CREATION OF PEAKS IN THE ENERGY SPECTRUM OF LASER-PRODUCED IONS BY PHASE ROTATION*

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Abstract

By focusing a short-pulse (250fs) and high power (240mJ) laser on a thin foil target of Ti 3μm in thickness with laser power density up to 9 x 10^{17}W/cm^2, proton production up to ~900keV was observed by optimization of parameters with the use of TOF measurement. Application of phase rotation to such protons resulted in creation of a few peaks in the energy spectrum and the intensity increase about factor of 3 in the peak positions.

INTRODUCTION

The cancer treatment with use of high energy (~a few hundreds MeV) ion beam has been applied successfully to various patients and is considered to be a very promising scheme to cure cancer keeping "Quality of Life" of the patients. For the wide spread use of such treatment, down sizing of the accelerator is inevitable. Very efficient acceleration of a beam with the use of laser plasma interaction has been paid attention since the first proposal by Tajima and Dawson [1] because of its merit of capability of downsizing the accelerator drastically, which, however, must wait until the development of the high-power laser technology owing to invention of chirped pulse amplification in order to be a practical scheme. We proposed to utilize such a laser-produced ion with the kinetic energy of 2MeV/u as an injection beam of a synchrotron dedicated for cancer-therapy, replacing the conventional linear accelerator as shown in Fig. 1 [2].

The laser produced particles had almost 100% energy spread showing the distribution like thermal equilibrium, which also imposed severe limitation on their real usage. For laser-produced electrons, creation of mono-energetic peak has been reported from various laboratories in recent two years [3-6], which opened up the future capability of application of laser acceleration. Also creations of quasi-monoenergetic ion beams by laser acceleration have been reported [7,8]. These are, however, limited in reproducibility or needs precise preparation of microstructured targets, which seems to require further developments for real usage. In parallel to above researches, we have experimentally investigated phase rotation scheme to create peaks in the energy spectrum of laser produced ions with the use of an RF electric field with the same frequency as the main oscillator of the pulse laser synchronized to it and attained the creation of energy peaks with the fractional energy spread of ~7% resulting in an increase of the intensity up to ~3 times at the peak energies.

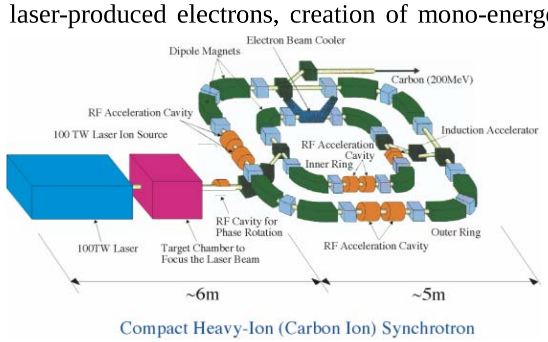

Figure 1: Proposed compact accelerator complex utilizing a laser ion source as an injector.

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LASER ION PRODUCTION

Proton production from a thin foil target (Ti foils with thickness of 3μm and 5μm are utilized) by a high power (maximum 10TW) and short pulse (minimum duration 35fs) Ti:Sapphire laser, JLITE-X at APRC, JAEA has been studied. The laser was focused on the target to the size of 11μm x 15μm by an off-axis parabolic mirror as shown in Fig. 2 and the maximum laser power density amounted to 9 x 10^{17} W/cm^2. The direction of laser-irradiation was declined by 45˚ to the target and protons produced in the direction to the target normal are detected by Thomson parabola or time of flight (TOF) measurement with the use of a scintillation counter described in the next section.

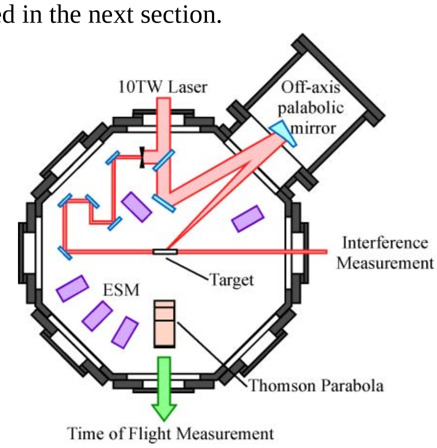

Figure 2: Experimental set up for laser proton production from a thin (3μm or 5μm) Ti foil target 10TW laser is focused on the target with a declination angle of 45˚.

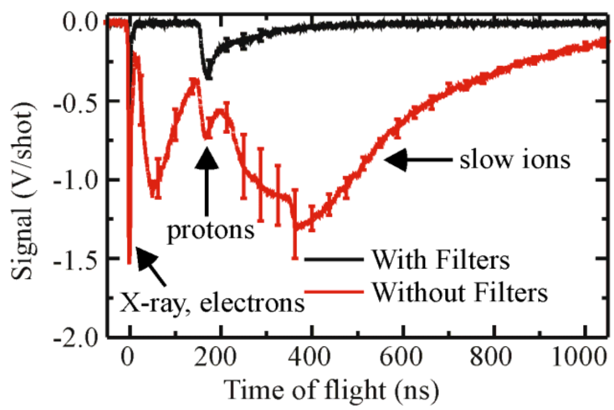

Figure 3: Noise reduction at scintillation counter by special filters.

Laser Parameter Optimization by TOF

For the efficient production of higher energy protons, it is very important to optimize various parameters; contrast ratio of the main peak to the pedestal or pre-pulse of the laser, relative position between the target and laser focus spot, target material and thickness and so on For this purpose, we had been utilizing Thomson parabola using CR-39 track detectors because of its feasibility of application under hard background condition caused by a high power laser. Its data analysis, however, needed a rather long time (a few days), almost all available time of the high power laser has been already expired when the optimum parameters are known.

Recent our development on filtering the background in a detected signal of proton by a plastic scintillation counter has enabled the energy measurement of laser-produced proton by TOF. In Fig.3, the background reduction by application of filters is shown. It is shown that the peak due to a proton in the TOF becomes to be clearly identified [9].

PHASE ROTATION

Scheme of Phase Rotation

In order to improve the Maxwellian distribution of laser-produced proton beams so far obtained, a phase rotation scheme to rotate the beam in a longitudinal phase space and decrease the energy spread with the use of an

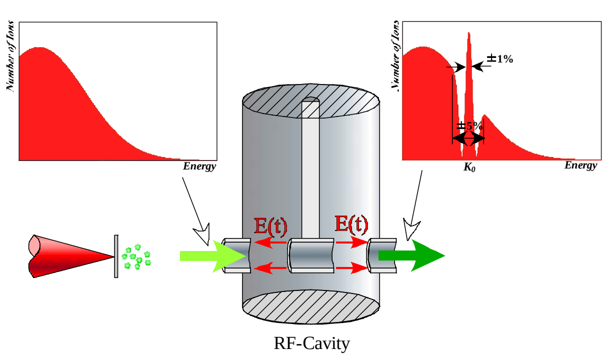

Figure 4: Principle of Phase Rotation.

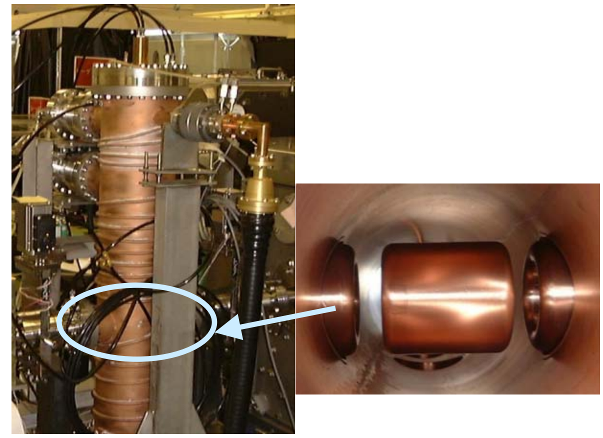

Figure 5: RF cavity of λ/4 resonator with two gaps for phase rotation with the resonant frequency of 80.6 MHz.

RF electric fields synchronized to the pulse laser is to be utilized. In Fig. 4, the operation principle of the "Phase Rotation" is illustrated. Utilizing the difference of the arrival timing at the gaps of the RF cavity due to energy difference, protons are accelerated or decelerated in the gaps as shown in the figure, which results in creation of an energy peak and increase the beam intensity at the peak position.

RF Cavity for Phase Rotation

As the RF cavity for phase rotation, a quarter wave length two-gap resonator is utilized with the same frequency (80.6MHz) as the pulse laser (Fig. 5). For the design, we assumed ions with kinetic energy of 2MeV/u and the distance between two gaps is determined to be 120 mm optimizing for such an energy. In Table 1, main parameters of the RF cavity for phase rotation are listed up.

Table 1: Main Parameters of RF Cavity

Frequency	80.6MHz
Power	<30kW
Repetition Rate	10Hz(Max.)
Structure	λ/4 resonator with double gaps
Outer Conductor	ID200mm×~1100mm
Inner Conductor	ϕ40mm×~700mm
Drift Tube	ID50×100mm
Gap	20mm
Distance between 2 Gaps	120mm
Port	Input RF Coupler (30kW) RF Pick Up Frequency Tuner (~250kHz) Vacuum Gauge
Cooling (Water cooling)	Temperature Variation < ~0.5 Degree Outer Conductor -Cooling by Cu Pipe Inner Conductor –Double Pipe

Synchronization between Pulse Laser and RF

For quantitative investigation of the effect of phase rotation on the energy spectrum of laser-produced ions, it

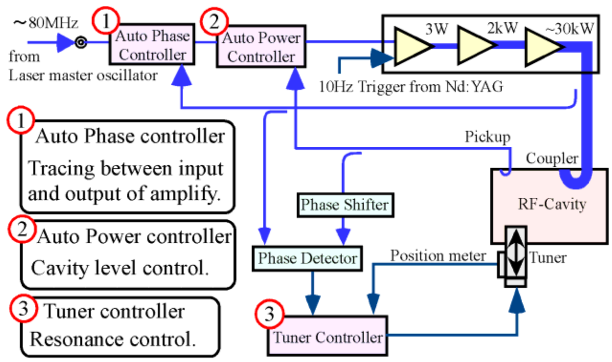

Figure 6: Phase synchronization system between the pulse laser and the RF electric field for phase rotation.

is needed to control the phase relation between the pulse laser and the RF electric field to be the same for every shot. For this purpose, a phase synchronization system between the pulse laser and the RF cavity as shown in Fig. 6, has been utilized. A pulsed RF with duration of ~100μs by the same repetition rate as the pulse laser (up to 10Hz) triggered by the master oscillator of the laser is provided to the cavity for phase rotation. With this procedure, an RF electric field keeping always the same phase relation with the laser can be applied to laser-produced ions (protons for the present case) for every shot.

EXPERIMENTAL ATTAINMENTS

Energy Peak Creation by Phase Rotation

Up to now, proton production up to ~900keV has been attained with the 10TW laser, JLITE-X with the laser power density of 9 x 10^{17} W/cm^2 on a Ti foil target with thickness of 3μm as shown in Fig. 7. Although the phase rotation cavity was optimized for 2MeV proton, the energy peak creation was found to be possible for such lower energy protons by reducing the applied voltage to the gaps of the cavity as shown in Fig. 7. Creation of a few peaks in the energy spectrum resulting in the increase of the intensity as large as ~3 times at the peak positions was experimentally demonstrated.

Future Perspectives

With the use of proton energy measurement system by TOF, efficient optimization of laser-proton production has become possible as described above. Such a system has already been utilized in the collaboration with Gwangju Institute of Science and Technology (GIST) in Korea and produced proton energy up to 2.3MeV was reported although the phase rotation could not be applied.

So as to apply phase rotation for 2MeV protons of design optimization, we are now trying laser proton production with use of a 100TW laser at APRC of JAEA. With preliminary irradiation on a thin hydrocarbon target, production of protons up to 2.1MeV has been observed and phase rotation is scheduled to be applied soon.

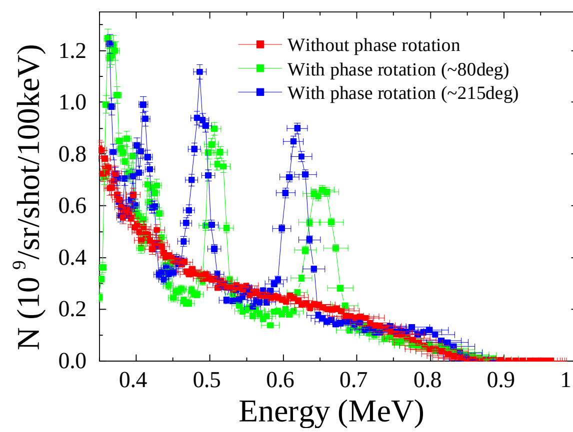

Figure 7: Energy spectra of laser produced protons with and without phase rotation. Typical examples with two different relative phases to the pulse laser are shown for the cases of with phase rotation.

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