Laser-Accelerated Proton Beams and their Medical Applications

By Eric Sacks

Contents

1) Basics of charged particle interactions in matter.
2) Proton-Therapy
3) Laser-Acceleration method for producing Proton Beams for Proton-Therapy.

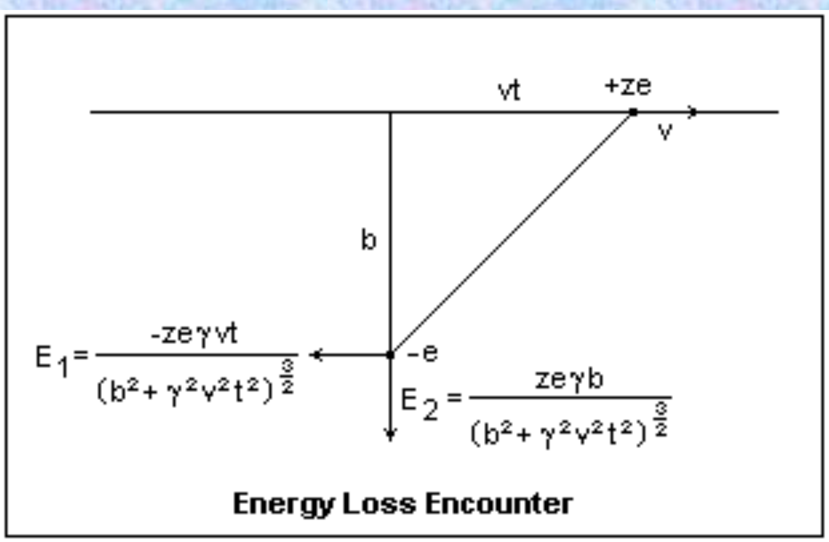
Basic Concepts – Stopping Power

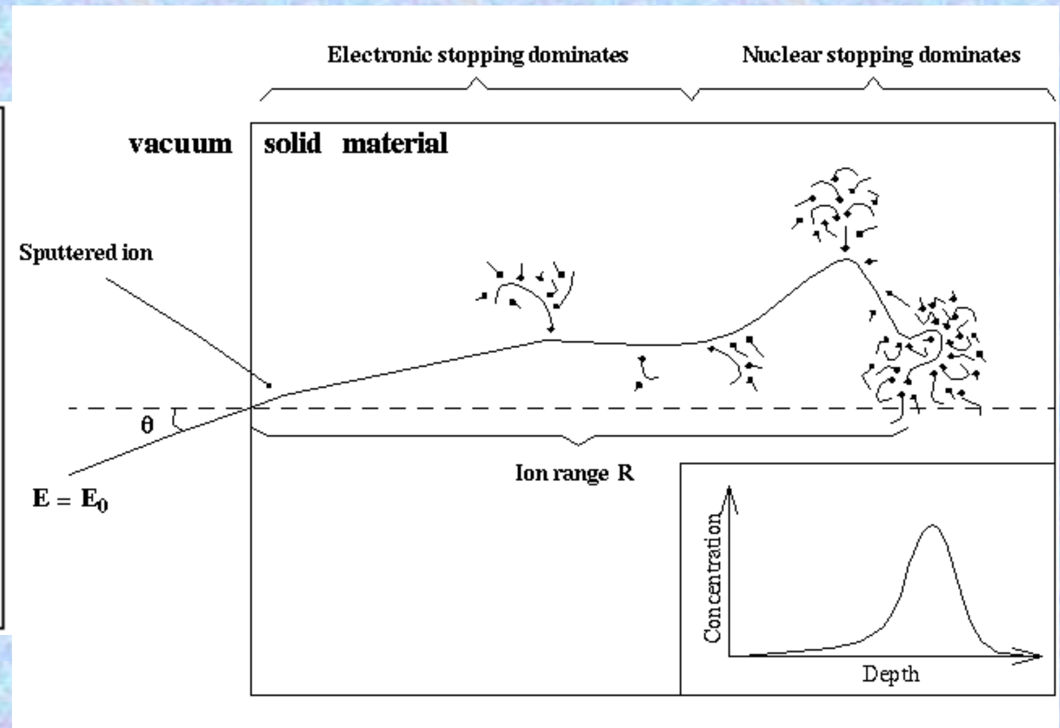
$$S(E) = -\frac{dE}{dx}$$

- Stopping power describes the energy loss of a particle per unit length as it travels through a target.
- Charged particles ionize the atoms of the target as they pass through, losing energy (slowing down) with each ionization.

Basic Concepts – Stopping Power

- Inelastic Electron Stopping dominates for high energies
- Elastic Nuclear Stopping dominates as particle slows down. This effect is also related to particle size.

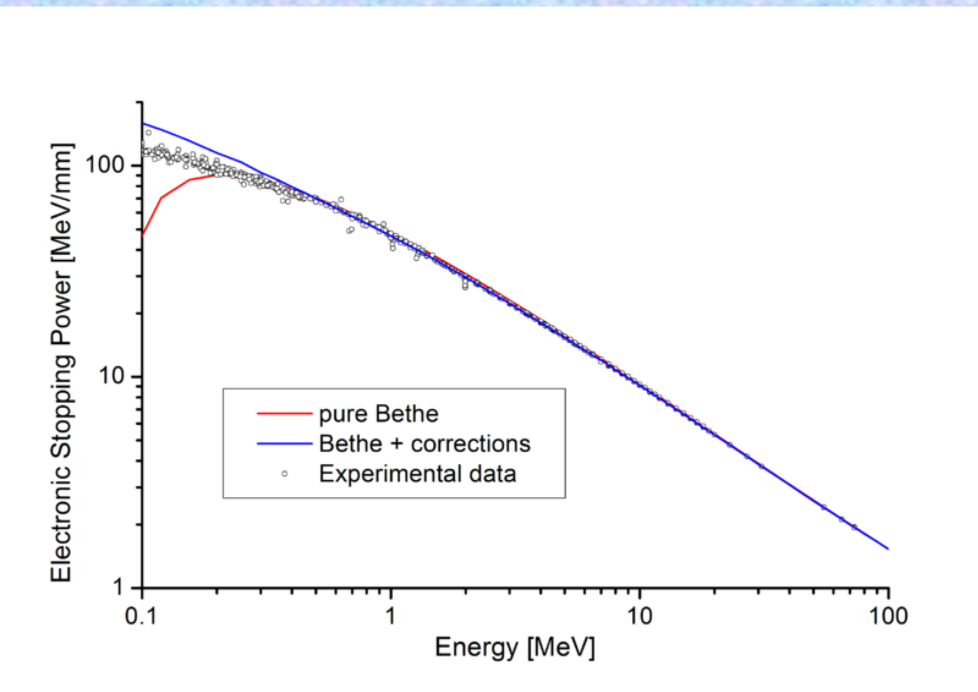




Stopping Power – Bethe Formula

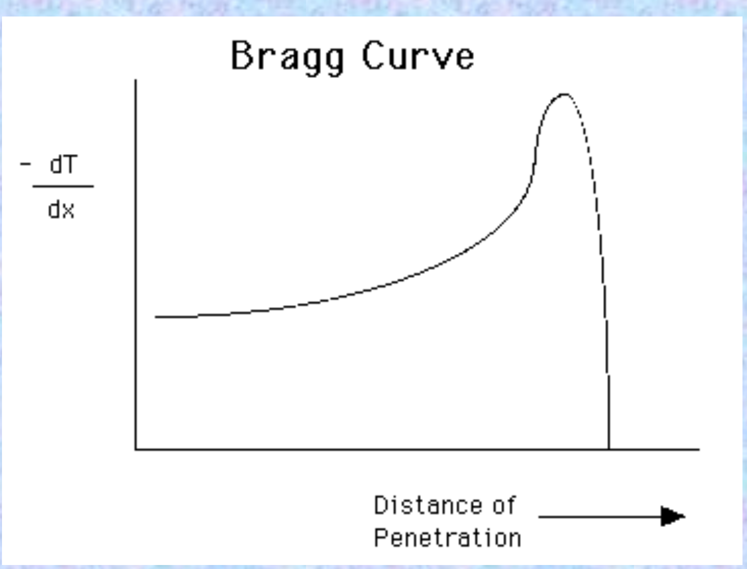
$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \cdot \left[\ln\left(\frac{2m_e c^2 \beta^2}{I \cdot (1-\beta^2)}\right) - \beta^2\right]$$

- Shows decrease in stopping power as the charged particle's energy increases.
- Oppositely, the slower the particle, the more stoppage (velocity decreases at decreasing rate).
- As particle slows down, relativistic formula simplifies and stopping power follows a general 1/v^2 relationship.



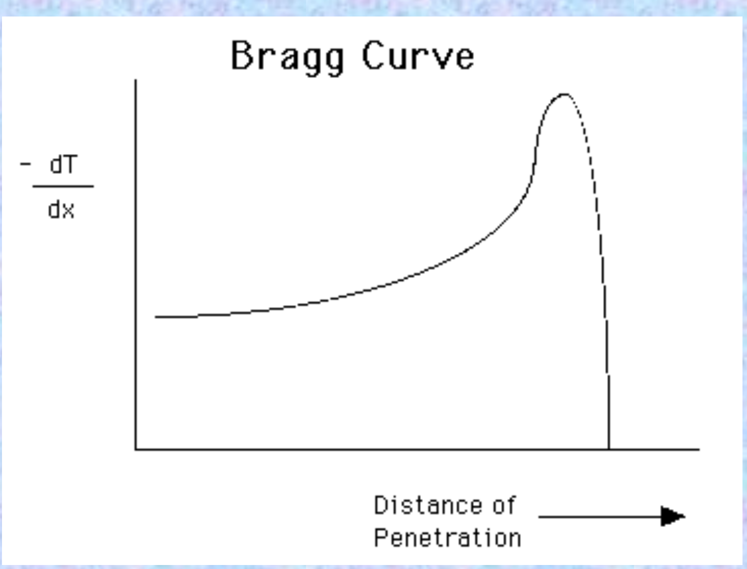
Bragg Curves and Bragg Peak

- Named for William Henry Bragg
- Bragg curves plot stopping power (energy loss per unit length) vs. the distance the particle has traveled.
- Bragg noticed that a peak occurs right before the particle comes to a rest. These are called Bragg Peaks.



Bragg Curves and Bragg Peak

- As particle slows down, interaction cross section increases.
- Increase in interactions causes an accelerating stopping power that reaches a peak just before particle comes to rest.
- Bragg Curve for a generic charged particle →



Bragg Peaks and Dosage

- Relative dosage graphs follow same pattern of Bragg Curve. Shows percentage of maximum dose (energy deposited per mass) as particle travels in medium.
- Sharpness of proton's Bragg curve implies a concentrated dose given in a small range, and little dose elsewhere.

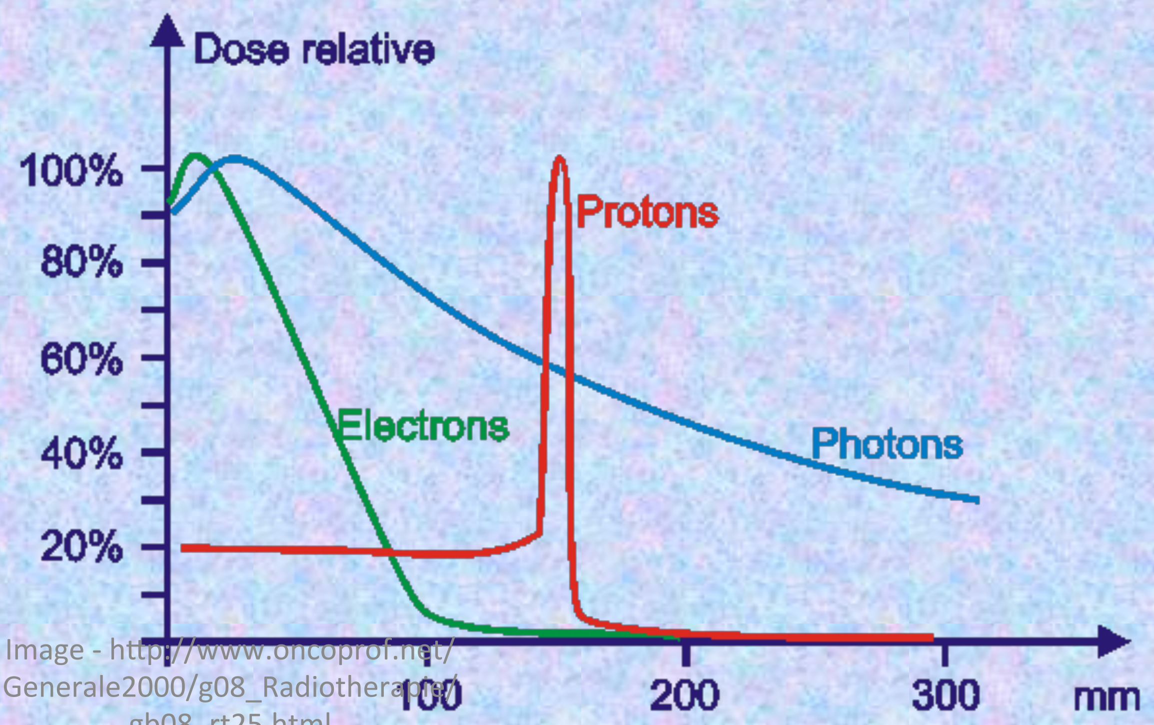


Image - http://www.oncoprof.net/Generale2000/g08_Radiotherapie/gb08_rt25.html

Medical Applications

- Proton beam deposits most of its energy in a small spatial range, and deposits little elsewhere.
- The sharp Bragg Peak for protons makes them useful for irradiating tumors while preventing damage to surrounding tissue.

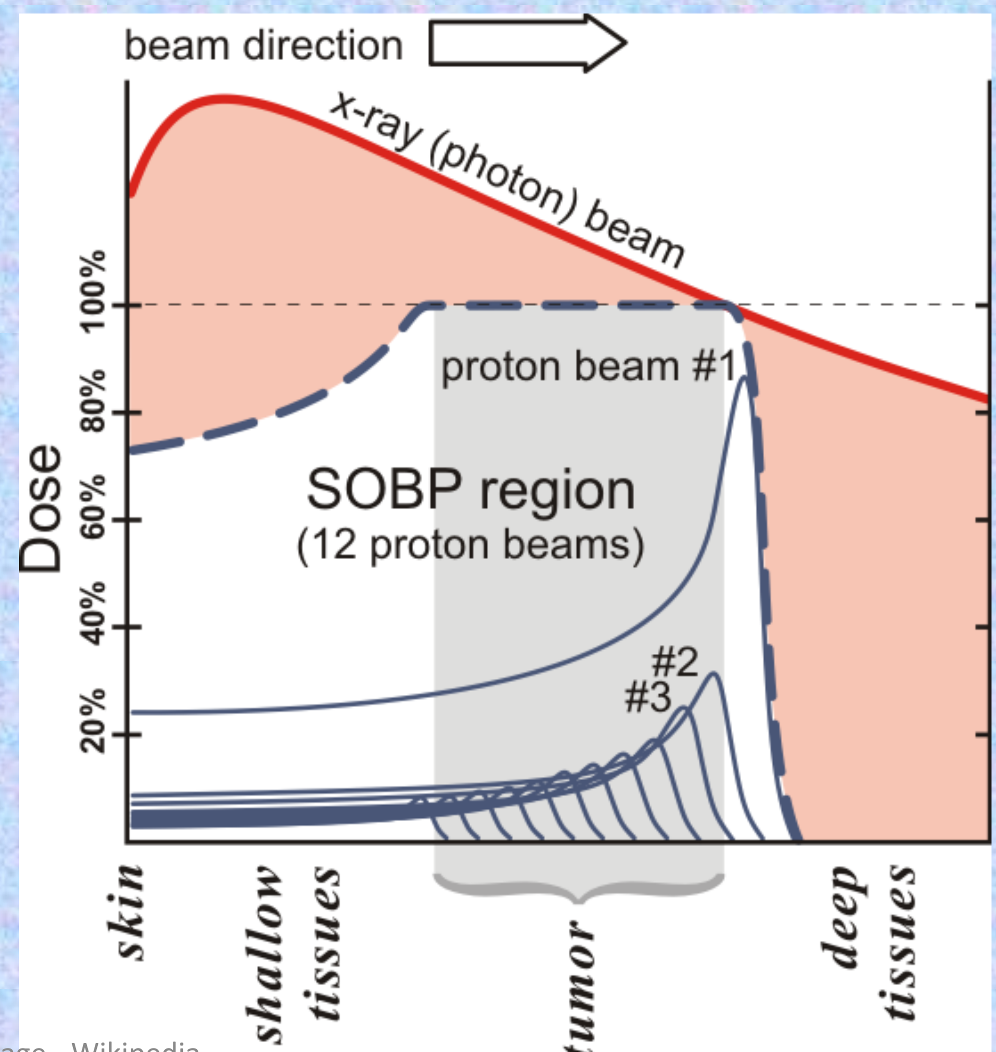
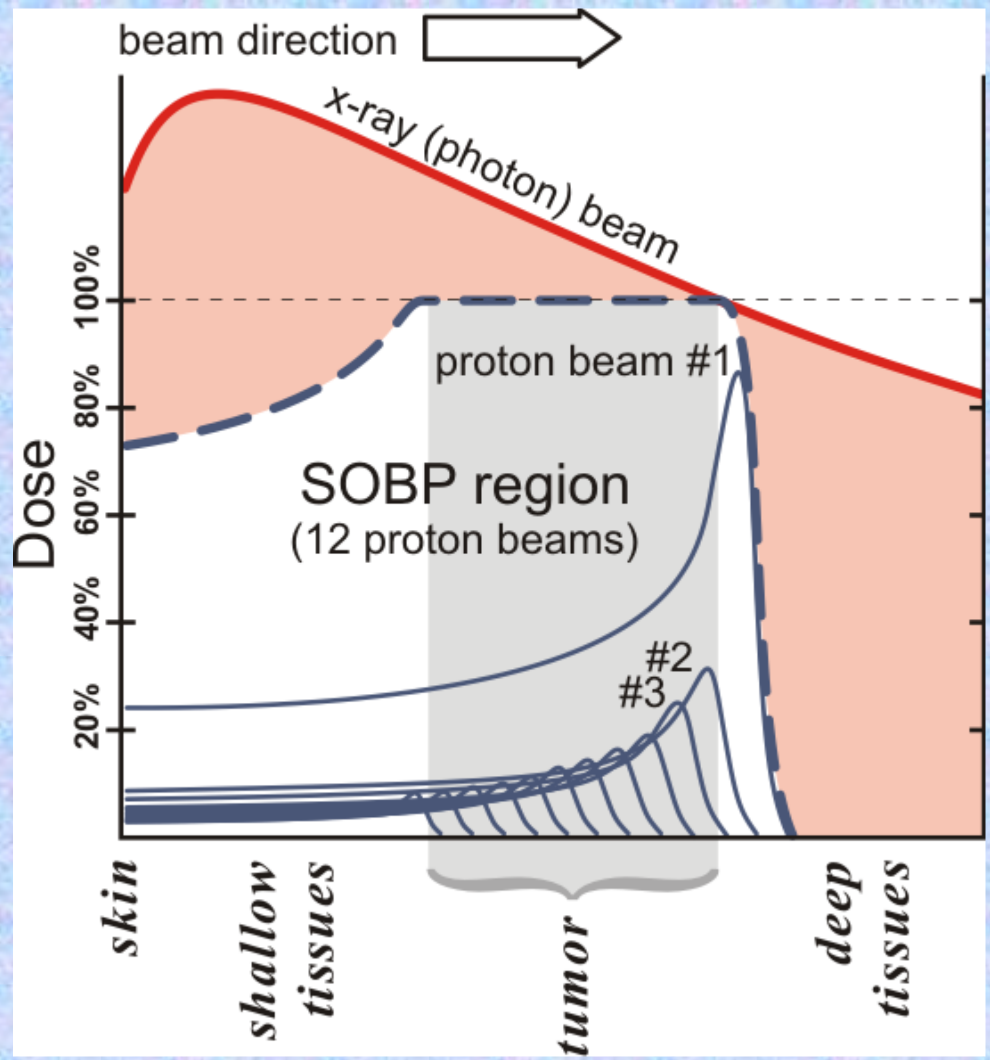


Image - Wikipedia

Medical Applications

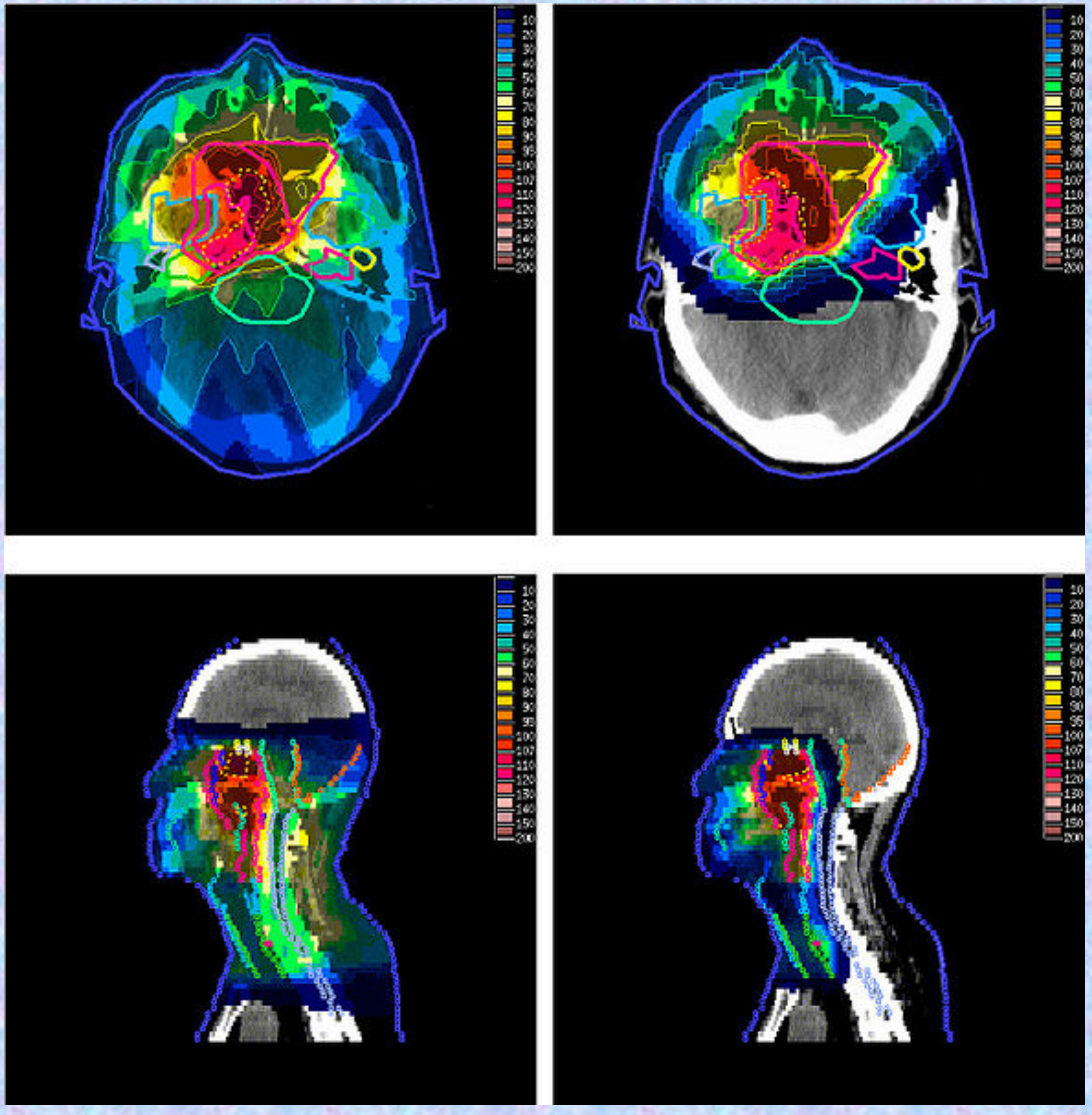
- Location of the Bragg Peak slides with beam energy.
- Width of Bragg peak is generally smaller than the tumor.
- SOBP is used to irradiate larger tumor. Requires energy spectrum for incident proton beam.
- Typical energies – 70-250 MeV.



Advantages of Proton Therapy

- Proton therapy provides a very localized radiation treatment to eradicate tumors.
- Much more precise compared to conventional radiotherapy (photon therapy).
- Sharp Bragg peaks concentrate dose and limit side effects caused by irradiating healthy tissue.
- Ex. Proton therapy for ocular tumors – High dose with high precision is needed.

- X-ray treatment on the right.
- Proton beam therapy on the left.

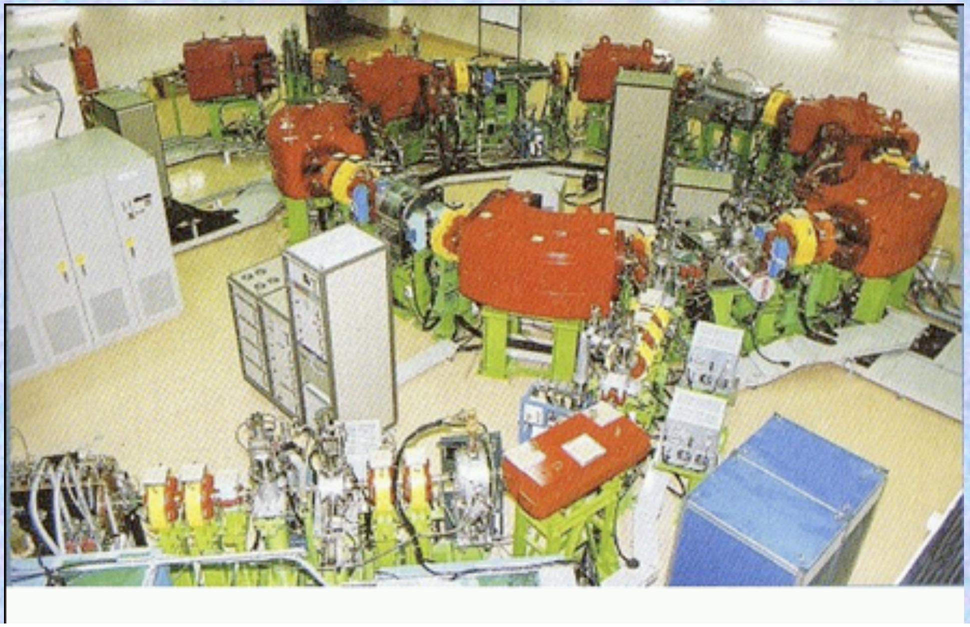


Taheri-Kadkhoda et al. Radiation Oncology 2008 3:4 doi:10.1186/1748-717X-3-4


Phillips , Harold

Where do Proton Beams for Medical Therapy Come From?

- Currently the answer is strictly particle accelerators – Synchrotrons and Cyclotrons!
- 41 Proton Therapy facilities.
- Only .8% of all Radiotherapy systems worldwide.



Hitachi Proton Therapy Synchroton

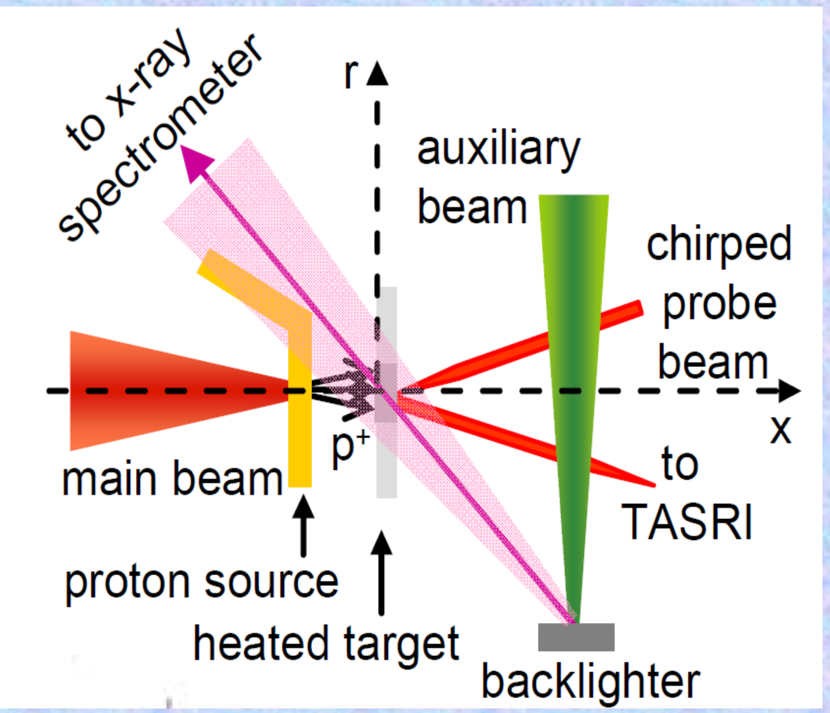
Why Hasen't it caught on?

Answer – TREATMENT IS INCREDIBLY EXPENSIVE!

- Facilities cost $100M -200M Each
- Cost of up to $100,000 per treatment.
- Many times greater than cost of alternatives.
- It can be said that current costs outweigh benefits of proton therapy.
- Cheaper method for producing protons is needed.

Solution?

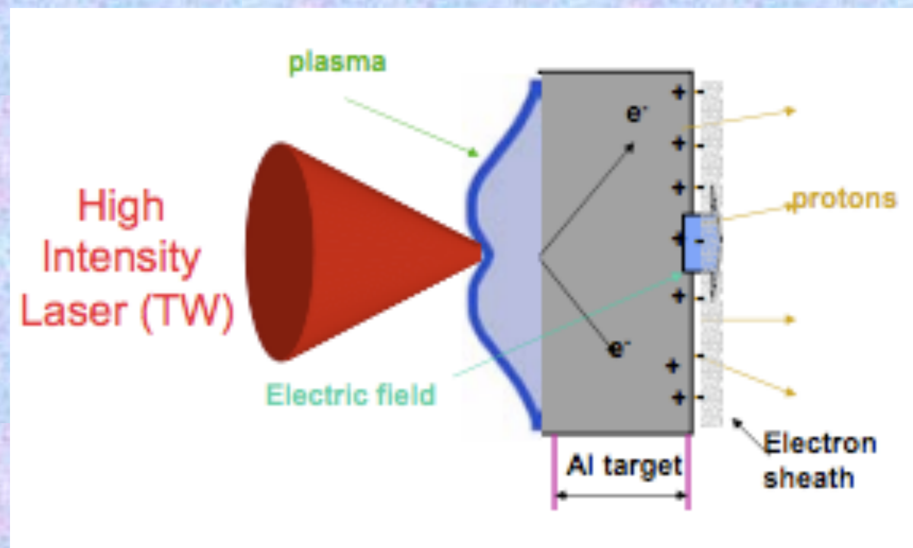
Laser-Accelerated Proton Beams



Isochoric heating of matter by laser-accelerated high-energy protons - Antici, et al.

TNSA – Target Normal Sheath Acceleration

- Short and Intense laser pulse (TW, ps) incident on target creates plasma on target's front surface.
- Electrons move from front to rear surface due to Ponderomotive Force and energy deposition.

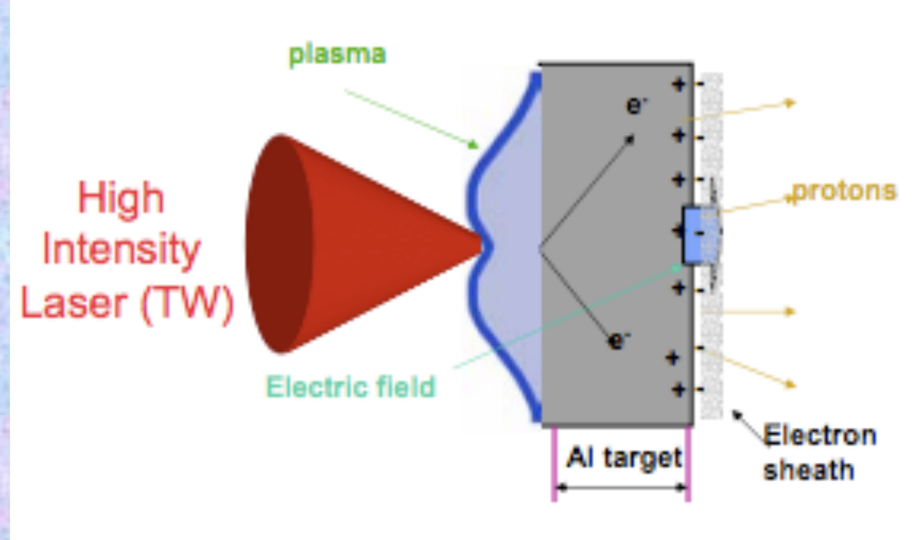


$$\mathbf{F}_{\mathrm{p}} = -\frac{e^2}{4m\omega^2}\nabla\mathbf{E}^2$$

Target normal sheath acceleration: theory, comparison with experiments and future perspectives - Passoni et al.

TNSA – Target Normal Sheath Acceleration

- Ponderomotive force displaces electrons away from incident laser – towards rear.
- Laser directly energizes a population of hot collisionless electrons that form electron cloud extending off back surface.



$$\mathbf{F_p} = -\frac{e^2}{4m\omega^2}\nabla \mathbf{E}^2$$

TNSA – Target Normal Sheath Acceleration

- Extremely high charge density - creates E-field as high as 10^{12} V/m near rear surface.
- Protons/ions on rear surface accelerate towards electrons and are ejected from target.
- Depending on experiment, protons originate from target material itself or from hydrocarbon layer deliberately put on surface of target (exhale on target – seriously!).

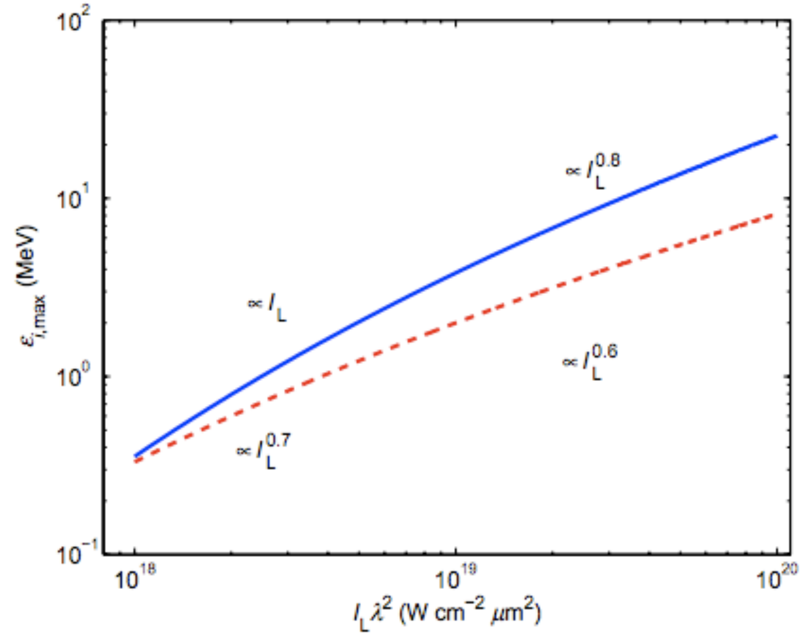


Figure 3. Maximum proton energy $\varepsilon_{i,\max}$ as a function of the pulse irradiance $I_L\lambda^2$, in the interval $10^{18} \leqslant I_L\lambda^2 \leqslant 10^{20}$ (W cm^{-2} μm^2). The laser parameters considered are as follows: blue solid curve: $\tau_L = 25$ fs, $f_L = 20\,\mu$m, $\lambda = 0.8\,\mu$m and the corresponding pulse energy interval is $0.1 \leqslant E_L \leqslant 12$ J; red dashed curve: $E_L = 0.1$ J, $\lambda = 0.8\,\mu$m. The effective power-law fitting is indicated for each irradiance decade.

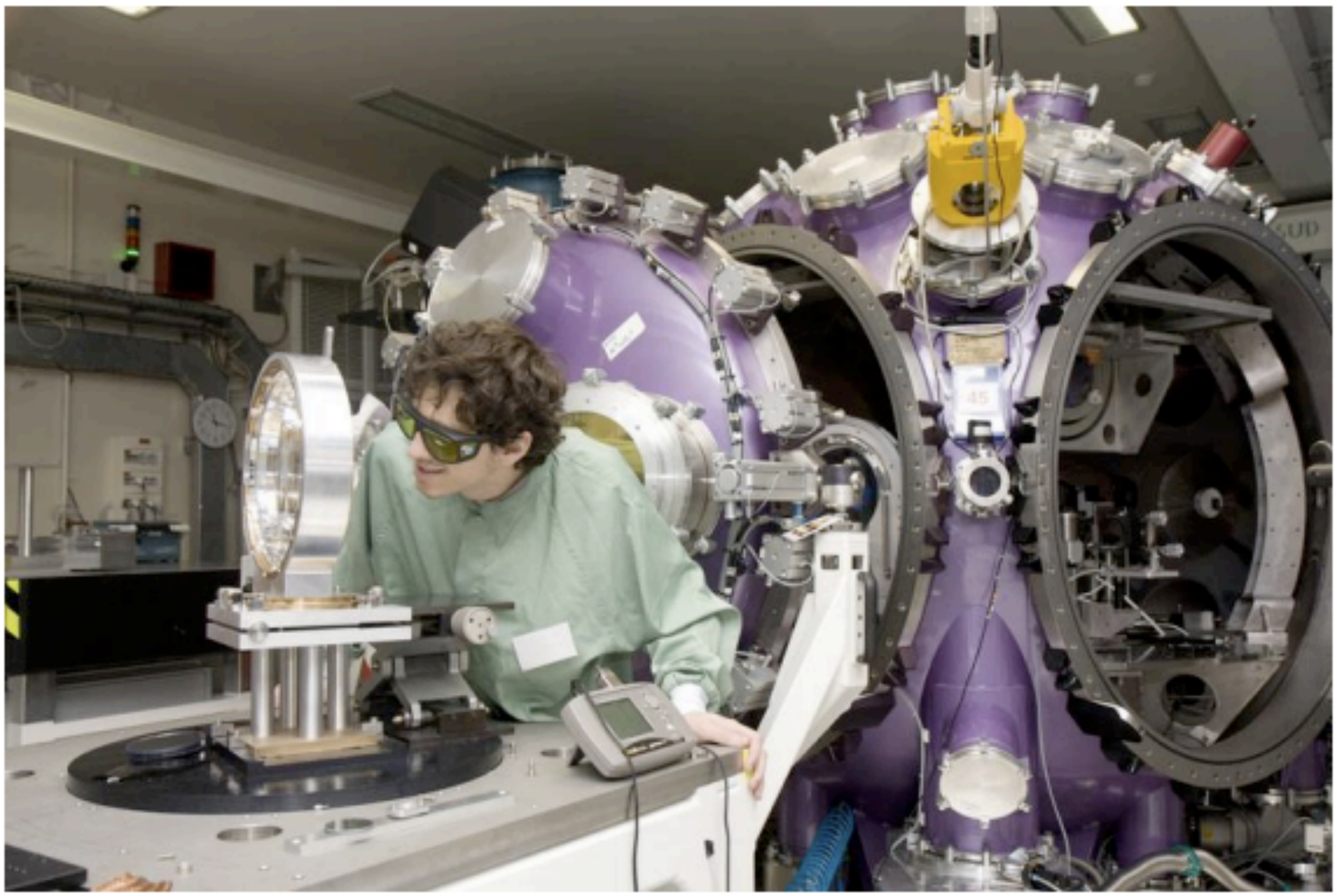
Theoretical calculations on proton energies. >100MeV (not shown) are possible with technique. – 70-250MeV is range needed for tumor destruction.

Advantages

- Laser accelerators can cost only $10-20M (10x less than current particle accelerators used.
- Low price per laser shot*
- In the next decade, we hope to achieve as high as 300MeV proton beams and make proton therapy the standard in tumor eradication due to low costs and high precision.
- Note – TNSA is also being looked into for initiating ICF reactions and for other basic accelerator applications.

LULI2000 – Ecole Polytechnique

Experiment Room for LULI2000



The End