Proton Facility Shielding Design

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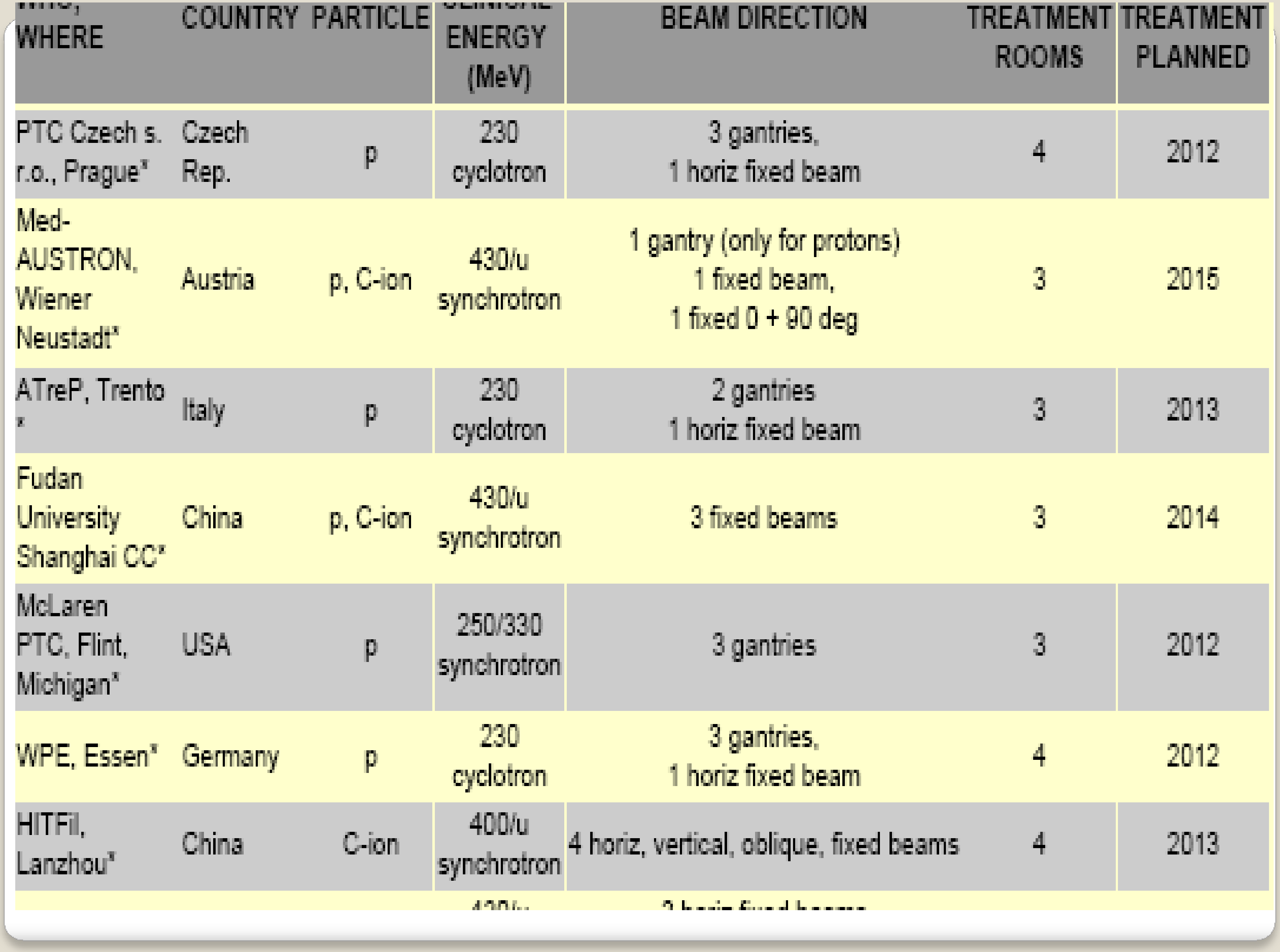
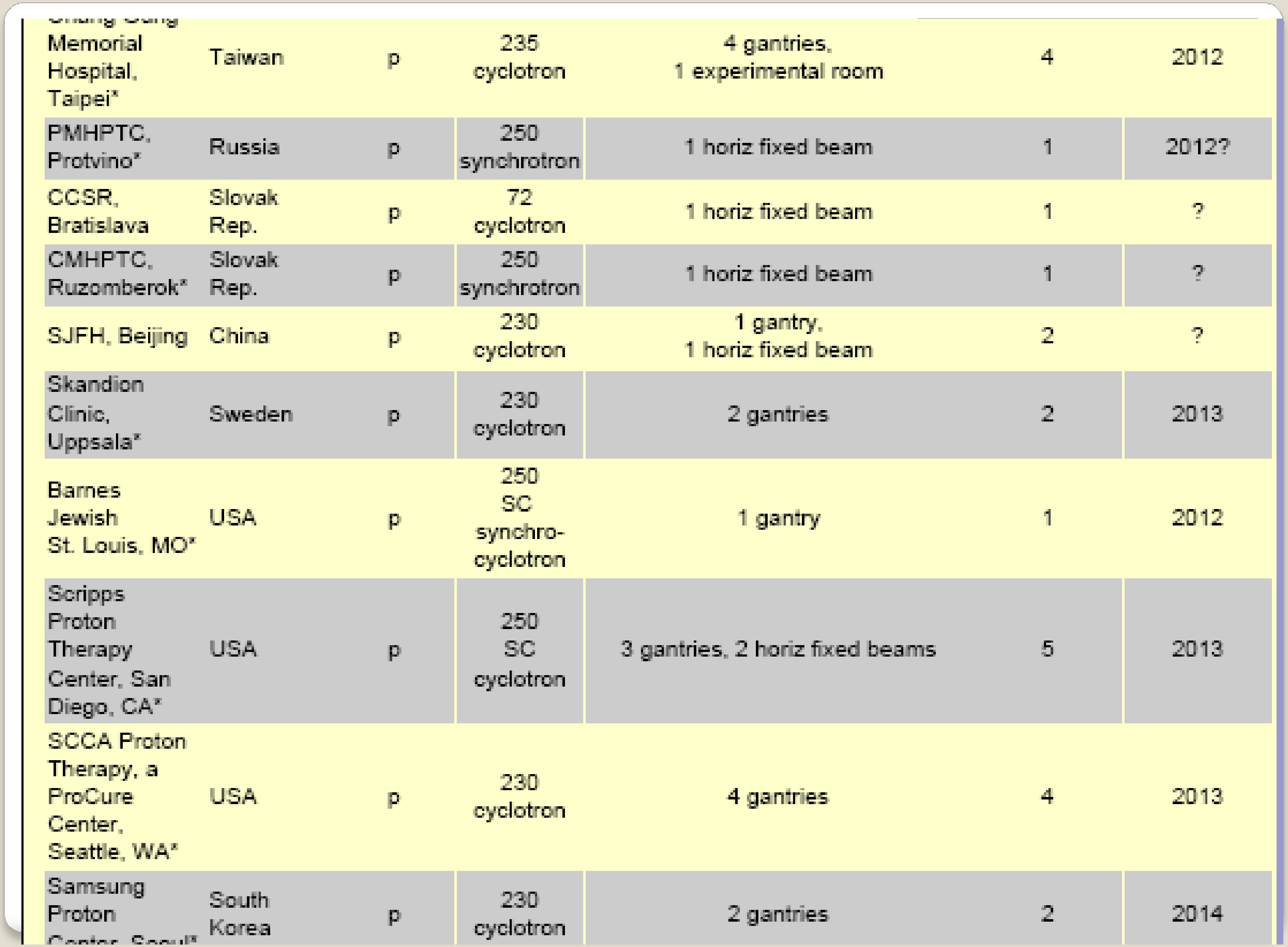
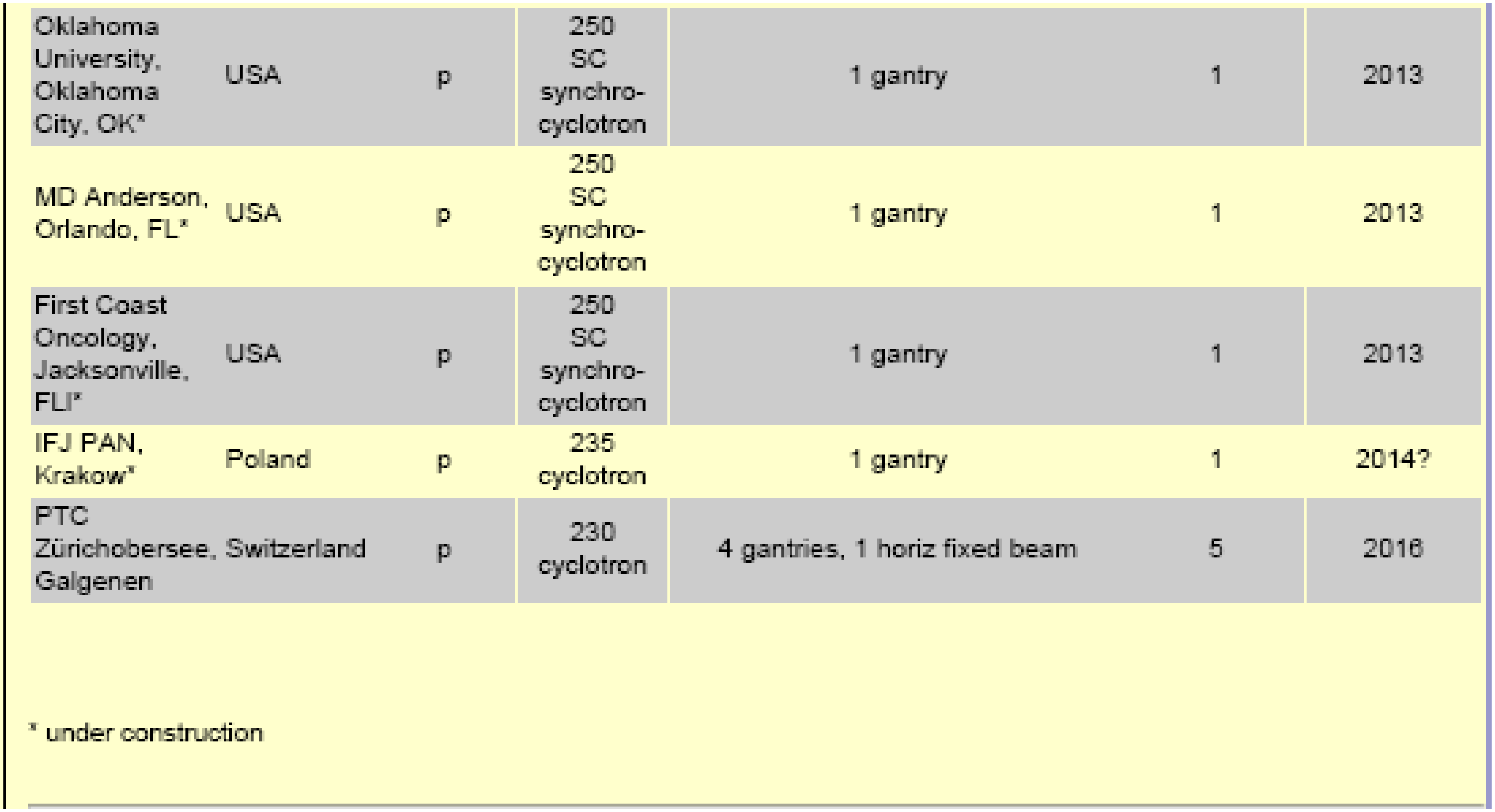
- Particle Therapy Facilities in the Planning Stage or under Construction



WHO, WHERE	COUNTRY	PARTICLE	CLINICAL ENERGY (MeV)	BEAM DIRECTION	TREATMENT ROOMS	TREATMENT PLANNED
PTC Czech s. r.o., Prague*	Czech Rep.	p	230 cyclotron	3 gantries, 1 horiz fixed beam	4	2012
Med-AUSTRON, Wiener Neustadt*	Austria	p, C-ion	430/u synchrotron	1 gantry (only for protons) 1 fixed beam, 1 fixed 0 + 90 deg	3	2015
ATreP, Trento *	Italy	p	230 cyclotron	2 gantries 1 horiz fixed beam	3	2013
Fudan University Shanghai CC*	China	p, C-ion	430/u synchrotron	3 fixed beams	3	2014
McLaren PTC, Flint, Michigan*	USA	p	250/330 synchrotron	3 gantries	3	2012
WPE, Essen*	Germany	p	230 cyclotron	3 gantries, 1 horiz fixed beam	4	2012
HITFil, Lanzhou*	China	C-ion	400/u synchrotron	4 horiz, vertical, oblique, fixed beams	4	2013
			430/u	2 horiz fixed beams		



Chang Gung Memorial Hospital, Taipei*	Taiwan	p	235 cyclotron	4 gantries, 1 experimental room	4	2012
PMHPTC, Protvino*	Russia	p	250 synchrotron	1 horiz fixed beam	1	2012?
CCSR, Bratislava	Slovak Rep.	p	72 cyclotron	1 horiz fixed beam	1	?
CMHPTC, Ruzomberok*	Slovak Rep.	p	250 synchrotron	1 horiz fixed beam	1	?
SJFH, Beijing	China	p	230 cyclotron	1 gantry, 1 horiz fixed beam	2	?
Skandion Clinic, Uppsala*	Sweden	p	230 cyclotron	2 gantries	2	2013
Barnes Jewish St. Louis, MO*	USA	p	250 SC synchro-cyclotron	1 gantry	1	2012
Scripps Proton Therapy Center, San Diego, CA*	USA	p	250 SC cyclotron	3 gantries, 2 horiz fixed beams	5	2013
SCCA Proton Therapy, a ProCure Center, Seattle, WA*	USA	p	230 cyclotron	4 gantries	4	2013
Samsung Proton Center, Seoul*	South Korea	p	230 cyclotron	2 gantries	2	2014



Oklahoma University, Oklahoma City, OK*	USA	p	250 SC synchro-cyclotron	1 gantry	1	2013
MD Anderson, Orlando, FL*	USA	p	250 SC synchro-cyclotron	1 gantry	1	2013
First Coast Oncology, Jacksonville, FLI*	USA	p	250 SC synchro-cyclotron	1 gantry	1	2013
IFJ PAN, Krakow*	Poland	p	235 cyclotron	1 gantry	1	2014?
PTC Zürichobersee, Galgenen	Switzerland	p	230 cyclotron	4 gantries, 1 horiz fixed beam	5	2016

* under construction

Updated August 2012

Reference for Information

- PTCOG Report # 1: Published 2010

"Shielding Design and Radiation Safety of Charged Particle Therapy Facilities"

Nisy Ipe, Ph.D., Task Group Leader
6 additional authors

PTCOG=Particle Therapy Co-Operative Group http://ptcog.web.psi.ch.

Charged Particle Therapy Facilities

- Protons
- Various Ions
  - Carbon
  - Lithium
  - Nitrogen
  - Neon
  - Helium
  - Boron
  - Oxygen
  - Argon
- Particle energies required to penetrate 30 cm or more of human tissue
- Report focuses on Protons and Carbon Ions

Typical Large Proton Therapy Facility Components

- Injector
- Cyclotron or Synchrotron to accelerate the particles
- High Energy Beam Transport Line
- Several Treatment Rooms
  - Fixed Beam Room
  - 360 degree Gantry Rooms
  - Research Area

Single Room Therapy Systems

- Mevion (Still River System) and other vendors
- Synchrocyclotron integrated into therapy treatment room
- Single room systems with accelerator room outside treatment room allowing for future expansion with additional rooms

Areas Requiring Shielding

- Secondary radiation is produced at locations where beam losses occur during operation of the facility
- Locations:

  In the Cyclotron or Synchrotron along the beam line during injection, acceleration, extraction, energy degradation, and transport of the beam particles in the beam line to the treatment room

Typical Dose Rates

- 1 to 2 Gy/minute for up to 30 x 30 cm fields for general treatments

- Special Beam Lines devoted to Eye Treatments of with less than 3 cm diameter run at dose rates of 15 to 20 Gy/minute

Processes/Locations Affecting Sheilding Calculations

- Beam shaping devices in the treatment nozzle
- Proton Beam Interactions in the Patient, Beam Stop, or Dosimetry Phantom

- Therefore, the ENTIRE FACILITY requires shielding

Types of Radiation Produced

- Interaction of Protons with matter results in “Prompt” and “Residual” Radiation
- “Prompt” radiation persists only while the beam is present (on)
- “Residual” radiation from activation continues after the beam is shut off

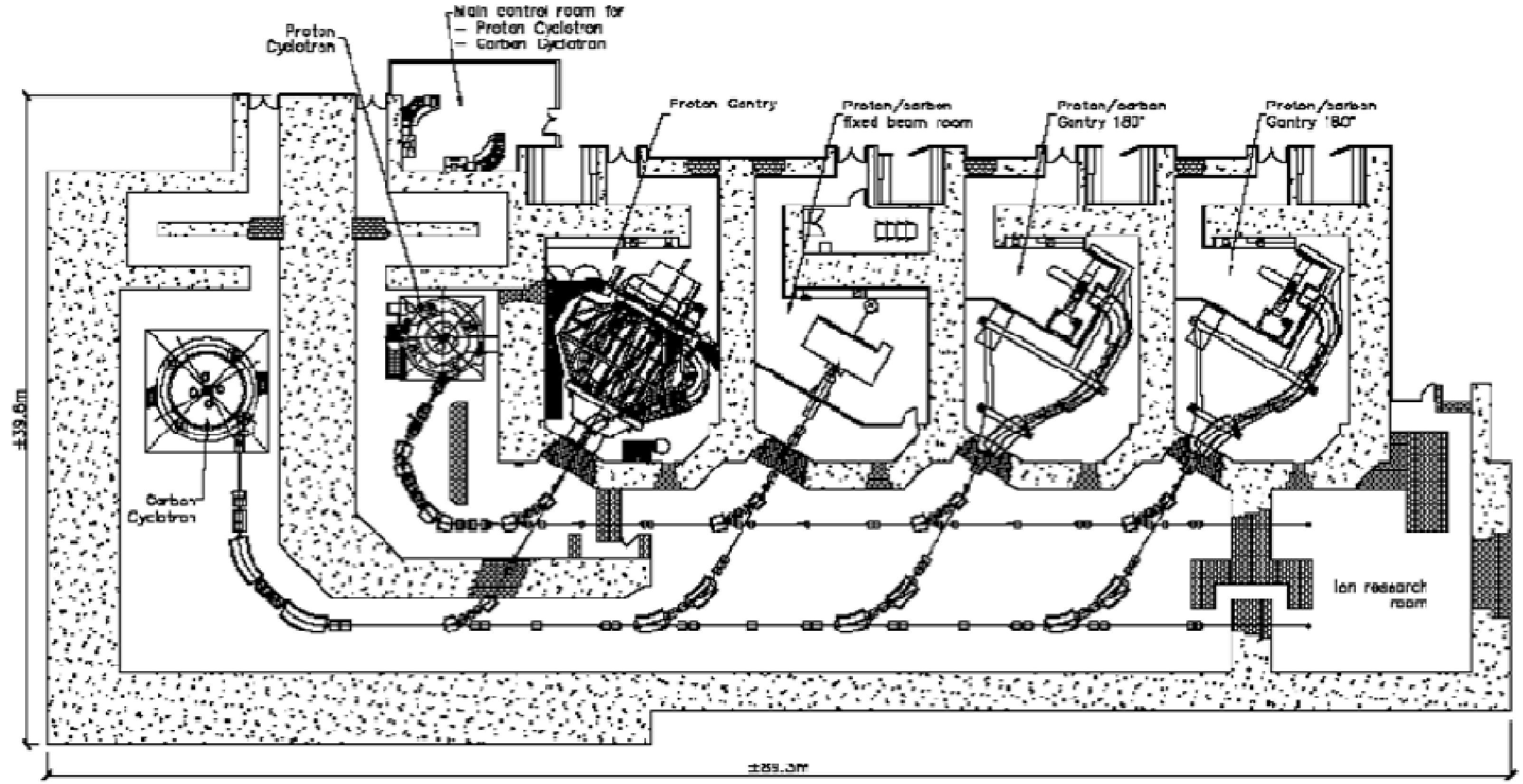
- For Proton Therapy Facilities, NEUTRONS dominate the prompt radiation dose outside the shielding

Proton Energies

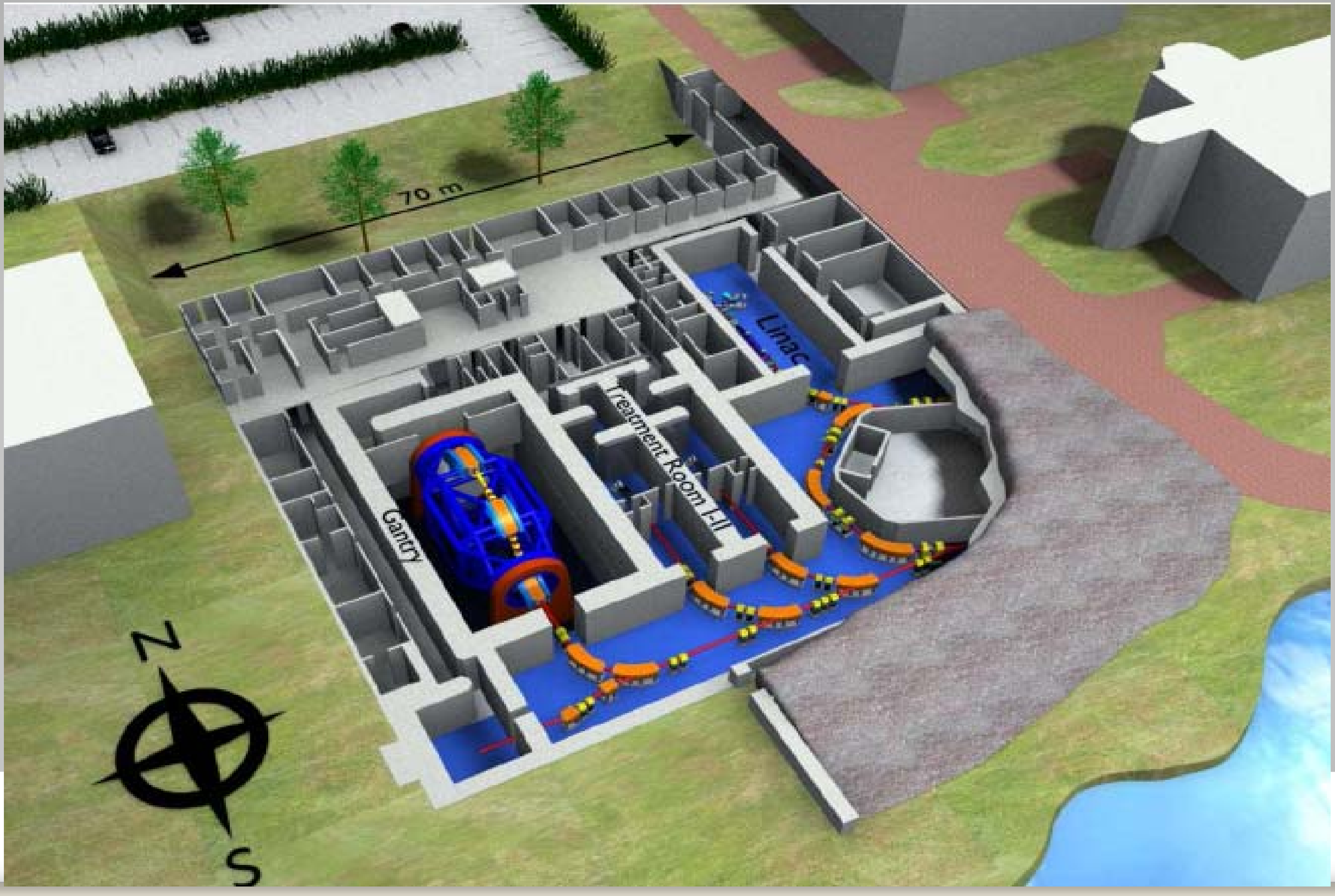
- Proton Energies in Therapy Facilities typically range from 230 to 250 MeV

- Neutron Energies extend to the maximum energy of the incident Proton

Cyclotron Based Proton/Carbon Ion Therapy Facility



Synchrotron Based Particle Therapy Facility



Radiation Fields Produced by Proton Therapy Beams

- When Protons react with matter, a spray of particles is produced in which the neutrons have energies as high as the initial proton energy.

- High energy neutron component (>100 MeV) propagates neutrons throughout the shielding and continuously regenerates lower energy neutrons and charged particles at all depths within the shield through reactions with the shielding material.

Neutron Energy Distribution

- Two Components
- # 1 - High Energy Neutrons produced by the cascade of particles which are forward peaked

- # 2 - Evaporation Neutrons with energy peaked at approximately 2 MeV which are isotropic and generated at the outer surface of the shielding material

Neutron Production

- Yield of High Energy (>100 MeV) neutrons in the primary collision of the protons with the target material determines the magnitude of the prompt radiation field outside the shield for intermediate-energy protons.
- High Energy Neutrons are anisotropic and forward peaked.

Neutron Production

- In the Therapeutic Energy Range of Interest, the charged particles produced by the protons will be absorbed in the shielding sufficiently thick to absorb neutrons.
- Therefore, NEUTRONS dominate the radiation field outside the shielding.
- Degraded neutrons may under go capture reactions in the shielding giving rise to capture neutron-capture gamma rays.

Goals of Shielding Design

- Attenuate secondary radiation to levels that are within regulatory and design limits for individual exposure and to protect equipment from radiation damage

- Provide this shielding at a reasonable cost and without compromising the use of the treatment unit for its intended purpose

Factors Affecting Shielding Design

- Accelerator type, Particle type, and Maximum Energy
- Beam Losses and Targets
- Beam-On Time
- Beam Shaping and Delivery
- Regulatory and Design Limits
- Workload: Number of Patients to be Treated, Energies for Treatment, Field Sizes, Dose per Treatment
- Use Factors
- Occupancy Factors

Methods for Shielding Design

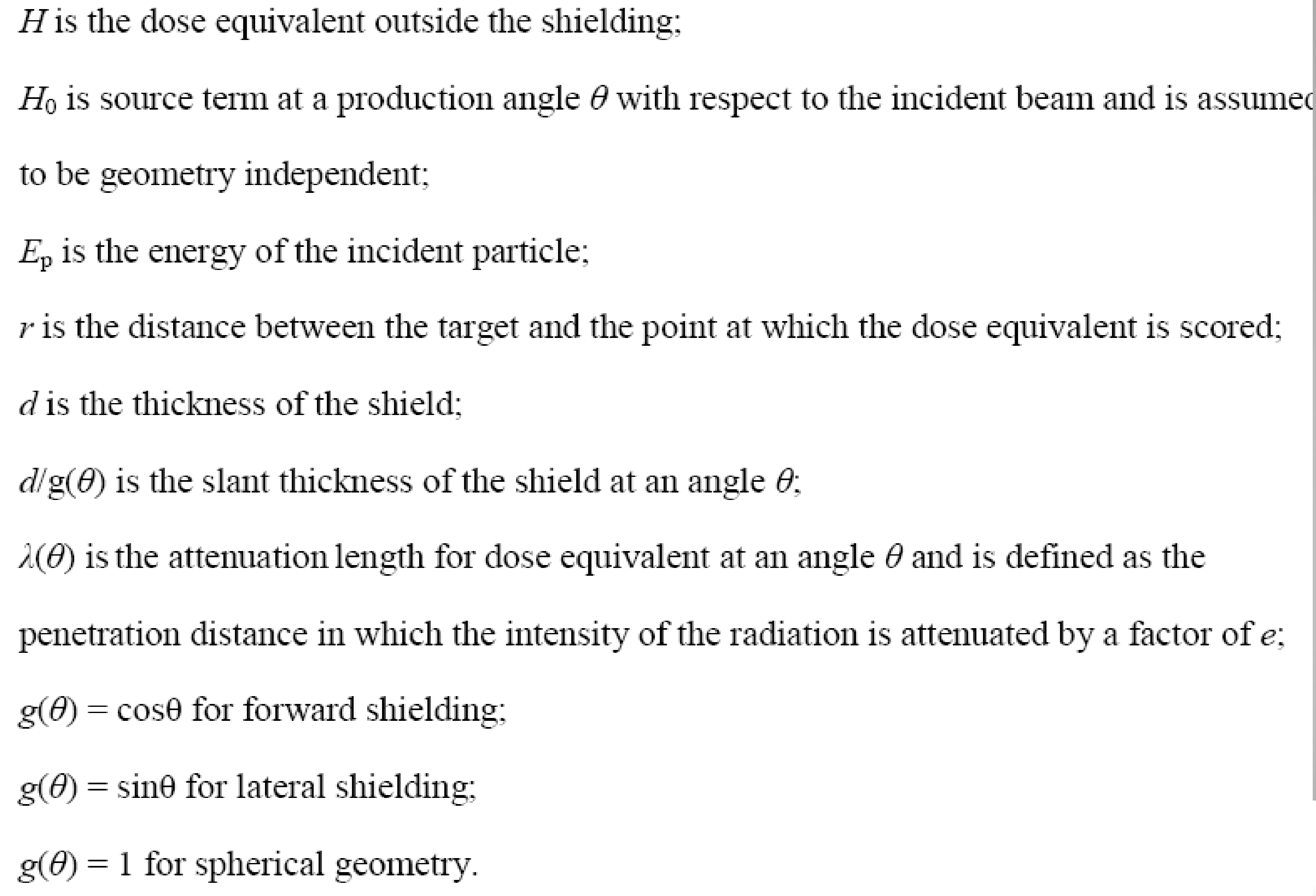
- Computer Codes for detailed spatial distributions of dose equivalent outside the shielding

- Shielding estimates using the Point Source Equation which uses Inverse Square Law and an Exponential Attenuation through the shield and is independent of geometry

Point Source Equation

$$H(E_{\mathrm{p}}, \theta, d/\lambda(\theta)) = \frac{H_0(E_{\mathrm{p}}, \theta)}{r^2} \exp\left[-\frac{d}{\lambda(\theta)\mathrm{g}(\theta)}\right]$$

Point Source Equation Components



H is the dose equivalent outside the shielding;

H_0 is source term at a production angle θ with respect to the incident beam and is assumed to be geometry independent;

E_p is the energy of the incident particle;

r is the distance between the target and the point at which the dose equivalent is scored;

d is the thickness of the shield;

$d/\mathrm{g}(\theta)$ is the slant thickness of the shield at an angle θ;

$\lambda(\theta)$ is the attenuation length for dose equivalent at an angle θ and is defined as the penetration distance in which the intensity of the radiation is attenuated by a factor of e;

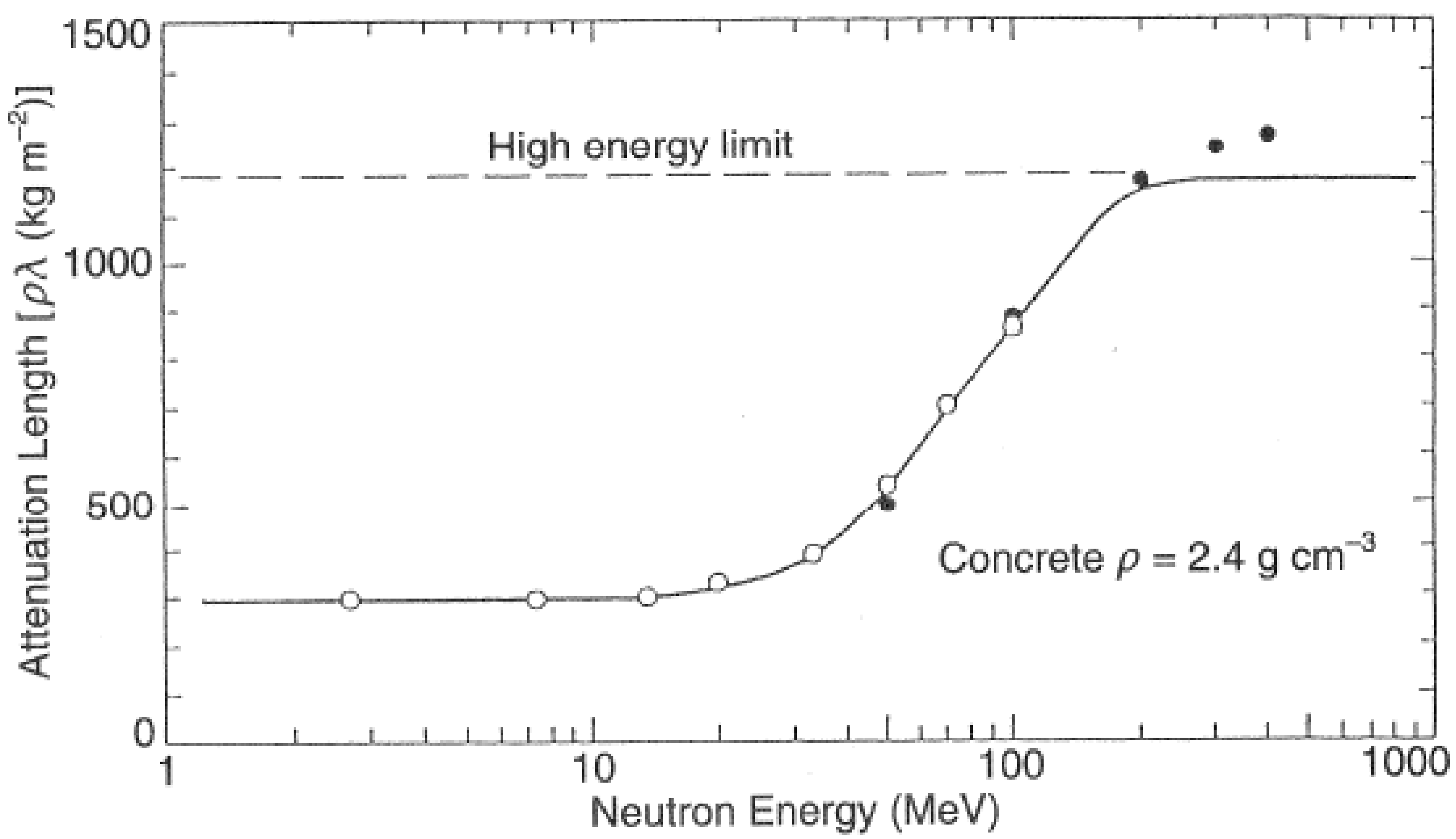
$g(\theta) = \cos\theta$ for forward shielding;

$g(\theta) = \sin\theta$ for lateral shielding;

$g(\theta) = 1$ for spherical geometry.

Attenuation in Concrete

- Attenuation length changes with increasing depth in the shield because the “softer” radiations are more easily attenuated and the neutron spectrum hardens.
- The following figure shows the variation of attenuation length for monoenergetic neutrons in concrete as a function of energy



Attenuation Length Increases with Increasing Neutron Energies >20 MeV

Shielding Materials

- Attenuation length of neutrons in the shielding material determines the thickness of the shielding required to reduce the dose to acceptable levels.

- Shielding for neutrons must be such that sufficient material is interposed between the source and the point of interest that neutrons of all energies are sufficiently attenuated.

Shielding Materials

- Dense material of high atomic number such as steel meets the first criterion
- Hydrogen meets the second criterion because of effective attenuation by elastic scattering
- However, steel is transparent to neutrons with energies of 0.2 to 0.3 MeV
- Therefore, a layer of hydrogenous material must always follow the steel

Shielding Materials

- Alternatively, large thicknesses of concrete or concrete with high-Z aggregates can be used in proton facilities to provide required shielding

Protection and Operational Dose Quantities

- Interaction of radiation with matter is a series of events in which the particle energy is dissipated and finally deposited in matter.

- Shielding calculations and radiation monitoring are performed to ensure adequate radiation protection

Protection and Operational Dose Quantities

- Shielding calculations are performed to ensure that the facility is designed so that exposures of personnel and the public are within regulatory limits.

- Radiation monitoring is performed to demonstrate compliance with design and/or regulatory limits.

Protection and Operational Dose Quantities

- Calculations and Measurements must be expressed in terms of quantities in which limits are defined.
- The International Commission on Radiological Protection (ICRP) defines dose limits. (US = NCRP)
- Compliance with these limits MUST be demonstrated by MEASUREMENT

Protection and Operational Dose Quantities

- ICRP Report # 60 (1991) recommended the use of the terms:

  Dose Equivalent (H_T)

  and Effective Dose (E)

  for protection quantities

Equivalent Dose

- Equivalent Dose, H_T, is the mean absorbed dose in the tissue or organ multiplied by the corresponding radiation weighting factor. The weighting factor for neutrons varies with energy.

- The unit of Equivalent Dose is the Sievert (Sv)

Charged Particle Interactions

- The interaction of charged particles with matter results in the production of different types of radiation.
- The yield (number of secondary particles emitted per incident primary particle) and types of secondary radiation generally increase with increased kinetic energy of the incident particle.

Proton Interactions

- Interactions of proton with matter result in the degradation of the energy of the protons and the production of a cascade of secondary particles known as a nuclear cascade.
- The extra-nuclear cascade is followed by an intra-nuclear cascade which occurs at proton energies between 50 MeV and 1000 MeV.

Proton Interactions

- The intra-nuclear cascade is of importance in proton shielding design in the proton energy range of interest (67 to 250 MeV)
- The yield of low-energy neutrons increases as the primary proton energy increases. However, the greater yield is more than compensated for by greater attenuation in the shield due to a higher cross-section at lower energies.

Neutron Spectrum at Shield

- The neutron spectrum observed at the surface of a shield is very similar to that which exists in the shield.
- The presence of holes or penetrations in a shield may perturb the shape of the neutron spectrum.
- Increased number of low-energy neutrons in the vicinity of penetrations.
- Typical neutron spectrum outside a thick shield peak at a few MeV and 100 MeV

Photon Production

- Photons are produced by inelastic neutron scattering and neutron capture by hydrogen within the concrete wall
- Contribution of dose from photons produced in the shield is important only for primary neutrons with energies below 25 MeV and for thick concrete shields.
- Total photon dose is much lower than the neutron dose for proton energies higher than 150 MeV and a thick concrete shield

Proton Interactions

- Energy loss at the lower proton energy is mainly due to ionization of the material in which the protons are stopped.
- The lowest-energy proton produces the greatest ionization resulting in the Bragg peak at the end of the proton range.
- This property is exploited in proton therapy.

Secondary Radiation Environment

- The secondary radiation environment for proton therapy facilities consist of:
  - Neutrons
  - Prompt gamma radiation from the interaction of neutrons with matter
  - Characteristic x-rays
  - Bremsstrahlung radiation
  - Residual radiation from radioactivation of materials in the treatment areas

Radiation Field for Proton Accelerators

- Neutrons dominate the prompt radiation field for proton accelerators outside the shielding.
- Radiation dose outside the shielding depends on energy and type of incident particle, beam-on time, target material and dimensions, and the shielding itself.

Neutron Energy Classifications

- For radiation protection purposes, neutrons are classified as follows:

Thermal:	$E_n < 0.5$ eV
Intermediate:	0.5 eV $<E_n<$ 10 KeV
Fast:	10 KeV $<E_n<$ 20 MeV
High Energy:	$>$ 20 MeV

where E_n is the energy of the neutrons

Neutron Interactions

- Because neutrons are uncharged, they can travel significant distances in matter without undergoing interactions
- When a neutron collides with an atom, it can undergo an elastic (maintains its energy) or inelastic (transfers some of its energy) collision.
- The neutron can also be captured or absorbed by the nucleus in reactions

Thermal Neutrons

- Thermal neutrons are in approximate thermal equilibrium with their surroundings and gain/lose only small amounts of energy through elastic scattering.
- They diffuse about until captured by atomic nuclei.
- Thermal neutrons undergo neutron absorption followed by the immediate emission of a 2.22 MeV.

Thermal Neutrons

- The capture cross section is 0.33 x 10^{-24} cm^2
- The capture cross sections for low energy neutrons decrease as the neutron energy increases
- This reaction occurs in shielding materials such as polyethylene and concrete
- Borated polyethylene is used because the cross section for capture in boron is much higher (3480 x $10^{-24}$$cm^2$ and the resulting capture gamma ray is much lower energy (0.48 MeV)

Intermediate Energy Neutrons

- Intermediate energy neutrons lose energy by scattering and are absorbed

Fast Neutrons

- Fast neutrons interact with matter through a series of elastic and inelastic scattering and are finally absorbed after giving up their energy

- On the average, approximately 7 MeV is given up to gamma rays during the slowing down and capture process

- Above 10 MeV, inelastic scattering is the dominant process in all materials

Fast Neutrons

- Below 1 MeV, elastic scattering is the principle process by which neutrons interact with hydrogenous materials such as concrete and polyethylene
- When a high-Z material such as steel is used for shielding, it must ALWAYS be followed by hydrogenous material because the energy of the neutrons may be reduced by inelastic scattering to an energy where they may be transparent to the non-hydrogenous material.
- For example, steel is transparent to neutrons of 0.2 to 0.3 MeV

Relativistic (High Energy) Neutrons

- Relativistic neutrons arise from cascade processes in the proton accelerators and are important in propagating the radiation field.
- This high-energy component (>100 MeV) propagates the neutrons throughout the shielding and continuously regenerates lower-energy neutrons and charged particles at all depths in the shield via inelastic reactions with the shielding material.

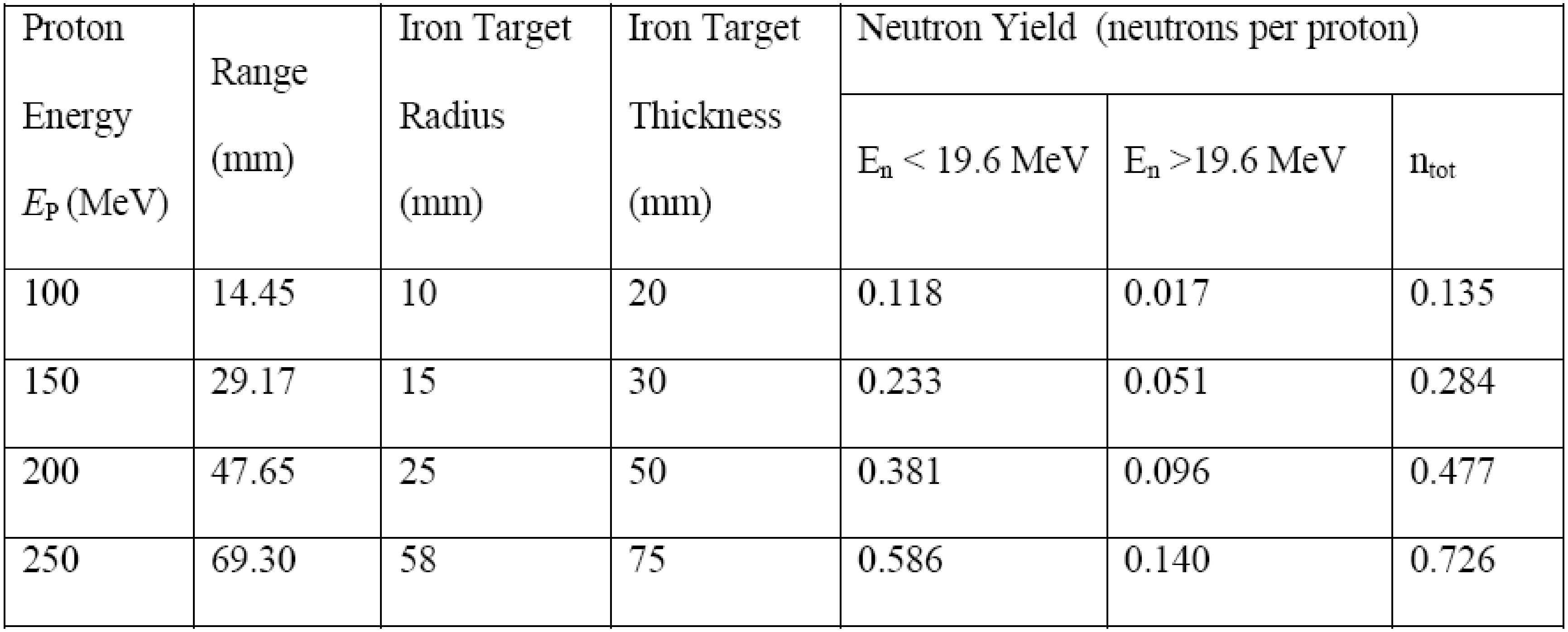
Targets - Proton Yields

- The neutron yield of a target is defined as the number of neutrons emitted per incident primary particle
- Neutron yield increases with increasing proton energy
- Following slide shows the neutron yield from 100 to 250 MeV protons impinging on a thick iron target

Targets-Proton Yields

- Thick targets are targets in which the protons are stopped (thickness is greater than or equal to particle range
- Thin targets are targets that are significantly less thick than the particle range. Protons lose an insignificant amount of energy in the target

Neutron Yields for 100 to 250 MeV Protons on a Thick Iron Target

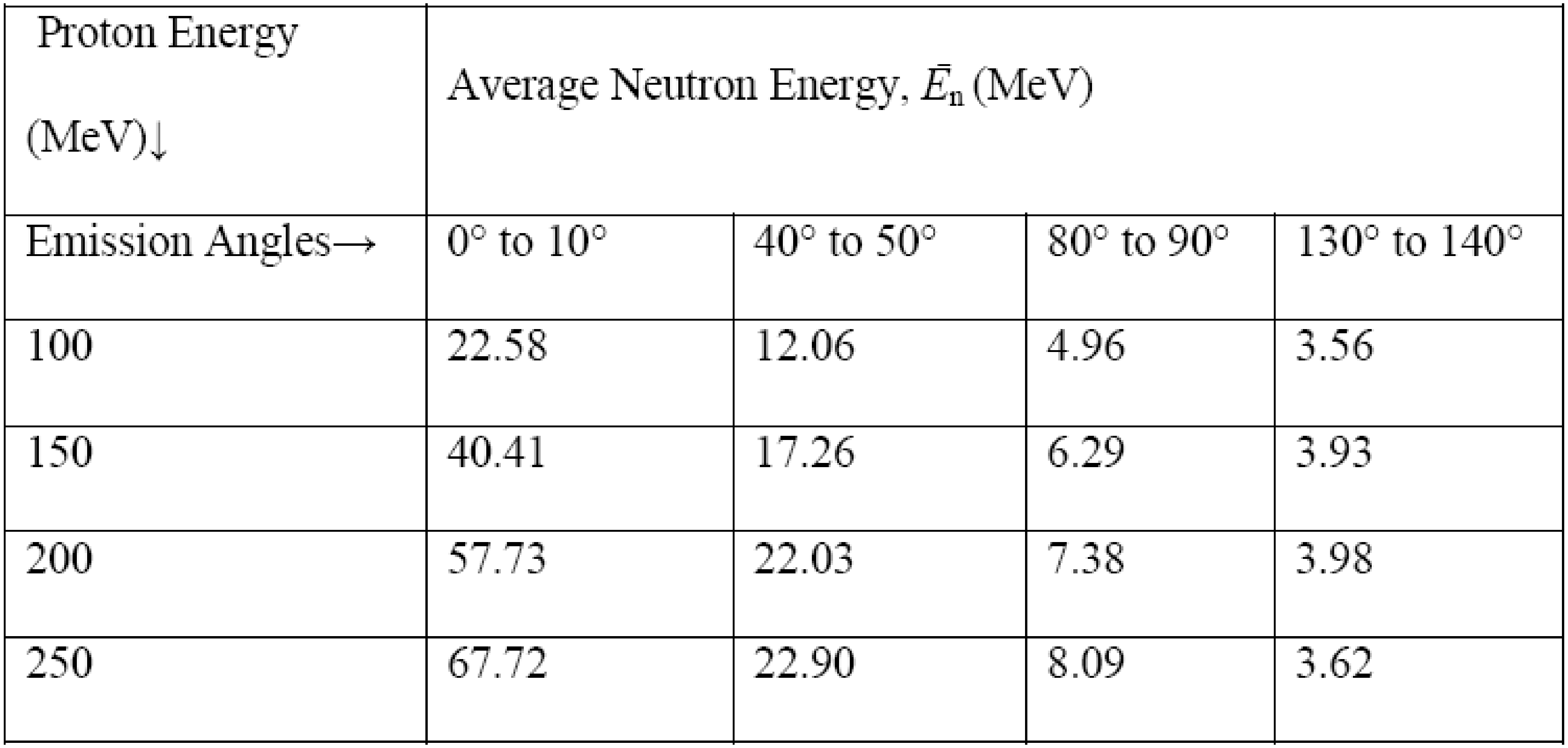


Proton Energy E_P (MeV)	Range (mm)	Iron Target Radius (mm)	Iron Target Thickness (mm)	Neutron Yield (neutrons per proton)		
				$E_n < 19.6$ MeV	$E_n > 19.6$ MeV	n_{tot}
100	14.45	10	20	0.118	0.017	0.135
150	29.17	15	30	0.233	0.051	0.284
200	47.65	25	50	0.381	0.096	0.477
250	69.30	58	75	0.586	0.140	0.726

Neutron Energies Per Emission Angle

- The average neutron energies are shown in the following slide.
- As the proton energy increases, the spectra in the forward direction hardens as is evidenced by the increasing average neutron energy
- For large angles (>130 degrees), the average energy does not change significantly with increasing proton energies

Average Neutron Energies for Various Emission Angles as a Function of Proton Energy



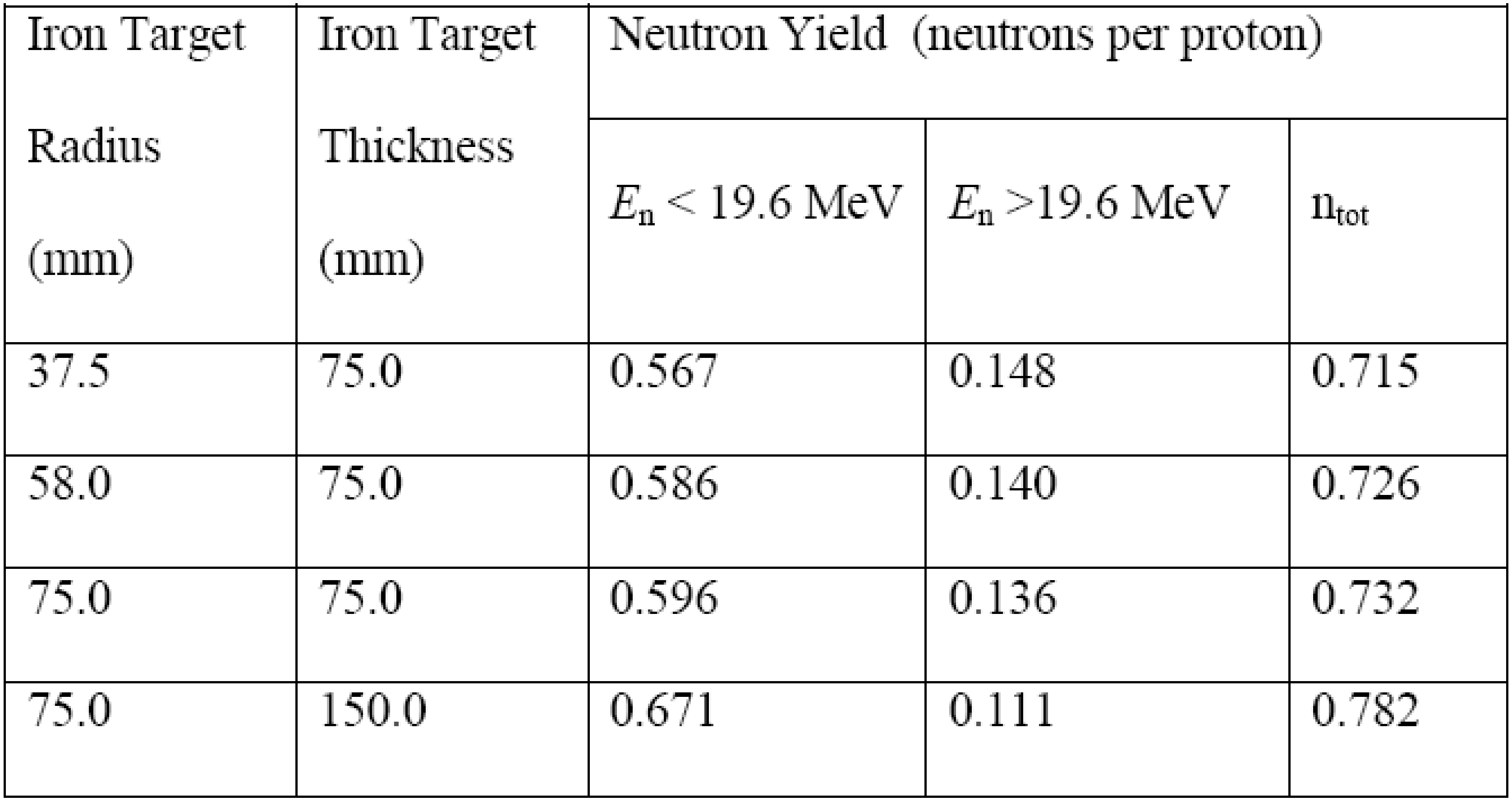
Proton Energy (MeV)↓	Average Neutron Energy, $\bar{E}_n$ (MeV)			
Emission Angles→	0° to 10°	40° to 50°	80° to 90°	130° to 140°
100	22.58	12.06	4.96	3.56
150	40.41	17.26	6.29	3.93
200	57.73	22.03	7.38	3.98
250	67.72	22.90	8.09	3.62

Neutron Yield Relative to Targets

- As the target radius increases, the total neutron yield increases; however, the yield for E_n >19.6 MeV decreases

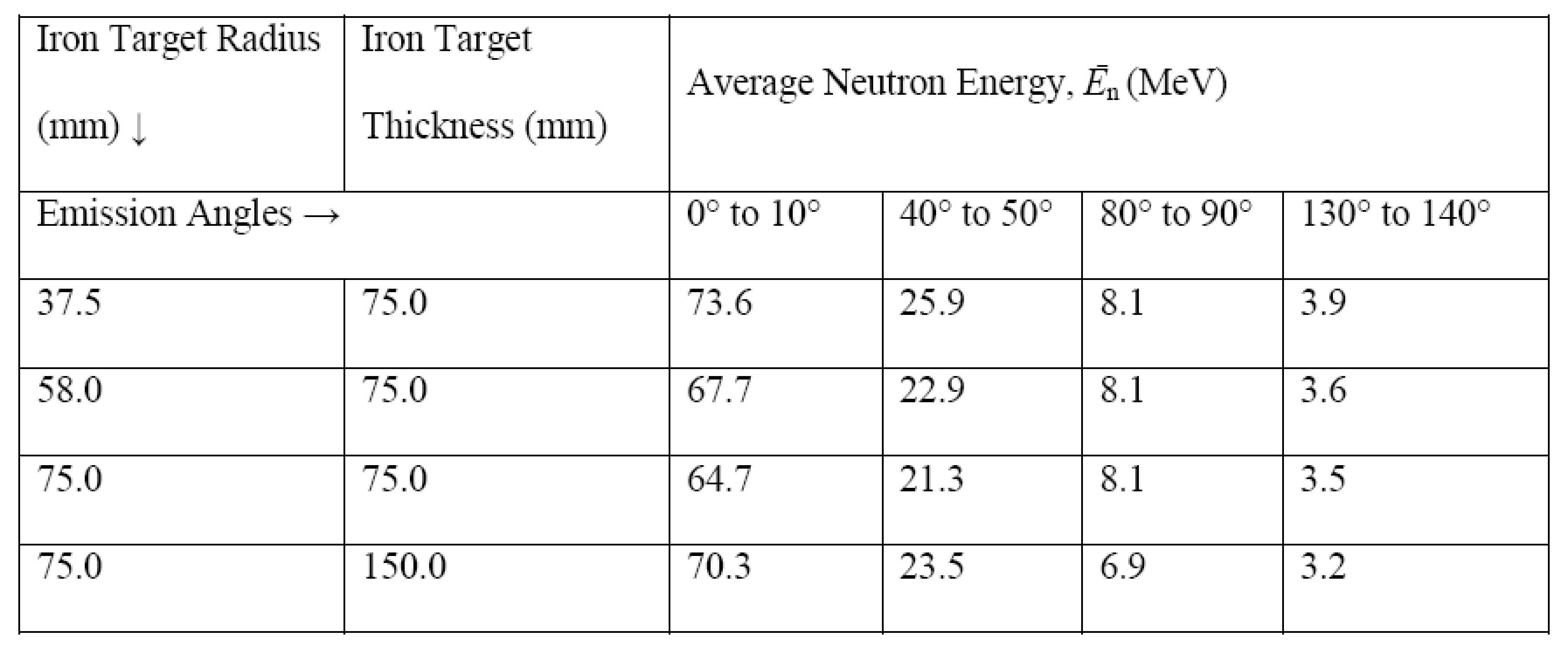
- As the target thickness increases, the proton interactions increase and the secondary neutron yield increases until it reaches a maximum

Neutron Yield for 250 MeV Protons as a Function of Iron Target Dimensions



Iron Target Radius (mm)	Iron Target Thickness (mm)	Neutron Yield (neutrons per proton)		
		$E_n < 19.6$ MeV	$E_n > 19.6$ MeV	n_{tot}
37.5	75.0	0.567	0.148	0.715
58.0	75.0	0.586	0.140	0.726
75.0	75.0	0.596	0.136	0.732
75.0	150.0	0.671	0.111	0.782

Average Neutron Energies at 250 MeV for Various Emission Anges



Iron Target Radius (mm) ↓	Iron Target Thickness (mm)	Average Neutron Energy, $\bar{E}_{\mathrm{n}}$ (MeV)			
Emission Angles →		0° to 10°	40° to 50°	80° to 90°	130° to 140°
37.5	75.0	73.6	25.9	8.1	3.9
58.0	75.0	67.7	22.9	8.1	3.6
75.0	75.0	64.7	21.3	8.1	3.5
75.0	150.0	70.3	23.5	6.9	3.2

Beam Losses and Sources of Radiation

- During operation of proton therapy facilities, the interaction of the particles with beam-line components and the patient results in the production of radiation with neutrons being the dominant component.
- Typical shielding thicknesses for various parts of the facility range from 60 cm to about 7 meters of concrete

Shielding Design Components

- Effective shielding can only be designed if the beam losses and sources of radiation for the facility are known.
- Specific details of beam losses, duration, frequency, targets and locations should be provided by the equipment vendor
- Note: Higher beam losses will occur during start-up and commissioning as the beam is tuned and delivered to the final destination and must be planned for

Cyclotrons

- Cyclotrons are used for proton and ion acceleration and essentially continuous beams.
- Fixed-energy machines are used for therapy and are designed to operate at energies required treat deep-seated tumors

Proton Cyclotron-Principle of Operation

- Protons are extracted from the ion source located at the center and are injected into the cyclotron.
- Cyclotron is comprised of a large magnet with an internal vacuum region located between the poles of the magnet
- Maximum radius of a commercial room-temperature therapy cyclotron is about 1 meter

Proton Cyclotron-Principle of Operation

- Large D-shaped electrodes commonly referred to as “dees”
- A sinusoidal-alternating voltage with a frequency equal to the revolution frequency of the protons is applied to the dees as the protons travel in their orbit
- As the protons cross a gap between the electrodes, they are accelerated and begin to spiral outwards
- The orbit radius is determined by the magnetic field

Inside View of IBA 230 Cyclotron

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Cyclotrons - Shielding Areas

- During acceleration, continuous beam losses occur in the cyclotron
- Depending upon the beam optics, about 20 to 50 percent of the accelerated protons can be lost in the cyclotron
- The magnet yoke is made of steel and provides significant self-shielding except in regions where there are holes in the yoke. These holes need to be considered in the shielding design.

Cyclotrons - Shielding Areas

- Beam losses of concern in the shielding design are those that occur at higher energies and those due to protons that are close to their extraction energy (230 to 250 MeV) striking the dees and the extraction septum which are made of copper.
- These beam losses result in activation of the cyclotron.

Energy Selection System

- For the treatment of tumors at shallow depths, the proton energy extracted from the cyclotron has to be lowered.

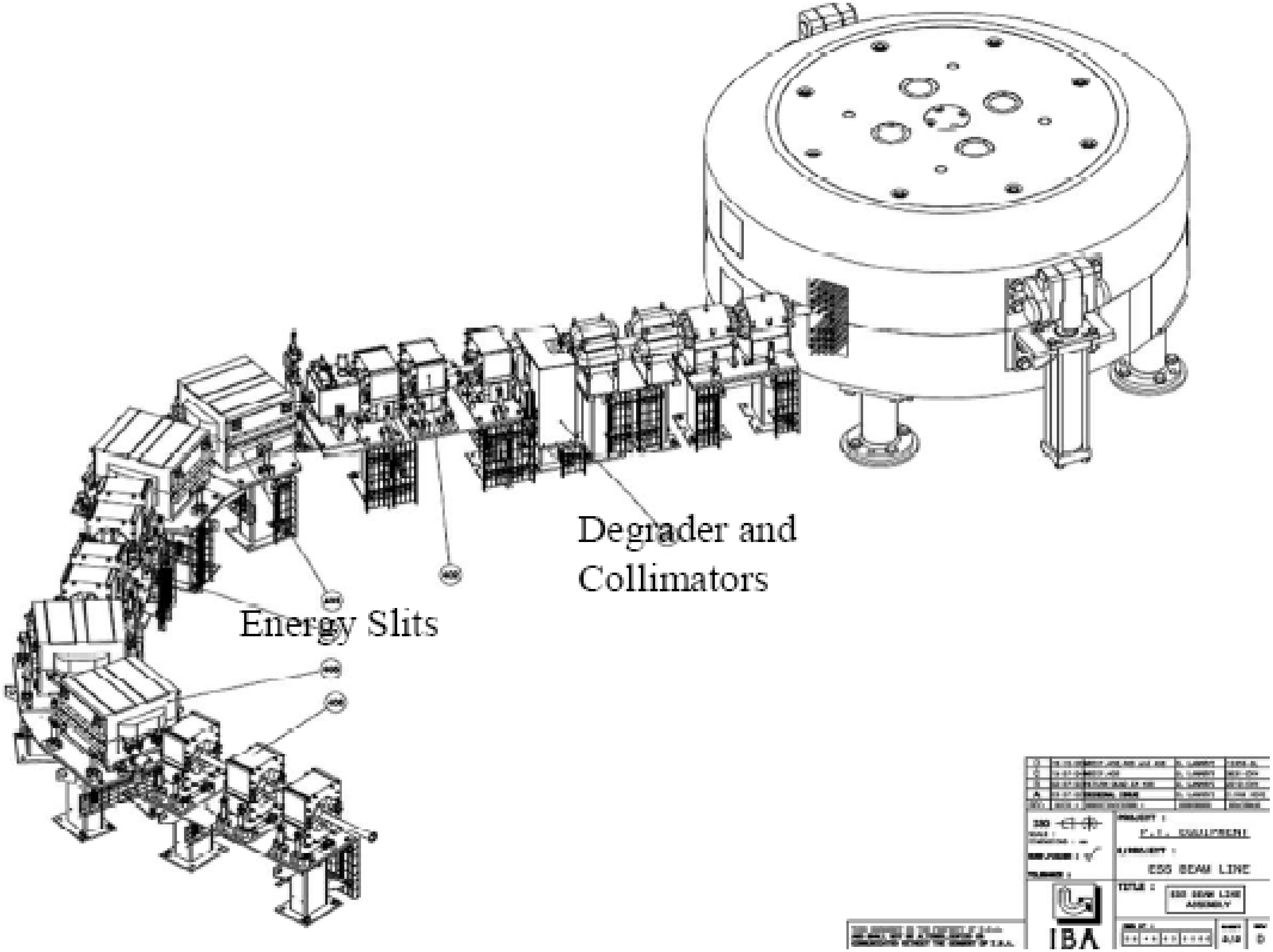
- Typically achieved by using an energy selection system (ESS) after extraction.

- The ESS is typically comprised of an energy degrader, a tantalum collimator, nickel energy slits and collimator, and a nickel beam stop.

Energy Degrader

- The energy degrader consists of a variable thickness material, typically graphite, arranged in a wheel that is rotated into position, thus reducing the proton energy down to the energy of interest.

- Sometimes, range shifters are used inside the nozzles in the treatment rooms to achieve these lower energies.



Degrader and Collimators

Energy Slits

Energy Selector Systems

- The intensity from the cyclotron has to be increased as the degraded energy is decreased in order to maintain the same dose rate to the patient.
- Large amounts of neutrons are produced in the degrader, especially at the lower energies, resulting in thicker local shielding requirements in this area.

ESS- Energy Degrader

- The degrader scatters the protons and increases the energy spread. Most of the scattered bean from the degrader is collimated in a tantalum collimator in order to reduce the beam emittance.

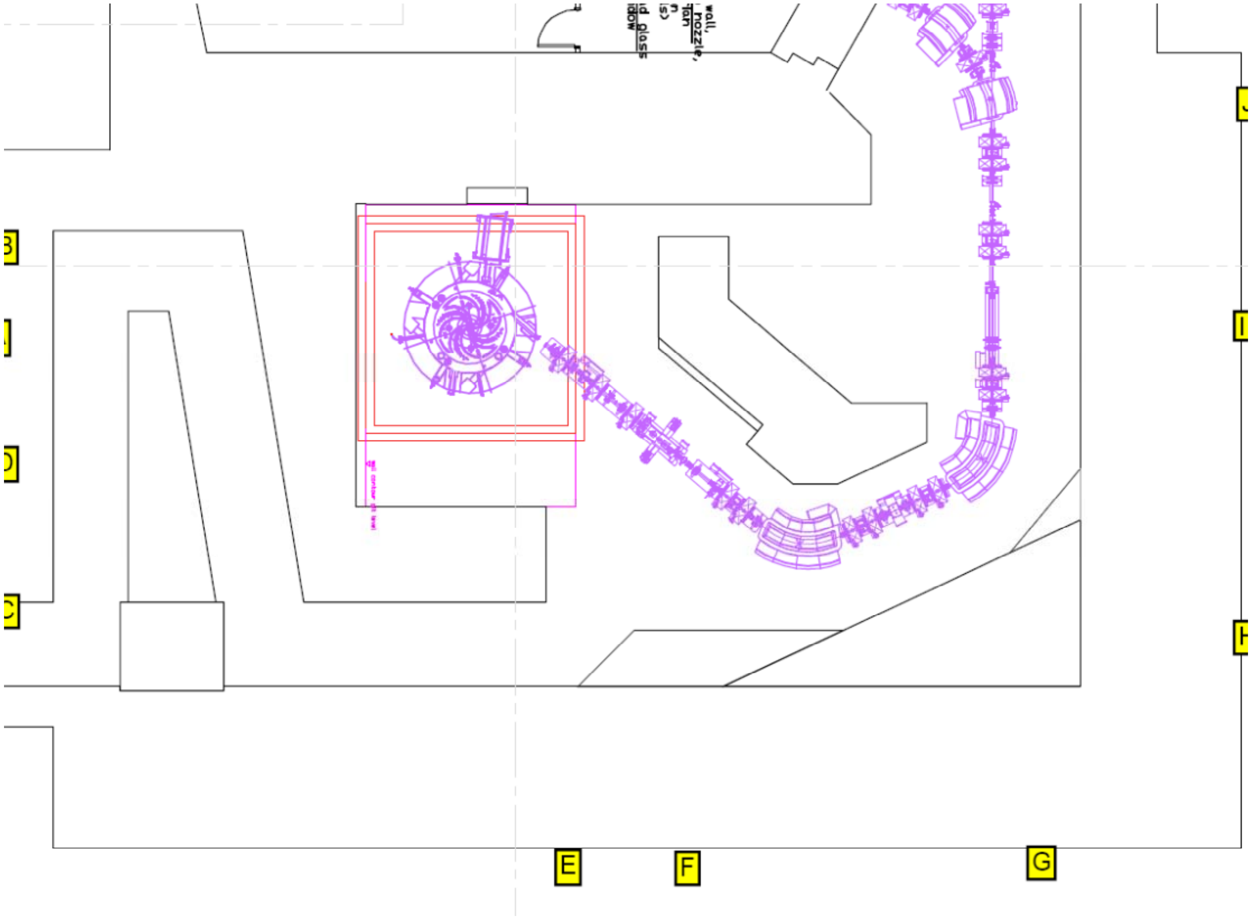
- A magnetic spectrometer and energy slits are used to reduce the energy spread.

- Beam stops are used to tune the beam.

Energy Selection System

- Neutrons are produced in the collimator and slits

- Losses in the ESS are LARGE and they also result in activation.



San Diego Proton Therapy Facility

ESS-Energy Selection System & Cyclotron

Synchrotrons

Synchrotrons are design to accelerate protons and ions to the exact energy needed for therapy; therefore, eliminating the need for energy degraders.

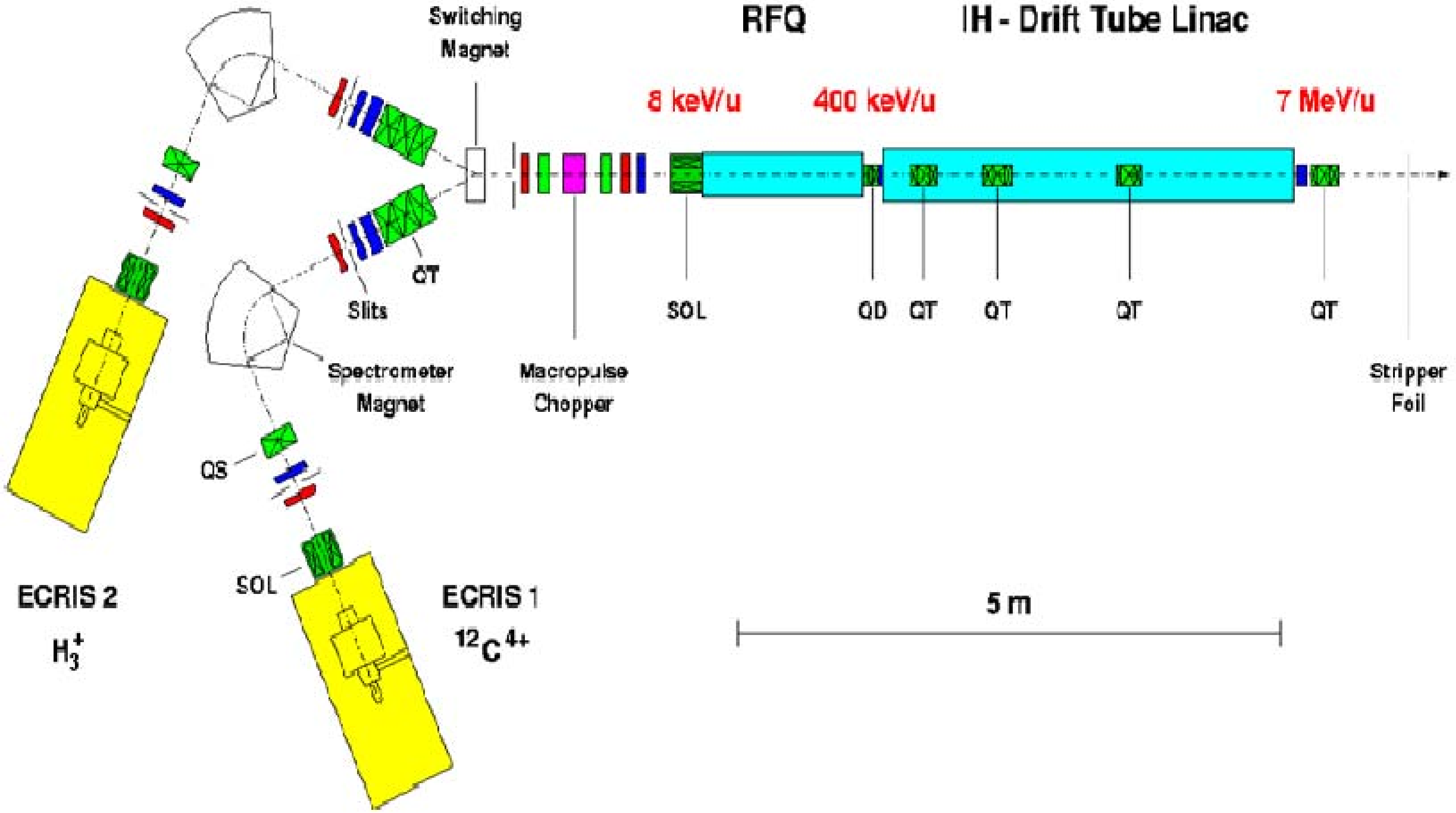
- This results in less local shielding and activation of beam-line components.
- Synchrotrons, however, are pulsed machines.

Synchrotrons

- For synchrotrons, the orbit radius is held constant and the magnetic field is increased as the particle energy increases

- Maximum proton energy for therapy is approximately 250 MeV with about 10^{11} protons per spill. A spill typically lasts from 1 to 10 seconds.

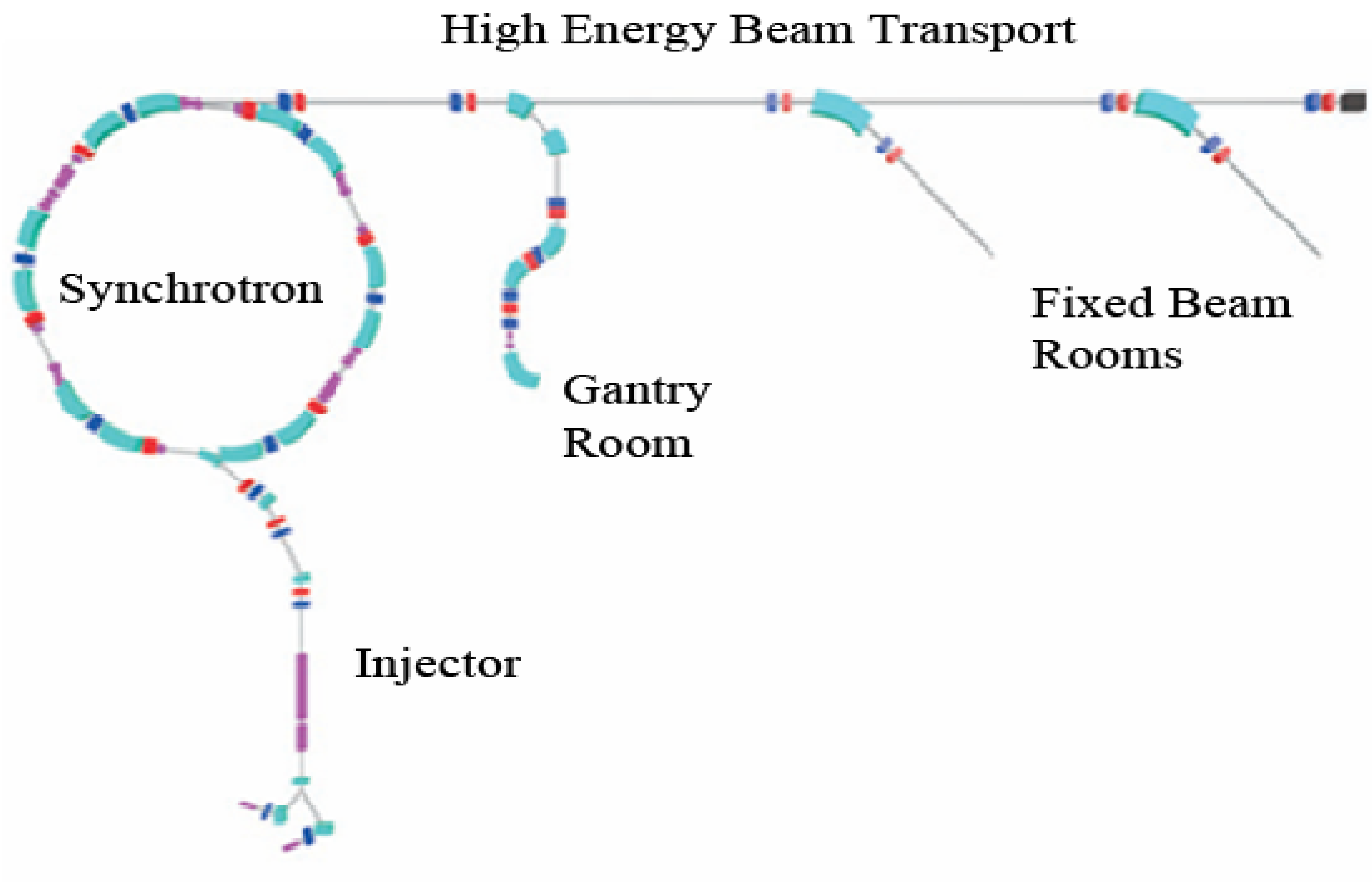
Typical Injector System for a Synchrotron



Synchrotrons

- Sources of radiation include x-rays from the ion source, x-rays produced by back-streaming electrons striking the linac structure, and neutrons produced the interaction of the ions with the linac structure at the end of the linac.
- The target material is typically copper or iron.
- The use of a Faraday cup to intercept the beam downstream of the linac must also be considered in the shielding design

Siemens Synchrotron, HEBT, and Transport to Therapy Rooms System



Synchrotrons - Shielding Considerations

- Beam losses can occur during the injection process, RF capture and acceleration, and during extraction.
- Losses will be machine specific and therefore the equipment vendor should supply this information.
- Particles that are not used in a spill may be deflected onto a beam dump or stopper and will need to be considered in the shielding design and activation analysis.

Beam Transport Line

- Losses occur in the beam transport line for both cyclotron and synchrotron systems.
- These losses are usually very low (<1%) and distributed along the beam line but do need to be considered in the shielding design.
- During operation, the beam is steered onto Faraday cups, beam stoppers, and beam dumps, all of which need to be considered in the shielding design.

Treatment Rooms

- The radiation produced from the beam impinging upon the patient (or phantom) is the dominant source for the treatment rooms.
- A thick-tissue target should be assumed for shielding calculations.
- Losses in the nozzle, beam-shaping and range-shifting devices must also be considered in addition to contributions from adjacent areas.

Treatment Rooms

- Typically, treatment rooms do not have shielded doors.

- Effectiveness of the maze design is critical

- Treatment rooms have either fixed beams or gantries.

Fixed Beam Rooms

- In fixed beam rooms, either a single horizontal fixed beam or dual (horizontal and vertical or oblique) beams are used.
- Shielding walls in the forward direction are much thicker than the lateral walls and the walls in the backward direction.
- The Use Factor is defined as the fraction of time that the primary proton beam is directed toward the barrier.

Fixed Beam Room with Two Beams

Fixed Beam Rooms

- For rooms with dual beams, the Use Factor for the wall in the Forward Direction must be considered for EACH BEAM. This may be 1/2 for each beam or 2/3 for one beam and 1/3 for the other.
- For a single beam room, the Use Factor for the wall in the Forward Direction is always 1.

Gantry Rooms

- In the gantry room, the beam is rotated about the patient.
- On average, it can be assumed that the Use Factor is 0.25 for each of the four primary barriers (two walls, floor and ceiling).
- Because of the lower use factor, the walls can be thinner than the forward wall in a Fixed Beam Room.

Single Room Systems

- Single Room synchrocyclotron-based systems are now commercially available (Mevion Systems)
- Maximum proton energy at the exit of the cyclotron is 250 MeV.
- The 250 MeV beam is scattered or spread in the treatment room by the field shaping system comprised of 1st and 2nd scatterers, energy degrader, and range modulator, which are located in the gantry

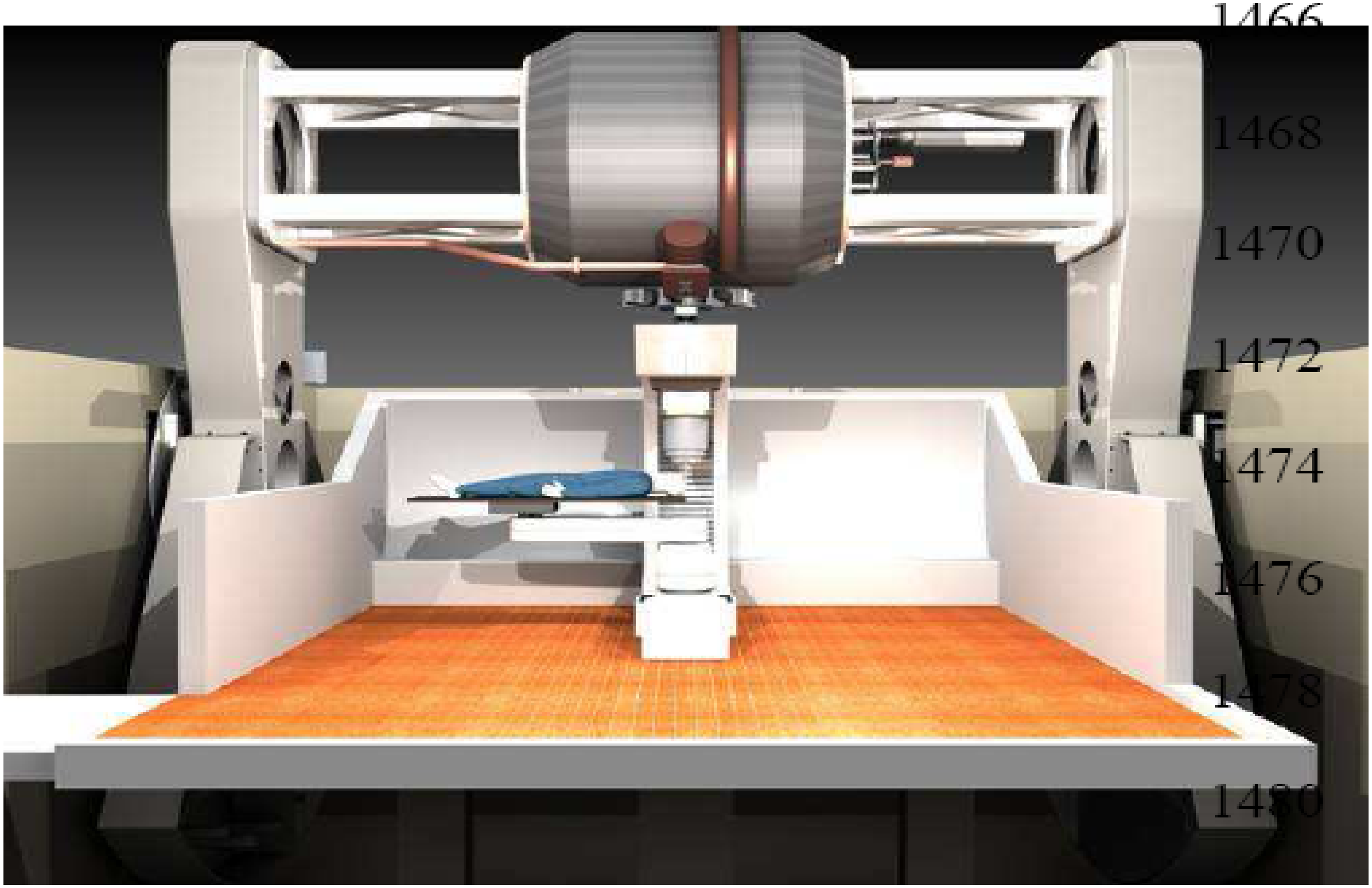
Single Room Systems

- Cyclotron is super-conducting, small, and located in the gantry head.

- Gantry is capable of rotating +/- 90 degrees about the patient plane.

- Therefore, only the ceiling, one lateral wall, and the floor intercept the forward-directed radiation. Each of these barriers is assumed to have a Use Factor of 1/3.

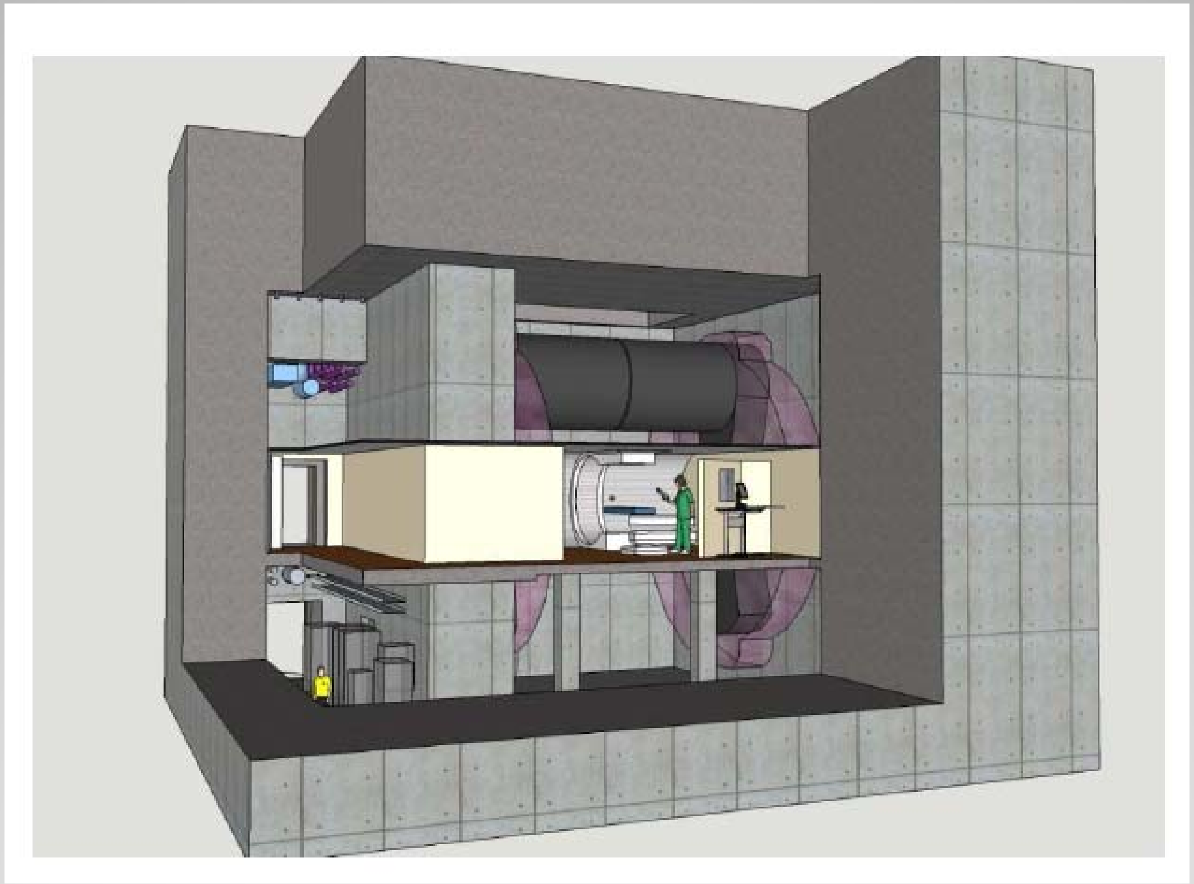
Synchrocyclotron Proton System



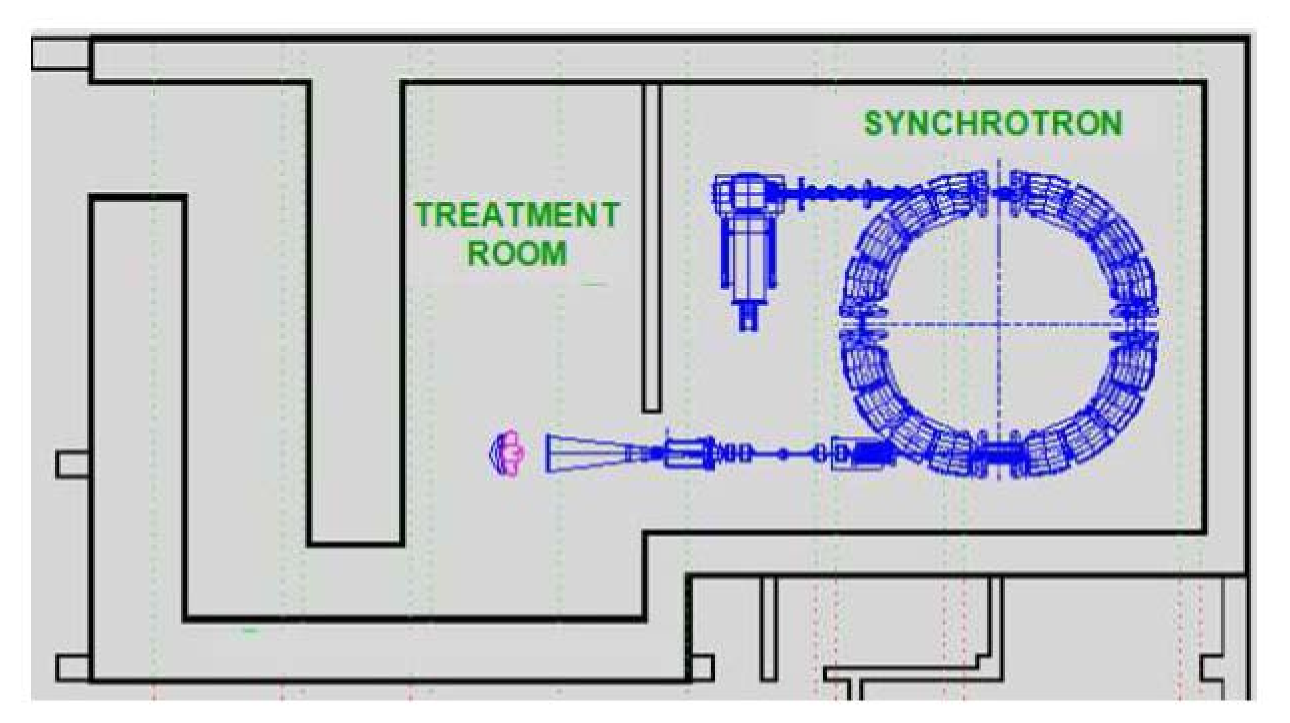
Mevion (Still River) System

- Room has two levels with entrances, a patient treatment level and a sub-basement. Two entrance mazes, one at each level.
- Both mazes will require shielded doors due to maze-scattered neutrons and neutron-capture gamma rays.
- Thicknesses of the barriers range from 1.5 to 4 meters of concrete.

Synchrocyclotron System-OK City



ProTom Single Room System



Regulatory Requirements

- Protection of the following groups of individuals exposed to secondary radiation has to be considered:
  - Occupationally exposed workers
  - Members of the public (visitors to the clinic and the public in the vicinity of the clinic)
  - Patients

Regulatory Requirements

- United States: National Council on Radiation Protection, Nuclear Regulatory Commission, Conference of Radiation Control Program Directors, and State Regulatory Bodies set the standards for individual exposure levels

Regulatory Requirements

- International Guidelines and Standards are set by the ICRP and adopted or modified to more strict standards by individual countries.
- It is up to each facility to comply with their local, state or national regulations.

- Thank you for your time and attention