October 22, 2002

Fermilab Accelerator Advisory Committee

Second Meeting: May 22-23, 2000

Committee Report

The second meeting of the Fermilab Accelerator Advisory Committee took place on May 22 and 23, 2000. The Committee consisted of V. Balakin, J.-P. Delahaye, G. Dugan (Chair), M. Harrison, C. Leeman, T. Shintake, and F. Willeke. The charge to the Committee for this meeting, and the agenda for the meeting, are included as appendices to this report.

At this meeting, the committee heard a comprehensive discussion of the plans for Tevatron operation with luminosities in excess of 10^{32} $cm^{-2}s^{-1}$. This was a follow-up to a briefer presentation made to the committee at its initial meeting. The committee was also presented with an update on Recycler commissioning, and was given a brief report on preparations for Run II commissioning.

Much of this meeting was devoted to discussions of long-range accelerator R&D. The committee heard reports on the recently completed study of a neutrino factory sited at Fermilab, the status of Fermilab's role in the NLC collaboration, and the status of superconducting magnet R&D for future accelerators.

The following sections present the committee's responses to each item in the charge.

Charge Item #1: *Beyond 1E32.*

The committee is asked to review and comment on possible parameter sets leading to a luminosity in excess of $1\times10^{32}cm^{-2}sec^{-1}$ *in the Tevatron collider. Specific feedback is solicited with regard to the general scheme for increasing the number of antiprotons, 132 ns operations with a crossing angle, and the effects of crossing angle and multiple interactions within the detectors.*

In order to increase the luminosity of the Tevatron beyond $10^{32}cm^{-2}sec^{-1}$, (called Run IIB) a number of improvements are planned. These improvements are all aimed at increasing the number of antiprotons, by an increase in the number of protons on target, an increase in the p-bar collection efficiency, and improvements in the cooling of p-bar beams.

The plans comprise proton beam manipulations in the Main Injector (slip stacking), sweeping of the proton beam on target, and the implementation of a liquid lithium lens. They also include increases in transport lines and ring apertures, an increase of the bandwidth of cooling systems, building a new transfer-line between the accumulator and the Recycler ring, and implementation of electron cooling in the Recycler.

The planning for Run IIB presented to the committee at this meeting was much better defined than in the past. All elements in the plan seem to be well justified and thought through.

However, the committee feels that the means of implementation of these measures needs better definition. Because of the different weights and different time scales of the components of the overall plan, a staging plan must be worked out in such a way that a step-by-step improvement of performance in the Tevatron can be achieved. This implies that certain measures must be combined in an appropriate way. Early planning is necessary to assure that necessary components are available in time. The committee recommends that the management assign in the near future a responsible person, who works out a plan and coordinates the actions.

Once the luminosity in the Tevatron exceeds about $2 \times 10^{32} cm^{-2} sec^{-1}$, operation with 36x36 bunches will result in a such a large number of interactions per crossing that the efficiency of the collider detectors will be seriously compromised. Hence, it is planned to increase the number of bunches, by decreasing the spacing between bunches to 132 ns. This will require new separators and kicker modifications.

A presentation was made to the committee on the effects of multiple interactions on detector performance. The committee feels that this was a good first step to begin to understand the issue, and urges the development of a quantitative tradeoff between integrated luminosity and number of interactions per crossing.

A thorough analysis of the benefits and the difficulties of operating the Tevatron with a small bunch spacing of 132ns was presented to the committee. The small bunch spacing requires operating the Tevatron with a crossing angle. The loss in peak luminosity and in integrated luminosity compared to a bunch spacing of 396ns (as in Run IIA) appears to be well understood and sufficiently well modeled. The difficulties of operating the Tevatron with a crossing angle of 360 μrad have been assessed in calculations and simulations. The result of these investigations is that there appears to be no obvious reason, which would prevent operation of the Tevatron with a crossing angle.

The committee recognizes that these investigations are not yet complete. Continued tracking calculations, now just beginning, are encouraged. Whether the scheme will work depends on information yet to be obtained: results from both the performance of the detectors with multiple interactions, and from accelerator experiments on crossing angle performance, long-range beam-beam, the performance of the Recycler, the recycling efficiency, etc. The committee urges that beam studies be carried out as soon as possible to begin to address some of these issues experimentally, as well as in simulations.

The committee also suggests investigating some potential problems, which have not been studied in detail so far. These problems are outlined in the following three paragraphs.

Fluctuations in the bunch currents may cause different closed orbits for different bunches due to the long-range beam-beam forces. This may lead in principle to undesirable beam-beam separation at the interaction points for some bunches. The consequence might be loss of luminosity, and increase of the multi-bunch tune footprint, which can cause reduced lifetime or poor stability for some of the bunches. Though it is not expected that there will be large bunch-to-bunch orbit variations, it should be calculated to avoid unpleasant surprises.

The proton intensity per bunch will be the same in Run IIB as in Run IIA, but there will be 140 bunches, rather than 36 bunches. The total proton intensity will be quite high, comparable to that experienced in high intensity fixed target operation of the Tevatron. This high total intensity goes along with a much higher single bunch intensity and different bunch gap structure than in the high intensity fixed target mode. The committee sees a potential problem here and suggests that experiments with high intensity proton fills be performed early on.

The crossing angle leads to large orbit deviations in the low-β quadrupole magnets. This could cause a limitation of physical and dynamic aperture or to a limit of the β-function. The committee suggests that tracking calculations with field errors in the low-β quadrupoles be performed to investigate this question.

The beam-beam linear tune shift compensation by an electron beam is a novel method to overcome a limitation of the Tevatron performance due to a spread in the bunch-to-bunch tune shifts. The committee is pleased to see the progress, which has been made in this project and believes that this system has a good potential of improving the Tevatron performance.

In view of the significant laboratory resources that are spent on this project, the committee encourages the management to make this system an integral part of the luminosity upgrade program. The performance improvement (increase in integrated luminosity) which can be achieved by applying tune shift compensation should be determined, and there should be a clear commitment to achieve this goal. The schedule for the tune shift compensation project should be incorporated into the timetable of the upgrade program.

Charge Item #2: Neutrino Factory Study.

The committee is asked to review and comment on the recently completed Neutrino Factory Feasibility Study at Fermilab. In particular we would like input with regard to the extent to which the committee feels the study has established a feasible basis for such a facility, identified the likely cost drivers, and identified the required associated R&D program.

The committee is very pleased by the impressive amount of work done during the last six months in collaboration with a large number of institutes all over the world on the feasibility of a neutrino factory based on a muon storage ring situated on the Fermilab site. A very detailed report has been published. It describes a coherent scheme and the corresponding beam performance tracked over the whole facility, built with systems based on a choice of realistic technological options. A cost estimate has also been established, which clearly points out for the first time the main cost drivers. This preliminary study, performed in a very short amount of time, obviously could not solve all the problems but it clearly identifies the performance limiting systems, and defines a logical program of study to improve the performance.

The study demonstrates that, with the present status of the technology, the performance achieved did not reach the design objectives. For example, the neutrino flux per year is $5x10^{19}$, instead of $2x10^{20}$; the neutrino production, capture and transmission to the muon storage ring is 0.02 to 0.03, instead of 0.1 muon per proton on target; and the transverse emittance is cooled by a factor 3, instead of 10.

The rotation and bunching sections of the machine appear to be the limiting factors. Given the beam provided by the bunching section, the cooling channel performance seems marginal in spite of the use of components that may prove technically impossible to fabricate. Lack of cooling then imposes a significant aperture requirement on all downstream components. It would appear that this is a crucial element of the facility optimization.

The cost estimate exercise, based on realizable technical designs, reveals a surprising system cost profile. Although, as expected, RLA2 is the dominant system cost, the cooling channel is more expensive than RLA1. The cooling channel cost is dominated by the cost of the superconducting solenoids. In terms of components, magnets (solenoids) and rf cavities are the dominant items.

Now that the performance of the overall facility has been established following an optimization of each individual system, the committee recommends that the study team perform an iteration, optimizing the overall scheme by a better matching of each system to the upstream and downstream systems.

A critical review of the whole scheme will then certainly be necessary to confirm or not the validity of the choice of the various technological options (target material, induction linac, phase rotation by low frequency RF cavities, etc.). This review should also identify whether there are entirely different approaches needed in certain areas.

The committee heard a discussion of staging plans for the facility. The committee endorses the concept of staging, and urges that the next iteration of the design, suggested above, specifically include the staging option.

The committee welcomes the identification of a 3 year R&D plan with the goals of demonstrating technical feasibility on those concepts and components deemed unproved to date, and of reducing the cost of those components identified as the cost drivers (superconducting solenoids and rf systems). In view of the inevitable resource limitations at Fermilab, the committee urges the study group to prioritize the required R&D carefully.

The high cost of the facility, the low performance of the cooling, and the small power transfer efficiency to the beam (a few tenths of a percent), resulting in high wall plug power consumption (160 MW), are especially a concern. They create doubt on the possible extrapolation of such a technology to a muon collider, where the cooling required is 10^5 times larger, and the beam power reaches several megawatts. The most that could be said was that the neutrino factory would address some (but by no means all) of the R&D issues required for a muon collider.

Charge Item #3: Recycler commissioning status.

The committee is asked to review and comment on progress since the fall meeting with particular attention to the timetable for achievement of performance goals and integration into the 2000 engineering run(s).

The commissioning activities have continued more or less continuously since the last meeting on both a parasitic and dedicated basis. Significant hardware improvements have been made in the vacuum system and beam position monitor electronics. Vacuum is now no longer an issue in terms of beam lifetime and, for the first time, believable beam position information is available. A significant amount of magnetic shielding is now in place and the magnetic coupling to the Main Injector has been reduced noticeably. These improvements have resulted in beam lifetimes on the order of several tens of minutes. In addition, proton stochastic cooling has been demonstrated, which provides added confidence that the antiproton stochastic cooling systems will function as expected.

In spite of this progress, much more will be necessary before the Recycler will be able to meet the design goals. Maximum lifetime is obtained with large closed orbit offsets, which is interpreted as indicating aperture restrictions at one (or more) locations. The injection efficiency remains at ~50%, though this could prove related to the aperture/closed orbit issues. While magnetic coupling has been considerably reduced, it has not been completely eliminated, and there are indications that further shielding will be necessary in at least one straight section.

A visit to the Recycler tunnel by one member of the committee led to specific concerns related to machine alignment, which may be contributing to the observed lifetime problem. These concerns are described in the following three paragraphs.

The mechanical supports from the ceiling may not be strong enough to maintain long-term stability. Also, at some locations, the pipe is "floating" from these supports.

The distance between two adjacent supports may be too long to keep the beam pipe straight. Even if the pipe was well machined at the factory, when it is installed in the tunnel and devices are mounted on it, its straightness may be open to question. The real situation in the tunnel should be carefully examined.

Some of the mechanical supports for the permanent magnets have a C-shaped structure, which show a deformation due to the mass of the magnet. The alignment and stability of these supports should be checked.

The committee is concerned that the commissioning progress, while evident, has been slow to date and that at the present rate will not be concluded before the start of Run IIA. In addition, the resources devoted to this topic to date look insufficient, resulting in a less coherent effort than desirable. While the Recycler will not be required for the early operation of Run IIA, the committee is uncertain to what extent parasitic commissioning will be possible. Dedicated time during Run IIA for continuing Recycler commissioning could be obviously disruptive to collider operation. The committee recommends that the Beams Division should ensure that the remaining dedicated machine commissioning time is utilized with maximum effectiveness. The Division is also encouraged to determine the impact of having to continue Recycler commissioning during collider operation should this prove necessary.

Charge Item #4: Status of NLC Collaboration

The committee is asked to review and comment on the development of the Fermilab component of work within the NLC collaboration. We are also interested in input from the committee on their views of how this work fits into the world-wide effort on linear colliders.

Building an electron/positron linear collider at a center of mass energy 1 TeV or even higher is a major technical challenge. The major advantage of the choice of X-band frequency for the driving RF power is that high frequency structures can have high shunt impedance, leading to a minimization of the site length and the wall plug power. Hardware development on X-band accelerators has been carried out at SLAC and KEK, where most of the hardware components required for the NLC project were successfully developed. The next steps in R&D for the NLC project, related to the main linac, are

- High power operation of one unit RF-system.
- Cost reduction of components, such as accelerating structures.
- Beam dynamics studies of more detailed models of the main linac.

An MoU has now been signed between SLAC and Fermilab on R&D about linear colliders and the collaboration on the NLC has effectively started. Fermilab will be responsible for the main linac. Among the tasks which Fermilab will participate in are

- Construction of an Engineering Test Facility (ETF) and high power test of the Delay Line Distribution System (DLDS) system
- Accelerating structure fabrication and industrialization.
- Development of permanent magnet quadrupoles for beam focusing along the main linac
- Studies of beam dynamics in the main linac

The committee is impressed by the rapidity with which Fermilab experts have introduced themselves to the linear collider field and have been able already to contribute usefully, especially in the areas of beam dynamics, accelerating structure fabrication, and focusing along the linac by permanent magnet quadrupoles.

As noted above, Fermilab is planning to build the so-called, Engineering Test Facility, ETF, constituted by a pack of 8 klystrons and modulators, powering 8 groups of 3 accelerating structures through a complete Delay Line Distribution System (DLDS) working at nominal power and field. The DLDS, originally invented at KEK, is an important key technique, which multiplies the RF power four times, with efficiency as high as 90%, in principle. However, its high power operation has not yet been proved anywhere, and so this is a particularly important task for the ETF.

Fermilab's engagement in the ETF is strongly supported by the committee. Through the fabrication and installation of the hardware, and its operation, Fermilab scientists and engineers will efficiently learn about electron linacs and contribute to improving their performance.

The committee endorses the schedule as presented, planning the installation of ETF in 2003, which seems realistic and leaves the time for the construction and optimization of the various components.

The A0 experiment has recently successfully demonstrated the possible generation of flat beam following the method proposed by Derbenev and Brinkmann (DESY). The committee encourages the study team to envisage if such a facility could be used as a injector for the ETF for further tests with beam.

One of the main components of the NLC is the accelerating structure in the main linac. The principal technical challenge in high frequency structure design is the control of the strong wake fields. The long range wake field, in the X-band design, will be managed by randomly detuning the cells along each structure, thus canceling the coherent transverse fields. The higher order power will also be damped to avoid the build up of harmful deflecting modes. Also, the rounded shape of the cell design enhances the energy transfer efficiency from RF to beam. The current design, equipped with all of those new ideas, is called the Rounded Damped Detuned Structure (RDDS). Its electrical performance was tested several times with the ASSET beam at SLAC and the basic principle has been well proved.

The major concern for the 8000 required RDDS accelerating structures is their fabrication at low cost by mass production techniques. Industrialization of the accelerating structure fabrication is a most important R&D issue, and one in which Fermilab will play a core role in managing. The approach of the team in charge of their fabrication, starting with visits of the corresponding experts at SLAC and KEK, and reviews of the various methods of fabrication, is well appreciated by the committee. The committee suggests that the team also pay the same visit at CERN, where alternative methods of damping of the transverse wake-fields have been developed. The committee also recommends a critical review of the tight tolerances, which are the principal cost driver in the fabrication of these structures. This review should look for the optimum cost performance for the structures, in collaboration with the beam dynamics experts.

Finally, the use of permanent magnets to build adjustable quadrupoles for focalization along the linac, without any individual power supplies, is very attractive. This scheme has potential for cost savings and is supported by the committee

Comments on other items, not explicitly addressed in the charge.

Run II Commissioning

A coherent plan to commission the Tevatron collider complex for Run II has been presented to the committee. Important progress has already been made. The intensity of the Main Injector beam is within 80% of the design; coalescing of nine proton bunches resulted in an intensity of 2.3 10^{11} protons per bunch which is 85% of the Run II goal. The proton beam parameter goal for antiproton production has been achieved. The p-bar stacking rate is within a factor of two of the level needed for Run II, with the promise of significant improvements in hand. There is a well laid-out and convincing plan of the necessary steps to achieve high luminosity.

Preparations for the high energy running have been made. Weak magnets have been identified and have been (or will be) exchanged. There seems to be no obstacle to run the Tevatron at beam energies very close to 1TeV.

The committee does not see major problems concerning the upcoming engineering run and the following Run II.

Superconducting Magnet R&D

The committee heard a series of presentations from the Technical Division on superconducting magnet R&D. These presentations focused on high field (>10T) magnets (for VLHC or muon collider applications) and low field (superferric) transmission line magnets, for a low-field VLHC. The high field magnets included 11-12 T cos-θ designs and an 11 T hybrid common coil design, using Nb_3Sn superconductor in all cases. Fermilab is also involved (with LBNL, BNL, and industrial producers of Nb_3Sn superconductor) in a national R&D effort to improve the quality and reduce the cost of Nb_3Sn superconductor for high energy physics applications.

As stated in the initial meeting, the committee supports superconducting magnet R&D work at Fermilab aimed at future accelerators. Fermilab is one of the world's leaders in building accelerator-style superconducting magnets, and it is essential to preserve and nourish this capability.

Appendix 1: Charge (Draft #2)

The initial meeting of the Fermilab Accelerator Advisory Committee (AAC) in November 1999 focused on the preparations for the upcoming collider run and on planning for pushing the performance beyond the initially established goals. Several issues were identified at that meeting, most notably in the areas of understanding how luminosities above $1\times10^{32}cm^{-2}sec^{-1}$ would be supported and of achieving Recycler performance design goals. We would like to revisit these areas at the May meeting, while also reviewing major activities on muon and linear collider facilities over the last six months.

The AAC is asked to review the status of preparations and plans, to comment on their appropriateness, and to recommend the next steps, if any, in the following areas:

- **Beyond 1E32.** The committee is asked to review and comment on possible parameter sets leading to a luminosity in excess of $1\times10^{32}cm^{-2}sec^{-1}$ in the Tevatron collider. Specific feedback is solicited with regard to the general scheme for increasing the number of antiprotons, 132 ns operations with a crossing angle, and the effects of crossing angle and multiple interactions within the detectors.

- **Neutrino Factory Study**. The committee is asked to review and comment on the recently completed Neutrino Factory Feasibility Study at Fermilab. In particular we would like input with regard to the extent to which the committee feels the study has established a feasible basis for such a facility, identified the likely cost drivers, and identified the required associated R&D program.

- **Recycler commissioning status.** The committee is asked to review and comment on progress since the fall meeting with particular attention to the timetable for achievement of performance goals and integration into the 2000 engineering run(s).

- **Status of NLC Collaboration**. The committee is asked to review and comment on the development of the Fermilab component of work within the NLC collaboration. We are also interested in input from the committee on their views of how this work fits into the world-wide effort on linear colliders.

The AAC will also be presented with short status reports on superconducting magnet R&D and on Run II commissioning activities. These presentations are intended to be primarily informative and as such no specific comments are solicited at this time. However, any comments the committee might wish to make are welcome.

It is requested that a concise report responsive to this charge be forwarded to the Fermilab Director by July 4, 2000.

Appendix 2: AAC Agenda

May 22-23, 2000

Monday May 22

8:30 Executive Session (G. Dugan)

8:50 Welcome. Presentation of charge (S. Holmes/5 minutes)

Beyond a Luminosity of 10^{32} $cm^{-2}sec^{-1}$

9:00 Motivation for 132 nsec bunch spacing (M. Church/15 minutes)

9:20 Effect of multiple interactions (R. Demina/10 minutes)

9:35 Separated orbits & tune shift calculations & studies plan (P. Bagley/20 minutes)

10:05 Beam Dynamics (T. Sen/10 minutes)

10:20 F17 Kicker results & plans and separators (B. Hanna/5 minutes)

10:30 Break

11:00 Beam-Beam Tune Shift Compensation (V. Shiltsev/15 minutes)

11:20 Plans for Run IIB (D. McGinnis/30 minutes)

12:00 Lunch

Neutrino Factory Study

1:30 Overview (N. Holtkamp/10 minutes)

1:45 Proton Driver for a Neutrino Factory (W. Chou/20 minutes)

2:10 Target and Muon capture (V. Balbekov/20 minutes)

2:35 Muon Cooling channel designs (G. Penn/20 minutes)

3:00 Break

3:20 Muon Acceleration (L. Harwood/20 minutes)

3:45 Summary, and R&D Required (N. Holtkamp/10 minutes)

Magnet R&D

4:00 Superconducting Magnet R&D Overview (P. Limon/7 minutes)

4:10 High field magnet R&D (G. Ambrosio/20 minutes)

4:40 Low field magnet R&D (V. Kashikhin /15 minutes)

5:00 Executive Session

6:30 Cocktails

7:00 Dinner

Tuesday, May 23

8:30 Run II Commissioning (M. Church/20 minutes)

Recycler Commissioning

9:00 Overview of Recent Progress (G. Jackson/20 minutes)

9:30 Status of the Recycler BPM System (A. Hahn/10 minutes)

9:45 Recycler Lattice Studies (W. Wan/10 minutes)

10:00 Results of Proton Cooling Studies (L. Spenzouris/10 minutes)

10:15 Break

NLC

10:45 Overview (T. Dombeck/10 minutes)

11:00 Structures (T. Arkan/20 minutes)

11:30 Beam Physics (C. Bohn/10 minutes)

11:45 Permanent Magnets (V. Kashikhin/10 minutes)

12:00 Working Lunch

Closeout time is tentative

3:00 Closeout