Muon Accelerator Program Simulation Fellow

DE-FG02-07ER41487

Final Report
August 15, 2010 – March 20, 2015

Principal Investigator

Gail G. Hanson
(951) 237-3032, Gail.Hanson@ucr.edu

Postdoctoral Scholar

Pavel Snopok (to December 31, 2010)
Yu Bao (June 1, 2013 – present)

Department of Physics and Astronomy
University of California, Riverside
Riverside, CA 92521-0413

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1. Introduction and Overview

We are reporting the progress during the grant DE-FG02-07ER41487 of Dr. Pavel Snopok and Dr. Yu Bao, Neutrino Factory and Muon Collider Collaboration (NFMCC)/Muon Accelerator Program (MAP) Simulation Fellows, as part of the University of California, Riverside (U.C. Riverside), muon beam group, which includes R&D towards future Neutrino Factories and Muon Colliders. We have also had substantial participation in the international Muon Ionization Cooling Experiment (MICE), funded by the National Science Foundation. Dr. Snopok moved to the Illinois Institution of Technology as an Assistant Professor in their joint program with Fermilab during the first year of the grant (he was also awarded a DOE Early Career Award in 2012), and he was replaced (after some delay) by Dr. Yu Bao.

During 2011 the unified national Muon Accelerator Program (MAP), hosted by Fermilab, was formed by the combination of NFMCC and the Muon Collider Task Force (MCTF) at Fermilab. The goal of MAP was to carry out the R&D necessary to establish the feasibility of a multi-TeV Muon Collider and an associated cost range by 2016. An end-to-end simulation of the Muon Collider accelerator complex has been part of the feasibility study. MAP included the technology development and system tests needed as part of the feasibility study, as well as contributions to the International Design Study for the Neutrino Factory (IDS-NF) to produce a Reference Design Report. The MAP proposal [1] was submitted to the DOE March 1, 2010, and was reviewed August 24-26 at Fermilab. MAP was formally approved by the DOE March 15, 2011.

The search for a replacement for Dr. Snopok was complicated by the transition from NFMCC to MAP because the funding for the second year of our DOE grant was transferred to Fermilab, and it took us many months to get an agreement in place between the University of California and Fermilab so that we could charge the salary for a new Postdoctoral Scholar to continue with our Muon Collider simulation program. We could not hire anyone without at least one year's funding for salary. It was also difficult to attract excellent candidates until Dr. Mark Palmer was hired as the Director of the Muon Accelerator Program and the re-organized program was in place. Dr. Palmer began his position in January 2012, starting on a part-time basis while he made the transition from Cornell University.

During this transition period we carried out several searches until we finally hired Dr. Yu Bao, who had been carrying out postdoctoral research on the slow muon project at the Paul Scherrer Institute (PSI), in Switzerland. Dr. Bao began his position at U.C. Riverside on June 1, 2013, and was funded by this grant until March 31, 2014, after which he has been supported by MAP funds.

In MICE [2] we are building and operating a muon-cooling device of a design proposed in Feasibility Study-II [3]. In addition to cooling the muons, MICE includes apparatus to measure the performance of the device. The experiment is being carried out by a collaboration of physicists from the U.S., Europe, Japan and China at the Rutherford Appleton Laboratory in the U.K. MICE began operation in 2008. Successful performance of the MICE experiment will provide the understanding needed to design a complete neutrino factory. Using a wedge-shaped absorber in MICE Step IV the emittance exchange concept can be demonstrated in addition to the transverse cooling. Members of our group who have worked full-time on MICE include Dr. Linda Coney, now at the European Spallation Source in Lund, Sweden, and graduate student Chris Heidt, who will complete his Ph.D. on Step IV data to be taken this summer.

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

During this grant and its extensions we have worked in the areas of simulations of six-dimensional cooling in the tapered Guggenheim channel, emittance exchange in MICE using a wedge absorber, energy deposition in the front end of the Neutrino Factory, and bunch merging in the Muon Collider.

2.1. Simulations of the Tapered Guggenheim 6D Cooling Channel (Snopok)

In a Muon Collider design the muon beam 6D phase space volume must be reduced by several orders of magnitude in order to be able to further accelerate it. Ionization cooling is currently the only feasible option for cooling the muon beam because of the small muon lifetime. One feasible option for ionization cooling is the RFOFO ring [4], in which 6D cooling is achieved by employing emittance exchange. When a dispersive beam passes through a wedge absorber in such a way that the higher momentum particles pass through more material, both the transverse and the longitudinal emittances are reduced. The RFOFO ring provides a significant reduction in the 6D emittance in a small number of turns with relatively low particle loss. However, the design of the injection and extraction channels and kickers is very challenging, the bunch train is too long to fit in the ring, and there is also a problem with overheating in the absorbers.

These problems are mitigated with the RFOFO helix, also known as the Guggenheim channel. Five consecutive turns of the Guggenheim helix are shown in Fig. 1. This channel was simulated up to 15 turns (495 m), and the performance is comparable to the original RFOFO ring [5].

The main issue with the Guggenheim channel of fixed radius and RF frequency is its gradual loss of cooling efficiency as the beam reaches equilibrium emittance. To keep cooling rates high throughout the cooling process, it was proposed to use a tapered channel in which the lattice parameters change along the cooling section so that the equilibrium emittances of the downstream portions are reduced compared with the early part of the channel [6]. This enables the beam emittance always to remain well above the equilibrium emittance—a condition that results in optimal cooling efficiency.

Such a channel was simulated in ICOOL using a linear approximation [7]. Snopok performed the full simulation using g4beamline [8]. The first 10 stages of the proposed tapered channel are shown in Fig. 2, where one can see the radius, the number of identical cells per turn, and how the sizes of the coils change from stage to stage. The parameters, excluding the coil geometries, are shown in Table 1. "Length RF" is the total length of RF per cell. Four cavities per cell are assumed. The RF gradient is 15.48 MV/m for all stages; the accelerating phase is 44° for the first five stages and 34° afterwards. B_0 is the magnetic field strength on the reference circle running through the centers of the RF cavities and absorbers. "Bend field" is the bending field required to keep the muons on a circular orbit; it also provides dispersion. "Coil tilt" is the coil tilt angle required to produce the necessary bending field. "Coil displ." is the displacement of the coils with respect to the reference circle that minimizes vertical excursion of the orbit. Starting with stage 6 there are two sets of coils per cell and hence two numbers. Eleven stages were simulated starting with the same beam that was used for the untapered Guggenheim simulations.

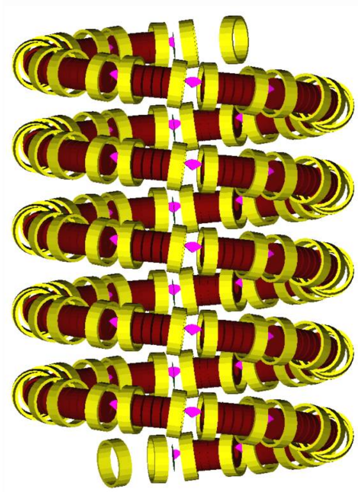

Figure 1: Five-turn slice of the Guggenheim helix. Simulated up to 15 turns (495 m) and used as a reference in assessing the tapered helix performance.

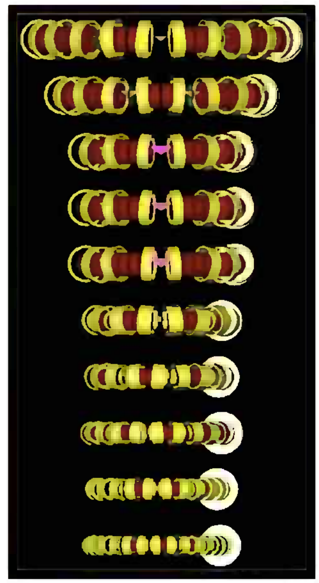

Figure 2: Geometry of the first 10 stages of the tapered Guggenheim.

Table 1: Lattice parameters of the tapered Guggenheim stages.

Stage number	Cell length [m]	Number of cells	RF freq. [MHz]	Length RF [m]	Length abs. [mm]	B_0 [T]	Bend field [T]	Coil tilt [deg]	Coil displ. [mm]
1	2.75	12	201.25	1.88	226	2.33	0.129	3.72	100
2	2.75	10	201.25	1.88	326	2.52	0.152	4.17	119
3	2.75	8	201.25	1.88	426	2.69	0.190	4.98	148
4	2.75	8	201.25	1.88	426	2.72	0.190	4.95	146
5	2.75	8	201.25	1.88	426	2.75	0.190	4.75	146
6	2.36	8	235.00	1.61	366	3.09	0.222	4.47	44/143
7	2.02	9	274.00	1.38	314	3.60	0.230	3.96	37/110
8	1.73	11	319.00	1.18	268	4.19	0.220	3.22	26/78
9	1.49	12	373.00	1.02	230	4.90	0.234	2.62	26/69
10	1.28	15	435.00	0.87	198	5.72	0.218	2.08	16/48
11	1.09	17	507.00	0.75	169	6.68	0.226	1.84	12/36.5

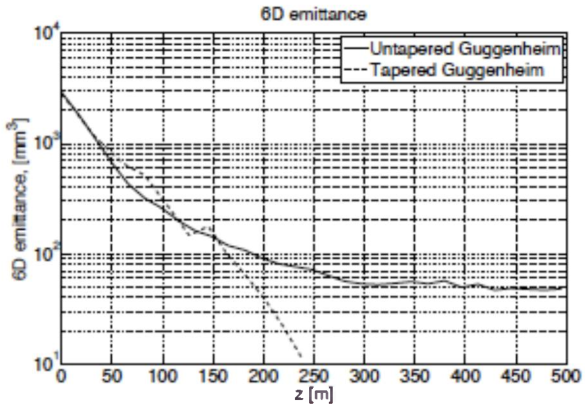

Figure 3: 6D emittance reduction in the untapered Guggenheim (solid) and the tapered Guggenheim (dashed).

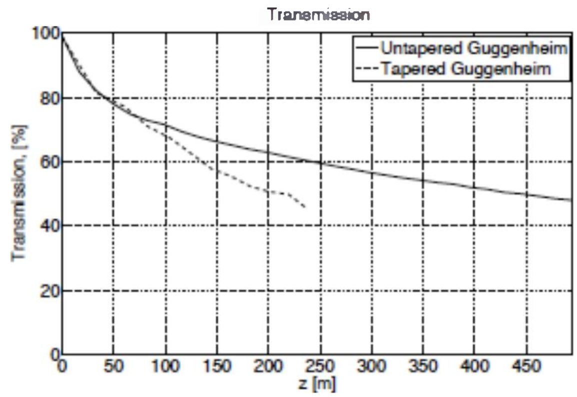

Figure 4: Particle transmission in the untapered Guggenheim (solid) and the tapered Guggenheim (dashed).

Individual rings corresponding to each stage were simulated rather than the multi-turn helix. It was shown previously [5] that the performance of the helical lattice is very similar to that of the individual rings assuming magnetic shielding between layers.

The results of the simulations are shown in Figs. 3 and 4. Both simulations use the same beam with parameters as described in [5]. The tapered channel is two times shorter than the original 201.25 MHz untapered Guggenheim when the two transmissions are the same (50%). At the same time, the final 6D emittance is 11 mm^3 for the tapered Guggenheim as compared to 48 mm^3 for the untapered case. The tapered Guggenheim clearly shows an improvement. There are two places where the longitudinal emittance for the tapered case demonstrates some growth, which is caused by the fact that the RF frequency changes from stage to stage and there are no special matching sections between the stages.

The study shows that tapering is a viable concept that reduces the length of the cooling and achieves a lower final 6D emittance. The next step is simulation of a proper helical channel rather than a set of rings, although it is expected that the performance will be similar. Another important improvement would be to implement a smaller number of different RF frequencies, ideally 201.25, 402.5, and 805 MHz only.

2.2. Studies of Emittance Exchange in MICE Using a Wedge Absorber (Snopok)

In order to contribute to investigating the emittance exchange in MICE, Snopok joined the MICE Collaboration in May 2009. U.C. Riverside's participation (Linda Coney, Gail Hanson, Chris Heidt, and undergraduate student Rob Roy Fletcher) in the MICE experiment was funded by the National Science Foundation (except for Dr. Snopok). In the MICE baseline design the transverse emittance is reduced while the longitudinal emittance remains unchanged or increases slightly due to stochastic processes in the energy loss.

By placing a wedge-shaped absorber in the dispersive MICE beam during Step IV, emittance exchange, necessary for the cooling section of the Muon Collider, can be demonstrated. The measurement of longitudinal emittance reduction in MICE will test the accuracy of the absorber physics models in a different geometry, demonstrate that the physics of emittance exchange is well understood, and demonstrate emittance exchange in a real magnetic lattice.

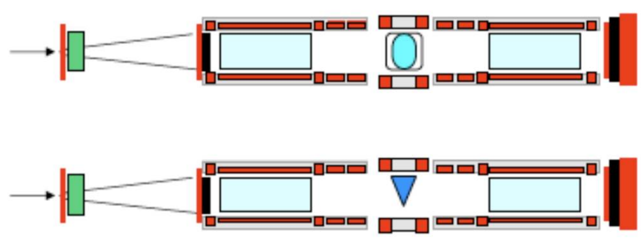

Figure 5: The geometry of MICE, side view. Top: the liquid hydrogen absorber module in MICE Step IV; bottom: the liquid hydrogen absorber is replaced with the wedge absorber.

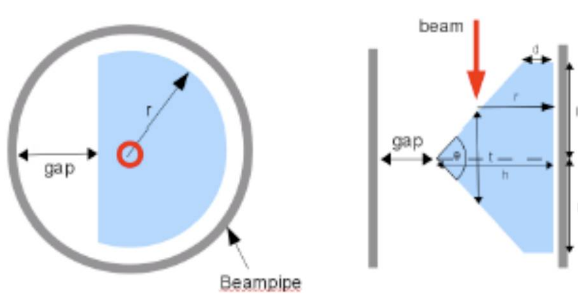

Figure 6: Schematic of the wedge geometry, which is parameterized by the on-axis thickness *t*, opening angle θ, and radius *r*.

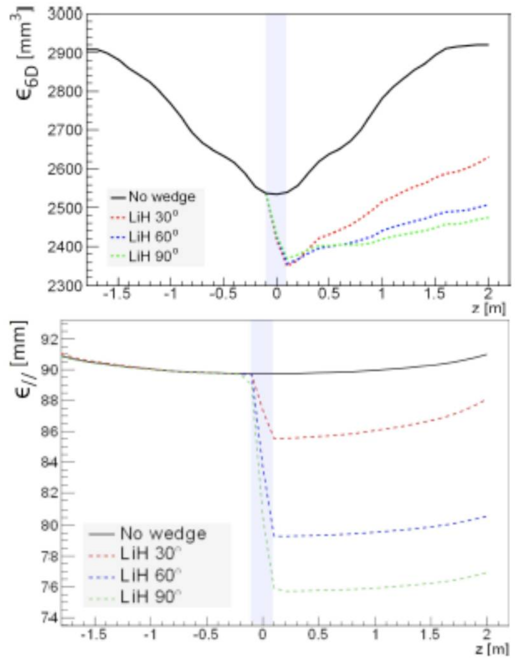

Figure 7: Simulated emittance along the beam line for canonical beam parameters and a dispersion of 200 mm.

A first simulation study of wedges in MICE was made in [9], where it was shown that even a large emittance dispersive beam could be passed through MICE Step IV with acceptably small nonlinear effects given care in the way the beam is selected.

In the study reported here, a wedge-shaped absorber is simulated in a straight solenoidal channel. The proposed layout of the experiment is shown schematically in Fig. 5. The case considered was MICE Step IV, where MICE is operated in flip mode without RF cavities. The choice for the wedge material is lithium hydride (LiH) because of its low average Z and low Z/A. If time permits, a polyethylene absorber will also be used. The wedge is shown schematically in Fig. 6. The MICE beam used in the simulation is matched to the canonical MICE lattice. Control of dispersion has not been planned for the MICE beam line; it is assumed that dispersion will be introduced using a beam selection algorithm similar to the one described in [10]. The cooling performance from the simulation is shown in Fig. 7.

2.3. Front End Energy Deposition and Collimation Studies for the IDS-NF (Snopok)

The function of the Neutrino Factory front end is the reduction of the energy spread and size of the muon beam to a manageable level that will allow reasonable throughput to subsequent system components. It consists of a pion decay channel and longitudinal drift, followed by an adiabatic buncher, phase rotation system, and ionization cooling channel. The present design is based on the lattice presented in the Neutrino Factory Study 2A report [11], with several modifications. The latest version of the front-end layout is presented in [12].

There are significant losses along the beam line, which may result in large energy deposition in superconducting magnets and other equipment. Two main risks have been identified: energy deposition by all particles may cause superconducting equipment to quench; and energy deposition by hadrons and other particles may activate equipment preventing handling for maintenance. Figure 8 shows the power deposited by transmission losses per unit length from various particle species as a function of distance along the channel. The bottom plot in Fig. 8 is based on the simulation carried out by Snopok using g4beamline code. Energy deposition in RF windows and absorbers is not included. It is expected that this equipment will absorb several kilowatts of beam power from each particle species. In currently operating accelerators, uncontrolled hadronic losses must be less than 1.0 W/m to enable "hands-on" maintenance without additional time, distance, or shielding constraints. Magnets are expected to quench with beam losses above a few tens of W/cm^3.

Four devices were under study for reducing the transmission losses in the front end:

- Proton absorber to remove low-momentum protons.
- Chicane system to remove particles with high momentum outside of the acceptance of the front end.
- Transverse collimation to remove particles with transverse amplitude outside of the acceptance of the front end.
- Shielding between the beam and superconducting coils.

Strategies have been outlined using these methods that can mitigate these risks. These studies indicate that the pollution of the muon beam line due to proton and electron secondaries can be dramatically reduced without strongly impacting the muon yield of the front end. Further studies are required to determine the configurations of beam dumps, collimators, and shielding.

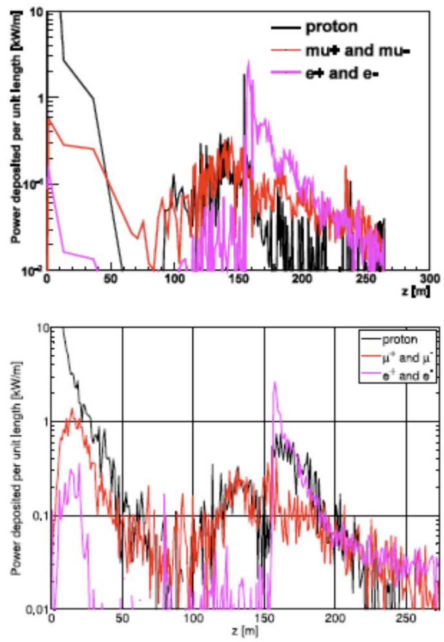

Figure 8: Power loss per unit length along the channel. Top: ICOOL; bottom: g4beamline.

2.4. Simulation of Bunch Merge for the Muon Collider (Bao)

Yu Bao has been working on the end-to-end simulation of the Muon Collider accelerator complex [13], shown in Fig. 9. In this scheme muons are first produced indirectly through pion decay by the interaction of a charged particle beam with a target. Then a set of properly tuned rf cavities captures the beams into a string of 21 bunches and phase rotates them into nearly equal energies. Following this a set of rf cavities with absorbers (ionization cooling channel) reduces the 6D emittance until the beam can be injected into a bunch-merging system. In order to obtain sufficient luminosity for a Muon Collider, the 21 bunches must be merged into a single bunch, one of each sign.

The single muon bunches are then sent through a second cooling channel where the transverse emittance is reduced as much as possible and the longitudinal emittance is cooled to a value below that needed for the collider. If necessary, the beam can then be recombined and sent through a final cooling channel using high-field solenoids that cools the transverse emittance to the required values for the collider while allowing the longitudinal emittance to grow. Finally, a series of acceleration stages takes the muon beams to the relevant collider energies. Figure 10 shows the longitudinal versus the transverse emittances as they evolve from their initial high values to the final desired values for a Muon Collider.

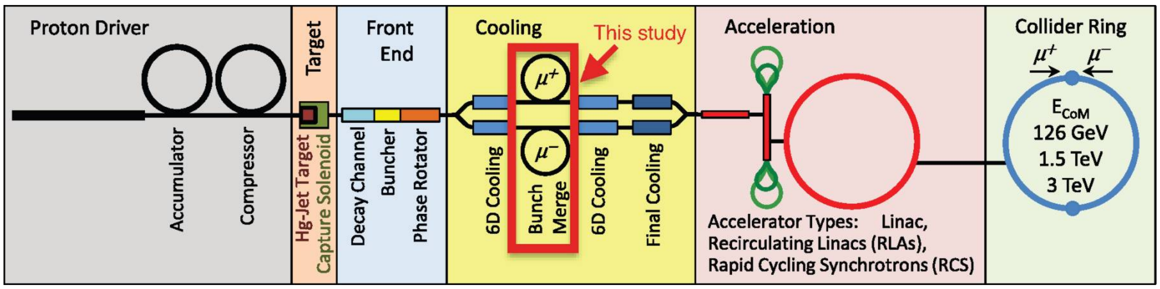

Figure 9: Muon Collider accelerator complex.

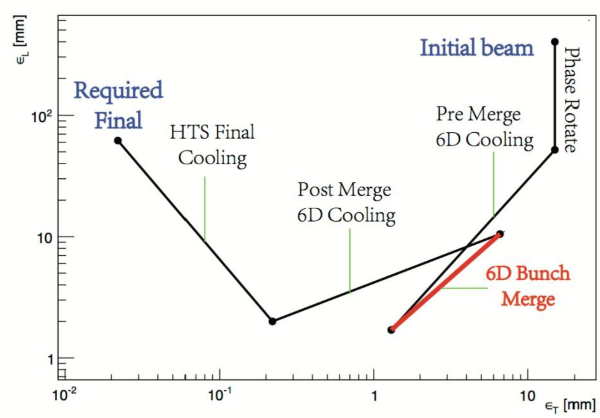

Figure 10: Longitudinal and transverse emittance evolution through the Muon Collider cooling.

While well-defined concepts for the phase-rotation, charge separation, and cooling channel subsystems had been developed previously, the conceptual design and simulation of a bunch-merging scheme suitable for a Muon Collider remained and has been the focus of Bao's research.

The bunch merge scheme is shown in Fig. 11. First the 21 bunches are merged longitudinally into seven bunches by using rf cavities with a series of rf harmonics. Then the seven bunches are transversely merged into one bunch using a kicker magnet that kicks the seven bunches into seven "trombones." Each trombone has a different arc length so that the seven bunches arrive at the collecting section at the same time. A "funnel" with a pair of dipoles for each bunch bends the seven bunches close to each other to form a single bunch. Figure 12 shows a schematic of the funnel, and Fig. 13 displays the beam spatial distribution after the funnel.

At the end a matching section consisting of three solenoids matches the bunch into the post-merge cooling section.

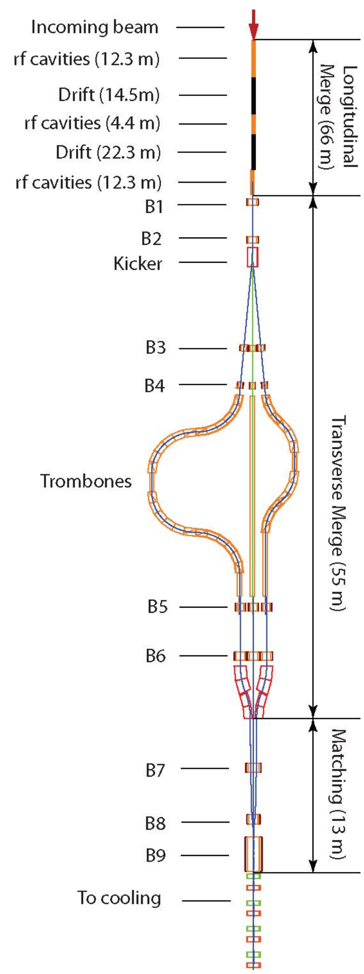

Figure 11: Merge scheme (only two of the seven trombones are shown).

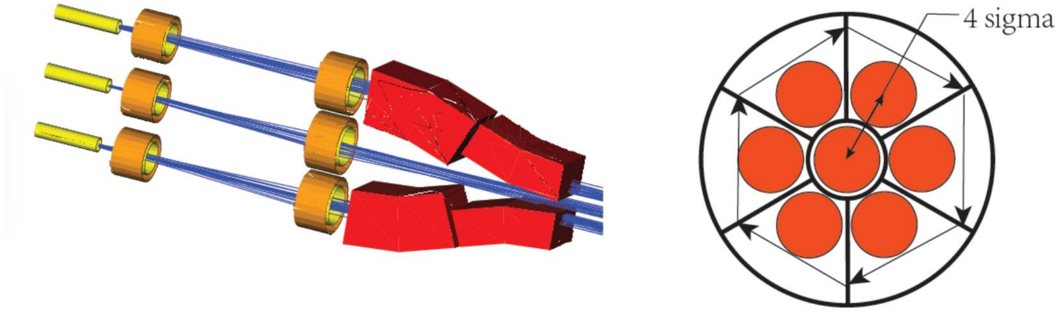

Figure 12: Schematic of the funnel with three channels shown (left); cross section of the funnel magnet – red circles represent the bunches (right).

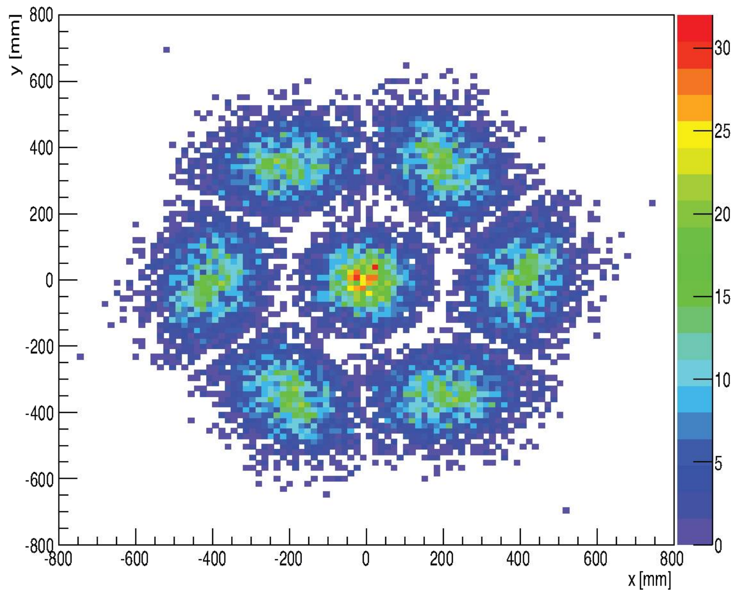

Figure 13: Beam spatial distribution after the funnel.

The performance of this scheme has been studied in detail in simulations. Table 2 summarizes the beam parameters before and after the bunch merge. Both the transverse and longitudinal emittances meet the requirements for later cooling. The transmission without decay is 87%, and 78% with decay. The bunch merging study will be reported at IPAC'15, and a paper is being prepared for publication.

	Before	After
N bunches	21	1
x/y [mm]	20	49
x'/y' [rad]	0.03	0.1
σ_{ct} [mm]	24.7	150
σ_p [MeV/c]	7.51	6.5
ϵ_T [m]	1.3	6.5
ϵ_L [m]	1.7	10.3

Table 2: Summary of beam parameters before and after the bunch merge.

Bao, Snopok, and Hanson 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 NFMCC/MAP contributions are listed in the Appendices.

Appendix A: Publications.

1. Y. Bao, G. Hanson, R. B. Palmer, and D. Stratakis, "Conceptual design and modeling of a six-dimensional bunch merging scheme for a high luminosity collider," publication in preparation.

2. Y. Bao, G. Hanson, R. B. Palmer, D. Stratakis, ID 1801, "End-to-end simulation of bunch merging for a muon collider," abstract submitted to IPAC'15, 6th International Particle Accelerator Conference, Richmond, Virginia, May 3-8, 2015.

3. Y. Bao, G. Hanson, ID 2024, "A High Intensity Muon Beam from a Spallation Target," abstract submitted to IPAC'15, 6th International Particle Accelerator Conference, Richmond, Virginia, May 3-8, 2015.

4. D. Adey *et al.*, "Light sterile neutrino sensitivity at the nuSTORM facility," *Phys. Rev. D* **89**, 071301 (2014), arXiv:1402.5250v1 [hep-ex].

5. D. Adams *et al.*, "Characterisation of the muon beams for the Muon Ionisation Cooling Experiment," *Eur. Phys. J. C* **73**, 2582 (2013).

6. S. Dawson *et al.*, "Higgs Working Group Report of the Snowmass 2013 Community Planning Study," arXiv:1310.8361 [hep-ex], October 19, 2013.

7. J.-P. Delahaye *et al.* (ed.), "Enabling Intensity and Energy Frontier Science with a Muon Accelerator Facility in the U.S.: A White Paper," FERMILAB-CONF-13-307-APC, arXiv:1308.0494 white paper for Snowmass 2013 (2013).

8. Y. Alexahin *et al.*, “Muon Collider Higgs Factory for Snowmass 2013,” FERMILAB-CONF-13-245-T, arXiv:1308.2143 [hep-ph], August 9, 2013, white paper for Snowmass 2013.

9. G. G. Hanson, “Progress in the Construction of the MICE Cooling Channel,” Proceedings of the XIIIth Workshop on Neutrino Factories, Superbeams, and Beta-beams (NuFact’11), CERN and the University of Geneva, Geneva, Switzerland, August 1–6, 2011.

10. G. G. Hanson, “The Muon Accelerator Research and Development Program,” Proceedings of the International Europhysics Conference on High Energy Physics (EPS-HEP 2011), Grenoble, France, July 21–27, 2011.

11. C. T. Rogers, P. Snopok, L. Coney, and G. Hanson, “Wedge Absorber Design and Simulation for MICE Step IV,” *Proceedings of the 2011 Particle Accelerator Conference (PAC’11), New York, NY, March 28 – April 1, 2011*, FERMILAB-CONF-11-046-APC (2011).

12. C. Rogers, D. Neuffer, and P. Snopok, L. Coney, and G. Hanson, “Front End Energy Deposition and Collimation Studies for IDS-NF,” *Proceedings of the 2011 Particle Accelerator Conference (PAC’11), New York, NY, March 28 – April 1, 2011*, FERMILAB-CONF-11-047-APC (2011).

13. P. Snopok, G. Hanson, and R. Palmer, “Simulations of the Tapered Guggenheim 6D Cooling Channel for the Muon Collider,” *Proceedings of the 2011 Particle Accelerator Conference (PAC’11), New York, NY, March 28 – April 1, 2011*, FERMILAB-CONF-11-048-APC (2011).

14. R&D Proposal for the National Muon Accelerator Program, Revision 6d, August 23, 2010, FERMILAB-TM-2459-APC, http://map.fnal.gov/proposals/pdfs/MAPproposal-R6d.pdf.

15. G. Hanson, “The Research and Development Program towards an Energy-Frontier Muon Collider,” *Proceedings of the 35th International Conference on High Energy Physics (ICHEP 2010)*, Paris, France, July 22–28, 2010, *PoS* (ICHEP 2010), 518 (2010).

16. P. Snopok, “MICE: Its Program of Ionization Cooling Measurements in the Subsequent Steps” (on behalf of MICE collaboration), *Proceedings of the XXIV*

International Conference on Neutrino Physics and Astrophysics, Athens, Greece, June 14-19, 2010, Nucl. Phys. **B** Proc. Suppl., Elsevier.

17. C. Johnstone, M. Berz, K. Makino, and P. Snopok, "Isochronous (CW) Non-Scaling FFAGs: Design and Simulation," *Proceedings of the 14th Advanced Accelerator Concepts Workshop, Annapolis, Maryland, June 13-19, 2010*, AIP Conf. Proc. **1299**, 682 (2010).

18. M. Ellis *et al.*, "The Design, Construction and Performance of the MICE Scintillating Fibre Trackers," MICE-Note-254, FERMILAB-PUB-09-259-APC, IC-PRE-09-01, May 2010, arXiv:1005.3491 [physics.ins-det], submitted to *Nucl. Instrum. Meth.*

19. P. Snopok and G. Hanson, "Six-Dimensional Cooling Lattice Studies for the Muon Collider," *Proceedings of the 1st International Particle Accelerator Conference (IPAC'10), Kyoto, Japan, May 23-28, 2010*, p. 3533 (2010).

20. C. T. Rogers, L. Coney, P. Snopok, and A. Jansson, "Wedge Absorber Design for the Muon Ionisation Cooling Experiment," *Proceedings of the 1st International Particle Accelerator Conference (IPAC'10), Kyoto, Japan, May 23-28, 2010*, p. 3533, FERMILAB-CONF-10-249-APC (2010).

Appendix B: Presentations.

- Y. Bao, "Compact Front-end for Muon Experiments," MAP 2014 Winter Meeting, SLAC, Menlo Park, California, December 4–7, 2014.

- Y. Bao, "End-to-End Simulation of Bunch Merge," MAP 2014 Winter Meeting, SLAC, Menlo Park, California, December 4–7, 2014.

- Y. Bao, "Bunch Merge Status," MAP 2014 Spring Meeting, Fermilab, Batavia, Illinois, May 27–June 1, 2014.

- Y. Bao, "Merge Status April," Vacuum rf 6D Cooling Meeting, April 29, 2014.

- Y. Bao, "Funnel Tests," RF 6D Cooling Meeting, Brookhaven National Laboratory, Upton, Long Island, New York, April 3, 2014.

- Y. Bao, "Merge Status," Vacuum rf 6D Cooling Meeting, March 4, 2014 (phone).

- Y. Bao, “Transverse Merge Status,” Vacuum rf 6D Cooling Meeting, February 13, 2014 (phone).

- Y. Bao, “6D Merge Status,” Vacuum rf 6D Cooling Meeting, December 10, 2013 (phone).

- Y. Bao, “First Stage of Transverse Merge,” Vacuum rf 6D Cooling Workshop II, Fermilab, Batavia, Illinois, November 5–6, 2013.

- Y. Bao, “Longitudinal Merge Simulation with G4Beamline,” Vacuum rf 6D Cooling Workshop, Fermilab, Batavia, Illinois, September 18–19, 2013.

- G. Hanson, “BSM Higgs Searches at a Muon Collider,” Snowmass Energy Frontier Workshop, University of Washington, Seattle, Washington, June 30–July 3, 2013.

- G. Hanson, “Muon Collider Higgs Factory – And Some $e^+ e^-$ Comparisons,” Higgs “Snowmass” Workshop, Princeton University, Princeton, New Jersey, January 14–15, 2013.

- G. G. Hanson, “Progress in the Construction of the MICE Cooling Channel” (on behalf of the MICE Collaboration), invited presentation at the XIIIth Workshop on Neutrino Factories, Superbeams, and Beta-beams (NuFact’11), CERN and the University of Geneva, Geneva, Switzerland, August 1–6, 2011.

- G. G. Hanson, “The Muon Accelerator Research and Development Program” (on behalf of the MAP Collaboration), International Europhysics Conference on High Energy Physics (EPS-HEP 2011), Grenoble, France, July 21–27, 2011.

- P. Snopok, “Simulations of the Tapered Guggenheim 6D Cooling Channel for the Muon Collider,” 2011 Particle Accelerator Conference (PAC’11), New York, NY, March 28–April 1, 2011.

- P. Snopok, “6D Cooling with MICE,” Muon Accelerator Program Review, Fermilab, Batavia, Illinois, August 24–26, 2010.

- G. Hanson, “The Research and Development Program towards an Energy-Frontier Muon Collider” (on behalf of the Neutrino Factory and Muon Collider Collaboration, Muon Collider Task Force, and Muon Accelerator Program), invited presentation at the 35th International Conference on High Energy Physics (ICHEP 2010), Paris, France, July 22–28, 2010.

- P. Snopok, “Cooling Simulations for the Muon Collider,” Workshop on Beam Dynamics and Optimization, St. Petersburg, Russia, June 28–30, 2010.

- P. Snopok, "The MICE Program of Ionization Cooling Measurements" (on behalf of MICE Collaboration), XXIV International Conference on Neutrino Physics and Astrophysics, Athens, Greece, June 14–19, 2010.

- P. Snopok, "Six-Dimensional Cooling Lattice Studies for the Muon Collider," 1st International Particle Accelerator Conference (IPAC'10), Kyoto, Japan, May 23–-28, 2010.

- P. Snopok, "Wedge Absorber Design for the Muon Ionization Cooling Experiment," 1st International Particle Accelerator Conference (IPAC'10), Kyoto, Japan, May 23-28, 2010.

- P. Snopok, "Wedge Absorber Simulations for the Muon Ionization Cooling Experiment," MICE Collaboration Meeting 26, Riverside, California, March 26, 2010.

Appendix C: Other Contributions.

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- P. Snopok, Scientific Program Committee, 2011 Particle Accelerator Conference (PAC'11), March 28 – April 1, 2011, New York, NY.

- G. Hanson, Muon Accelerator Program Institutional Board, 2010-present.

- G. Hanson, International Muon Ionization Cooling Experiment (MICE) Speakers Bureau, 2003-present.

- G. Hanson, Neutrino Factory and Muon Collider Collaboration Executive Board, 2003-2011.

- G. Hanson, Chair, Neutrino Factory and Muon Collider Collaboration Speakers Bureau, 2002-2010.

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