MUTAC Committee Report
Review April 18–19, 2007, BNL

Charge

1) *Review and comment on the R&D progress achieved since the last MUTAC review.*

2) *Review and give advice on the R&D plans and corresponding budgets for FY07 and directions for FY08.*

3) *Assess and comment on progress toward the international MERIT experiment.*

4) *Assess and comment on the MUCOOL R&D program and progress toward the international MICE experiment.*

5) *Review and comment on Simulation Group plans, including Neutrino Factory design optimization, FFAG acceleration system activities, Muon Collider studies, and participation in the International Design Study.*

6) *Review and comment on the plans of the Fermilab Muon Collider Task Force and their relationship to the ongoing program of the Neutrino Factory and Muon Collider Collaboration.*

Organization of this report:

We start with an Overview and Executive Summary section. Next we comment on the Physics case for Neutrino Factories and Muon Colliders. The remainder of the report responds to the questions in the charge. For each element of the charge we list findings, comments, and recommendations from the committee. In the last section the committee comments on the relationship between this effort and that in the UK and Japan. The membership of the MUTAC review committee is attached as Appendix 1. The agenda for the review and links to the presentations can be found at http://www.cap.bnl.gov/mumu/MUTAC/

Overview and Executive Summary

The committee congratulates the Neutrino Factory and Muon Collider Collaboration (NFMCC) on the continued impressive technical progress in the past year. The physics case for Neutrino Factories and Muon Colliders was briefly reviewed and, in the opinion of the committee, remains strong. Several experimental initiatives of the collaboration (MERIT, MICE, MUCOOL, etc.) have matured to the point that significant hardware is on the ground and first operation is imminent. These experiments are intended to demonstrate key components required to create intense muon beams for long baseline neutrino experiments and ultimately to reduce their phase space and accelerate them with the goal of a feasible high energy Muon Collider. The experimental program is backed by a design and simulation effort intended to explore various alternative machine designs. The international connection of the collaboration has been strong in Europe (UK) and Japan. We note as a positive step the addition of a Chinese effort on MICE. We note also the very positive step of the Muon Collider Task Force (MCTF) effort at FNAL which seems likely to bring needed financial and human resources to the overall effort. The committee notes that it will be a challenge to MCOG and FNAL management to ensure that these new MCTF resources and those of the U.S. part of NFMCC are coordinated effectively. MCTF brings with it a new suite of interesting and important tasks for development of a Muon Collider. MCOG and FNAL should continue to encourage a process for prioritization across the program to insure that the highest priority tasks receive appropriate support.

The NFMCC collaboration remains viable but diffuse. It consists of about 140 people corresponding to 30 FTE in the last year. In FY05 the collaboration prepared a 5 year plan assuming flat-flat funding and developed strawman budgets. The hardware focus in FY06 was on finishing MERIT, and advancing the MUCOOL test area (MTA) facility. Work has proceeded on hardware for MICE, but it appears that the collaboration remains behind 1–2 years with respect to the stated MICE schedule. In general, the committee notes that technical progress by the NFMCC collaboration is limited by the available funding.

One high priority item is the Coupling Coil. Although the MICE experiment requires two such coils, the highest priority should be given to completing one coil and using it to verify achievable gradients with the 201 MHz cavity in MTA. Last year, the committee recommended that the funding agencies make every effort to provide $1M to fund the coupling coil as soon as possible. NSF did not fund this effort last year, but DOE provided $300k of supplemental funds. Arrangements with China to collaborate on building several coils are attractive. However, the highest priority should be to obtain one coil and test it with a cavity in MTA. We encourage the funding agencies to work with NFMCC to secure the needed resources for the coupling coil in FY07.

For the last three years it has been the opinion of this committee that funding levels substantially above the FY05–07 levels could be used effectively to advance the goals of NFMCC. The committee recommends that the funding agencies make every effort to provide ~$1M to fund the coupling coil as soon as possible. In addition, the agencies should increase the annual funding to the NFMCC. The scale of the needed incremental resources is at least $500K per year.

The committee notes the excellent use of SBIR funds including Muons, Inc to advance the R&D activities of the collaboration.

<u>The Physics Case:</u>

There exists a number of very convincing theoretical reasons for physics beyond the Standard Model (SM) which motivate a strong experimental program. One direction of research aims at understanding electro-weak symmetry breaking and the mechanism that gives mass to elementary particles. The search for the Higgs particle, supersymmetry, or other extensions related to the deficits of the Higgs sector of the SM are therefore particularly promising areas of exploration. Understanding the origin of generations (flavor) is another equally interesting fundamental question and the apparent regularities in the fermion masses and mixings of quarks and leptons suggest that some explanation exists. Precision neutrino physics is likely to play an important role in understanding the origin of flavor and the discovery of neutrino masses is indeed the first solid evidence for physics beyond the Standard Model. In addition, neutrino properties also play an important role in both astrophysics and cosmology.

The fact that large mixings among neutrino generations came as a complete surprise demonstrates that neutrino experiments can lead us to new and unexpected results. Similarly, given the large solar and atmospheric mixing angles, it is now surprising that $\sin^2 2\theta_{13}$ is small and measuring a very tiny $\sin^2 2\theta_{13} < 0.01$ would suggest some new protective flavor symmetry or another special reason connected to the origin of flavor. On the other hand, larger values of $\sin^2 2\theta_{13}$ would guarantee a measurement of leptonic CP violation. Improved determinations of $\sin^2 2\theta_{13}$ are therefore very interesting independent of the size of $\sin^2 2\theta_{13}$.

Neutrino mass splittings (and therefore non-zero masses) were discovered in recent years by the observation of neutrino oscillations. New experiments aim now at improved measurements of oscillation parameters and at the determination of the absolute neutrino mass scale. The possible Majorana nature of neutrinos would imply that the minimally extended Standard Model violates lepton number. This allows for leptogenesis, perhaps the most natural candidate for the explanation of the observed baryon asymmetry of the universe. Neutrinos often play a special role in scenarios beyond the Standard Model and precision oscillation experiments may therefore be very well the place where corresponding new phenomena might be observed. Precision measurements allow, for example, tests of three-flavor unitarity. Even though the LSND evidence has not been confirmed by MiniBooNE, there are still very good theoretical reasons for the existence of sterile neutrinos with small mixings. Since the origin of generations (flavor) is not yet understood, it is quite conceivable that unexpected flavor effects first show up in precision oscillation experiments. Precision measurements with neutrinos also provide interesting tests of many non-standard scenarios, like mass varying neutrinos, extra dimensions, etc. Similarly, the existence of right-handed neutrinos would have interesting consequences for Grand Unified Theories (GUTs).

Future neutrino experiments with beams and nuclear reactors are by far the best place for very precise neutrino oscillation measurements. The determination of generic three-flavor oscillation effects and a measurement of the leptonic Dirac-like CP-phase are very promising goals for this program. The strategy for measurements of leptonic CP-violation depends crucially on the size of the mixing angle, $\sin^2 2\theta_{13}$. The Double Chooz and Daya Bay reactor experiments will provide essential input on this question within a few years. If the mixing angle $\sin^2 2\theta_{13}$ is not too small, the combination of reactor experiments with the results from the T2K and/or NovA experiments may even be able to discover leptonic CP-violation. A neutrino factory could also lead to impressively precise measurements of neutrino parameters for a scenario with a not-too-small $\sin^2 2\theta_{13}$. However, upgraded superbeams or so-called beta-beams could also be interesting alternatives in this case. For the smallest $\sin^2 2\theta_{13}$ values, neutrino factories will be required to discover CP violation.

There is no question that the physics case for further exploration of the neutrino sector is compelling. The issue for this collaboration is the role of a neutrino factory in this exploration. In describing the physics case for neutrino factories the collaboration described under the conservative assumption of a three-neutrino scenario, various physics measurements that might only be possible with a neutrino factory. There remains considerable uncertainty as to whether a neutrino factory is the only viable option as long as the neutrino mixing angle $\sin^2 2\theta_{13}$ is not yet known. However, the collaboration argues that a neutrino factory is a very powerful instrument for all conceivable values of this angle.

- For $0.04 < \sin^2 2\theta_{13} < 0.1$ a neutrino factory would measure δ, the parameter controlling CP violation, with very good precision.
- For $0.01 < \sin^2 2\theta_{13} < 0.04$ a neutrino factory is probably needed to reliably resolve the mass hierarchy (and to have any hope of measuring CP violation).
- For $\sin^2 2\theta_{13} < 0.01$ a neutrino factory is needed to measure this angle or to set the best limits.
- Precision is in all cases very sensitive to new physics beyond the conventional three-neutrino case.

There is no question that measurements of these parameters constitute important contributions to beyond-standard-model physics, leptogenesis, and perhaps cosmological questions. Reactor experiments will make measurements indicating the relative need for the neutrino factory by about 2010–2012. Existing or approved long baseline experiments will further clarify the case, such that 2012–2015 should be the time scale where R&D should be ready for a decision towards a neutrino factory.

Physics case for a muon collider and connection to a neutrino factory:

It is important to keep in mind that much of the R&D towards a neutrino factory is also important for a potential muon collider. The LHC, which will soon start operations, has during the next 5-10 years a very good potential to make major discoveries related to the origin of electro-weak symmetry breaking. However, the spectrum of possible outcomes is broad, ranging from seeing nothing, only a Standard Model Higgs particle, discovering supersymmetry, or very spectacular effects like those connected to potential extra dimensions. Whatever the LHC finds, it seems likely that some essential questions will remain unanswered. There is therefore a strong case for a machine with even more potential going far beyond the LHC. The International Linear Collider (ILC) was considered until recently the natural and only viable option for this next generation machine. However, due to recent changes in the conceivable schedule, an ILC might only be a realistic option on a considerably longer time scale. This delayed schedule and the possible need to go to higher center-of-mass energies may make a muon collider a viable alternative. However, significant R&D remains to demonstrate that such a machine is both feasible and affordable.

The physics case for a muon collider stems from the fact that muons are about 200 times heavier than electrons. Gauge interactions are identical for electrons and muons, but the coupling to the Higgs boson (or whatever is responsible for electro-weak symmetry breaking) is proportional to the mass. Therefore, s-channel production of scalars is enhanced by $(m_\mu/m_e)^2 \sim 5 \times 10^4$. This leads to an improved ability to explore the particularly interesting symmetry breaking sector in the single Higgs scenario where a muon collider essentially becomes a Higgs Factory. Similarly, a muon collider can provide very good spectroscopy for scenarios with more than one Higgs particle. There are also good reasons to expect that some effects beyond the Standard Model are more easily observed with muons, for example, effects connected to R-parity violation in supersymmetric scenarios.

A muon collider also has potential advantages on the machine side. The fact that muons are 200 times heavier than electrons makes them less subject to energy loss from synchrotron radiation in magnetic fields. Therefore, a very high energy muon beam can be bent at smaller radii and can be recirculated for multiple passes through the acceleration section of a machine. As a result, muon colliders are attractive as machines where very high energies can be possibly be reached at a relatively low cost compared with electron linear colliders where the RF is used only once per particle. However, there are also disadvantages associated with the use of muons which tend to make muon colliders technically challenging and which demand feasibility demonstrations. Muon beams originate from the decay of pion beams and are very diffuse in terms of their initial phase space. Also muons are unstable particles with a lifetime of 2.2 microseconds in the rest frame which limits time for beam manipulation and storage. The challenge of a muon collider is to collect a large number of muons and quickly reduce their phase space and accelerate them before they decay. In practice, the technological challenges for the front end of a muon collider are very similar to those encountered in neutrino factories. **The R&D towards a muon collider therefore has naturally a large overlap with the R&D towards a neutrino factory and these two efforts should be synchronized.**

Charge Point 1: Review and comment on the R&D progress achieved since the last MUTAC review.

Findings:
Significant hardware and design progress for MUCOOL, MERIT, and MICE were again described in the presentations. Beam is imminent for the MERIT experiments and the initial configuration of MICE will be in operation later this year. Large pieces of hardware are under construction. Work in FY06 included fabrication of the MERIT Target magnet, development of the MUCOOL test area (MTA) at Fermilab, and development and successful test of a 201 MHz NCRF cavity that reached its no-field design goal. The collaboration also obtained money for MICE and explored 6-D cooling performance.

Comments:
In FY05 the collaboration prepared a 5-year plan assuming flat-flat funding and developed strawman budgets. The committee supports the collaboration's decision to focus on funding MERIT and MUCOOL. However, we note that this choice means that the collaboration is behind 1–2 yrs with respect to the desired MICE schedule. The committee notes that technical progress by the NFMCC collaboration and its ability to participate in MICE in a timely way continues to be limited by the available funding.

Overall, we believe that the R&D is well focused on critical issues. The collaboration has remained flexible and creative in its use of resources.

Charge Point 2: Review and give advice on the R&D plans and corresponding budgets for FY07 and directions for FY08.

Findings:

The NFMCC R&D plan for FY07 is part of an overall 5-year plan starting in FY05. This overall plan represents a balanced approach under a flat funding scenario that in principle is in coordination with efforts elsewhere in the world.

NFMCC has established an R&D management process (under leadership of a project manager) intended to achieve as much progress as possible within available funding. This process includes negotiation of milestones with the various US labs and universities using NFMCC funds. The R&D activities can be lumped into four broad categories: Cooling channel component development at MUCOOL at Fermilab, Targetry (at MERIT at CERN as well as at BNL), System studies and simulation, and MICE in the UK. The priorities for FY06 and FY07 are MERIT and MICE.

An early step in this plan includes activities centered at MUCOOL, the first integrated demonstration of many fundamental hardware elements of ionization cooling. MuCool includes a 201 MHz RF cavity operating in a high magnetic field. This plan carries through with hardware commitments by NFMCC for MICE in the UK.

NFMCC members have participated in the International Scoping Study (ISS) and expect to continue to play a role in the International Design Study (IDS). This effort is centered in Europe and focuses on the design of a neutrino factory.

The budget available to NFMCC has been nearly flat at $3.6M from FY03 to FY07. (In FY04 and FY06 there was additional funding of $400K and $300K, respectively, from DOE.) This includes salary support from national labs. In addition the NSF is providing $1M over three years (starting in FY06), and funding for Muons Inc. through the DOE SBIR program.

The directions for FY08 will be continuations of those from FY07. These are dominated by longer standing efforts including simulations, MUCOOL, MICE and MERIT. The committee also heard presentations on the non-scaling FFAGs, the International Design Study, the Japanese Program, Muons Inc., and the Muon Collider Task Force.

Comments:

The NFMCC plan for MUCOOL includes testing a fundamental element of the cooling channel composed of an RF cavity in a strong magnetic field. This test is intended to prove the design for two more of these RF/magnetic elements in MICE. This test at the MTA requires a coupling coil for the magnet. The negative impact from the lack of the coupling coil to create the high magnetic field has been called out in two prior MUTAC reports. These reports have encouraged efforts to find the money to procure it from US funding agencies, but to date only partial funding has been identified (as of FY06 about $300K out of about $1M needed). The current tack is that collaboration with the Chinese Institute for Cryogenic and

Superconductivity Technology at Harbin will result in the delivery of the coupling coil for MUCOOL as soon as possible. The MICE plan calls for the delivery of the two RF/magnet assemblies by 2009.

It appears that R&D progress is beginning to suffer from the flat budget year after year, not only in procuring hardware but also in maintaining staff. The erosion of staff supported directly by NFMCC funds is being partially offset by the activities of Muons, Inc. It appears that there are sufficient resources and staff to support fuller participation in EMMA, but NFMCC should make a final evaluation of the benefit of fuller participation in the longer term.

Recommendations:

1) Give highest priority to acquisition of a coupling coil for MUCOOL.

2) Continue participation in MICE and MERIT as much as possible.

3) Continue to grow ties with IDS for a neutrino factory.

4) Take advantage of newly established efforts on a design of a Muon Collider (MCTF).

Charge Point 3: Assess and comment on progress toward the international MERIT experiment.

The **MER**cury **I**ntense **T**arget experiment at CERN is a 'proof-of-principle' test of a target station suitable for a Neutrino Factory or Muon Collider source, using a 24-GeV proton beam incident on a target consisting of a free mercury jet inside a 15 T capture solenoid magnet.

Findings:
Studies continue on solid targets, irradiation tests of solid target candidate materials, laser based shock studies, etc. The collaboration continues to monitor relevant solid target activities elsewhere, but most of these devices are not suitable for a 4 MW proton beam target. Target challenges identified for a high energy, large repetition rate and small beam size proton beam include problems due to radiation damage, melting and cracking. Radiation damage appears to be the ultimate limitation with up to ~5–14 day lifetimes for a NF target. High-Z targets are preferred for $E_p > 10$ GeV to attain highest π and μ yields. Thermal issues dominate for a 4 MW NF solid target. Carbon or tungsten are candidate materials. The best target materials have high yield strength and low thermal expansion. As a result, low thermal expansion materials such as ATJ graphite and a carbon-carbon weave composite are being investigated. Tests have revealed that the carbon-carbon material exhibits much lower strain than graphite, but it is more susceptible to radiation damage. Graphite target tests continue at CNGS and JPARC. The committee encourages continued NFMCC involvement with these efforts.

Impressive progress has been made in preparing for the MERIT experiment. The 15 T pulsed cryogenic solenoid and the Hg delivery system are now complete. The solenoid was tested to full field in March 2006 and both were tested together at MIT in March 2007. The last components were shipped to CERN later that month. The solenoid is undergoing first cryogenics tests at CERN and a leak has been identified that is currently being addressed. Installation in the CERN tunnel is scheduled for 24^{th} April. The installation/commissioning schedule is already tight (only 6 days contingency) and thus the repair must be expedited, so as to not impact the June 19^{th} experiment start date. The solenoid power supply and experimental services are all near completion. MHD simulations of mercury-jet flow in magnetic fields, which include proton beam interactions, cavitation, and bubble simulation, are impressive and represent good progress in theoretical understanding of the dynamics of the mercury-jet target. The MERIT cryogenic system is complete and infrastructure work at CERN is well advanced. Experiment planning is under way and the relevant safety reviews of the cryostat and cryogenics have been completed. Mercury handling and radiation safety reviews are almost complete. Beam diagnostics (*x-y-z* profile, intensity) and particle detectors (diamond and ACEM) are defined and on schedule for installation by 24^{th} April. The experiment is on track for a June–July 2007 beam test. Experiment components will remain in the CERN tunnel until November 2007 to allow for cool down of radioactivity levels before decommissioning during the planned 2008 shutdown. Components will then be stored at CERN for an additional 1-year cool down period, before being classified safe for shipment back to ORNL.

Operational tests of the Hg loop system were completed at MIT in March 2007 and consisted of 14 runs at varying Hg jet velocity and solenoid field. In contrast to expectations, no increase in Hg pressure with magnetic field was observed. Back-illuminated laser shadow photography is used to capture events in the Hg jet (100μs/frame). A full 4-port diagnostic optics has been tested with excellent resolution. Observations revealed: *i*) downstream jet breakup at 0 T, which cleans up considerably when field is increased; *ii*) surface perturbation at 15 T are less on the bottom than the top of the Hg jet; and *iii*) its transverse profile changes vs. applied field point to possible quadrupole effects. Analysis is ongoing. Assessment of jet size vs. velocity and field showed an increase for both, except at 10 T where this trend is not followed, again possibly due to quadrupole effects. A strip heater was added to both the primary and secondary Hg containment vessels to mitigate residual water vapor condensation issues during operations. Two Hg fill/drain tests, performed at ORNL, successfully tested all safety controls and operational procedures. A leak was effectively detected in the secondary containment vessel and a safe repair and clean-up performed. The MERIT system is now at CERN awaiting installation starting 24^{th} April, ready for in-situ commissioning on 7^{th} May.

Comments:
The committee commends the excellent progress made on the MERIT experiment since the last review, especially in light of previous concerns regarding procurement/testing of outstanding components, scheduling the experiment at CERN, and completion of the necessary safety process. The collaboration has done an excellent job and the various tasks have come together, albeit with very little flexibility in the remaining schedule. The committee does note a new concern as a result of the recent leak failure of the solenoid during cryogenic tests at CERN. We encourage the collaboration to give high priority to solving this

problem and to mitigating the associated potential schedule risk.

With regard to the recommendations from last review, all four have been addressed. For recommendation 2, it was reported that CERN had discouraged an application for a follow-up run, indicating that beam time could be made available once the data from the first run had been analyzed. The committee feels that a more formal commitment from CERN is needed should problems arise in the first run.

The committee encourages the continued development and analysis of a solid target alternative, which may become more viable in light of ongoing tests using graphite material.

Recommendation:

1) Continue work to obtain a formal commitment from CERN for a follow-up run if required.

Charge Point 4: Assess and comment on the MUCOOL R&D program and progress toward the international MICE experiment.

MUCOOL R&D Program

Findings:
The 201 MHz cavity was first tested over a year ago, but it has only been operated about four weeks during the past year. This was due in part to the unavailability of the RF source, which is a spare for the Fermilab linac. When operated, the cavity is run 'bare' (sans magnetic solenoid), typically at 2 Hz with 200 microsecond pulses (both modulator limited) at gradients up to 16-18 MV/m as required for a neutrino factory (which would operate in a ~ 3T field at 15 Hz with 150 microsecond pulses). At the highest gradients, which are RF power limited, the cavity operates stably (no RF breakdown). Data from various x-ray detectors show evidence of multipacting in the cavity, but this appears benign and would likely be suppressed with operation in a solenoidal field. As for dark-current generated radiation, the committee notes that it is hard to predict what an acceptable level would be so as not to affect the muon tracking system performance at MICE, but that this is worthy of further investigation.

Recently, the TiN coated copper cavity windows were replaced with TiN coated Be windows, which are needed in a neutrino factory. Essentially no damage (pitting) was observed when the cavity was open, and the TiN coating was still intact. The cavity will be run again to check its performance and to see whether the heating of the thin Be windows changes the cavity frequency noticeably. As noted in the last two reviews, the main performance issue that remains is whether emersion of the cavity in a 3 T solenoid field lowers its sustainable gradient as occurs in the 805 MHz cavity (see below). Thus far, the 201 MHz cavity has only been operated in the 300 G fringe field of the 5 T solenoid used for the 805 MHz program.

Efforts to secure the first coupling coil sooner than the 2009 MICE schedule date are under way and are discussed elsewhere in this report.

The 805 MHz LBNL cavity has been run ~ 40% of the past year at 5–10 Hz with 20 microsecond pulses. Tests confirmed the earlier Lab G results that the sustainable gradient is more than halved (from ~ 40 MV/m to ~ 15 MV/m) when the cavity is operated in a solenoidal field above a few Tesla. The gradient is breakdown limited with or without the field, but the conditioning is particularly slow with the field. Recently, buttons have been added to the windows to measure gradient hold-off, x-ray emission and magnetic field effects for various materials (Cu, TiN Cu, electro-polished Cu, Be, SS, Cr and W/Mo). This program is just starting.

An 805 MHz high pressure cavity from Muons Inc was also run for about 6 weeks at similar operating parameters as for the LBNL cavity. Using windows with buttons made of Cu, Be and Mo, 50–65 MV/m surface fields were achieved with ~1000 psi pressurized H_2, and there was little effect on performance with operation in a 3 T magnetic field. The cavity processed quickly and was ultimately limited by breakdown (no comparable data exist for vacuum operation with this cavity design). There are still many challenges to create a larger version that would work both as an absorber and accelerator for a neutrino factory. In particular, it would need to be shown that ionization produced by passage of a high intensity beam would not ‘short-out’ the cavity.

The KEK convection-cooled LH_2 absorber, which runs at 19 K, has been upgraded to generate larger heat loads. The current plan is to show stable operation up to 70 W, where it is expected to be limited by boiling based on earlier measurements at 20 W. The KEK group has also designed a version for MICE that will use a cryo-cooler instead of a He gas exchanger. In contrast, the absorbers for a neutrino factory would need to dissipate 600 W of power and would likely use a forced-flow cooling system. Currently, KEK has no funding to continue the absorber R&D. Elsewhere; research is being done to develop LiH absorbers, which have their own set of safety concerns. A setup is being built to study heat flow in 30-cm diameter cast LiH disks, where the center will be heated and the outer edges cooled.

FNAL is making good progress installing a 500 W, 4 K cooling system in the MTA (to be operated initially at 250 W). This effort is being funded internally to FNAL and the system will initially be used to cool the 5 T solenoid magnet for the 805 MHz cavity program (it currently costs 3–5 k$ per week to provide cooling with dewars). This system will also be used as part of the cooling system for the LH_2 absorbers. In addition, FNAL has well-developed plans for installing a 400 MeV proton beam line in the MTA. This effort will start during the summer shutdown and the beam line is intended to run initially with low average intensity. The plan includes changes to the MTA layout to accommodate a coupler coil that will surround the 201 MHz cavity.

Comments

The MUCOOL group is making good progress testing the components they have. No new cavities, absorbers or solenoids are expected for at least a year, but the tests that are planned should keep them busy much of the year.

FNAL is generously supporting the planned facility upgrades at MTA.

It was not clear from the talks how and when the critical components for MICE would be provided in the next few years.

No update of the SC cavity work was given; it would have been nice to hear about the final results from this program.

As noted in the last review, stress on the Be windows from average heating may be a problem at MICE with long pulse (1 ms) operation.

Recommendations:

The collaboration should continue to give high priority to acquiring a coupling coil as soon as possible.

FNAL should consider providing a dedicated 201 MHz RF source at MTA to allow uninterrupted operation of the cavity there.

At the next review, the collaboration should present a better overview of the critical-path technical and construction issues and how they are being addressed for the MICE experiment and for a neutrino factory in general.

MICE

Findings:
The overall status of the MICE experiment was presented. Phase I is proceeding towards first operations with beam in October 2007. A separate presentation provided details of the US contribution to MICE. The phase I contributions include a Cerenkov counter for muon/pion identification (CKOV1) and the solenoid spectrometers. The committee was told that all of the components for MICE Phase I are nearly on schedule. CKOV1 is on schedule for delivery in mid-2007. The spectrometer solenoid is under assembly with completion on schedule for shipping to FNAL in October 2007. The scintillating fiber trackers are nearly on schedule and the tracker DAQ is proceeding as planned. A detailed schedule for this effort was not provided to the committee but should be developed if it does not already exist. The overall beamline design is being made using G4beamline.

A proposal to continue with MICE-phase II has been submitted to the UK science administration. Phase II will add the coupling coils, accelerating cavities, absorbers, and focus coils. The primary technical uncertainty for this phase is the achievable accelerating gradient in the presence of the solenoid magnetic field. It is critical that the MUCOOL R&D program provide results in this area. The US contributions to MICE-phase II are centered on the 201 MHz cavities and solenoid magnets (Coupling Coils). The inclusion of the Institute for Cryogenic and Superconductivity Technology (ICST) of the Harbin Institute of Technology in the collaboration has significantly improved the prospects for timely fabrication of the coupling coil within the limited finances of the collaboration. In this collaboration, ICST-Harbin would build the coupling coils for the MUCOOL R&D program and for MICE. The engineering design is a collaborative effort of Harbin and the US and is in progress. A design review is scheduled for May 2007. A detailed plan for the production of the RF accelerating cavities was not presented. However, it was stated in discussion that this will be developed in FY07 if sufficient finances are obtained to begin fabrication of the coupling coils.

Comments:
We commend the collaboration for their continued progress towards a crucial step in verifying muon ionization cooling despite formidable financial and technical barriers.

The operation of MICE would provide the first opportunity for experimental verification of the G4beamline code. This is an important step for verifying this tool for future studies.

We commend the collaboration on seeking out and pursuing the collaboration with ICST-Harbin. This not only provides some financial incentive but raises the international profile of the NFMCC.

Recommendations:
Finalize the negotiations of the coupling coil with ICST-Harbin and begin fabrication if funds allow.

Provide a detailed plan for fabrication of the RF accelerating cavities for MICE. Begin fabrication of the cavities if coupling coil fabrication has begun and funds allow. Develop an overall schedule for the U.S. contribution to MICE.

Charge Point 5: Review and comment on Simulation Group plans, including Neutrino Factory design optimization, FFAG acceleration system activities, Muon Collider studies, and participation in the International Design Study.

Physics Simulations

Comments:
Simulations of the physics potential of a neutrino factory and optimization studies are important in order to identify the crucial R&D issues and to aim at the best possible physics program. The ongoing physics and R&D studies have made significant progress. Several variations of neutrino factories have been identified that show excellent physics potential. The exchange of information between machine, detector and physics simulations has improved and crucial R&D issues, like a lower threshold for muon identification, are being addressed. Interesting new detector options, like Totally Active Scintillation Detectors (TASD) or hybrid detectors, have been considered. Further R&D on the detector side is important, since a

considerable imbalance between the total cost and the spending for detectors exists in most setups considered so far. Therefore, further efforts to intensify the exchange between physics, detector and machine simulations are encouraged, in order to optimize the physics output for a given total cost. The International Scoping Study (ISS) was a very useful framework to coordinate this work internationally and this will naturally be carried over in the International Design Study (IDS). Within the IDS, efforts are being made to better link the machine and detector design to the studies of physics potential. Within Europe, an application for funding for IDS related R&D activities is in preparation within the seventh framework program of the European Union (FP7).

In addition to the work done towards a neutrino factory, the feasibility and the performance of super beams and beta beams needs to be further studied to find how much they could compete with a neutrino factory. Currently super beams are limited by their inherent background, while beta beam studies appear considerably less mature than neutrino factory studies.

The value of $\sin^2 2\theta_{13}$ is crucial for the optimal strategy for future oscillation experiments. Reactor experiments may determine if $\sin^2 2\theta_{13}$ is small or tiny by 2010. The NOvA experiment, in combination with T2K could in principle determine the sign of Δm^2 (mass hierarchy). However, NOvA is being constructed with reduced mass (~20 kt) such that the required integrated neutrino flux may too small for a determination of the sign of Δm^2 . Depending on the size of $\sin^2 2\theta_{13}$, a more intense source than currently exists at Fermilab might be necessary (e.g., the Proton Driver). Moreover, the baseline from Fermilab to Ash River is not optimal for a determination of the sign of Δm^2. Given these uncertainties, it is quite realistic that determination of the neutrino mass hierarchy may end up as a topic for a future neutrino factory. Matter effect uncertainties for the largest possible values of $\sin^2 2\theta_{13}$ are non-negligible, and conventional beams may perform better than a neutrino factory unless the matter uncertainties are improved. The case for a low energy neutrino factory at a shorter baseline should be further investigated.

The optimal roadmap for a neutrino factory and a potential muon collider depends on crucial results of ongoing R&D and, of course, on the physics results of ongoing experiments. It should be stressed that interim results may change the program substantially. Examples include an observation of a large $\sin^2 2\theta_{13}$, LHC results, measurement of Lepton Flavor Violation (LFV), etc. A critical point in time seems to be around 2010–2012, where results on $\sin^2 2\theta_{13}$ from reactor neutrino experiments and next-generation neutrino beam experiments, as well as results from LHC and LFV experiments will allow a better decision on the optimal physics program.

Machine Simulation

Design simulations for muon based facilities include: a muon collider; a neutrino factory: the design of a proton driver, designs of high power targets, front-end designs; acceleration schemes: muon phase space cooling: and storage of muons. There is also a simulation effort to support the experimental program: MICE, MERIT, and EMMA (non-scaling FFAG). Additional simulation studies include RF breakdown, solid target shock effects, hydrodynamic effects of Hg in a high magnetic fields, and beamline design. Indeed, we were told that one deliverable for the MICE experiment is a benchmarking of the code used to model the beam transport and cooling process. There is also a simulation effort outside of the collaboration at Muons Inc. and the MCTF.

The collaboration recently completed ISS, an attempt to consolidate neutrino factory machine options. New efforts are currently underway to evaluate various muon collider schemes.

Findings

Proton driver. An analysis of the dependence of muon yield on proton energy indicates best efficiency at about 10 GeV. The positive muon yield is about 0.65% per proton-GeV and the yield for negative muons is slightly higher at 0.75%. Another study quantifies the dependence of the acceptance of the cooling line on the length of the proton driver pulse and finds that acceptance declines if the pulse length is greater than 1 ns.

Target System. Simulation shows that for a 4 MW, 16 GeV proton beam on a liquid-metal-jet target, optimum muon yield is for a 6 mm radius jet. Alternatively, a solid carbon target may be suitable for a lower power beam, and then the proton energy optimization gives a peak at a proton energy of about 5 GeV and a yield of 0.5% muons per proton-GeV.

Cooling. There has been an optimization of phase rotation channel parameters to minimize energy spread after phase rotation. In view of the possibility that the 15 MV/m gradient achieved in zero magnetic field is not attained at full magnetic field, there has been an investigation of the consequences of reduced accelerating gradient. If the cavities operate at 10 MV/m then the muon transmission is reduced by only 20% if other parameters of the channel are reoptimized. Similarly, the loss of one of 12 cavities results in a 3% reduction in transmitted muons per proton.

Muon Helicity. For some strange reason in a train of bunches, there is an average helicity of 8% and a bunch dependent helicity that varies from +15% at the head of the train to –15% at the tail as the train emerges from the cooling channel.

Cooling vs acceptance. A larger acceptance of the muon accelerator implies that less cooling is required, suggesting a real tradeoff in design optimization. The simulation quantifies acceptance in terms of the length of the cooling channel. Some cooling will be required for a neutrino factory unless the FFAG transverse acceptance proves very large.

Acceleration. There has been simulation of various acceleration scenarios, including various combinations of RLAs and FFAGs. Simulations are the tool of choice to evaluate possible solutions for the problem of the dependence of time-of-flight on amplitude in the FFAG. Evaluating the use of scaling FFAGs at low energy and studying effects of errors are also in progress.

Decay ring. Studies include the relative advantages of different configurations, such as racetrack, triangle and bowtie geometries.

There is also simulation effort in support of EMMA.

Comments

There is an impressive body of modeling and simulation in support of the experimental effort and the design of the components of a neutrino factory and muon collider. It is very important that critical calculations be completed with independent codes, and that as much as possible the predictions of codes be checked against measurements. MICE and EMMA are both important tests of models, approximations, implementations, etc.

The issue of amplitude dependence on tune in non-scaling FFAG's is yet to be resolved, and presently there is no clear approach to the type of FFAG that could be used.

If the time scale is 2012, more effort is required, including optimization of acceleration scenarios, stability of accelerated beams, ion effects, electron cloud effects, beam-beam interaction, parasitic interactions in accelerating arcs, effects of lost decay electrons, optimization of FFAG optics, RF, etc. There is no shortage of computing power, but people to write, run, and interpret the results need to be identified.

The committee strongly supports and encourages the continued exploration of muon collider schemes. At this very early stage of the project, both high and low emittance schemes should continue to be studied, and critical R&D items should be identified and addressed.

Space-charge effects need to be included in the simulations, and matching between the various cooling sections needs to be simulated as well.

Recommendation

Leverage resources within the MCTF and UKNF collaborations, and Muons, Inc. to increase the manpower directed towards simulations of the acceleration system and storage ring.

Parametric studies of RLAs should be carried out to explore and identify their limits of operation and optimization. Further, a process should be outlined and followed to allow one to arrive at the optimum choice of the accelerator type [RLA, vs. various types of FFAGs] for every stage of the machine. Intense simulation efforts are required in support of EMMA, if the benefits of the experiment are to be maximized. Significant simulation effort is required to more accurately evaluate the performance of the various muon collider schemes, including space-charge effects, and simulations of the matching sections, leading ultimately to self-consistent front-to-end simulations of the entire complex.

Charge Point 6: Review and comment on the plans of the Fermilab Muon Collider Task Force and their relationship to the ongoing program of the Neutrino Factory and Muon Collider Collaboration.

MCTF

Findings:
The task force was set up by the Fermilab director to develop an R&D plan for a muon collider, based on ionization cooling.

Over 50 people have been identified to be a part of it including Muons, Inc, BNL, LBNL, Jlab, and ANL

MCTF anticipates submitting a proposal for

- Collider and cooling channel design studies
- 6D cooling experiments in MTA
- Design and development of a helical cooling channel, 50 T HTSC solenoids, and storage ring dipoles
- Beam tests

MCTF Plan

FY07 – Initial design report for 1.5 TeV low emittance collider. MTA high power proton beam plan. HTS solenoid development. Helical CC design and prototype.

FY08 Presurized RF cavity and absorber tests in MTA. Installation of target and transport line. HTS insert tested at 15 T. HCC and matching sections designed and prototypes built.

FY09 Commission muon beam. HCC magnet construction. HTSC solenoid engineering finished.

FY10 HCC magnets completed and 6D cooling experiment starts. High field HTSC solenoid built. MC cooling channel results.

Development of a viable 1.5 TeV center-of-mass collider will depend on study of ring optics, especially the interaction region, backgrounds, and various scenarios (IR dipole to generate dispersion in IR to couple to sextupoles). The relative merits and feasibility of high (12.3 μm) vs low (2.1 μm) emittance must be understood and quantified.

The radiation generated by interactions of the neutrino beam with the earth scales as E^3 and with the beam current. At a muon beam energy of 750 GeV, the radiation is not yet a problem, but at 2.5 TeV it will be unless emittance (and beam current) can be significantly reduced.

The MCTF proposes a collaboration with manufacturers of HTSC cable to develop conductor for 50 T solenoids.

Comments:
Creation of the MCTF promises to bring much needed resources to the muon collider R&D effort, including people for design, modeling and simulation, exploration of the various cooling, accelerating, storage, collider ring scenarios, and it may serve to further build and support the NFMCC experimental program through enhancements to the MTA. That FNAL has taken the step of creating the task force is in some sense to the credit of the NFMCC for raising the profile and establishing the credibility of such a machine. The relationship between the two organizations is fuzzy. The committee did not have a clear point of view on whether this was a good or a bad situation.

Recommendations

Coordination of MCTF with NFMCC is essential to ensure that the muon collider effort makes best use of limited resources, avoids duplication, and shares infrastructure, codes, and results. Although coordination is important, we recommend that the NFMCC remain independent, so that initiatives are not restricted by local (FNAL) preferences and constraints.

Current NFMCC Collaboration

The NFMCC is part of the worldwide effort in the development of next generation neutrino facilities and is playing a significant role in the ongoing IDS, MICE and MERIT collaborations. Both the IDS and MICE projects are fully international with members from the major HEP regions of the EU, Asia and the US. The ISS served as a precursor to an international design study (IDS) and was a significant step in evaluating the various different technical approaches under consideration.

The NFMCC currently involves 140 people with several standing committees guiding various aspects of the work. The management and structure of the NFMCC have been stable for several years. The NFMCC management has developed a multi-year R&D plan to address the highest priority topics related to demonstrating the ability to construct a Neutrino Factory. Funding is spread across several sources as well as the US base program and has been limited to constant dollars during the recent past. The NFMCC has worked effectively to derive technical benefit from the SBIR program and utilization of these resources continues to grow

Comments:
The steady trend towards the internationalization of many aspects of this work continues to be apparent. MUTAC continues to support this evolution, which permits more effective use of the limited global resources. The ISS activities, together with the MICE experiment, have required a close integration of the various regional programs. The NFMCC is to be commended for its role in facilitating this process. MUTAC suspects that, at some point in the not-too-distant future, better clarification of the international structure will be required.

The NFMCC is to be congratulated on its work with Muons, Inc. to bring additional resources to bear on various topics via the SBIR Program.

<u>Recommendations</u>:

Continue to work at the international level towards creating a unified management structure.

Work to insure coordination between NFMCC and MCTF.

UK, Japan, and other international issues

<u>Findings:</u>

The UK and Japan both pursue very aggressive R&D programs addressing the issues of future neutrino factories and muon colliders. Both the UK and Japan devote significant funding and resources towards these projects. Many of the R&D activities in the UK and Japan such as MUCOOL, MICE and EMMA are connected to broad international collaborations. CERN is a major player in the MERIT experiment. NFMCC uses these collaborations very wisely and inventively to make maximum impact using limited resources. The level of coordination with other participants is excellent and there are no indications of duplication of efforts. There is a new issue with common fund fees for participation in the MICE experiment at RAL, UK, which should be addressed. In addition, NFMCC would like to have 2–3 new post-doctoral positions.

In addition to its international efforts, Japan pursues significant development, construction and commissioning of various non-scaling FFAGs as a part of its national program. Japan took part in ISS activities and is involved in ISD efforts on neutrino factories.

<u>Comments:</u>

The issue of "common fund fees" and their impact on the budget should be understood.

<u>Recommendations:</u> none

Appendix 1:

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