PROTON Physics and Technology

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THE UNIVERSITY OF TEXAS MD ANDERSON CANCER CENTER
Making Cancer History®

Topics Covered

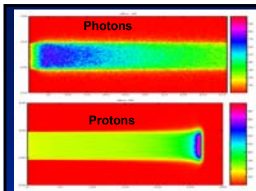
- Rationale for Proton Therapy
- Physics of Proton Beams
- Treatment Delivery Techniques
- Proton Therapy Technology

Rationale for Proton Therapy

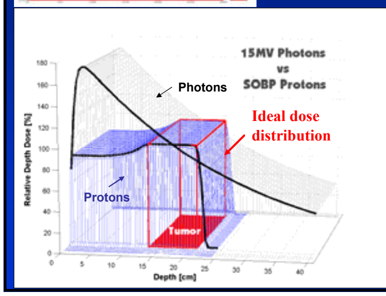
Need for Improved Local Control in Cancer Treatment (selected sites)
(all numbers are estimates)

Tumor Site	Deaths/ year	Deaths due to Local Failure
Head/Neck	22,000	13,200 (60%)
Gastrointestinal	135,000	54,000 (40%)
Gynecologic	28,000	14,000 (50%)
Genitourinary	55,000	27,500 (50%)
Lung	160,000	40,000 (25%)
Breast	41,000	4,920 (12%)
Lymphoma	20,000	2,400 (12%)
Skin, Bone, Soft Tissue	15,000	5,000 (33%)
Brain	12,000	10,800 (90%)
Total	488,000	171,820 (35%)

Over 1,350,000 new cancer patients per year in the US

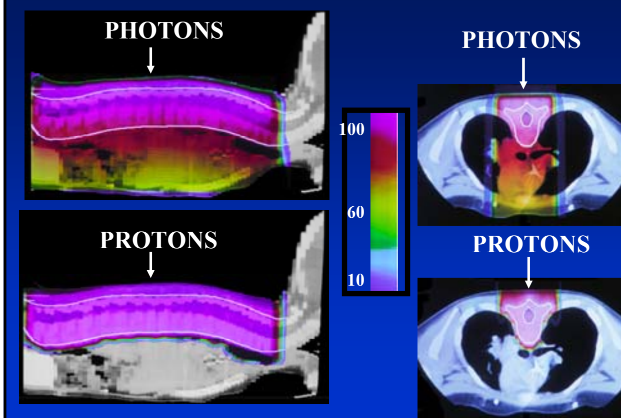


Dosimetric advantages of proton beams



- Protons Stop!
- Photons don't stop.
- Proton dose at depth (target) is greater than dose at surface.
- Photon dose at depth (target) is less than dose at d_{max}.

MEDULLOBLASTOMA



Advantages of Proton Therapy

Highly localized dose distributions→

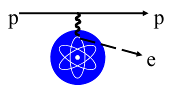
- Increased local control of tumors
- Decreased treatment-related side effects
- Improved Quality of Life

Proton Physics

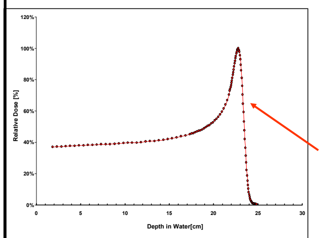
Protons lose energy by:

- ionizations
- multiple Coulomb scattering
- non-elastic nuclear reactions.

Electromagnetic energy loss of protons



1. The incident beam has a narrow energy spread ($\Delta E/E \approx 0.2\%$)
2. Bragg peak is "broadened" by range straggling (statistical differences in energy losses in individual proton paths).



Mass Electronic Stopping Power is the mean energy lost by protons in electronic collisions in traversing the distance dx in a material of density ρ.

$S/\rho = 1/\rho[dE/dx] \propto 1/v^2$

Where v = proton velocity

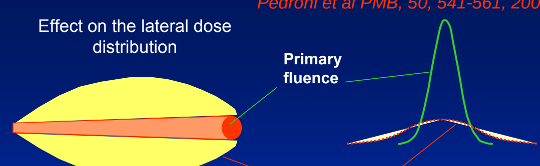
This is the main interaction that causes formation of Bragg peak.

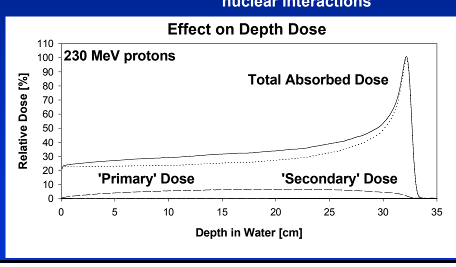
Nuclear interactions of protons

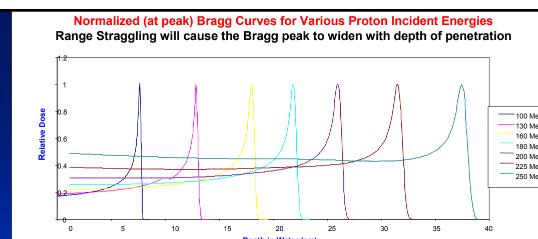
- A certain fraction of protons undergo nuclear interactions, mainly on ^{16}O (~ 1%/cm)
- Nuclear interactions lead to secondary particles and thus to local and non-local dose deposition, including neutrons.

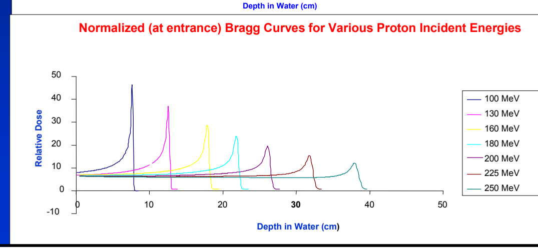
Pedroni et al PMB, 50, 541-561, 2005

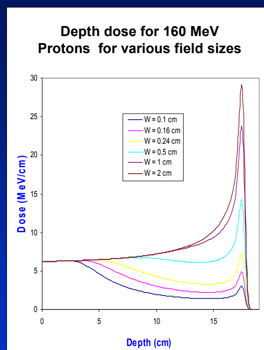
Effect on the lateral dose distribution







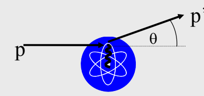


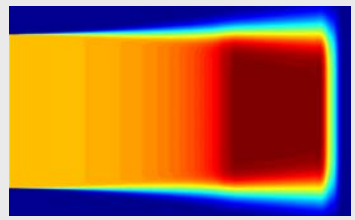


For small fields, loss of in-scattering (charged particle equilibrium) results in deterioration of Bragg peak and non uniformity of SOBP.

Multiple Coulomb Scattering (MCS) leads to broadening of lateral penumbra as beam penetrates in depth.

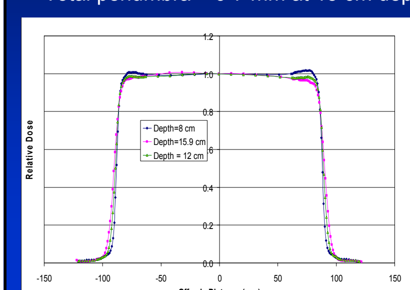
- Protons undergo multiple deflections through elastic coulomb interactions with atomic nuclei
- Beam broadening can be approximated by a Gaussian distribution

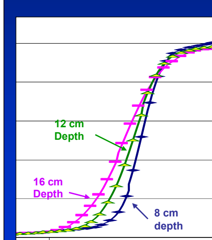




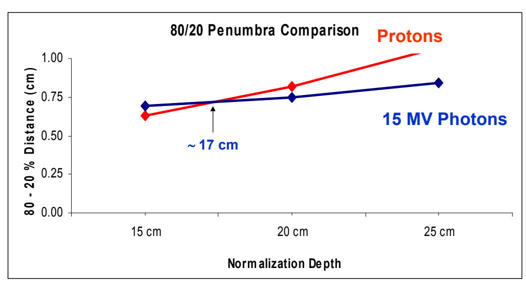
Lateral penumbra:

- Dominated by Multiple Coulomb Scattering
- $d_{80-20} \approx 1.68\ \sigma \approx 3.3\%$ of range $\Rightarrow \sim 5$ mm at 15 cm depth
- Wide angle scattering and nuclear interaction products add
- Total penumbra ~ 6-7 mm at 15 cm depth



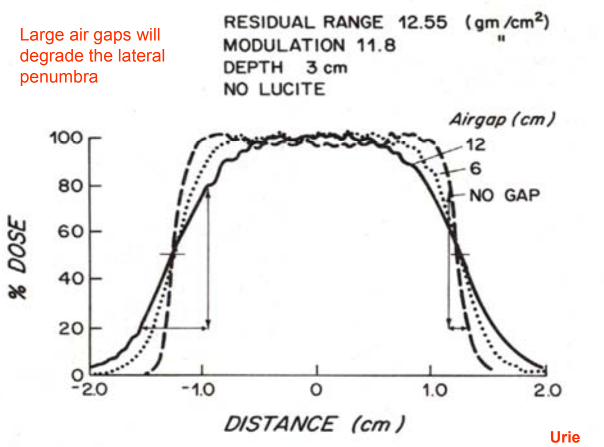


Lateral dose fall-off: Protons vs. Photons



Paganetti

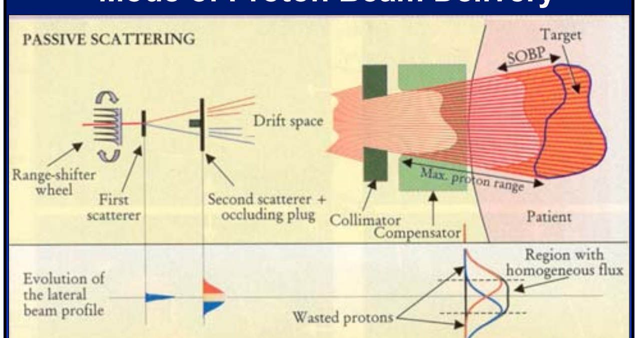
Large air gaps will degrade the lateral penumbra



Urie

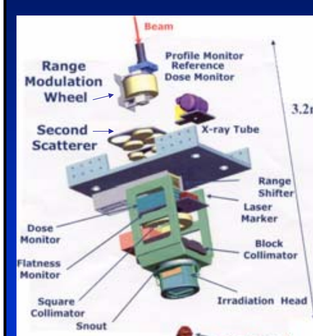
Proton Therapy
Beam Delivery Technology

Physics of the Passive Scattering Mode of Proton Beam Delivery



Goitein, Lomax, Pedroni - Med. Phys.

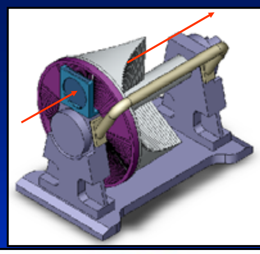
Passive Scattering Nozzle with Range Modulation Wheel

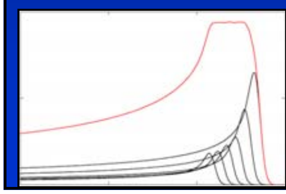


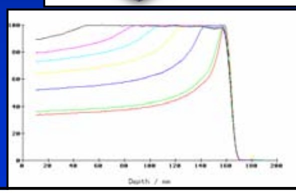
Hitachi Passive Scattering Nozzle

How a Spread Out Bragg Peak (SOBP) is formed.

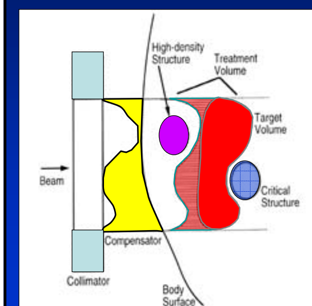
- Modulation wheel rotates in the beam.
- Pull-back (energy shift) determined by height of step.
- Weight determined by width of step.
- Multiple SOBPs can be obtained by gating beam.







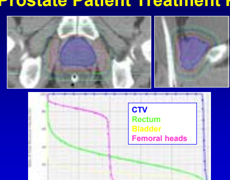
Deficiencies of Proton Passive Scattering Techniques



- Excess normal tissue dose.
- Increases effective source size which increases lateral penumbra.
- Requires custom aperture and compensator
- Inefficient - high proton loss produces activation and neutron production.

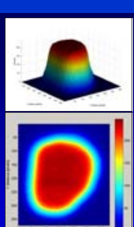
Chu, Ludewigt, Renner - Rev. Sci. Instrum.

Prostate Patient Treatment Plan

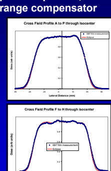


QA of Prostate Treatment using patient treatment parameters/appliances and EBT film in water phantom.

Treatment plan on CT anatomy converted to dose distribution in water phantom.

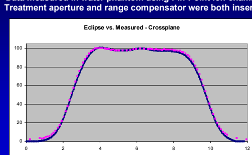


Measurements in water phantom using EBT film, patient aperture, and range compensator

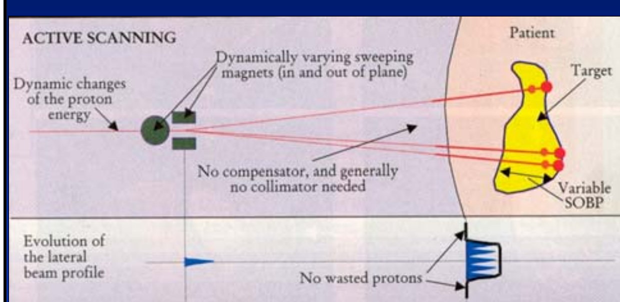


Patient Treatment QA – Measurements compared with treatment planning calculations converted to water phantom.

Data measured in water phantom using Pin-Point ion chamber. Treatment aperture and range compensator were both inserted.

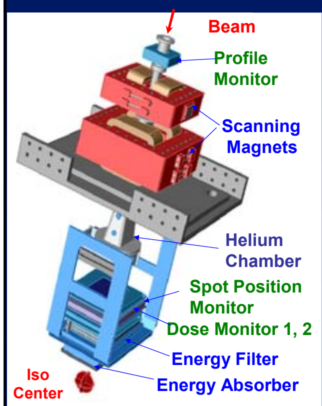


The Pencil Beam Scanning Mode of Proton Beam Delivery



Goitein, Lomax, Pedroni - Med. Phys.

Pencil Beam Scanning Nozzle



Hitachi Spot Scanning Nozzle

Performance

Range	4 – 36 g/cm^2
Adjustability	0.1 g/cm^2
Max. field size	30 x 30 cm
Beam size in air	5 – 10 mm σ
SAD	> 2.5 m
Dose compliance	+/- 3% (2 σ)

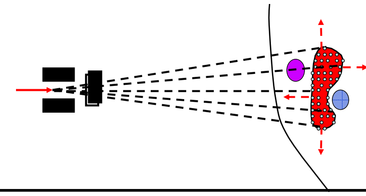
Irradiation time < 1.5 min to deliver 2 Gy to 1 liter at any depth.

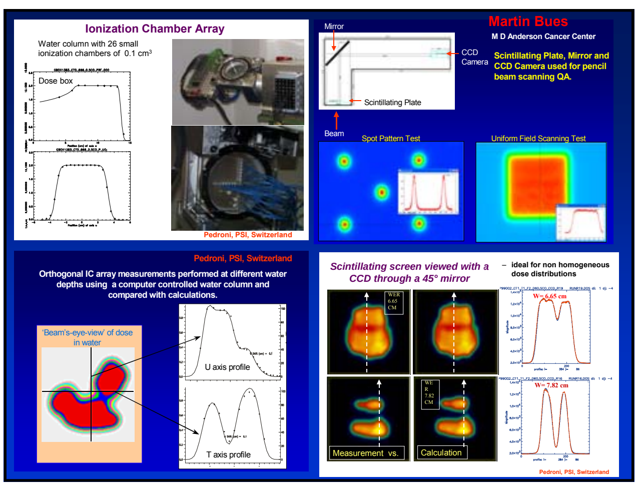
A major problem with spot scanning:

The target can move during treatment leading to dose errors!

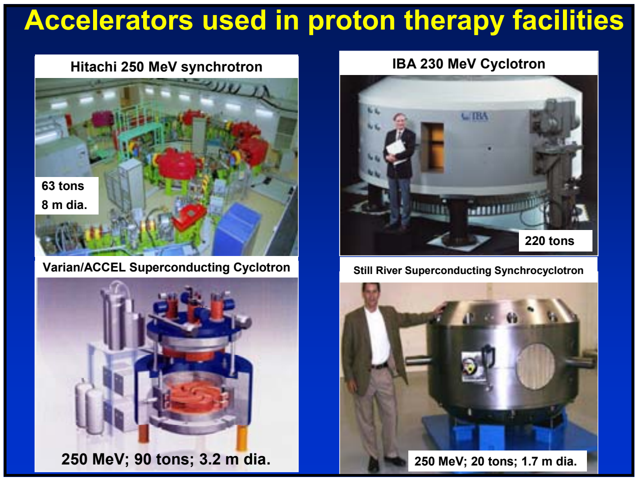
Remedies:

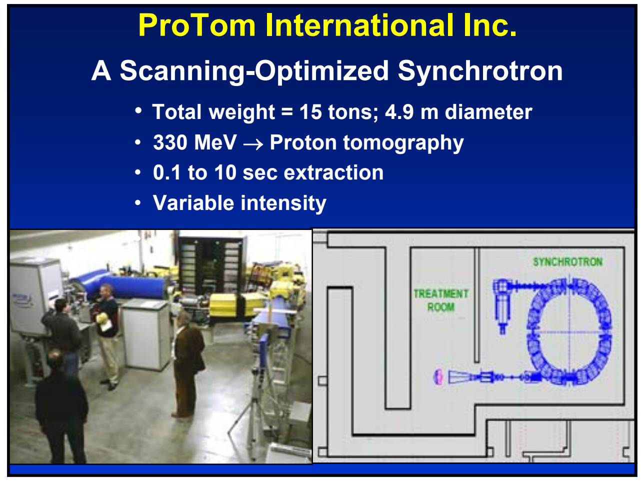
- Rescanning (spot, layer, volume)
  - $\Delta D/D \propto 1/\sqrt{n}$, where n = number of scans
- Beam Gating
- Real time tracking with markers

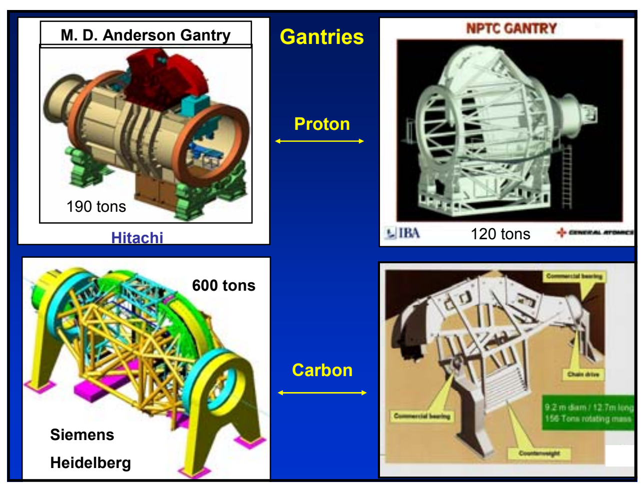




1. Proton Accelerators
2. Isocentric Gantries
3. Typical Facility

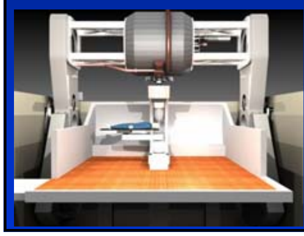

Accelerators used in proton therapy facilities
Hitachi 250 MeV synchrotron
63 tons
8 m dia.
IBA 230 MeV Cyclotron
220 tons
Varian/ACCEL Superconducting Cyclotron
250 MeV; 90 tons; 3.2 m dia.
Still River Superconducting Synchrocyclotron
250 MeV; 20 tons; 1.7 m dia.


ProTom International Inc.
A Scanning-Optimized Synchrotron
• Total weight = 15 tons; 4.9 m diameter
• 330 MeV → Proton tomography
• 0.1 to 10 sec extraction
• Variable intensity
SYNCHROTRON
TREATMENT ROOM


M. D. Anderson Gantry
190 tons
Hitachi
Gantries
Proton
NPTC GANTRY
IBA
120 tons
600 tons
Siemens
Heidelberg
Carbon

Still River Proton Therapy System

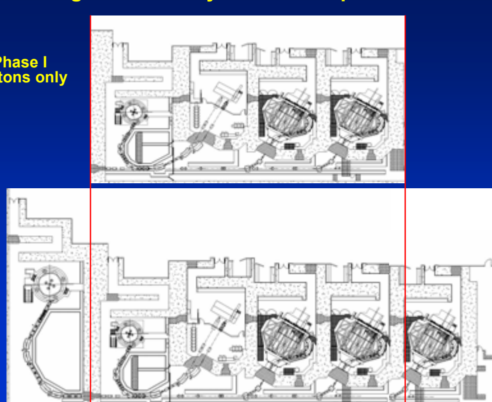
- Accelerator mounted on Gantry
- Entire system contained in one room
- Multiple independent rooms can be installed



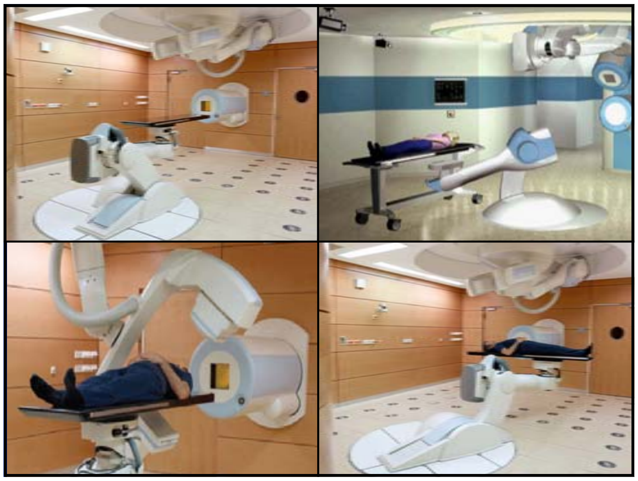
Typical Proton Therapy Facility

1. Accelerator	4. Gantry room
2. Beam transport line	5. Fixed beam room
3. Gantry room	6. Patient support area

A Proton + Light Ion Facility built in two phases



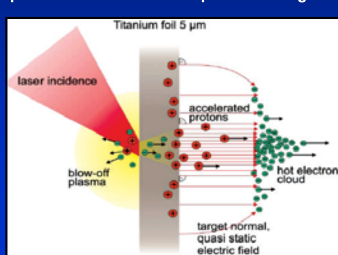
Robotic Applications



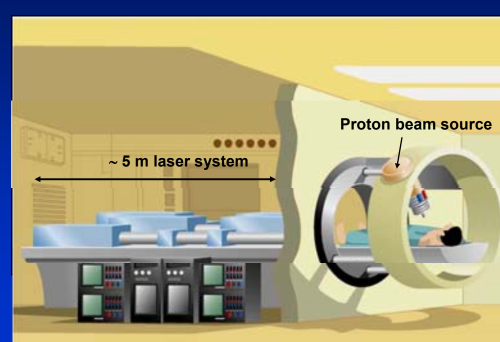
New Technologies

Laser Accelerated Proton Beams

Proton acceleration is achieved by focusing a high-power laser on a thin target. The short (10^{-16} sec) laser pulse width produces a high peak power intensity that causes massive ionization in the target, expelling a large number of relativistic electrons. The sudden loss of electrons gives the target a high positive charge and this transient positive field accelerates protons to high energies.

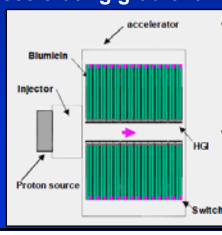


Laser accelerated proton therapy has a time frame of 5 – 10 years.



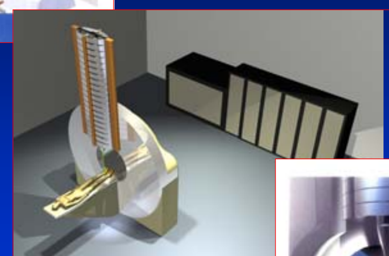
Dielectric Wall Proton Accelerator (DWA)

Conventional accelerator cavities have an accelerating field only in the gaps which occupy only a small fraction of their length. In a DWA, the beam pipe is replaced by an insulating wall so that protons can be accelerated uniformly over the entire length of the accelerator yielding a much higher accelerating gradient.



The goal is to have a full scale prototype in ~ 4-5 years, which will be installed at UC Davis CC.

Thomotherapy is the private sector partner



Artist Concepts for DWA clinical installation

THE UNIVERSITY OF TEXAS
MD ANDERSON
CANCER CENTER
Making Cancer History®

Thank You!