



BSI Standards Publication

Radiological protection — Medical proton accelerators — Requirements and recommendations for shielding design and evaluation

National foreword

This British Standard is the UK implementation of ISO 24427:2025.

The UK participation in its preparation was entrusted to Technical Committee NCE/2, Radiation protection and measurement.

A list of organizations represented on this committee can be obtained on request to its committee manager.

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© The British Standards Institution 2025
Published by BSI Standards Limited 2025

ISBN 978 0 539 19423 4

ICS 13.280

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This British Standard was published under the authority of the Standards Policy and Strategy Committee on 30 September 2025.

Amendments/corrigenda issued since publication

Date	Text affected
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**International
Standard**

ISO 24427

**Radiological protection —
Medical proton accelerators
— Requirements and
recommendations for shielding
design and evaluation**

*Radioprotection — Accélérateurs médicaux de protons —
Exigences et recommandations pour la conception et l'évaluation
du blindage*

**First edition
2025-09**

Reference number
ISO 24427:2025(en)

Full document details: BS ISO 24427:2025

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Published in Switzerland

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Foreword

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This document was prepared by Technical Committee ISO/TC 85, *Nuclear energy, nuclear technologies, and radiological protection*, Subcommittee SC 2, *Radiological protection*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Protons deliver most of their energy at a prescribed, programmable distance inside the body, known as the Bragg Peak. With this feature, proton therapy is used to treat many cancers and is particularly appropriate in situations where treatment options are limited and conventional radiotherapy using photon beam presents unacceptable risks to patients. The use of proton accelerators to administer external beam radiation has been evolving and the proton therapy centres are rising worldwide.

A typical large proton therapy centre consists of an injector, a cyclotron or synchrotron to accelerate the particles, high-energy beam selection and transport system, several treatment rooms (fixed beam and/or gantry) and, occasionally, a research room. Strong secondary radiation, particularly high energy neutrons, is produced at locations where beam losses occur. Such losses may occur in the cyclotron or synchrotron along the beam transport system during acceleration, extraction, energy degradation and transport of the protons to the treatment room, and in the treatment and research nozzles. In addition, the production of proton beam interactions in the patient, beam stop, or dosimetry phantom also results in stray radiation production. As a result, meters-thick barriers are generally used around the entire accelerator system. The radiation shielding of proton therapy centre is quite complex and become one of the key elements to commission a proton therapy centre, in the perspective of both capital and time consumed.

IEC 60601-2-64 relates to the design and the construction of the light ion, including proton, accelerators to ensure the safety of their operation^[1]. Several national^{[2][3]} or international^{[4][5][5]} reports propose recommendations concerning the installation, the commissioning, and the operation of these accelerators, the safety devices, the design and the calculation of protection barriers, the radiological control and monitoring. National standards^{[7][8][9][10]} have been established in certain countries. Moreover, national regulations generally impose rules of protection against radiation, in particular relating to the definition of the controlled area and supervised area and the calculation of shielding.

Considering the developments of proton therapy techniques and of new designs of proton therapy facilities on the one hand, and the variety of guidelines or normative documents on the other hand, it appeared judicious to establish an international standard to be used as a general framework. This document is intended to be complementary to the other international standards (IEC and IAEA).

The following items are discussed in this document:

- shielding design assumption and goals;
- radiation fields;
- materials for radiation shielding: concrete (ordinary or high density), steels;
- role of stakeholders;
- general formalism for shielding calculations;
- calculation methods;
- radiation survey of the completed installation to ensure national requirements have been met and the shielding design is fit for purpose after installation of the accelerator.

Radiological protection — Medical proton accelerators — Requirements and recommendations for shielding design and evaluation

1 Scope

This document is applicable to the radiation shielding design and evaluation work for medical proton accelerators of proton energies ranging from 70 MeV to 250 MeV, with subsystems such as beam transport system and nozzle components.

The radiation protection recommendations given in this document cover the aspects relating to regulations, shielding design goals and other design criteria, role of the manufacturers, of the radiation protection officer or qualified expert, the medical physicist, the licensee and interactions between them, sources and radiations around a proton accelerator, shielding for accelerators and its subsystems (including shielding materials and transmission values, calculations for various room configurations, duct impact on radiation protection) and the radiological measurements.

FLASH proton therapy is not covered by this document.

NOTE 1 [Annex A](#) provides a list of the most used Monte-Carlo codes for shielding calculation.

NOTE 2 [Annex B](#) provides the analytical methods and the corresponding necessary data for shielding calculation.

NOTE 3 [Annex C](#) provides a set of examples on shielding calculation of barriers, maze and skyshine problems.

NOTE 4 [Annex D](#) provides radiation shielding consideration on special topics.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 12749-2, *Nuclear energy, nuclear technologies, and radiological protection — Vocabulary — Part 2: Radiological protection*

ISO 16645, *Radiological protection — Medical electron accelerators — Requirements and recommendations for shielding design and evaluation*

ISO 80000-10, *Quantities and units — Part 10: Atomic and nuclear physics*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 12749-2, ISO 16645, ISO 80000-10 and the following apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <https://www.electropedia.org/>

3.1 Quantities

3.1.1

absorbed dose

D

differential quotient of $\bar{\epsilon}$ with respect to m , where $\bar{\epsilon}$ is the mean energy imparted by ionizing radiation to matter of mass m :

$$D = \frac{d\bar{\epsilon}}{dm}$$

Note 1 to entry: The gray (Gy) is special name for Joule per kilogram ($\text{J}\cdot\text{kg}^{-1}$) to be used as the coherent SI unit for absorbed dose.

[SOURCE: ISO 12749-2:2022, 3.1.20]

3.1.2

dose equivalent

H

product of the *absorbed dose* D (3.1.1) to tissue at the point of interest and the quality factor Q at that point:

$$H = D \cdot Q$$

Note 1 to entry: The sievert (Sv) is special name for Joule per kilogram ($\text{J}\cdot\text{kg}^{-1}$) to be used as the coherent SI unit for dose equivalent.

[SOURCE: ISO 12749-2:2022, 3.1.22]

3.1.3

effective dose

E

tissue-weighted sum of the equivalent doses in all specified tissues and organs of the body, given by the expression:

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

where H_T or $w_R D_{T,R}$ is the equivalent dose in a tissue or organ, T and w_T is the tissue weighting factor.

Note 1 to entry: The sievert (Sv) is special name for Joule per kilogram ($\text{J}\cdot\text{kg}^{-1}$) to be used as the coherent SI unit for effective dose.

[SOURCE: ISO 12749-2:2022, 3.1.24]

3.1.4

instantaneous dose equivalent rate

$\dot{H}_{\text{IDR}}$

"ambient/personal" dose equivalent rate ($\text{Sv}\cdot\text{h}^{-1}$) as measured with the accelerator operating

Note 1 to entry: This is the direct reading of the ratemeter that gives a stable reading in dose equivalent per hour.

[SOURCE: ISO 16645:2016, 3.1.5, modified by deleting "at the absorbed dose rate DR_0 ($\text{Gy}\cdot\text{h}^{-1}$) and $\dot{H}_{\text{IDR}}$ is specified at a reference point (30 cm) beyond the penetrated barrier"]

3.1.5

time averaged dose equivalent rate

$\dot{H}_{\text{TADR}}$

barrier attenuated dose equivalent rate averaged over a specified period of accelerator operation

Note 1 to entry: $\dot{H}_{\text{TADR}}$ is proportional to *instantaneous dose equivalent rate*, $\dot{H}_{\text{IDR}}$ (3.1.4), and depends on the values of workload (W) and orientation or use factor (U).

[SOURCE: ISO 16645:2016, 3.1.14]

3.1.6 occupancy factor

T

typical fraction of time for which a location is occupied by an individual or group.

[SOURCE: ISO 12749-2:2022, 3.2.23]

3.1.7 orientation or use factor

U

fraction of the time during which the radiation under consideration is directed at a particular barrier

[SOURCE: ISO 16645:2016, 3.1.8]

3.1.8 shielding design goal

P

practical values of *dose equivalent*, H (3.1.2) or *effective dose*, E (3.1.3), for a single proton therapy source or set of sources, evaluated at a reference point beyond a protective barrier

Note 1 to entry: The shielding design goals ensure that the respective annual values for effective dose limit defined by national regulation or IAEA/ICRP for controlled and uncontrolled areas are not exceeded.

[SOURCE: ISO 16645:2016, 3.1.10]

3.1.9 transmission factor

B

ratio of radiation field intensity at a location behind the barrier on which radiation is incident to the field intensity at the same location without the presence of the shield, for a given radiation type and quality

Note 1 to entry: B is a measure of the shielding effectiveness of the barrier.

[SOURCE: ISO 16645:2016, 3.1.15]

3.1.10 attenuation length

λ

thickness of a specific material that reduces a specified radiation field intensity by a factor of e of its original value, under broad beam condition

Note 1 to entry: e is the natural constant.

3.1.11 half-value layer

d_{HVL}

thickness of a specific material that reduces a specified radiation field intensity half of its original value, under broad beam condition

Note 1 to entry: d_{HVL} is expressed in m or cm of a defined material or in $\text{kg}\cdot\text{m}^{-2}$ (thickness $\times$ density).

3.1.12 tenth-value layer

d_{TVL}

thickness of a specific material that reduces a specified radiation field intensity by a factor of 10 of its original value, under broad beam condition

Note 1 to entry: d_{TVL} is expressed in m or cm of a defined material or in $\text{kg}\cdot\text{m}^{-2}$ (thickness $\times$ density).

Note 2 to entry: d_{TVL_1} is the first tenth-value layer in the shield nearest the radiation source.

Note 3 to entry: d_{TVL_e} is the equilibrium tenth-value layer, and for each subsequent tenth-value layer in the region in which the directional and spectral distributions of the radiation field are practically independent of thickness.

3.1.13

workload

W

number of proton particles delivered to target volume by a proton therapy system

Note 1 to entry: The workload is specified in number of proton particles for proton therapy system, while it is generally specified in Gray for traditional radiotherapy.

Note 2 to entry: The workload shall include also the *proton accelerator* (3.2.1) usage not associated to patient treatment (e.g. QA (3.2.13), maintenance, and research activities). A separate workload allocation may be appropriate for modalities such as research activities.

Note 3 to entry: The workload is used further as an input for the estimation of lost proton particles (positions, directions, energies and the intensities/numbers) with the whole proton therapy system, for radiation shielding calculation.

Note 4 to entry: The time period should be consistent between *shielding design goal P* (3.1.8) and *workload W* (3.1.3).

3.2 Definitions other than quantities

3.2.1

proton accelerator

machine that uses electromagnetic fields to propel protons to very high speeds and energies, and to contain them in well-defined beams

Note 1 to entry: For medical treatment, the proton energy for therapy is generally from 70 MeV to 250 MeV.

Note 2 to entry: Cyclotron, synchrotron and synchrocyclotron are the typical medical proton accelerators.

3.2.2

beam transport system

system that transports and manipulates the proton beam from the *proton accelerator* (3.2.1) to the treatment nozzle in a proton therapy system

Note 1 to entry: The beam transport system performs multiple functions, such as the energy selection (for cyclotron), beam shaping, beam monitoring, beam stop etc. By performing the functions, proton beams are consumed, and the corresponding secondary radiation are produced.

3.2.3

passive scattering

technique by using passive scatterers to shape and spread the narrow proton beam, to allows precise three-dimensional dose deposition in the target volume

3.2.4

pencil beam scanning

PBS

technique that uses magnets to sweep a narrow proton pencil-beam and allows precise three-dimensional dose deposition. Both the intensity and energy of the protons can be manipulated throughout the scan

Note 1 to entry: For radiation shielding design and evaluation, it sometimes includes similar techniques such as "spot scanning" and "raster scanning". In this document, the pencil beam scanning is used in general.

Note 2 to entry: In some PBS systems, respiration-gated technology that uses tracking and interception methods to reduce the dose to normal tissues surrounding the tumour that moves due to respiration, without compromising the dose to the tumour.

3.2.5

equipment reference point

ERP

point in space used for referencing dimensions of equipment and performing dosimetry measurements

Note 1 to entry: Typically, the equipment reference point is coincident with the isocentre. If the beam delivery equipment is not isocentric, then the centre of the patient alignment systems may be used.

[SOURCE: IEC 60601-2-64:2014, 201.3.212]

3.2.6

Bragg peak

pronounced peak on the Bragg curve that plots the energy loss on ion beams during their passage through matter

Note 1 to entry: For protons, the peak occurs near the end of their range.

Note 2 to entry: In proton therapy, the term 'Bragg peak' is used for the peak in the curve of *absorbed dose* (3.1.1) against depth in the irradiated patient or phantom.

[SOURCE: ICRP Publication 127, 2014 Glossary^[11]]

3.2.7

barrier

protective barrier

protective wall of radiation attenuating material(s) used to reduce the *dose equivalent* (3.1.2) on the side beyond the radiation source

[SOURCE: ISO 16645:2016, 3.2.1, modified by deleting "to an acceptable level compatible with national legislation or international guidance"]

3.2.8

controlled area

defined area in which specific protection measures and safety provisions are or could be required for controlling exposures or preventing the spread of contamination in normal working conditions, and preventing or limiting the extent of potential exposures

[SOURCE: ISO 12749-2:2022, 3.6.5]

3.2.9

supervised area

defined area in which specific protection measures and safety provisions are or could be required for controlling normal exposures during normal working conditions, and preventing or limiting the extent of potential exposures

[SOURCE: ISO 12749-2:2022, 3.6.6]

3.2.10

occupied area

room or other space, indoors or outdoors, that is likely to be occupied by any person, either regularly or periodically during the course of the person's work, habitation or recreation, and in which an ionizing radiation field exists because of radiation sources in the vicinity

[SOURCE: ISO 16645:2016, 3.2.12]

3.2.11

radiation safety officer

radiation protection officer

RSO

a person technically competent in radiation protection matters relevant for a given type of practice who is designated by the registrant, licensee or employer to oversee the application of regulatory requirements

[SOURCE: IAEA Nuclear Safety and Security Glossary^[12]]

3.2.12

qualified expert

individual who, by virtue of certification by appropriate boards or societies, professional licence or academic qualifications and experience, is duly recognized as having expertise in a relevant field of specialization, e.g. medical physics, radiation protection, occupational health, fire safety, quality management or any relevant engineering or safety specialty

[SOURCE: ISO 16645:2016, 3.2.14]

3.2.13

quality assurance

QA

the maintenance of a desired level of quality in a service or product, especially by means of attention to every stage of the process of delivery or production

3.2.14

regulatory body

an authority or a system of authorities designated by the government of a State as having legal authority for conducting the regulatory process, including issuing authorizations, and thereby regulating the nuclear, radiation, radioactive waste and transport safety.

Note 1 to entry: The regulatory body is generally a national entity, established and empowered by law, whose organization, management, functions, processes, responsibilities and competences are subject to the requirements of IAEA safety standards.

Note 2 to entry: it supersedes the term regulatory authority, which should not be used.

[SOURCE: IAEA Nuclear Safety and Security Glossary]

3.2.15

commissioning

the process by means of which systems and components of facilities and activities, having been constructed, are made operational and verified to be in accordance with the design and to have met the required performance criteria.

[SOURCE: IAEA Nuclear Safety and Security Glossary]

3.2.16

low level waste

LLW

radioactive waste that is above clearance levels, but with limited amounts of long-lived radionuclides.

Note 1 to entry: LLW is one of the waste classes defined in IAEA GSG-1, which is organized to take into account matters considered of prime importance for the safety of disposal of radioactive waste.

Note 2 to entry: LLW covers a very broad range of waste. LLW may include short lived radionuclides at higher levels of activity concentration, and also long-lived radionuclides, but only at relatively low levels of activity concentration.

[SOURCE: IAEA Nuclear Safety and Security Glossary and IAEA GSG-1^[13]]

4 Shielding design goals and other design criteria

4.1 Shielding design goals

The shielding design should follow the principle of optimization of protection and safety, i.e., the process of determining what level of protection and safety would result in the magnitude of individual doses, the number of individuals (workers and members of the public) subject to exposure and the likelihood of exposure being “as low as reasonably achievable, economic and social factors being taken into account” (ALARA)^[14].

Shielding design goals, P , are levels of dose equivalent, H , or effective dose, E , used in the design calculations and evaluation of barriers constructed for the protection of workers or members of the public. Different shielding design goals shall be defined for supervised area, controlled area and areas accessible to members of the public. They have to be in accordance with existing national regulation or if not available according to IAEA basic safety standards on radiation protection related to effective dose limits for workers and members of the public.

The P value (Sv) set by national authorities should be a fraction of dose limits for workers or for members of the public. They can be expressed as weekly values (mSv·week). But according to national regulation, other time periods can be used.

Shielding design goals, P , are practical values that are evaluated at a reference point beyond a protective barrier.

4.2 Shielding design assumptions and conditions

The medical proton accelerator is always delivered and utilized in conjunction with subsystems such as beam transport system and treatment nozzle(s), forming a proton therapy system.

A proton therapy system that uses the assumption proposed above would produce effective dose values lower than the regulation statements for supervised area, controlled area, and areas accessible to members of the public. This is the result of the conservatively safe nature of the shielding design methodology recommended.

Some design assumption should be made:

- it is essential to avoid human exposure to the primary proton beams, except for patients being exposed for medical purposes;
- to avoid the direct impinging of primary proton beams on shielding walls, a sufficient load should always be set or added in front of nozzle, when proton beam is delivered;
- the attenuation of the secondary particles from proton beam by the patient should be neglected. The self-shielding of equipment or components of the proton therapy system, such as the yoke of cyclotron and the counterweight in front of nozzle with gantry, are usually considered in the shielding design;
- effective thickness (i.e. oblique incidence) should be used in the analytical calculations of recommended barrier thickness for the secondary neutron attenuation;
- the minimum distance to the occupied area from a shielding wall (or barrier) is assumed to be 0,3 m (considered as representative for whole body exposure).

Because of the operating characteristic and large dimensions of a proton therapy system, the calculated and measured dose rate of a concern position behind the shielding barriers may be a summation, which results from multiple prompt radiation sources.

5 Role of stakeholders and the interactions

5.1 General

Ensuring adequate protection for both workers and the members of the public from medical proton accelerator radiation is a cooperative effort. This clause provides general guidance on the roles, responsibilities, and interaction among the various stakeholders involved in this process.

It is highly noted that the roles, responsibilities, and interaction of the stakeholders depend on the commercial contracts between them and should be in accordance with existing national regulation. The licensee of a proton therapy system is primarily responsible for the radiation safety.

The stakeholders may include:

- manufacturer of the proton therapy system;

- general contractor/architectural firm;
- radiation protection officer or other;
- medical physicist or other;
- the licensee or other.

For a typical turnkey system, the stakeholders may be independent companies or personnel. Meanwhile, in certain case, a proton therapy centre may run in a total owner-control style.

5.2 Manufacturer of the proton therapy system

The manufacturer of the proton therapy system shall provide detailed technical documents containing at least the following information, according to the contract.

- a) Dimension sheets containing:
 - the required vault dimensions of the proton therapy system, including the medical proton accelerator, beam transport system, treatment rooms; minimum dimensions, location, and requirements for control rooms.
 - requirements on electrical cables, water pipes, heating, and air-conditioning ventilation ducts necessary to operate the equipment.
- b) Functional performance characteristics:
 - the highest energy and intensity of the proton beam deliverable, and their variations;
 - the positions, directions, energies and the intensities of the proton beam loss during injection, acceleration, extraction, energy degradation (if any), and transportation of the particles in the beam line to the treatment room, and beam shaping devices in the treatment nozzle, at required energies and intensities;
 - the general size and materials of components with which the beam is lost.
- c) Other necessary information and data to be used for radiation shielding:
 - the component(s) of proton therapy system, that can be considered as shielding barrier(s);

5.3 General contractor/architectural firm

To ensure that the facility is built according to the intent of the licensee, the general contractor/architectural firm should:

- ensure the facility is constructed in consistent with the radiation shielding design;
- specify the overall density and composition of the shielding material. If Monte-Carlo calculations are to be performed, further information on atomic composition for elements (Ca, Fe, H, O, Si... in atom densities or atom fractions or mass fractions) relevant to evaluate the shielding properties shall be provided;
- coordinate with the radiation protection officer or qualified expert any situation arising during construction that may compromise the shielding. In particular, shielding for locations where structural constraints exist shall be coordinated between stakeholders.

If precast normal or high-density concrete block, pre-moulded high-density interlocking blocks of different materials, or specific patented building methods are used, the effectiveness of shielding should be evaluated in collaborative with the radiation protection officer or qualified expert. Attention should be paid on the penetration and gap effect resulting from these prefabricated blocks.

Information on all radiation pathways shall be communicated to the contractor (e.g. via beam lines, electrical cables, water pipes, heating, and air-conditioning ventilation ducts, doors, openings).

5.4 Radiation safety officer or other

The radiation safety officer for the medical proton accelerator installation or other (such as the qualified expert) should provide, in close collaboration with the other stakeholders (medical physicist, radiation oncologists...), detailed documents containing the specifications essential for construction and the intended operation. The shielding plan should use conservative and realistic shielding assumptions to reach the facility's shielding goal.

The documents should contain information according to national regulation. They should at least contain the following specifications:

- the positions, directions, energies and the intensities/numbers of the protons delivered and lost with the whole proton therapy system, according to the workload, W ;
- specifications regarding the intended demarcation of supervised area, controlled area and areas accessible to members of the public, and, in particular, specifications regarding the intended demarcation of the access prohibited areas within controlled area when the proton beam is transported;
- drawings of the buildings, rooms and external facilities belonging to the supervised area and controlled area of the proton therapy system and of any adjacent buildings, rooms and traffic areas from which the dimensions and distances required for radiation shielding calculation can be derived;
- type and use of areas outside the proton therapy system and related occupancy factors, T , on basis of conservative assumption;
- specific requirements regarding type of treatments planned to be realized and their impact on dimensions of the treatment room. Specific requirements regarding type of research activities planned to be realised in a research room (if it exists).

The radiation protection officer or qualified expert should provide a shielding evaluation report demonstrating that the barriers in the structure (material type, thickness, and location) can provide adequate protection for workers and members of the public. A clear statement of all assumptions used to generate the shielding design should be included in the report. It should be ensured that a radiation survey after machine installation is performed and that a report is provided demonstrating the dose rate outside the structure housing the proton accelerator is suitable for occupancy by the workers and, for locations with uncontrolled access, the members of the public.

Data on activation of components to be considered for the occupational exposure of workers and the decommissioning stage report.

5.5 The medical physicist or other

The medical physicist for proton therapy or other should provide, in close collaboration with the other stakeholders (radiation protection officer or qualified expert, radiation oncologists...) detailed information about:

- the treatment plans with the highest dose delivered to patient, beam stop or dosimetry phantom;
- the maximum number of each type of intended treatment and the related mean dose during the reference period defined for achieving the shielding goal;
- the maximum number of each type of intended QA procedure and the related mean dose during the reference period defined for achieving the shielding goal. Other intended maintenance and research activities.

Based on the maximum number of each type of intended treatments, QA procedures, maintenance and research activities, a complete workload, W , estimation should be defined as one of the key inputs for the radiation shielding calculation.

The radiation shielding evaluation report should be checked by the medical physicist.

5.6 The licensee or other

As required by local or national regulations, the radiation survey report should be submitted by a representative of the licensee or other to the appropriate regulatory body for approval prior to the start of clinical treatment.

6 Radiation sources of a medical proton accelerator

6.1 General

High energy proton losses may occur during the acceleration and extraction of protons in the accelerator, the energy degradation (as needed), selection and transport of the protons in beam transport system, and the beam shaping in nozzle with PBS or passive scattering technique. At the end, protons with requested energies are delivered to tissues, dosimetry phantom or beam dump. These proton losses and delivery shall be clearly identified as the primary proton source. As the human exposure to the primary proton beams is not allowed except for patients being exposed for medical purposes, only the radiation of secondary particles are concerned.

To allow reasonable penetration in tissue, the maximum proton energy typically range from about 200 MeV to 250 MeV. When these protons react with matter, a hadronic or nuclear cascade (spray of particles) is produced and the corresponding secondary radiation field is quite complex^[6]. In the point of radiation shielding, the prompt radiation mainly consisting of a mixture of:

- secondary neutrons, with energies as high as the proton energy;
- photons.

With high energy primary protons and the corresponding secondary particles, the activation issues shall also be concerned for the exposure of workers, the disposal of activated components and the decommissioning of accelerator.

6.2 Prompt radiation sources

6.2.1 Secondary neutron

In the proton therapeutic energy range, neutrons are basically produced in two processes. Intra-nuclear cascade occurs when protons interact with individual nucleons inside the nucleus, which generate "forward-peaked" neutrons known as cascade neutrons. The maximum energy of cascade neutrons is up to the initial protons. On the other hand, after interaction with the incoming hadron, the excited nucleus will de-excite by emitting particles, mainly neutrons and protons with relatively lower energies. In this process, the emitted neutrons peaked at ~2 MeV are called evaporation neutrons and have an isotropic spatial distribution^[6]. Meanwhile, neutrons are also moderated to thermal energy during the transmission through shielding barrier. As a result, secondary neutrons have a wide energy span from thermal to fast neutrons and up to the full incident proton energy.

6.2.2 Photon radiation

Photon radiation mainly consists of the prompt gamma radiation from the interaction of neutrons or ions with matter; Meanwhile, degraded neutrons might undergo capture reactions in the shielding, giving rise to neutron-capture gamma rays.

6.3 Radiation during shut down

When the accelerator is shut down, the radiation comes from activation instead of prompt radiation sources. More details can be found in [D.2](#).