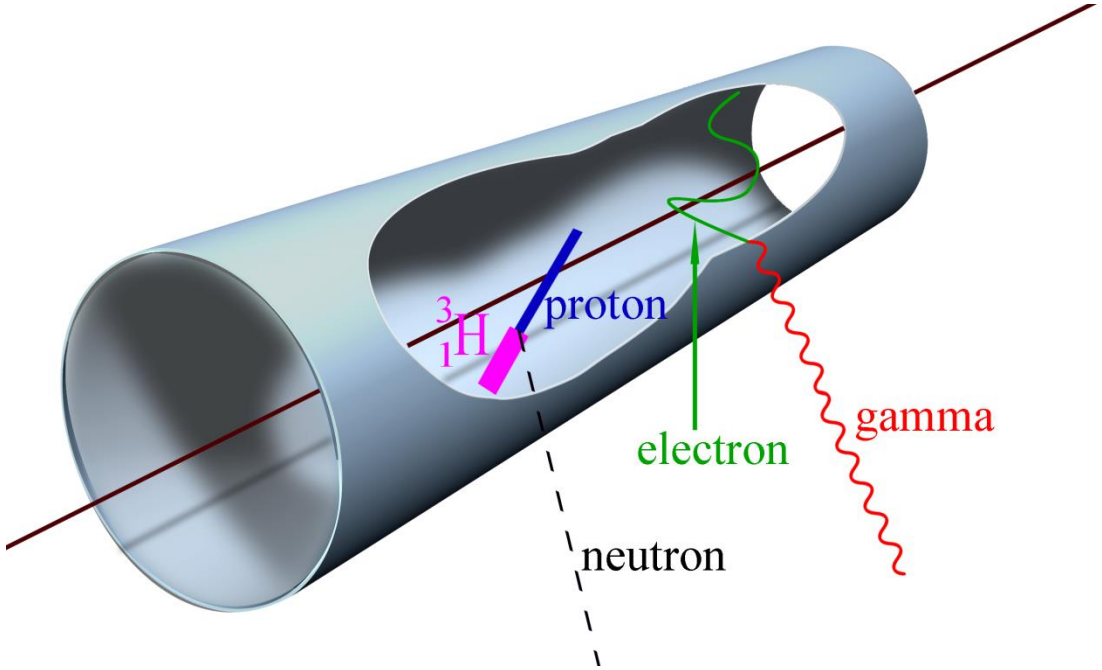


Proportional counters for slow neutron detection

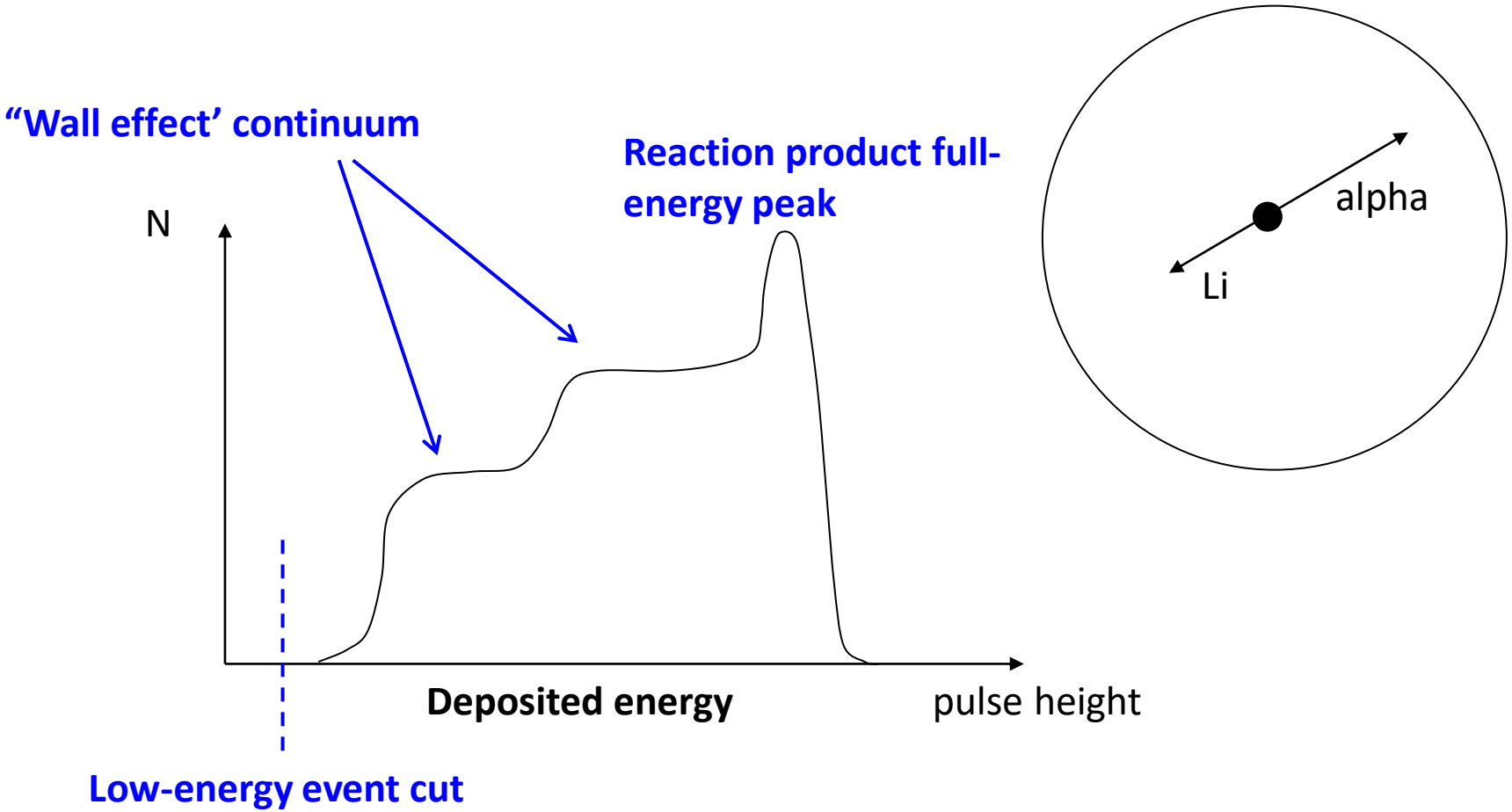
BF_3 gas and ^3He gas make detectors for slow neutrons with excellent gamma discrimination

Gamma rays can interact in the walls and produce electrons in the gas, but the energy loss of electrons is small (≈ 2 keV/cm), so that these pulses are much smaller than those due to neutrons

A suitable pulse amplitude threshold can thus eliminate most gamma interactions.

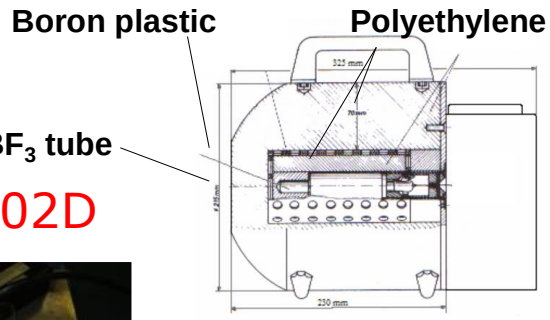


Pulse height spectrum from a BF_3 proportional counter

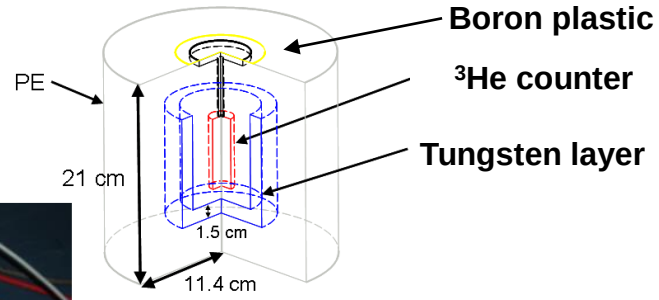


The shape of the pulse height spectrum is due to the energy loss of the recoils in the gas

Rem counters

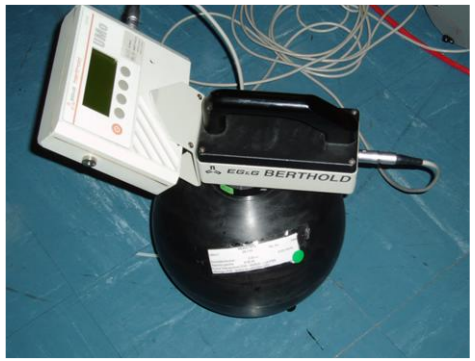


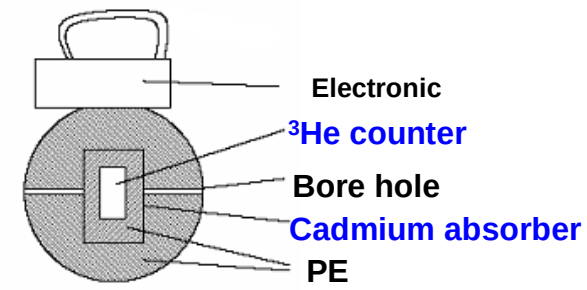
Studsvik 2202D



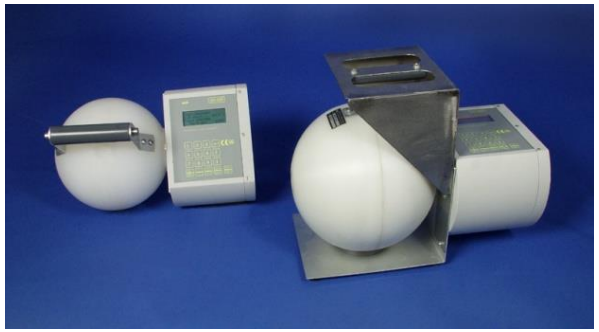
ELSE NUCLEAR LUPIN
Rem counter for pulsed fields

Eberline WENDI-2





Berthold LB6411 (also LB6411Pb)



MAB SNM500(X)

EURADOS WG9-WG11 rem-counter intercomparison at Maastro

MEVION S250i HYPERSCAN

Extremely-compact pencil-beam pulsed synchrocyclotron

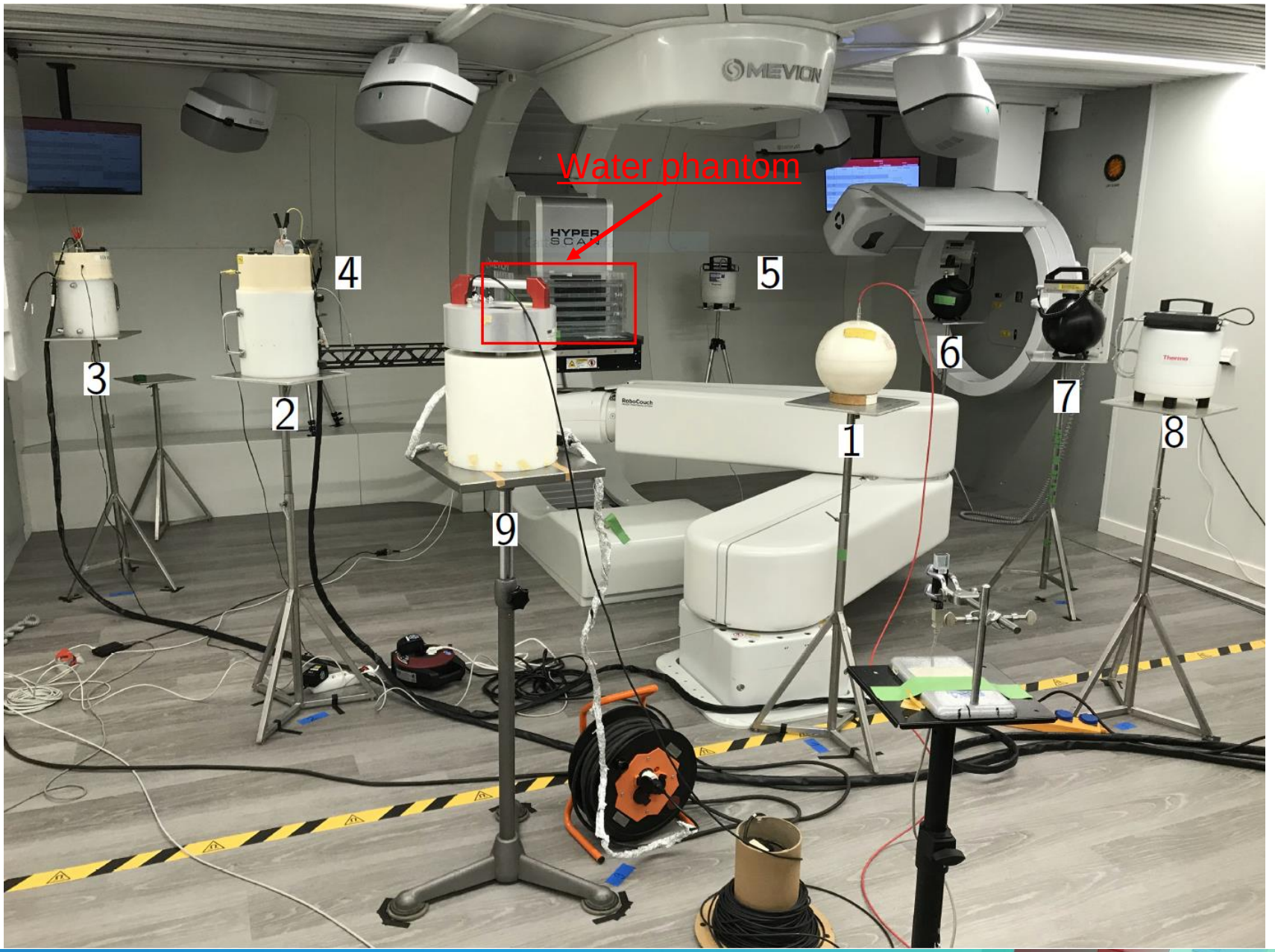
EURADOS

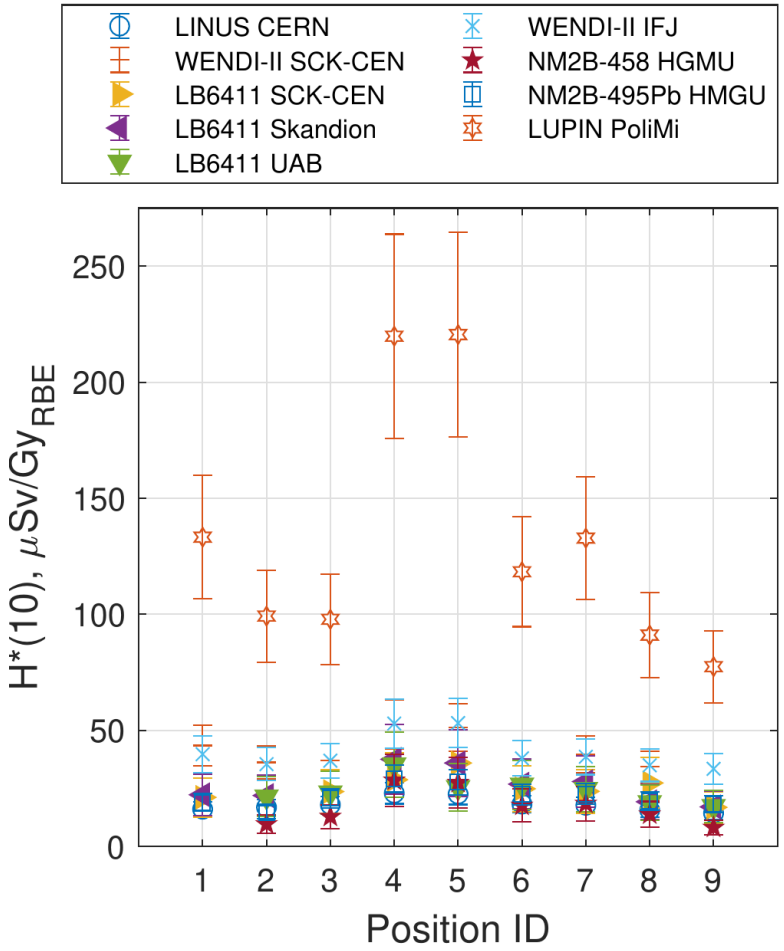
Large neutron dosimetry experiments at Maastro Proton Therapy Centre (Maastricht, NL)

1. Patient dosimetry
2. Neutron spectrometry
3. Rem-counter intercomparison

Proximity to patient → High neutron dose
Pulsed beam → Pile-up

G. Zorloni et al., Joint EURADOS WG9-WG11 rem-counter intercomparison in a Mevion S250i proton therapy facility with Hyperscan pulsed synchrocyclotron, submitted for publication in Physics in Medicine and Biology (2021)





LUPIN: rem-counter specifically designed for pulsed neutron fields (*)

(*) M. Caresana et al, Nucl. Inst. Methods A, 712:15-26 (2013)

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Assumptions for shielding design

- Type of equipment (accelerator)
- Permissible dose allowed behind the shielding (area classification)
- Occupancy factor T of room behind the shielding
- Planned use of the equipment: workload W (or beam current I, operation time t)
- Use factor of barrier U (i.e., beam orientation)
- Beam loss pattern (secondary radiation sources)
- Amount of leakage and scattered radiation (differential dose albedo α)

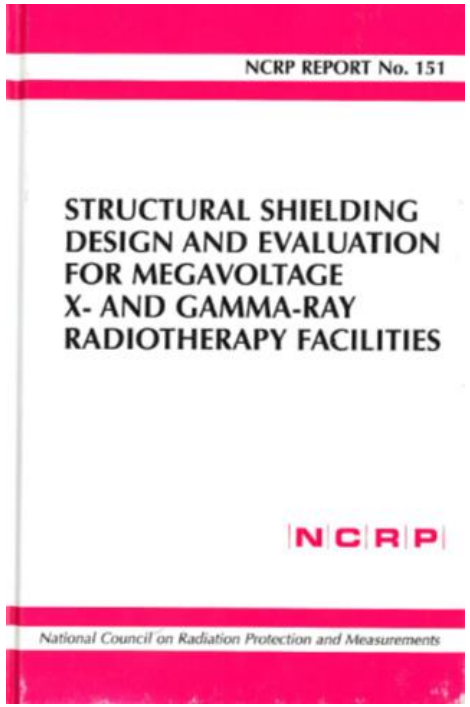
Shielding is an important part of the design of radiation therapy facilities, to protect staff and the public from undue radiation exposures.

Barrier use factor U

- In radiation therapy, the beam is delivered by isocentric gantries capable of rotating from 0° to 360° with respect to the vertical direction
- U accounts for the fraction of time during which the primary beam is directed towards the shield (e.g. ceiling, floor, left, right, front, rear wall, etc.). U is:
  - ✓ U = 1 for a fixed beam system;
  - ✓ 0 < U < 1 for an isocentric gantry
- The shields can be classified into:
  - ✓ Primary barriers: which can be directly invested by the radiation, for which $U \leq 1$;
  - ✓ Secondary barriers: shielding against secondary and diffused radiation, for which U = 1 always

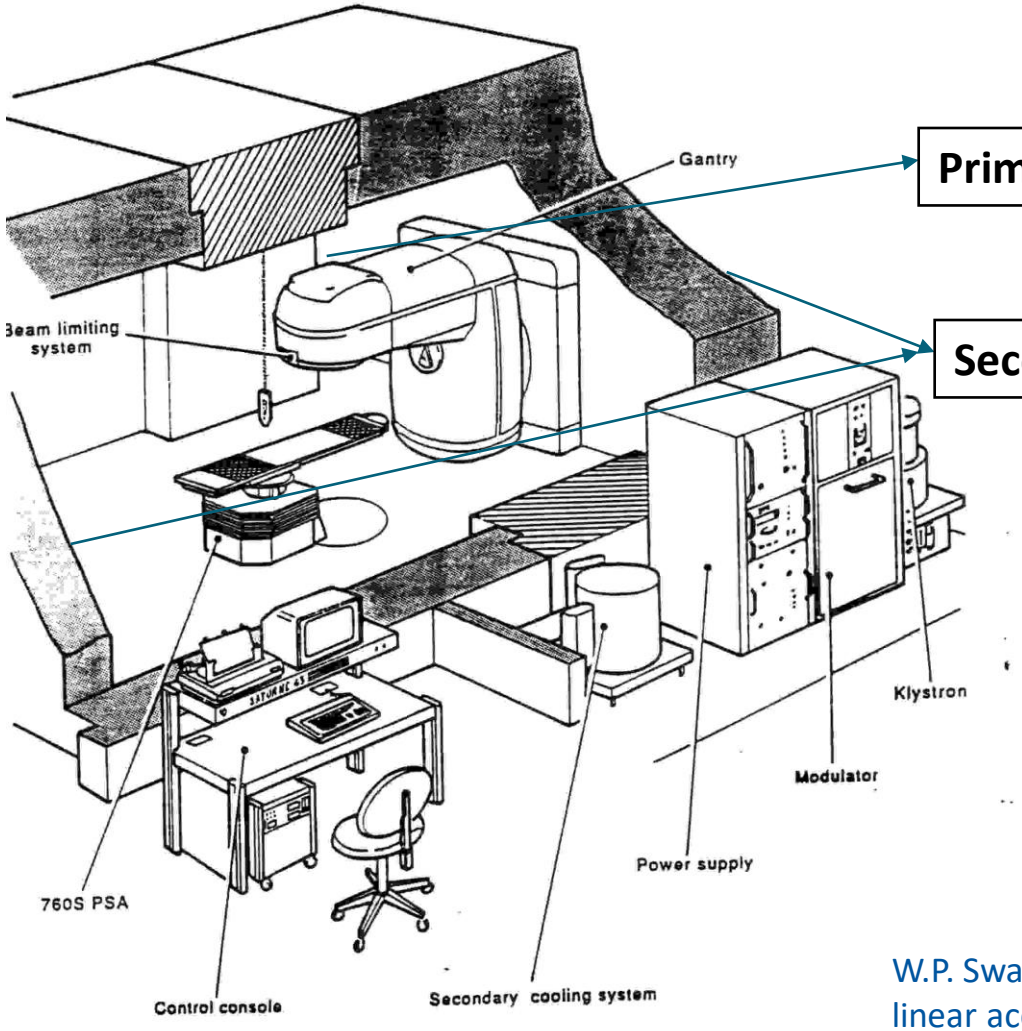
Room occupancy factor T

Location	T
Full occupancy areas	1
Adjacent treatment rooms, patient exam rooms adjacent to shield	1/2
Corridors, employee lounges, staff rest rooms	1/5
Treatment vault doors	1/8
Unattended waiting rooms, toilets, restrooms, storage, mechanical	1/20
Outdoor areas with only transient pedestrian or vehicular traffic, unattended parking lots, stairways	1/40



Careful that T x U be not too small!

Electron linac - Treatment room shielding



Rotating unit

Beam stopper

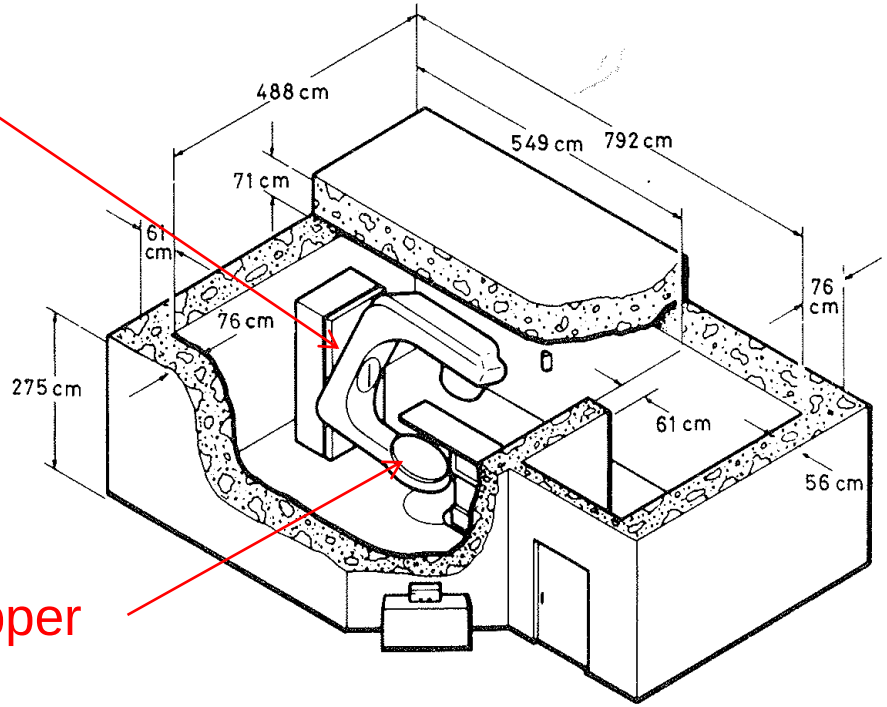
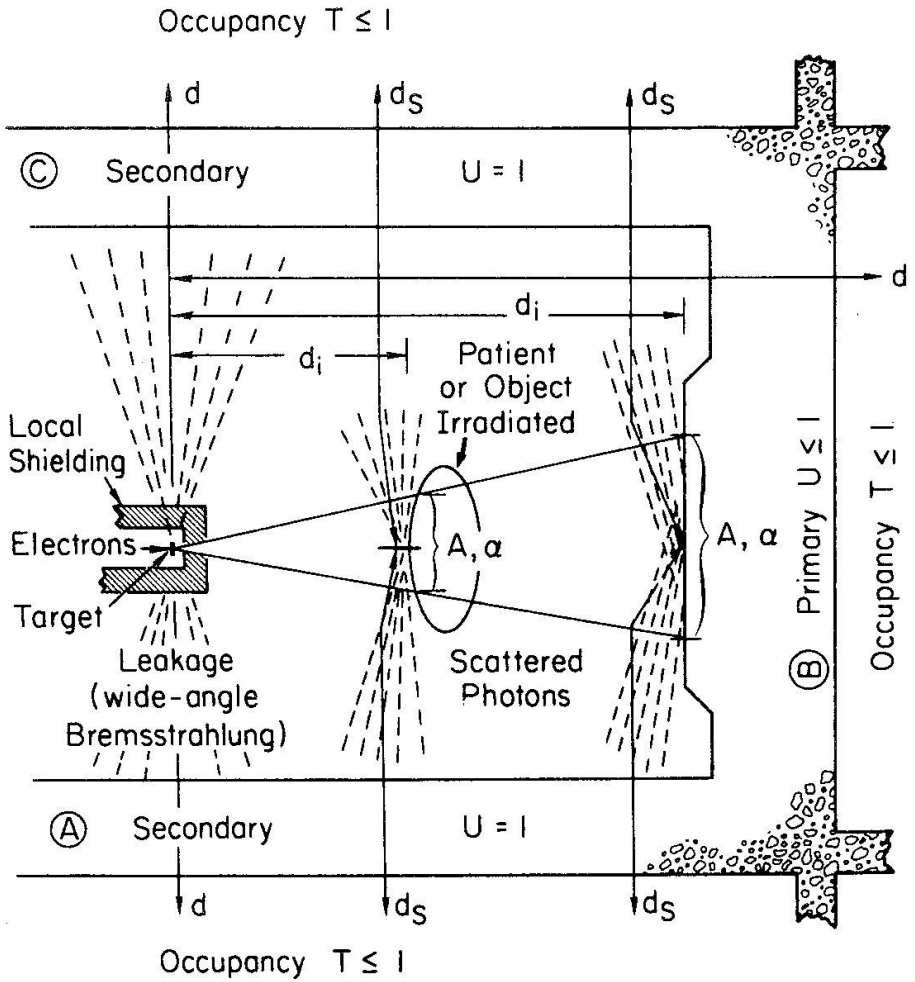


FIG.57. Cutaway view of a frequently used clinical accelerator arrangement for rotational therapy. The dimensions shown are typical for a 4-MeV, 1000 Gy·m²·week⁻¹ (100 000 rad·m²·week⁻¹) installation. The lower therapy-unit member is a beam stopper which permits a reduction in primary barrier thickness. Without the beam stopper, the primary barriers (the ceiling and two 76 cm walls) would have to be augmented by about 85 cm of concrete or the equivalent of other materials (original data in inches). (Adapted with kind permission of Varian Associates.)

W.P. Swanson, Radiological safety aspects of the operation of electron linear accelerators, IAEA Technical Report Series 188 (1979).

Electron linac - Treatment room shielding



Primary barrier

$$B = \dot{H}_M d^2 / (WUT)$$

H_M is the limiting value of the dose equivalent (effective dose) (Sv week^{-1});

d is the distance between the source and the point where H_M is evaluated (m);

W is the workload (Gy m^2 week^{-1})

Photoneutrons

The photoneutron fluence rate Φ_{tot} inside the treatment room can be expressed as:

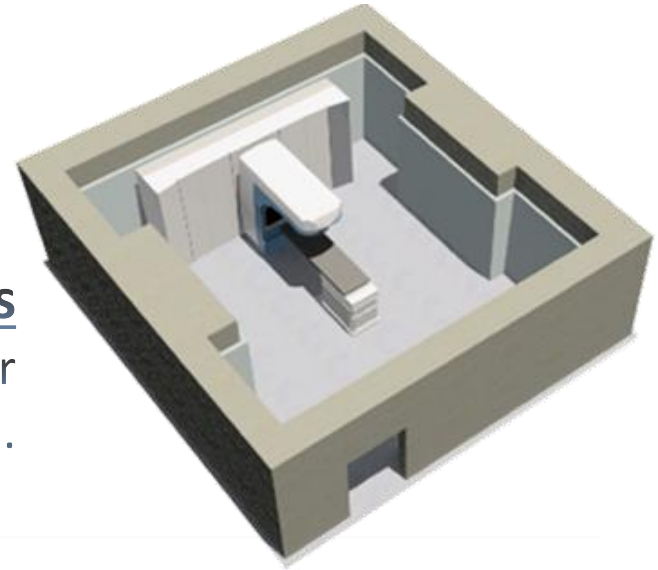
$$\Phi_{tot} = \Phi_{dir} + \Phi_{sc} = \frac{aQ}{4\pi R^2} + \frac{kQ}{S}$$

- ✓ Φ_{dir} direct component, Φ_{sc} scattered component;
- ✓ R distance from the source (usually the bremsstrahlung target);
- ✓ Q photoneutron yield (s^{-1});
- ✓ a = 1 for gantries locally shielded with Pb, a = 0.85 (W);
- ✓ S surface of the treatment room;
- ✓ k = 5.4 (Pb), k = 4.6 (W).

Access to the treatment room

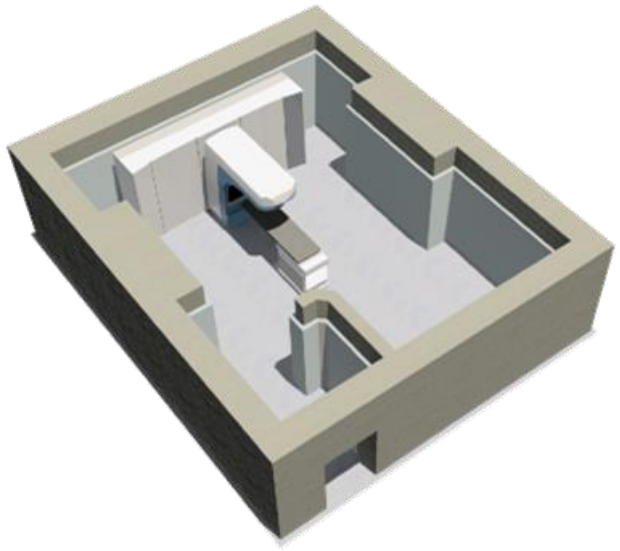
Shielded rooms can be entered with two types of access

Taken from a presentation by Steven Johnston to the Chicago Healthcare Knowledge Community, 23rd July 2013



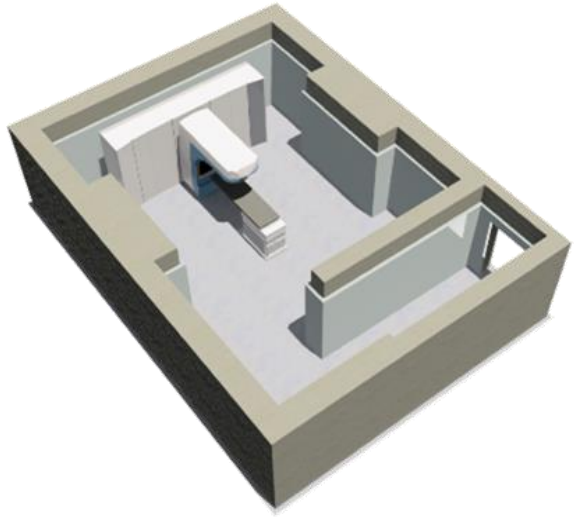
Direct-entry / Mazeless

A thick shielded door is used to enter and exit the room.



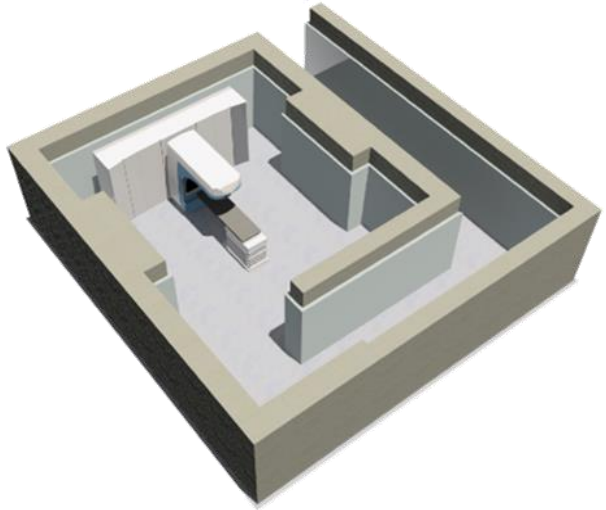
Mini-maze

A short stub wall is used to reduce the shielded door thickness



Maze

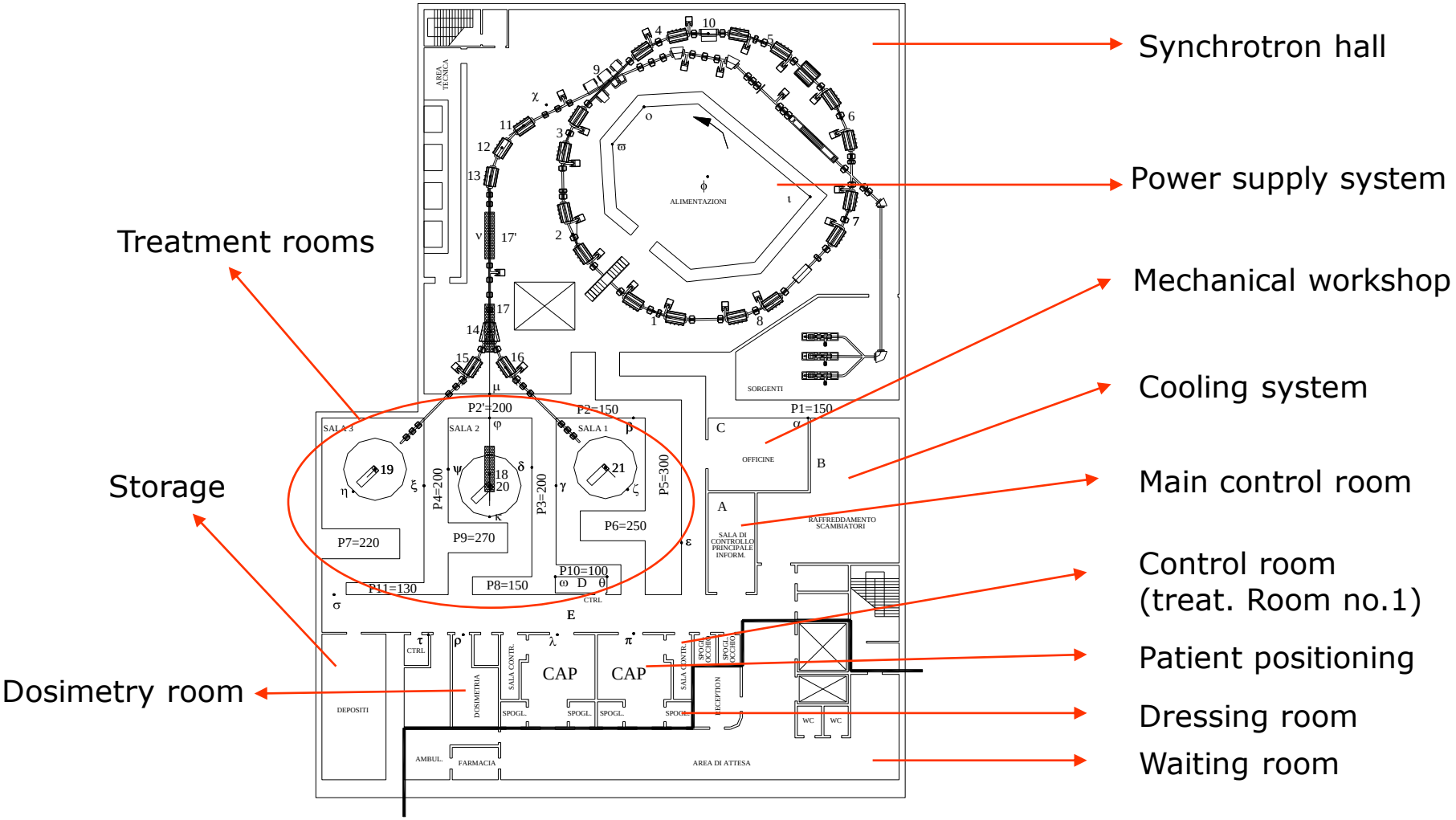
A long corridor is used to allow a thin shielded door thickness



Doorless

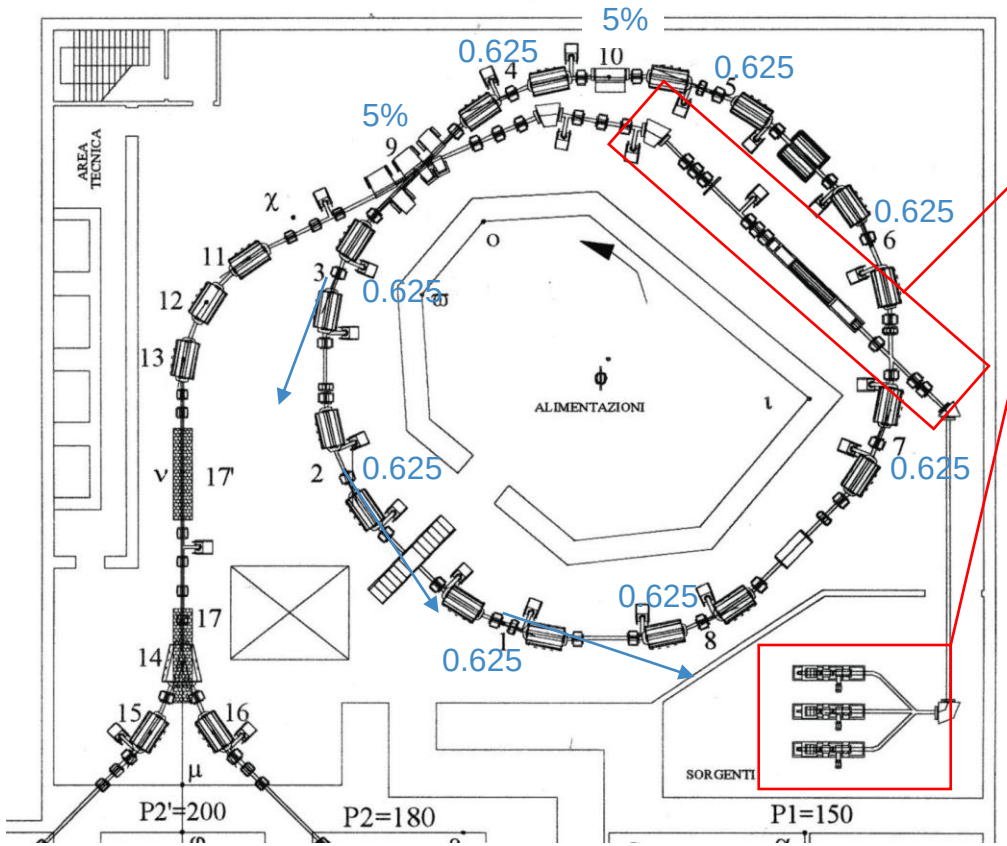
A long, double-turn corridor is used to allow eliminate the shielded door

Shielding design of a particle therapy facility (CNAO)



Courtesy S. Agosteo, Polytechnic of Milano

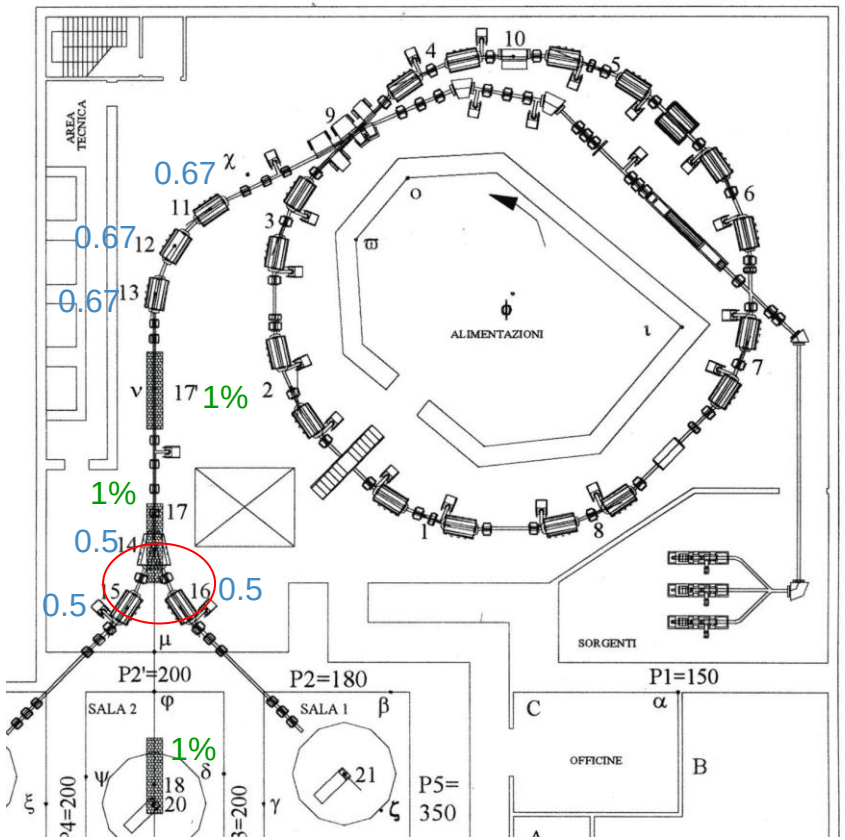
Shielding of CNAO: synchrotron



- Beam losses occurring in the low-energy components can usually be neglected
- Synchrotron ring: 5% of the circulating current
- Assumed to be concentrated at the centre of 2 adjacent dipoles
- Extraction septa (9-10): 5%

Courtesy S. Agosteo, Polytechnic of Milano

Shielding of CNAO: transfer lines



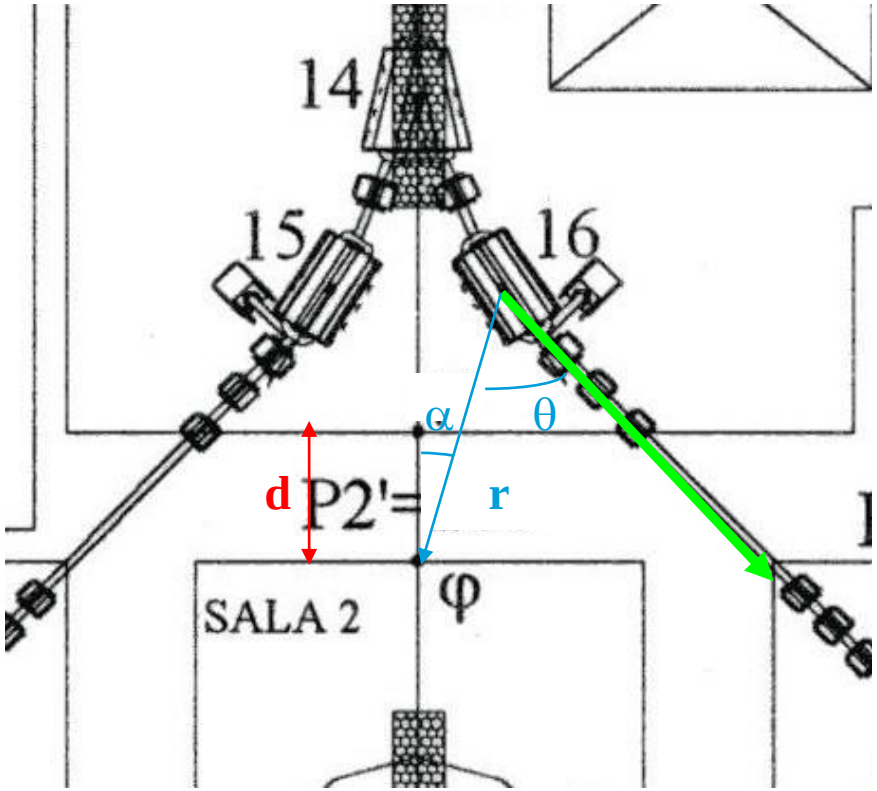
- Losses assumed concentrated at each bending magnet
- Dipoles of the extraction line (11-13): 2% (total)
- Switching magnet (on for delivering the beam in rooms 1 and 3, off for room no. 2) (14-16): 0.5%
- Vertical line (to room no. 2) (17,17’,18): 1%

Courtesy S. Agosteo, Polytechnic of Milano

Shielding of CNAO: beam loss at a bending magnet

- The shielding thickness d required for attenuating the H*(10) below the limiting value H_M is:

$$\frac{d}{\lambda(\theta)g(\alpha)} = \ln\left(\frac{H_0(E_p,\theta)\cdot S}{\dot{H}_M \cdot r^2}\right) = \ln\left(\frac{H_0(E_p,\theta)\cdot I \cdot f_{loss} \cdot t_{loss} \cdot U \cdot T}{\dot{H}_M \cdot r^2}\right)$$



- ✓ S = I × f_{loss} × t_{loss} × T × U
- ✓ I = beam particles per unit time
- ✓ f_{loss} = beam loss factor
- ✓ t_{loss} = duty factor
- ✓ T = occupancy factor
- ✓ U = use factor
  - → g(α) = cosα

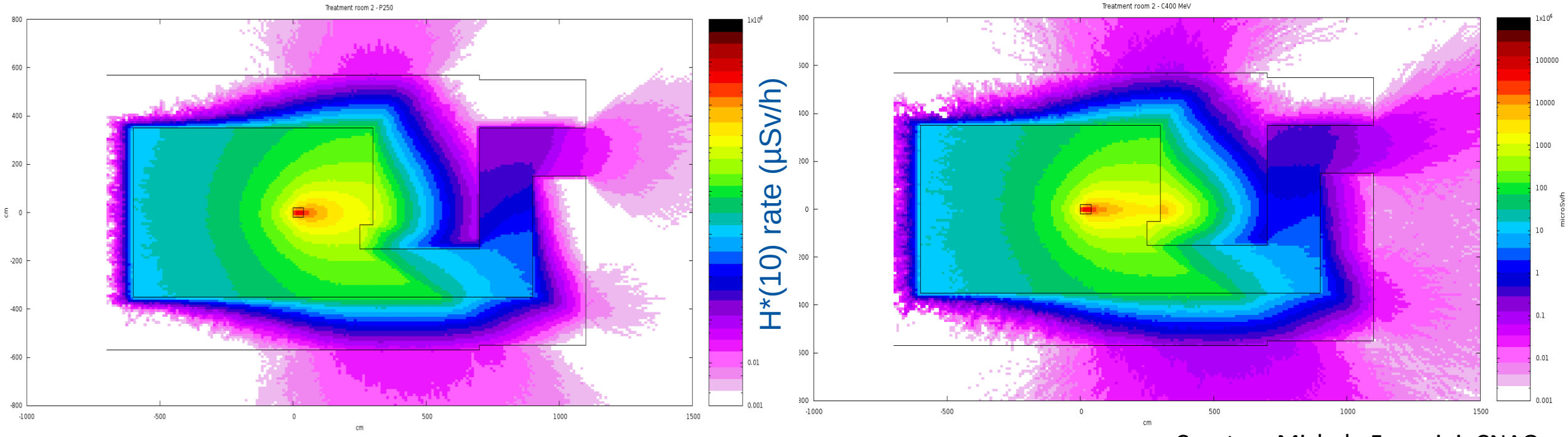
Courtesy S. Agosteo, Polytechnic of Milano

Shielding of CNAO: full Monte Carlo simulation

Treatment room 2 – Fixed beam

250 MeV protons

400 MeV/u carbon ions



Courtesy Michele Ferrarini, CNAO

CONV vs FLASH: pulse duration and dose per pulse

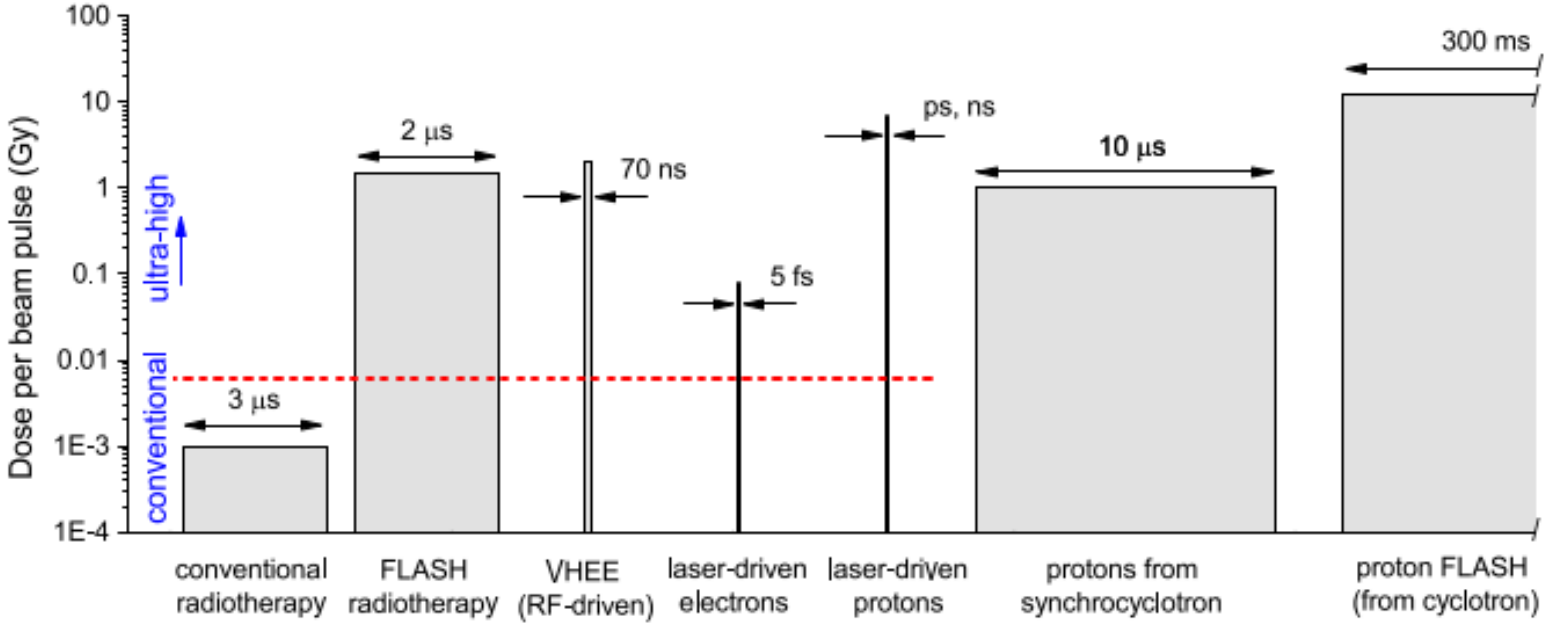


Illustration of typical achievable dose per beam pulse and the pulse duration at medical LINACs for conventional radiotherapy and at novel radiotherapy techniques with ultra-high pulse dose rates. Red dashed line: upper limit, where the ion collection efficiency of an Advanced Markus ionization chamber starts to deviate considerably from unity.

A. Schüller et al., The European Joint Research Project UHDpulse – Metrology for advanced radiotherapy using particle beams with ultra-high pulse dose rates, Physica Medica 80 (2020) 134–150

CONV vs FLASH: ideal pulsed FLASH RT delivery

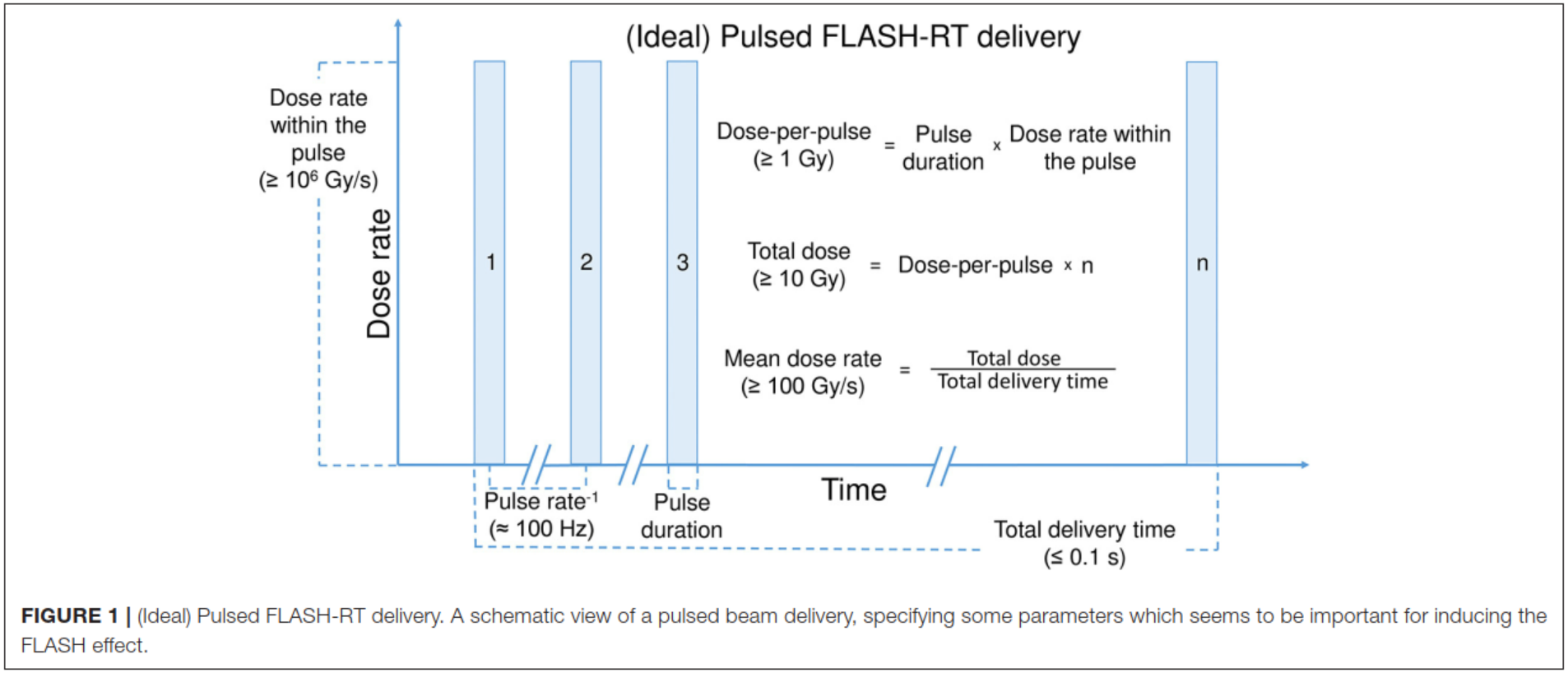


FIGURE 1 | (Ideal) Pulsed FLASH-RT delivery. A schematic view of a pulsed beam delivery, specifying some parameters which seems to be important for inducing the FLASH effect.

J.D. Wilson et al., Front. Oncol. 9:1563 (2020). doi: 10.3389/fonc.2019.01563

CONV vs FLASH: consequences for radiation protection

- Shielding design:
  - The thickness of the shield depends on the permissible dose allowed behind the shielding, on the occupancy factor T of the area behind the shielding, on the accelerator workload W, on the use factor of the barrier U (i.e., beam orientation), on the beam loss pattern (secondary radiation sources) and on the amount of leakage and scattered radiation
  - It DOES NOT depend on the time structure of the radiation
- Measurements: the time structure of the primary and secondary radiation DO influence the performance of a radiation detector

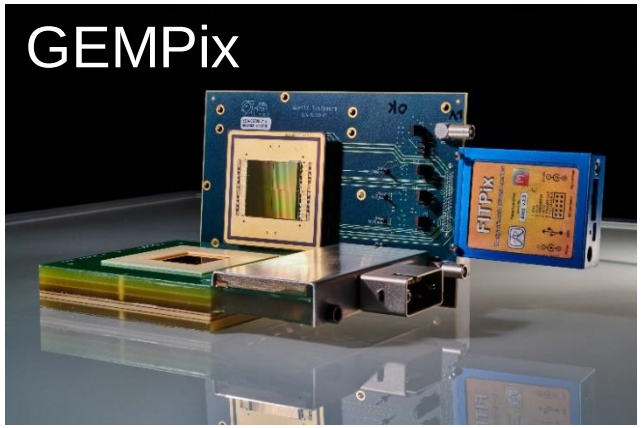
Outline of the lecture

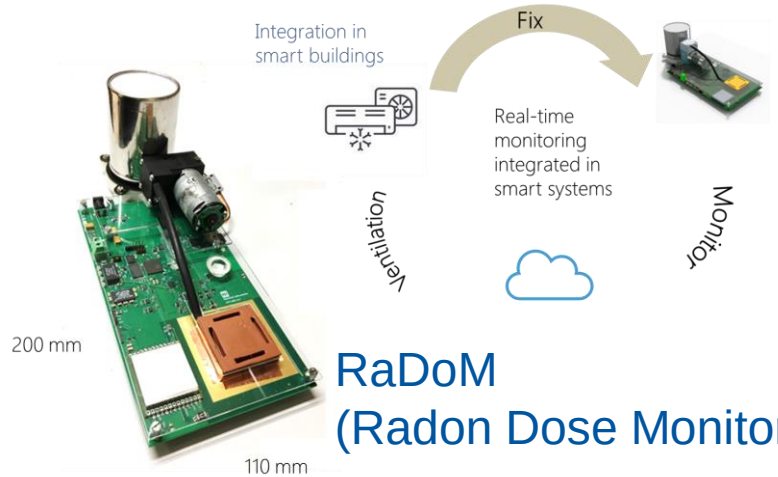
- Particle accelerators in medicine
- Radionuclide production
- Radiation therapy
  - Conventional radiation therapy
  - Particle (hadron) therapy
- Principles of radiation protection
  - Justification, optimization and dose limitation
  - Radiological quantities and units
  - Protection means
  - Instrumentation
- Radiation shielding of medical accelerators
- CERN technology transfer in health and safety

CERN Technology Transfer

B-RAD survey meter

ELSE NUCLEAR





RaDoM
(Radon Dose Monitor)

Kryolize

Software for sizing pressure relief valves in cryostats

CARA
COVID Airborne Risk Assessment

App to estimate the probability of infection, via airborne transmission, in enclosed spaces

Timepix 3 photon fluence measurement in hospitals

Main features

ELSE NUCLEAR B-RAD (device 100% made in Italy)

- Developed for operating also in very intense magnetic fields (up to 3 T intensity)
- Equipped with $LaBr_3$ crystal, 15 mm diameter x 15 mm height
- Energy resolution approximately 3% (Cs-137)
- User friendly, with double display (small with fast reading, big for detailed analysis)
- Leather bag for easy transport
- Radioisotope identification capability

ELSE NUCLEAR B-RAD portable gamma spectrometer for use in magnetic fields

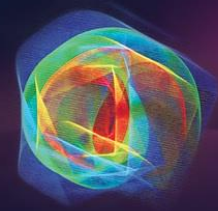
B-RAD

ELSE NUCLEAR

A. Fazzi and M. Silari, Patent Grant number 9977134 (2017)
A. Fazzi and M. Silari, U.S. Patent 20170199284A1 (2017).
D. Celeste, A. Curioni, A. Fazzi, M. Silari and V. Varoli, Journal of Instrumentation 14, T05007 (2019).

ELSE NUCLEAR B-RAD portable gamma spectrometer for use in magnetic fields

Main technical specs



ELSE NUCLEAR

TECHNICAL SPECIFICATIONS

- Crystal:
  - Type: $LaBr_3:Ce^{3+}$ (8%)
  - Dimensions: 0.6”×0.6”
- Housing material: aluminum
- Dose rate range: 100 nSv/h – 10 mSv/h
- Sensitivity: 90 cps/µSv/h
- Energy range: 30 keV ÷ 2 MeV
- Temperature range: 0 ÷ 40 °C
- Battery life up to 12 hours
- Detector dimensions:
  - Main unit: 156 x 191 x 92 mm
  - Probe: 180 x 50 mm (diameter)

CERN technology

ELSE NUCLEAR B-RAD portable gamma spectrometer for use in magnetic fields

www.cern.ch