MUTAC Committee Report
Review April 8-10, 2008, LBNL

Charge

1. ***Review and comment on the R&D progress achieved since the last MUTAC review, including both NFMCC and MCTF activities.***

    a. ***Assess and comment on results and possible follow up to the international MERIT experiment.***
    b. ***Assess and comment on the MUCOOL R&D program***
    c. ***Assess program and comment on first results from the international MICE experiment.***
    d. ***Review and comment on Simulation Group accomplishments and plans, including Neutrino Factory design optimization, FFAG acceleration system activities, Muon Collider studies, and participation in the International Design Study.***
    e. ***Review and comment on goals, strategy, and progress in the Muon Collider design and technology development programs.***

2. ***Review and give advice on the R&D plans and corresponding budgets for FY08 and directions for FY09.***

3. ***Offer comments/advice as appropriate, on longer range strategies for the NFMCC and MCTF.***

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 elements in the charge. For each 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/conf/MUTAC-080408/

Overview and Executive Summary

The committee congratulates the Neutrino Factory and Muon Collider Collaboration (NFMCC) and Muon Collider Task Force (MCTF) on the 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. Neutrino Factories may be needed to explore the mass hierarchy and CP violation in the neutrino sector, especially if θ_{13} is found to be small. The extended timelines and costs now envisioned for other lepton colliders (ILC, CLIC) and the possible need for higher energy reach increase the importance of the R&D program for a possible Muon Collider. Several experimental initiatives have reached the point of first operations. Impressive results were reported from the MERIT experiment at CERN which indicate that mercury jet targets can, in principle, work at power levels of 4 MW or more. The MICE beam line construction is done and has begun testing. The MICE spectrometers are nearing completion. The coupling coils were listed as a concern in previous MUTAC reports. The committee was pleased to see that the design of the MICE coupling coils is complete and that the coils are being fabricated. The coils will be commissioned in the next year. The MUCOOL R&D program has made significant progress and is likely to begin beam operations in the next year. The committee endorses the collaboration's proposal that DOE/NSF fund a coordinated national effort to develop High Temperature Superconductors (HTS) for high magnetic field applications like Muon Collider solenoids. Extensive simulations of Neutrino Factory designs, as part of the International Scoping Study (ISS), are complete and will continue as part of the International Design Study (IDS). The collaboration has set itself the goal of a Neutrino Factory Reference Design Report and a Muon Collider Feasibility Study by 2012. These technology demonstrations and machine simulations collectively are intended to demonstrate machine designs and existence proofs for key technical components required by a Neutrino Factory or a high energy Muon Collider. The addition of the MCTF effort to NFMCC has significantly increased the overall resources available. Currently about $8M per year is being invested in the U.S roughly equally in NFMCC and MCTF. This means that the overall effort has approximately doubled. However, the workforce of both NFMCC and MCTF remains diffuse and consists of about 15-20 FTE distributed across 140 individuals. In past years the international connection of the collaboration has been strong in both Europe (UK) and Japan. The strong European effort on MICE is expected to continue. In addition, a new neutrino R&D effort has been funded at about 4 M€ as part of FP7. The committee notes with some concern that all funding for Muons and Neutrinos in the US-Japan agreement has been zeroed in JFY08. We note as a positive step the large Chinese contribution to the MICE coupling coils.

The committee supports the effort that has begun to create a 5 yr integrated NFMCC and MCTF R&D plan. The 2012 goal of both the Neutrino Factory Reference Design Report and a feasibility report for the Muon Collider will be a significant challenge with current available resources. The committee notes that the collaboration believes that a factor of three increase in resources will be required to meet their stated goals. Such an increase will require strong support from P5 and powerful technical justification. Although the committee believes a significant increase is required, a detailed justification for the requested funding increase was not provided at this meeting. The committee remains both impressed with the flow of new ideas for muon colliders and concerned that given limited resources, options must be reduced. The 5 yr plan should include milestones and mechanisms to down-select technology and design options. Integrated resource requests should be made such that the needs of both NFMCC and MCTF can be understood and displayed in the same spreadsheet. The committee applauds efforts to move towards a common management structure for the R&D program but recognizes that this common management must preserve the strong international relationships NFMCC has established. A crucial part of the integrated R&D plan will be timely estimates for the costs of a neutrino factory and/or a muon collider to demonstrate that such machines are both technically and financially feasible. It will also be important to involve the larger HEP community to study and determine the feasibility of muon collider detectors.

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

The Physics Case and Context:

Particle physics is at an important point in its history. The Standard Model (SM) has been shown to be highly successful in explaining almost all measurements. But the uncertainties associated with the source of electroweak symmetry breaking indicate that it is likely that new phenomena will become visible soon as the LHC program begins and ramps up to high luminosity. Theoretical speculations cover a wide range of new physics possibilities from a SM Higgs discovery, to detection of supersymmetric particles or other new phenomena associated with possible SM extensions.

Many believe that the LHC even with luminosity upgrades will not be able to fully explore these new physics signals and will need to be augmented by a lepton collider to provide needed complementary capabilities. This has led to two very active R&D programs associated with an electron linear collider or a muon collider. As the R&D program has progressed, it looks as if the electron linear collider may be limited to center of mass energies of 0.5 to 1.0 TeV which might be too low to cover the new physics signals. On the other hand, a muon collider could in principle reach much higher energies and may have higher coupling to new physics signals due to the higher mass of muons relative to electrons. For these reasons, R&D towards realizing a muon collider is becoming an even more important component of a future particle physics program.

The observation of neutrino oscillations has also opened a new area of beyond the SM physics to explore. The confirmation of the solar and atmospheric neutrino oscillation phenomena has given an unquestioned new physics signal where neutrinos have mass and where there is mixing among the flavors. The small size of neutrino masses and the violation of lepton number in the neutrino sector have given unique new insights into models of mass generation and flavor generation. For example, small neutrino masses may be generated through new Terascale particles or interactions and explanations of the baryon asymmetry in the universe may be related to Majorana neutrinos and CP violation in the neutrino mixings. Many extensions of the SM include new types of neutrinos including sterile neutrinos and/or right-handed neutrinos. Observation of such particles would provide unique information for understanding how the SM needs to be modified.

The clear next steps for neutrino oscillation measurement are: 1) measure the value of the mixing angle, θ_{13}, which is already known to be fairly small, 2) improve the measurements of θ_{23} to see how close it is to 45°, 3) determine the mass hierarchy of the three types of neutrinos, and 4) measure any CP violation associated with the neutrino mixing matrix. In addition, testing the unitarity of the mixing matrix with more precise measurements coupled with disappearance searches could uncover indications of other neutrinos or interactions beyond the SM. (The determination of the Dirac or Majorana nature of the neutrinos will call for new double beta-decay experiments and is not directly probed by oscillations experiments.) As happened with the original neutrino oscillation observations, measurements of any of these parameters and properties could lead to surprises that would significantly change our theoretical understanding and models.

The current suite of neutrino oscillation experiments, T2K, NOvA, Double Chooz, and Daya Bay, will be limited in physics reach due to the size of θ_{13}. Various studies, such as the International Scoping Study (ISS), have shown that it will be difficult to make definitive hierarchy measurements unless $\theta_{13} > 3°$. Sensitivity to CP violation with these experiments demands an even larger θ_{13}, probably greater than the current limit. For this reason, accomplishing the above list of measurements will, most likely, require upgrades of the current suite of experiments followed by new and more sensitive experiments. The capabilities of these new programs have been considered in the ISS including long baseline, superbeam experiments, beta-beam experiments, and experiments using a neutrino factory beam. The neutrino factory measurements were shown to be several orders of magnitude more sensitive compared to the superbeam experiments and shown to have sensitivities to CP violation effect for θ_{13} values as small as 0.2°. A neutrino factory beam is unique for neutrino oscillation studies since one can make measurements for muon and electron neutrinos and antineutrinos. The flux is very well understood and oscillation measurements to τ-neutrinos can also be accomplished.

For both the neutrino factory and muon collider, a decision point is coming up in about five years. For the muon collider, one will have the first results from the LHC and will therefore better understand how a muon or electron collider will address any observed new physics signals. Of prime importance at this stage is to understand the capabilities of these lepton collider experiments to address any new physics discovered at LHC. Understanding of the electron collider capabilities is fairly well known. However, for the muon collider, the energy, luminosity, and detector requirements have not been extensively studied. For the neutrino factory, the question of whether θ_{13} is greater than 3^0 will be known in about five years. If θ_{13} is smaller than this 3^0 level, superbeams will have some window to measure θ_{13} down to 1^0 but will not have much sensitivity to CP violation. Thus, a neutrino factory will be required in this case to complete the crucial neutrino oscillation measurements.

The neutrino factory and muon collider will be unique new tools that will be of prime importance for understanding Terascale and flavor physics and could provide the key window for making future progress in the field. Although new information may become available over the next five years to modify this view, it is important that a strong, well-supported R&D program go ahead now so that these facilities can be viable options for the future. Although not discussed at this review, it should also be noted that either a neutrino factory or a muon collider assumes a powerful multi - MW class source of protons as a starting point.

Recommendation:

The muon collider feasibility study needs to quantify the energy, luminosity, and detector requirements for addressing the various physics signal scenarios that might be observed at the LHC.

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

Findings:

Impressive progress has been made in the last year on many fronts. Notable achievements are the installation, commissioning and completion of the MERIT experimental run at CERN, the beginning of fabrication of the coupling coils at Harbin for MUCOOL and MICE, first beam at the MICE experiment at RAL, fabrication of components for EMMA (the non-scaling FFAG test bed), progress in the MUCOOL program, construction of the MTA transfer line, further advances in understanding of 6-D cooling approaches, and progress in neutrino factory and muon collider designs.

In particular, the completion of the MERIT experiment already answers the basic question of feasibility of a mercury-jet target for high power proton beams. Further analysis of results promises to answer the more detailed questions related to the allowable bunch structure and the repetition rate.

The collaboration continues to make good progress within the constraints of limited funding.

Comments:

Most of the recommendations from the last MUTAC review have been addressed. In particular, a solution has been found for one of the issues of greatest concern at the last review, the production of the coupling coils.

A critical issue remains the achievable RF gradients in the presence of high magnetic fields, which is the main focus of the MUCOOL cavity testing program. Additionally, the viability of high-pressure H2-filled RF cavities in the presence of ionizing-beam traversal is another critical question, the answer to which awaits the arrival of beam via the new MTA line.

Results from MICE are needed by the end of 2011. There is much to be done in order to meet that schedule in terms of production and delivery of “Phase 2” components. In particular the coupling coils and RF cavities must be manufactured, tested, installed and commissioned in two years. In addition, given the lack of funding contingency, schedule slippage is the only practical way of covering shortfalls in other aspects of the NFMCC program. This highlights the importance of pursuing the most direct approach toward acquiring the necessary MICE hardware.

Additional resources brought about by the formation of the MCTF have energized the Muon Collider (MC) and Neutrino Factory (NF) efforts. The MCTF completed its first year of activities, and has documented the results in an annual report. The R&D program is focused on the main MC challenges: 6-D cooling and MC ring design. Further refinements and development of the helical cooling channel concept are progressing well.

The NFMCC and MCTF management have been very effective at keeping the R&D program moving forward to answer the critical questions, in the face of limited funding

The committee feels that the limited available resources are addressing the most critical R&D issues.

CHARGE 1 a) ***Assess and comment on results and possible follow up to 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.

<u>Findings:</u>

The experimenters overcame a variety of logistical and technical problems to demonstrate the viability of the mercury jet as a suitable target for a 4 MW proton beam. Measurements were performed with 14 and 24GeV beams with variable bunch structure and timing. The ability to vary the delay between pump and probe bunches permitted measurement of the time dependence of the cavitation of the mercury target, and target disruption length. The dependence of the disruption of the jet on the beam intensity and magnetic field was determined. The experiment was well instrumented. Profile monitors measure the transverse beam size. An intensity monitor measured the number of protons in each bunch. Distributed particle detectors provided a measure of the angular distribution of the charged particle flux resulting from the interaction of beam with target with bunch by bunch capability. Optical diagnostics provide a picture of the time dependence of the disruption of the mercury jet.

Time delay photographs indicate the mercury jet is intact after passage of 16e12 protons then disrupted by the shockwave. The observed breakup is consistent with the beam trajectory and with cavitation caused by energy deposition. It was observed that a magnetic field does indeed preserve the stability of the jet traversed by the proton bunch. The optical measurements of the dependence of the disruption of the mercury stream on magnetic field show that the fluctuations in the width of the jet are reduced with increasing magnetic field. Photographs taken at intervals of about 0.1 ms show that the disruption length at 24 GeV beam energy is about 20 cm for 10-15 T magnetic fields. Then at a flow rate of 20 m/s the jet is renewed in 14 ms, permitting a 70 Hz repetition rate or an equivalent of 8 MW of beam power. As anticipated, the splash velocity is observed to increase with beam intensity, and the disruption length with proton energy. The disruption length is reduced with increasing magnetic field. But while the jet is apparently stabilized with higher magnetic field, its transverse size is observed to increase with magnetic field above 10T, a phenomenon that bears further study.

The distributed particle detectors provide a measurement of the charged pion flux production from individual bunches spaced by as few as 131 ns. Measurement of the angular distribution of the charged particle flux is in good agreement with simulation when there is no mercury jet target. But there is a large discrepancy with simulation when the mercury target is in the beam. Further analysis is required.

The data from the pump/probe study includes measurements with 15TP pump bunch and 5TP probe with delays from 2 to 700 microseconds. Analysis of time and bunch intensity dependence of the charged particle flux can in principle reveal details of the time dependence of the disruption and cavitation of the jet. Simulations of the hydrodynamics of the jet and resulting pion production can be benchmarked against the measurements and thus improve design tools.

Comments:

The committee commends the MERIT team for successful completion of the experiment. The measurements demonstrate the viability of a mercury jet target for a beam power in excess of 4MW. The data that remains to be analyzed can provide details of the time dependence of the disruption of the jet, and the dependence of the stability of the jet on beam parameters, jet flow rate, and magnetic field. Comparison of the results of the ongoing analysis with calculations will provide critical guidance for the design of the targets.

Recommendation:

1) Complete the analysis of the data from the MERIT experiment and compare with hydrodynamic calculations and benchmark particle production simulations. Determine what further targetry studies are required to establish the feasibility of a muon collider.

CHARGE 1 b) ***Assess and comment on the MUCOOL R&D program***

Findings:

Tests of the 805 MHz LBNL single-cell cavity continued throughout the past year. It is typically run at 10 Hz with 20 microsecond pulses while located inside a SC solenoid magnet that can produce fields up to 4.5 T. In 2007, the earlier Lab G results were reproduced that showed the sustainable gradient is more than halved (from ~ 40 MV/m to ~ 15 MV/m) when the magnetic field increases above a few Tesla. During the past year, buttons made with various materials and coatings were attached to one window to study their impact on gradient hold-off, x-ray emission and magnetic field dependence. So far, no major difference has been observed in the sustainable gradient versus magnetic field curves measured for buttons made of Mo, W, Cu with a TiN coating that was largely burned off, and Cu with a TiN coating that remained intact.

The group doing these tests is also involved in the broader studies being done at ANL to understand the origins of RF breakdown. These studies include simulations (with TechX) of breakdown evolution initiated when a sharp tip on the surface breaks off due to field stresses, and is then vaporized. Also, surface treatments and preparations (including atomic layer deposition) are being developed to eliminate sharp tips, which will hopefully increase the achievable gradients. More relevant are the studies being planned to understand how magnetic field affects breakdown (e.g., does it enhance electron back-bombardment or does the resulting focusing of the breakdown currents create damage and initiate further breakdown on the opposite wall). To help reveal the origin of the field dependence, tests are planned in which the 805 MHz cavity will be tilted at various angles to the solenoidal field and its sustainable gradient measured.

The magnetic field studies are motivated by the need to run the 201 MHz cavities in a strong field (~3 T) for muon cooling. In lieu of a large solenoidal coupling coil that will be used to generate these fields (see below), the collaboration had been limited to testing their single 201 MHz cavity in stray fields of a few hundred Gauss from their solenoid. At these levels, as with no magnetic field, the cavity operates stably (without breakdowns) at the power-limited gradient of 19 MV/m (typically, they run at 10 Hz with 150 microsecond pulses that includes a 60 microsecond, 3-tau fill time). During the past year, they were able to move the cavity closer to the solenoid to produce a field up 1.5 T at one of the Be windows. In this configuration, they have achieved 14 MV/m with a 0.75 T field at the window so far, limited by breakdown and multipacting (which occurs at some level at all fields strengths). They also see increased dark current with the magnetic field (up to ten times), as was expected given dark current simulations (done with SLAC) that showed the focusing effect of the fields. **These currents are a concern for the MICE experiment where the tracking detectors could be swamped by these electrons.** They next want to RF process the cavity longer to see if the multipacting diminishes and perhaps allows for higher gradients.

The available time to run the 201 MHz cavity was limited during the past year because the RF test stand is also used to process new klystrons for the FNAL linac. This will likely continue to be an issue as FNAL has no plans to provide a dedicated RF source. Nonetheless, much has been learned about the cavity performance besides its sensitivity to magnetic fields. The Be windows, whose design was improved before they were installed about a year ago, perform as well as the original copper ones. At 16 MV/m, the cavity heat load is 8.4 kW, including 100 W in each window, which produces window stresses far below the damage limit. These heat loads are similar to that expected in a neutrino factory, at least in the older designs where the cavity operated at 15 Hz with 150 microsecond pulses. In the latest design with 50 Hz operation, removing the heat would likely be a problem as would the detuning compensation, which may exceed the range of the current mechanical tuners.

For the MICE program, eight 201 MHz cavities are required. A plan was presented to produce four more cavities at LBNL with modest improvements by 2010. Although a detailed schedule exists, there were some concerns about meeting the production time line as they have yet to finalize where the cavity e-beam welding and electro-polishing will be done.

After years of anxiety about acquiring coupling coils in a timely manner to do the critical field versus gradient tests, a supplier was found during the past year. The Institute of Cryogenics and Superconductivity Technology (ICST), at the Harbin Institute of Technology in China, will fund and build the coupling coils. Currently the design is 90% complete and the first of several test coils is being wound. These test coils will be used to train the assembly crew, test the quench protection system and characterize the magnet training under normal and worst-case strain conditions. Three coils will be produced: one for MUCOOL, which will be shipped to FNAL in early 2009, and two for MICE, which will be shipped to LBNL by mid-2009. The coils will be cooled using one or two cryo-coolers (1.5 W at 4.2 K and 55 W at 50 K) per coil, which include HTS leads in the 4-50 K section. Of concern is the lack of experience by this institute (which has worked mostly to produce refrigeration systems), demonstration of the ability of the cryo-coolers to handle the magnet heat loads, and the lack of contingency in the schedule.

The KEK convection-cooled LH_2 absorber, which runs at 19 K, was upgraded in early 2007 to generate larger heat loads for tests at MTA. However, funding (US-Japan JFY07) was cut before they were able show stable operation up to 70 W, where operation is expected to be limited by boiling based on earlier measurements at 20 W. JFY08 funding was not restored, although it appears they will continue to build a version for MICE that uses a cryo-cooler instead of a He gas exchanger. The heat load at MICE is small whereas the absorbers for a neutrino factory would need to dissipate 600 W of power and would likely use a forced-flow cooling system. It was not clear from the presentations when a more realistic LH2 absorber would be developed.

In a parallel program, the feasibility of using LiH as an absorber is being examined by a group at FNAL. They are in the process of contracting Y12 (at ORNL) to make LiH disks through a hot isostatic pressing (150 deg C, 30,000 psi) process. Various size disks will be made for studies of thermal stress and radiation damage, and for use in MICE. A setup to do the thermal tests has been prepared, including the appropriate safety precautions for handling this type of material.

Much of the planned improvements at MTA were completed in the past year. Magnets were installed and shielding calculations were done in preparation to bring a proton beam into the MTA hall. The beam will have an rms radius of less than 1 cm (which is much smaller than the expected muon beam size in a neutrino factory cooling line), an intensity of up to 2e14 protons per second and a repetition rate up to 15 Hz (but limited to 1 Hz at full intensity). In addition, the installation of a 250 W, 4 K cryogenics system is nearly complete and will replace the expensive Dewar system to cool the solenoid magnet. The switch-over should occur by June 2008 and first beam, to a dump upstream of MTA, should occur that time. To make use of the beam, the equipment in the MTA will need to be raised in height.

The program with the new facilities (called MUCOOL Phase II) includes running beam through Muons Inc's high pressure RF cavity by the end of this year to determine whether the induced ionization will load down the cavity (simulations are also being done to predict the outcome). Other tests envisioned for the next year include the continuation of the 805 MHz program of studying gradient hold-off of buttons made with various materials and surface treatments, and further operation of the 201 MHz cavity in the Tesla-level fringe field of the solenoid. This latter program is imperative as the key requirement for neutrino factories or muon colliders is that RF cavities operate at high gradients (>10 MV/m) in strong magnetic fields. Also, thermal and mechanical tests of LiH disks will be completed within the next year. Finally, the coupling coil will be installed if the production schedule is met.

With the upgraded facilities at MTA, the committee suggests that a more aggressive program be pursued that exploits its resources. Possibilities include continuing the LH2 absorber program with US funds, testing a LiH absorber with beam, building more realistic, high pressure rf cavities (in addition to any from Muons Inc. or other sources), and building RF cavities that would be used in helical cooling channels.

Recommendations:

1) Measure the energy spectrum of dark currents from the 201 MHz cavity as a function of magnetic field and gradient, and use these data to predict backgrounds in the MICE tracking system.

2) Pursue a more aggressive program at MTA, taking advantages of its unique facilities to do experiments that compliment the MICE program.

CHARGE 1 c) ***Assess program and comment on first results from the international MICE experiment.***

Findings:

The international Muon Ionization Cooling Experiment (MICE) is located at Rutherford Appleton Laboratory (RAL) in the United Kingdom. Its purposes are to demonstrate the principle of 4-dimensional transverse ionization cooling of muons and to operate a cooling channel safely. MICE intends to quantify the performance of 4-dimensional transverse cooling, a technique that has been simulated but remains untested at the present time.

First beam was delivered to the MICE hall on March 29/30, 2008.

To date MICE has been operating during ISIS machine development periods. The ability to run parasitically during ISIS user runs has recently been demonstrated. This will become the normal running mode for MICE after satisfying operational and radiation safety reviews. The experiment plan calls for six steps. Step I has begun; the first pion was detected in the last week in March 2008 using a Cherenkov counter provided by NFMCC. Step VI is anticipated in about 2011. Some MICE shift work has begun and it will continue until the measurement program is completed, probably in 2011. The US collaborators on MICE need to provide common funds both to support the experiment operations and to be authors on papers.

Resources to begin fabricating MICE coupling coils and RF cavities are now available. ICST-Harbin has nearly finished the magnet engineering, and fabrication of three coupling coils has begun, two of which are for MICE. The MICE coils are scheduled to be delivered to LBNL on March 15 and June 10, 2009. Approximately $2.2M was provided by DOE and NSF in FY2008 to NFMCC for MICE (and other cooling efforts). Component delivery by NFMCC to MICE is based on a “success oriented” schedule, and delays of up to a year are likely because of the developmental nature of the work and because of the assumed continuation of the present level of funding which permits no contingency, except schedule delay. The components which may be delayed include the RF cavities and the coils. On the other hand, the spectrometer solenoids, trackers and Cherenkov counters seem likely to be delivered on time.

The International Design Study (IDS) for a neutrino factory and a feasibility study for a muon collider are both expected to be complete by 2012.

Comments:

The committee notes the accomplishment of first beam to the MICE hall and all the teams involved are to be commended. Although there is much yet to be done before cooling of muons can be demonstrated, this accomplishment bodes well for the muon ionization R&D effort.

Ionization cooling is the leading concept for reducing the emittance of a muon beam quickly compared to the 2.2 microsecond (rest frame) muon lifetime. This rapid reduction in emittance is absolutely crucial for achieving intense muon beams in a reasonable manner. A successful demonstration of 4-dimensional muon ionization cooling by MICE would help inform the design of a neutrino factory. The committee looks forward to seeing comparisons of the MICE measurements with simulations in order to quantify understanding of this technique based on a real setup.

The schedule for the completion of MICE is slipping into 2011. The schedules for delivery of the feasibility study for the muon collider and the design report for the neutrino factory indicate they might be finished before MICE analysis will be completely finished. It is important that information from MICE which might be used by the muon collider feasibility study be identified, if any. However, the 6-dimensional cooling ideas being pursued by Muons Inc. are more appropriate for a muon collider.

A particular concern for MICE is whether dark currents generated in the 201 MHz cavities will swamp the muon tracking system and prevent measurement of the cooling at reasonable (> 10 MV/m) gradients. As noted in the MUCOOL section, data on the spectrum of dark currents should be made at MTA to assess the severity of this problem, which has been a concern since the inception of this project.

Recommendations:

1) **NFMCC should focus on completing all the remaining steps in MICE.**

2) **Working together, NFMCC and MCTF need to identify those pieces of information from the MICE experiment expected to contribute to the muon collider feasibility study.**

CHARGE 1 d) ***Review and comment on Simulation Group accomplishments and plans, including Neutrino Factory design optimization, FFAG acceleration system activities, Muon Collider studies, and participation in the International Design Study.***

Machine Simulations: 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 6D phase-space cooling, and storage of muons. During this year the International Scoping Study (ISS) was completed and issued in the form of a preprint. The International Design Study (IDS) has been launched and the neutrino factory baseline has been defined including detector design and physics performance. Muon collider studies have intensified with focus on component design studies for cooling, acceleration and collider ring. New Muon Collider Physics and Detector Studies have been initiated.

Simulation effort to support the experimental program: MICE, MERIT, and EMMA (non-scaling FFAG) continues. Additional simulation studies include RF breakdown, solid target shock effects, hydrodynamic effects of Hg jets in high magnetic fields, and beam-line design. One deliverable for the MICE experiment is a benchmarking of the code used to model the beam transport and cooling process.

The collaboration funded two new simulation post-doc positions to increase simulation efforts and is looking to fill an NSF-supported post-doc position for MICE.

There is also a simulation effort outside of the collaboration by Muons Inc. and Tech-X.

Findings:

The NFMCC & MCTF simulation activities are closely coordinated. The collaboration uses the term "simulations" very broadly and includes accelerator theory and facility designs. In the presentations there was no clear separation of simulation from concept development or estimates. The committee was shown an overview of recent NF and MC facility-related simulations and a list of near-and long-term simulation plans.

Simulation activities covered three broad categories: neutrino factory facility design (IDS), muon collider facility design and non-facility simulation efforts. The later included simulations of ionization cooling for MICE, magneto-hydrodynamics for MERIT and beam dynamics for EMMA experiments, breakdown in RF cavities, muon collider detector and solid target shock.

There was an active collaboration on simulation with SBIR-supported Muons Inc., Tech X and Particle Beam Lasers Inc. There were two dedicated simulation workshops: PIC/REMEX Workshop at FNAL and Muon Collider Design Workshop at BNL.

Neutrino Factory: NF design work now is taking place under auspices of IDS. The focus was on shorter bunching and a phase rotation channel. This approach seems likely to give similar performance at lower cost compared to present designs. Another study of alternative gas-filled quad cooling channel promises similar performance of the cooling channels with less magnetic field in RF cavities. Other activities on NF include linear lattice designs for linacs and RLAs, longitudinal beam dynamics, arc crossing in dog-bone RLA's, injection chicane lattice, and linear, non-scaling FFAG. Initial design of a muon accelerator was established and the detailed study of injection lattice designs has been initiated.

Muon collider: This year many simulations were focused on muon collider. Three muon collider designs were pursued by the collaboration and Muons Inc. Major design areas were proton driver, high power targets, π-collection, front-end, π-decay, bunching, phase rotation, ionization cooling, muon acceleration, storage and collider ring. Because of limited resources, many design areas remain on a conceptual level and are lacking details or simulation.

Proton Source: This year a focus was on high intensity proton sources for a muon collider. Two new schemes were based on upgrades of the FNAL Project-X linac. Studies showed that the use of the accumulator and debuncher rings with high rep rate can provide 2 MW at 8 GeV. The use of the Main Injector at 56 GeV will provide for 2-6 MW with the use of the Recycler and a new rebunching ring.

Target System: Cavitation was added to hydrodynamics simulations to study instabilities of the mercury jet leaving the nozzle and jet transverse distortion as function of the longitudinal position.

Front end: Extensive simulation work took place in the past year associated with simulating 6D cooling, including modeling of the helical channel in ICOOL and G4BL. A new cooling lattice design tool, MICCD was developed to handle tipped, displaced solenoids. Three schemes – Guggenheim, FOFO-snake and HCC were actively studied. Results of earlier simulations of the HCC scheme were independently confirmed. New schemes for low energy bunch merging were considered. The model for muon scattering and straggling was updated.

Special attention was paid to the breakdown in RF cavities immersed in high magnetic fields. The direction involved computations of beam interactions in gas-filled cavities using Mathematica. Studies include coil location, cavity shape for magnetic insulation, and breakdown simulations using the OOPS code (Tech-X Corp.)

Acceleration: RLA preliminary designs have been developed and the rapid cycling synchrotron option was also considered. A first look was given to strong wake field excitation in ILC-like structures by intense muon beams, beam loading, transverse kicks and emittance growth.

Collider ring: Three new lattice designs has been developed for a muon beam energy of 1.5 TeV, $\beta^* = 1$ cm. They differ in assumed emittances. COSY studies of high-order chromatic effects & corrections have been initiated.

High priority in the near-term, is given to improving the realism of 12-bunch phase rotation simulations, the modeling of vacuum and gas-filled RF cavity breakdown and to the understanding of the upcoming MuCool measurements. The stated priorities for simulation are: 1) to refine design of magnetically-insulated phase rotation and cooling channels, 2) to demonstrate high efficiency in a tapered Guggenheim cooling lattice, 3) to simulate performance of a FOFO-snake cooling lattice, 4) to improve performance of low-β bucked coil cooling lattices and 5) to find practical design for HCC with RF. The final goal is to have all simulations tools necessary for start-to-end simulation of a muon collider.

Comments:

There is a clear need for a significant increase in the simulation effort, both in breadth and depth. 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, but many systems are still at a conceptual level. Collective effects need serious considerations. 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. With the first experiment (MERIT) completed, it is important to demonstrate not only qualitative but also quantitative agreement between simulations and measurements.

The limited simulation resources need to be very well coordinated and focused. At least one muon collider design should be studied in detail.

If the time scale for completion of a muon collider feasibility study is 2012 then more effort is required. This effort must include optimization of acceleration scenarios, stability of accelerated beams, collective effects, 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. Use of external collaborators, such as Tech X, for intensive computer simulation should be encouraged.

The committee strongly supports and encourages the continued exploration of muon collider schemes.

Recommendation

1) **The committee strongly supports significantly increasing the manpower and scope of simulations studies. It also emphasizes the need for well coordinated efforts with focus on the bench-marking of the key process and cross-checking of the codes. Leveraging resources within the MCCC and UKNF collaborations, and Muons Inc., and Tech X to increase the manpower directed towards simulations of the acceleration system and storage ring is critical.**

2) **Parametric studies should be carried out to explore various scenarios of muon colliders leading to an optimal choice of accelerator type for each stage of a muon collider.**

3) **Significant simulation will be required to more accurately evaluate the performance of the chosen muon collider scheme. Phenomena in need of study includes wake-field and space-charge effects, and simulations of the matching sections, etc. The simulation effort should lead ultimately to self-consistent start-to-end simulations of the entire complex.**

4) **The committee recommends the collaboration aggressively pursue code development for full-blown simulation of key components with a clear plan of bench-marking codes with planned experiments. Recent results from MERIT should be used as the test bed for such bench-marking.**

CHARGE 1 e) ***Review and comment on goals, strategy, and progress in the Muon Collider design and technology development programs.***

Comments:

Muon collider studies are on the threshold of a very exciting period. The emphasis over the past few years has been on neutrino factories. The present outlook of extending the energy frontier beyond the ILC or instead of ILC in a cost-effective way has sparked increase interest in muon colliders. The collaboration has stated the goal of producing a feasibility study for a MC by 2012. This is an ambitious goal given the financial, technical, and human resources presently available. An outline of a plan was presented to reach this goal. It is clear the details of this plan will take some time to develop. This effort will require coordination with MCTF to maximize the resources.

The ongoing Muon Collider design and technology development programs have made significant progress. Several 6D cooling schemes are being considered. There is a promising effort in MCTF to experimentally demonstrate 6D cooling using the helical cooling channel as the first test case. There several other schemes under study such as the Guggenheim channel, etc. Given the limited resources, it is critical that a process for down-selecting these options be developed for inclusion in a feasibility study. All of these schemes depend of the achievable RF accelerating gradient in a magnetic field.

The cooling schemes to reduce the emittance to acceptable levels for the muon collider require very high field solenoids. Since performance increases with field, solenoids up to 50 T are under discussion. The muon collider would greatly benefit from a broad coordinated national program to develop HTS technology to achieve high current density at high fields.

Several scenarios were presented for the acceleration stage and steady progress was reported in exploring options. Options under consideration range from rapid-cycling synchrotrons, FFAGs, and RLAs. Each option has its own challenges. It is important that the critical R&D be identified so that a process for selecting among these options can be implemented.

The status of the FFAG demonstration experiment, EMMA, was presented. The results of this effort will help guide the technology choice for acceleration. This experiment is dependent on the ERL prototype, ALICE, as an injector. Unfortunately, ALICE is in danger of cancellation which would effectively stop EMMA. The committee recognizes the value of the EMMA experiments to the MC and recommends that efforts be made to persuade funding authorities to continue support.

Very little was heard on the design of the collider ring. In particular, the committee did not hear any reports on MC detector studies, particularly of the machine-detector interface which will be challenging because of the backgrounds from decaying muons. A MC feasibility study will have to address this issue.

Recommendations:

1) Develop a detailed plan to reach the goal of a MC feasibility study by 2012 for presentation to the MUTAC in 2009.

2) Develop tools to narrow the options for a MC. This includes a parametric optimization of the entire muon collider facility in terms of cost and performance, particularly the acceleration section, 6D cooling, and decay ring.

3) The MC will require high field solenoids. We strongly endorse the formation of new DOE technology effort to promote the development of HTS for high field applications.

4) Reassess the feasibility of a MC detector and incorporate detector issues into the optimization of the decay ring.

Charge Point 2: Review and give advice on the R&D plans and corresponding budgets for FY08 and directions for FY09.

<u>Findings:</u>

The NFMCC R&D plan for FY08 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.

The FY08 budget continues the long standing position of flat-flat funding at the level of $3.8M (comprising $2.1M DoE-Base plus $1.7M DoE-NFMCC). The $1.7M allocation is added to $1M NSF funding and salary support from national labs, with $575k attributed directly to MICE. Muons, Inc. continues to have great success in obtaining SBIR grants, providing valuable resources that target specific areas for both NFMCC and MCTF. To deliver the MC feasibility study by 2012, the collaboration argued that funding needs to be increased from $8M total (including FNAL core funding for MCTF activities) in FY08 to about $25M in FY12. A breakdown of funding allocations was shown for all NFMCC and MCTF activities, however these are only estimates at this stage. For the NFMCC allocation, it was not shown how much was being attributed explicitly for NF activities.

Based on overall NFMCC budget guidance from DOE, yearly budget requests are made by R&D program priorities rather than "institutional commitments". The Project Manager subsequently negotiates deliverable milestones with each institution, consistent with R&D plans. Audit reports for each activity are generated at year end and a detailed report issued to DoE and MCOG at the annual MUTAC review meeting.

NFMCC R&D priorities for FY08-09 include:

- Cooling channel component development at MUCOOL (FNAL) and MICE (RAL):
    - Continue 201MHz cavity testing with magnetic field
    - Test gas-filled cavity with beam at MTA (MCTF)
    - Begin MICE beam commissioning
- Targetry at MERIT (CERN, BNL and ORNL):
    - Decommission MERIT and publish results
- System studies and simulations:
    - Participate in IDS-NF
    - Continue collider studies with MCTF
    - Muon Collider feasibility study by 2012

- Participation in the design of EMMA, the electron model for a non scaling FFAG

In FY08, additional NFMCC support is needed in these areas:
a) Completing hardware commitments to international experiments (mainly MICE). Currently, there is a plan to honor commitments, but delivery may be ~1-year late. The collaboration has stated that their only contingency is schedule delay.
b) Restoring simulation effort for IDS-NF, MICE analysis, EMMA design and MCTF work.
c) Provide common funds for the MICE experiment (estimate ~$150k this year).

MCTF R&D priorities for FY08 include:

- Build and test a viable Helical Cooling Channel
- Continue HCC simulations with realistic engineering constraints and optimize RF integration
- Build and test HCC RF 4 Coil
- Test Muons Inc HPRF cavity in MUCOOL, next step being with magnetic field.
- Complete beamline for HPRF test ($300k)
- Continue HTS conductor development
- Assess viability of 'dipole-first' collider ring design, w.r.t detector backgrounds
- FY08 budget must meet travel needs for MICE

A combined NFMCC-MCTF 5-year R&D plan is being prepared for August 2008 and provisional cost estimates for this R&D were presented to HEPAP's P5 subcommittee. Resources to execute this program are in short supply. Strong support from P5 will be required to ensure that feasibility studies can be completed by 2012.

<u>Comments:</u>

There appears to be effective management of NFMCC and MCTF activities such that overlap and/or duplication is currently being avoided. However with significant funding increases anticipated, it becomes imperative that closer integration and coordination occur between NFMCC and MCTF. This will also be need to coherently complete the 5-year plan by August 2008 and the feasibility study by 2012. If achieved, this should ensure a more focused effort and target those tasks which are synergetic with the Neutrino Factory IDS program.

The committee remains concerned that staff is being eroded due to lack of funding, this is particularly evident at BNL. There are currently only 3-4 post-docs actively working on NFMCC activities. This shortfall needs to be addressed. Organizational issues in the UK at STFC have also affected MICE hardware procurement and staffing. The committee applauds first beam delivery into the MICE experimental hall. Clearly there is still a lot of installation work to be done to achieve Phase I tests with the first solenoid and emittance tracker in September 2008. Phase II tests of the complete MICE configuration is expected Q4 2010.

The committee welcomed the fact that the coupling coil fabrication is now underway with ICST Harbin, for both the MUCOOL RF cavity tests (early 2009) and also the MICE module integration (mid 2009). The cavity tests are fundamentally required in order to validate the RF module design for the MICE experiment and so must remain very high priority for the collaboration. The original 5-year R&D plan shows significant increase in MICE funding from $700k in FY08 to $1280k in FY10. The funding profile for MICE hardware delivery under these presented circumstances, does not quite meet what is required in FY08/09 to match the overall MICE phase-II delivery plan, as an additional $300K would be needed. The consequence being that hardware procurement is expected to slip into FY09/10 to account for this funding deficit in FY08/09. Anticipated results from MICE look precariously late already, compared to when the feasibility study is required in 2012 and so this is of major concern to the committee. It is not clear whether additional funding prioritization for MICE is either possible, or could expedite US hardware delivery to better match the 2012 milestone date.

With the successful completion of the MERIT experiment, analyzing the data and decommissioning the experiment at CERN are clear priorities, however on the basis of what was presented, the committee is not convinced that continuing R&D with the equipment at ORNL is NFMCC's best use of available resources and question whether these funds could be utilized more effectively elsewhere, i.e. for MICE.

As was reported at the previous MUTAC review, R&D progress is being hampered by the flat budget profiles both for procuring hardware and maintaining staff. The reduced number of post-docs is a concern and avenues to addressing this issue should be pursued. The P5 response will hopefully assist this problem directly if ramped up funding is approved for a MC feasibility study.

Recommendations:

1) To organize and complete the 2012 feasibility study, NFMCC and MCTF must become more tightly coordinated, in order to optimally manage the resources available across the national labs, its integration with international experiments and the US participation for the neutrino factory IDS.

2) A detailed costing breakdown of the 5-year plan and its activities is requested before the next MUTAC review, to ensure that task priorities are effectively matched to meet both international commitments and feasibility study deliverables by 2012.

Charge Point 3: *Offer comments/advice as appropriate, on longer range strategies for the NFMCC and MCTF.*

Findings:

Both organizations, the NFMCC and MCTF, are in the process of outlining the R&D goals for the future. A 5-year plan is being assembled to provide a roadmap for the R&D with the goals of completing a MC Feasibility Study, and a NF Reference Design Report in the 2012 timeframe. The NFMCC/MCTF recognizes the need for increased resources to accomplish these goals, and has prepared a notional funding profile, which grows to approximately $25M in combined R&D funds by FY 2012.

Comments

The time frame 2012-2013 is emerging as a critical period for MC and NF studies. With LHC results pointing toward the required energy scale for the next lepton collider, and with clarification on the ILC and CLIC programs, it will be a natural timeframe for the community to consider all the viable options for extending the energy frontier in the lepton sector. The muon collider development needs to have reached the level of feasibility determination in order to be considered at this critical juncture. The committee endorses and encourages the MCTF and NFMCC plan to establish the muon collider as a credible and viable option for a lepton collider by 2013 with the completion and publication of a feasibility study.

Likewise, in 2012 critical results in the neutrino sector should be in hand from the next generation reactor and accelerator-based experimental programs. The neutrino factory studies are envisioned to proceed to a Reference Design Report in the same time frame. The committee endorses and encourages the international plans to produce an RDR to establish the cost range and performance of a neutrino factory.

To achieve this increased level of understanding and realism by 2012 will require an increase in funding and manpower beyond the present level of support. The committee agrees with the assessment that a substantial increase in resources will be required to enable this level of detailed study within the required time frame but awaits a plan with detailed justification for the requested increase.

The committee notes with pleasure the appearance “at the table” of the muon-related activities at the recent P5 meetings.

The committee fully endorses the plan to reformulate a 5-year plan to identify, enumerate and prioritize the required R&D tasks in order to be in a position to prepare a Zeroth order Design Report (ZDR) by 2012 for the MC, and an RDR for the NF. The committee considers this to be an essential step that must be completed in a timely manner. Given that MCTF and NFMCC resources are shared amongst these tasks, the committee feels that it is very important for this plan to truly be a fully-integrated joint-effort between the MCTF and NFMCC in order to maximize productivity.

One aspect of the five year plan should be an evaluation of the various potential physics scenarios, circa 2012, to establish the energy and luminosity requirements for a muon collider in order to focus the design and optimization effort.

Regarding the elements of the R&D plan, the question of the sufficiency of the three major hardware demonstration programs, MERIT for targetry, MICE for ionization cooling and EMMA for non-scaling FFAG dynamics, must be addressed. Do these three efforts constitute a sufficient set of major sub-system demonstration activities needed to produce an RDR and cost estimate to 50%, and to demonstrate feasibility of a muon collider? The committee feels that a necessary step in demonstrating the viability of a muon collider will be a 6-D cooling demonstration. While it is obviously too early to select a cooling technique and specify a demonstration experiment, it should be possible within the timeframe of the 5-year plan to begin planning for a demonstration experiment.

Now that beam into the MTA is imminent, it is important to enumerate the beam experiments and utilization in the 5-year plan.

The R&D activities that will be pursued over the next 5 years offer tremendous opportunities for training accelerator physicists. The committee encourages continued pursuance of opportunities to make use of graduate students and post-docs in this effort.

Recommendations

1) The committee recommends that the 5-year plan be a fully-integrated, joint effort, to capture and enumerate the full scope of R&D plans for both NFMCC and MCTF activities.

2) The committee recommends that the 5-year plan include the initiation of planning for a 6-D cooling demonstration experiment.

3) Consider in the 5-year plan the evaluation of the various physics scenarios, circa 2012, to establish requirements for energy and luminosity of a MC and to help narrow the range of parameters.

UK, Japan, and other international issues

Findings:

The international effort on R&D for future neutrino factories and muon colliders appears to be working well and the organization has made important progress in several key areas associated with the MUCOOL, MICE, MERIT, and EMMA projects. In the UK, special emphasis has been put on the R&D for a neutrino factory with good support from their funding agencies. In Japan, besides participating in MUCOOL and MICE, the groups have concentrated on building and operating FFAG prototypes that could be important for both neutrino factories and muon colliders. Due to funding pressures from a broad range of other projects in Japan, the expected funding for MUCOOL and MICE has been eliminated and will force the Japanese groups to seek other funding to complete their responsibilities. In Europe, there has been strong support for doing neutrino factory R&D and studies but little encouragement for muon colliders. Europe is committed to providing five lead people and 21 man-years of effort starting in 2008 for the 4-year international neutrino factory design study (IDS - See below.)

Under joint leadership from Europe, the US and Japan, an International Scoping Study (ISS) was completed and has laid out the physics capabilities for a neutrino oscillation program including long base line superbeam, beta-beam, and neutrino factory experiments. A key accomplishment of the study was the development of baseline design for a neutrino factory complex. An International Design Study (IDS) is to follow on as the next step, with the goal to produce a "Reference Design Report" (RDR) for the neutrino factory by 2012. The RDR is conceived as a document that will allow "decision makers" to consider initiating a neutrino factory project. The IDS will therefore differ from the ISS in that the emphasis will increasingly be placed on engineering in order to demonstrate the technical feasibility of the various systems and to allow a cost evaluation of the facility at the 30% to 50% level. A key component of the IDS will be the results from the various ongoing experiments, MUCOOL, MICE, and MERIT.

Comments:

The US should continue the strong connections with the international community on neutrino factory research. Expanding these connections to include muon collider R&D and studies is an important step to pursue in the future.

Recommendations: None

Appendix 1:

MUTAC Committee:

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