RESEARCH AND DEVELOPMENT OF FUTURE MUON COLLIDER*

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Abstract

Muon collider is a considerable candidate of the next-generation high-energy lepton collider machine. A novel accelerator technology must be developed to overcome several intrinsic issues of muon acceleration. Recent research and development of critical beam elements for a muon accelerator, especially muon beam phase space ionization cooling channel, are reviewed in this paper.

WHY MUON COLLIDER?

The Large Hadron Collider (LHC) has started operation since 2008. It has already begun to provide us the epoch-making results that support the standard model and may go beyond the modern particle physics theory. The LHC is the energy frontier machine in next couple of decades. On the other hand, the high-energy physics community requests that the next-generation high-energy lepton collider project needs to develop to follow up the LHC. International Linear Collider (ILC) and Compact LInear Collider (CLIC) have been proposed and studied for this purpose. These machines accelerate the lightest lepton particle, i.e. electron and positron. Therefore, these machines need to fight with synchrotron radiation. As a result, the size of these machines becomes enormous even if they could import state of the art technology of high gradient RF accelerator. In case of ILC and CLIC, the total length of acclerator complex are 30 and 50 km at the center of mass (CoM) energy 0.5 and 3 TeV, respectively.

On contrary, muon does not have such a synchrotron radiation problem because it is 200 times heavier than electron. Muon beam can be accelerated up to 0.75~1.5 TeV energy by using a circular accelerating machine. In fact, the size of 1.5 TeV CoM muon collider can be small enough to fit in the present Fermilab site (see Figure 1).

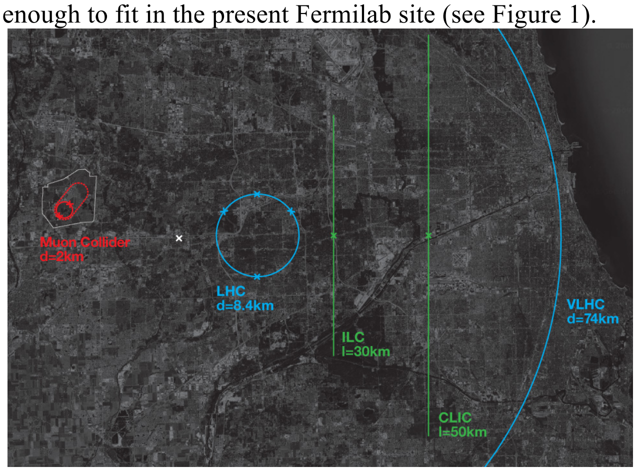

Figure 1: Scale of future accelerators [1]. Red object is the expected size of muon collider, which is located in Fermilab site.

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The available invariant mass in a 1.5 TeV muon collider is comparable with the LHC although the CoM in the LHC is almost one order of magnitude higher than the muon collider. In case of hadron collision, the invariant mass is determined by the energy of parton, i.e. $\sqrt{\hat{s}} = \sqrt{x_1 x_2}\sqrt{s}$. In most cases, only 10 % of the CoM energy of proton beam contributes to generate a heavy particle in proton collision. Since muon is an elementary particle, the invariant mass energy can be fully applied for a particle generation. Thus, more numbers of heavy particles can be generated in a muon collision. It also makes less background events in collision by comparing in a hadron collision event.

MUON ACCELERATOR PROGRAM

There are many critical issues to realize a muon collider. One of the biggest challenges is the muon acceleration and cooling. Muon Accelerator Program (MAP) has established since 2012 to maximize efforts of muon accelerator R&D [2]. The mission of the MAP is to develop and demonstrate the concepts and critical technologies required to produce, capture, condition, accelerate, and store intense beams of muons for muon colliders and neutrino factories. The goal of MAP is to deliver results that will permit the high-energy physics community to make an informed choice of the optimal path to a high-energy lepton collider and/or a next-generation neutrino beam facility. Coordination with the parallel Muon Collider Phyiscs and Detector Study and with the International Design Study of a Neutrino Factory will ensure MAP responsiveness to physics requirements.

The priorities of the present MAP activity is

- Demonstrate the feasibility of key concepts that would allow us to build a multi-TeV collider
- Continue to develop the critical elements of the Neutrino Factory and Muon Collider designs
- Support the ongoing accelerator R&D and concept demonstration program
- Establish close coordination with the detector and High Energy Physics experimental community
- As able, continue to support fundamental technical development in the field that has the potential to contribute significantly to the machine design
- Overarching goal during this phase of the program is to establish conceptual feasibility

Based on above concepts, the MAP supports many remarkable activities. Some of them are shown in the following document.

R&D OF RF CAVITIES FOR MUON ACCELERATION AND COOLING

MAP highly supports the RF cavity R&D that is taken place in MTA (Mucool Test Area). MTA is a unique facility in which high power (800 & 200 MHz) RF transports, an LHe cryogenic system, a 3 Tesla solenoid, and a 400 MeV intense proton beam are available. R&D of RF cavities for muon accelerator and cooling as shown below have been taken mainly at the MTA.

Since muon is generated in pion decay process, the volume of muon beam phase space after a pion decay channel is too large to be accepted in a conventional RF accelerator. It requires the muon beam phase space cooling. Besides, muon has a finite lifetime that is 2.2 μs at the stationary state. Fortunately, muon lifetime is long enough to condition the muon phase space by using a novel cooling technique, namely ionization cooling. The ionization cooling theory is similar as the electron cooling one. A heat transfer takes place between a projectile (muon beam) and a cooling object (ionization cooling material) via Coulomb interaction. A great advantage of ionization cooling is providing a dense electron during the cooling process. Achieved cooling decrement in ideal case can be estimated,

$$\varepsilon_n = \varepsilon_0 \exp\left(-\frac{\langle dE/dx\rangle}{\beta^2 E} z\right),$$

where β is a normalized particle velocity by speed of light and E is a kinetic energy of beam. $<dE/dx>$ is the ionization energy loss of muon. If an RF accelerator recovers the ionization energy loss, $<dE/dx>$ can be replaced to the acceleration gradient from the RF energy recovery cavity in the cooling channel. Figure 2 shows the required length of ionization cooling channel as a function of the RF recovery acceleration field gradient. The goal phase space cooling factor is 10^6. The designed RF recovery acceleration field gradient is 10~15 MV/m, thus the length of cooling channel can be 150~250 m.

There are another scattering processes between a projectile and nuclei of an ionization cooling material. It inflates the transverse beam phase space, i.e. a multiple scattering process. Therefore, the transverse beam phase space evolution is given by the balancing between a cooling and heating terms. The normalized equilibrium beam emittance in a transverse phase space is given,

$$\bar{\varepsilon}_{norm} = \frac{\beta_t (13.6\ \ MeV)^2}{2\beta m_\mu L_R}\langle\frac{dE}{dz}\rangle^{-1},$$

where L_R is a radiation length of cooling material and β_t is a transverse beta function. This relation gives us a clear picture that the best ionization cooling material must have a large ionization energy loss and a long radiation length (i.e. a low Z material) and a beam cooing lattice must provide a low beta function at a cooling material. Figure 3 shows the expected cooling efficiency of various cooling material. Gaseous or Liquid hydrogen is usually selected as the ionization cooling material.

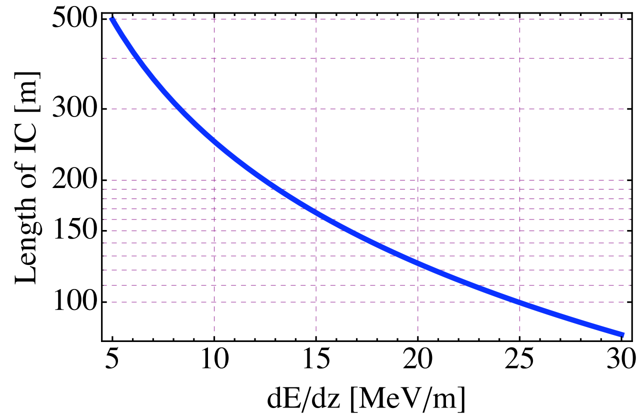

Figure 2: Required length of ionization cooling channel as a function of RF regain field gradient to achieve cooling factor 10^6.

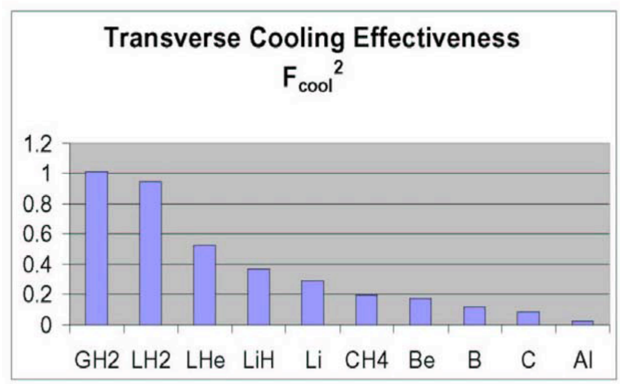

Figure 3: Cooling figure of merit in various light materials. The merit factor is given, $F_{cool} = <dE/dx> L_R$. The plot shows the square of merit factor because the transverse cooling takes place in two vertical planes [3].

Figure 4 shows a schematic view of ideal ionization cooling channel. A solenoid magnet is prefer to use in a muon ionization cooling channel because of its large momentum acceptance and simultaneous beam focusing in both x and y planes. It should also note that ionization cooling absorber locates at the lowest beta function. Therefore, the heat transfer efficiency is maximized. The RF energy recovery accelerator can be located either in front or behind the ionization cooling material but it should be embedded in a strong magnetic field. Designed magnetic field strength at the RF cavity is 3 Tesla and higher.

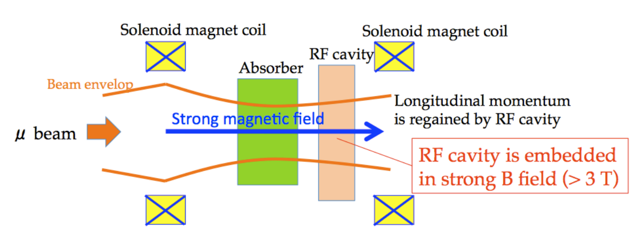

Figure 4: Schematic drawing of ionization cooling channel.

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Operating RF cavity in a strong magnetic field is essential to realize the ionization cooling channel. However, available RF accelerating field gradient in a vacuum RF pillbox cavity is limited by the strength of magnetic field because the field concentrates the dark current density in the cavity [4,5]. Consequently, the probability of RF breakdown that is ignited by the dark current is higher in stronger magnet. In past 805 MHz vacuum pillbox RF cavity operation in a strong magnetic field, the available peak acceleration field gradient was degraded by 1/3 at 3 Tesla from the field gradient at zero magnetic field. This value is about a half smaller than the desired RF energy recovery field gradient.

By filling a dense buffer gas in a RF cavity, the dark current flow can be diffused by Coulomb scattering. Molecular hydrogen is the ideal buffer gas since it makes the lowest multiple scattering angle in ionization process that minimizes the inflation of muon beam transverse phase space. Besides, a dense hydrogen gas can be used as the best ionization cooling material [3]. High pressure gas filled RF test cell was demonstrated in a strong magnetic field and found no RF field degradation by the magnetic field [6]. However, a dense hydrogen gas generates a dense beam-induced plasma in the cavity that makes a huge RF power loading effect. It is called the beam-plasma loading effect. Figure 5 shows the observed beam-plasma loading in an 800 MHz high pressure gas filled RF test cell by injecting a 400 MeV proton beam.

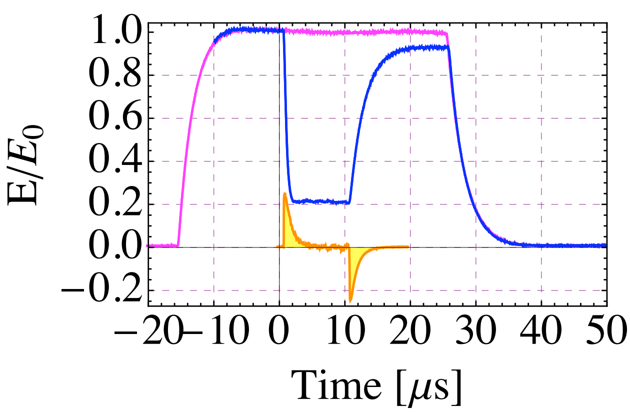

Figure 5: Beam-plasma loading effect in a 800 MHz high pressure gas filled RF test cell. A magenta and blue curves are a RF envelop without and with beam. A yellow curve is a toroid current monitor that indicates the beam arrival time (first positive peak) and beam off time (second negative one).

The beam-plasma loading effect was mitigated by doping a small amount of electronegative gas [7,8]. In the demonstration experiment, we doped a 1 % of dry air in a pure hydrogen gas, i.e. the cavity contains 0.2 % of oxygen gas. Figure 6 shows the observed beam-plasma loading effect in a 1 % dry air doped 1470 psi H_2 gas. The RF system is significantly improved with a doped gas. The small amount of RF power dissipation is the dissipated energy by the residual ions in the cavity. If this hypothesis is correct, we can estimate the beam-plasma loading effect in a realistic high-pressure hydrogen gas filled RF cavity with a realistic muon collider beam parameter.

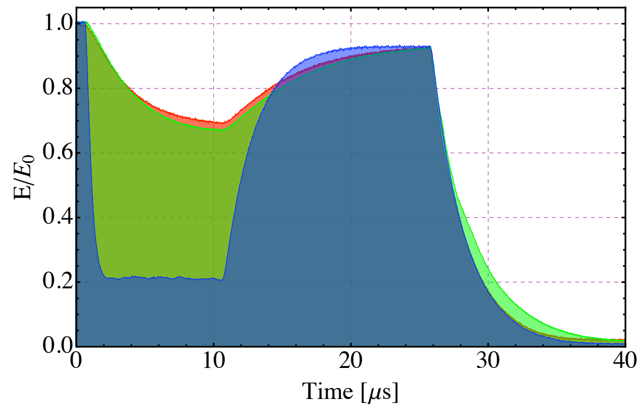

Figure 6: Observed beam-induced plasma loading effect in the cavity. Blue, Red, and Green areas are a pure H_2, a 1 % dry air doped H_2, and a 1 % dry air doped H_2 with 3 Tesla magnetic field, respectively.

Realistic muon collider beam parameter is discussed here to evaluate a realistic high-pressure gas filled RF cavity. A 4 MW 8 GeV proton beam is generated in a proton driver [8,9,10]. In order to maximize pion/muon capture rate in a muon beam frontend channel, proton beam is accumulated and compressed in 2 ± 1 ns in a bunch compressor ring. The protons would be formed into 2ns-long bunches that hit the target at 15 Hz (2.1 10^{14} /pulse). The pion's from that collision would be captured by the front end transport and RF into a series of μ^+ and μ^- bunches that will propagate through the cooling channel. 12 μ^- bunches are obtained in 200 MHz spacing of varying intensity (with fewer muons toward later bunches), and one will also have a similar train of μ^+ bunches. For a first estimate of the resulting secondary beam, we estimate that each proton would produce ~0.2 $\mu^\pm$ and that these are split into 12 bunches spaced by 5ns; in this model there would then be 3.5 10^{12} $\mu^\pm$ charges per bunch. Therefore, 4.2 10^{13} μs go through the cavity in 60 ns.

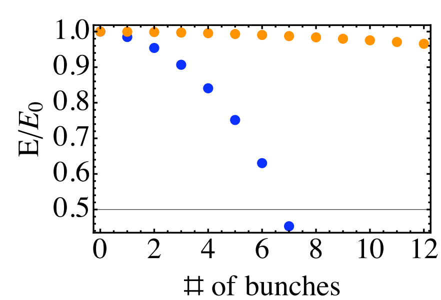

Figure 7: Estimated RF amplitude drop due to beam-induced plasma loading effect. Orange and blue points are with and without an electronegative dopant, respectively.

Figure 7 shows the estimated RF amplitude drop due to the beam-plasma loading in a realistic high-pressure gas filled 200 MHz RF pillbox cavity. The cavity contains a 180 atm hydrogen gas. Orange and blue points are with

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and without an electronegative dopant in the cavity. The RF amplitude drops only 5 % after 12 muon bunches go through the cavity with the dopant. It should note that the plot only represents the beam-induced plasma loading effect. From the demonstration experiment, the cavity can fully recovered from the beam-loading effect.

Apply High Pressure RF Cavity in Precooler

The actual power to use for muon production in the front end section is $p_\mu = qen_\mu\gamma m_\mu c^2$. Since the total number of muons in the front end section is 6.2 10^{14} μ/s, only 20 - 40 kW out of 4 MW of beam power is used for the muon production. The rest of power, 99~99.5 % should be absorbed somewhere. A high-pressure gas filled RF cavity will handle the unwanted electrons in the front end section. Hydrogen gas has a good thermal conductivity. Thus, even the secondary particle locally deposits a heat on the wall of a beam pipe hydrogen gas will unify the temperature distribution very quickly.

Apply High Pressure RF Cavity in Six-dimensional Space Ionization Cooling Channel

The ionization cooling works only on the transverse phase space. The emittance exchange process is needed to make a longitudinal phase space cooling. Figure 8 shows a concept of the emittance exchange in the ionization cooling process. On the left-hand side of drawing shows a conventional way to generate the emittance exchange, i.e. muon that is spatially distributed by a dispersion magnet with respect to its momentum penetrates through a wedge cooling absorber. Its path length depends on its momentum. Thus, the cooling beam lattice is designed as a separated function. On the other hand, the emittance exchange can take place in the dispersion magnet with a homogeneous ionization cooling absorber. In this concept, the designed cooling lattice can be a continuous field structure [11].

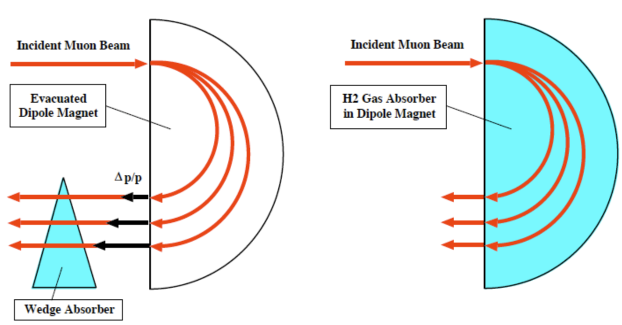

Fig. 8: Conceptual drawing of emittance exchange with ionization cooling.

A novel six-dimensional phase space ionization cooling channel is proposed by using a high pressure gas filled RF cavity [11]. A continuous dispersion structure can realize by using a helical dipole magnet with a solenoidal one. To stabilize the beam phase space, a continuous helical quadrupole component is superimposed. Figure 9 shows a particle tracking in a helical cooling channel.

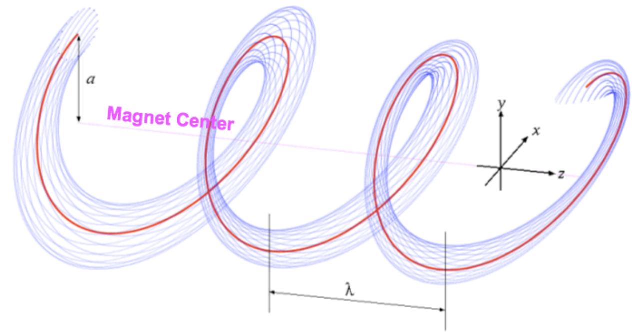

Figure 9: Particle tracking in a helical cooling channel. A red line is a reference particle. A blue line is the beam envelop.

Figure 10 shows the roadmap of transverse and longitudinal phase space evolution including with the six-dimensional ionization cooling channel. The six-dimensional cooling section has been demonstrated in various cooling channels including with the helical coolng channel that can make such a cooling performance in 300 m length with 40 % (60 % for high RF energy recovery gradient) of muon beam transmission efficiency [12].

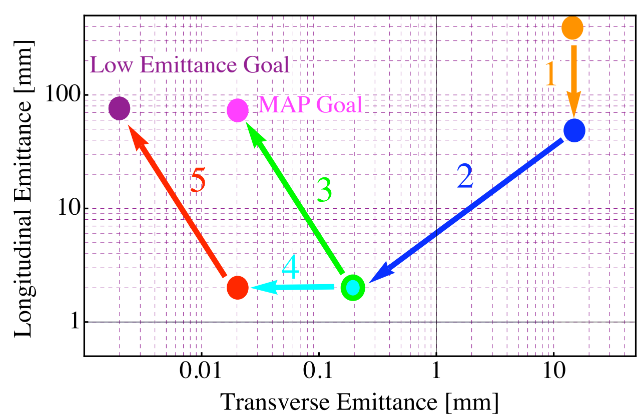

Figure 10: Roadmap of transverse and longitudinal beam phase space evolution in a cooling channel. 1. Longitudinal phase rotation in the frontend section, 2. A six-dimensional ionization cooling channel, 3. Final cooling channel, 4. (Optional) Extra transverse phase space cooling, and 5. (Optional) Final cooling channel.

Other R&D Program in MAP

Other RF breakdown study in a strong magnetic field has been performed in the MTA. Recent Be button cavity test in a magnetic field shows a positive result, i.e. the surface field gradient on the button reaches ~30 MV/m in a 3 Tesla solenoid [14]. In order to test all new concepts of RF cavity technologies, a real pillbox Cu cavity was built. The cavity can operate either vacuum or a high pressure gas condition. The cavity test is planed under various conditions including cryogenic circumstance.

MAP also highly supports the Muon Ionization Cooling Experiment (MICE) that is carried out at Rutherford Appleton Lab in the UK. The goal of MICE is to show that it is possible to design, engineer and build a section of cooling channel capable of giving the desired

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performance for a Neutrino Factory and to place it in a muon beam and measure its performance in a variety of modes of operation and beam conditions. The MICE has started taking data since 2011 and kept commissioning the detector system [15].

Some beam elements requires a high field magnet, e.g. a 20 Tesla solenoid field is needed in the target section. One of final cooling channel design requires 30 – 50 Tesla solenoidal field to make extremely low beta function. The final quadrupole focusing magnet at the interaction region also needs an enormous field gradient, 250 T/m in an 80 mm coil aperture [16]. A high temperature superconducting technology has been significantly developed in these days [17,18]. This technology will realize above critical devices.

MAP also promotes the design simulation efforts. The great progress has been taken place to design a muon collider ring. Design of collider ring is very challenging by comparing with a conventional collider ring. The main reason is that the ring must accept a very large momentum spread and produce a very low beta star. Besides, the momentum compaction factor is very small in the muon collider ring. The key parameter is how to deal with the chromaticity correction at the interaction region. By changing the order of aberration corrections, they can find the optimum collider ring parameters. Table 1 shows the result [19].

Table 1: Beam Parameter in the Muon Collider Ring

√s (TeV)	1.5	3.0
β^* (cm) (bare lattice)	1 (0.5-2)	0.5 (0.3-3)
Av. Luminosity /IP (10^{34} cm^{-2} s^{-1})	1.25	4.4
Max. bending field (T)	10	10
Av. bending field in arcs (T)	8.3	8.4
Circumference (km)	2.5 (2.7)	4.45
No. of IPs	2	2
Repetition rate (Hz)	15	12
Beam-beam parameter / IP	0.087	0.087
Beam size @ IP (μm)	6	3
Bunch length (cm)	1	0.5
No, muons/ bunch (1012)	2	2
Energy spread (%)	0.1	0.1

Design study of the muon collider detector is another critical subject since the collider detector will meet a huge radiation background, i.e. one high energy electron and two high energy neutrinos from muon decays. Decay electron can be a source of high energy gamma, which makes a pair of muons in nuclei, so called Bethe-Heitler muon. Fortunately, these background noises can be significantly eliminated by triggering individual calorimeter pixel in proper time and gate length. Then, the background noise can be suppressed by two orders of magnitude from the original detector design. Other unique idea is to use the Tungsten cone to be instrumented. This helps to distinguish the background noise from the true event [21].

SUMMARY

The MAP has begun since 2012 and it has already provided several remarkable results. Operating high gradient RF energy recovery cavity in a strong magnetic field is one of the most critical beam elements in the muon accelerator and cooling. A high pressure hydrogen gas filled RF cavity is the breakthrough technology to solve the issue. It demonstrates that the ionization cooling channel is feasible.

ACKNOWLEDGMENT

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