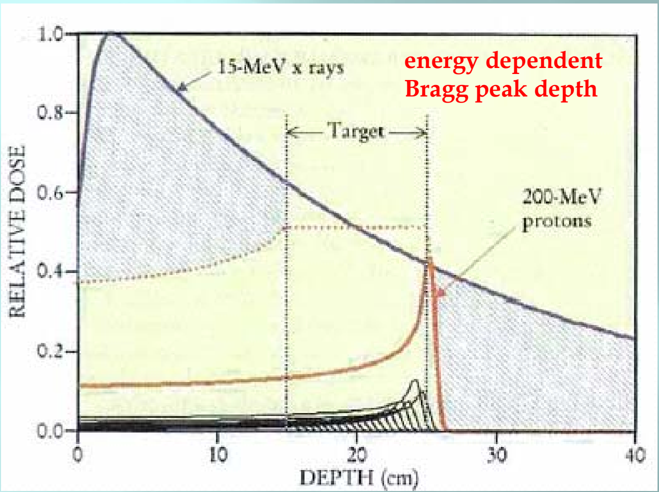
LASER-DRIVEN PROTON ACCELERATOR DEVELOPMENT AT THE PHOTO-MEDICAL RESEARCH CENTER IN JAPAN

Paul R. Bolton,
Photo-Medical Research Center,
Japan Atomic Energy Agency

ICUIL2008 , October 27-31, Shanghai, China

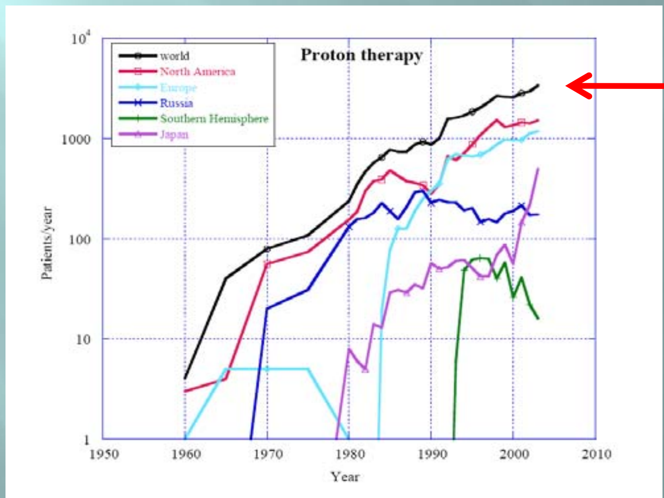
The Case for Hadron Radiotherapy: Benefits and Need are Clear

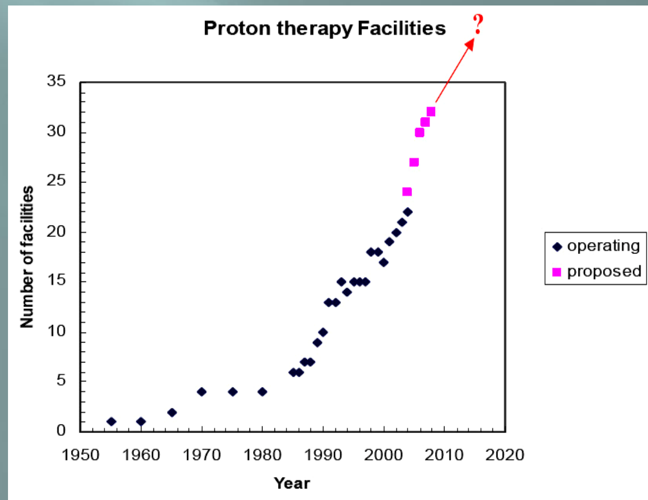


" It is no exaggeration to say that the history of radiotherapy is the history of struggling to improve the dose localization and cell killing effects of radiation " M. Abe in Proc. Jpn. Acad. Ser B83 [6], 151 (2007).

shallow tumors (ocular melanoma) can require ~ 40-60 MeV protons and deeper tumors can require ~ 250 MeV protons

add laser-driven proton treatment facilities to this growing list

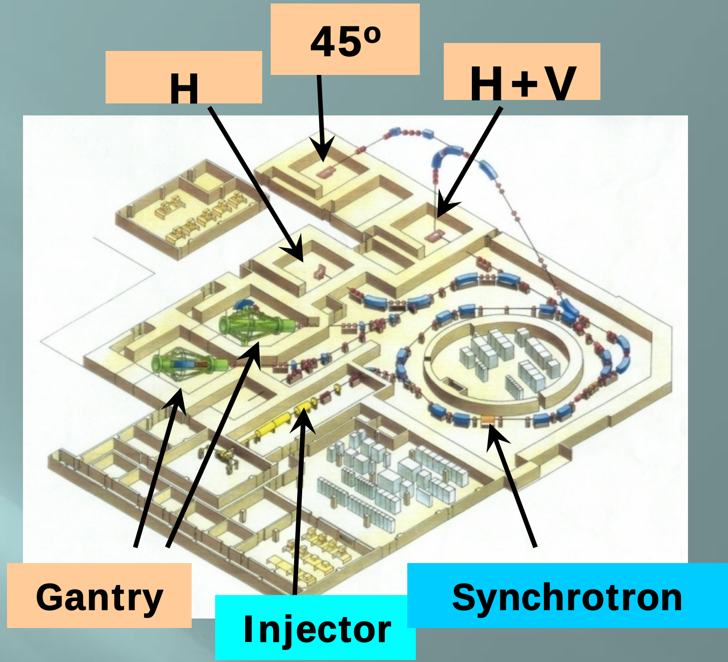


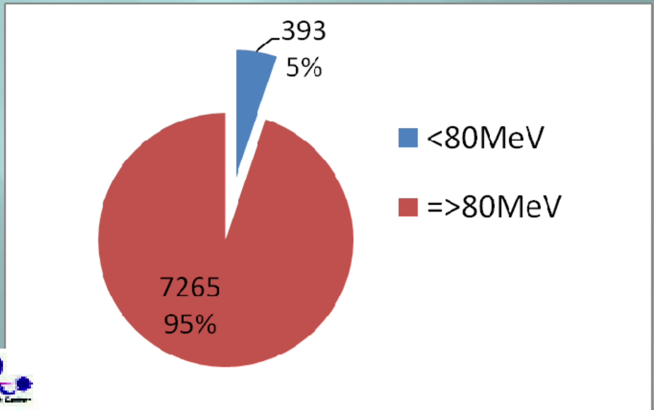


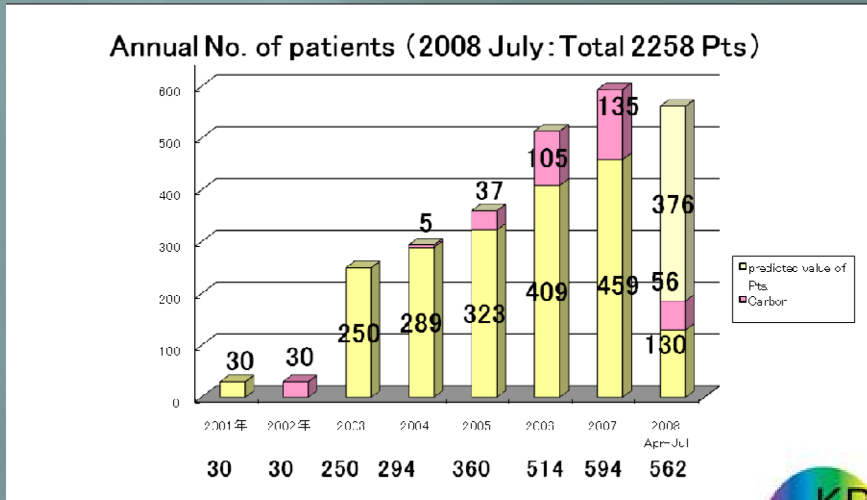
V. Khoroshkov and G. Klenov, International Workshop on Laser-Driven Ion Sources Applied to Industry and Medicine, March 17-21, 2008 KPSI,PMRC,JAEA

Irradiation System at HIBMC: 2634 Patients Treated with Proton and Carbon Ions Within Past 7 Years *

Building (w/o hospital)	$12{,}000 m^2$
Synchrotron circum.	93.6m
# of treatment rooms	Gantry x 2 H+V H (small field) 45 deg. Diagonal
Ions / Energy	P 70 – 230MeV (150, 190, 230) C 70 – 320 MeV/u (250, 320)



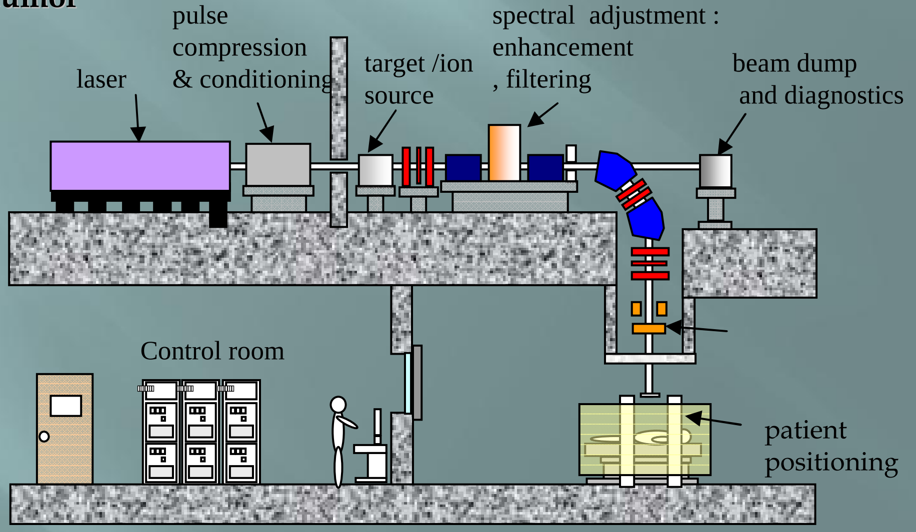




** Courtesy of Dr. M. Murakami, HIBMC*

Why Laser-Driven Protons ?

- laser pulse control of proton irradiation (direct control ir-vis photons instead of energetic protons)
  - bunch charge, energy
  - highly laminar bunches - small spotsizes and pencil beam generation (50-200 microns)
  - high peak current - short duration with high charge
  - repetition rated operation with fast-off switching (due to laser pulse duration)
- laser-driven PTF can be more compact than current ion accelerator technology, enabling placement within hospital infrastructures thus improving access to treatment with potential for significant cost reduction
- **medical imaging diagnostics can be more local (in-beam) and prompt (eg. use of abundant, shorter lifetime positron emitters for PET with larger detection solid angle)**
- **potential for enhanced capabilities for the radio oncologist – biologically conformal radiation therapy (BCRT) that is tailored to specific tumor**
- **can be safe, reliable and efficient**



sketch by H. Sakaki, PMRC

PMRC: A FAMILY OF PARTNERS

PMRC is a JAEA program fostered by KPSI and funded by both PMRC corporate partners and by JAEA through *"The Special Coordination Fund (SCF) for Promoting Science and Technology commissioned by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan"*

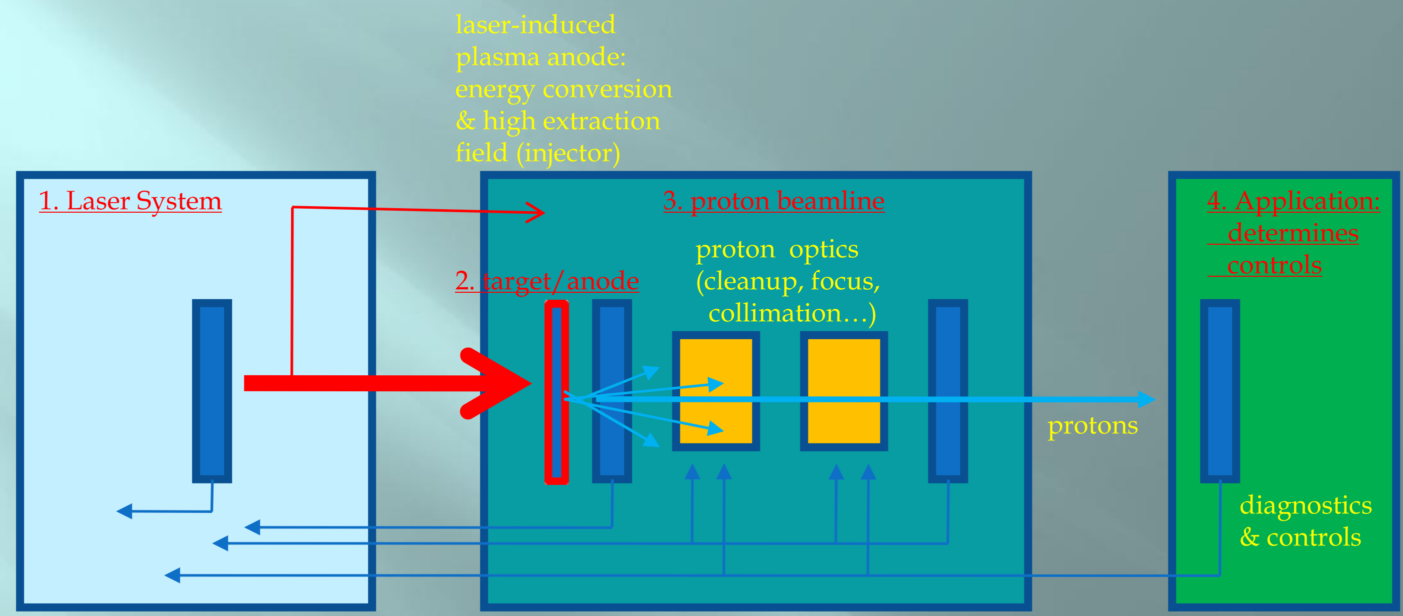
R&D hub that promotes collaboration and cooperation with industrial, academic, medical, and government partners aimed at innovation in medical and photonic technologies

Targeted Innovation in a community setting: creates and fosters technical innovation for industry and medical science with our community as an implicit partner

Intrinsically interdisciplinary: training , outreach

Flagship Theme: Development of a Compact Laser-Driven Proton Treatment Facility, in particular ,early stage treatment of small and superficial tumors that is safe, reliable and efficient

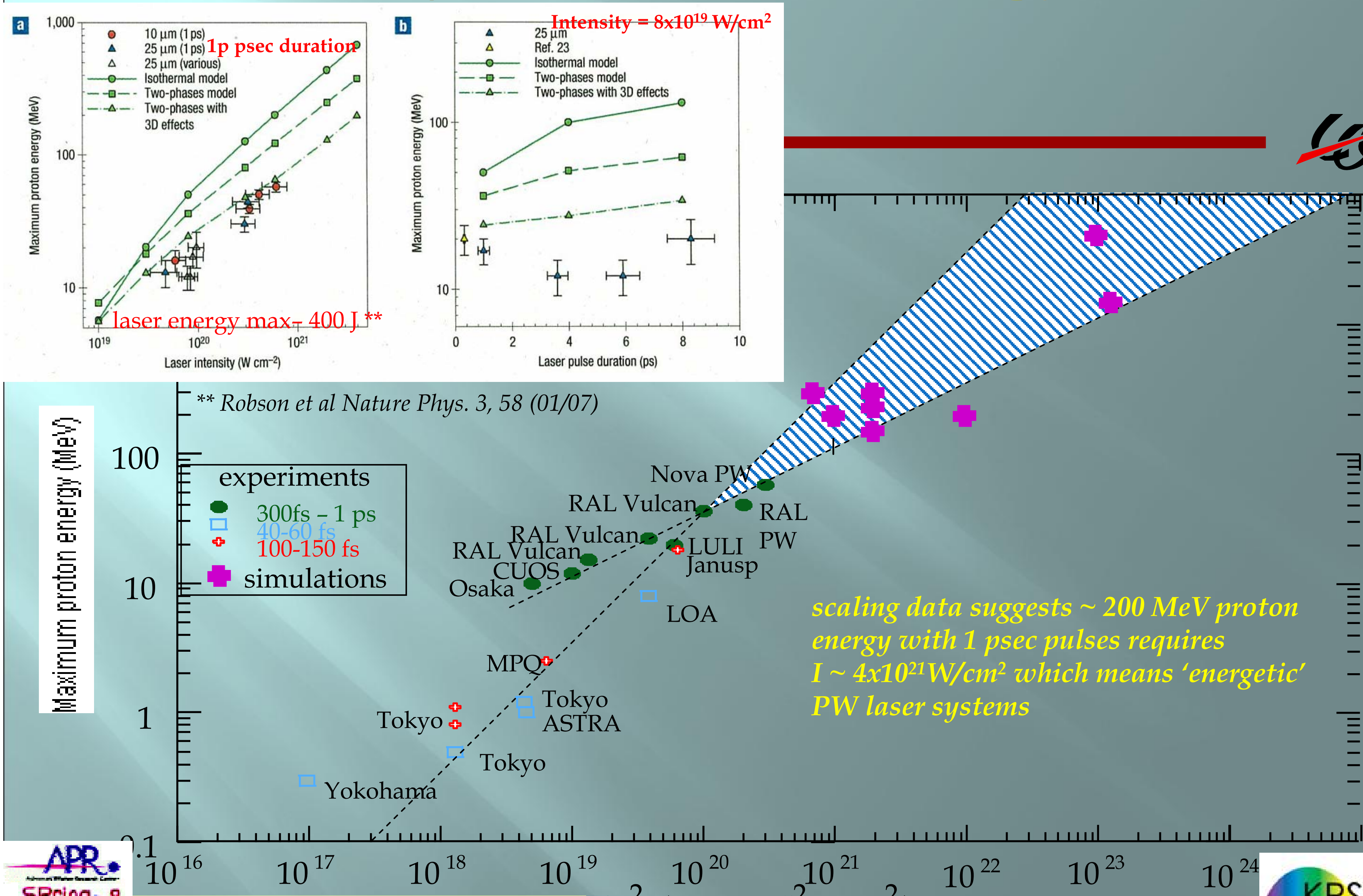
Integrated Laser-Driven Proton/Ion Accelerator Systems at PMRC (ILDIAS)



ILDIAS:

- integrated high power laser and accelerator technology (for compact systems)
- generic beamline designs
- laser pulse tailoring (shaping, prepulse control, ellipticity control…)
- diagnostic s - conventional and innovative with feedback capability
- optics - conventional and innovative (eg. plasma micro-lens *(Toncian et al Science 312, 4190 (2006))*
- controls – steering, energy, flux (repetition rated systems, separable controls, algorithmic…)
- medical guidance on control requirements/algorithms (tracking tumors…)
- target development/design
- design to applications (medical is most important and source of key guidance)
- gantry design issues
- new applications
- conventional accelerator comparisons

Precent status of laser-accelerated protons: maximum energy *



J. Fuchs et al., Nature Physics **2**, 48 (2006)

* Courtesy of Julien Fuchs

Evolving Target Design: Support High Acceleration Gradient and Efficient Conversion to High Peak Current

- thin foil targets:
  - Al, Cu, Ti and Au are common
  - polyimide tape
  - thicknesses from 10's nm to 10's microns
  - areas ~ laser spotsize have been studied ***

- maximum proton energy and total energy conversion efficiency can increase with decreasing target thickness
  - because of increased hot electron density and higher accelerating field at target rear (downstream) surface

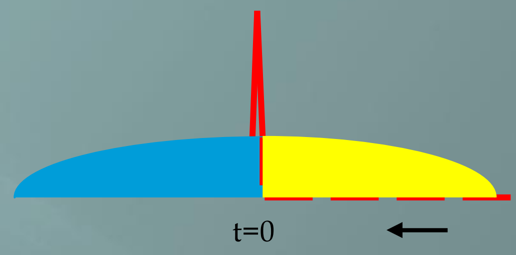
- prepulse control of targets:
  - optimum thickness decreases with lower prepulse
  - adequate prepulse intensity can drive a shock wave that can distort/ionize the target rear surface, forming a long scale length plasma that can inhibit proton acceleration
  - adequate control of laser prepulse level to *contrast ratios* $< 10^{-10}$ and of prepulse *duration* are shown to be critical

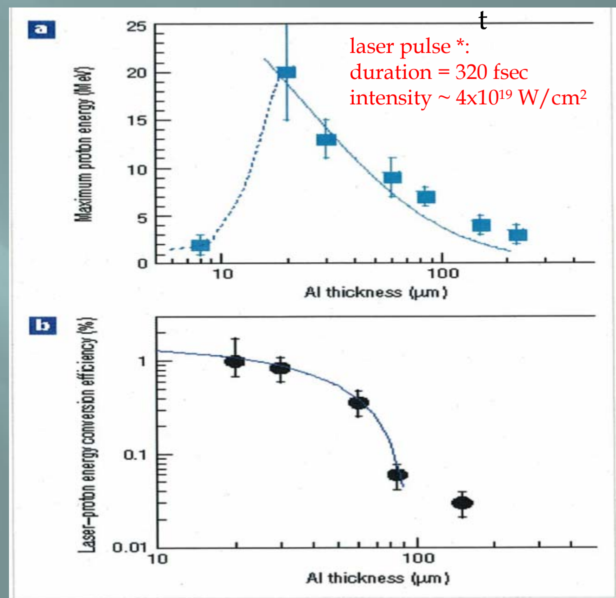
$$d_{target} > V_{shock}\tau_{prepulse}$$

$$I_{prepulse} \approx 10^{12} - 10^{13}\frac{W}{cm^2} \rightarrow P_{shock} \approx 1-2\ Mbar\ \&\ V_{shock} \approx 10^6 cm/sec$$

- nanotubes and curved target surfaces

- repetition rated operation mandates regenerative feature:
  - gas and cluster targets as ion sources
  - moving polyimide tape

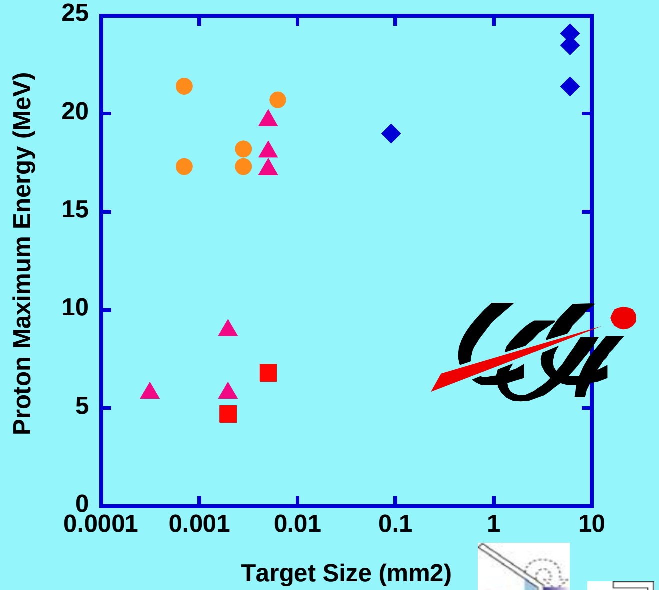


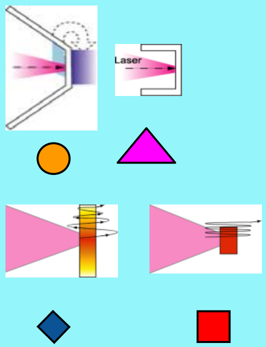


* J. Fuchs et al., Nature Physics 2, 48 (01'06)

Assessing Structured Targets

Recent LULI/PMRC experiments
Scaling Target Size *



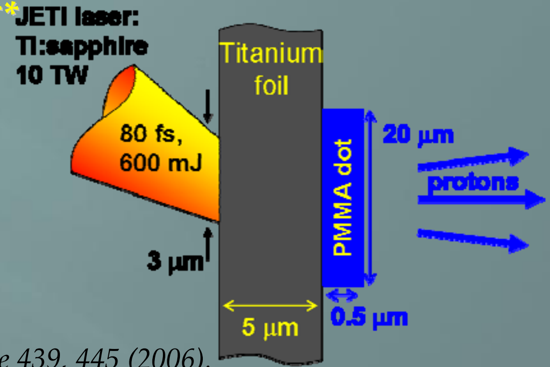


intensity ~ 4x10^{19} W/cm^2
energy ~ 30 Joules at 1053 nm
spotsize ~ 10 microns
(30% energy)
duration ~ 300-400 fsec
contrast ~ 10^{-8}
P polarization

** Courtesy of J. Fuchs (LULI) and M. Tampo (PMRC)*

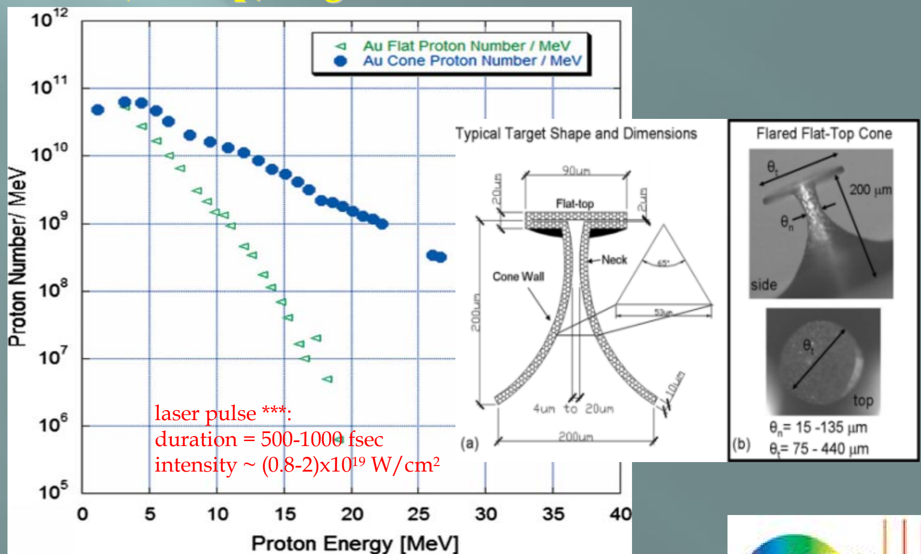
structured targets (nano and microfabrication):

Proton rich layers - improved efficiency and peaked spectra (~ MeV at 10^{19} W/cm^2) with proton rich using PMMA dots (0.5 micron) on rear foil surface of 5 micron Ti foil **



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

cone (flat-top) targets ***

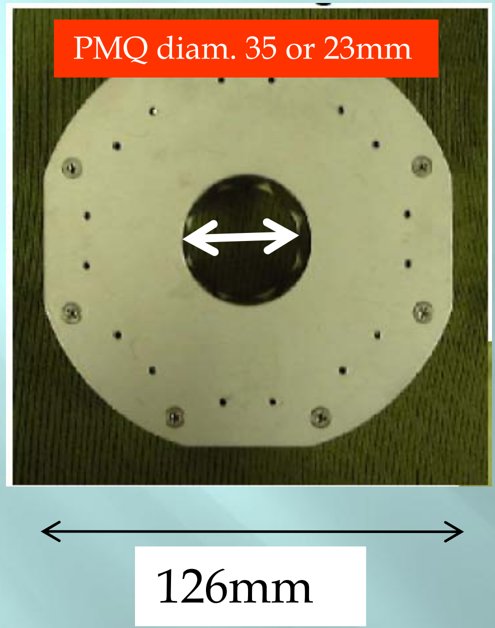


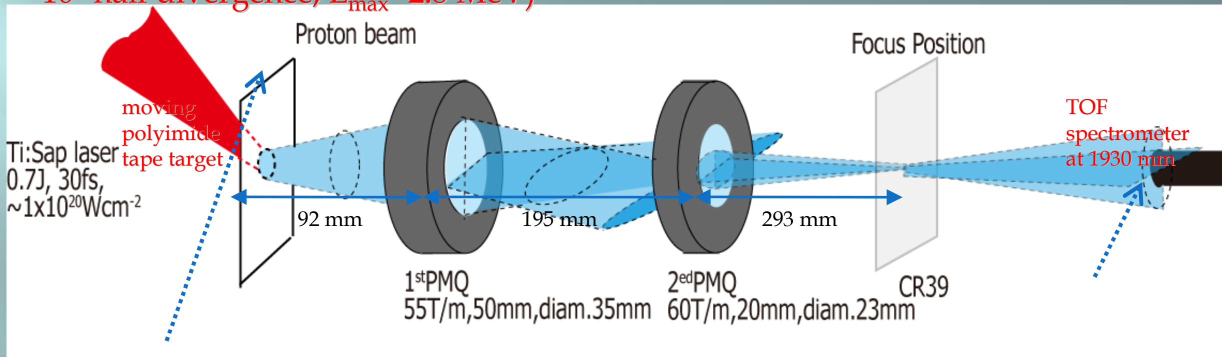
**** K.A. Flippo et al., Phys. Plasma. 15, 056709 (2008).*

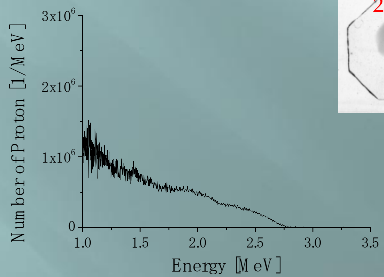
Laser-Driven Proton Focusing: Single Shot and Repetition-Rated Demonstrations *

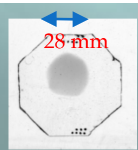
Stable , 1Hz proton source from a polyimide tape target is focused with conventional PMQ pair

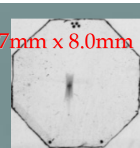
(~10^7 protons at 2.4 MeV (0.2 MeV slice); 10° half divergence, E_{max}~2.8 MeV) (large aperture PMQ's for 0.5 MeV design)

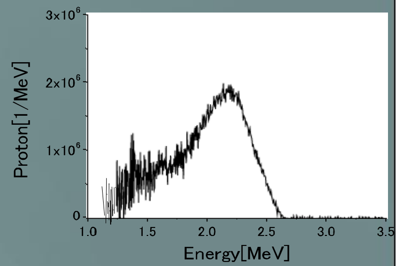








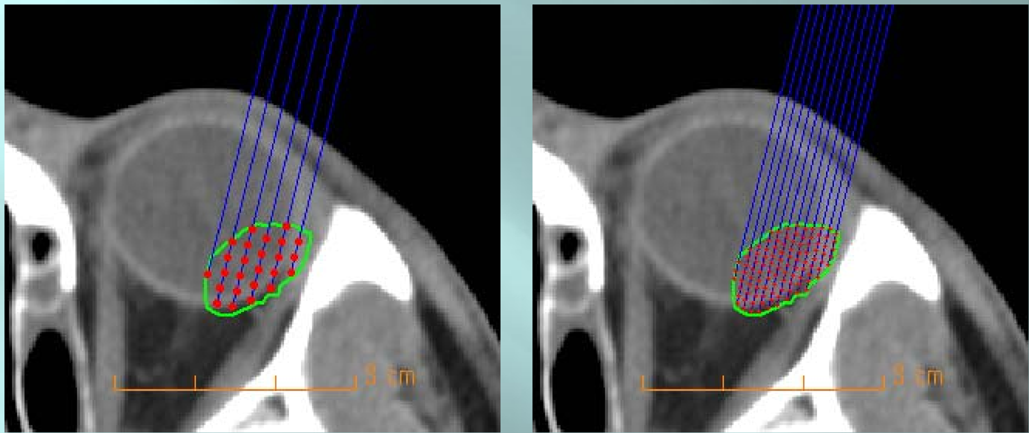




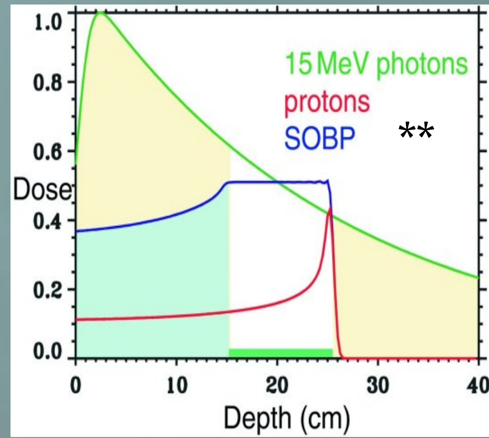
Single-shot results recently reported at 14 MeV (M. Schollmeier etal., PRL 101, 055004 (2008))

* *courtesy of M. Nishiuchi, KPSI/PMRC*

Dose Distribution Simulations for Ocular Melanoma *

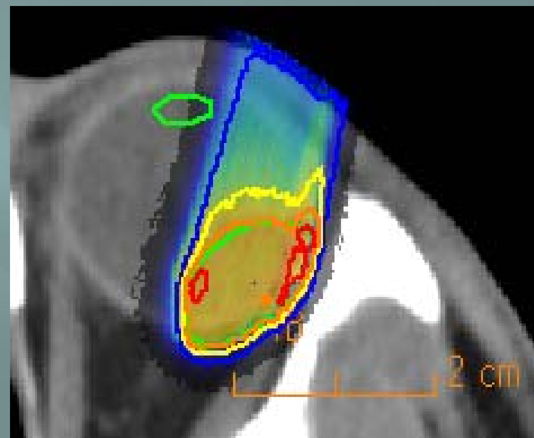


Beam diameter and energy spread determines
the number of target spots for spot scanning



Proton radio therapy via 'spot scanning'
requires precise proton beam control:

- beam diameter
- beam steering and lateral offset
- correlated particle energy variation
  (to obtain a Spread Out Bragg Peak, SOBP)
- correlated flux control
- controlled shut off capability
- prompt feedback/confirmation is valuable (PET confirmation)
- beam control procedures and beam requirements from medical community



Dose distribution for ~ 40-60 MeV protons with
beam diameter of few mm (using ~ 10^6 protons)

** Ken Sutherland at Hokkaido University Hospital has developed applications for examining energy, energy spread, beam diameter and beam spacing effects in spot scan simulations with laser-driven proton beams*

*** Courtesy of Dr. M. Murakami, HIBMC*

Dose Distribution Simulations for Ocular Melanoma: Typical Results *

Estimating # of protons of therapeutic relevance (relevant protons) per laser pulse, N :

$$N = \frac{DM}{fRT\varepsilon}$$

absorbed dose in Gy (J/kg)

tumour mass (kg)

single particle kinetic energy (J)

radiation interval (sec)

laser repetition rate (pps)

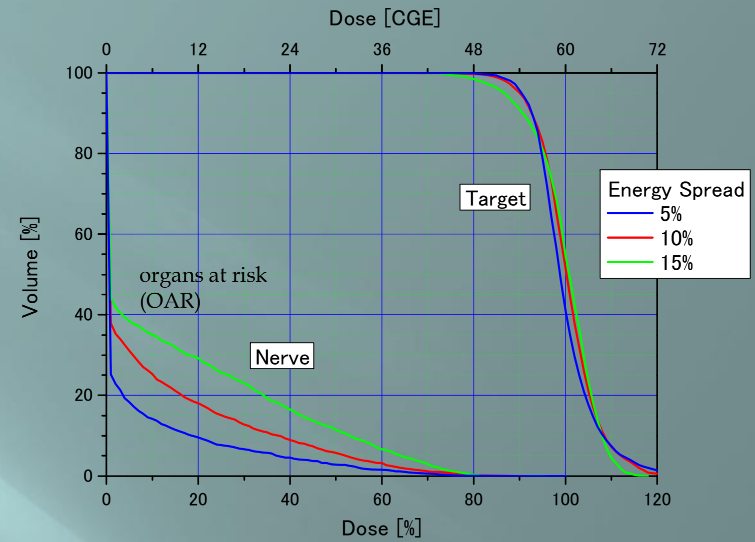
# of fractions (radiation sessions)

ocular example: $N \sim 10^5$

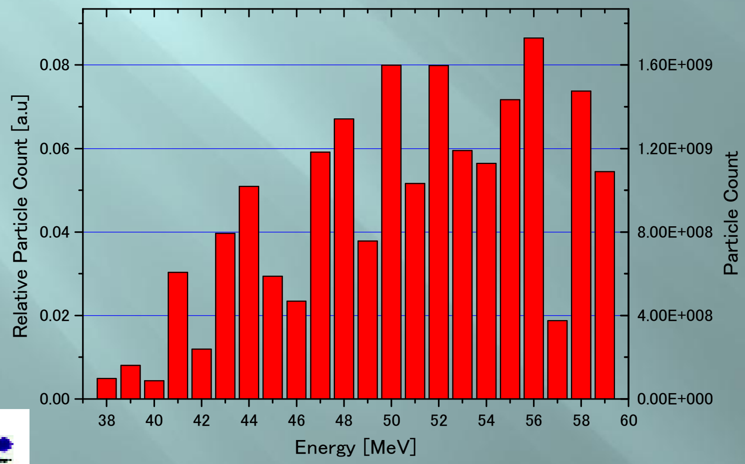
for D = 55 Gy, M= 1 gram,

proton energy ~ 40 - 60 MeV

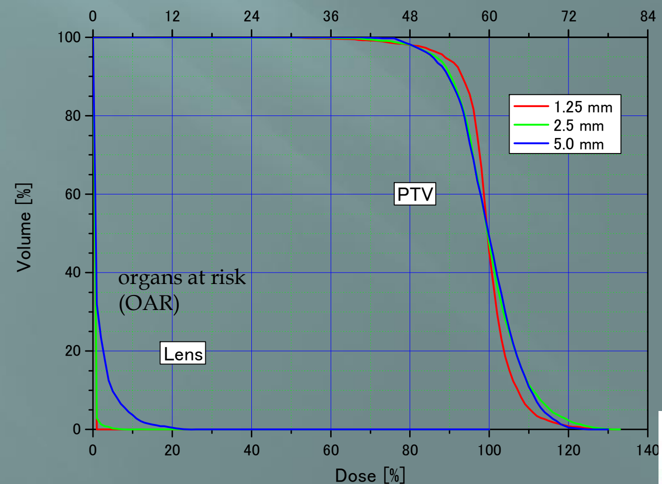
and f R T = 10^5 (with R = 100 Hz)



Dose-Volume Histograms, DVH
(target is ocular melanoma site on retina)



Simulated treatment proton spectrum



* *courtesy of Ken Sutherland, Hokkaido University Hospital*

PMRC News

Volume 01 [Issue 03] of November 28, 2008

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Next issue contributions due by October 18, 2008

In summary…

- Program of parallel efforts
  - TW - PW experiments at KPSI (yields from thin foils, clusters….)
  - laser development (PW upgrade for J-KAREN…)
  - PMRC partners (laser development, proton beamline prototyping…)
  - key collaborations with medical community (PET, simulations…)
  - science agenda development (include nonmedical applications that expedite goals)
  - ILDIAS – new group
  - aggressive outreach

- Technical challenges:
  - compact proton beamline development
  - compact laser development and pulse tailoring
  - target development – proton flux, energy, divergence, repetition-rated capability
  - proton diagnostic advancement with prompt readout and control capability
  - control algorithms – for laser systems and beamlines (key guidance from medical community)
  - close coupling with nuclear medicine training and education – interdisciplinary

- PMRC welcomes your help…

Thankyou