

## LASER-DRIVEN PROTON ACCELERATOR FOR MEDICAL APPLICATION \*

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### Abstract

The concept of a compact ion particle accelerator has become attractive in view of recent progress in laser-driven ion acceleration. We report here the recent progress in the laser-driven proton beam transport at the Photo Medical Research Center (PMRC) at JAEA, which is established to address the challenge of laser-driven ion accelerator development for ion beam cancer therapy.

### INTRODUCTION

Following the first observation of proton acceleration by intense laser pulses irradiating thin solid targets [1,2] and with continued development of high peak power repetition-rated laser systems, laser-driven proton beam line development continues to be widely examined both experimentally and theoretically. The interaction between the high intensity laser and the solid target produces a strong electrostatic proton acceleration field (1 TV/m) with extraordinary small size, contributing to downsizing of the particle accelerator. The proton beam accelerated from this strong field exhibits significant features. It has very small source size ( $\sim 10$   $\mu\text{m}$ ), short pulse duration ( $\sim \text{ps}$ ) [3], thus realizing extra-ordinary high peak current, and very low transverse emittance[4,5,6]. Because of these peculiar characteristics the proton beam attracts many fields. Noteworthy among them is the potential for development of compact accelerators that could be used in laser-driven ion beam radiotherapy (L-IBRT) [7,8,9]. Existing medical facilities that are based on conventional ion accelerator facilities are typically large (in size and cost) thus limiting their number and ultimately access to ion beam radiotherapy. Consequently there is a strong interest in technologies that show promise for significantly reducing the size and cost of a medical ion accelerator.

However in contrast to current medical ion accelerators, laser-driven proton beam is a diverging beam (half angle of  $\sim 10$  deg) and has wide energy spread of  $\sim 100\%$ . These features force us serious challenges to preserve the peculiar characteristics of the laser-driven proton beam at a source, such as, short pulse ( $\sim \text{ps}$ ), high number density, and high peak current, which are not possessed by those beams from the conventional accelerators, towards the

irradiation points. We need to establish a peculiar beam transport line.

As the first step, here we report the demonstration of the proto-type laser-driven proton medical accelerator beam line in which we combine the laser-driven proton source with the beam transport technique already established in the conventional accelerator for the purpose of demonstrating the spot scanning irradiation method with the laser-driven proton beam. In previous work, we had demonstrated the use of permanent magnet quadrupoles (PMQs) for focusing protons from a laser-driven source where we also observed, as a spectral bump, an increase in the number of protons at the high energy end [10]. The transport line reported here includes a PMQ triplet, an RF cavity device [11], a conventional bending magnet and a scanning magnet.

### EXPERIMENTAL SETUP AND RESULTS

Figure.1 shows the experimental setup. The irradiation of a thin polyimide target by an intense laser pulse generates accelerated protons that emerge from the downstream target surface as a single bunch for each laser pulse. We use the J-KAREN Ti:sapphire laser system at the Kansai Photon Science Institute of the Japan Atomic Energy Agency. P-polarized laser pulses with energy near 630 mJ, central wavelength of 800 nm, and duration of 45 fs (FWHM) irradiate a moving polyimide tape target of 12.5  $\mu\text{m}$  thickness at a 45 degree incident angle at a 1 Hz repetition-rate. Peak irradiances up to  $10^{19}$   $\text{Wcm}^{-2}$  have been achieved by focusing with an off-axis parabola (300 mm focal length) to spot sizes near  $6 \times 3$   $\mu\text{m}^2$  (FWHM, horizontal x vertical). An intensity contrast ratio, which holds an important key for producing stable proton generation, typically at the  $10^{10}$  level are obtained approximately 100 picoseconds prior to the peak of the main pulse. The duration of the ASE prepedestal is set to 0.5 ns before the main pulse with a fast pockels cell.

The transport line is oriented parallel to the target normal direction. The PMQ triplet is used as a first collection optics to collect and collimate a part of the emergent proton bunch for the further transport. The first, second and third quadrupoles are placed at 79.5 mm from the target, 128.5 mm from the downstream end of the first one, and 89.3 mm from the downstream end of the second

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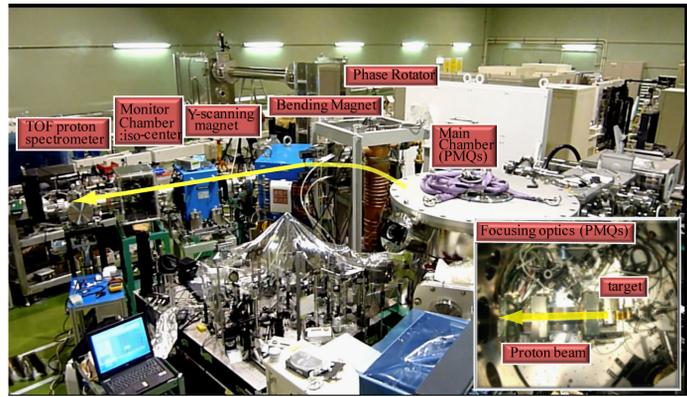
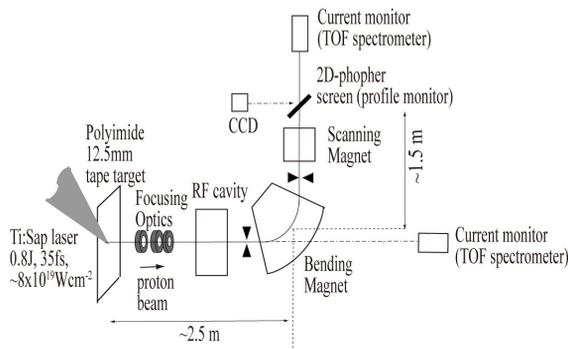


Figure 1: Experimental setup.

one. The field strengths (and magnet lengths) are 55 T/m (50 mm), 40 T/m (50 mm) and 60 T/m (20 mm), respectively.

An RF cavity that establishes phase space rotation in the proton bunch is placed downstream of the PMQ triplet. The timing of the 80 MHz RF is synchronized to that of the laser pulse with a 45 degree phase offset. The RF cavity field amplitude is 115 KV.

Protons with higher energy than the selected 1.9 MeV are decelerated by the RF intracavity phase on arrival. By contrast those with lower energy reach the cavity at a later phase and are accelerated. Consequently the number of the protons near the chosen central energy of 1.9 MeV is significantly increased.

A 90 degree bending magnet (with an entrance collimator and exit slit) is set to select a 1.9 MeV proton bunch with a 5 % energy spread to send to the profile monitor and current monitor set at downstream of the bending magnet. The field strength is 0.53 Tesla with a bending radius (gap height) of 400 mm (65 mm).

Just after the bending magnet, we set scanning magnet, which is used to vary the position of the proton beam at the iso-center.

Near the end of the transport line the position and transverse spatial profile of the bunch are measured using a luminescent single bunch profile monitor, LSBPM [12]. We obtained prompt single bunch profiles at a repetition-rate by imaging proton-induced light emission onto a CCD camera. At the end of the transport line which is located ~4 m from the source we directly measure the bunch duration with the same TOF unit that is also used to measure source spectra.

Left and right panels in Fig.2 show the typical proton spectra measured with absolutely calibrated TOF spectrometer set at 2.4 m from the source, and the spatial distribution of the proton beam (energy band of >0.9MeV) detected with CR-39 nuclear track detector set at 80 mm from the source. The proton beam half divergence is determined to be ~10 deg in the energy of ~2MeV. The number of protons transported through the beam line in the energy band of (1.9±0.05)MeV is (5±0.9)×10<sup>5</sup> protons/shot. The shot-to-shot fluctuation of the number of the proton beam at a source is within 20%.

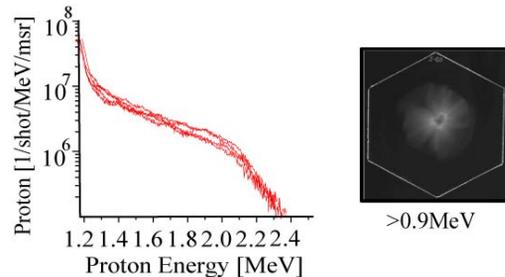


Figure 2: Typical proton spectra measured with TOF spectrometer (left) and spatial profile (>0.9MeV) at 80 mm from target (right).

The arrival time information of the proton beam transported through the beam line and detected with the TOF spectrometer at the end of the beam line is shown in Fig.3. It clearly shows that the proton beam is successfully quasi-mono-energetized, that is to say, selected out of the continuum spectrum at source. The corresponding energy spread at the iso-center is measured to be (1.9 ± 0.05)MeV. Figure 4 shows the spatial distribution of the proton beam at the iso-center. The size of the proton beam at the iso center is successfully collimated to be ~2x2cm<sup>2</sup>. The position of the proton beam changes as the current to the scanning magnet changes.

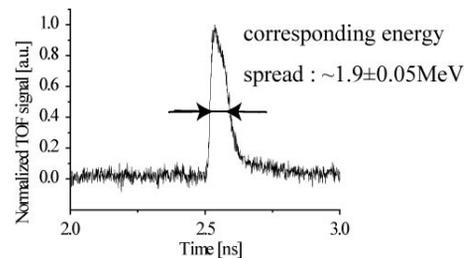


Figure 3: Proton arrival information detected at TOF spectrometer at the end of the beam line. It shows the transported proton beam has quasi-mono-energetic spectrum (1.9 ± 0.05) MeV.

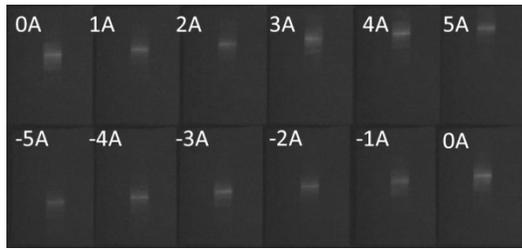


Figure 4: The proton beam spot at the iso-center, detected by the 2D phosphor screen (LSBPM). The change of the position of the proton beam is seen as the current to the scanning magnet changes.

## CONCLUSION

We have demonstrated the spot scanning of the laser-driven proton beam. The beam transport test through the beam line for the laser-driven proton beam is carried out for the first time. The beam which is successfully selected out from the continuum spectrum to have quasi-monoenergetic spectrum ( $1.9 \pm 0.05$  MeV) is spot-scanned at the iso-center. The size of the spot is collimated to be  $\sim 2 \times 2 \text{ cm}^2$ . The change of the spot position according to the current to the scanning magnet is measured by prompt single bunch profiles monitor in a repetition-rated fashion.

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