MUTAC Committee Report
Review April 6-8, 2009
Fermilab

Charge

1. ***Review the progress of the last year***
2. ***Evaluate the five year plan***

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<u>Organization of this report:</u>

We start with an Overview and Executive Summary section. Next we comment on the Physics case for Neutrino Factories and Muon Colliders. In the remainder of the report we comment on all of the major components of the NFMCC and MCTF activities. 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 Europe and Japan. The membership of the MUTAC review committee is attached as an Appendix. The agenda for the review and links to the presentations can be found at http://www.cap.bnl.gov/mumu/conf/MUTAC-090406/

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. Ongoing analysis of MERIT measurements will help to benchmark hydrodynamics codes used to predict the behavior of the mercury jet. The MICE civil engineering is nearly complete and the beam line construction is done. The proton target has been tested and operated in a parasitic mode with ISIS. There is substantial progress in the fabrication of the seven new solenoidal magnets for the MICE beam line. Prototype coupling coils have been wound and welded and tests are planned for later this month. It is anticipated that fabrication of the first coil will begin at the completion of the prototype test. The coils will be commissioned in the next year. The MuCool R&D program has made significant progress with first beam in the MTA. RF breakdown tests indicate that surface field breakdown limits increase with gas pressure. The committee endorses the plan to do high pressure RF beam tests as soon as possible. Tests of a 201MHz cavity in the magnetic fringe field show strong dependence of limiting surface electric field on magnetic field. The committee agrees that it is essential to test cavity performance in the full field of the coupling coil as soon as it is available.

The committee is pleased with the proposal to improve coordination with Project X at FNAL. There has also been significant progress in simulation of various subsystems and design of collider optics. Results of simulations of the three alternative cooling schemes were presented. The collaboration has set itself the goal of a Neutrino Factory Reference Design Report by 2012 in the context of the IDS, and a Muon Collider Feasibility Study by 2013. The technology demonstrations and machine simulations collectively are intended to demonstrate machine feasibility and to guide the design effort.

The committee endorses the 5 year integrated NFMCC and MCTF R&D plan with stated goal of a Neutrino Factory Reference Design Report in 2012 and a feasibility report for the Muon Collider in 2013. In addition to the existing commitments, notably a NF-RDR, the plan delivers: MC performance requirements based on physics, a first end-to-end MC simulation, critical component development and testing, and a first MC cost estimate. The collaboration estimates that a factor of three increase in resources will be required to meet their stated goals and the committee believes such an increase to be essential to meet those goals. The laboratories have stated that they are prepared to commit only half of the required number of engineers and scientists. The remainder is expected to come from universities and SBIRs. It is not clear to the committee that the required expertise can be made available on the appropriate time scale. 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 as presented included a date for a decision on the cooling technology that depended on the outcome of RF tests. The 5 yr plan should also include milestones and mechanisms to down-select technology and design options. In particular, the collaboration should create a figure of merit for accelerating gradient/magnetic field combination and a target that defines success. The five year plan includes an ambitious magnet R&D program and collaboration with magnet R&D efforts outside of high energy physics. The collaboration should determine minimum requirements for cooling channel solenoids, rather than an open ended, more is better, strategy. In addition to specific technical milestones, the committee recommends some prioritization of the list of magnet R&D projects in the plan. 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.

Recommendations:

The five year plan should include:

1. Milestones (i.e. figure of merit for gradient/B-field, B-field for cooling channel magnets, B-field for downstream cooling solenoids, etc.) and target values for each milestone that when achieved define success,

2. Mechanism for down selecting among technology choices,

3. Decision on a baseline design to be developed for the muon collider feasibility study should be made as early as possible. The committee is concerned that the three years allowed may be inadequate to complete a defensible study.

a) <u>The Physics Case and Context:</u>

Findings:

The committee was again shown the strong physics cases for a neutrino factory and a muon collider, and was told that not much has changed in the past year. The current situation shows all data consistent with the Standard Model, but the picture is incomplete with regard to: dark matter, dark energy, neutrino masses and mixing, and baryon asymmetry. In addition, there are experimental hints of cracks in the SM including, for example, differences between direct and indirect bounds on the Higgs mass as well as a 3 sigma disagreement between theory and the observed experimental value of g-2 for the muon. And there remain theoretical questions on the origin of mass, gauge unification (which may imply new interactions), and gravity (which may imply strings and extra dimensions.)

A physics program based on three major accelerator stages was described to the committee. It starts with an intense proton source for an experiment such as one searching for muon to electron conversion. The second stage is a neutrino factory, initially with a low energy configuration (based on 4 GeV muons) followed by a high energy configuration (25 GeV muons.) The third stage is a muon collider with center-of-mass energy of 1.5 or 4 TeV.

Results from already planned neutrino experiments (especially with respect to measurement of, or limit on, the mixing angle θ_{13}) and from the LHC are needed to inform decisions on a neutrino factory and a lepton collider. The committee was shown that a neutrino factory based on 25 GeV muons and/or a muon collider providing up to 4 TeV in the center-of-mass could fit under the Fermilab site.

Some issues related to neutrino physics include: the mass hierarchy, their Majorana or Dirac identity, and measurements of three-neutrino mixing parameters: θ_{12} , θ_{23} , θ_{13} , and the CP violating phase δ. Current measurements of mass differences and mixing angles are provided by several experiments including KamLand, K2K, MINOS, SNO, SuperK and Chooz. Soon to be made measurements (with special focus on the mixing angle θ_{13}) will be provided by experiments including Daya Bay, NOνA and T2K. The committee was assured that regardless of the outcome of these experiments that a neutrino factory would almost certainly have a role. If θ_{13} is large ($\sin^2(2\theta_{13}) > 0.005$), a neutrino factory could be used to explore new physics in sub-leading effects, and if it is small, a neutrino factory could provide unchallenged sensitivity that will be needed to disentangle θ_{13}, the mass hierarchy and the CP violation.

The committee was reminded that precise knowledge of the neutrino sector might have wide impact from cosmology to signaling new interactions at scales above, or well above, the TeV scale.

The committee heard that a multi-TeV lepton collider is required for complete characterization of TeV scale physics. The physics potential of a muon collider with center-of-mass energy around 3 TeV and integrated luminosity of 1 ab^{-1} is outstanding, and especially in the event that the LHC reveals SUSY or some new strong dynamics. Narrow s-channel states play an important role in electron-positron colliders, oftentimes as precision measurements of states first observed with hadron beams. If such states are found with the LHC in the multi-TeV region, lepton colliders can play a similar role in precision studies for new physics, and this will set the minimum required luminosity scale.

It was noted that a detailed study of the physics case for a 1.5 to 4 TeV center-of-mass muon collider is needed. The dependence on initial beam characteristics such as polarization and beam energy spread should be considered in addition to the luminosity. Estimates of the viability of equipment in the collision point environment, as well as detector parameters, are needed. It was suggested that only after ten years of running at the LHC, would there be enough information available to make an informed decision on beam energy, polarization, luminosity, etc.

Comments:

For the neutrino factory, the International Study for a Neutrino Factory (ISS-NF) Reference Design Study Report (RSDR) will provide the design paradigm, and an estimate of required resources. Among the lepton collider choices are a muon collider, the ILC and CLIC. At this time, the ILC sets the standard for rigor regarding cost estimates based on complete engineering designs.

A muon collider with 4 TeV in the center-of-mass would be a powerful tool for exploring the energy frontier, but only if it can reliably deliver sufficient integrated luminosity to detectors capable of recording physics-quality data in the intense interaction region environment.

Recommendation:

The committee would like to see a more detailed plan for (or progress on) the proposed MC physics and detector design study.

b) R&D progress achieved since the last review and the status of MC and NF designs including both NFMCC and MCTF activities

Findings:

Significant progress has been made over the last year in the NC and NF design and the critical R&D areas of system simulations, targetry, and muon cooling. In addition a 5-year plan with the goal of demonstrating the feasibility of a MC by 2013 was described to the committee. This plan has been submitted to DOE for approval and funding.

A NF acceleration scenario was presented including a SC linac, 2 RLAs, and an FFAG. Work has restarted on optics for the MC ring with a “dipole first” design showing the most promise.

The MERIT experiment has come to a satisfying conclusion. The successful completion of this experiment, including data analysis, simulation, and decommissioning is something of which the entire collaboration should be proud. It reflects the level of commitment and leadership of the NFMCC.

In muon cooling, there has been progress on several fronts. The fabrication of the RF Coupling Coil in collaboration with Harbin ICST is well underway, with a complete design and a prototype ready for testing. Although the delivery date is delayed by about a year, no technical issues are anticipated to affect the schedule. The MICE experiment has made steady progress. However, equipment problems have made coordination with the ISIS schedule a critical issue. There has been substantial progress in the MuCool Test Area (MTA) at FNAL. The development of the RF and cryo-infrastructure will be invaluable for continued R&D progress over the next 5 years. The MTA represents a significant demonstration of support from FNAL to the MC R&D effort. There has been considerable experimental effort on characterizing the limits on RF gradient in the presence of magnetic field. Experiments on the 201 MHz cavity at 3 T fields are awaiting the solenoid from Harbin. The limit on the RF gradient has led to the development of a model for RF breakdown in magnetic fields with several proposed solutions. A substantial effort has begun to simulate the 3 proposed 6-D cooling schemes.

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. The documentation of a comprehensive 5-year plan towards a MC is a significant step towards presenting MC as a realistic option in 2013. Review and approval of this plan by DOE is crucial to achieving this goal. Adhering to this plan will present additional challenges to the NFMCC and MCTF management. Coordination with the Project X team has begun.

The NFMCC and MCTF management have effectively coordinated the R&D program with substantial results and investment in future activities. Limited available resources are addressing the most critical R&D issues.

If the 5-year plan, with stated goal of demonstrating MC feasibility by 2013, is approved and funded, managing the required resources will present a very significant challenge.

Recommendations:

None.

c) MERIT results and targetry plans

Findings:

The MERcury Intense Target (MERIT) experiment at CERN successfully accomplished a ‘proof-of-principle’ test of a 4MW target station suitable for a Neutrino Factory or Muon

Collider source, using a 24-GeV proton beam from the CERN PS incident on a target consisting of a free-standing mercury jet inside a 15 T capture solenoid magnet.

The MERIT experiment also showed that beam pulses up to several hundred micro-seconds can be accepted without degradation of the pion production rate.

Much of the MERIT equipment has now been moved to Oak Ridge, except for the magnet which remains at CERN. During the last year the data from the experiment were analyzed and 3D magneto-hydrodynamic simulation started. These simulation calculations show filament development from cavitations that match the observations quite well. The 3D simulations also show less jet stabilization from the magnetic field than was anticipated from the 2D simulations.

Comments:

Although the proton beam pulse intensity was appropriate for a 4 MW beam, the repetition rate was much lower. Pictures of the Hg jet down-stream of the interaction region with the beam show that the Hg jet reconstitutes itself in less than 20 ms as required for a 50 Hz repetition rate. However, the shape and likely also the jet density does not look very reproducible. An opportunity to measure the jet reproducibility with MERIT was unfortunately missed.

The quality of the 3D magneto-hydrodynamic simulations is very impressive and should be continued to achieve as much benchmarking with the MERIT experiment as possible. This will then form a better basis for the target design work. It may also provide an estimate of the reproducibility of the Hg jet target thickness for 50 Hz operation.

The beam dump for the 4 MW proton beam inside the superconducting capture solenoid is still an unsolved problem. This issue requires prompt attention either within the IDS-NF or the 5-year R&D plan since such a high power beam dump could be a major cost driver for a neutrino factory or muon collider.

Recommendations:

1. Develop a requirement for the pulse-to-pulse reproducibility of the pion production rate and compare with estimates based on the 3D magneto-hydrodynamic simulations.

2. Develop a design for a beam dump of the 4 MW proton beam.

d) MuCool and MTA R&D program

The MuCool Test Area (MTA) is a dedicated facility at the end of the FNAL Linac. The function of the MTA is to perform tests of muon collider technologies. This facility is at the forefront of the 5-year plan of MC feasibility studies and will play a critical role in addressing the most important issues and challenges on the way to having credible components for the MC cooling channel design.

Findings:

The MuCool program does R&D on muon cooling channel components including RF cavities and absorbers. MuCool R&D is carried out in the MuCool Test Area (MTA) located at the end of the Fermilab 400 MeV linac in a shielded vault for dedicated beam tests.

The MuCool Test Area (MTA) will be equipped with RF power transmitters (13 MW at 805 MHz, 4.5 MW at 201 MHz), a superconducting magnet (5 T solenoid), a large coupling coil (under construction), 805 and 201 MHz pillbox cavities, radiation detectors (to be reinstalled), a cryo plant (to be commissioned), and a 400 MeV proton beamline (commissioned).

RF

One of the motivations for the cavity test program is the observed degradation in cavity performance in the presence of strong magnetic fields. Presently a 201 MHz cavity reached 19 MV/m without magnetic field. Initial tests in the fringe field of the Lab G solenoid show some degradation of its performance. Other RF tests at the MTA are focused on a pressurized button cavity with high-pressure hydrogen gas limiting breakdown, where degradation by the magnetic field effect has not been observed.

The delay of the coupling coil construction at Harbin has resulted in a significant delay of the 201 MHz RF cavity tests in a strong realistic magnetic field. The experiments to date have relied on the fringe field of the Lab G solenoid.

There is progress towards a new experiment to test a cavity with high pressure hydrogen gas with a beam as well as modeling of the breakdown processes in HPRF cavities.

Cooling channel

The MCTF has carried out an impressive R&D program of optimizing cooling channels, including the HCC, the Guggnheim and the FOFO snake. There are new HPRF test results with different gases and optical diagnostics.

LiH

There is significant progress with selecting the absorber for ionization cooling. LiH test discs have been engineered and are now the "baseline" for the initial 4D cooling. This is one example whereby an early technology choice has been made to replace liquid hydrogen. The issues to explore are the material properties of LiH, its thermal characteristics with respect to conductivity and stability, and its radiation resistance. The goal of this sub-program is to characterize Hot-Isostatic Pressed LiH. The process promises to yield a material with 98% of the theoretically possible density and best thermal conductivity. Test LiH absorber discs will be fabricated in FY2012 using an existing mold design. Then mechanical properties of final parts will be measured including the density and the hardness. The parts will be chemically tested and X-Rayed to ensure there are no voids. Disks will be also mechanically inspected and coated with a vapor barrier. Production will consist of 30 and 50 cm diameter disks with a sub-set of 2" disks for destructive testing.

MTA reconfiguration work

First beam has been sent along the MTA beamline. The MTA is undergoing a major reconfiguration with expected completion by mid-2009. Installation of LN_2 and LHe transfer line systems is at an advanced stage. Work is underway to raise the equipment to beam height, and to re-route RF power (both the 201 MHz coaxial feeder and the 805 MHz waveguide). The cryo plant is being commissioned, while cryo instrumentation and hook-ups are in progress. New pit shielding wall, and the 805 MHz cavity and detectors will be installed in the near future. Reconfiguration is still on track for completion in 2009.

After completion of these modifications the beam will be delivered to MTA for the HPRF cavity test with beam.

Beamline

All beamline components have been installed and aligned and integration with the Linac control system has started. Beam was successfully transported to the first beam stop upstream of MTA in November 2008.

Recommendations from 2008

The 2008 recommendations of MUTAC have been addresses in full.

R1. 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.

A1. Measurements were performed in the fringe field of the existing magnet and the projected background levels pose no problems for MICE tracking. More realistic data requires the coupling coil. MICE will be mainly running on-crest (8 MV/m), MICE detectors are shielded by the LH2 absorbers (converting electrons to low-energy X-rays), and electrons are deflected away from axis by focusing field.

R2. Pursue a more aggressive program at MTA, taking advantage of its unique facilities to do experiments that complement the MICE program.

A2. 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. MTA has focused its limited resources on the most critical issues: HPRF in beam and vacuum RF in a magnetic field. The LiH absorber program is under way. Further work on the LH2 absorber program requires significant cryo engineering resources currently unavailable for this effort at Fermilab.

Comments:

The MTA carried out an impressive R&D program in the last year with major achievements in RF tests (especially HPRF), MTA reconfiguration and in developing LiH absorber.

The MTA is making very important contributions to the MC and NF R&D programs.

The future plan is very impressive and has very well defined priorities, but still look too diverse.

Recommendations:

1. Select and identify goals for the MTA with a short and well-defined list of target parameters to be reached, and corresponding milestones.

2. Clearly define priorities: for example, prioritize tests of 201 MHz, 805 MHz, HPRF and E x B study with new rectangular cavity.

3. Clearly define MTA's 5-year plan and required resources.

e) Status of the International MICE experiment

Findings:

The international Muon Ionization Cooling Experiment (MICE) at the Rutheford Appelton Laboratory (RAL) in the United Kingdom will design, build, commission and safely operate a realistic section of cooling channel and measure its performance in a variety of modes of operation and beam conditions. It will demonstrate the principle of 4-dimensional transverse ionization cooling of muons allowing the benchmarking of codes used in the simulations of muons through such systems including importantly the stragglers. The program takes place over a series of 6 steps. The final step requires approval of a further bid to STFC which is planned for submission towards the end of 2009. Step I is currently in progress. There is a proposed ISIS shutdown scheduled between August 2010 and April 2011 which is anticipated to come at the conclusion of the stage IV tests with the absorber.

During the past year the installation of all components from the target to the downstream beamline has been completed. On the instrumentation side the beam monitors, trigger/rate scintillators, CKov and B, TOF01, 02 and KL are all in place. TOF2 will be installed in June. Almost all the large civil engineering has been completed. Parasitic running can now take place within an agreed safe window. There has been progress towards achieving the required particle production rate as measured by the linear relation to particle loss (V). 1 V has been achieved for short periods, whereas 10-25V is the required level. At levels up to 500 mV losses no activation of the machine has been measured.

There was a failure of the target mechanism that has been identified and interlocks have been installed to prevent a similar incident. The beam line has been characterized without the decay solenoid. Momentum scans show the detection of pions and protons. Tracker 1 was tested at RAL in a cosmic-ray test stand and Tracker 2 is now installed and will soon be under cosmic test as well. The electron muon ranger prototype has been tested at CERN and the FNAL produced scintillator was delivered to Geneva for integration. The absorber prototype is under test at KEK with delivery to match that of the focus coil.

The RF cavity final design review took place in October 2008. The detailed design is being completed, the first fabrication contracts let, 1/2-shell spinning has started with 5 cavities ordered and with an option for 5 more. The Decay Solenoid, a contribution from PSI, has been installed. Much of the magnet is within the ISIS radiation shielding, which makes repairs difficult. The magnet has achieved maximum stable current to date ~330 A, which may be compared to a nominal operating current of 720 A. Excessive heat leaks into the magnet are believed to have prevented it from reaching full current. This is being addressed and tests will take place after Easter. During the test of the first spectrometer solenoid in the summer of 2008 slow cooling was observed. The shield could not be cooled until the magnet was cooled to 4 K and the magnet then reached 75% of its specification. The second solenoid has been modified to address the cooling issue and testing will take place imminently. The first will be modified and delivered after the second. The focus coil contract was let to Tesla Ltd in the summer of 2008. For the coupling coils the two ICST test coils have been wound and welded and installed in their cryostat vessels. The large prototype coil test will occur in late April 2009. The winding of the MuCool coil will start as soon as testing of the large prototype coil is completed and the contract with industry is signed. The second coil will be delivered to MICE.

Comments:

The committee was impressed with the progress, in particular the realization of extensive experimental runs within the MICE facility, towards the delivery of a suite of solenoids vital to the program. Although these magnets are conventional in nature, the delivery of a series of working SC magnets from differing sources to the collaboration is driving the program in many areas. Driving the early part of the program is the failure of the decay solenoid to achieve nominal operating current. This solenoid is required to complete step I and the committee was concerned that the problems with the solenoid maybe more serious than the assessments indicate. The spectrometer solenoid is the driver on step II and III. The first coupling coil will be delivered to the MTA, where it will be used for 201MHz cavity performance evaluation in magnetic fields expected in the MICE experiments. The committee believes that the MICE level of operation of 3T and 8MV/m with 201 MHz had not been adequately assessed and that without that assessment it is impossible to anticipate the dark current effect on MICE detectors.

The five year plan commits the collaboration to the MICE experiment through Stage VI. Stage VI is a critical step in the demonstration of a realistic cooling channel and keeping to the timescales of delivery will ensure that the program is consistent with the decision process for the neutrino factory IDS and for verifying the direction being pursued for muon cooling. STFC only has a commitment to fund out to stage V. Although the NFMCC and MCTF are minimizing exposure to at risk forward funding by options on major procurements, prompt clarity on intentions from the UK would ensure the most effective allocation of resources.

Phase III could provide expeditious and cost effective assessment of some aspects of 6D cooling.

Recommendations:

1. Assess the performance of the 201 MHz RF in the magnetic field levels specified for MICE in order to verify that dark current levels are acceptable.

2. Recognizing the vital contribution that a timely delivery of MICE step VI will make to both the neutrino factory IDS and a Design Feasibility Study (DFS) for a Muon Collider, this committee recommends that maximum pressure be exerted by the collaboration on UK funding bodies to make a timely decision to fund the entire program to the aspirational timescale.

3. Provide an assessment of the timescales and costs of phase III MICE.

f) Acceleration system progress and plans

Findings:

Over the past year much work has been performed to generate plans for all stages of acceleration, especially in the Neutrino Factory area. A detailed plan is emerging, especially for the initial acceleration stages. The optical properties of the RLAs, including chromatic correction schemes, are evolving very well. The use of a graduated focusing field in the linacs has helped to increase the number of possible passages through the RLAs. Full designs are foreseen for the NF and much of this work may be directly applicable to MC systems as well.

Studies of the potential use of FFAGs for latter stages of acceleration are proceeding well. The use of an FFAG as the final acceleration stage in a Neutrino Factory at 25 GeV has been explored and further refinements continue. This effort is not as far along as for the RLA designs, and FFAGs are an untested technology. However, the EMMA experiment at Daresbury will soon come on line to test the FFAG concept, and the collaboration is engaged in the design of the experiment design and the beam dynamics studies to be carried out.

The final stage of acceleration for a Muon Collider will be very demanding. A presentation was made discussing the use of a synchrotron system which uses an 8 GeV recirculating linac for its acceleration system. This is an extremely challenging approach, and will require much further study and understanding. As the specific details that will be outlined in the Five-Year Plan need to be formalized in the very near future, well-understood acceleration processes will need to be used in the write-up, and on-going investigations will need to have lower priority over the upcoming months.

Recommendations:

1. A master "parameters list" should be developed in order to help keep track of the design status for the 5-year plan. This will also be of use for future committees and new collaborators. A form of "change control" should be implemented to keep track of changes and their impact upon other accelerator systems.

2. A scenario for the final stage of acceleration should be chosen soon and future work should concentrate on its development. A fair amount of effort will be required for a feasible design to emerge.

g) R&D Plans in Context of Available Resources

Findings:

The collaboration is a participant in the International Design Study for a Neutrino Factory (IDS-NF) effort which is expecting to produce a Reference Design Study Report (RDSR) for a neutrino factory including a cost estimate. An interim design report is required in 2010/2011 and a final report in 2012/2013. There will be several siting options and Fermilab will be one of them. On the other hand, the collaboration leads the Muon Collider (MC) effort. It is largely a US effort at this time, although the collaboration is quite open to changing this.

The committee was reminded that it reviewed the 5 year plan before it was presented to P5 and sent to MCOG. The P5 presentation included the vision that this plan is a path to bring the energy frontier back to the US. In December 2008 the plan was submitted to DOE/OHEP. As of this time, the 5 year plan has not been formally reviewed by DOE, and the collaboration is anxiously awaiting the outcome of that review

The committee was told that the 5 year plan is prioritized and thus the funding per year will be one of the considerations that determine how many years are needed to complete the plan.

The 5 year plan includes existing commitments to MICE and the IDS-NF, and it has four additional deliverables: 1) MC performance requirements based on physics; 2) A first end-to-end MC simulation; 3) Critical component development and testing; and 4) A first MC cost estimate.

Down-selection of the RF options is to occur following 2 years of extensive RF R&D. This will then define the baseline cooling option, which will facilitate the building and testing of a short cooling section in years 3-5.

A bottom-up resource estimate and staffing commitments associated with the collaborating laboratories were shown. The difference between the bottom-up and the laboratory resources is identified as "Other" additional resources needed, assumed to be provided by university or SBIR initiatives. Over the 5-year plan FTEs increase from the present level of 37/yr to 48, 79, 81, 86 and 88/yr respectively. Post-plan R&D activities and resources are also identified. The largest staffing increases (in year 2) are to be applied to WBS elements “Design, Simulations, Report” (from 9 to 23FTEs), and “6D Cooling Section & Tests” (from 0 to 12 FTEs.)

The total cost for the 5 year plan is $88.25M, representing an increase of about $58M over the present level of funding (about $6M/yr) for 5 years.

The 5 year plan includes the formation of a team to consider MC backgrounds and radiation issues. This team will have available the work done in 1996 on these same topics.

The committee was given a presentation from Muons Inc. Muons Inc. (partly supported by the DOE/OHEP SBIR-STTR funds) is continuing to make contributions to the neutrino factory and muon collider R&D efforts. These contributions include conceptual development, simulations, and hardware design, fabrication and testing. Over the years, the participation of Muons Inc. has grown to include the support of the G4beamline simulation program, and conceptual design of a helical cooling channel for 6-D cooling. In addition the company has supported R&D for high temperature superconductors (HTS) for high field magnets in collaboration with Florida State University and Fermilab, and RF cavities with pressurized hydrogen gas for muon cooling which are to be beam tested at the MTA (MuCool Test Area) at Fermilab. This company has also supported workshops at Fermilab and JLab, provides leadership in the MANX proposal to Fermilab, and recently has joined the MICE collaboration. Muons Inc. intends to participate in the 5 year plan, if it is approved.

Comments:

It is not clear from the 5 year plan that a suitable prioritization has been performed across all technical solutions being investigated. The collaboration management needs to be selective in directing resources as appropriate. The type of questions to be addressed includes:
1) Where are the “Other” resources coming from?
2) What is being done now to facilitate the rapid staffing increases, in the event that DOE approves the plan?
3) What down-selection criteria for the RF and cooling channel are acceptable in terms of gradient and B-field? These criteria should be identified now, so that immediate resource re-direction can focus on appropriate solutions.

SBIRs continue to make important contributions to the muon collider effort. One example is Muons Inc. which is organizing another Low Emittance Muon Collider (LEMC) workshop in June at Fermilab. (The workshop in June will be the fourth such workshop.)

DOE support for the 5-year plan is imperative if the NFMCC and MCTF are to deliver a NF-RDR in 2012 and a MC-DFS in 2013.

Recommendation:

The 5 year plan needs to be augmented with details showing how the step function increase in FTEs from the "Other" category is to be managed by the collaboration.

h) Progress in design and simulation group and five year plan

Findings:

Many new results, especially in the simulations of various cooling channels were presented and good progress is being made. In particular, a "realistic" Guggenheim simulation was performed, as was requested at the last meeting. Though the phase space reduction was indeed observed in the simulation, the 60x reduction in 6-D phase space (= 2^6) is not as encouraging as had been hoped by the Committee. The "realism" employed was the inclusion of vacuum windows, etc., in the simulation. Once error sources and misalignments are included the realized reduction in phase space density will likely decrease.

The Committee welcomed the recent resumption of studies of the collider optical design. New options in the interaction region design, which appear to be tending toward a "dipole-first" IR arrangement, are very encouraging. Its better chromatic properties and lower amplitude functions will ease tuning of the optics and reduce sensitivities to errors.

Meanwhile, very impressive simulations of the targeting process were shown, as well as simulations of RF breakdown in cavities, which are also progressing well. These simulation efforts are making great strides and will be extremely helpful in the future design of these systems.

The Five-Year Plan describes how the above issues will continue to be addressed leading to the final design of a coherent system. While there is obviously a very strong collaboration between the various laboratories and university groups, as well as industrial partners (in particular, Muons Inc.), the Committee worries about the ability to find the 30+ FTE's required to carry out this part of the mission over the scheduled time period.

Recommendation

As the collaboration's efforts are geared toward increased RF gradients, possible new cooling channel options, etc., a design/simulation of a muon collider using "today's" realistic and obtainable parameters should be performed as a snapshot of what is doable at this time. This will be useful for future reference and will help dictate directions for further work.

i) RF R&D and five year plan

Findings:

Overcoming the gradient limitation in the presence of high B-field is the primary RF R&D activity for both NFMCC and MCTF. Breakdown model simulations are being developed to try and predict E_{acc} vs B-field limitations. Three alternative cavity solutions are being pursued:

1. Use of alternative materials
2. Atomic Layer Deposition
3. Cavities filled with high pressure gas

805 MHz cavity tests have utilized TiN coated Cu and Mo, bare Cu and Mo and W. The best performance has been achieved with TiN coated Cu at LBNL (23 MV/m in 3.5T). Field emission radiation curves are consistent with Fowler-Nordheim theory with visible damage observed on both the button and cavity iris, with clear removal of the TiN coating. The cavity is currently being rebuilt at JLab for further tests.

201 MHz cavity tests with curved a Be window in the presence of a solenoid fringe field achieve 14 MV/m at 0.37T, limited by the quench field of the solenoid. Frequent cavity reconditioning is required following breakdown with B-field at 0T to remove induced emitters. X-ray measurements have been taken to estimate MICE backgrounds.

A box cavity experiment is being prepared to assess E x B dependence and sensitivity. Hardware is under fabrication for tests on MTA.

A High Pressure RF (HPRF) gas filled cavity provides 3 functions:

1. H2 provides ionization
2. Energy lost to ionization is compensated by the RF accelerating field.
3. Suppression of dark current and thus permitting operation at higher B-fields

The HPRF project started with SBIR/STTR funding in 2002 to Muons Inc. For a Helical Cooling Channel (HCC), the E_{acc} required is 10 – 20 MV/m. In tests using an electro-negative gas (H2 + SF6 (0.01%)) gradients of 39 MV/m have been achieved at 325 psia, with good simulation correlation. Inspection revealed sulphur contamination on the Cu surface, which is most likely from the SF6, but is being investigated. Fast diagnostics are required to understand the dynamics of HPRF electrons and a fast spectrometer system is being developed to facilitate this.

The 5-year RF R&D plan was presented, highlighting a 2-year program of activities, before down-selection of an RF solution in year 3. During this 2-year timeframe, the critical tests include: MTA validation of a HPRF 805 MHz cavity with beam and B-field tests of the 201 MHz cavity with a SC coupling coil. Parallel R&D includes box cavity development, HPRF cavity tests at other frequencies, Atomic Layer Deposition (ALD) tests and a series of simulation validation of measured cavity breakdown characteristics.

Comments:

The committee felt that the overall RF R&D plan was consistent to develop an appropriate RF solution to meet the 2013 MC-DFS; however it was not clear that the chosen RF solution could then be implemented into the optimum cooling channel design within the same timescale. Can the RF down-selection process be appreciably expedited?

Having clearly defined RF parameter goals is fundamental for an appropriate RF down-selection to be achieved and the committee suspects a partial down-selection can already be made, based on a minimum defined RF performance specification. This could focus the available resources and potentially reduce the RF R&D period to less than 2 years.

A resource loaded breakdown for the RF R&D plan was not shown and the committee sees this as imperative in order to maximize the effectiveness of the RF down-selection process. There did not appear to be a prioritization applied to available resources and this would be useful to incorporate into the developed plan.

As has been reported in previous MUTAC reviews, the limited availability of the 201 MHz RF source has hampered progress and this last year has restricted the opportunity to pursue the solenoid fringe field cavity tests in the MTA. A more optimum exploitation of the hardware availability could be explored, e.g.. working additional shifts.

The committee was concerned to learn that the QA processes employed to change out the 201 MHz cavity Be windows may not have been appropriate to safeguard particulate contamination of the cavity surfaces. Following the EP processes performed at JLab, the integrity of these surfaces should be protected and the committee proposes that the QA processes be modified as appropriate in order to mitigate any performance degradation in the future. As the fundamental limit and root cause of the preliminary fringe field tests have not yet been determined, extreme care must be taken to ensure RF surface integrity.

Having shown evidence of breakdown at modest gradients and B-fields in the 201 MHz cavities, the committee has concerns that the required nominal performance (16 MV/m at 3.5T) can actually be achieved with these structures if the breakdown events are causing surface damage. The extensive breakdown work already done at SLAC and CERN on NLC and CLIC structures respectively, has shown that surface damage induced breakdown is extremely difficult to process away and ultimately limits gradient performance. As yet there has been no systematic investigation performed on the 201 MHz surfaces to assess whether the observed breakdown events are actually causing surface damage and this must be a critical part of the investigation process.

Progress on the ALD activity looks extremely promising, however it is at an early stage and the committee encourages demonstrated tests of this cavity in a high B-field environment.

Recommendations:

1. Provide a resource loaded RF R&D schedule, highlighting prioritized activities and any potential for expediting the down-selection process.

2. Define a minimum RF specification to expedite the RF down-selection.

3. Modify the employed QA processes to change the 201 MHz Be windows to ensure more appropriate protection of the RF surfaces.

j) Magnet R&D and five year plan

Findings:

The MC relies on a number of magnets that are beyond the state-of-the-art. In particular, there are three families of magnets that require significant R&D:
1) High field solenoids for the final cooling stages with fields of ~50 T
2) Magnets for the HCC cooling channel with fields up to ~15 T
3) Open mid-plane magnets for the collider rings
4) Technical and cost studies will be needed for many of the other MC magnets to optimize the designs including magnets such as fast ramping synchrotron magnets, the pion capture solenoids, etc.

The 5-year plan for magnet development is a large effort requiring roughly 25% of the total NF/MC labor and a larger fraction of the M&S funding. The funding is divided between the four topics discussed above with the largest fraction of the effort directed towards the HCC cooling channel.

The final cooling stage requires high field solenoids to achieve the desired final transverse emittances. It was stated that the MC luminosity will be a linear function of the final cooling channel solenoid field. Solenoids with fields as high as 20 T have been built using HTS but R&D will be need to extend these designs to higher fields with good field quality. High field magnets are required by other fields and the National Academy of Sciences set a goal of 30 T for NMR solenoids.

The goal of the HTS solenoid 5-year plan is to have a complete design and be ready to build a 1-meter >30 T solenoid at the end of the 5 year program. The plan for the HTS solenoids relies on the VHFSMC to develop conductor for fields well beyond what Nb can support. There is a request for $4M of initial funding for two years. Future funding depends on performance of the 1st stage. The VHFSMC plans to design a 30 T magnet with a size suitable for muon cooling. The magnet will not be built – only designed. The program does not have funding for a full scale magnet but this might be done in collaboration with other agencies.

The VHFSMC will first focus on Bi 2212 conductor. However, there is other collaborative work on YBCO tape and, if Bi 2212 does not work, then the effort will switch and work on YBCO.

The HTS collaboration is expected to receive ARRA (American Recovery and Reinvestment Act) funding this year and plans to build a modular HTS test facility that would allow different HTS inserts into a 16 T solenoid. It was noted that parts are being procured although detailed plans were not presented.

The HCC cooling technology requires a complicated magnet with combined solenoid, dipole, and gradient fields. The magnet concept consists of a number of ring coils shifted in the transverse plane such that the coil centers follow the helical beam orbit. The magnet parameters vary along the cooling channel ranging from solenoidal fields of ~7 T to ~17 T.

In 2008, a 4-coil prototype was constructed using NbTi coils. In tests the prototype performed close to expectations. An autopsy showed a number of places for improvement including large voids between coils, bending of the G10 spacers and excess epoxy. A second prototype is planned for FY09. An additional challenge for the HCC magnets is developing concepts for integrating the RF systems which are needed throughout the channel. The 5-year plan includes development of a 1-meter section of the HCC with RF after the RF technology down-select which is expected two years into the 5-year plan.

Comments:

The magnet development program is a large program. It will be important to develop a model for the magnet development versus project performance and cost risk to help optimize the R&D plan and then develop priorities for the different aspects of the magnet R&D program.

The magnet program must support a design that is still changing. In particular, there are multiple cooling approaches with different magnet requirements that are being considered. Developing a program with milestones and decision points will be essential to coordinate the different R&D programs and understand how the magnet R&D program needs to evolve as the NF/MC design evolves. Milestones would include the choice of final cooling stage field, the cooling technology, and the ring magnet design.

The high field solenoids are a critical challenge. The plan to first develop HTS conductor and then to apply the HTS conductor to hybrid magnets seems sound. It would be important to benefit as much as possible from similar programs being pursued in other fields such as the NMR magnets. Understanding the radiation performance of the HTS could be very useful – if the HTS is radiation hard, it could have broad benefits to the NF/MC design. The effort in developing the HTS conductor should examine similar programs around the world to see if additional collaboration is possible.

The modular HTS test facility sounds like a good development. It would be good to hear plans and progress at the next review.

HCC magnets have a range of specifications. The 5-year plan includes development of a 1-meter section of the lowest field portion of the HCC with the integrated RF. Developing concepts for inserting and powering the RF cavities in the HCC could be useful before progressing too far along the prototyping route.

In addition, it is planned to develop a 4-coil prototype of the highest field potion of the HCC using the HTS presumably developed by the VHFSMC. Given the challenges of the HCC and the HTS hybrid solenoids, it would be useful to focus on the HTS solenoid prototypes while developing detailed designs of the high field HCC magnets including the necessary inserts etc. The HCC detailed design may be a necessary element of the cooling channel down-select and should be scheduled accordingly.

The committee did not hear about plans to develop magnets designs for the Guggenheim, the FOFO-snake or the collider ring magnets.

Recommendations:

1. Develop a model for the magnet development program including crucial milestones and decision points.

2. The committee would like to hear plans and progress on the modular HTS test facility at the next review.

<u>k) Five year plan for physics and detector</u>

Findings:

The main reference for the physics performance of the MC is still the 1996 Snowmass design study. Since then there has been significant progress in the accelerator design and detector technologies. Furthermore, the physics landscape has changed with additional measurements and better understanding of the expected LHC performance.

The 5-year plan describes a broad study to understand the physics program that can withstand the physics environment and is relevant after 10 years of LHC operation. It was stated that detector studies should proceed in parallel with the accelerator development. The 5-year plan presentation listed 7 goals including updating the physics case and developing the detector and Machine Detector Interface (MDI) designs. Particular emphasis would be focused on understand the backgrounds in a MC which are a serious technical challenge and the MDI would be designed to prevent these from spoiling the physics program. It was noted that, given the expected timescales for construction, the LHC will likely have over a decade of data by the time a MC begins operation.

The teams that developed the 1996 Snowmass design have dissipated. The 5-year plan that was presented listed required resources of roughly $1M per year however the required effort off-project was not listed and it was noted that it is hard to find people to engage. The linear collider (LC) detector efforts are investing significant effort into modeling the physics performance and developing LOI's for different detector options. If the timescale for a future linear collider is not as rapid as hoped, there is significant effort that might be more broadly applied to studying the future lepton collider options.

Comments:

The 5-year plan describes a broad study to understand the physics program that can withstand the physics environment and is relevant after 10 years of LHC operation. The goals, constraints and deliverables of the plan were detailed. The case for a MC depends critically on understanding the detector performance. The committee endorses the plan and the deliverables.

The plan would develop a physics case that is competitive with a comparable LC and the physics studies will be used to set minimum performance parameters for the MC. It was noted that it may be hard to engage sufficient effort to fully support the plan. This effort is very important for the MC effort and needs full support from the MC collaboration and the management of the collaborating laboratories.

The plan outlines the goals defining the key physics studies and finding or developing the software platform that will be necessary to perform the studies. These deliverables are very important. Key physics processes should be chosen that highlight the strengths of the muon collider. Collaboration with the linear collider community would be useful and would likely benefit both lepton collider efforts.

The plan described studies that would be performed for a variety of center-of-mass energies and the physics potential should be studied over a broad range of muon collider parameters to develop an optimized set of baseline parameters. While desirable, such a complete study may be difficult to complete with limited resources. Priority should be established in developing the different parameter sets.

The plan noted that a particular challenge for the MC detector may be the hadron calorimetry. The LC detectors have adopted particle flow algorithms to obtain improved energy resolution. It would be important to understand the applicability of the algorithm in the multi-TeV regime and in the particular case of the MC.

Finally, the 5-year plan noted that detector R&D programs need to be started to tackle the most critical R&D and stated that they would explore and exploit synergies with ongoing detector R&D programs. This would strengthen the program and a broader program on future lepton colliders may make it easier to engage the necessary experimental physicists.

Recommendations:

1. Priority should be established in developing the different parameter sets for the muon collider in terms of energy, luminosity, etc. as a starting point for detector R&D.

2. Understand the applicability of particle flow algorithms in the multi-TeV regime and in the particular case of the MC.

3. Explore and exploit synergies with ongoing linear collider detector R&D programs. This would strengthen the program and a broader program on future lepton colliders may make it easier to engage experimental physicists.

l) IDS, Europe, Japan, and other international issues

Findings:

The Committee heard a report that included a discussion of the Japanese program, mostly concerned with neutrino physics (J-PARC) and the on-going investigations into the muon-to-electron conversion experiments, COMET/PRISM/MUSIC, at Osaka. The report also pointed out that at CERN it is currently difficult to get attention for anything that is not LHC related. However, future upgrades at CERN to their injector system are being discussed which may give rise to new opportunities for high intensity programs. Several European studies are going on, with some amount of coordination. For example, EUROnu -- a study of neutrino factories and super-beams, beta-beams, etc. -- has been awarded 4M Euro from Europe, 13.5M Euro overall, to deliver three design reports on the aforementioned topics.

The Five-Year Plan calls for strengthened international cooperation, especially with MICE and Neutrino Factor RDR work. The collaboration is seeking additional international participation for developing the advanced muon accelerator physics and technology concepts.

Recommendation:

The Collaboration should continue to develop stronger ties with the international community, as it plans to do, and particular attention should be paid to the exploration of further connections with Japanese counterparts.

Appendix

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