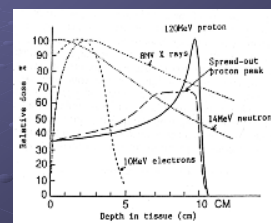
Laser-Accelerated protons for radiation therapy

E Fourkal, I Velchev, J Fan, J Li, T Lin, C Ma
Fox Chase Cancer Center, Philadelphia, PA

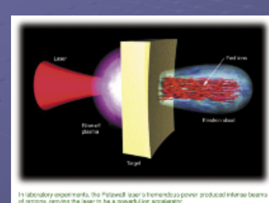
Motivation

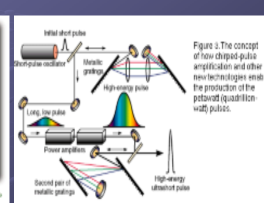
- Proton beams provide better conformity to the treatment target as well as better sparing of healthy tissue
- Through modulation of proton energy distribution it is possible to attain superior dose distribution within the target volume and surrounding tissue



- Requirements on laser-proton accelerator for clinical implementation?
  - *Has to provide proton beams with variable energy 60-230 MeV*
  - *Proton energy spectrum has to have small energy spread in it*
  - *Laser pulse has to be stable with well controlled pulse characteristics*

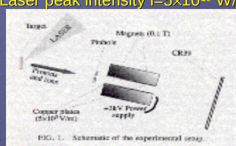
Basic mechanism behind particle acceleration

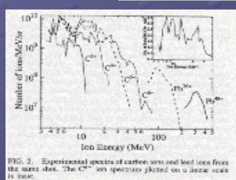


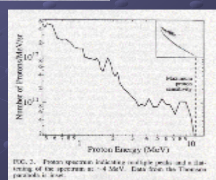


Recent Experiments*

(Laser peak intensity $I=5\times10^{19}$ W/cm^2)



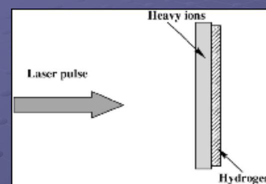


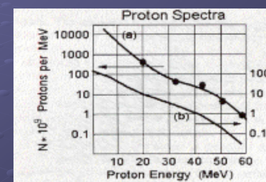


*E. L. Clark, *et al.*, *Phys. Rev. Lett.* Vol. 85, 1654, (2000)

Recent Experiments*

(Laser peak intensity $I=3\times10^{20}$ W/cm^2)

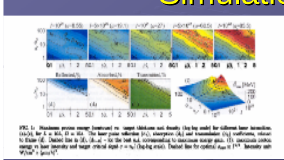


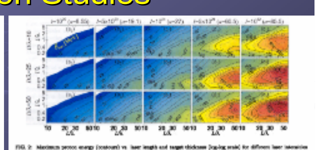


- Maximum proton energy reported so far is $E_p \approx 60$ MeV
- The number of protons needed to get 1 Gy of dose is $N \sim 10^9 \div 10^{10}$ depending on the Bragg peak location and its extent.

*R. A. Snavely, *et al.*, *Phys. Rev. Lett.* Vol. 85, 2945, (2000)

Results of Multi-Parametric Simulation Studies*





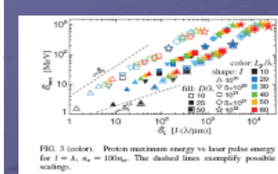
Proton energy curves are nearly parallel to the line $\sigma=n_e l$, i. e. the number of electrons per unit area (critical width).

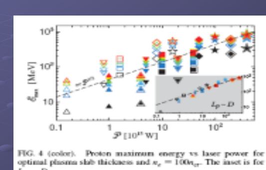
The maximum energy gain corresponds to some optimal $\sigma=\sigma_{opt}$

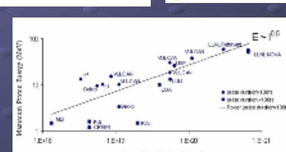
$$\frac{\sigma_{opt}}{n_{cr}\lambda} \approx 3+0.4\left(\frac{I}{I_1}\right)^{1/2}, I_1 = 1.368\times10^{18} W/cm^2 \times (\mu m/\lambda)^2$$

*T. Esirkepov *et al.*, Phys. Rev. Lett. **96**, 105001 (2006).

Results of Multi-Parametric Simulation Studies

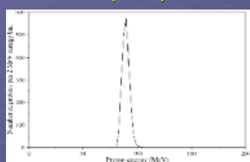


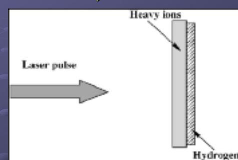




Results of computer simulations for a double-layer target

(Laser peak intensity $I = 2\times10^{21}$ W/cm^2)



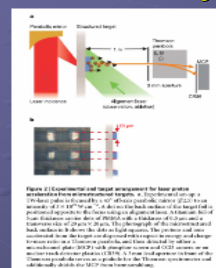


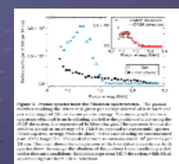
A quasi-monoenergetic proton beams may be obtained if care is taken in designing the target[*].

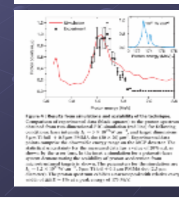
PIC simulation results suggest that more robust ion expansion (described by the parameter $\zeta = Z_i m_e/m_i$) leads to more energetic protons[**]

[*]T. Z. Esirkepov *et al.*, Phys. Rev. Lett. **89**, 175003 (2002).
[**]E. Fourkal *et al.*, Phys. Rev. E **71**, 036412 (2005).

Recent experimental results, reporting monoenergetic proton beams[*]



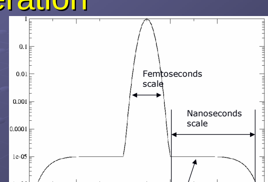




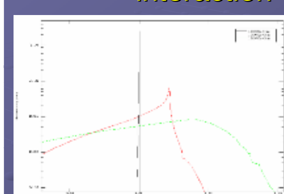
[*]Schwoerer *et al.*, Nature **439**, 445 (2006)

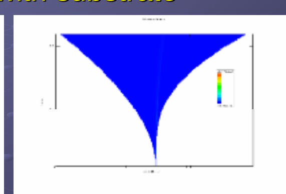
Factors affecting proton acceleration

- Laser-driven proton acceleration depends on the structure of the laser pulse.
- "Parasitic" parts of the laser pulse such as a pre-pulse and an amplified spontaneous emission (ASE or pedestal) can substantially change the solid target before the main pulse arrives.

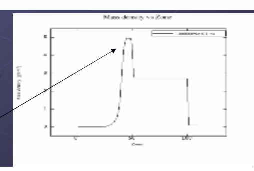


Simulation of the laser pre-pulse interaction with substrate





Shock wave propagating through aluminum target of initial thickness 1μm dramatically changes its properties.



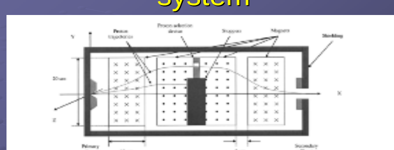
Summary-I

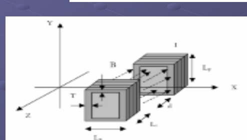
- Multi-dimensional PIC simulation studies show that present-day laser technology can be used to accelerate protons to therapeutic energy range.
- With proper target design it should be possible to obtain quasi-monoenergetic beams
- Tight control over laser prepulse needed to obtain high-quality therapeutic particle beams !!!

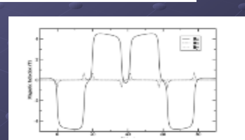
Production of clinically useful beams

- It is necessary to produce a beam that will give a homogeneous dose distribution tailored as close as possible to the target volume - *energy modulation*
- It is necessary to be able to irradiate large volume beginning with a beam with small cross-section extracted from the accelerator
- The beam must be widened, the depth of penetration controlled.

Schematic diagram of proton selection system



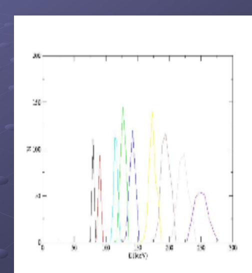




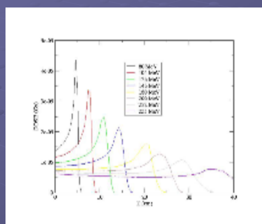
W. Luo, E. Fourkal, J. Li, C. Ma, Med. Phys. **32**, 794, 2005

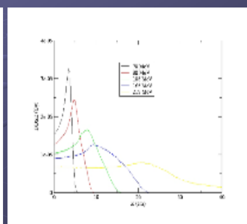
Effect of spatial mixing and proton energy distributions

- Due to proton angular distributions, there is a spatial mixing of different energy particles .
- The proton energy distribution is no longer monochromatic, but has a spread around its peak



Depth dose distributions versus primary collimator opening





The depth dose distributions become wider for larger collimator openings, leading to larger doses to distal tissues

Energy modulation

- 3D Energy modulation requires an “intelligent” way of proton energy shaping.
- It is usually accomplished through a weighted superposition of the individual Bragg peak doses with requirement to achieve SOBP
- This method requires a maintenance of a “huge” data file that contains all possible 3D Bragg peak depth-dose distributions
- It is possible to find an analytical form of the SOBP proton energy spectrum using Boltzmann kinetic equation

Calculation of SOBP distribution function

- Any practical implementation of the SOBP distributions is realized through the superposition of a discrete number of individual Bragg peaks.
- The weights for each individual Bragg peak can be readily calculated by integrating the continuous energy spectrum over the finite sampling size δ yielding

$$W_{mono}(E,\delta)=\left[\left(E_{\max}^2-\left(E-\frac{\delta}{2}\right)^2\right)^{\beta}-\left(E_{\max}^2-\left(E+\frac{\delta}{2}\right)^2\right)^{\beta}\right],\quad E_{\min}\le E<E_{\max}$$

$$W_{mono}(E,\delta)=\left(E_{\max}^2-\left(E_{\max}-\frac{\delta}{2}\right)^2\right)^{\beta},\quad E=E_{\max}$$

$$\beta=\left(0.43-0.05\frac{E_{\max}}{E_p}\right)-0.4\left(\frac{E_{\max}}{E_p}\right)^2\left(1-\frac{E}{E_{\max}}\right),$$

Accounting for finite energy spread

- The problem at hand is connected to finding “realistic” weights that would yield the required SOBP depth-dose profile through the superposition of the **poly-energetic** proton beamlets

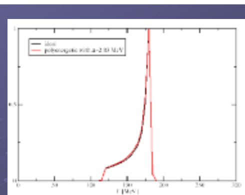
$$N(E)=\int N(E_i)\,\delta(E_i-E)\,dE_i$$

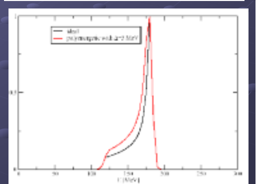
$$\delta(E_i-E)=\lim_{\Delta\to 0}\frac{1}{\sqrt{\pi}\Delta}e^{-\frac{(E_i-E)^2}{\Delta^2}}$$

$$W_{poly}(E,\Delta,\delta)=\frac{W_{mono}(E,\delta)}{\sqrt{\pi}\Delta}\delta$$

- Convolution of these weights with Gaussian distributions must yield an energy spectrum, which closely follows that given by the expression for the monoenergetic protons.

- Ratio parameter δ/Δ cannot be arbitrary
- For $\delta/\Delta > 1.7$, convolution of Gaussian distributions results in the energy spectrum that closely follow that for the mono-energetic particles.
- There is a threshold requirement on how wide the initial energy spectrum should be for the given sampling size δ, in order to obtain acceptable quality SOBP dose distributions

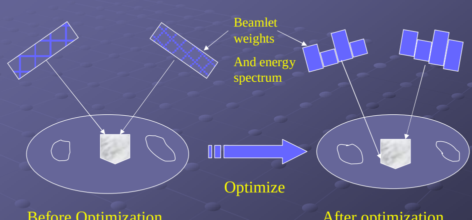




Summary-II

- 3D spotting scanning technique is a “natural” clinical delivery method for laser-accelerated proton beams
- The initial energy spread in the particle distribution has to be limited according to the condition $\delta/\Delta > 1.7$
- Particle dosimetry needs to be investigated because of extremely high instantaneous dose (many protons~10^9 are delivered per single laser shot).

Intensity modulation calculations



E. Fourkal, *et al*, Physics in Medicine and Biology Vol. 48, p. 3977, 2003

Results

- Two prostate cases have been studied:

  1. First case → the same 7-field arrangement and the same optimization parameters

  2. Second case → a comparative study using 2-field (parallel-opposed) and 3-field (parallel-opposed and anterior) IMPT on one hand and 7-field photon IMRT on the other.

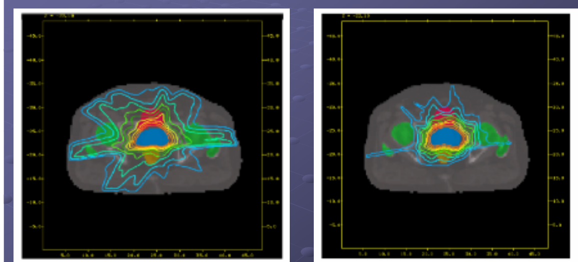
Table 1. Prescription/tolerance doses and weights for each volume of interest for the first case study.

Volume of interest	% of volume	Prescription/tolerance dose (Gy)	Relative importance
Prostate PTV	100	[illegible]	1.0
Prostate PTV	5.0	72.0	1.0
Prostate PTV	10.0	76.0	1.0
Rectum	90.0	10.0	0.5
Rectum	50.0	20.0	0.5
Rectum	10.0	30.0	0.5
Bladder	90.0	10.0	0.2
Bladder	50.0	20.0	0.2
Bladder	10.0	30.0	0.2
Femoral heads	90.0	10.0	0.2
Femoral heads	50.0	20.0	0.2
Femoral heads	10.0	40.0	0.2

Table 2. Prescription/tolerance doses and weights for each volume of interest for the second case study.

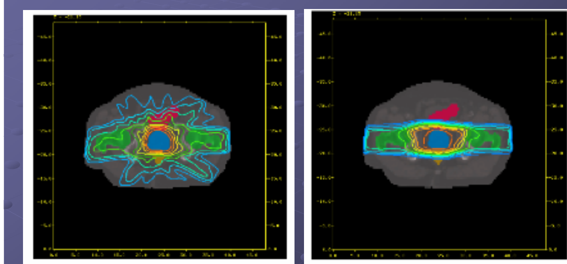
Volume of interest	% of volume	Prescription/tolerance dose (Gy)	Relative importance
Prostate PTV	100	71.0	1.0
Prostate PTV	5.0	72.0	1.0
Prostate PTV	10.0	75.0	1.0
Rectum	90.0	12.0	0.1
Rectum	50.0	22.0	0.1
Rectum	10.0	32.0	0.1
Bladder	90.0	12.0	0.09
Bladder	50.0	22.0	0.09
Bladder	10.0	32.0	0.05
Femoral heads	90.0	12.0	0.05
Femoral heads	50.0	22.0	0.05
Femoral heads	10.0	42.0	0.09

7-field IMPT versus 7-field IMXT



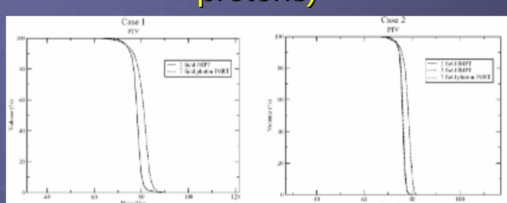
- Outermost line represents 20% of the prescription dose

2-field IMPT versus 7-field IMXT



- Outermost line represents 20% of the prescription dose

DVH distributions (photons versus protons)

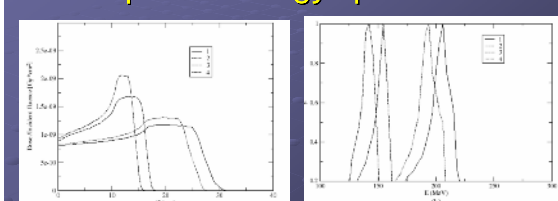


- 2-3 field proton plan yields 4.5 % target dose inhomogeneity,

$$\eta = \frac{D_5 - D_{95}}{D_{95}}$$

7-field proton plan exhibits 9.5 % dose inhomogeneity

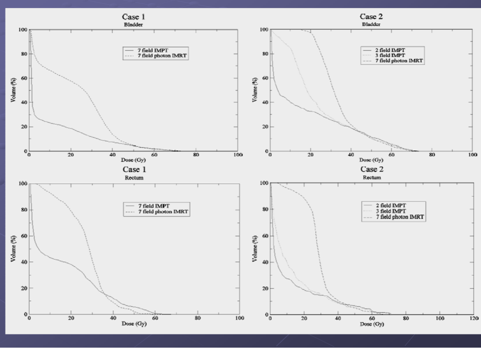
Correlation between the SOBP and proton energy spectrum



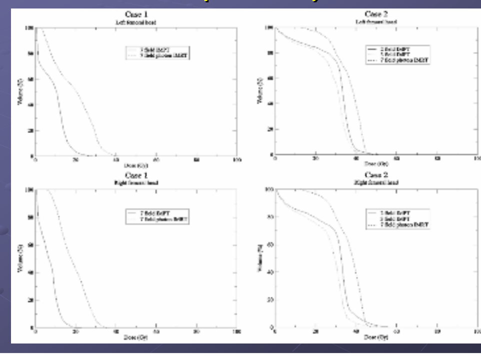
Superposition of proton beams with different energy spectra will lead to inhomogeneous total dose distribution

If there were no critical structures, the optimization algorithm would easily find the proper weight distributions that would give highly homogeneous dose

DVH distributions (photons versus protons)



DVH distributions (photons versus protons)



Mean doses to critical structures

Table 3. Mean dose to all normal tissues (Gy) for different particle modalities.

Particle modality	Case 1	Case 2
Photons	8.96	5.06
Protons	3.42	2.29

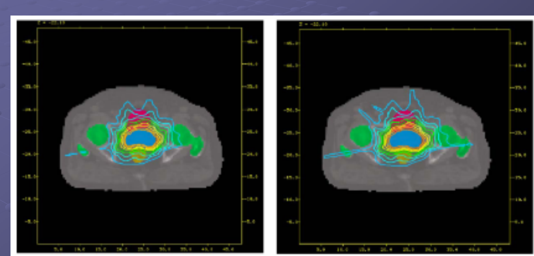
Table 4. Mean dose to the rectum (Gy) for different particle modalities.

Particle modality	Case 1	Case 2
Photons	27.52	28.68
Protons	15.17	10.64 (2-field), 12.89 (3-field)

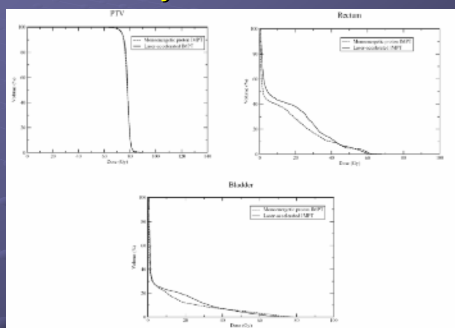
Table 5. Mean dose to the bladder (Gy) for different particle modalities.

Particle modality	Case 1	Case 2
Photons	22.79	33.46
Protons	8.4	16.3 (2-field), 23.54 (3-field)

IMPT using LAP versus IMPT using cyclotrons



IMPT using LAP versus IMPT using cyclotrons



Summary

- Laser-accelerator-based technology has a potential of providing radiation therapy plans that are superior to those using photon beams and comparable to plans generated using conventional proton accelerators
- Dosimetric limitations of LA based therapeutic beams stems from the initial physical characteristics of the accelerated protons (energy spectrum, angular distributions etc.)
- The possibility of generating better quality proton beams with low initial energy spread can lead to even better dosimetric characteristics of the final proton beams