Fermilab Accelerator Advisory Committee Meeting
February 3-4, 2009

Final Report
May 18, 2009

AAC Committee:

Members present: Katherine Harkay (ANL) (acting chair), Ilan Ben-Zvi (BNL), Gunther Geschonke (CERN), Roland Garoby (CERN), Stuart Henderson (ORNL), Kwang-Je Kim (ANL), Katsunobu Oide (KEK), Tor Raubenheimer (SLAC), Jamie Rosenzweig (UCLA), Hans Weise (DESY)
Excused: Swapan Chattopadhyay (Cockcroft Institute) (chair), Hasan Padamsee (Cornell)

Tasks/Assignments:

***Overview*:** K. Harkay (lead), K. Oide
***PX Linac/SRF*:** H. Weise (lead), G. Geschonke
***PX Rings/other*:** S. Henderson (lead), T. Raubenheimer, R. Garoby
***6-D cooling theory/simul.*:** K.-J. Kim (lead), K. Oide
***MANX vs. mu2e*:** I. B-Z. (lead), R. Garoby, G. Geschonke, J. Rosenzweig

Contents:

1. Executive Summary 2
2. Project X 4
   - 2.1 Summary response to charge 4
   - 2.2 Linac 6
     - 2.2.1 ILC/SRF and Project X 6
     - 2.2.2 Cavities 7
     - 2.2.3 Cavity and module testing 7
     - 2.2.4 Cryostats 8
     - 2.2.5 Cavity string and module assembly 8
     - 2.2.6 ß=0.81 cavities 9
     - 2.2.7 SRF materials 9
     - 2.2.8 Project X Linac RD&D plan 9
   - 2.3 MI/Recycler, Transfer Line and Injection, Civil, Controls, Cryogenics, Instrumentation 10
     - 2.3.1 Beam Dynamics 10
     - 2.3.2 Cryogenic Systems 11
     - 2.3.3 Control Systems 11
     - 2.3.4 Beam Instrumentation 11
     - 2.3.5 Summary technical risks 12

3. Muon Cooling 12
   - 3.1 Summary response to charge 12
   - 3.2 HCC 6-D Cooling Theory/Simulation 14
   - 3.3 MANX and Mu2e 15
     - 3.3.1 The MANX Experiment 16
     - 3.3.2 Conclusions 17

Charge 19
Agenda 22

1. Executive Summary

The AAC was convened from February 3-4, 2009 and asked to comment on several topics supporting Fermilab's strategic plan in the post-Tevatron era. About two thirds of the material concerned Project X and about one third concerned muon cooling. The hard work by FNAL staff and collaborators in preparing the scientific and technical talks is much appreciated, as is responding to committee requests for additional material in real time. Supplemental talks requested include: design criteria for alternative PX configurations, NML beam structure, HINS milestones through 2011, beam dynamics calculations plan, stabilization of low-beta linac, Muon 5-year plan schedule details, and MANX demo total cost estimate.

First and foremost, the FNAL staff is to be commended for their dedication and tenacity in carrying the national accelerator-based HEP program. In particular, the AAC commends Steve Holmes and FNAL staff for much progress since the last AAC meeting (May 2008) in developing the Initial Configuration Document (ICD) (31 October 2008) and updated Research, Design and Development (RD&D) plan for Project X (PX) presented at this meeting. It is acknowledged that many of the AAC's prior recommendations have been addressed for PX.

Fermilab is preparing for PX CD-0, anticipated in 2009. Project planning appears to be progressing well, and the focus on the physics mission need and specification of high-level goals is highly commendable and at the appropriate level. Beyond the ICD, investigations of promising alternative configurations (ACD) are in the early stages, too preliminary for comment by the committee. But further studies are strongly encouraged, to include cost and performance analysis. This is particularly stressed in anticipation of the natural trend of rising scope and cost of the PX. This committee is not qualified to comment on the "physics value-matching to cost", but feels obliged to raise concerns and request vigilance in its monitoring.

Project X is a Fermilab-led national collaboration. As such the AAC believes that Fermilab needs to prioritize the R&D program and should require clear reporting and management of critical R&D. The collaboration organization and responsibilities were not entirely clear from the presentations.

Many technical issues are addressed adequately in the RD&D plan. However, the committee recommends increased emphasis on beam dynamics, especially in the ring systems, and system design optimization studies in several areas. Project X will be a large undertaking and will need focused resources. While much progress has been made in the ILC/SRF and HINS programs, a plan for hardware and infrastructure integration with both the ILC/SRF and HINS effort is needed so as to ensure optimum alignment with Project X goals. Although not part of the official charge, defining a plan for integration with Fermilab's electron program at NML is recommended.

The committee was also asked to comment on the MANX proposal, an experimental demonstration of enhanced muon 6-D ionization cooling in a Helical Cooling Channel (HCC). Fermilab has been asked to participate. The committee was asked to address MANX in terms of technical feasibility, schedule, and relationship to mu2e upgrade and the muon 5-year plan. As background, the Muon 5-year plan and Mu2e experiment and plans were described in excellent presentations, and the physics cases are both compelling and scientifically exciting. The MANX proposal was described with enthusiasm and the potential enhancement in cooling, if it can be realized, is significant.

Recent muon cooling developments are far from mature, and the compressed agenda did not allow sufficient time to consider all the details. Firm recommendations would necessitate much more information about the status and proposals concerning alternative schemes. For these reasons, the committee offers only general comments and conclusions on this topic, while advising the laboratory management to encourage the MANX team to further pursue their R&D, particularly emphasizing detailed simulations with realistic system configurations and associated errors and undertaking a comparative analysis of alternatives.

The committee respects the consensus reached by the NFMCC and MCTF in the 5-yr plan, but encourages taking advantage of the momentum generated by the MANX effort. The 6-D cooling scheme that was presented is novel and encouraging. The committee believes more homework is needed to better understand the HCC technology, particularly in specifying the tolerances and optimizing the parameters. More homework is also needed to evaluate its role with respect to mu2e applications and the muon program in general.

The committee expresses sincere appreciation to the FNAL directorate for its hospitality during this review.

2. Project X

2.1 Summary response to charge

Does the ICD describe a configuration that is likely to meet the proposed mission objectives?

Observations

- Focus on mission needs is commendable.
- Mission needs are, in priority order:
  - Long-baseline neutrino oscillation (2 MW proton source at 60-120 GeV)
  - Muon-to-electron (mu2e) conversion (150 kW at 8 GeV)
  - Compatibility with future upgrade to 2-4 MW at 8 GeV
- Project X linac beam parameters has been redefined in ICD to address mission, i.e., decoupled from ILC, as appropriate.
- Revised baseline configurations addresses greater compatibility with mu2e (60 GeV MI and 160 kW mu2e or 120 GeV MI and 225 kW mu2e).
- Alternative config. (ACD) studies have been initiated for future PX power upgrades that are compatible with muon collider beam requirements.

Recommendations

1. The ACD schemes, especially the one with a synchrotron, need further evaluation of the performance and the cost. FNAL recognizes that beam power is limited in this case. Further ACD studies are encouraged.
2. Compare costs of Recycler rf upgrade with adding H- injection region to MI.

What are the primary technical risks associated with the ICD? Are these risks recognized and addressed effectively in the RD&D plan?

Observations

- Project X relies on a new linac system and reuse of the existing Fermilab ring infrastructure.
- Design of the new linac systems has lots of flexibility while PX team will need to design around limitations of the ring systems.
- Important to establish performance limits of the rings using experiments and simulations as soon as possible.
- 325 MHz low-energy linac essential ingredient for PX. Focus on more limited HINS program is well aligned with PX program. Concerns:
  - Slow progress of HINS and dropping of SSR2 leaves gaps in the injector R&D program.

    - Low energy (30 MeV) removes opportunity for important study of beam halo generation.
    - R&D program for triple spoke (TSR) cavities was not discussed.
- Electron cloud expected to be an important effect according to simulations; RD&D experimental program is appropriate.
- Primary elements for SRF/Linac RD&D appear reasonable.
    - 1.3 GHz β=1 cavity systems are relatively well established and national collaboration exists.
    - 1.3 GHz β=0.81 cavities need design effort. Recently started collaboration with Indian institutes needs strong FNAL leadership since cavity modification much more than technology transfer.
    - Need design study to optimize transition from β =0.81 to β =1.
    - Long pulse (up to 2.5 ms) might be an issue for klystrons/modulators.

Recommendations

3. Increased effort on beam dynamics and design studies for the rings is highly recommended in order to evaluate and optimize performance in several key areas; e.g., space charge tune shift, collective effects, and beam loss in rings.
4. The 1.3 GHz β=0.81 cavities require significant design effort, and strong FNAL leadership is recommended.
5. Establish beam instrumentation design requirements based on beam dynamics analyses and accelerator tune-up requirements.
6. Develop a plan to test beam instrumentation *in situ;* explore opportunities elsewhere as needed if this cannot be done locally.
7. For Linac HOM couplers, strongly suggest solving technical issues rather than consider eliminating them.
8. High average power dissipation the challenging issue for the RF input couplers; need a strong team for coupler R&D.
9. Choice of cryogenic segmentation should be carefully evaluated for expense vs. risk and should be based on assessment of world-wide experience in this area.
10. Once PX linac replaces Booster, rf frequency for rings could be reconsidered with respect to cost and electron cloud mitigation (EC accumulation is sensitive to bunch spacing).

Is the RD&D plan appropriately integrated with the ILC, SRF, HINS, and Muon programs?

Comments

- Cavity/cryomodule test requirements and test rates differ between ILC and PX programs. PX cavity gradient (25 MV/m) more modest than ILC; PX can benefit from ILC R&D. Scale of testing plans for PX (at ~400 cavities) should be compared with XFEL project (twice the cavities).

- The role of electron beam R&D within the lab should be clarified with respect to PX, e.g. A0 and New Muon Lab (NML). What are the motivating applications? How does the PX RD&D plan address them?
- Beam tests in NML may be relevant if electron gun can produce PX bunch structure.
- Integration with the Muon program was not evaluated at this time.

Recommendations

11. Present progress of SRF and HINS programs are aggressive and much progress has been made, although progress appears slower than desired. Further delays should be avoided.
12. Hardware and infrastructure development plans for both SRF and HINS should be better aligned with Project X goals. The 325-MHz linac is an essential ingredient to PX. Resources should be allocated by PX management as far as specifications are driven by PX. Extent that HINS program goals differ from PX requirements should be clarified.
13. The cryomodule test should be given the highest priority. CM test rate is an issue: evaluate whether assumed capacity of one module per month is sufficient for PX.
14. Fermilab now has several high-gradient (> 35 MV/m) cavities tested at Jlab and delivered to FNAL. The work to dress these cavities with a He vessel and couplers needs to be accelerated to assemble a second module as soon as possible with these good cavities. This will strengthen FNAL's module assembly capability and improve FNAL's prospects of delivering a 31.5 MV/m module for ILC. It will also be essential to the long-term effort of determining how to achieve the target one-module-per-month rate.
15. Adoption of type-IV ILC cryomodule a good choice for PX β=1 linac to leverage the ILC/SRF program for PX. Major difference is location of quadrupoles. The linac lattice and cryomodule design should be modeled and optimized as soon as possible.

2.2 Linac

2.2.1 ILC/SRF and Project X

The ILC/SRF program's mission is to contribute to the ILC machine design and to further develop the field of superconducting accelerator technology with main emphasis on ß=1 cavities. The detailed plan for Fermilab's SRF infrastructure development was reviewed in the past. The new infrastructure offers a vertical test as well as a horizontal test system and includes the now-completed and commissioned string and cryomodule assembly facilities. This infrastructure and the expertise gained in SRF technology at Fermilab will be available not only for the ILC/SRF program but also for Project X. All future SRF work at Fermilab will strongly profit from the experience with cavity installation and processing but also from the recent assembly of the 3.9 GHz accelerator section consisting of four nine-cell structures, rf input couplers, frequency tuners, etc.

Fermilab's work with the GDE Americas Regional Team to develop the ILC machine design includes participation in the Technical Design Phase and work towards the GDE SRF goals (S0: a cavity gradient of 35 MV/m with good yield; S1: complete cryomodules with an average gradient above 31.5 MV/m; S2: one or more ILC RF units with ILC beam parameters; design improvements for cost reduction). In addition, Fermilab is pursuing a study to host ILC. The work towards the GDE SRF goals is important and is not expected to be compromised by Project X prototyping.

Project X, construction being planned for 2013 to 2017, is going to use the same accelerator technology, although some differences between ILC and Project X modules exist. Project X is aiming for a higher beam current over longer macro pulses (20 mA × 1.25 ms × 5 Hz) at moderate accelerating gradient (25 MV/m). The upgrade path assumes a macro pulse length of 2.5 ms at 10 Hz repetition rate. The strategy with respect to the cold linac is to base the cryomodule development on the ILC program, and to take full profit from the Fermilab's SRF infrastructure. The final goal is a cryomodule assembly and testing rate of one module per month. In total there is need for 38 ILC-like ß=1 cryomodules and possibly another 8 low ß=0.81 modules; the latter depends on the success of the Fermilab – Indian collaboration.

2.2.2 Cavities

For Fermilab it is important to transfer the SRF technology to U.S. industry. The first U.S. cavities were delivered and tested, but improvement in gradient is clearly needed. Even if some first cavities have reached quite acceptable performance for Project X, more cavities need to be produced in order to establish cavity production. This, unfortunately, needs time. A successful cavity program requires on the order of a dozen well-performing cavities. As frequently discussed in the SRF community, e-beam welding during cavity production is one of the main issues. In case the U.S. program proceeds at a slower pace, i.e., new U.S. vendors are not qualified within approximately the next two years, this is an acceptable risk for Project X since European vendors could be seen as a backup. Project X might profit from the forthcoming ordering of 800 XFEL cavities in European industry.

The Project X cavity design differs from the ILC and XFEL cavities with regards to the end groups and the HOM couplers. All changes especially in the end groups require a series of tests. A decoupling from the standard cavity tests might be required, thus additional cavities are needed. The time needed from the final test of a prototype cavity to the ordering of 300 cavities should not be underestimated. The first-series cavities have to be available in 2014, i.e. the call for bids is in less than 3 years. As a first step, reproducibility in surface treatment is a must, i.e. the closed-loop testing started in collaboration with JLAB should be continued.

2.2.3 Cavity and module testing

Fermilab has established the successful operation of vertical and horizontal testing. The test rate and duration is acceptable for the ILC/SRF R&D program; it can be compared with similar activities at KEK and DESY. The qualification of cavities from new vendors should be possible.

Nevertheless, Project X is a different order of magnitude. Plans to further develop SRF infrastructure were mentioned. A horizontal test stand and two more vertical test stands with larger radius to accommodate the Project X spoke resonators are under design. Processing facilities are to be expanded (with industry and JLAB involvement as well as ANL/FNAL). These plans should clearly be compared with the actually planned and ordered XFEL infrastructure at Saclay, Orsay, and DESY. Project X requires 38 + 8 CMs of 8 cavities each, i.e. almost 400 cavities, or 50% of the XFEL project's cavities. Maybe Fermilab can profit from mechanical design work actually done in Europe, e.g. transport frames being part of the test cryostat inserts. Plug-in compatibility might be desirable.

For Project X a yield of 80% at 25 MV/m in the years 2014+ was mentioned; this yield seems to be conservative if not pessimistic. The acceptable gradient spread should be discussed and a minimum gradient be specified. The choice of 25 MV/m seems to be reasonable. If higher gradients are available in 5 years then Project X can profit in terms of higher availability, i.e. 'spares' can be included in the original design / number of components.

The test of completely assembled accelerator modules requires attention. So far no cryomodule test was carried out at Fermilab due to last year's budget cuts. The cryogenic test and the test of the accelerator cavities in the first module are now scheduled for summer 2009. Highest priority should be given to this test. Project X requires changes in the cryomodule design. These necessary changes need a larger number of tests of prototype modules.

The final test rate for the modules is clearly an issue. A comparison with the work done and planned for the XFEL might be useful to align the activities.

Horizontal cavity testing is under discussion. Here the rational for testing should be understood. Are there other reasons than field emission, i.e. a check of the assembly procedure? Is the rf power coupler assembly seen as more risky than the final string assembly?

2.2.4 Cryostats

The work on the type-IV cryomodule is a good basis for the future Project X modules, as it leverages the ILC/SRF program for Project X. One of the major differences is the location of the quadrupole package. Here it should be understood that varying the position along the string may become a challenge with respect to clean assembly (pump and purge during the string assembly is usually done in one well-defined direction) and with respect to mechanical issues. If cryomodule production is to be established at U.S. companies, it would be timely to integrate the prototype production in the project plan. The qualification of a new company, the production of at least one prototype, the assembly and test of such a Project X cryomodule requires approx. two years after the final specification. The first type-IV cryomodule is scheduled for 2011, and the second for 2012; therefore, the first Project X cryomodule could be available in 2014 if no parallel development is foreseen.

A critical question is to what extend U.S. regulations require similar if not additional 'destructive' tests such as the one carried out with the TESLA-like module at DESY last year. Which module type has to be used – the final Project X type cryomodule? If so, one should take this into account in the project plan.

2.2.5 Cavity string and module assembly

There was and still is quite convincing 3.9 GHz assembly work. The final acid test will be the module test after arrival at DESY. The experience gained should be used for further work at Fermilab, and expertise should be integrated wherever it has not yet occurred.

Very important steps in the FNAL SRF program are the cold test of the 'assembly kit' and the complete string and module assembly of the second cryomodule using the existing cavities at

FNAL; both are scheduled for FY09. Again, the assembly and test should be given high priority. The critical issue will be field emission at the design gradient.

Is the assumed capacity of one accelerator module per month sufficient for Project X? To what extent can assembly problems be covered? Do the components arrive just-in-time? Does the plan assume the integration of industrial partners for the assembly?

2.2.6 ß=0.81 cavities

One design option for these cavities is a compressed 'standard' TESLA-style cavity, but the number of cells, HOM couplers, RF input couplers, and possible other design options are under discussion. This requires a full RD&D program, and the design issues should addressed over the next several months. The final solution will have significant impact on the cryostat design so it might become time critical. The recently started collaboration with Indian institutes needs strong leadership and a well-though-out project organization since the cavity modification adds a lot to the 'simple' task of technology transfer.

2.2.7 SRF materials

Impressive work was reported and Fermilab is contributing to generic cavity R&D. Unfortunately, a prediction of cavity performance based on optical inspection is not yet possible and might need quite some more R&D within the SRF community.

R&D on the gradient and yield is important not only for the ILC R&D but also for all other SRF projects. Further studies of the e-beam welds and the heat-affected zone are extremely important; the goal should be to understand the differences between different vendors. According to most of the SRF experts, we are dealing with a welding 'problem' and not with a material problem.

Laser melting and healing could become a repair method for some clearly identified defects in select cavities, i.e. it could be used to rescue some individual cavities. But the yield in gradient is the essential question, and the project needs the result of the first vertical test. Temperature mapping and other more sophisticated diagnostics (second sound) can only be used during the R&D phase.

2.2.8 Project X Linac RD&D plan

The breakdown of primary elements in the Project X Linac RD&D plan looks reasonable, as is the technical strategy as reported. Nevertheless, some comments:

- **Need for HOM couplers:** Go through the exercise, check if the HOM couplers are needed, but as a suggestion: it is better to solve the technical problems than lose flexibility in beam time structure. HOM couplers cannot be added later on.

- **RF couplers:** The average power dissipation is the issue; another might be to identify the RF coupler team developing the necessary Project X coupler. There are some good starting points as referenced in the AAC contribution. .

- **Klystrons/modulators:** The long pulse of up to 2.5 ms (upgrade scenario) might become an issue. The TESLA Multi Beam Klystron was characterized as somewhere between a pulsed and a cw klystron; is 2.5 ms / 10 Hz now quasi cw?

- **325 MHz Linac:** The scope is clear; the 325 MHz part of the linac with its source is an essential ingredient to the Project X. Resources should be allocated by the Project X management team as far as the specifications are driven by Project X. A number of important technical milestones were identified in the past and are still valid; further delays should be avoided. It might be useful to clarify to which extent the goals of the HINS program differ from the requirements of Project X.

2.3 MI/Recycler, Transfer Line and Injection, Civil, Controls, Cryogenics, Instrumentation

The AAC acknowledges that significant progress has been made since the last AAC meeting in May 2008, both in the content of the Project X proposal (ICD) and in the analysis of alternative configurations to better address the future needs (ACD). The operating modes envisaged in the ICD better take into account the capabilities of the recycler and debuncher rings. Preliminary attempts are being made in the context of the ACD to design solutions meeting the characteristics required by a future Muon Collider from the 8GeV - 4 MW proton beam. Although important, the work started for the ACD is not advanced enough and has not been sufficiently explained to be commented by the AAC at this stage.

As a way to reduce the risk associated with accumulating in the recycler, we suggest exploring the benefits of accumulating in the Main Injector for the neutrino program and perhaps accumulating for mu2e in another machine.

2.3.1 Beam Dynamics

The Main Injector and Recycler are existing rings at Fermilab that would be modified to operate with roughly 3 times the present beam current for Project X. It is critical for Project X that the performance of these rings be understood. There are many open questions in regards to beam dynamics in the Recycler and Main Injector, even in the ICD. These include maximum allowable space-charge tune-shift, allowable phase-space painting amplitudes, KV-painting schemes, estimates of conventional instability thresholds, estimates of electron-cloud effects and mitigation, performance of collimation systems, etc.

We urge a dedicated, vigorous effort of beam dynamics evaluation for the Recycler and Main Injectors as an urgent task. This effort should include both an experimental effort to benchmark existing simulation codes and a strong beam dynamics effort to make predictions for the new operating regimes.

We recommend the development of a beam-studies program aimed at exploring, to the extent possible, parameters more typical of those to be encountered in Project X.

In the Project X era, once Linac/Booster operations cease, the choice of RF frequency in the Main Injector is no longer constrained. This opportunity should be used to optimize the overall performance of the future facility, for example, with respect to electron-cloud effects which strongly depend upon the time structure of the beam and especially upon the distance between bunches.

We recommend reconsidering the choice of RF frequency in the MI and RR based on beam dynamics.

With every-other pulse in the linac having a different intensity, there may be other dynamics effects that could influence the beam quality. With the same linac peak current, space-charge in the linac dynamics is identical pulse-to-pulse. The low-level RF system response will be different every other pulse, which can readily be incorporated into the design. There may be other effects worth considering.

Exceedingly small beam loss can be tolerated in the transfer lines. The AAC takes note and finds adequate the work planned to meet that goal and allow for hands-on maintenance.

2.3.2 Cryogenic Systems

The choice of cryogenic segmentation in the superconducting linac is a critical one with far-reaching operational implications. The risk associated with limited segmentation is that the thermal cycling of a large segment may result in cold-leaks. On the other hand, full segmentation is expensive. At one extreme, SNS requires warming up individual cryomodules (which is possible due to the parallel feed system), at a rate of a few per year to gain access to components in the insulating vacuum space. At another extreme, the FLASH accelerating sections are treated as a single continuous cryomodule, which is rarely cycled.

An assessment of world-wide experience in this area is essential in order to make an informed decision.

Cryogenics infrastructure and Civil Engineering will represent a significant part of the cost of Project X. The AAC agrees with the content and schedule of the corresponding activities.

2.3.3 Control Systems

Controls have to smoothly evolve from their present status to first fulfill the needs of Nova and later support the upgraded accelerator complex. The control system for Project X is being developed to be back-ward compatible with the existing CAMAC-based Fermilab control system. Project X will be a large accelerator and care should be taken in the choice of the control system architecture and technology to ensure the desired performance and the ability of external users to collaborate. The plans to test new control system ideas at NML and HINS should be supported. The Committee is satisfied with the foreseen plans for the control system.

2.3.4 Beam Instrumentation

The existence and placement of beam instrumentation must be derived from the beam dynamics simulations and requirements for machine tune-up. One cannot overstate the importance of establishing a high-quality beam for injection into a high-power linac. Beam instrumentation must be incorporated into the front-end design to ensure that the capabilities for transverse and longitudinal matching are there, and that emittances and emittance growth and halo can not only be measured, but used to refine set-points in order to minimize halo and beam loss.

We recommend an approach to beam instrumentation deployment that is based on beam dynamics evaluation and accelerator tune-up requirements. Perform a beam dynamics evaluation to establish the optimum spacing for BPMS, BLMs, profile monitors, emittance measurement etc, keeping in mind the routine tune-up activities that are required at any high intensity linac (trajectory correction, RF setpoint determination, transverse and longitudinal matching).

Instrumentation developed for Project X will require in-beam tests to validate performance. The project should pursue possibilities for beam tests at other institutions, SNS for example, if they cannot be obtained locally.

2.3.5 Summary technical risks

Regarding the charge question, "What are the primary technical risks associated with the ICD? Are these risks recognized and addressed effectively in the RD&D plan?", we see the following primary technical risks:

- Main Injector and Recycler: The three-fold increase in intensity in the Main Injector, and use of the Recycler as a high-throughput, high-intensity accelerator demands very careful consideration of collective effects. There are plans to evaluate collective effects in the RD&D plan.

- Transfer Lines and Injection: The Injection region is arguably the most complicated region in the Project-X complex. Risks include the proper transport and handling of waste beams, achieving sufficient phase-space painting amplitudes to minimize space-charge effects and therefore minimize halo growth.

- Civil Facilities: The risk in Civil construction is primarily related to cost and schedule; we do not see substantial technical risks.

- Cryogenic Facilities: The choice of segmentation is critical. There are risks to the operational efficiency and flexibility of the facility associated with the choice of segmentation. This decision requires very careful consideration.

- Controls: The primary risk relates to the smooth deployment and integration of new control system components with existing legacy systems. The risk is identified and plans are in place to address this.

- Instrumentation: There is technical risk associated with insufficient beam instrumentation deployment, particularly in the longer term era, when multi-MW beams are needed for the linac.

3. Muon Cooling

3.1 Summary response to charge

Observations

- 6-D ionization cooling in a helical solenoid version of a helical cooling channel (HCC) is a novel idea in a very compact configuration.
    - Scheme appears promising, but as other cooling schemes were not discussed, the committee was unable to make a comparative judgement. The magnet part of the HCC concept is relatively advanced, including construction of demo magnets, thanks to SBIR funding (Muons, Inc).
    - Analytical work and system optimization via simulations appears correct without obvious flaws.
- MANX experiment aims to test the 6-D HCC cooling model without resorting to the use of RF (RF acceleration problems are common in all ionization schemes).
- An achievement of a factor of two cooling would be a convincing demonstration of the concept and significantly stimulate the NF/MC R&D program.
- We were told that MANX has the potential to increase the physics reach of the Mu2e experiment.
- In view of the Mu2e timeline, it would be useful for the potential MANX upgrade to be considered.
- The question of the timeline and resources is the most difficult.
    - The cost of MANX was estimated as ~$10M, assuming it is a follow-up to MICE and reuses a significant portion of the equipment. The committee had no basis for evaluating this estimate. A detailed cost and schedule should be prepared, providing the basis for the estimate and including expected funding sources.
    - Both the magnetic channel and RF system need major R&D effort.
    - MANX should consider applying for SBIR/STTR funding for the TOF detectors and magnets.
    - FNAL may consider providing resources for MANX in equipment that may become available from the HEP experiments, as well as limited personnel based on their availability. One possible item, if and when the design is well developed, is to provide the magnets. Another possibility is help with cryogenics.

Recommendations

16. Firm recommendations by the AAC are not possible without a comparison of MANX with alternative schemes. But the laboratory leadership is strongly encouraged to help the MANX team accelerate its R&D effort to establish its critical cost and performance advantages with respect to alternatives as fast as possible, given its significant promise.
17. More homework is needed for MANX and the HCC. We encourage a more detailed simulation effort, on the scale of one year, to better understand the technology, to determine the acceptance and matching tolerances, and to optimize the parameters.
18. We encourage a study, on the scale of one year, of the impact of HCC on the Mu2e upgrade (est. in ~2020.) This is not inconsistent with the decision by the NFMCC/MCTF 5-yr plan to adopt a particular 6-D cooling scheme by ~2013, followed by 5 yrs construction and 2 yrs testing at RAL.

3.2 *HCC 6-D Cooling Theory/Simulation*

A novel, 6D ionization cooling scheme employing the "Helical Cooling Channel" (HCC) was presented during the AAC meeting. The HCC is a very valuable new idea that can be applied in numerous parts of a Muon Collider, as well as in physics experiments (e.g. Mu2e). As other cooling schemes were not discussed, this Committee is not able to make a comparative judgment of the proposed scheme against other schemes. However, the scheme appears to be promising since cooling and emittance exchange occur continuously in HCC.

The magnetic field of HCC is a clever superposition of several different types of magnetic fields – solenoidal field, and helical dipole and helical quadrupole fields. The combined field provides a helical reference orbit, and longitudinal-transverse coupling (thus emittance exchange) and focusing of trajectories around the reference orbit. The direction of the solenoidal field remains constant. By filling the channel with a homogeneous absorbing medium and providing rf acceleration, cooling can occur continuously in 6D phase space. The HCC can therefore be more compact with a larger acceptance compared to other schemes in which the direction of the solenoidal field needs to be reversed periodically and the absorbers are placed in discrete locations. It is claimed that a 6D cooling of 10^{-6} can be achieved in a sequence of three HCC sections of decreasing cross sections (increasing RF frequencies).

The optimization of the system was performed analytically and also with particle-tracking simulation. These analyses look correct without any obvious flaw. However, it may help to understand the system by describing the beam optics with usual linear optical functions such as beta, phase advance, dispersion, and x-y coupling parameters. For instance, the acceptance and the matching tolerance may be more easily discussed with such linear optical functions. Also it will help the optimization of the parameters.

For tracking simulation, it is always important to define the independent variable(s) and the associated canonical variables, otherwise one cannot discuss the emittance. Some notations on the presented slides may have not been clear concerning this point.

The HCC scheme provokes excellent hardware development: Design of the "helical solenoid" (HS) producing an appropriate magnetic field for HCC was presented consisting of a sequence of solenoidal coils whose centers follow a helical path. A concept for an RF cavity fitting within the helical solenoid was also discussed, consisting of wedge-shaped cells. The cavity cross section can be further reduced by using a suitable dielectric lining.

The HCC is not the only 6-D cooling idea. Others include what are called a RFOFO ring or "Guggenheim" cooler. However, thanks for significant SBIR funding (given to Muons, Inc.), the HCC cooling scheme is in a relatively most advanced stage, down to the construction of demo magnets. The HCC theory and simulation effort, as well as the hardware development, may be regarded as one of the particularly successful SBIR programs.

A test experiment, MANX, was proposed aiming for a factor of two reduction in 6-D phase space volume in a 10-m HCC. More details on MANX are described in the next section. The channel would not be equipped with RF since RF acceleration problems inside an absorbing material have not been solved yet—a problem common to all ionization cooling schemes. The Committee supports the proposal in principle; an achievement of a factor of two cooling would be a convincing demonstration of the ionization cooling concept providing a significant stimulation for the neutrino factory/muon collider R&D program.

However, MANX can cost up to $10M. An experimental effort of this magnitude should be fully integrated with the mainstream ionization cooling R&D program coordinated by NFMCC and MCTF. The Committee notes that MANX is currently not in the Muon 5-year plan of NFMCC and MCTF**.** We therefore endorse the Muon 5-year plan to decide on proceeding with experiments after MICE, to take advantage of HCC and other schemes.

3.3 MANX and Mu2e

The Mu2e experiment and the MANX helical cooling experiment have to be seen in the broader context of the FNAL plan for future facilities and the international collaboration pursuing the particle physics and accelerator physics of muon generation, acceleration and cooling.

The Neutrino Factory and Muon Collider Collaboration (NFMCC) and the Muon Collider Task Force (MCTF) are strong, international and productive activities. These collaborations are pursuing a broad and well-managed R&D plan, including design, theory, simulations and component testing.

The Mu2e experiment and the MANX helical cooling experiment were described in a few excellent presentations. Clearly the subjects are scientifically exciting and the material was delivered with passion. The Mu2e physics potential is very impressive. A design is in place based on the proposed (and cancelled) MECO experiment on the AGS at BNL. This design, which is being used for the Mu2e experiment, represents a large investment, and a good use is being made at FNAL of that effort.

Clearly, the benefits to the reach of Mu2e from the beams that may be delivered by Project X are significant. MANX potentially adds even more reach, as we were informed, of about 2 orders of magnitude. That adds to the potential uses of MANX, which thus go beyond its significance as a demonstration of 6-D muon cooling scheme.

The committee was presented with the NFMCC and MCTF's five-year plan, which describes in detail the R&D program for muon accelerators. This plan calls for a NF Reference Design Report (RDR), to be done through participation in the International Neutrino Factory Design Study by 2012. The emphasis of the proposed U.S. participation in this RDR is on: a) design, simulation and cost estimates for those parts of the NF front-end that are (or could be) in common with a MC; b) develop overall system design and staging scenarios; and c) address siting issues.

The five-year plan also calls for a MC Design Feasibility Study Report (DFSR) to be completed in 2013. The DFSR is aimed at a multi-TeV MC including a physics and detector study, an end-to-end simulation of the MC accelerator complex using demonstrated or expected technologies, a cost estimate, and an identification of further needed R&D.

In particular we note that the five-year plan calls for hardware development, needed for cooling down-selection and the completion of MICE. Other work is associated with RF (considered the most critical item, attaining high RF gradient in strong magnetic fields), magnets, absorbers and target.

3.3.1 The MANX Experiment

The Helical-Cooling Channel, of which MANX is a proposed demonstration experiment, is one possibility to achieve the required muon cooling. The theoretical studies need to be complemented by experiments. If this were successful, it would be a great step forward towards the feasibility demonstration of a muon collider.

In the context of this Accelerator Advisory Committee it is impossible to review the concept of HCC or appreciate all its implications and limitations. We note that the scheme that was presented has some issues, such as the magnetic channel and the RF system. For the MC, this is a 1.5 GV system, which has to work under adverse conditions. Both magnetic channel and RF system need a major R&D effort.

The MANX experiment's purpose is to design, engineer and build a 10-m section of HCC cooling channel for physics and technology demonstration aimed at a muon collider and/or a neutrino factory. In particular it will test a six-dimensional helical cooling model, aiming for a factor of two reduction in 6-D phase space volume, and investigate the capability and limitations of a helical cooling channel without resorting to the use of RF.

The most cost-effective location of MANX is at RAL, following and on the site of the Muon Ionization Cooling Experiment, MICE. Studies that were presented to the AAC indicate that MANX can fit in the MICE hall, actually in two configurations, an in-line (matched) version and an off-axis version. The off-axis version reduces the cost of the magnets and improves the performance of the experiment.

The questions of the timeline and resources are the most difficult.

Considering first the timeline, there are two issues. One is the completion of MICE, the other is the 5-year plan of the NFMCC and MCTF. First, the MICE experiment is currently expected to be done 2013. Based on observation of past progress and the tasks that remain to be done at this time, this schedule is expected to slip. The second issue is the 5-year plan. The MC collaboration plan is that a 6D cooling experiment should start only at year 5, after a bench test, end-to-end simulations and planning of 6D demo experiment, that is after year 5. Furthermore, due to the various cooling options that exist, the 5-year plan calls for the selection of a baseline 6D channel in year 3. After selection, build and bench test cooling channel section. This is limited by developing confidence, making decisions and limited manpower.

A statement by the 5-year plan developers underscores the last item, limited manpower. The 5-year plan is pushing the envelope of financial and manpower resources, even as it expects a significant growth in funding. This plan does not allow for funding a 6-D cooling experiment at this time.

The cost of MANX, as provided to the AAC, is estimated at $8M + 23 FTE for the matched MANX, or $5.5M + 18 FTE for the off-axis version of MANX. This cost assumes MANX to go into the MICE location and use a significant portion of the MICE equipment. The committee did not receive a detailed schedule for the MANX experiment, showing at what time these resources are needed.

One motivation that the AAC was asked to evaluate was the benefit of MANX to the Mu2e experiment schedule and when does Mu2e need MANX working. The benefit is clear, being the addition of two orders of magnitude to the reach of Mu2e, beyond the large increase provided by Project-X.

We were told that the fastest time possible for Mu2e to start is by 2016. With that, the next stage of using a HCC channel upgrade is at about 2020. Therefore we conclude that a decision resulting by the 5-year plan at about 2013 which adopts a particular 6-D cooling scheme (possibly HCC), followed by five years of construction and perhaps two years or testing at RAL is not inconsistent with the demand for the HCC channel to go into Mu2e by 2020, but is seems tight. One concludes that it is desirable to make progress on MANX during the next five years (taken by the 5-year plan), subject to the availability of resources.

Given that the whole muon program is resource limited, one could take advantage of the SBIR program to move ahead and in parallel to the main program. It is somewhat unfortunate that SBIRs do not lend nicely for cryogenics, which is a large expense item for MANX.

We recommend that the impact of HCC on the Mu2e plan be evaluated within one year**.**

3.3.2 Conclusions

If successfully executed, the MANX experiment can provide a partial validation of the HCC 6-D ionization cooling scheme, based on requirements for a Muon Collider. There is a much more significant cooling needed in parametric ionization cooling (PIC) and reverse emittance exchange (REMEX), of which the committee heard little more than a mention of the name.

An optimum mix of simulations and experimental demonstration to provide validation should include execution of MICE followed by a 6-D cooling scheme with full simulations. Much more homework needs to be done, results and lessons learned from Mice should be taken into account before one can decide if MANX is the right thing to do.

The primary technical risk within the MANX proposal is the high magnetic field with unusual configuration. In particular, the return field of the magnet has to be accommodated. It is appropriately mitigated through the development program, which includes the construction of high field magnets.

New high-resolution TOF counters (<5 psec resolution) are needed, and are being developed, but this represents another risk.

Given the anticipated timelines within the Muon five-year plan and the Mu2e development plan, the appropriate place and schedule for implementation of MANX (assuming MANX is not displaced by a new scheme) are RAL for the location, installation as soon as possible after MICE ends (2013). Equipment should be prepared ahead of time subject to previous remarks about resources.

The AAC was asked also to consider if the MANX resource requirements appear reasonably estimated. The committee has no basis for making this evaluation.

The application aspect of MANX to Mu2e is very appealing. Physics-wise, we heard that “Mu2e might be the only stepping stone between Neutrino physics and muon collider, if NF disappears”. Still, in applying MANX to Mu2e, we are talking about an upgrade of an experiment that has not even started. However, the benefit for the Mu2e experiment is expected be large. There were many decision points on the road and MANX should be carefully considered in the mix.

Simulation of the cooling process is very important. It seems that the programs still need to be significantly improved to include many more physical effects.

The time is right to start thinking what will be a follow-up experiment to MICE. MANX is a fairly well developed 6-D cooling scheme. Given the limited resources as outlined by the 5-year plan, and respecting the consensus reached by NFMCC and MCTF, one solution would be that FNAL considers providing resources for MANX from FNAL in equipment that may become available from the experiments, as well as limited personnel based on their availability. One possible item, when the design is well developed, is to provide the magnets. Another possibility is help with cryogenics. However it goes however beyond the capability of the FNAL AAC to firmly recommend such a solution, which would necessitate much more information about the status and proposals concerning alternative schemes.

MANX should pay attention to the return field path of the magnet and its effect on the field and environment. Another recommendation is, if possible, use wedges, not liquid helium since LHe is not appropriate for the NF/MC application due to the large expected heat load. The MANX collaboration should carry out a detailed comparative study of the on-axis (matched) MANX and the off-axis version. We were led to believe that there are clear advantages to the off-axis approach.

MANX should consider applying for SBIR/STTR funding for the TOF detectors and magnets.

A detailed cost and schedule of MANX should be prepared, providing the basis for the estimate and outlined expected funding sources. The MANX collaboration should identify results from MICE are needed to proceed with a follow-on like MANX, and estimate the likely impact the MANX schedule.

Fermilab Accelerator Advisory Committee
February 3-5, 2009

Charge (Draft Rev. 2)

The Fermilab Accelerator Advisory Committee is asked to look at several activities supporting the Fermilab strategic plan for the post-Tevatron era. The primary topics for review and discussion are:

1. Project X ICD and R&D Plan

An Initial Configuration Document (ICD) has been developed and released for Project X (see http://projectx.fnal.gov). The ICD is based on specific mission objectives that are expected to form the basis for the establishment of a mission need for Project X (CD-0 in the Department of Energy system). The purpose of the ICD is to provide the basis for a preliminary cost range estimate for Project X (required for CD-0), for the refinement of the Research, Design, and Development (RD&D) plan developed early in 2008, and to establish a starting point for consideration of design alternatives.

The Project X RD&D effort is aimed at supporting all activities required to complete a technical, cost, and schedule baseline (CD-2 in the language of DOE) by the end of 2012. The RD&D plan is integrated with R&D programs running in parallel on ILC, SRF Infrastructure, High Intensity Neutrino Source (HINS), and Muon-based Facilities.

The Committee is asked to review and offer comments/recommendations relative to the ICD and the accompanying Project X RD&D plan. In particular we request specific comments and recommendations in the following areas:

- Does the ICD describe a configuration that is likely to meet the proposed mission objectives?
- What are the primary technical risks associated with the ICD? Are these risks recognized and addressed effectively in the RD&D plan?
- Is the RD&D plan appropriately integrated with the ILC, SRF, HINS, and Muon programs?

More generally, we would be happy to receive comments and suggestions from the AAC on how the initial configuration and associated RD&D program could be strengthened.

2. Muon 6-D Cooling Development

A proposal for experimental demonstration of six-dimensional ionization cooling in a Helical Solenoid (HS) version of a Helical Cooling Channel (known as MANX) has been received by Fermilab. This proposal goes beyond the scope of the Muon Ionization Cooling Experiment (MICE) being mounted at RAL, in particular by aiming to demonstrate cooling techniques that would be applicable to muon colliders, neutrino factories, and stopping muon beams. The MANX HS design also serves as a prototype for a stopping muon beam system for an upgrade to the mu2e experiment that could benefit from 1 MW of Project-X beam power.

In parallel, two related developments are in place: First, the Neutrino Factory and Muon Collider Collaboration (NFMCC) and the Muon Collider Task Force (MCTF) have jointly prepared and submitted to the DOE a five year proposal for the U.S. muon program with primary goals of: 1)contributing to the International Design Study for a Neutrino Factory currently being pursued by an international collaboration; and 2)completing a first feasibility study for a Muon Collider operating at an energy above 1 TeV with a luminosity of order 10^{34} $cm^{-2}sec^{-1}$. It is anticipated that the DOE will conduct a formal review of this proposal sometime over the next six months. Second, the laboratory has received a proposal to mount an experiment to search for muon to electron (mu2e) conversions at unprecedented sensitivity utilizing the existing Booster and Antiproton Source.

The Committee is asked to review and offer comments/recommendations relative to the MANX proposal both within the context of the Muon five year proposal and possible upgrades to the mu2e experiment. More specifically we would like the Committee to comment on:

- If successfully executed does the MANX proposal provide a validation of 6-D ionization cooling, based on requirements for a Muon Collider. What does the Committee view as the optimum mix of simulations and experimental demonstration required to provide such validations?
- If successfully executed does the MANX proposal provide a validation of an upgrade of the mu2e experiment based on a collection scheme that reduces "flash" deadtime and the use of the ionization-cooling energy-absorber to range out hadronic backgrounds? What does the Committee view as the optimum mix of simulations and experimental demonstration required to provide such validations?
- What are the primary technical risks within the MANX proposal and are they appropriately mitigated through the development period?

- Given the anticipated timelines within the Muon five year proposal and the mu2e development plan, what is the appropriate schedule for implementation of MANX, either at Fermilab or at RAL?
- Do the MANX resource requirements appear reasonably estimated?
- Can the MANX approach to a mu2e upgrade impact the outlook for Project X?

As usual the committee is invited to issue comments or suggestions on any aspect of the programs discussed beyond those specifically included in this charge. It is requested that a concise report responsive to this charge be forwarded to the Fermilab Director by April 1, 2009. Thank you.

Fermilab Accelerator Advisory Committee

Agenda

Feb 3-5, 2008
Comitium, Wilson Hall 2SE
Revision 12-Jan-2009

Tuesday, February 3

8:30-9:00	Committee Executive Session	K. Harkay
9:00-9:20	Welcome, Meeting Context, and Presentation of Charge	S. Holmes

Project X (Session organized by Sergei Nagaitsev and Steve Holmes)
Overview of the ICD and RD&D Plan

9:20-9:50	Overview of the ICD	P. Derwent
9:50-10:20	Overview of the RD&D Plan Including evolving thought on operating scenarios and design alternatives	S. Nagaitsev
10:20-10:45	Break	
10:45-11:10	Overview of the ILC and SRF programs With emphasis on PX components	S. Mishra

RD&D Plan

This set of talks should cover the elements of the RD&D plan:
- *Description of the scope of the system*
- *Performance specification of the system*
- *Primary technical issues and the strategy to address them*
- *Goals of the plan by year*
- *Role of outside collaborators.*

11:10-11:30	325 MHz Linac Includes HINS program	R. Webber
11:30-12:00	1300 MHz Linac	M. Champion
12:10-12:30	Discussion	
12:30-1:30	Lunch	
1:30-1:50	MI and Recycler Rings	I. Kourbanis
1:50-2:10	Beam Transfer Line	D. Johnson
2:10-2:30	Civil Facilities	R. Alber
2:30-2:50	Cryo facilities	A. Klebaner
2:50-3:05	Controls	J. Patrick
3:05-3:20	Instrumentation	M. Wendt
3:20-3:45	Discussion	
3:45-4:00	Break	
4:00-5:00	Committee Executive Session. Requests for supplementary or breakout presentations on Wednesday	

6-D Cooling Experiment (MANX – Session organized by Rol Johnson and Vladimir Shiltsev)

The opening two talks are meant to set the context for evaluation of the proposal. Each presentation should define the role of ionization cooling, the required cooling performance, and the time at which such performance needs to be demonstrated.

<u>*Context*</u>

5:00-5:35	Muon Collider 5 year plan Plan, timeline, resources	A. Jansson
5:35-5:50	Mu2e Plans and needs	R. Bernstein
5:50-6:35	Overview of MANX Helical Cooling Channel basics, MANX as part of larger muon program	R. Johnson
6:35-8:00	Dinner	

Wednesday, February 4

6-D Cooling Experiment (MANX - continued)

8:30-8:50	Theory of the HCC History, derivation, epicyclic channel	S. Derbenev
8:50-9:10	Uses of the HCC Muon collection, 6D cooling, extreme cooling for MC, NF, and stopping muons	M. Cummings
9:10-9:35	Mu2e applications Overview, upgrade to HCC, relationship to Project X	C. Ankenbrandt
9:35-9:55	Helical Solenoid Magnet concept, 4-coil model, cost estimates	V. Kashikhin
9:55-10:20	Break	
10:10-10:40	MANX Concepts, simulations	K. Yonehara
10:40-11:00	RAL Siting Detectors, logistics, resources	R. Abrams
11:00-11:20	MANX at RAL Integration, timeline, MICE viewpoint	D. Kaplan
11:20-12:30	Discussion Break Supplementary presentations/discussion as requested by the committee	
12:30-4:00	Working Lunch Committee Executive Session	
4:00-5:00	Closeout	
5:00	Adjourn	