TOWARD INTEGRATED LASER-DRIVEN ION ACCELERATOR SYSTEMS AT THE PHOTO-MEDICAL RESEARCH CENTER IN JAPAN

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OUTLINE

The Case for Ion Beam Therapy

What is PMRC?

Integrated, laser-driven ion accelerator systems (ILDIAS)

Laser intensity (power) requirements for acceleration of protons

Laser development at PMRC

Proton yield and beamline design

Applications of current interest

Important R&D requirements for a laser-driven proton beam facility

Closing Comments

PMRC News
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The Case for Ion Beam Therapy (IBT): 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.

Goal is to ultimately 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,JAEE
PMRC: STARTED IN 10/07 AS 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, institutional 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 intrinsic partner

Intrinsically multidisciplinary: training, outreach are critical

Flagship Theme: Development of a Compact Laser-Driven Proton Treatment Facility (PTF), in particular, for early stage treatment of small and superficial tumors that is safe, reliable and efficient
Integrated Laser-Driven Ion Accelerator System at PMRC (ILDIAS) – Critical Next Step

**ILDIAS**

- **Laser System**
  - driver, probe master clock, laser role in target definition

- **Target / Injector**
  - plasma anode and site of energy conversion, source and extraction, target as a proton optic

- **Proton Optics for Transport**
  - beam cleanup, collimation, focusing, spectral filtering, shielding, diagnostics and controls, gantry

- **Proton Optics for Delivery**
  - collimation/focusing, moderation, gantry, scanning, motion tracking, dosimetry, shutter

- **Patient Treatment:**
  - treatment planning imaging, PET,…

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Integrated, Laser-Driven, Ion Accelerator System (ILDIAS): develop a systems mindset

- laser development plus unique broadband diagnostics
- target development (repetition-rated)
- beamline optics for transport and irradiation delivery for a PTF
- beam cleanup, stabilities, dosimetry
- diagnostic and control system development suitable for the accelerator and for a PTF
- detailed guidance for performance requirements by medical community is critical
- compatibility with cancer treatment technologies (PET and other imaging…)
- ‘shakedown’ philosophy where we need to know as soon as possible what is impossible

Need sustained coordinated effort from three main communities: medical, laser/laser-plasma, and accelerator
Laser Intensity (Power) Requirements for Acceleration of Protons
Ion Acceleration by Laser-Driven Charge Separation at High (Relativistic) Intensity

Target

Laser pulse

ions

charge separation → electrostatic field → ion acceleration

Collective field phenomena

Transverse Normal Sheath Acceleration (TNSA): \( I \sim 10^{18} - 10^{21} \text{ W/cm}^2 \)

Radiation Pressure (RP) / Laser Piston (LP) *: \( I \sim 10^{22} - 10^{24} \text{ W/cm}^2 \)

very high conversion efficiency scales with laser pulse energy and can approach 100 %

In addition to proton and electrons there are ions, x-rays, laser light….

\( I = 10^{18} - 10^{24} \text{ W/cm}^2 \)

figures courtesy of T. Esirkepov, KPSI

* T. Esirkepov et al PRL 92, 175003 (2004),

Laser-driven result is a complex, abrupt (picosecond) laminar proton ‘spray’ with:

- high peak current (100 KA – MA at source)
- small source size (energy dependent) and low emittance
- energetic protons with large energy spread (~ 100 %)
- large divergence (energy dependent)
- background particles and photon radiation
Laser Needs for 100 MeV (a major challenge):
- peak power ~ 1 PW
- pulse duration, 100’s femtoseconds
- pulse energy, ~ 100’s Joules
  (focused to ~10 micron spotsizes)
- peak intensity, few x 10^{21} Watts/cm^2
- repetition rate, 10 Hz - 100 Hz
  (depends on proton charge from single laser pulse)
Clean pulses - prepulse energy must be greatly suppressed.
Peak power (energy) alone is not enough.
Pulse 'Tailoring' and Compact!!
Two Parallel Paths: 1. highest achievable peak power lasers at J-KAREN (scaling experiments for proton yield to determine single laser pulse requirements best targets and appropriate diagnostics)

II. high average power (repetition-rated) lasers (development of a test beamline at available energies, for medical/biological investigations, nonmedical science and technology, scaling to a medical prototype)

Laser Pulse ‘Tailoring’: pulse shaping (includes ‘cleaning’ to improve contrast) (finesse engineering) diagnostic development (laser and plasma correlated to proton yield) options for laser control of proton beam *high pulse energy and peak power are not enough*
Laser Development I: Chirped Pulse Amplification (CPA) for ~ 0.5 PW Peak Power at J-KAREN

J-KAREN; JAEA Kansai Advanced Relativistic ENgineering

Laser Development I: J-KAREN is Not Compact

- Nd:glass pump lasers (~80J, Single-shot)
- Ti:sap. booster amplifier (~40J, Single-shot)
- Compressor (~30J, ~30fs, ~PW)
- Compressor (~1.7J, ~30fs, ~60 TW, 10Hz, ~10^10)
- Cryogenic-cooled Ti:sap. power amplifier (~3J, 10Hz)
- Ti:sap. preamplifier
- OPCA preamplifier
- Stretcher (~μJ, ~ns)
- Saturable absorber
- 6 Nd:YAG pump lasers (~7J, 10Hz)

courtesy of H. Kiriyama

振興調整費
0.5 PW Upgrade: Diffractive Optical Element (Homogenizer) Generates Top-Hat Intensity Profile at 100 J level (Green)

- View of beam homogenizer
- Green beam
- Diffractive Homogenizer
- SILIOS Technologies

Large Aperture Booster Amplifier for ~ 0.5 PW: IR Pulse Energy Up to ~ 31 J

✓ View of Ti:sapphire final amplifier

✓ Extraction energy

Experimental data

Theoretical curve

Output energy [J]

Pump energy [J]

Signal pulse

Pump pulse

To compressor

80 mm diameter Ti:sapphire crystal
Laser Development II – High Peak and Average Power: Repetition-Rated Tabletop System Using a Yb Doped Thin Disk Amplifier

2009 Goal:
1 TW @ 10 Hz

Current Progress:
~ 0.3 TW @ 10 Hz
(100 mJ in 300 fs)

Future:
higher pulse energy
higher rep rate (10-100 Hz)
- next 10 TW @ 100 Hz

courtesy of H. Kiriyama
Proton Yield and Beamline Development
June 2009 TOF Spectrum at PMRC: 51 TW (1.8J) on Target

- Target: stainless steel (2.5 micron thickness)
- Intensity: ~10^{20} W/cm^2
- Contrast: 10^{-10}

ToF: thin plastic scintillator with Al film cover
Light guide
ND+bandpass filters
Laser-Driven Proton Focusing: Repetition-Rated (1 Hz) Demonstration at ~ 2 MeV *

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); (large aperture PMQ’s for 0.5 MeV design) 10^7 half divergence, E_{max} ~ 2.8 MeV)


Single-shot results also reported at 14 MeV (M. Schollmeier etal., PRL 101, 055004 (2008))
Novel Proton Optics: Exploring Spectral Modulation with Synchronous RF Phase Rotation *

field amplitude ~ 2MV/m
Frequency ~ 80.7 MHz
demonstrated with ~ MeV protons
from 3 micron Ti target
affords spectral control that is independent of laser target

10 Hz operation & tunable

* S. Nakamura et al., JJAP Exp Lett 46[29], L717 (2007)
Laser-Driven Proton Treatment Facility Concept

Concept: with bends for beam ‘clean up’ and no gantry

Proton Beam Requirements (ocular melanoma):
- Energy for therapy: 40 to 60 MeV with ~ few mm beam size (tunable and steerable for spot scanning)
- Maximum proton energy (cutoff): ~ 70-80 MeV
- Energy spread at ‘tuned’ energy: ~ 0.1 % to 1 %
- Bunch charge at source (laser target): ~ 1 nC (full spectrum)
- Bunch charge to patient: ~ $10^{-4}$ nC (~6x$10^5$ protons)
- Integrated dose: ~ 55 Gy (~$10^{10}$ protons in ~ 20 x 2 minute fractions with 10 Hz laser operation)

Laser at target:
- Wavelength: ~ 1030 nm
- Peak intensity: ~ 5x$10^{20}$ W/cm$^2$
- Peak power: ~ 500 TW
- Pulse energy: ~ 150 J
- Pulse duration: ~ 300 fs
- Repetition rate: 10 to 100 Hz
55 MeV Laser-Driven Proton Source and Beamline (80 MeV Cutoff) Embedded into a Gantry* (Double Bend Achromat)

(in this example transmission to the application is about 1.3%. Therefore $10^7$ protons per pulse at the patient requires ~ nC bunch charge at source; so the ‘effective’ laser-to-proton conversion efficiency to ‘useable’ protons is smaller ($<10^4$) at the application end. Production of quasi-monoenergetic proton spectra and beam focusing can significantly improve transmission)
55 MeV Transport: Energy Spread and Transmission
(single pulse nC production at source means ~100KW to patient)

Divergence angle: ±5 degree
Energy spread: 100%
Max energy: 80 MeV
Total particle: 1.0 x 10^5

Energy spread: 1.31% 0.718 MeV (1sigma)
Center energy: 55 MeV
Total particle: 1153

Beam size (1sigma): X = 0.125 (cm)
y = 0.156 (cm)

Final beam by using DBA

Bunch duration: ~1.4 ns
Energy spread: > 100%

Energy spread (1sigma): 0.718 MeV [1.31%]

Beam transmittance: 1.15%

(* simulation using Trace3D and Parmila by H. Sakaki)
Applications of current interest:

- radioisotope production
- autonomous PET (at HIBMC)
- proton irradiation of human cancer cells
- dose distribution for ocular melanoma
thin layer activation (TLA):

- material studies - example $^{56}\text{Fe}(p,n)^{56}\text{Co}$ requires > 5.6 MeV protons

$$^{56}\text{Co} \rightarrow ^{56}\text{Fe} + e^+ + \nu + \delta \tau \sim 78.8 \text{ days}$$

potential proton beam monitor:

- examples $^{11}\text{B}(p,n)^{11}\text{C}$ and $^{63}\text{Cu}(p,n)^{63}\text{Zn}$

$$^{63}\text{Zn} \rightarrow ^{63}\text{Cu} + e^+ + \nu + \delta \tau \quad \text{half life } \sim 38.4 \text{ min}$$

$$^{12}\text{C} \rightarrow ^{12}\text{N} + e^+ + \nu + \delta \tau \quad \text{half life } \sim 20.3 \text{ min}$$

GSO scintillator signal
$I_{\text{laser}} \sim 10^{20} \text{ W/cm}^2$ (60 shots)
@ 10 Hz; $C \sim 10^{-10}$
proton $E_{\text{max}} \sim 3.5 \text{ MeV}$

*IAEA cross section database at http://www-nds.iaea.org/medical/
PMRC interest in autonomous PET using short lived isotopes: in situ, closer, more prompt

Preliminary results from HIBMC (Hyogo Ion Beam Medical Center):

- $2 \times 10^{10}$ protons
- 80 MeV
- 5 mm pencil beam
- Lucite phantom

PET scanner: Clairvivo

(* courtesy of Akagi, HIBMC)
First RBE Experiment Using Laser-accelerated MeV Protons: Double Strand Breaking in Human Cancer Cells (in vitro A549) *

Laser energy: 0.6 J
Duration: 35 fs (FWHM)
Intensity: $5 \times 10^{10}$ W/cm²

J-KAREN laser at 1 Hz can generate proton bunches with $10^{10}$ charge level (>1MeV) and peak current ~ 1k A @ 1 mm, (5 A @ 200 mm from the target).

Irradiation level ~ $10^3$ /ns mm² with ~ 15 ns bunch duration (0.8 - 2.4 MeV) with integrated dose at 20 Gy level (200 laser shots)

*(A. Yogo et al., Appl. Phys. Lett. 94, 181502 (2009) and recently extended to 5 MeV protons)*
Dose Distribution Simulations for Ocular Melanoma at Hokkaido University

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

‘spot scanning’ will require precise control of proton beam direction, energy and dose with repetition-rated laser operation:

- can achieve laser repetition rate with multiple beams if needed
- is the laser pulse a control parameter? (i.e. laser modulated treatment)

For 55 Gy, # protons per laser pulse \( \sim 10^6 \) assuming:

10 Hz laser
20 x 2 minute fractions
Dose Distribution Simulations for Ocular Melanoma: Typical Results *

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

\[
N = \frac{DM}{fRT}\]

- absorbed dose in Gy (J/kg)
- tumour mass (kg)
- # of fractions (radiation sessions)
- single particle kinetic energy (J)
- laser repetition rate (pps)
- radiation interval (sec)

ocular example: \(N \sim 10^5\)

for \(D = 55\) Gy, \(M = 1\) gram,
proton energy \(\sim 40 - 60\) MeV
and \(fRT = 10^5\)
(with \(R = 100\) Hz)

* Ken Sutherland, Hokkaido University Hospital
Important R&D Requirements for a Laser-Driven Proton Treatment Facility (PTF): basis of a PMRC Strategic Plan

Laser development -
(i) single shot, highest peak power - power scaling
(ii) repetition-rated high average and peak power - power scaling
(iii) pulse tailoring (‘cleaning’, shaping…) - new methods and diagnostics?

Single shot and repetition-rated proton yield (laser-plasma) scaling experiments
(energy spectra, bunch charge, plasma diagnostic development)

Targetry - efficiency, compatible with repetition rate – scaling for proton yield, focusing?

Proton optics compatible with laser-driven case (high peak current, energy spread, divergence)

Beam transport designs – low energy (~ 5-10 MeV) and higher energy medical prototype (< 80 MeV)

Diagnostics/Instrumentation/Controls of laser-driven accelerator
- plus noninvasive, redundant single bunch detection/sorting?
- identify possible direct laser controls of proton beam and relation to other controls

Medical requirements/guidance detail for performance of laser-driven accelerator
- confirm therapy niche!!
- dosimetry and other diagnostics, image-guided therapy
- medical/biological science and technology focus
  (modeling, dose simulations, autonomous PET, cell and tissue irradiation experiments, spot scanning, treatment planning,…)

Engineering design for compactness and ongoing comparisons with other methods *

Gantry requirements?/design (based on anticipated compactness)
PMRC is in Good Company

- LIBRA (UK)
- SAPHIR (France)
- onCOOPtics (Germany)
- MAP (Germany) & LANL
- Fox Chase Cancer Center (USA)
Closing Comments

- Laser-driven ion acceleration for ion therapy is novel with high risk with major challenges and not yet at the applied science/engineering stage
- Limited by laser and target technology yet steered by medical requirements
- Why do this? – as a new possibility we must provoke the issue and force these assessments with a healthy spirit of enquiry (note the LWFA e-case)
- ILDIAS is the next major step for PMRC (a move that forces us to consider accelerator issues and other challenges and move beyond the single shot high intensity laser-plasma experiment)
- Strategic plan is toward ILDIAS development that is a viable basis for a proton treatment facility (PTF) with aim of significant cost and size reduction (~ order of magnitude) and must represent a balanced, multifaceted agenda (eg. includes medical/biological agenda) open to all new developments
- Eye treatment (ocular melanoma) is an attractive ‘niche’ – no gantry?
- Must continue ongoing comparisons with other PTF approaches (compact superconducting cyclotrons)
- Compactness is relative, dynamic, and usually the deliberate result of engineering and design (early prototypes might not be compact but we assess the potential for compactness once a functional prototype is developed)
- This is a critical review year for PMRC (request continued funding to 03/2017)
- Contact us to receive our quarterly electronic newsletter, ‘PMRC News’

Thankyou
PMRC News

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