Laser-Accelerated Proton Beams and their Medical Applications

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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

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

• 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_Radiotherapy/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.
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.
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 Synchrotron
Why Hasn’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.

\[ F_p = -\frac{e^2}{4m\omega^2} \nabla E^2 \]

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.

\[ F_p = -\frac{e^2}{4m\omega^2} \nabla E^2 \]
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!).
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