【Grant-in-Aid for Scientific Research (S)】

A New Horizon in Quantum Beams: Technological Innovations Toward Realization of a Muon Accelerator

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Project Information	Project Number : 25H00401　　　Project Period (FY) : 2025-2029 Keywords : Muon, Accelerator, Beam monitor

Purpose and Background of the Research

●Outline of the Research

For over a century, humanity has advanced accelerator technologies capable of propelling tiny particles to speeds approaching that of light. These developments have significantly enhanced our understanding and daily life, including unraveling mysteries of the universe’s origins, and even revolutionizing cancer treatments through quantum beam therapy. The next frontier of accelerator technology involves the acceleration of "muons.“

Muons are elementary particles discovered through observations of cosmic rays reaching. They possess a remarkable ability to penetrate matter, functioning like an extremely powerful form of medical X-ray imaging. Leveraging this unique characteristic, muons have been utilized to explore hidden chambers within Egypt’s pyramids, visualize volcanic structures, and inspect shipping containers for concealed threats. While current imaging techniques use cosmic rays, artificially generating and accelerating muons could enable rapid, high-precision imaging, creating groundbreaking new technological applications.

However, controlling and efficiently accelerating muons was previously considered nearly impossible due to technical challenges. We have recently developed a breakthrough method enabling muons to be nearly stationary initially and then efficiently accelerated. This advancement allows precise targeting and control of muon beams.

Our next goal is to accelerate muons to nearly the speed of light. Achieving this would allow us to examine fundamental particles with unprecedented precision. In particular, precise measurements of muon anomalous magnetic moments could provide vital clues for unraveling major cosmic mysteries, such as the nature of dark matter, which cannot currently be explained by existing physics theories. Furthermore, accelerated muon-based precision imaging techniques hold promise for innovative wide-ranging applications (Figure 1).

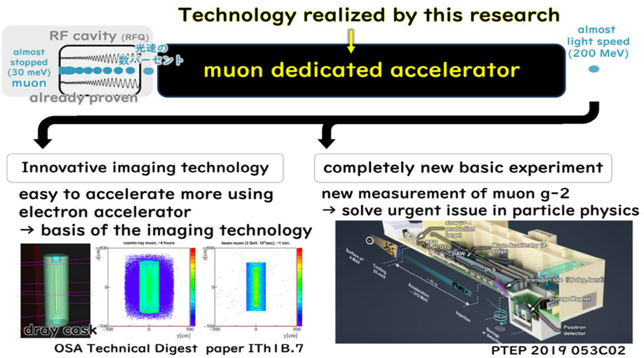

Figure 1. Outline of this study

●Realization of muon dedicated accelerator

This research aims to establish the technology needed to accelerate muons to an energy of approximately 200 MeV, nearly the speed of light.

Unlike electrons or protons typically used in accelerators, muons have a very short lifespan of about two usec. Therefore, muons must be accelerated to the target speed within an extremely brief period. The technology enabling this rapid acceleration is called a "radio-frequency linear accelerator." However, since muons drastically change speed—from nearly stationary to close to the speed of light—the structure of the accelerator must be precisely adjusted according to their velocity.

We have addressed this challenge by adapting accelerator technologies originally developed for medical applications and high-speed electron acceleration, specifically refining them for muons. As a result, we have successfully designed an accelerator capable of reaching 200 MeV for muons within approximately 0.7 microseconds. Nonetheless, to realize the world's first dedicated muon accelerator, certain technical challenges still remain. Our current research aims to solve these remaining issues and establish the technological foundation necessary for the first-ever dedicated muon accelerator.

Expected Research Achievements

We have successfully established and demonstrated the initial-stage acceleration technology for the upstream section of a muon accelerator. Additionally, preliminary demonstrations of downstream acceleration techniques have been conducted. Based on these achievements, three primary technical challenges must be addressed to fully realize a dedicated muon accelerator.

Challenge 1: To accelerate muons to 200 MeV within approximately 0.7 microseconds, highly efficient acceleration and achieving a maximum gradient of 20 MV/m are necessary. This research involves developing and testing prototype accelerators to establish dedicated muon-acceleration technology.

Challenge 2: Since muons are generated as secondary particles with significantly lower intensity than primary proton or electron beams, and due to their unique characteristics, highly sensitive and accurate beam measurement technology is essential. We are developing a novel quantum-beam monitoring technique that employs Cherenkov light to distinguish signal from background noise, thereby achieving the required measurement accuracy.

Challenge 3: The final dedicated muon accelerator will include four accelerating cavities along with beam transport lines equipped with beam monitors and magnets to measure and correct acceleration field errors. Due to the exceptionally low muon beam intensity and potential interference from background electrons, achieving a high signal-to-noise ratio is essential. This research addresses these unprecedented challenges through integrated design, simulation, and experimental validation to establish a comprehensive dedicated muon accelerator system.

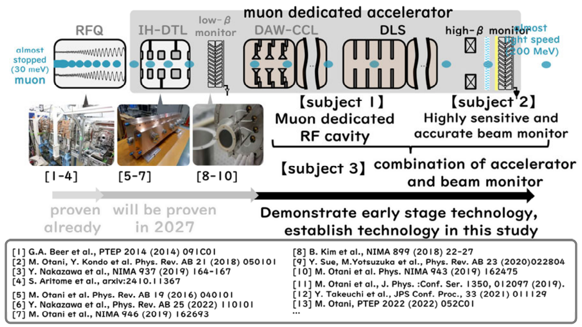

Figure 2. Purpose of this research

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