Experiment Concepts of Heavy-Ion Driven Plasma Acceleration with Muon Beams at the HIAF

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Abstract

The muon beams decay quickly at low energy. Therefore, it is important to rapidly accelerate the muon beams to higher energy to ensure sufficient lifetime for beam manipulations or further acceleration. Plasma acceleration offers higher acceleration gradients compared to conventional RF cavities. It is the most promising acceleration method for muon research projects at the HIAF facility. The HIAF can provide multiple proton or heavy ion beams at the same time, which can be utilized to produce muon beams by hitting targets and drive the plasma oscillations to provide acceleration fields. Preliminary simulation studies indicate that employing heavy ion beams in the HIAF to drive plasma oscillations, or wakes, through self-modulation instabilities can accelerate the muon beams from 800 MeV to 1.95 GeV within a length of 0.6 m. Ongoing research on plasma acceleration of muon beams at the HIAF will focus on introducing the generation and cooling simulation results to refine the existing plasma acceleration scheme based on self-modulation instabilities, and finding a way to enhance the energy gain of the muon beams in this scheme. Additionally, new plasma acceleration mechanisms will be explored to efficiently utilize the energy carried by the high intensity heavy ion beams.

Introduction

In the High Intensity heavy-ion Accelerator Facility (HIAF)[1] project and its upgrading facility, HIAF-U, high energy muon beams will be employed to perform high energy particle physics experiments, or large-scale imaging for crack detections of the whole equipment. However, the muon beams decay too quickly at low energy. Rapid acceleration is necessary to accelerate the muon beams to the energy of GeV, even TeV to ensure enough life time for further manipulations, experiments or other applications.

The acceleration gradient of plasma accelerators can reach hundreds of GV/m, even several TV/m. They provide a promising way to rapidly accelerate muon beams. Heavy ion beams can carry MJ level energy, much larger than other beams like lasers, electron beams, or proton beams, which may accelerate high intensity muon beams to much higher energy in only one stage plasma cavity. However, the driven efficiency of heavy ion beams is severely limited by relatively low energy, large sizes and final focusing limitations. It is necessary to find new ways to fully utilize the energy of driven beams.

The HIAF-U shows an opportunity to provide multiple heavy ion beams at the specific terminal, which will make a new muon acceleration experiment possible. We can use one beam to generate muon beams, one beam to drive the plasma to construct high acceleration fields, and other beams to confine the plasma fields to realize highly-efficient acceleration with high energy gain in single stage plasma cavity, which provides an innovative way to construct a high energy muon research facility. Proof-of-concept experiment is under design and will be performed in the HIAF facility before the construction of the HIAF-U.

Experiment Layout

In the HIAF, the high energy and density matter research terminal can provide two heavy ion beams at the same time, as is shown in the Figure 1. The beams from the BRing will be used to produce muon beams as the intensity is high enough for the targets. The heavy ion beams which drive the plasma to generate high acceleration fields will come from the SRing. However, those beams are also extracted from the BRing, stripped orbital electrons to higher charge state at the HFRS, and accumulated to $3 \sim 5$ times intensity in the SRing, waiting for the extraction to drive the plasma. They can pump more energy into the plasma compared with the beams from the BRing.

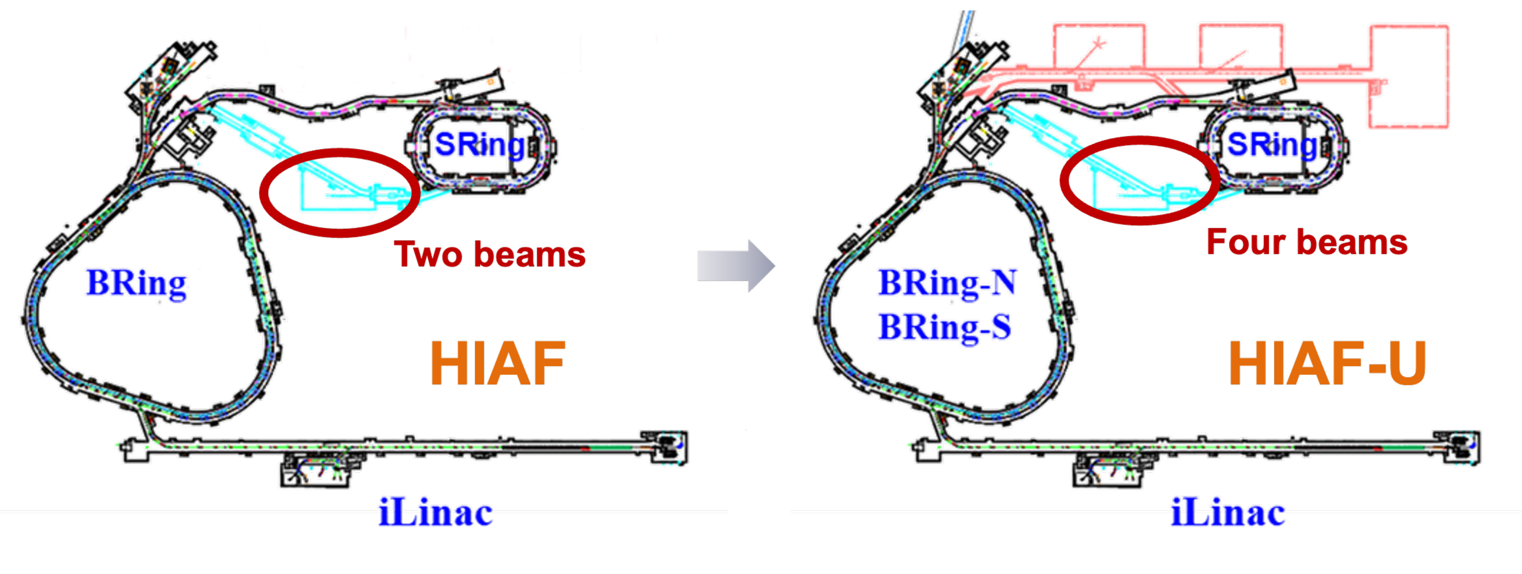

Figure 1: The location of the muon acceleration experiment in the HIAF and HIAF-U

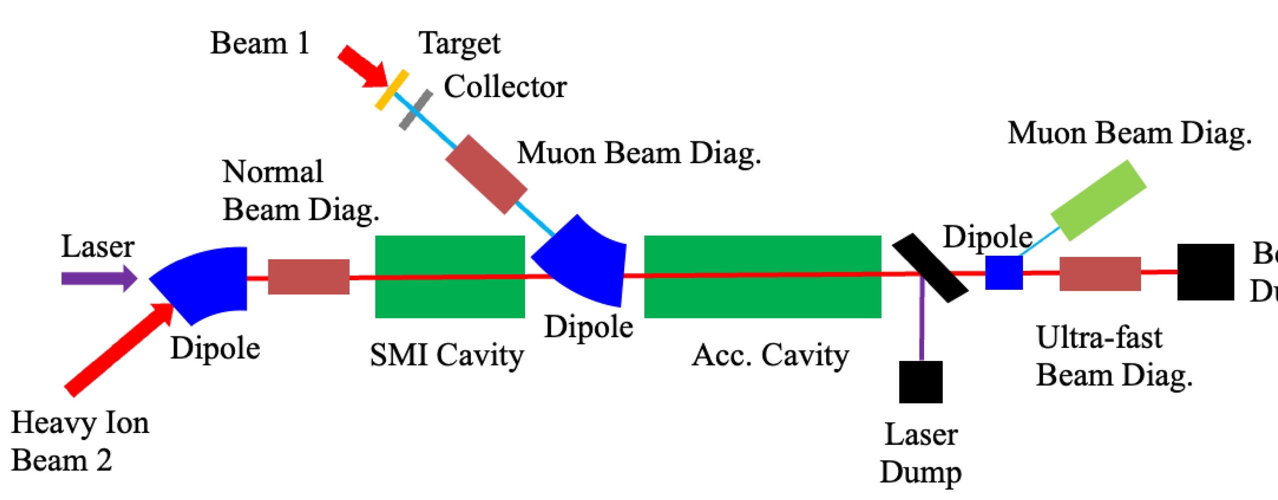

Figure 2: The layout of the muon acceleration experiment in the HIAF

In the future, the superconducting booster BRing-S will be built in the same tunnel of the BRing, as the space is already reserved for this upgrading. And a new superconducting storage ring MRing will also be installed in the same tunnel of the SRing. Four beams can be provided at the high energy and density matter research terminal at the same time. Then, new plasma acceleration methods driven by multiple beams and multiple lasers can be tried at this terminal.

For the experiment in the HIAF, self-modulation instability (SMI) seeded by a laser will be employed to produce micro heavy ion bunches that are matched with plasma wavelength. The laser will also ionize the gas to generate the plasma. Meanwhile, the intensity modulation of the plasma should be introduced to ensure the phase of the acceleration field always keeps pace with the muon bunches, which is quite important. On-axis injection can be used because we will generate micro heavy ion bunches in the SMI plasma, not in the acceleration plasma. The muon beams and micro heavy ion bunches will be lined before they enter the acceleration plasma cavity. The experiment layout is illustrated in the Figure 2, including muon beam line, heavy ion beam line, laser beam line, SMI plasma cavity, acceleration plasma cavity, diverse beam diagnostics stations for different beams, and several beam dumps.

Preliminary Research

Based on the previous experiment concepts, some preliminary research is conducted via LCODE[2] simulations. The SMI development process of the driven beam is already studied by many simulations and verified by the AWAKE[3] experiment at the CERN. We will go directly to the muon acceleration stage with a train of micro heavy ion bunches. In the plasma acceleration simulations, a single $^{209}Bi^{83+}$ driven bunch before the SMI cavity is assumed at the energy of 9.58 GeV/u and with the bunch intensity of 1×10^{12} particles. The total length of the $^{209}Bi^{83+}$ bunch is about 30 meters, and the transverse radius is 0.1 mm at the entrance of the SMI cavity. According to the threshold of the SMI, the intensity of the plasma should be $\sim 2.8 \times 10^{15}$ cm^{-3}, and the related plasma wavelength is about 0.63 mm which is much shorter than the length of the heavy ion driven bunch. So, in the simulations, only 13 micro bunches with the length of 0.315 mm and the space of 0.315 mm between each two of them picked from the center of the driven bunch are used to drive the plasma and accelerate the muon beams. The energy of the injected muon beams is 850 MeV.

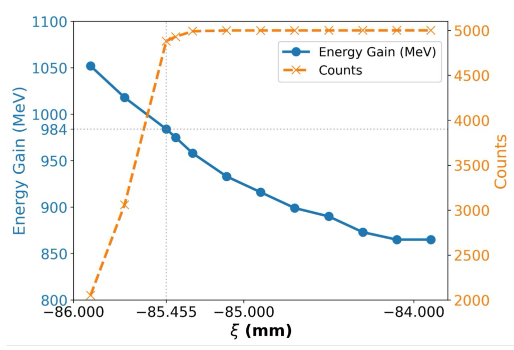

Figure 3: Injection Phase

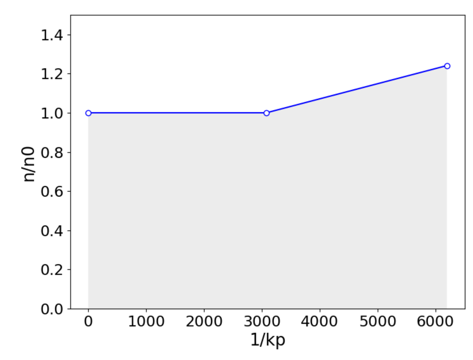

Figure 4: Density Modulation

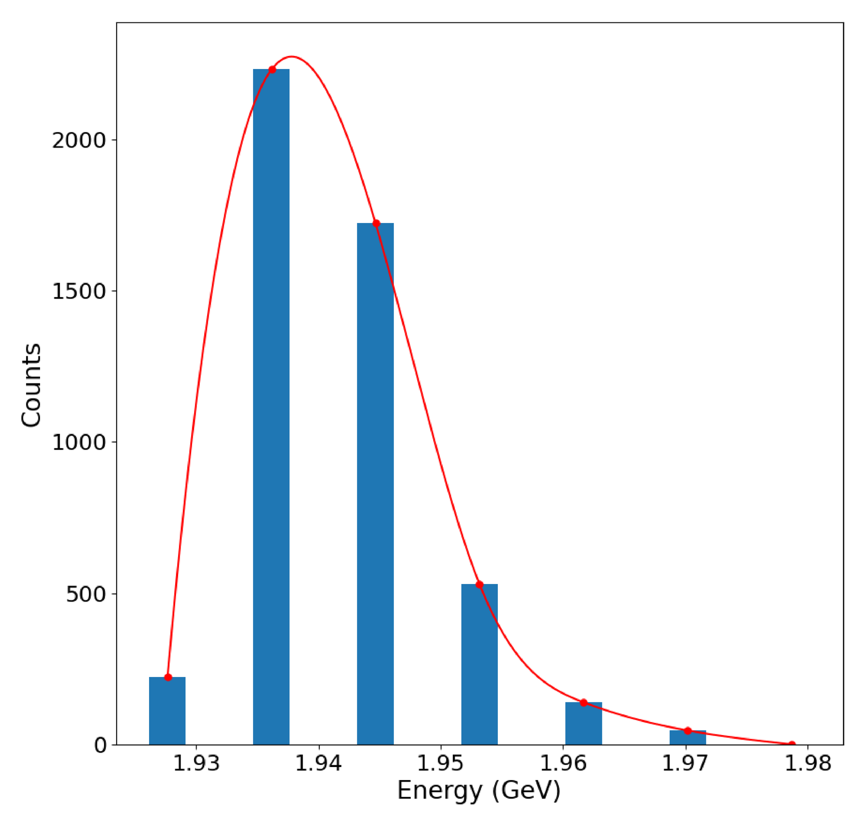

Figure 5: Final energy distribution with the maximal energy gain

At a specific distance or phase behind the train of micro heavy ion bunches, the muons will experience the largest acceleration fields. Simulations are performed to find this best phase. As is shown in the Figure 3, after balancing between the energy gain and the muon beam loss, the phase $\xi = -85.455$ mm is chosen for the further research. However, the energy gain can only reach about 984 MeV because of the rapid dephasing between the muons and the acceleration fields.

Intensity modulation of the gas, also the intensity modulation of the plasma, is an important technology to keep the accelerated muons and the plasma wave in phase. A simple linearly-increasing intensity modulation in the Figure 4 is tried with the same parameters of the previous simulation, in which the intensity of the gas linearly ramps from $\sim 2.8 \times 10^{15}$ cm^{-3} to about 3.5×10^{15} cm^{-3} in the length of 0.312 meters. The total length of the acceleration plasma cavity is 0.62 meters. From the simulation results, the maximal final energy of the muons is 1.97 GeV, and the energy distribution is shown in the Figure 5. The maximal energy gain is 1.12 GeV, while most of the accelerated muons are at the energy of around 1.94 GeV, corresponding to the energy gain of 1.09 GeV, which is just slightly higher than the energy gain of 0.98 GeV shown in the Figure 3. How to modulate the plasma intensity should be studied in the future.

In the previous simulations, only a quite small part of the driven beam energy is transferred to the muons. Maybe new intensity modulation designs or even new particle beam driven plasma acceleration methods should be proposed to further utilize the energy of the driven beams.

Summary

The muon acceleration experiments with the heavy ion driven plasma accelerator will be performed in the HIAF and its upgrading facility, HIAF-U. By fully utilizing multiple heavy ion beams at the high energy and density matter research terminal of the HIAF, a new operation mode and its feasible conceptual experiment layout are designed and presented, aiming at producing muon beams and accelerating them at the same time. Preliminary research is already conducted and shows that the 850 MeV muon beams from the target will be accelerated to the energy of 1.94 GeV and the maximal energy of 1.97 GeV of which the energy gain is about 1.10 GeV in the length of 0.62 meters. However, the energy gain is too small that only a quite small part of the driven beam energy is transferred to the muon beams, which is not acceptable for this experiment. New intensity modulation schemes or new particle beam driven plasma acceleration methods should be developed, designed, and simulated in the future to fully use the energy of the heavy ion beams.

[1] Zhou, X., Yang, J. & the HIAF project team. Status of the high-intensity heavy-ion accelerator facility in China. AAPPS Bull. 32, 35 (2022). https://doi.org/10.1007/s43673-022-00064-1

[2] LCODE, https://lcode.info

[3] Adli, E., Ahuja, A., Apsimon, O. et al. Acceleration of electrons in the plasma wakefield of a proton bunch. Nature 561, 363-367 (2018). https://doi.org/10.1038/s41586-018-0485-4