Part 1:
a) Basic Proton Physics,
b) Proton Treatment Planning and optimization
Part 2:
a) Current State of Volumetric image guidance for proton therapy,
b) Clinical Application of CBCT for Proton Therapy

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Outline: Basic Proton Physics

- Physics of charge particle motion
- Particle accelerators
- Proton interaction with matter
- Delivery systems
  - Scattering systems
  - Uniform scanning
  - Pencil beam scanning
- Spread out Bragg Peak
- Pencil beam characteristics
- The advantage of using proton therapy

Physics of Charge Particle Motion

- Electric and magnetic fields influence on charge particle (CP) :
  - Electric field is used to accelerate/push the CP.
    - A charge particle (q) with mass (m) in Electric field (E), experiences force (F) and gains velocity (v)

$$\vec{F} = q\vec{E}$$

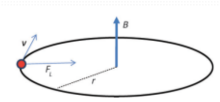
- The kinetic energy (T)

$$T = \frac{1}{2}mv^2$$

Physics of Charge Particle Motion

- Magnetic field is used to guide/turn the CP.
  - The motion in magnetic field (B) is governed by Lorentz force (F_L).

$$\vec{F_L} = q(\vec{v} \times \vec{B})$$



- If the motion is in a plan perpendicular to magnetic field, then the centripetal force keeps the particle in a circular motion.

$$F_L = qvB = \frac{mv^2}{r} \Rightarrow B = \frac{mv}{qr}$$

Physics of Charge Particle Motion

- For constant B; as v increases, r has to increase

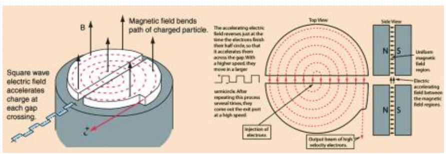
$$B = \frac{mv}{qr}$$

- For constant r; as v increases, B has to increase

$$r = \frac{mv}{qB}$$

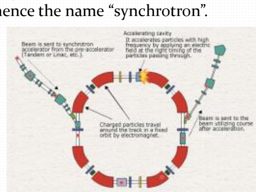
Particle accelerators

- There are Cyclotron, synchrotron, and synchrocyclotron (a cyclotron with variable RF electric field):
  - Cyclotron:
    - Maintains a constant magnetic field while increasing the energy of particles:



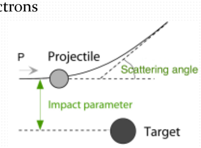
Particle accelerators

- Synchrotron:
  - Magnetic field is varied to maintain the particle in the same orbit as the energy is increased. In other word the magnetic field strength is synchronized with the increase in particles' energy, hence the name "synchrotron".

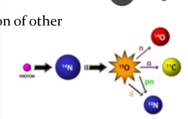


Proton interaction with matter

- Proton interact with matter by:
  1. Coulomb interaction with atomic electrons leading to continues energy loss and slowing down
  2. Scattering by atomic nuclei

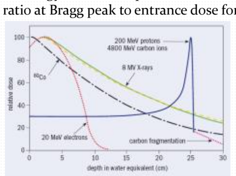


  3. Head-on collision with nucleus
     - Results in nuclear reaction and production of other particles (~7 MeV threshold).



Proton interaction with matter

- High energy proton have very low ionization density (energy loss per unit path length)
  - Range can be calculated based on continuous slowing down approximation (CSDA).
- Ionization density increases gradually to a point where a very high ionization density occurs called Bragg Peak.
  - At this point energy of most protons are 8-20 MeV.
- Proton interaction with atomic electron produces delta rays that travel a few micron and deposit their energy close to the proton's track.
- The typical ionization ratio at Bragg peak to entrance dose for proton is 3:1.



Proton interaction with matter

- There is a small amount of dose due to neutron production beyond Bragg peak:
  1. This amounts depends on energy of protons
  2. Atomic number of material
     - The higher the energy of protons and higher the Z value of material, the larger the neutron-generation.
- The Stopping power (S):

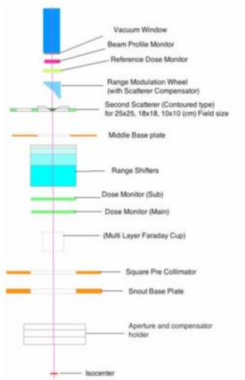
$$S \mu \frac{z^2}{v^2} \log[f(v^2)]$$

Delivery system

- Scattering system:
  - Single scattering and double scattering
    - Single scattering –for used eye beam treatment.
    - Double scattering- produces uniform dose distribution in transverse and longitudinal direction in water.
- Uniform scanning system
  - Single scattering with steering magnets to produce uniform dose in transvers direction. Uses energy stacking to irradiate different depth layers.
- Pencil beam scanning system
  - Positioning spot-by-spot (discrete delivery system)
  - Continuous scanning
  - Can deliver IMPT- Used steering magnet and energy staking to deliver dose.

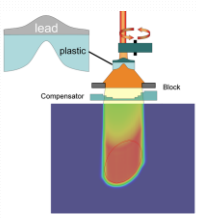
Clinical beam

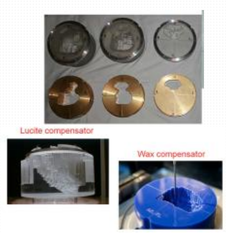
- Double scattering:
  - Single scatterer is used to spread the beam to widen the Gaussian shape beam.
  - Second scatterer is used to flatten the field
  - A Modulation wheel is used to change the range of the beam and to spread the Bragg peaks (SOBP).
  - Aperture is used to shape the field to specific target
  - Compensator (bolus) is used to limit the range to specific depth and shape the beam distally to the target.



Clinical beams

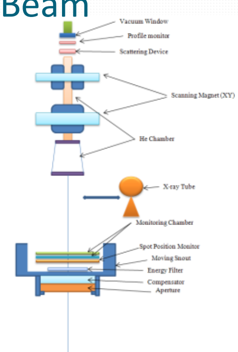
- Beam shaping device used in double scattering delivery system.





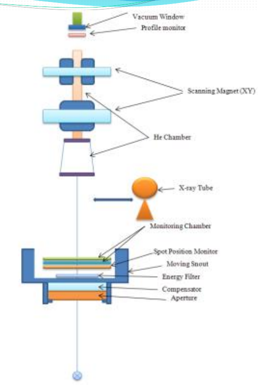
Uniform scanning Beam

- Uniform scanning
  - Scatterer is used to spread the beam to a wider Gaussian shape in order of few cm at FWHM.
  - Magnets are used to steer and move the beams along a layer at specific depth.
  - Range of protons are changed either by introducing a wedge degrader (cyclotron) or changing the energy of accelerator (synchrotron)- energy stacking.



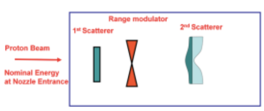
Pencil Beam

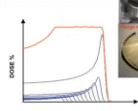
- Uses pristine Bragg peaks to deliver the useful fields.
  - Steering magnets are used to move the pencil beam to different pre determined spots for shaping the field.
  - The energy is changed to deliver beams at different layers using energy stacking system.



Spread out Bragg peak (SOBP)

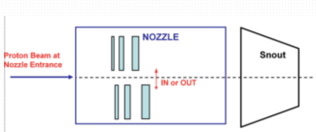
- To produce a clinical useful beam, the Bragg peaks are spread over a region of interest either by range modulation wheels or energy stacking system. The Bragg peaks depth doses are summed to produce a flat depth dose distribution (water) which covers the distal and proximal of the target. The range of proton is normally specified at depth specified by 90% distal dose and SOBP width is defines between the depths corresponding to 90% distal dose and 90% or 95% proximal dose of depth dose distribution.

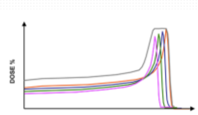




Spread out Bragg peak (SOBP)

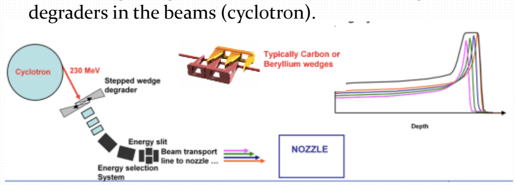
- SOBP created by inserting varying thickness of material in path of the beam:
  - Range shifter
  - Range modulation in step mode
    - Used for uniform scanning





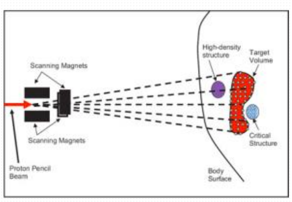
Energy modulation

- In active scanning; energy is changed either by changing accelerating energy (synchrotron) or by inserting degraders in the beams (cyclotron).



Pencil Beams

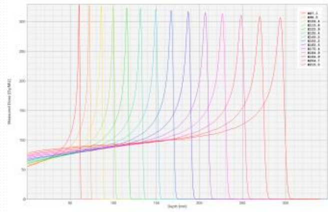
- In intensity modulated proton therapy (IMPT):
  - The pencil beam is delivered to predetermined (TPS) spots in the target.



  - The intensity of the each spot is governed by the optimization criteria to cover the target and to reduce the dose to OAR.

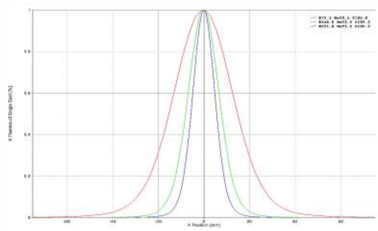
Pencil Beam Characteristics

- Proton pencil beams suffer multiple collisions when traveling through media, resulting in a slight variation in their range, referred to as range straggling or energy straggling. This results in spread of beam under Bragg peak. The higher energy proton beams suffer larger energy straggling.



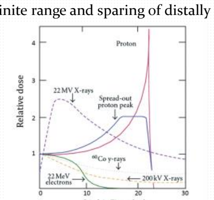
Pencil Beam Characteristics

- low energy proton beams suffer more lateral scattering than high energy proton beams



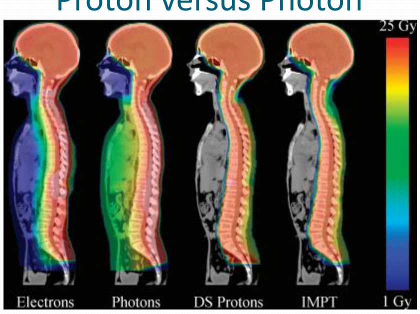
The advantage of using proton therapy

1. Provides a finite range and sparing of distally organ at risk to the target.



2. Lower entrance dose (if multiple fields are used).
3. Higher linear energy transfer (LET)

Proton versus Photon



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- Thank you for your attention.

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