MUON COOLING R&D FOR THE MUON COLLIDER - A 5 YEAR PLAN FOR THE US *

A. D. Bross#, Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510, U.S.A.
for the US Neutrino Factory and Muon Collider Collaboration and Fermilab Muon Collider Task Force

Abstract

The Neutrino Factory and Muon Collider Collaboration and the Fermilab Muon Collider Task Force have recently submitted a proposal to the US Department of Energy Office of High Energy Physics to deliver a Design Feasibility Study for a Muon Collider after a 5 year R&D program. This paper presents a brief physics motivation for and the description of a Muon Collider facility and then discusses in some detail the technical components of the proposal with respect to the muon ionization cooling R&D needed for an Energy-Frontier, high luminosity Muon Collider.

INTRODUCTION

The physics potential of a high-energy lepton collider has captured the imagination of the high energy physics community. Understanding the mechanism behind mass generation and electroweak symmetry breaking, searching for, and perhaps discovering, supersymmetric particles and confirming their supersymmetric nature, and hunting for signs of extra space-time dimensions and quantum gravity, constitute some of the major physics goals of any new lepton collider. In addition, making precision measurements of standard model processes will open windows on physics at energy scales beyond our direct reach. Sensitivity to the unexpected is, of course, of fundamental importance. The Muon Collider (MC) provides a possible realization of a multi-TeV lepton collider, and hence a way to explore new territory beyond the reach of present colliders. A muon accelerator facility also presents the opportunity to explore new physics within in a number of programs.

A schematic that shows the evolution of a muon accelerator complex which ultimately reaches a multi-TeV Muon Collider [1] is shown schematically in Fig. 1. The front-end of the facility provides an intense muon source that can perhaps support both an energy-frontier Muon Collider and a Neutrino Factory (NF). The muon source is designed to deliver $O(10^{21})$ low energy muons per year within the acceptance of the accelerator system, and consists of (*i*) a multi-MW proton source delivering a multi-GeV proton beam onto a liquid Mercury pion production target, (*ii*) a high-field target solenoid that radially confines the secondary charged pions, (*iii*) a long solenoidal channel in which the pions decay to produce positive and negative muons, (*iv*) a system of RF cavities in a solenoidal channel that capture the muons in bunches and reduce their energy spread (phase rotation), and (*v*) a muon ionization cooling channel that reduces the transverse phase space occupied by the beam by a factor of a few in each transverse direction. At this point the beam will fit within the acceptance of an accelerator for a Neutrino Factory. However, to obtain sufficient luminosity, a Muon Collider requires a great deal more muon cooling. In particular, the 6D phase-space must be reduced by $O(10^6)$, which requires a longer and more complex cooling channel. Finally after the cooling channel, the muons are accelerated to the desired energy and injected into a decay (NF) or storage ring (MC). In a Neutrino Factory the ring has long straight sections in which the neutrino beam is formed by the decaying muons. In a Muon Collider, positive and negative muons are injected in opposite directions and collide for about 1000 turns before the luminosity becomes marginalized due to the muon decays.

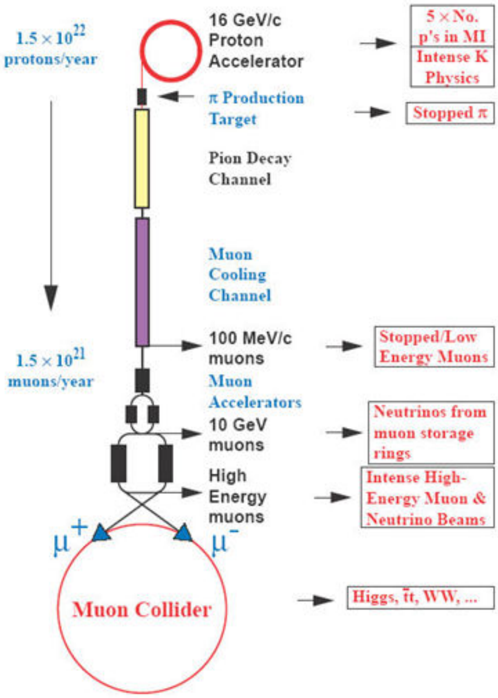

Figure 1: Schematic of muon acceleration complex.

6 D COOLING FOR THE MUON COLLIDER

Overview

Intense 6D cooling for the Muon Collider is not yet under experimental study, but is being modeled, studied with theoretical and computation tools and an

---

* This work was supported by the Fermi National Accelerator Laboratory, which is operated by Universities Research Association, under contract No. DE-AC02-76CH03000 with the U.S. Department of Energy

#bross@fnal.gov

experimental program exploring some of the major component parts of the system is being developed. At this point in time, we do not have a full end-to-end simulation for the cooling needed for a muon collider, but a self-consistent end-to-end cooling scheme has been developed and is shown schematically in Figure 2 [2].

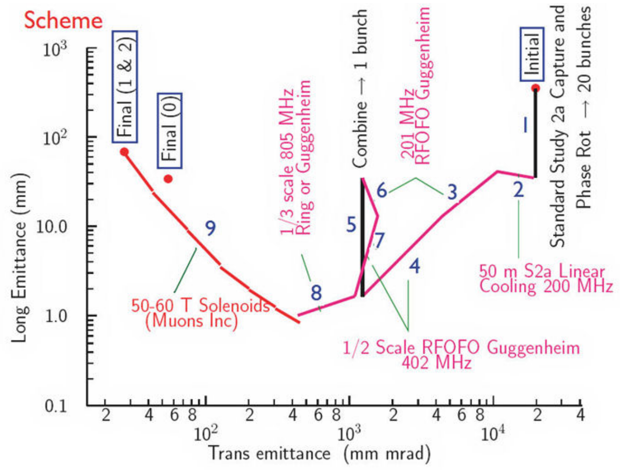

Figure 2: Cooling scheme for the muon collider.

This scheme utilizes the initial transverse cooling scheme from the Neutrino Factory Study 2a [3], the "Guggenheim" ring-FOFO (see P. Snopok's paper in these proceedings) and final cooling with 50T solenoids and LH_2 absorbers. Other alternate concepts being considered for parts of the cooling include: the Helical Cooling Channel (HCC) [4], the FOFO-Snake [5] and Parametric Resonance Ionization Cooling (PIC) [6]. As seen from above, the bulk of the muon cooling for the MC is done in the 6D cooling channels. To date the R&D has lent its primary focus on three main schemes for doing the 6D cooling for the Muon Collider and these concepts remain the central focus of 6D cooling in our R&D proposal. These are the Guggenheim channel, the Helical Cooling Channel (HCC) and the FOFO-Snake channel. However, additional subsystems for charge separation and charge recombination are required, and low-energy bunch merging may also be needed and other cooling schemes are also being explored.

Guggenheim Channel

The Guggenheim channel uses a large-pitch helical lattice (see Figure 3) in order to avoid the injection and extraction problems with a Ring-FOFO. The component parts of the Guggenheim are the same as that for the Ring-FOFO and include vacuum 201 MHz normal-conducting RF cavities, liquid hydrogen absorbers and solenoids. This approach has been under study for a number of years, but much work remains to be done which is incorporated into the 5 Year R&D program. Code must be developed and comparisons must be made between alternative ways of modeling the fields, either using 3D field maps or a multipole expansion. The benefits of a "tapered" channel must also be assessed. Matching sections must be designed and realistic parameters for absorbers and windows must be used in the simulations. If magnetic shielding is needed between "turns" in the lattice, its effect must also be evaluated.

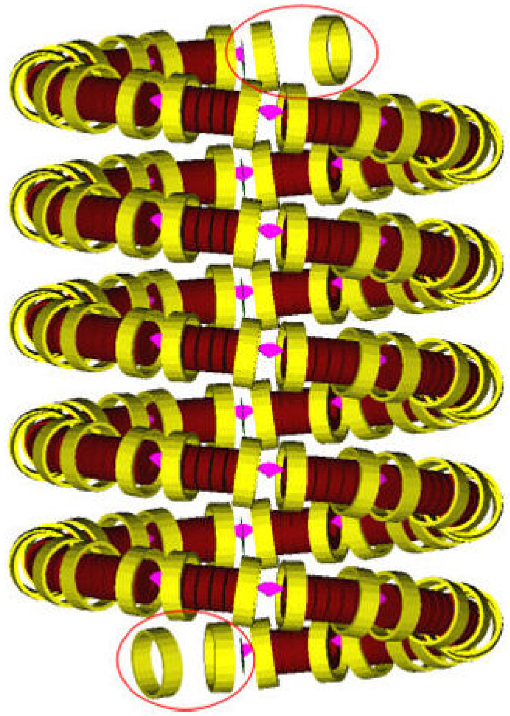

Figure 3: Schematic of the Guggenheim Cooling Channel. The RF cavities are in red, the solenoids in yellow and the LH_2 wedge-absorbers in pink.

Helical Cooling Channel

The basic HCC is composed of solenoidal, helical dipole, and helical quadrupole current coils to provide focusing and dispersion needed for emittance exchange as the beam follows an equilibrium helical orbit. Dense hydrogen gas fills the channel and acts as the energy absorber for ionization cooling and also is expected to suppress RF breakdown (see K. Yonehara's talk in these proceedings). A tight-pitched HCC made up of a series of solenoids with their centers arranged along a helical path (see Figure 4), however, effectively produces the magnetic field required for the HCC and is now the favored solution. The implementation of such a channel with embedded RF cavities is extremely challenging. A model incorporating realistic cavity parameters still needs to be developed and tested via simulations and a model of the helical magnet must be fully developed and its properties incorporated into the simulations. These tasks are part of the 5 Year R&D plan. Matching sections between the HCC and the rest of the front end need to be designed and simulated. In addition, overall optimization of the entire system must be carried out. Work needs to be done modeling space-charge effects at the end of the channel to make sure collective effects are benign. These space charge studies will have to be done for all cooling schemes, of course. As this system is pressurized with H_2

gas, we will need a structural analysis of the isolation windows and a detailed safety analysis.

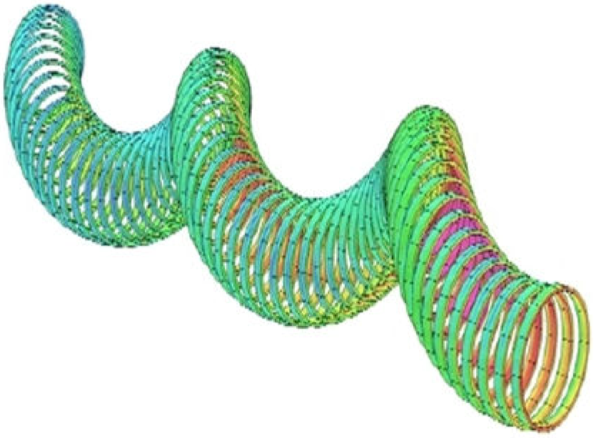

Figure 4: Schematic of the favored coil system proposed for the HCC.

FOFO-Snake Channel

The FOFO-snake channel consists of a series of tilted, translated solenoids following a straight path [11]. It acts like a planar wiggler and has the great advantage that both muon charges can be cooled in the same channel. There are several possible implementations of this design that will be studied in the 5 Year plan and include a gas-filled cavity version, a vacuum cavity version, and a magnetically insulated version. The other activities required to assess this approach are the same as those for the other cooling channel options, namely, studies of the matching sections, space-charge effects, and error sensitivity.

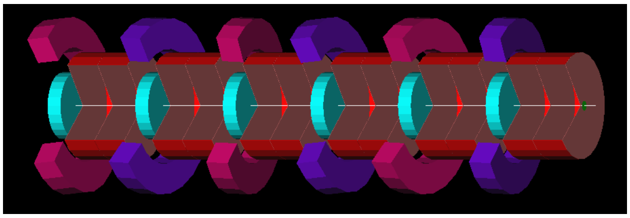

Figure 5: Schematic of FOFO-Snake Cooling channel. The cavities are in red, the solenoids in magenta and purple and the LH_2 absorbers in teal.

Final Cooling

One of the most challenging goals in the cooling for Muon Collider is to get a final normalized transverse emittance on the order of 2–25 μm. The strategy used in the cooling channel design is to end the 6D cooling section when the longitudinal emittance is well below the value needed by the collider. Then, either brute force transverse cooling or reverse emittance exchange can be used to obtain the required transverse emittance. Four alternatives are being considered for the final stage of cooling. Some schemes use an additional subsystem for high-energy bunch merging.

One of these schemes is the 50T channel which uses a straight lattice of very high field high-temperature superconductor (HTS) solenoids (Figure 6) to do the final cooling [7]. Development of this channel requires an optimization of the lattice parameters for various assumed maximum values of the solenoid strength. Lattices must also be matched on both ends and these sections need to be designed and simulated. Studies of collective effects, especially space charge, will be a component of the R&D in the 5 Year plan. As part of the 5 Year plan work, the selected design will be subjected to an error sensitivity study to validate its performance. The Very High Field Superconducting Magnet Collaboration [8] will study HTS wire and cables in order to gain a better understanding of the technology needed to fabricate the very-high-field solenoids needed in this application.

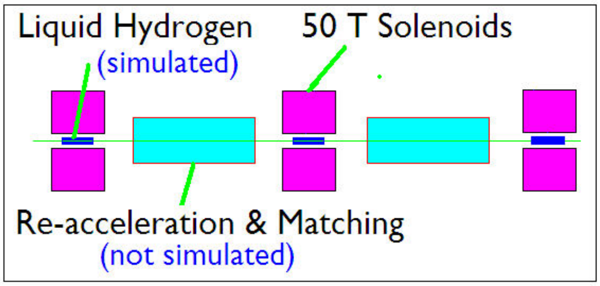

Figure 6: Conceptual diagram of final cooling channel utilizing 50T solenoids and LH_2 absorbers.

Finally, two novel concepts that would collect muons at low energy and then bring them almost to rest are also being studied. These are the “Particle Refrigerator” [9] shown in Figure 7 and the Inverse Cyclotron [10]. The “Particle Refrigerator” uses the concept of frictional cooling which has long been known (at least conceptually) to be capable of producing very-low emittance beams. Frictional cooling works for muons with very low kinetic energy (<10 keV), so the idea presented in Figure 7 requires muons to climb a few mega-volt potential, stop and then reverse direction in order to enter the frictional cooling channel. This increases the acceptance of the system from a few keV to a few MeV.

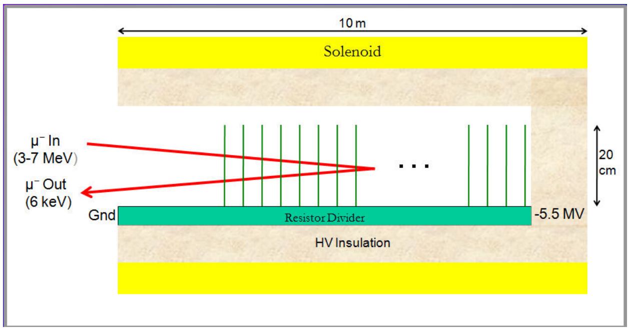

Figure 7: Concept for the particle refrigerator.

In the inverse cyclotron, a large admittance sector cyclotron filled with LiH wedges surrounded by helium or hydrogen gas is utilized. Muons are cooled (and slowed) as they spiral inward into the center of the cyclotron after they are injected at the outer rim of the cyclotron. As the muon momentum approaches zero, the momentum spread also approaches zero and long bunch trains coalesce. Finally when the bunch train has coalesced into a central swarm, it is ejected axially with an electric kicker pulse.

CRITICAL TECHNOLOGIES

As can be seen from the previous section, many possibilities are being pursued with respect to 6D cooling for a Muon Collider. Many of these concepts are quite elegant, but at present no scheme can be realized without the development of new technologies. Two areas that are of critical importance are operation of high-gradient RF cavities in a magnetic field of up to approximately 3T and the fabrication of ultra-high field (50T) solenoids.

A crucial challenge for the Neutrino Factory and Muon Collider Front-End Design and cooling channels is the operation of high-gradient normal-conducting RF (NCRF) in the presence of high magnetic field. This problem has been the primary focus of the MuCool [11] program. What has been observed in MuCool is that the safe operating gradient limit degrades significantly when a NCRF cavity is operated in magnetic field (see figure 8).

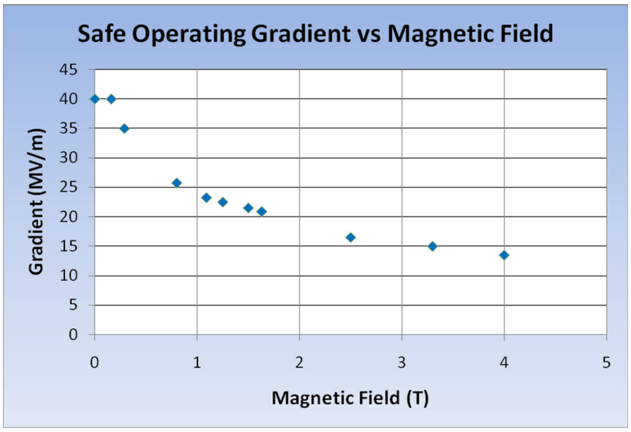

Figure 8: Safe operating gradient vs. B field.

The data shown in Figure 8 are for an 805 MHz pillbox test cavity and seem to follow a universal curve. The maximum stable gradient degrades quickly with increasing B field. The cause of this effect is understood and comes from field emission from emitters (surface field enhancements in the regions of high gradient) in the cavity. The field emission is focused to spots by the B field when B is parallel to E, as is the case with a pillbox cavity. These beamlets then initiate the breakdown event in the cavity.

In order to address this problem, three approaches are being investigated. The first is to eliminate field emission by processing the NCRF copper cavities using superconducting RF techniques. This has been done in MuCool for a 201 MHz copper cavity with promising results. This cavity reached a stable operating gradient of 21 MV/m (the design gradient was 16 MV/m) in the absence of B field. Initial tests of this cavity with applied external B (B<0.5T) field have shown a B field degradation, but in comparison with the results from the 805 MHz pillbox cavity, the B field effect is qualitatively different. Much more work needs to be done in this area and is part of the 5 Year R&D program. A new concept in processing for SCRF which can, in principle, also be applied to NCRF is Atomic Layer Deposition (ALD) [12]. Initial tests of a superconducting cavity coated with 5 nm of ZrO2 plus 30 nm of Pt were performed at TJNL. The ALD treatment greatly reduced the dark current while maintaining the achievable cavity gradient. The next step will be to test a similarly treated normal conducting cavity in a magnetic field to evaluate its performance. To this end, the 5 Year R&D plan contains an option to build an 805-MHz cavity for ALD coating and testing in the 5-T solenoid at the MuCool Test Area (MTA).

The second approach for abating the magnetic field effect is to prevent the magnetic focusing. In this case an open cell geometry is required and additional coils are added in the lattice to modify the B field direction and thus eliminate the B field focusing effect. However, the open-cell structure does mean that additional power (X2) is needed in order to reach the same on-axis accelerating gradient.

The third approach to dealing with the magnetic field effect is to operate RF cavities filled with high pressure H_2 gas (an underlying principle of the Helical Cooling Channel). The results from tests in the MuCool Test Area done by researchers at Muons Inc [13] using a RF test cell filled with H_2 gas are quite promising. In these data no degradation in maximum stable operating gradient was observed at B fields up to 3.5T for Mo electrodes. However, such a cavity has never been tested with beam. In pure hydrogen, ionization electrons will remain in the gas for a significant portion of the RF pulse, being accelerated back and forth by the RF fields, and transferring the electromagnetic energy stored in the cavity to the gas through collisions. Depending on the intensity of the incident beam, the Q of the cavity could be reduced by several orders of magnitude. It is possible that introducing another gas species may capture these free electrons. However, a good candidate gas has not yet been found. (SF6 is frozen at LN2 temperature, and also may form hydrofluoric acid.) In addition, it must be demonstrated that the large numbers of ions created do not present a problem. A beam test of a HPRF test cavity is presently being prepared at the MTA. If successful, this initial test would be followed by the design, construction and testing of a prototype 805-MHz HPRF cavity having entrance and exit windows more suitable for beam passage.

THE US 5-YEAR PLAN PROPOSAL

A proposal that presented a 5-year R&D program aimed at completing a Design Feasibility Study (DFS) for a Muon Collider and, with international participation, a Reference Design Report (RDR) for a muon-based Neutrino Factory has been submitted to the US Department of Energy as a joint proposal from US Neutrino Factory and Muon Collider Collaboration and the Fermilab Muon Collider Task Force [14]. The goal of the R&D program is to provide the HEP community with detailed information on future facilities based on intense beams of muons and give clear answers to the questions of the expected capabilities and performance of these muon-based facilities, while providing defensible estimates for their cost. This information, together with the physics insights gained from the next-generation neutrino and LHC experiments, will allow the HEP community to make well-informed decisions regarding the optimal choice of new facilities.

With regard to muon ionization cooling (or more generally speaking, the Front-End of the facility), the R&D plan will embark on both design and simulation and hardware efforts. The design and simulation work will study and optimize:

- Pion capture and decay, bunching and phase rotation.
- Precooling.
- 6D Cooling.
- Final Cooling.

A full end-to-end simulation of muon production and cooling (through final cooling) with all interfaces between cooling sections will be a major component of the effort. The hardware effort on cooling has 3 main objectives:

- Established the operational viability and engineering foundation for the concepts and components incorporated into the Muon Collider Design Feasibility Study and the Neutrino Factory Reference Design Report.
- Establish the engineering performance parameters of these components.
- Provide the basis for a defendable cost estimate.

The most critical technical challenge for the Muon Collider is the demonstration of a viable cooling scenario. To this end, the R&D proposal will support the MICE experiment (see Derun Li's talk, these proceedings) which will study the initial transverse muon ionization cooling, and will strive to develop a single scheme for 6D cooling that is backed by rigorous component testing for this chosen scheme. The various candidate cooling schemes that have been outlined in this paper will become more or less attractive as viable options depending on the results of component testing within this program. We anticipate critical results from the RF tests in the first two years of our R&D program, at which time we will proceed with building a short cooling section for one, and only one, cooling scheme. It is not envisioned that during this 5 year R&D program a 6D muon ionization cooling demonstration experiment will be performed. Figure 9 presents what we believe will be the Muon Collider Technical Foundation after the 5 Year program is completed, relative to where we believe the technology is today.

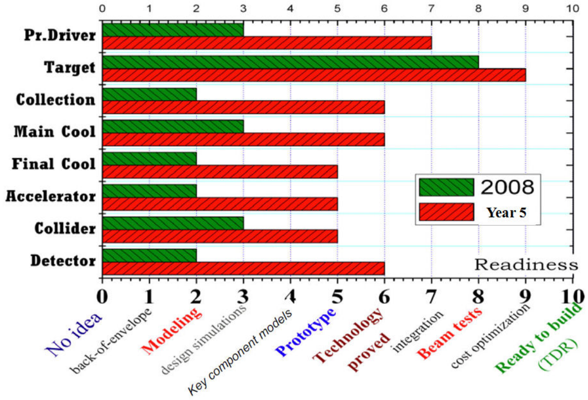

Figure 9: Technical foundation of the various sub-systems in the Muon Collider complex after the 5 Year R&D program.

REFERENCES

[1] M. Alsharo'a et al., (Muon Collider Collaboration), Phys. Rev. ST Accel. Beams, 6 081001 (2003).

[2] R. B. Palmer *et al.*, "A complete scheme of ionization cooling for a muon collider," in Proc. PAC 2007, p. 3193.

[3] S. Geer and M. Zisman (Eds.), "The neutrino factory and beta beam experiments and development," APS Neutrino Study, BNL-72369-2004, FERMILAB-TM-2259, Nov 2004. 115pp., e-Print: physics/0411123.

[4] K. Yonehara *et al.*, "Simulations of a Gas-Filled Helical Muon Beam Cooling Channel, in Proc. PAC 2005, p. 3215.

[5] D. Newsham *et al.*, "Simulations of parametric resonance ionization cooling," in Proc. PAC 2007, p. 2927.

[6] Y. Alexahin *et al.*, "6D ionization cooling channel with resonant dispersion generation," in Proc. PAC 2007, p. 3477.

[7] S. A. Kahn et al., "A high field HTS solenoid for muon cooling," in Proc. PAC 2007, p. 446.

[8] See http://www.cap.bnl.gov/mumu/conf/MUTAC-080408/talks/09AM/ATollestrup1-080408.pdf

[9] T.J. Roberts and D. Kaplan, "The Particle Refrigerator," Proceedings of PAC09, paper WE6PFP096.

[10] D.J. Summers, Stephen B. Bracker, L.M. Cremaldi, R. Godang, R.B. Palmer, "*6D muon ionization cooling with an inverse cyclotron*," AIP Conf.Proc.821:432-436,2006.

[11] MuCool WEB page: http://mice.iit.edu/mta/

[12] Norem *et al., "Results from Atomic Layer Deposition and Tunneling Spectroscopy for Superconducting RF Cavities,"* in the Proceedings of 11th European Particle Accelerator Conference (EPAC 08), Magazzini del Cotone, Genoa, Italy, 23-27 Jun 2008, pp WEPP099

[13] Muons Inc. WEB page: http://muonsinc.com

[14] NFMCC web page: http://www.cap.bnl.gov/mumu/
MCTF web page: http://apc.fnal.gov/
5-Yr. proposal: http://apc.fnal.gov/groups2/MCCC/