FINAL TECHNICAL REPORT FOR DOE AWARD DE-FG02-03ER41267
NEUTRINO FACTORY AND MUON COLLIDER FELLOW

1. Introduction

By providing an intense, well controlled, well characterized, narrow beam of muon neutrinos (ν_μ's) and electron antineutrinos ($\bar{\nu}_e$'s) from the decay of muons (μ^-'s) in a storage ring, a neutrino factory can advance neutrino physics beyond the current round of approved and proposed experiments using conventional neutrino beams produced from a beam of decaying pions and kaons [1, 2]. There is no other comparable single clean source of electron neutrinos (from the decay of μ^+'s) or antineutrinos. A muon storage ring producing 10^{19} to 10^{21} muon decays per year should be feasible. These intense neutrino beams can be used to study neutrino oscillations and possible *CP* violation. An entry-level muon storage ring that could provide 10^{19} decays per year would allow a determination of the sign of Δm^2_{31} and a first measurement of $\sin^2 2\theta_{13}$ for favorable values of this parameter. An improved muon storage ring system that could provide 10^{20} muon decays per year would allow measurement of $\sin^2 2\theta_{13}$ to $\sim 10^{-4}$. A high performance muon storage ring capable of providing more than 10^{20} muon decays per year would allow the exciting possibility of a measurement of *CP* violation in the leptonic sector. An intense cold muon beam at the front end of a neutrino factory could enable a rich variety of precision muon physics, such as a more precise measurement of the muon anomalous magnetic moment ($g - 2$) and searches for $\mu \rightarrow e\,\gamma$ and $\mu^- N \rightarrow e^- N$ conversion [3]. In addition, colliding beams of μ^+ and μ^- in a muon collider can provide an effective "Higgs factory" or multi-TeV center-of-mass energy collisions [4]. A muon collider will be the best way to study the Higgs bosons associated with supersymmetric theories and may be necessary to discover them.

Two neutrino factory feasibility studies have been carried out in the U.S. [5, 6]. International design efforts are now under way. The International Neutrino Factory and Superbeam Scoping Study (ISS) [7] began at the NuFact05 Workshop in June 2005 with the goals of elaborating the physics case, defining the baseline options for such a facility and its neutrino detectors, and identifying the required R&D program to lay the foundations for a complete design study proposal, and an International Design Study of the Neutrino Factory is

beginning. These studies entail iterative cost and technical difficulty evaluations, thereby providing guidelines for the advancing R&D program. One of the central subsystems of a neutrino factory or muon collider is the muon cooling system. The muon beam is cooled to increase the phase space density and allow the muons to pass through smaller apertures, thus reducing the cost of the following accelerator systems. This cooling is accomplished through ionization cooling, in which the beam is passed through liquid hydrogen absorbers and then accelerated in RF cavities to restore the longitudinal momentum.

Ionization cooling was proposed more than twenty years ago [8] but has not yet been demonstrated in practice. The International Muon Ionization Cooling Experiment (MICE) [9, 10] seeks to build and operate a muon-cooling device of a design proposed in Feasibility Study-II [6]. In addition to cooling the muons, MICE includes apparatus to measure the performance of the device. The experiment will be carried out by a collaboration of physicists from the U.S., Europe, and Japan at the Rutherford Appleton Laboratory in the U.K. MICE will begin operation in late 2007. Successful performance of the MICE experiment will provide the understanding needed to design a complete neutrino factory, in which the muons are cooled, accelerated, circulated in a storage ring, and decay to produce the neutrino beam. The first neutrino factory might be built in the U.S., Europe, or Japan. A Muon Collider Task Force (MCTF) has recently been organized at Fermilab.

2. Neutrino Factory and Muon Collider R&D at U.C. Riverside

Neutrino Factory and Muon Collider R&D began at U.C. Riverside in January 2002 with the arrival of Distinguished Professor Gail Hanson, who had begun research with the NFMCC several years earlier while at Indiana University. Dr. Amit Klier joined U.C. Riverside as a postdoctoral research associate in December 2002. Dr. Klier took the web-based accelerator physics course from Michigan State University when he first arrived.

The ring cooler was the first demonstration of a cooling system that simultaneously cools in both the transverse and the longitudinal directions (emittance exchange or six-dimensional cooling). Emittance exchange is necessary for muon colliders. V. Balbekov [11] of Fermilab designed the first ring cooler, leading to several other designs [12]. We initially worked with a simulation team led by Dr. Rajendran Raja of Fermilab, using the GEANT3 simulation code. Dr. Klier's GEANT3 simulation of the Tetra ring cooler,

originally developed by Balbekov, showed the expected longitudinal cooling, which had been demonstrated previously only with Balbekov's own code. Klier then simulated the RFOFO cooling ring using GEANT3 and found agreement with the previous ICOOL [13] simulation. The RFOFO simulation studies were published [14]. Klier then worked on simulations of dipole ring coolers [15] and the "Guggenheim," a helical version of the RFOFO ring cooler [16]. Klier was initially supported by the National Science Foundation as part of the consortium of university-based particle and accelerator physicists led by Cornell University until August 31, 2004. He was then supported by Hanson's startup funds from September 2004 through March 2005 and was appointed an NFMCC Simulation Fellow on April 1, 2005. Klier continued as an NFMCC Simulation Fellow through August 2005, after which he was again supported on Hanson's startup funds.

Hanson was one of four Co-PI's on the 2002 proposal to the National Science Foundation requesting funding for the U.S. part of the MICE effort. Funding was awarded at the level of $100k per year to the Illinois Institute of Technology from which Klier and Hanson have had some modest support for travel. In MICE, spectrometers measure the parameters of muons entering and exiting the cooling section. At U.C. Riverside we have been working on the spectrometer fiber tracking. During 2005 Klier worked on the preparation of the four-stage fiber tracker prototype at Fermilab and participated in testing this prototype in a beam at KEK in Japan. He has also done some work on MICE software.

In addition, Klier worked with the International Scoping Study for a Future Accelerator Neutrino Complex Accelerator Working Group.

Hanson and collaborators have also been actively working on ideas for a Higgs Factory as a first muon collider.

Hanson and Klier have given many presentations on our research and on the physics and accelerator physics ideas of neutrino factories and muon colliders. Our presentations, publications, and other Neutrino Factory and Muon Collider Collaboration contributions are listed in Section 3.

3. Neutrino Factory and Muon Collider Collaboration Contributions

Publications:

1. G. G. Hanson and A. Klier, "Geant Simulation of Muon Cooling Rings," *Proceedings of the 7th International Workshop on Neutrino Factories and Superbeams (NuFACT'05), June 21-26, 2005, Frascati, Italy, Nucl. Phys. Proc. Suppl.* **155**, 277 (2006).

2. R. Palmer, *et al.*, "Ionization Cooling Ring for Muons," *Phys. Rev. ST Accel. Beams* **8**, 061003 (2005).

3. Amit Klier and Gail G. Hanson, "Geant Simulation of Six-Dimensional Cooling of Muon Beams in Ring Coolers," *Proceedings of the 2005 Particle Accelerator Conference, Knoxville, Tennessee*, May 16-20, 2005, p. 2580 (2005).

4. Mohammad M. Alsharo'a, *et al.*, "Recent Progress in Neutrino Factory and Muon Collider Research Within the Muon Collaboration," *Phys. Rev. ST Accel. Beams* **6**, 081001 (2003).

5. G. Hanson, "Towards the Higgs Factory/Muon Collider," *Proceedings of the 3rd International Workshop on Neutrino Factories Based on Muon Storage Rings – NuFACT'01, Tsukuba, Japan, May 2001, Nucl. Instrum. Meth.* **A503**, 96 (2003).

6. G. Hanson, "Status of R&D on Neutrino Factories and Muon Colliders," *Proceedings of the XXXI International Conference on High Energy Physics (ICHEP02), Amsterdam, The Netherlands, July 24-31,* 933 (2002).

7. S. Ozaki, R. Palmer, M.S. Zisman, and J. Gallardo, eds., "Feasibility Study-II of a Muon-Based Neutrino Source," BNL-52623 (June 2001). See http://www.cap.bnl.gov/mumu/studyii/FS2-report.html.

8. D.B. Cline and G.G. Hanson, "A Muon Collider as a Higgs Factory," *Proceedings of the IEEE Particle Accelerator Conference (PAC2001), Chicago, Illinois, June 18–22, 2001*, p 3579.

9. D.B. Cline and G.G. Hanson, editors, "Higgs Factory Muon Collider," prepared for Snowmass 2001. See http://www.physics.ucla.edu/snowmass.

10. D.B. Cline and G.G. Hanson, "A Muon Collider as a Higgs Factory," *Proceedings of the APS/DPF/DPB Summer Study on the Future of Particle Physics (Snowmass 2001), Snowmass, Colorado, June 30–July 21, 2001*, p. M103.

11. N. Holtkamp and D. Finley, eds., "A Feasibility Study of a Neutrino Source Based on a Muon Storage Ring," Fermilab-Pub-00/108-E (2000). See http://www.fnal.gov/projects/muon_collider/nu-factory/nu-factory.html.

12. C.M. Ankenbrandt, *et al*. (Neutrino Factory and Muon Collider Collaboration), "Status of Muon Collider Research and Development and Future Plans," *Phys. Rev. ST Accel. Beams* **2**, 081001 (1999).

Presentations:

- G. Hanson, "Accelerators of the Future: Neutrino Factories and Muon Colliders," Department of Physics and Astronomy Colloquium, University of Southern California, November 27, 2006.

- A. Klier, "Muon Colliders: Challenges and Prospects," invited seminar at Caltech, May 23, 2006.

- A. Klier, "Studies of Six-Dimensional Cooling of a Muon Beam," invited talk in parallel session C14 DPB at the American Physical Society Meeting, Dallas, Texas, April 22-25, 2006.

- A. Klier, "Guggenheim Cooling Channel," Neutrino Factory and Muon Collider Collaboration Meeting, Illinois Institute of Technology, Chicago, Illinois, March 12-15, 2006.

- A. Klier, "How to Guggenheim the RFOFO Ring," Low Emittance Muon Collider Workshop, Fermilab, February 6-10, 2006.

- A. Klier, "'Shielding' Demonstration in a Simplified RFOFO Cell," 2nd International Scoping Study Meeting of Neutrino Factory and Super-beam Facility, KEK, Tsukuba, Japan, January 23-25, 2006.

- A. Klier, "The 'Guggenheim RFOFO Ring,'" ISS Machine Working Group Meeting, Brookhaven National Laboratory, December 15, 2005.

- G. Hanson, "Neutrino Factories and Muon Colliders," Freshman Seminar, Department of Physics, University of California, Riverside, November 9, 2005.

- A. Klier, "Neutrino Factories and Muon Colliders," invited seminar at the Weizmann Institute, Rehovot, Israel, June 16, 2005.

- A. Klier, "Neutrino Factories and Muon Colliders," invited seminar at the Technion University, Haifa, Israel, June 15, 2005.

- A. Klier, "Neutrino Factories and Muon Colliders," invited seminar at Tel Aviv University, Tel Aviv, Israel, June 9, 2005.

- A. Klier, "Physics at a Future Muon Collider," Electroweak Symmetry Breaking Working Group, 20th International Workshop on Weak Interactions and Neutrinos (WIN05), Delphi, Greece, June 6-11, 2005.

- A. Klier, "GEANT Simulation of Six-Dimensional Cooling of Muon Beams in Ring Coolers," poster presentation at the 2005 Particle Accelerator Conference, Knoxville, Tennessee, May 2005.

- G. Hanson, "Neutrino Factories and Muon Colliders," Freshman Seminar, Department of Physics, University of California, Riverside, October 2004.

- G. Hanson, "Neutrino Factories and Muon Colliders," Joint Particle Seminar, Department of Physics and Astronomy, University of California, Irvine, June 2, 2004.

- G. Hanson, "Muon Colliders," SLAC-Novosibirsk International Symposium "Forty Years of Lepton Colliders" (COLLID04), BINP, Novosibirsk, Russia, May 15-17, 2004.

- G. Hanson, "Neutrino Factories and Muon Colliders," Colloquium, Department of Physics, University of California, Riverside, March 4, 2004.

- A. Klier, "Simulating the RFOFO Ring with GEANT," MC Collaboration Meeting, Riverside, California, January 27-31, 2004.

- G. Hanson, "Neutrino Factories and Muon Colliders," Freshman Seminar, Department of Physics, University of California, Riverside, October 22, 2003.

- G. Hanson, "Muon Collider and Neutrino Factory R&D," invited seminar at University of California, Santa Barbara, Kavli Institute for Theoretical Physics, April 22, 2003.

- G. Hanson, "Neutrino Factories and Muon Colliders," Physics Department Colloquium at Harvey Mudd College, Claremont, California, December 3, 2002.

- G. Hanson, "Neutrino Factories and Muon Colliders," Freshman Seminar, Department of Physics, University of California, Riverside, October 30, 2002.

- G. Hanson, "Muon Colliders," invited ICFA Seminar on "Future Perspectives in High Energy Physics," CERN, Geneva, Switzerland, October 8-11, 2002.

- G. Hanson, "Status of R&D on Neutrino Factories and Muon Colliders," invited parallel session talk in Parallel Session 13, R&D for Future Accelerators and Detectors, ICHEP02, XXXI International Conference on High Energy Physics, Amsterdam, The Netherlands, July 24-31, 2002.

- G. Hanson, three lectures on "Muon Supercolliders" at the NATO Advanced Study Institute on Techniques and Concepts of High Energy Physics, St. Croix, U.S. Virgin Islands, June 13-24, 2002.

- G. Hanson, "Towards the Higgs Factory/Muon Collider," invited plenary talk at the Third International Workshop on Neutrino Factories Based on Muon Storage Rings – NuFACT'01, Tsukuba, Japan, May 24-30, 2001.

Other Contributions:

- G. Hanson, Neutrino Factory and Muon Collider Collaboration Executive Board, 2003-present.
- G. Hanson, International Muon Ionization Cooling Experiment (MICE) Speakers Bureau, 2003-present.
- G. Hanson, Chair, Neutrino Factory and Muon Collider Collaboration Speakers Bureau, 2002-present.
- G. Hanson and A. Klier, Co-organizers of the Emittance Exchange and Ring Cooler Workshop at the Mission Inn, Riverside, California, January 21-26, 2004.
- G. Hanson and A. Klier, Co-organizers of the Neutrino Factory and Muon Collider Collaboration Meeting at the Mission Inn, Riverside, California, January 27-31, 2004.
- G. Hanson, Co-organizer of the Third Higgs Factory Workshop "From the Neutrino Factory to the Higgs Factory: Muons All the Way," University of California at Los Angeles, February 28 – March 1, 2001.
- G. Hanson, Co-organizer of the Muon Collider Higgs Factory Joint E1/M1 Session at Snowmass 2001, Snowmass, Colorado, June 30 – July 21, 2001.
- G. Hanson, Co-organizer of the Workshop on Emittance Exchange, Brookhaven National Laboratory, September 11-29, 2000.
- G. Hanson, Scientific Advisory Committee, Workshop on Physics at the First Muon Collider and at the Front End of a Muon Collider, Fermilab, November 6-9, 1997.

References Cited

[1] S. Geer, "Neutrino Beams from Muon Storage Rings: Characteristics and Physics Potential," *Phys. Rev.* **D57,** 6989 (1998).

[2] P. Huber, "Oscillation Physics at Neutrino Factories," *Proc. of the International Europhysics Conference on High Energy Physics (EPS), Aachen, Germany, July 17–23, 2003, Eur. Phys. J.* **C33**, S849 (2004).

[3] J. Aysto *et al.*, CERN-TH/2001-231 and hep-ph/0109217.

[4] V. D. Barger, M. S. Berger, J. F. Gunion, and T. Han, "*s*-Channel Higgs Boson Production at a Muon-Muon Collider," *Phys. Rev. Lett.* **75**, 1462 (1995);
V. D. Barger, "Overview of Physics at a Muon Collider," *AIP Conf. Proc.* **441**, 3 (1998).

[5] N. Holtkamp and D. Finley, eds., "A Feasibility Study of a Neutrino Source Based on a Muon Storage Ring," Fermilab-Pub-00/108-E (2000).
http://www.fnal.gov/projects/muon_collider/nu-factory/nu-factory.html.

[6] S. Ozaki, R. Palmer, M.S. Zisman, and J. Gallardo, eds., "Feasibility Study-II of a Muon-Based Neutrino Source," BNL-52623 (June 2001).
http://www.cap.bnl.gov/mumu/studyii/FS2-report.html.

[7] See http://www.hep.ph.ic.ac.uk/iss/.

[8] A. N. Skrinsky and V. V. Parkhomchuk, *Sov. J. Part. Nucl.* **12**, 223 (1981);
D. Neuffer, *Part. Accel.* **14**, 75 (1983);
E. A. Perevedentsev and A. N. Skrinsky, in *Proc. 12th Int. Conf. on High Energy Accelerators*, F. T. Cole and R. Donaldson, eds. (Fermilab, 1984), p. 485;
D. Neuffer, in *Advanced Accelerator Concepts*, F. E. Mills, ed., *AIP Conf. Proc.* **156** (American Institute of Physics, New York, 1987), p. 201;
R. C. Fernow and J. C. Gallardo, *Phys. Rev.* **E52**, 1039 (1995).

[9] G. Gregoire *et al.*, "An International Muon Ionisation Cooling Experiment (MICE)," January 10, 2003, available from http://mice.iit.edu/mnp/MICE0021.pdf.

[10] G. Gregoire *et al.*, "MICE: An International Muon Ionisation Cooling Experiment, Technical Reference Document," October 2004, available from
http://www.isis.rl.ac.uk/accelerator/MICE/TR/MICE_Tech_ref.html.

[11] V. Balbekov, "Ring Cooler Update," Neutrino Factory/Muon Collider Note Number 0189 (2001).

[12] See M. M. Alsharo'a *et al.*, "Recent Progress in Neutrino Factory and Muon Collider Research within the Muon Collaboration," *Phys. Rev. ST Accel. Beams* **6**, 081001 (2003).

[13] R. Fernow, in *Proceedings of the 1999 Particle Accelerator Conference, New York*, p. 3020, http://pubweb.bnl.gov/people/fernow/.

[14] R. Palmer *et al.*, "Ionization Cooling Ring for Muons," *Phys. Rev. ST Accel. Beams* **8**, 061003 (2005).

[15] Amit Klier and Gail G. Hanson, "Geant Simulation of Six-Dimensional Cooling of Muon Beams in Ring Coolers," *Proceedings of the 2005 Particle Accelerator Conference, Knoxville, Tennessee*, May 16-20, 2005, p. 2580.

[16] A. Klier, "The 'Guggenheim RFOFO Ring,'" talk at the ISS Machine Working Group meeting, Brookhaven National Laboratory, December 15, 2005 – see http://www.cap.bnl.gov/mumu/project/ISS/051213/.