# Evaluation of ultra-low emittance characteristics of proton beams in laser-driven ion acceleration

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Name

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Title　(レーザー駆動イオン加速によるプロトンビームの超低エミッタンス特性評価)

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論　文　内　容　の　要　旨

## Thesis Summary

The interaction of ultra-high peak intensity lasers with matter has established a new research field that enables ion acceleration. When a high-intensity short pulse laser with a focused intensity of >$10^{18}$ W/cm$^2$ is irradiated to a thin foil target, high accelerated field gradients of the order of TV/m are produced on the rear-side of the target resulting in the acceleration of protons to multi-MeV energies. This acceleration mechanism is called Target Normal Sheath Acceleration (TNSA), and has been expected to be applied as a miniaturized accelerator due to its high acceleration gradient. TNSA has advantages in terms of the number of accelerated particles, continuous beam supply, and understanding of the acceleration mechanism compared to other mechanisms such as break-out afterburner, radiation pressure acceleration with an ultra-thin target (~nm thickness), and the ion acceleration with a gas target.

TNSA mechanism is expected not only to miniaturize current accelerators but also to open up new research fields as a powerful probe for nuclear, physical property, biological, and medical applications, where current accelerators are in practical use. In TNSA, fs pulse laser is focused to a few μm in diameter, so the ion beam is accelerated from a transverse source size of ~ several tens of μm in a very short time of < ps. These ion beams have a spatio-temporal focusing characteristic that cannot be achieved with beams accelerated from the microsecond and cm regions of current accelerator ion sources. Therefore, the ion beam in the TNSA can produce a "high-brightness microbeam" with short pulses and high current, which is difficult to achieve with current accelerators. Achieving the correlation between laser irradiation parameters and accelerated ion beam characteristics must be understood, and the physical mechanism to control beam quality must be clarified. The transverse emittance characteristics (laminarity) is an important physical parameter in producing a high-brightness beam by focusing, and this characteristic needs to be diagnosed and controlled with high precision.

In this study, a diagnostic system for ultra-low emittance characteristics of proton beams generated in the TNSA will be established and the beam performance as an ion accelerator is evaluated in order to realize a new research field with a laser-driven ion acceleration. In order to establish a diagnostic method for the ultra-low emittance, an optimization simulation of the emittance diagnostic system using the slit method was performed. The influence of measurement geometry and dosimeter conditions on measurement accuracy was evaluated, and the conditions that guarantee measurement accuracy were derived. And a high spatial resolution measurement system using radiochromic film (RCF) was developed to satisfy the optimization conditions.

Using these optimized conditions and a high spatial resolution measurement system, emittance diagnostics of MeV-class proton beams were performed for several irradiation target conditions. It was found that the emittance of the laser-accelerated proton beam is more than one order of magnitude better than that of the current accelerator beam. To compare the micro-focusing performance of the laser accelerated proton beam given by experiments with beam of current accelerators, the focusing performance with quadrupole triplets was analyzed by particle-in-cell (PIC) simulation, in which space-charge effects can be taken into account. These results indicate that laser-accelerated proton beams have the potential to produce excellent microbeams that cannot be achieved with current accelerators. These findings not only contribute to the systematization of laser-accelerated proton beam characteristics, but also show that these beams allow us to explore new research fields. The results of this work will contribute significantly to the fundamental physics of laser plasmas and their application fields.

This thesis is divided into six parts.

In Chapter 1, the background and objectives of this thesis are described. An overview of the laser-driven ion acceleration mechanism and the basics of beam characteristics are explained. The emittance diagnostics of laser-accelerated ions in previous studies and their problems are summarized.

Chapter 2 describes the method and results of analyzing beam dynamics and emittance characteristics of accelerated protons by laser plasma simulations using a 2D PIC code. The current status and challenges of the study of laser-accelerated ion beam dynamics by simulation are discussed, and the importance of experimental characterization of laser-accelerated proton beams is indicated.

In Chapter 3, optimization of the diagnostic conditions and high-spatial-resolution dosimeters are performed to establish a diagnostic system for the low-emittance characteristics. Optimization calculations led to diagnostic conditions for a beam with a normalized rms emittance of ~0.01 π-mm-mrad with <5% systematic error. The dosimeter with a spatial resolution of ≤25 μm was needed, the spatial resolution of the RCF-based diagnostic system was evaluated. The high-end flatbed scanner commonly used for RCF reading did not satisfy the optimization conditions because it could only guarantee accuracy with a resolution of up to 83.3 μm. A two-dimensional scanning test bench microdensitometer was developed in this study, and its spatial resolution was improved to 11.9 μm, which guarantees accuracy.

Chapter 4 describes diagnostic experiments for emittance characteristics of MeV proton beams in a laser-driven ion acceleration. The slit and transverse profile experiments were carried out to diagnose the ultra-low emittance and energy spectrum characteristics of laser-accelerated proton beams using the laser system at the Kansai Institute for Photon Science of the National Institutes for Quantum Science and Technology. In these experiments, the high-spatial-resolution dosimeters in Chapter 3 was used. The beam performance for several μm thick Polyimide and Ni target was evaluated. The results demonstrate that MeV-class laser-accelerated proton beams can be controlled with a normalized rms emittance of 0.012~0.026 π-mm-mrad, which is more than one order of magnitude better than that of current accelerators.

Chapter 5 describes the simulation results of the evaluation of the transverse micro-beam focusing and dose concentration using the input data of the laser-accelerated proton beams obtained experimentally. The focusing of the laser-accelerated proton beams by a quadrupole triplet was simulated and compared to current accelerator proton beams of about the same energy. The results show that the beam diameter at the focusing position of the laser-accelerated proton beams is nearly an order of magnitude smaller than that of current accelerator beams. Simulated microbeam collimation of laser-accelerated proton beams showed >200 times higher extraction efficiency and better bunch dose rate than current accelerator beams. These results demonstrate the usefulness of ion beams in TNSA as a new beam source for micro-PIXE analysis and FLASH radiotherapy.

Chapter 6 summarizes this thesis and discusses prospects for the development of laser-driven ion accelerators.