MUON COOLING AND FUTURE MUON FACILITIES

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

Keywords: collider; cooling; muon; neutrino.

1. Introduction

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

(1) Radiative processes ($\propto 1/m^2$) are highly suppressed, allowing use of recycling accelerators. This reduces 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) Beam-beam electromagnetic interactions (negligible for muons) make achieving high luminosity more difficult as the energy of an e^+e^- collider increases.[3]

A muon storage ring is an ideal source for long-baseline neutrino-oscillation experiments: via $\mu^- \to e^-\nu_\mu\overline{\nu}_e$ and $\mu^+ \to e^+\overline{\nu}_\mu\nu_e$, it can provide collimated, high-energy neutrino beams whose composition and properties are well understood.[4] The very clean identification of final-state muons in far detectors enables low-background appearance measurements using ν_e and $\overline{\nu}_e$ 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).

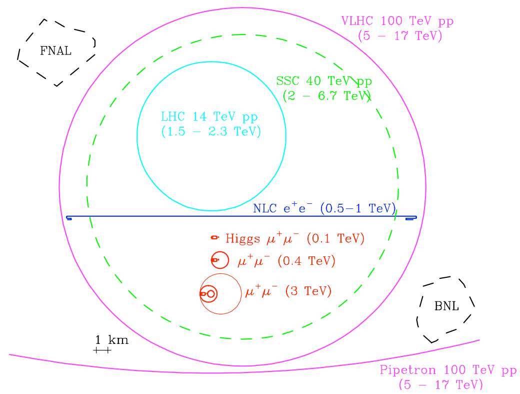

Fig. 1. Sizes of various proposed colliders compared with FNAL and BNL sites. A muon collider with $\sqrt{s}$ of 3 TeV or more fits on existing sites.

These advantages come with clear disadvantages: muon decay and large muon-beam size require development of new, rapid beam manipulation and acceleration techniques if intense muon beams are to be accelerated, stored, or collided. Both stored-muon "neutrino factories" (Fig. 2) and colliders can 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 μs muon lifetime.

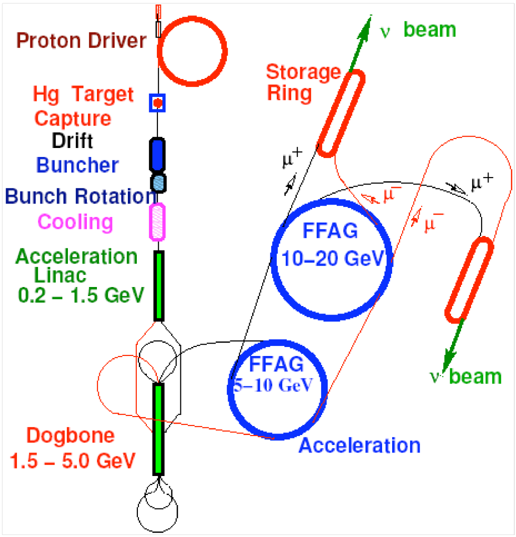

Fig. 2. Sketch of a recent neutrino-factory design:[6] pions created by beam from high-intensity "proton driver" are captured and decay in a focusing channel; decay muons undergo phase-space manipulations, including transverse ionization cooling; are accelerated in a linac, a "dogbone" recirculating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

However, the muon's penetrating character enables rapid muon cooling via *ionization*.[7] 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 beam emittance ϵ, the volume of a beam in phase space. To account for the adiabatic decrease in beam size with acceleration, normalized emittance ϵ_n is employed, in which the phase-space volume is scaled by the momentum. Normalized emittance is a constant of the motion in normal beam transport and acceleration. Cooling is the process of reducing a beam's normalized emittance.

In a medium, normalized transverse emittance depends on path length s as[7,8]

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

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, $\beta_\perp$ the lattice betatron function, and L_R the radiation length of the medium. A portion of this cooling effect can be "rotated" into the longitudinal phase plane by suitably shaped absorbers in dispersive regions of the lattice ("emittance exchange"),[8,9] or using path-length-dependent energy loss in a homogeneous absorber.[10] (Longitudinal ionization cooling *per se* is impractical due to energy-loss straggling.[8])

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 $\beta_\perp$, the smallest $\epsilon_{n,eq}$ is for minimal $\beta_\perp$ (i.e., maximum focusing strength) at the absorbers. Most design studies use 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 material[?]).

It is the absorbers that cool the beam, but for typical "real-estate" accelerating gradients (≈10 MeV/m, vs. $\langle dE_\mu/ds\rangle \approx$ 30 MeV/m for liquid hydrogen[12]), the rf cavities dominate the length of the cooling channel (see, e.g., Fig. 3). 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

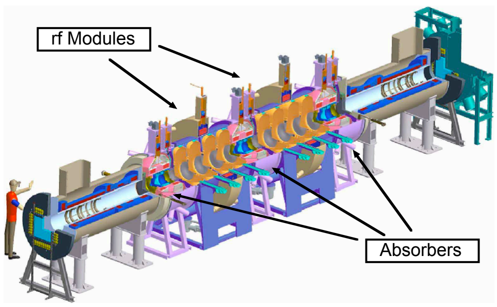

Fig. 3. Three-dimensional cutaway rendering of the MICE apparatus (see text). The muon beam enters from the lower left and is measured by time-of-flight (TOF) and Cherenkov detectors and a first solenoidal tracking spectrometer. It then enters the cooling section, where it is alternately slowed down in LH_2 absorbers and reaccelerated by rf cavities, while being focused by a lattice of superconducting solenoids. Finally it is remeasured by a second solenoidal tracking spectrometer and its muon identity confirmed by TOF detectors and a calorimeter.

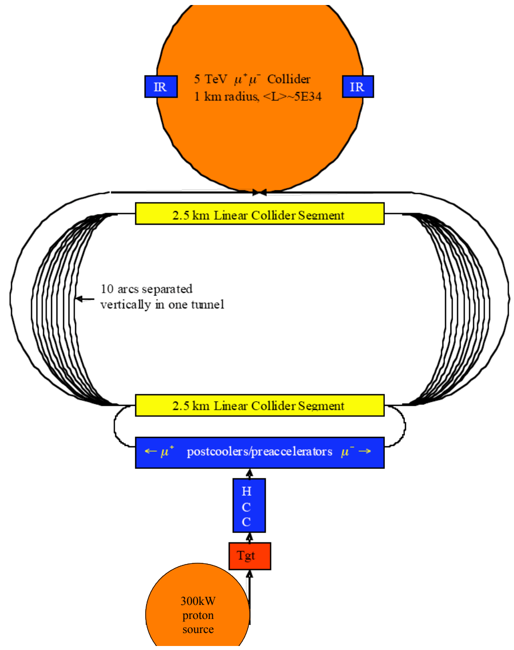

Fig. 4. Sketch of a Muons, Inc. muon collider concept with $\sqrt{s}$ = 5 TeV, using a helical cooling channel[16] to cool the μ^+ and μ^- beams in all six dimensions sufficiently that they can then be accelerated in an RLA based on Linear Collider segments.

fraction of the muons have decayed or drifted out of the bucket. High-gradient rf cavities for muon cooling are under development,[13] as is an alternative approach: cavities pressurized with hydrogen gas, thus combining energy absorption and reacceleration.[14] Goals are $\gtrsim$15 MeV/m at $\approx$201 MHz in $\approx$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,[12] the greater ease of beam focusing, and since less accelerating voltage is then required. Most neutrino-factory and muon-collider beam-cooling designs and simulations to date have used momenta in the range $150 - 400$ MeV/c. This is also the momentum range in which the pion-production cross section off of thick targets tends to peak and is thus optimal for muon production as well as cooling. The cooling channel of Fig. 3 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,[15,16] from both the Neutrino Factory and Muon Collider Collaboration (NFMCC)[17] and Muons, Inc.[18] These are essential to a high-luminosity muon collider and may enable higher-performance or lower-cost neutrino factories. As Fig. 4 suggests, muon colliders offer the prospect of much higher collision energies than are feasible with electrons; they thus provide a potential upgrade path beyond the ILC.

4. Technology Demonstrations

The R&D on muon cooling[19] 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 Hg-jet target for a 4 MW proton beam with solenoidal pion capture.[20]
(2) MICE (the Muon Ionization Cooling Experiment, see Fig. 3), approved at Rutherford Appleton Laboratory and under construction, aiming to verify the feasibility and performance of transverse ionization cooling by 2010.[21]
(3) EMMA (Electron Model of Muon Accelerator), proposal to build and operate at Daresbury Laboratory a model "non-scaling" FFAG accelerator.[22]
(4) MANX (Muon collider And Neutrino factory eXperiment), proposal to build and test a helical cooling channel segment.[18]

With a strong physics case and the key techniques established by ≈2010, a facility could possibly be built during the coming decade.

5. Acknowledgments

This work was supported by the US Dept. of Energy and the National Science Foundation.

References

1. V. Barger, M. Berger, J. Gunion, T. Han, Phys. Rep. **286**, 1 (1997).
2. A sensitivity advantage is expected in most models that account for mass generation; see e.g. R. Casalbuoni *et al.*, Phys. Lett. B **285**, 103 (1992); C. T. Hill, Phys. Lett. B **345**, 483 (1995); K. Lane, E. Eichten, Phys. Lett. B **352**, 382 (1995); K. Lane, Phys. Rev. D **54**, 2204 (1996); E. Eichten *et al.*, Phys. Rev. Lett. **80**, 5489 (1998).
3. R. B. Palmer and J. C. Gallardo, in *Proc. XXVIII Int. Conf. on High Energy Physics*, ed. Z. Ajduk, A. K. Wroblewski, World Scientific, Singapore (1997), p. 435.
4. S. Geer, Phys. Rev. D **57**, 6989 (1998); *ibid.* **59**, 039903E (1999); C. Albright *et al.*, Fermilab-FN-692 (May, 2000), hep-ex/0008064; M. Apollonio *et al.*, CERN-TH-2002-208 (Oct. 2002.), hep-ph/0210192; M. Lindner, in *Neutrino Mass*, ed. G. Altarelli, K. Winter, Springer Tracts in Modern Physics Vol. 190 (2003), p. 209.
5. E.g., cooling is cost-effective and worth a factor ≈1.7 in ν intensity in the ISS design.[6]
6. M. S. Zisman, "International Scoping Study Accelerator Working Group Summary Report," presented at NuFact 06 Workshop, Irvine, CA, 24–30 August 2006; available from `http://nufact06.physics.uci.edu/Workshop/Program/Plenary.aspx` ; see also ISS web page `http://www.hep.ph.ic.ac.uk/iss/iss-plenary-meetings/iss-benemain.html`
7. A. N. Skrinsky, V. V. Parkhomchuk, Sov. J. Part. Nucl. **12**, 223 (1981); D. Neuffer, Part. Acc. **14**, 75 (1983); E. A. Perevedentsev, A. N. Skrinsky, in *Proc. 12th Int. Conf. on High Energy Accelerators*, ed. F. T. Cole, R. Donaldson (Fermilab, 1984), p. 485; R. Palmer *et al.*, Nucl. Phys. Proc. Suppl. **51A**, 61 (1996).
8. D. Neuffer, CERN-99-12 (1999).
9. C. M. Ankenbrandt *et al.*, Phys. Rev. ST Accel. Beams **2**, 081001 (1999).
10. Y. Derbenev, R. P. Johnson, Phys. Rev. ST Accel. Beams **8**, 041002 (2005).
11. D. M. Kaplan, in *Proc. NuFact'02 Workshop*, J. Phys. G **29**, 1585 (2003).
12. W.-M. Yao *et al.* (Particle Data Group), J. Phys. G **33**, 1 (2006).
13. Y. Torun *et al.*, in *Proc. COOL05 Workshop*, ed. S. Nagaitsev, R. Pasquinelli, AIP Conf. Proc. **821**, 437 (2006)
14. P. Hanlet *et al.*, in *Proc. EPAC 2006*, p. 1364 (2006).
15. R. Palmer *et al.*, Phys. Rev. ST Accel. Beams **8**, 061003 (2005).
16. R. Johnson *et al.*, in *Proc. COOL05*, *op. cit.*, p. 405.
17. See `http://www.cap.bnl.gov/mumu/`
18. See `http://www.muonsinc.com`
19. M. Alsharoa *et al.*, Phys. Rev. ST Accel. Beams **6**, 081001 (2003).
20. See `http://proj-hiptarget.web.cern.ch/proj-hiptarget/`
21. See `http://www.mice.iit.edu/`
22. See `http://hepunx.rl.ac.uk/uknf/wp1/emodel/`