

MUON COOLING AND FUTURE MUON FACILITIES

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Muon colliders and neutrino factories are attractive options for achieving the highest lepton-antilepton collision energies and the most precise measurements of the parameters of the neutrino mixing matrix. The performance and cost of these future facilities depends sensitively on how well a beam of muons can be cooled. The recent progress of muon-cooling prototype tests and design studies nourishes the hope that such facilities can be built during the next decade.

Keywords: collider; cooling; muon; neutrino; factory.

1. Introduction

The muon offers important advantages over the electron for use in a high-energy collider:

- (1) The $1/m^2$ suppression of radiative processes enables the use of storage rings and recirculating accelerators, reducing the size (Fig. 1) and cost of the complex.
- (2) In the Standard Model and many extensions, the muon/electron cross-section ratio for s -channel annihilation to Higgs bosons is $(m_\mu/m_e)^2 = 4.3 \times 10^4$, giving the muon collider a unique window on electroweak symmetry breaking.^{1,2}
- (3) “Beamstrahlung” interactions, which limit e^+e^- -collider luminosity as energy increases,³ are negligible for muons.

Moreover, a muon storage ring is an ideal source for long-baseline neutrino-oscillation experiments: via $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$ and $\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$, it can provide collimated, high-energy neutrino beams with well-understood composition and properties.⁴ The very clean identification of final-state muons in far detectors enables low-background appearance measurements using ν_e and $\bar{\nu}_e$ beams. The separation of oscillated from non-oscillated events requires only that the detector be magnetized so as to distinguish μ^+ (the oscillated events if μ^- are stored in the ring) from μ^- (the oscillated events if μ^+ are stored).

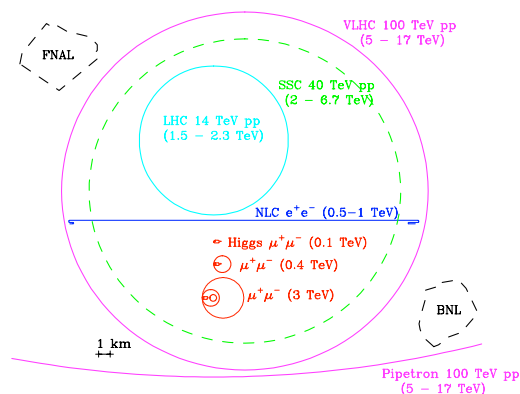


Fig. 1. Sizes of various proposed colliders compared with FNAL and BNL sites. A muon collider with $\sqrt{s} > 3$ TeV fits on existing sites.

These advantages come with clear disadvantages: the short muon lifetime and large beam size require development of new, rapid beam manipulation and acceleration techniques if intense muon beams are to be accelerated, stored, or collided. Stored-muon “neutrino factories” (Fig. 2) and colliders (Fig. 3) benefit from muon-beam cooling,⁵ which allows smaller-aperture (hence less costly) accelerators and higher luminosity.

2. Muon Cooling

Standard (electron, stochastic, and laser) beam-cooling methods are far too slow to be effective within the $2.2 \mu\text{s}$ muon lifetime. However, the muon’s penetrating character

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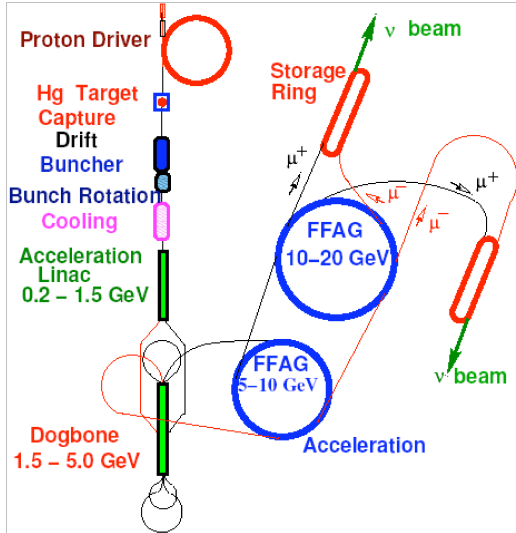


Fig. 2. Sketch of a recent neutrino-factory design:⁶ pions created by beam from high-intensity “proton driver” are captured and decay in a focusing channel; decay muons undergo phase-space manipulations, including transverse ionization cooling; are accelerated in a linac, a “dogbone” recirculating linac (RLA), and two fixed-field alternating-gradient (FFAG) accelerators; and are stored in two racetrack-shaped decay rings whose long straight sections each form oppositely directed neutrino and antineutrino beams aimed at near and far detectors.

enables rapid muon cooling via *ionization*.^{7,8} An ionization-cooling channel comprises energy absorbers and radio-frequency (rf) accelerating cavities placed within a focusing magnetic lattice. In the absorbers the muons lose energy by ionization; the rf cavities restore energy only along the beam axis. In this way, the (initially highly divergent) muon beam can be made more parallel.

Cooling is best understood in terms of normalized beam emittance ϵ_n , the volume of a beam in phase space, which is a constant of the motion both in linear beam transport and during acceleration. Cooling is the process of reducing a beam’s normalized emittance. In a medium, normalized transverse emittance depends on path length s as^{9,10}

$$\frac{d\epsilon_n}{ds} \approx -\frac{1}{\beta^2} \left\langle \frac{dE_\mu}{ds} \right\rangle \frac{\epsilon_n}{E_\mu} + \frac{1}{\beta^3} \frac{\beta_\perp (0.014)^2}{2E_\mu m_\mu L_R}, \quad (1)$$

where β is the muon velocity in units of

c , E_μ the muon energy in GeV, m_μ its mass in GeV/c^2 , β_\perp the lattice betatron function, and L_R the radiation length of the medium. A portion of this cooling effect can be transferred to the longitudinal phase plane by placing suitably shaped absorbers in dispersive regions of the lattice (“emittance exchange”)^{8,9,10} or using path-length-dependent energy loss within a homogeneous absorber.¹¹ (Longitudinal ionization cooling *per se* is impractical due to energy-loss straggling.¹⁰)

The terms of Eq. 1 represent muon cooling by energy loss and heating by multiple Coulomb scattering. Setting the two terms equal gives the equilibrium emittance $\epsilon_{n,eq}$, at which the cooling rate is zero and beyond which a given lattice cannot cool. Since the heating term scales with β_\perp , a low $\epsilon_{n,eq}$ requires low β_\perp (i.e., high focusing strength) at the absorbers. Most design studies have

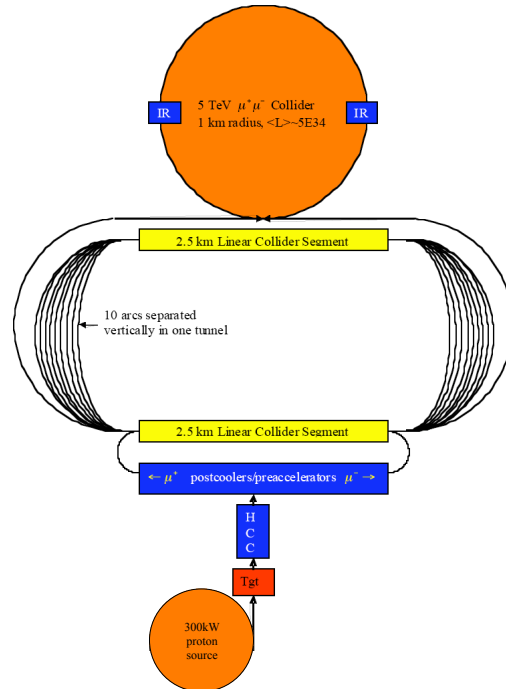


Fig. 3. Sketch of a Muons, Inc. muon collider concept with $\sqrt{s} = 5\text{TeV}$: a helical cooling channel¹⁷ cools the μ^+ and μ^- beams in all six dimensions sufficiently that they can then be accelerated in an RLA based on ILC-style rf-cavity modules.

used superconducting solenoids, which can give $\beta_{\perp} \sim 10$ cm, as the focusing element of choice. Concerning L_R , low- Z absorber media are favored, the best being hydrogen (approximately twice as effective for cooling as helium, the next best material¹²).

It is the absorbers that cool the beam, but for typical “real-estate” accelerating gradients (≈ 10 MeV/m, to be compared with $\langle dE_{\mu}/ds \rangle \approx 30$ MeV/m for liquid hydrogen¹³), the rf cavities dominate the length of the cooling channel (see e.g. Fig. 4). Ideally, the acceleration should exceed the minimum required for energy replacement, allowing “off-crest” operation. This gives continual rebunching, so that a beam with large momentum spread remains captured in the rf bucket. The achievable rf gradient thus determines how much cooling is practical before an appreciable fraction of the muons have decayed or drifted out of the bucket. High-gradient rf cavities (normal-conducting due to the magnetic field in which they must operate) for muon cooling are under development,¹⁴ as is an alternative cooling approach: cavities pressurized with hydrogen gas, thus combining energy absorption and reacceleration.¹⁵ In the first cooling stages the large size of the uncooled beam requires relatively low rf frequency. Goals are ≥ 15 MeV/m at ≈ 201 MHz in ≈ 2 T fields.

In the cooling term of Eq. 1, the percentage decrease in normalized emittance is proportional to the percentage energy loss, thus (approximating $\beta \approx 1$) cooling in one transverse dimension by a factor $1/e$ requires $\sim 100\%$ energy loss and replacement. Despite the relativistic increase of muon lifetime with energy, ionization cooling favors low beam momentum because of the increase of dE/ds for momenta below the ionization minimum,¹³ the greater ease of beam focusing, and the lower accelerating voltage required. Most muon-cooling designs have used momenta in the range 150–400 MeV/ c . This is also the momentum range in which

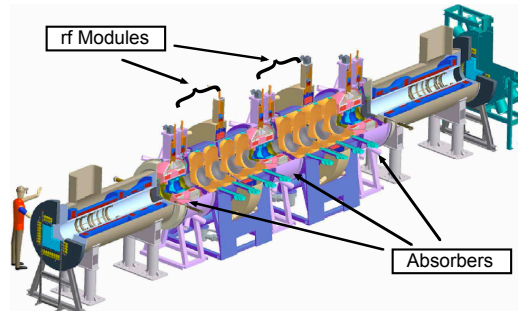


Fig. 4. Three-dimensional cutaway rendering of MICE apparatus (see text): muons entering at lower left are measured by time-of-flight (TOF) and Cherenkov counters and a solenoidal tracking spectrometer; then, in cooling section, alternately slowed in LH₂ absorbers and reaccelerated by rf cavities, while focused by a lattice of superconducting solenoids; then remeasured by a second solenoidal tracking spectrometer and their muon identity confirmed by TOF detectors and a calorimeter.

the pion-production cross section from thick targets tends to peak and is thus optimal for muon production as well as cooling. The cooling channel of Fig. 4 is optimized for a mean muon momentum of 200 MeV/ c .

3. Towards a Muon Collider

Cooling lattices using longitudinal-transverse emittance exchange to cool simultaneously in all six dimensions are receiving increasing attention,^{16,17} from both the Neutrino Factory and Muon Collider Collaboration¹⁸ and Muons, Inc.¹⁹ These are essential to a high-luminosity muon collider and may enable higher-performance or lower-cost neutrino factories. As Fig. 3 suggests, muon colliders offer the prospect of much higher collision energies than are feasible with electrons; they thus provide a potential next step beyond the ILC.

4. Technology Demonstrations

The R&D on muon cooling²⁰ has identified a number of technologies crucial to future muon facilities, each of which has a demonstration experiment proposed or in progress:

- (1) The MERIT (Mercury Intense Target) experiment, approved at CERN and under construction for operation in 2007; the goal is to show feasibility of a mercury-jet target for a 4 MW proton beam with solenoidal pion capture.²¹
- (2) MICE (the Muon Ionization Cooling Experiment, see Fig. 4), approved at Rutherford Appleton Laboratory and under construction, aiming to verify the feasibility and performance of transverse ionization cooling by 2010.²²
- (3) EMMA (Electron Model of Muon Accelerator), proposal to build and operate at Daresbury Laboratory a model “non-scaling” FFAG accelerator.²³
- (4) MANX (Muon collider And Neutrino factory eXperiment), LoI to build and test a helical cooling channel segment.¹⁹

Experimental results may soon strengthen the physics case for a muon facility. With the key techniques established by ≈ 2010 , a facility could then be built in the ensuing decade.

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