Executive summary

Charge

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

Organization

- Physics cases for a neutrino factory and muon collider *(Finley)*

a) Overview R&D progress achieved since the last review and the status of MC and NF designs including both NFMCC and MC activities *(Byrd)*
b) MERIT results and targetry plans *(Roser)*
c) MUCOOL and MTA R&D program and plans *(Litvinenko)*
d) Status of the international MICE experiment *(Smith)*
e) Acceleration system progress and plans(Syphers)
f) Progress in Design and simulation group and five year plan*(Syphers)*
g) IDS, Europe, Japan and other international issues *(Syphers)*
h) Five year plan in terms of available resources *(Finley)*
i) RF R&D and five year plan *(McIntosh)*
j) Magnet R&D and five year plan *(Raubenheimer)*
k) Fvie year plan for Physics and Detector *(Raubenheimer)*

The collaboration is to be congratulated for the impressive technical progress in the last year

The physics case for both neutrino factory and muon collider remains strong but fluid in view of the new measurements that will be made on the timescale of these machines

Impressive results from MERIT targeting experiment

- Demonstrate feasibility of 4MW target
- Comparison of MERIT results with modeling codes will eventually extend predictive power

Very significant progress on MICE experiment - an essential demonstration of ionization cooling

- Near completion of civil engineering
- Test of proton target in parasitic operation with ISIS
- Substantial progress in design and fabrication of the seven new solenoids for the MICE beam line

  Prototype coupling coils will be tested this month and fabrication will begin with the completion of that test

Significant progress in the MUCOOL R&D program with first beam in MTA.

- RF breakdown tests indicate high pressure gas effectively reduces breakdown
  Critical test with beam to be performed as soon as MTA is fully credentialed
- Strong dependence of limiting accelerating gradient on magnetic field - tests will continue with availability of first coupling coil

Impressive progress in design and simulation of various subsystems

- Mercury jet hydrodynamics
- Progress in developing simulation of all three cooling schemes
- Design/simulation of collider optics
- Simulation of RF breakdown in magnetic fields

The committee endorses the integrated NFMCC and MCTF 5-year plan with the following goals:

- NF RDR
- muon collider feasibility report which depends on:
  - MC performance requirements based on physics
  - End to end MC simulation
  - Critical component development and testing
  - First cost estimate

The collaboration estimates a factor of 3 increase in people resources is required and the committee agrees

- Laboratories are not prepared to commit the full increment.
  The remainder will come from universities and SBIR initiatives
  - it is not clear to the committee that the expertise is available

We are impressed with the flow of new ideas, but concerned that given limited resources, options must be reduced.

The 5 year plan included a decision date for 6D cooling technology.

Recommendation: The plan should also include

- milestones
  (I.e. figure of merit for gradient/B-field and a target that defines success, B-field for cooling channel magnet and final focusing solenoids, etc.)
- mechanism for down selecting among technology choice
- Decision on a baseline design for study should be made as early as possible. The committee is concerned that three years may be inadequate to complete the study.

The committee agrees that it is essential to involve the larger HEP community to study and determine the physics potential as well as feasibility of the muon collider

Physics Case

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 the 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.)

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

Results from planned neutrino experiments are eagerly awaited, particularly on the value (or a more stringent limit on the value) of the mixing angle q13, and results from the LHC are needed to inform a decision on 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.**

Physics Case

Findings:

Some issues related to neutrino physics include: the mass hierarchy, their Majorana or Dirac identity, and measurements of three-neutrino mixing parameters: q12 , q23 , q13 , and the CP violating phase d. 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 q13) will be provided by experiments including Daya Bay, NOvA and T2K. **The committee was told a neutrino factory has a role whether theta13 is large (meaning sin^2(2theta13) is larger than or equal to about 0.005) or small.** If q13 is large 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 and will be needed to disentangle q13, 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 full coverage of TeV scale physics. The physics potential for a muon collider with center-of-mass energy around 3 TeV and integrated luminosity of 1 ab-1 is outstanding, and it has a particularly strong case for SUSY and 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.

Physics Case

Findings:

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. The specific energy and required luminosity will likely depend on measurements not available until the LHC has run for about ten years.

Physics Case

Comments:

In addition to near-future physics results, decisions by governments on constructing a neutrino factory or a lepton collider will also be based on the best information available at the time for the decision.

For the neutrino factory, **the International Design Study for a Neutrino Factory** (IDS-NF) Reference Design Study Report (RSDR) will provide the design paradigm, and it **will provide 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 could be used to explore the energy frontier. However **in order for a muon collider complex to be a useful physics tool, in addition to the energy, the luminosity would have to be high enough, the detectors would have to be capable of recording physics-quality data, and the reliability of the entire complex would have to be high enough.**

Physics Case

Recommendation:

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

Charge Point 1: Overview of R&D progress achieved since the last MUTAC review, and the status of MC and NF designs including both NFMCC and MCTF activities.

Impressive progress has been made in the areas of

- Designs of NF and MC
  - NF acceleration scenario with SC linac, 2 RLAs, and FFAG
  - Resumption of MC ring lattice design
- Targetry
  - Completion of MERIT
- Muon cooling
  - MICE
  - MTA infrastructure development
  - 6-D Simulations of 3 proposed schemes
  - RF gradient limits in magnetic field
- High field magnets
  - Many new options introduced
- Management
  - Continued coordination of NFMCC and MCTF
  - 5-year plan submitted to DOE for review approval and funding.

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 is approved and funded, adherence to this plan will present significant challenges to reach the goal of demonstrating MC feasibility by 2013.

MERIT results and targetry plans (T. Roser, D. Finley)

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 simulations were 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.

Comments (cont'd):

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.

Recommendation:

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.

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

MUCOOL and MTA R&D program and plan

- **MuCool Test Area (MTA) is a dedicated facility at the end of the Linac built to address MuCool needs.**
- **This facility is on the forefront of the 5-year plan of MC feasibility studies and addresses the most important issues and challenges on the way to have a credible components of the cooling channel for MC.**
- MTA carried out impressive R&D program in last year with major achievements in RF tests (especially HPRF), MTA reconfiguration and in developing LiH absorber.
- MTA clearly moved to the forefront of MC and NF R&D and became a clear leader
- Future program is very impressive, has very well defined priorities, but still look too diverse
- 2008 recommendations of MUTAC had been addresses in full

MUCOOL and MTA R&D program and plan

Recommendations:

- Select and identify goals for the MTA with a short and well-defined list of target parameters to be reached, and corresponding milestones.
- Clearly define priorities: example, prioritize tests of 201 MHz, 805 MHz, HPRF and E x B study with new rectangular cavity.
- Clearly define MTA’s 5-year plan, resources

MICE

- Impressive progress
  - MICE experimental running (parasitic)
  - Civil engineering
  - Instrumentation installation and testing
  - Magnet design and procurement drives the early steps in the programme.
  - Cavity
- Coordination with the ISIS schedule puts constraints on a complex and demanding programme. Moms will be increasingly important in ensuring reactive scheduling.
- Five Year Plan
  - Six step programme matches both Neutrino and Muon programmes.

MICE

- **Recommendations**
- To assess the performance of the 201 MHz RF in the magnetic field levels for MICE to verify the assumption of dark current levels.
- Recognising 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 is exerted by the collaboration on UK funding bodies to make a timely decision to fund the entire programme to the aspirational timescale.
- Provide an assessment of the timescales and costs of a wedge absorber test MICE

Acceleration System

- Findings
  - Much work performed to generate plan for all stages of acceleration, especially in NF; thorough plan emerging especially for initial stages; most of these studies likely will carry over to influence the MC design
  - Optics of RLA’s, including chromatic corrections, are evolving very well
  - FFAG studies, and participation with EMMA, proceeding well
  - Final stage of acceleration for MC being discussed, but needs much more attention
- Five-Year Plan
  - Need to concentrate soon on specific design for 5-yr-plan; will need to use well understood processes;
- Recommendations
  - Develop a master, consistent “parameters list” to help keep track of design status for 5-year plan (and for committees); use form of “change control” to update
  - Choose soon a scenario for the final stage of acceleration for MC and concentrate on its development; this will take quite a bit of effort for a feasible design to emerge.

Design and Simulations

- Findings
  - Many new results, especially in simulation of various cooling channels
  - Good progress with new Collider design options; going toward dipole-first IR design with better chromatic properties
  - Targeting simulations very impressive
  - Good collaboration between labs, universities, and industry (esp. Muons, Inc.)
  - Guggenheim simulation performed, including windows in the system; worry that the 60x reduction in 6-D phase space (= 2^6) is not encouraging enough
  - Simulations of RF breakdown are progressing well
- Five-Year Plan
  - Continues to address above issues; worried about how to find the 30+ FTE's required to carry out this part of the mission
- Recommendations
  - Perform design/simulation using "today's" parameters (rf gradients, etc.) to obtain snapshot of what is obtainable today
  - First-pass sensitivity analyses on various design options are needed in order to assist in the down-selection process, and will be required for the eventual design documentation.

International Issues

- Findings
  - Well connected with MICE, IDS efforts, especially with UK
  - Japan -- mostly neutrino program (J-PARC) and COMET/PRISM/MUSIC at Osaka
  - CERN: hard to get attention for anything “not LHC”
    - opportunities in future, w/ sLHC (injector upgrades part)
    - CNGS, strong involvement from EU in T2K, D-CHOOZ, ...
  - Many EU studies going on, with some amount of coordination
    - EUROnu -- 4M€ for studies of nu fact's and super-beams, beta-beams, etc.
- Five-Year Plan
  - Plan calls for strengthened international cooperation, especially with MICE and NF RDR work; plan will seek additional international participation for developing the advanced muon accelerator physics and technology concepts.
- Recommendations
  - Continue to develop stronger ties with international community; perhaps further explore connections with Japanese counterparts.

RF R&D and 5-Year Plan

- **Gradient limitation in presence of high B-field is primary challenge.**
- 805 MHz tests:
  - coated Cu and Mo, bare Cu and Mo and W
  - 23 MV/m in 3.5T with TiN coated Cu at LBNL
  - Damage observed on both button and iris
    - TiN removed due to breakdown events
- 201 MHz Tests:
  - MTA tests showed 14 MV/m at 0.37T
    - Limited by solenoid quench
- HP gas filled cavity tests:
  - H2 can provide ionisation cooling
  - RF compensates for energy loss
  - Dark current suppression allows operation in high B-field
  - Demonstrated 39 MV/m @ 325 psia of H2 + SF6 (0.01%)
  - Sulphur contamination under investigation
  - Fast diagnostics developed to understand electron dynamics in HPRF
- Other activities:
  - ALD
  - Box cavity (E x B)
  - Simulation validation

RF R&D and 5-Year Plan

- 5-year Plan:
  - 2-year R&D followed by RF downselection process
  - Critical tests will be the 201 MHz test with coupling coil and MTA test of HPRF cavity

- Comments
  - RF R&D plan was consistent to develop an appropriate RF solution to meet the 2013 MC-DFS, but not clear that its implementation into the cooling channel can be achieved within the same timescale.
  - RF parameter goals are fundamental for RF downselection to be achieved and the committee questions whether a partial downselection 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 downselection process.
  - As reported in previous MUTAC reviews, availability of the 201 MHz RF source is limited and this last year has restricted solenoid fringe field tests in the MTA. A more optimum exploitation of the hardware availability could be explored, i.e. working additional shifts.
  - Concerned to learn that the QA processes employed to change out the 201 MHz cavity windows may not have been appropriate to safeguard contamination of the cavity surfaces.
  - Having shown evidence of breakdown at modest gradients and B-fields in the 201 MHz cavities, concerns are that the required nominal performance (16 MV/m at 3.5T) can actually be achieved with these structures if surface damage is occurring.
  - 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.

RF R&D and 5-Year Plan

- Recommendations:

1. To provide a resource loaded RF R&D plan, highlighting prioritized activities and any potential for expediting the downselection process.
2. To define a minimum RF specification to expedite RF downselection.
3. The QA processes employed to change the 201 MHz Be windows to be modified accordingly to ensure appropriate protection of the RF surfaces.

Magnet Program (1)

- Magnet development program is large
  - Important to develop a model for the magnet development versus project risk to help optimize R&D plan and then
  - Develop priorities for the different aspects of the magnet R&D program.
- The design is still changing.
  - 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. These selection milestones should be scheduled as early as possible during the 5-year period.

Magnet Program (2)

- The high field solenoids are a critical challenge.
  - The plan to develop HTS conductor 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. The effort in developing the HTS conductor should examine similar programs around the world.
  - 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 modular HTS test facility sounds good.
  - It would be good to hear plans and progress next at the 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.

Magnet Program (3)

- 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 downselect and should be scheduled accordingly.

Detector Design and MDI (1)

- 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 data.
  - 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.

Detector Design and MDI (2)

- 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 cms 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.

Detector Design and MDI (3)

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

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 2012/2013. **There will be several siting options and Fermilab will be one of them.** On the other hand, the collaboration leads the effort for the muon collider effort and it is largely a US effort at this time, although the collaboration is quite open to changing this.

The committee was reminded 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 start down the path that brings 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 a reply from DOE.**

The committee was told 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 meeting its existing commitments to MICE and the IDS-NF, and it has four additional deliverables: 1) Muon Collider performance requirements based on physics, 2) A first end-to-end MC simulation; 3) Critical component development & 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.

R&D Plans in Context of Available Resources

Findings:

A bottom-up resource estimate has been developed, 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, which are assumed to be provided by university or SBIR initiatives. FTEs over the 5-year plan 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 should they be required. The largest staffing increases identified 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 which represents an increase of about $58M compared to assuming the present level of funding (about $6M/yr) continues for 5 years.

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

The committee was given a presentation on 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 with Florida State University and Fermilab, and RF cavities with pressurized hydrogen gas for muon cooling which are to be tested with beam 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 MICE. 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 include:

R&D Plans in Context of Available Resources

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R&D Plans in Context of Available Resources

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 include:**

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.

R&D Plans in Context of Available Resources

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.