Laser-Driven Targetry:
The Road to Clinical Applications

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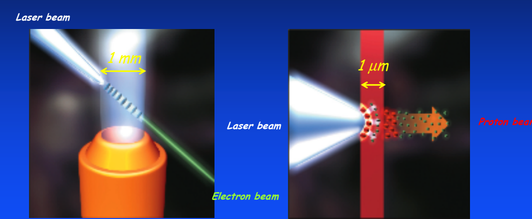
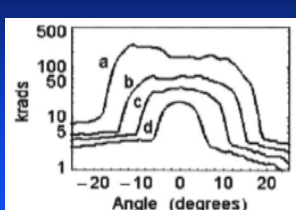
Laser Plasma Acceleration for Electrons and Protons



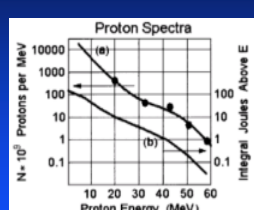
Ma et al Med Phys (2006) POINT/COUNTERPOINT

Laser Proton Acceleration at LLNL

Proton angular distribution



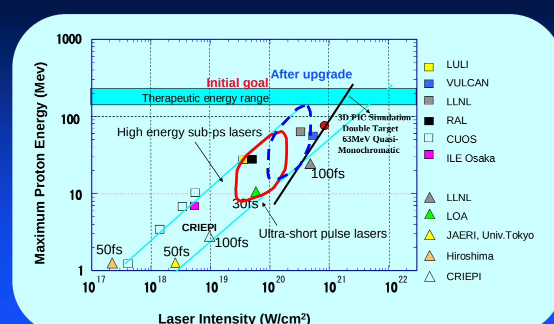
Proton spectrum



Snavely et al Phys Rev Lett (2000)

Present status of the proton generation(2004)

Laser proton acceleration: intensity vs energy



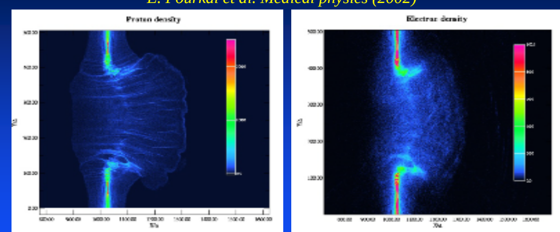
Theoretical Results

Particle in cell (PIC) simulation results (Ueshima 1999b) on ion and electron acceleration by laser irradiation on three thin targets. A laser intensity of 10^{21} W/cm^2 on the target surface is applied.

	Case 1	Case 2	Case 3
Energy conversion	50%	24%	31%
Ion	4%	8%	14%
Electron	48%	16%	17%
Peak energy H^+	200 MeV	400 MeV	400 MeV
Peak energy Al^{10+}	1 GeV	2 GeV	2 GeV
Peak energy electron	25 MeV	15 MeV	20 MeV
Average energy H^+	58 MeV	95 MeV	115 MeV
Average energy Al^{10+}	130 MeV	500 MeV	500 MeV

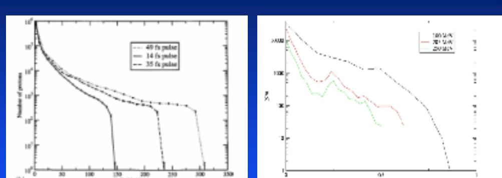
Proton and Electron Densities (t=100 fs)

E. Fourkal et al. Medical physics (2002)



Electrons and protons expand ballistically into vacuum

Energy and Angular Distribution

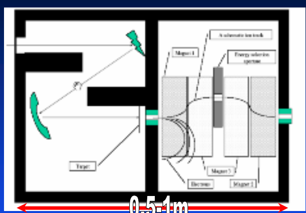


There is a large spread in energy and angular distribution.

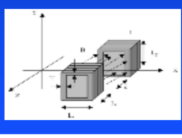
E. Fourkal et al. Medical physics (2002)
V. Malka et al., Med. Phys. 31, 6 June (2004)

Particle Selection and Beam Collimation

Particle Selection and Beam Collimation

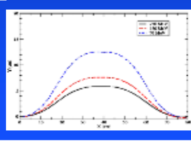


Ma (2000)
Movable aperture to select protons of desired energy with sharp beam penumbra



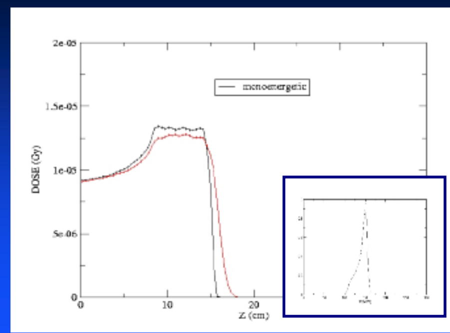
Nb_3Ti superconducting coils can provide I = 85 A per loop with magnetic field to 4.4 Tesla by Biot-Savart law:

$$B = \oint \frac{\mu_0 I dl \times r}{4\pi r^3} = \sum_i^4 \int \frac{\mu_0 I dl \times r_i}{4\pi r_i^3}$$



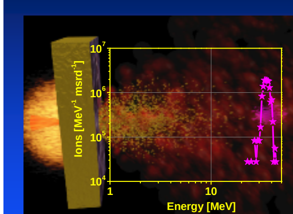
Luo et al Med Phys 2005

Combined Dose Distribution



Energy and Dose Rate

Monoenergetic Laser-driven Ion Beams



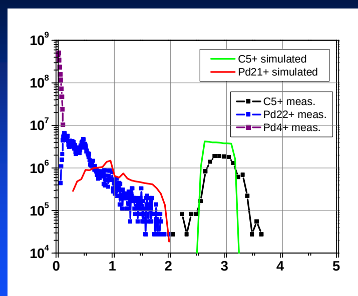
LETTERS

Laser acceleration of quasi-monoenergetic MeV ion beams

Demonstration and modelling of monoenergetic carbon ions from shortpulse driven laser acceleration.

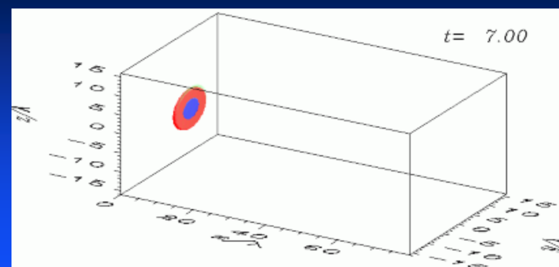
Experiment:
30 TW LANL Trident laser using ~20 µm palladium targets.

Simulation:
Hybrid code BILBO (Backside Ion Lagrangian BlowOff), parameters set to match experiment.



Hegelich *et al.*, Nature **439**, 441 (2006)

Monoenergetic Proton Acceleration



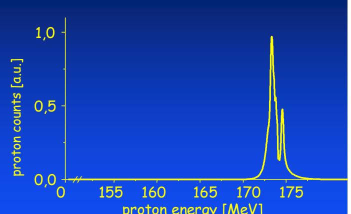
Courtesy of S. Bulanov

Monoenergetic proton acceleration

Future steps to improve results:

PIC-Simulation for POLARIS:

- E =150 J, τ = 150 fs, d_{foc} = 10µm ⇨ P ~ 1 PW
- d_{dot} = 2,5 µm, s_{dot} = 0,1 µm
- obtain peak at E = 173 MeV with DE/E ~ 1%
- total proton number ~ 10^9
- Reduce dot size
  - better localization of dot within homogeneous field
  - higher stability
- Increase laser power
  - for sufficient thin targets cutoff energy scales with E_{cut} = 230 MeV x $(P_{laser}/1\ PW)^{1/2}$



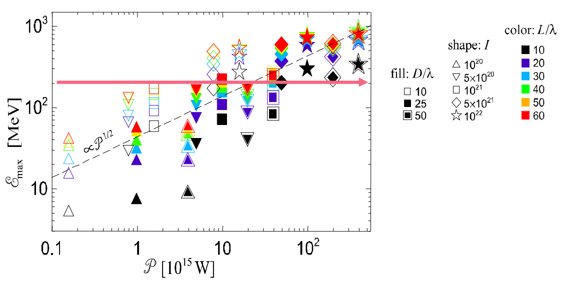
Courtesy of R. Sauerbrey

Indications of a multi-parametric scaling law

Experiments with foil targets at intensity 10^{18} - 10^{20} W/cm^2 show that the ion energy depends on

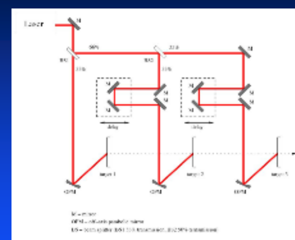
	model parameters
intensity (e.g., $\mathcal{E}_{max} \propto I^{1/2}$) →	dimensionless amplitude $a=eE/m_e\omega c$
foil thickness, **material**, **pulse contrast** →	effective plasma density, n_e; effective plasma thickness l
focal spot size →	focal spot size D
laser polarization →	fixed (p-polarized)
target geometry →	fixed (planar)

Ion max. energy vs. laser energy and power



[Timo.Esirkepov et al., PRL 96, 105001, 2006]

Multistage proton acceleration

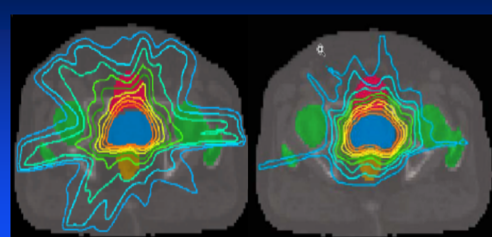


Up to 100% increase in max. proton energy with multistage stages.

Veltchev et al 2007

Treatment Optimization

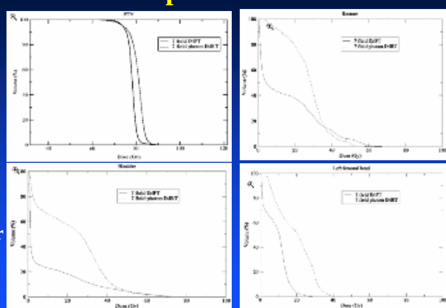
Comparison of Isodose Distribution



7 field IMRT | 7 field laser protons

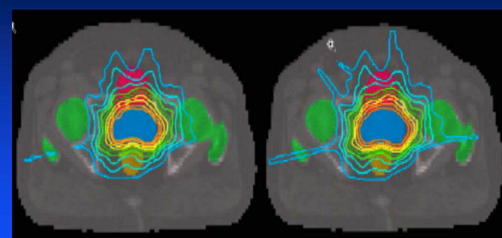
Fourkal et al 2003

Comparison of DVH



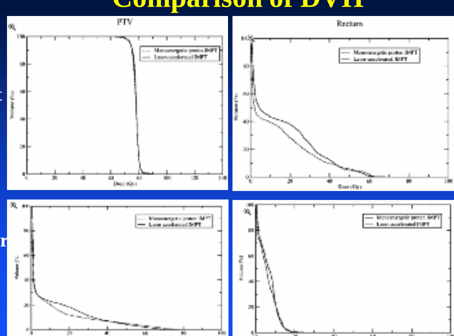
Target Rectum
Bladder Femur

Comparison of Isodose Distribution



7 field IMPT(mono-E) 7 field laser protons

Comparison of DVH

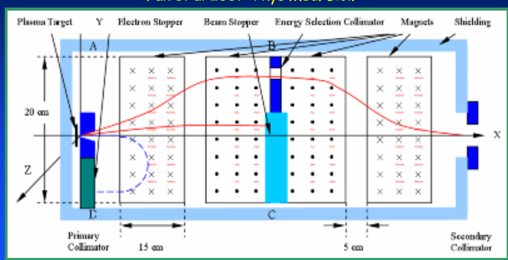


Target Rectum
Bladder Femur

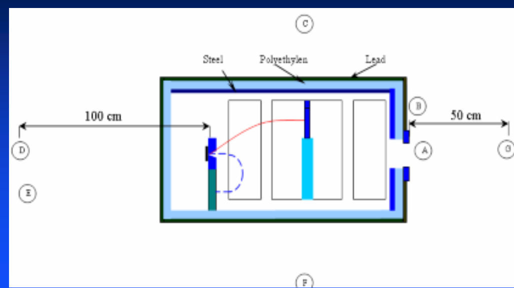
Shielding for the Treatment Head

Secondary Sources for Shielding Considerations

Fan et al 2007 Phys Med. Biol.



Head Leakage Measurement



0.5cm steel, 10cm polyethylen, 3cm lead

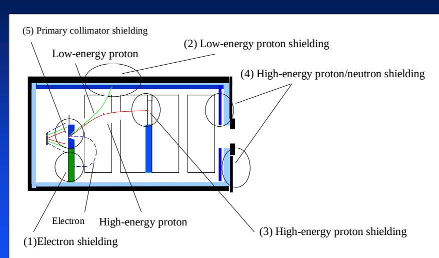
Head Leakage Dose

Table 1. Dose equivalent per therapeutic absorbed dose H/D, in units of Sv/Gy around treatment head.

	Proton beam		Electron beam	
Detector	Neutron	γ -ray	X-ray	Total
B	9.72E-04	5.00E-06	0.00E+00	9.77E-04
C	8.29E-04	1.30E-05	3.60E-05	8.78E-04
D	3.71E-04	8.00E-06	1.64E-04	5.43E-04
E	3.59E-04	1.40E-05	1.94E-04	5.67E-04
F	4.46E-04	1.00E-05	4.80E-05	5.04E-04
A	6.41E-03	1.40E-05	3.70E-05	6.46E-03
G	1.86E-03	1.00E-06	0.00E+00	1.86E-03

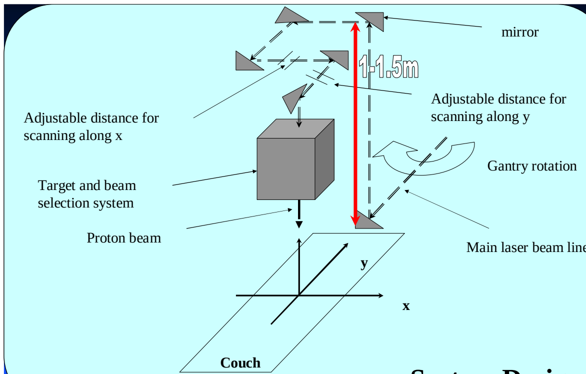
Leakage dose < 0.1% of treatment dose

Shielding Issues for Laser-Accelerated Protons



Fan et al 2007 Med Phys Biol

System Design

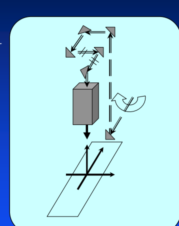


System Design

Ma 2000

The Cost of a Laser-Proton Unit

- The building/shielding – \$0.5million × N
- The high-power laser – \$2-3million
- The gantries - \$1-2million × N

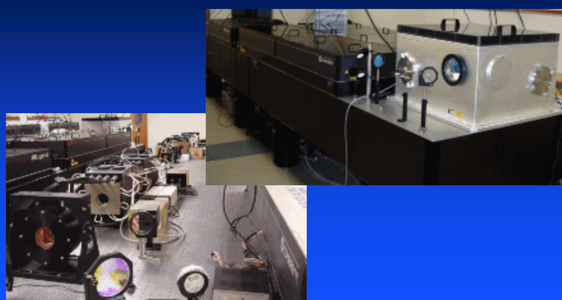


The cost of a carbon unit will be slightly higher!

The Laser-Proton Facility

- Renovation completed in June 2005
- An off-campus facility for experimental studies
- Laser/target chamber/shielding installed/commissioned in Sept 2006
- Research laser-proton accelerator license granted by the State

The FCCC Laser System



The Experimental Setup

The FCCC Laser-Proton Team

- Dr. Charlie Ma — Program director
- Dr. Eugene Fourkal — Physicist, target and PIC studies
- Dr. Jason Li — Physicist, dosimetry and treatment planning
- Dr. Iavor Veltchev — Physicist, laser physics research
- Dr. James Fan — Physicist, shielding calculations, Monte Carlo
- Dr. Teh Lin — Physicist, laser-proton acceleration.
- Dr. Alain Guemnie Tafo — RA, laser-proton acceleration experiments.

CM EF JL IV JF TL AGT

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