Summary Report from the Accelerator Working Group

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ABSTRACT

The Accelerator Working Group at Snowmass discussed possibilities for new accelerator facilities in the post-LHC era. Included were discussions of Tevatron luminosity upgrades, next generation (e^+e^-) linear colliders, muon colliders, very high energy hadron colliders, and advanced acceleration techniques. The emphasis was on identification of required R&D and establishment of reasonable performance goals. Activities of the five working groups are summarized.

I. INTRODUCTION AND SUMMARY

The Accelerator Working Group at Snowmass was organized into five working sub-groups (all energies refer to center-of-mass):

1. Next Linear Collider (0.5 upgradable to 1.5 TeV)
2. Tev33 (Tevatron operating at 2 TeV, 10^{33} cm^{-2}sec^{-1} luminosity)
3. Muon Colliders (0.5 ->2.0 TeV)
4. Really Large Hadron Collider (>60 TeV)
5. Advanced Accelerator Technologies (5 TeV electron collider)

This division of effort was chosen to cover what were perceived to be the major options for new forefront facilities that could be constructed over the next two decades. The list was not presumed to be exhaustive--specifically not included were the Large Hadron Collider (LHC) project itself nor a possible electron-proton collider facility based on the LHC.

Facilities plans associated with each of the five subgroups arrived at Snowmass in different stages of maturity. This diversity was reflected in differing goals and operating modes of the working groups during the Snowmass period. The NLC arrived with a "Zeroth Order Design Report" (ZDR) that had been produced by SLAC in the spring of 1996 and which represented a reasonably comprehensive and integrated concept. Significant progress on technical design issues during the Snowmass Workshop was deemed unlikely given the level of effort that had been previously invested. As a result this group concentrated on education of the community with respect to technical issues and identification of possible paths to a 1.5 TeV collision energy. In contrast the Muon Collider arrived with a design feasibility study that identified concepts and related technical issues. This group established goals of making real progress on technical issues and identifying future R&D priorities. The Tev33 effort differed from the two lepton collider efforts in that it represented an upgrade to an existing facility, presumably carrying a significantly lower price tag. This group concentrated on identifying technical solutions related to known performance limitations in the Tevatron collider and antiproton source at Fermilab. The Really Large Hadron Collider arrived with some preliminary work completed on both low and high field approaches to colliders with energies in the 50-100 TeV/beam range. This group devoted itself to developing concepts, identifying common issues, and identifying productive R&D directions. Finally, the Advanced Accelerator Technologies group, buoyed by recent successes in accelerating particles through super-high (~1 GeV/m) gradients, worked to establish ideas for large scale application to usable HEP facilities.

Overall goals established by the Accelerator Working Group for each of the sub-groups included: 1)education of the broader accelerator community on design and/or construction issues and possible implementations; and 2)examination and identification of profitable R&D directions. In addition, hanging over all discussions was the common theme of cost reduction, as measured in dollars/GeV. These common goals were augmented by a specific charge to each of the sub-groups as indicated below (group leaders in parenthesis):

NLC (J. Irwin and T. Raubenheimer): Discuss the prospects for achieving a 0.5 TeV linear collider and the R&D required. Examine issues related to energy upgrades in the 1.0-1.5 TeV range.

Tev33 (G. Jackson and J. Marriner): Evaluate options for production of sufficient antiprotons to produce a luminosity of 10^{33} cm^{-2}sec^{-1} in the Tevatron. Undertake a critical evaluation of Tevatron beam dynamics issues. Identify R&D required to support this upgrade.

Muon Collider (R. Palmer and A. Tollestrup): Examine critical technology and physics issues in the strawman design. Discuss possible small scale experiments or demonstration projects that could validate operational principles. Identify issues relating to energy extensions.

Really Large Hadron Collider (G. Dugan, P. Limon, and M. Syphers): Examine both the high field and low field approaches to a hadron collider operating at >30 TeV/beam. Identify key technology and R&D issues that need to be pursued.

Advanced Accelerator Technologies (S. Chattopadhyay and D. Whittum): Discuss and evaluate concepts for achieving 5 TeV (center-of-mass) e+e-γ collisions with luminosity of 10^{35} $cm^{-2}sec^{-1}$. Attention should be given to gradient, emittance, efficiency & collective effects. Promising R&D directions should be identified, particularly for power-sources, structures & instrumentation.

The complete reports from each of these groups follow this summary report. It is felt that mature designs could be brought to fruition over periods ranging from years, in the case of an e+e- linear collider or Tev33, to a decade or more in the case of the muon collider, a next generation hadron collider, or a collider based on truly new acceleration technologies. However, in all cases accelerator R&D is required now, as is serious consideration on cost efficiencies in construction and manufacturing, in order to make progress towards these goals. Leadtimes associated with development of new forefront facilities are now measured in decades. The implication is that the U. S., and the world, need to be investing now in the technologies that will support continued advances in high energy physics in the post-LHC era.

II. NEXT LINEAR COLLIDER SUMMARY REPORT

At Snowmass the NLC (Next Linear Collider) subgroup presented and discussed the status of the design and the status of the R&D programs for an NLC. Many of the details can be found in Refs. [1,2,3].

The goals of the present design are for a 0.5 TeV, center of mass, linear collider with expansion capabilities to 1.0 or 1.5 TeV. Much of the discussion centered on the technology choices and the energy upgrade path. The choice of X-band (11.4 GHz) accelerator technology was presented as an appropriate one for the 0.5 to 1.5 TeV energy range, and there were many presentations of the developments in these areas of R&D. These included developments in klystrons, RF pulse compression, accelerator structures and an NLCTA (Next Linear Collider Test Accelerator).

Some of the highlights of these developments presented at Snowmass were, for example, the recent successes with X-band klystrons. A robust 50 MW tube has been developed and a series of identical tubes is being manufactured for use in the Test Accelerator. These tubes incorporate lessons learned over several years of experimental testing and computer simulation. The outstanding development was the initial test results from the first PPM focused tube, i.e., periodic permanent focusing. This tube does not have the large, power hungry solenoid surrounding it and will allow greater simplicity in future design and manufacture. The agreement between the results (60 MW output with 60% electrical efficiency) and the computer simulations is excellent, and SLAC is now moving directly to a 75 MW design.

The design and construction of a damped, detuned 1.8 meter accelerator structure was presented. The design effectively detunes and damps the higher mode wakefields (dominated by the first dipole mode) and couples these troublesome modes into damping slots that run along the length of the structure. These damping slots also double as beam position sensors which will allow precision alignment of the structure to the beam. Multibunch wakefield effects are now severely attenuated. This structure was tested in the SLC just after Snowmass, with excellent results.

Another subject which was presented and discussed was the measurements of ground motion on the SLAC site which is neither a deep tunnel nor a particularly quiet site. The main emphasis here was in studying the correlations in the motion as a function of frequency and distance. The more correlated the motion, the smaller the impact on the accelerator beam. The results indicate strong correlations over long distances down to very low frequencies which means that the ground motion is not a problem in meeting the dynamic alignment tolerances of an X-band NLC accelerator. Only in a few quadrupoles in the final focus will there be an active alignment system required and work is underway to demonstrate this technique using what are called “optical anchors.” These are interferometers which use long paths into bedrock as the reference for direct measurement of a quadrupole position. Techniques like this have been used in delicate geophysical measurements to isolate oneself from near surface effects.

There were interesting discussions on the lessons learned from the SLC (SLAC Linear Collider) and how these have and continue to influence the design of the NLC. The importance of advanced precision instrumentation and control was strongly emphasized and examples were presented where present performance has demonstrated the precision required for an NLC. The FFTB (Final Focus Test Beam) is an example where an international collaboration has built and operated a scaled final focus system of NLC design using the SLC beam as input and demonstrated a demagnification of beam size of 300, producing a beam size of 70 nanometers. In achieving this performance various technologies were developed and demonstrated at the required NLC performance level, e.g., beam position monitors with 30 nm resolution, magnet movers with 1 µm precision, etc.

During the Snowmass workshop, there were discussions of approaches to even higher energies. A parameter set for a 5 TeV design was developed and presented, which uses 34 GHz “conventional” RF technology and would fit on the same site as the NLC. A paper on this design can be found in these proceedings. Also, in these proceedings, there is a paper on a 1.5 TeV design which uses the same technology as the 0.5 to 1.0 TeV NLC but has increased linac length and minor modifications to the final focus.

Much of the discussion at Snowmass centered on what R&D is required to complete the design of an NLC. It was agreed that the technology demonstrated at the present time is adequate for the design goals of the NLC. More work is required to move towards a totally engineered design which incorporates DFM (design for manufacture) ideas and mass production concepts. Many systems design issues need further development in order to develop a reliable cost estimate for an NLC. This should be the major thrust of activity in the near future.

III. TEV33 SUMMARY REPORT

The goal of the Tev33 project is to exploit fully the Tevatron Collider during the period subsequent to the initial run with the Main Injector but prior to the startup of LHC. "Tev33" refers to a series of improvements to the accelerator complex at Fermilab, as it is expected to exist in the year 2000, with the goal of achieving a luminosity equivalent to 10^{33} cm^{-2}sec^{-1} in the Tevatron proton-antiproton collider. More specifically, a goal of providing an integrated luminosity of at least 30 fb^{-1} at 2 TeV in the center of mass system by the year 2006 has been suggested[4]. This goal is believed by Fermilab to be technically feasible. An upgrade to a higher energy or a higher luminosity proton-proton collider is also technically possible but is judged to be an unrealistic competitor for the Large Hadron Collider (LHC) based on performance, cost, and schedule considerations.

The goal of the Tev33 group at Snowmass was to examine those technical issues that need to be resolved before a realistic plan for Tev33 can be developed. As a starting point the Tev33 group assumed the successful completion of the Main Injector and other upgrade projects that are associated with Run II, including construction of the antiproton "Recycler" ring and completion of a series of stochastic cooling upgrades in the antiproton source.

A. Luminosity Limitations

The luminosity achieved in the Tevatron proton-antiproton collider is given by the expression:

$$L = \frac{fBN_p N_{\bar{p}}}{2\pi(\sigma_p^2 + \sigma_{\bar{p}}^2)} = \frac{3\gamma f N_p (BN_{\bar{p}})}{\beta^* \varepsilon_{Np}(1 + \frac{\varepsilon_{N_{\bar{p}}}}{\varepsilon_{N_p}})} \quad (1)$$

where f is the revolution frequency, B is the number of bunches in each beam, N is the number of particles in a bunch, σ is the transverse rms beam size, γ is the normal relativistic factor, β* is the beta function at the interaction point, and ε is the 95%, normalized beam emittance. Suppressed in this expression are form factors relating to the bunch length and the crossing angle. Current Tevatron performance is characterized by a luminosity of about 1.6×10^{31}cm^{-2}sec^{-1} based on 900 GeV/beam operations with B=6, $N_p=2.5\times10^{11}$, $N_{\bar{p}}=6\times10^{10}$, and ε=24π mm-mr.

Fundamental limitations in the Tevatron collider are related to the factors $BN_{\bar{p}}$, N_p/ε, and BN_p. The first factor represents the total number of antiprotons in the ring, the second is proportional to the head-on beam-beam effect experienced by the antiprotons in the presence of the proton beam, and the third is proportional to the total long-range beam-beam effect experienced by the antiprotons. In present operations at Fermilab the sole limitation on $BN_{\bar{p}}$ is the ability to make antiprotons. Experience indicates that the maximum acheivable N_p/ε corresponds to a beam-beam tune shift of approximately 0.024. This limit appears to be related to the area in tune space available between resonances below order twelve or so. For B=6 long range beam-beam effects are not significant.

B. Technical Issues

Increased antiproton production and storage capability are the keys to increasing the luminosity in the Tevatron. Luminosities of order 10^{33} cm^{-2}sec^{-1} would be achieved if the antiproton bunch populations could be brought to the level of the proton bunches accompanied by an increase in the number of bunches. Significant improvements in antiproton targeting, accumulation, and recovery are required.

Packaging of luminosity is also important. With 36 bunch operation, as planned for Run II, the number of interactions/crossing is about two-and-a-half for a luminosity of 10^{32}. Clearly operations with a luminosity of 10^{33} will require even more bunches--approximately 100.

A number of key technical issues have been identified that require resolution as part of the formulation of a complete plan for Tev33:

1. The antiproton production rate must be improved to ~10^{12}/hour--roughly a factor of five beyond the goal of the initial run with the Main Injector.

2. The Tevatron will contain approximately 100 bunches. Long-range beam-beam effects will be roughly three times those of the initial run with the Main Injector.

3. A number of experimental interface issues need to be investigated including luminosity leveling and background issues.

Work at Snowmass concentrated on a few key aspects of the Tev33 plan, most notably long-range beam-beam effects, proton targeting, electron cooling and luminosity leveling.

C. Antiproton Production

Providing a source of antiprotons that will support a Tevatron luminosity of 10^{33} cm^{-2}sec^{-1} requires both an increase in the antiproton production rate to ~10^{12} /hour and the ability to store an accumulated 10^{13} antiprotons. The primary elements envisioned to provide these capabilities are:

1. Construction of the antiproton Recycler Ring [5]. This facility was not discussed extensively at Snowmass but rather, was assumed to exist as a starting point for Tev33 discussions. It is assumed that this ring would have a storage capability of 10^{13} antiprotons and the capability of allowing recovery from the Tevatron of unspent antiprotons at the completion of collider stores.

2. Increased proton flux onto the antiproton production target.

3. Improved Debuncher and Antiproton Accumulator acceptance.

4. 4-8 GHz stochastic cooling in the existing Debuncher and Accumulator Rings.

5. Electron cooling in the Recycler Ring.

1. Proton Targeting

The goal is to increase by a factor of ~five the number of protons on target relative to the Main Injector upgrade. This will result in a flux of about 3×10^{13} protons on target every 2 seconds. Two schemes were examined to provide the increased flux. First, slip-stacking (stacking in longitudinal phase space) in the Main Injector was considered. This technique capitalizes on the large ratio of the longitudinal acceptance of the Main Injector relative to the longitudinal emittance being delivered from the 8 GeV Booster. This technique appears to hold promise for either doubling or tripling the bunch intensities in the Main Injector. A second scheme that has been suggested involves targeting the entire Main Injector circumference for antiproton production. This would result in a proton pulse on target six times as long as the Debuncher circumference and hence would require development of a rather unique Debuncher injection kicker to interleave bunches. The potential here is a factor of six increase in proton flux. In both cases some sort of target sweeping scheme is required to keep energy deposition below target destruction limits. Such a system is currently under development.

2. Antiproton Acceptance

It is desired to double the overall collection efficiency of the existing antiproton source. This is envisioned as being achieved through several improvements:

1. Increasing the strength of the Li lens from 750 T/m to 900 T/m. A liquid Li lens is also under consideration.

2. Increasing the acceptance of the AP2 line from 17π to 32π mm-mr.

3. Increasing the momentum aperture of the Debuncher beyond the current 4%.

3. Antiproton Cooling

Upgrades to the stochastic cooling systems in the Debuncher and Accumulator rings are required to accommodate the increased antiproton fluxes anticipated. The primary requirement is increased bandwidth. 4-8 GHz systems appear to be the required. An R&D program aimed at the development of these systems is currently underway at Fermilab.

In addition, maintenance of large (~1×10^{13}) antiproton stacks in the Recycler ring will require the development of electron cooling--the stochastic cooling systems planned for the initial implementation are just not fast enough to overcome the intrabeam scattering in this ring. The requirement is for a 0.2-1.0 A dc electron beam with an energy of 4.8 MeV. Implementations based on either a recirculating Pelletron or a modified betatron were discussed at Snowmass.

D. Beam-Beam Effects

In order to keep the number of interactions/crossing observed in the detectors manageable it will be necessary to run with approximately 100 proton and antiproton bunches as the luminosity approaches 10^{33} cm^{-2}sec^{-1}. With this number of bunches the number of long-range encounters experienced by the antiprotons becomes significant. With 108 bunches there are 214 long-range encounters as compared to 10 in current operations and 70 planned for Collider Run II. The effect of these long-range interactions is significant in Tev33.

The effect of the long-range encounters is to generate macroscopic electromagnetic fields that impact the antiproton bunches. Because the ring is not uniformly populated with protons (a typical scheme would have three bunch trains of 34 bunches each with a interbunch separation of 132 nsec within the train and a 2.8 μsec separation between trains) not all antiproton bunches are affected equally. As a result the different antiproton bunches can have different closed orbits, different tunes, and different couplings. Analyses of closed orbit shifts, coupling variations, and tune footprints were undertaken at Snowmass. This work will have to be extended to full tracing simulations to understand impacts and correction schemes in detail.

E. Other Issues

The reduced bunch spacing represented by ~100 bunch operations will probably require the introduction of a crossing angle into the Tevatron. In order to preserve luminosity it will be necessary to shorten the bunches significantly relative to current operations. It is felt that this would most efficiently be accomplished with a higher (150-400 MHz) frequency rf system. R&D on such systems has not yet been initiated and was not discussed at Snowmass.

Means to deal with the large number of interactions per crossing were discussed at Snowmass. An old concept, continuous detuning β* to keep the luminosity fixed for the first ten hours of a store, was reexamined. Models for beam evolution including emittance growth from intrabeam and residual gas scattering and from particle burn off were used to evaluate the effectiveness of such schemes. As an example, a 25 hour store with the β* detuned to hold the luminosity fixed at 5×10^{32} $cm^{-2}sec^{-1}$ over the first ten hours, followed by integration of luminosity at β* tuned to its minimum value over the balance, yields an integrated luminosity of 69% of the non-detuned case. Whether useful luminosity on tape is enhanced by this mode of operation needs to be evaluated.

F. Conclusions

Nearly all technical issues associated with a ten-fold increase in luminosity beyond that anticipated following the initial Main Injector run have been identified. Solutions were pursued on a number of these at Snowmass, most notably in the areas of proton targeting for antiproton production, electron cooling, and Tevatron beam-beam effects. Further work in these areas needs to be pursued in order to support development of a coherent and detailed upgrade plan over the next year or two.

IV. MUON COLLIDER SUMMARY REPORT

Work at Snowmass on the muon collider built upon the collaboration's "Muon Collider Feasibility Study" [6]. Each day of working group activity focused on a particular component of the collider complex, with the exception of the detector group, which met separately throughout. Each day began with an overview of each component of the collider, followed by detailed presentations of the various subsystems. Critical issues were discussed in detail and possibilities for experimental verification of these were considered. At the conclusion of the workshop it was decided to have a series of workshops devoted to specific aspects of the machine. An overview of the machine itself can be found elsewhere in the proceedings [7]. Below, for each of the components of the complex, we give summaries of the discussions and work initiated at Snowmass.

A. Proton Source

A major focus of the discussion was on the optimization of the proton driver. The characteristics of this machine are completely determined by the demands of the rest of the complex. The bunches need to be 1ns long in order for energy compression to work in the decay channel. The intensity of 2×10^{13} is set by the required number of secondary muons, and the repetition rate of 15 Hz is set by the lifetime of the 2 TeV muons in the collider which is 40 ms. The main problems being studied are centered on optimizing the energy of the driver and on heating in the target. In order to achieve a 1 ns bunch after rotation, it is necessary to have a momentum acceptance of ~10% in a 10 GeV machine but only ~3% in a 30 GeV machine. However the heating in the target per muon for 30 GeV production is twice that at 10 GeV. The dominant problems are to keep low losses in the machine, keep the wall power as low as possible, and ensure a target with a long lifetime. While these are problems effect the cost and reliability of the machine, they do not pose serious obstacles for the feasibility, and an in depth study has been set up at FNAL.

B. Production and Decay

Work continued on modeling the production and decay. Measurements from BNL (E910) on the production of pions by protons in the energy range 12 - 20 GeV were just becoming available. Targets being studied are Be, Cu, and Au. Shortly we will have good information on the production cross section and spectrum from various targets, and this data will be used to tune the Monte Carlo programs. At present there are three programs (at least!) that give predictions of the production: MARS, DPMJET, and ARC. The main disagreement is at low pion momentum (less than 200 MeV/c) and it is in this region that there are no measurements. The experiment being carried out at BNL will provide this data soon.

The design and integration of the energy compression into the decay channel continues to be studied. Two methods are under study: A series of rf cavities and an induction linac. The rf system can provide a higher gradient at lower power but much work remains to be done to integrate it into the 5 T solenoid decay channel.

C. Cooling

Cooling was discussed at length. The need for a coherent and complete cooling simulation became apparent, and work has started to assemble such a set of computational tools. Much work remains to be done on this key problem, and it will be a main focus of our studies over the next year. The transition in and out of solenoidal lenses causes losses for large angle particles. Progress is being made in understanding cooling in single stage systems, and the role of quadrupoles, solenoids, and lithium lenses as focusing elements is being studied.

D. Acceleration

At Snowmass the results of simulation studies of the acceleration of the muon bunches was presented by Neuffer [8]. The effects of wake fields in the accelerator structure were included and the losses and phase space dilution were studied. Losses of less than 20% and longitudinal phase space dilution of less than 10% were exhibited.

The linac structures are arranged in a cascade system of four different accelerators whose frequencies are 100, 350, 800, and 1350 MHz. Because of the small orbit size, the pulse length is short for the first system, but as the energy increases so does the orbit length. Hence SCRF is considered in the later stages. In fact the TESLA system may be a first approximation to that required in the last stage. The large aperture of these cavities reduces the wake field associated with the intense muon bunches.

Questions of just what voltage can be attained in the various systems were raised. As a result, a test of the LEP cavities at CERN would be very valuable, and negotiations are in progress for such tests. An additional question that must be studied experimentally is the effect of radiation on the field attainable in the SCRF cavities

Since a recirculating accelerator requires a different magnetic field paths for each turn, considerable cost savings could be achieved if a rapidly increasing field in a single aperture could be used. A number of suggestions are being investigated. On scheme involves fixed field SC magnets of 8 T combined with pulsed iron magnets that go from -2 to +2 T. A second variation is a rapid cycling synchrotron.

An interesting suggestion (submitted to the proceedings) would involve building TESLA and using it at 250 x 250 GeV for electrons, and later configuring it to accelerate muons with a collider ring at one end. A number of interesting configurations are possible as the need for increased energy arises.

E. Collider Ring

In order to achieve the desired luminosity of 1×10^{35} $cm^{-2}sec^{-1}$, it is necessary to have bunches of 2×10^{12} muons. In addition, a β^* of 3 mm is specified. The small β^* means that the bunch σ_z is also 3 mm. Such short intense bunches in a collider pose a number of design problems.

The first is that the ring must be isochronous. There were two designs available at the time of Snowmass. One by Oide that displayed the necessary momentum acceptance, but used many higher multipole corrections, and a second design that did not have the required dynamical aperture.

However, studies initiated at Snowmass, and submitted to the proceedings [9], have now produced a lattice with the required properties.

There was some concern that the beam-beam interaction would be a problem. The muon collider is unique in that the beams need only hold together for about 1000 crossings due to the muon decay lifetime. As a result, good tracking studies are possible and one does not have to deal with the problem of 1×10^8 crossings which was so important for the SSC. The tracking studies that have been done so far show a remarkable robustness to beam-beam effects, and do not seem to support these fears.

However, it is clear that there are very interesting problems that can be studied in this ring, and plans are in progress to pursue them vigorously. In addition to the beam-beam interaction, there needs to be tracking studies done with realistic lattice errors. There is also the question collective beam instabilities (the peak beam current is 13 kA!) that needs further study.

Good progress has been made on shielding the detector and the low beta quads from the intense radiation from the decay electrons. Originally, it was calculated that 6 cm of W was necessary in the low beta quads in order to shield the SC coils from the radiation induced heating. This same radiation was causing an intolerable background in the detector. Both problems have been greatly ameliorated by placing sweep dipoles in the low beta insertion. Reducing the radiation to the quads means that the W shielding can be reduced with a consequence that the SC coils can be placed closer to the beam and thus produce a higher gradient quad. This higher gradient field has greatly improved the low beta insertion design. The design also includes a "Bitter Quad" located next to the IR region that has a pole tip field of ~4 T. It is hoped that this element may be changed to a normal SC quad as more understanding of the IR design is gained.

F. Detector

The detector backgrounds were the object of detailed study [10]. Muons that decay after the last low beta quad are moving essentially in the direction of the muons, and can be absorbed on the opposite side of the interaction point without too much trouble. However muons that decay before any of the low beta quads get swept out of the beam upstream by the quads and cause intense EM showers upstream of the collision hall.

It was discovered that a serious background in the detector arises from Bethe-Heitler pairs of muons produced in these EM showers. The chance of this happening in a shower is small (order of 1×10^{-3} or less) but the range of the muons is many meters and they are hence hard to shield. The main interference with the detector is in the hadron calorimeter where the muon flux occasionally produces a deep inelastic scattering in the calorimeter material. The muons are passing through the detector roughly parallel to the beam direction and interactions of this kind can influence the measurement of MET.

An additional problem comes from a large flux of neutrons and soft photons. The use of pixel detectors is being investigated, and it was noted that the neutron radiation was comparable to that expected in CMS detectors at LHC. The life time of the silicon is estimated to be about a year, but it was also pointed out that the neutron damage is dependent on the energy spectrum of the flux and that is now under study. The hit density is comparable to working detectors at SLD.

A number of inventions were made to cope with these detector backgrounds. Most involved applying some logical at a low level. For instance, dividing the calorimetery into a number of depth segments so that the development of the shower can be followed, or putting the pixels into a local coincidence to give the silicon some directionality. All of these ideas are now being investigated.

G. Future

A first attempt to map out the work for the future was made. Paper studies for the next year are quite well defined. However, it is obvious that a stronger experimental effort is rapidly becoming necessary. This will take some source of funding, and we attempted to estimate the magnitude of the needed support. A small experiment is presently underway at BNL to measure the pion yield from protons of various energies on an assortment of targets. This is just the start of the necessary R&D. Cooling must be demonstrated in a realistic way. SC magnets must be modeled. Pion production from a target in a high field Bitter magnet must be tested. SCRF in radiation environments must be studied. Low momentum compaction and high-current ring operation will need to be studied. Funds and people will have to be made available for these studies. A more detailed discussion of these issues can be found in the paper of Palmer and Tollestrup [7].

V. REALLY LARGE HADRON COLLIDER SUMMARY REPORT

There were about 50 participants in the Really Large Hadron Collider (RLHC) sub-group with informal seminars held each morning during the working sessions. With the encouragement of our theoretical colleagues, it was decided that the Snowmass meeting would define a strawman RLHC to be a 50 x 50 TeV machine with a peak luminosity of 1×10^{34} $cm^{-2}sec^{-1}$. The working assumption was that this facility would be a post-LHC machine, and thus, the time scale on which such a device might be started would be beyond the year 2005. Within this context the charge to the sub-group was to identify key technologies and R&D issues which should be pursued in the foreseeable future towards this goal.

Following earlier workshops on the subject of future hadron colliders at Indiana and Indianapolis, two different design concepts were examined at Snowmass; the low-field and high-field options. It is significant to note that while an SSC-like approach to access this energy range is technically feasible the cost of such a device is deemed prohibitive. There is general agreement that new technologies are necessary to achieve a cost breakthrough and as such that the dominant technical challenges for the future are driven by cost considerations, unlike linear or muon colliders, where cost is merely important. The organizing committee challenged the sub-group with a cost goal of $50M per TeV, and although neither option is sufficiently mature at this point to attempt any meaningful cost estimate, this figure gives an indication of the potential challenge facing the machine designers. The basic accelerator concept for an RLHC is perceived to be similar to today's machines: long repetitive arcs in a 2-in-1 magnet scheme with a few interaction regions encompassing the experimental regions and accelerator utilities. While a wide variety of design issues were covered during Snowmass by the working groups it was not deemed terribly important to produce any integrated RLHC design at this point in time.

The low-field option is essentially a direct attack on the problem on lowering the unit costs of the repetitive structures. Based around a novel 1.5 -> 2 T superferric 'double-C transmission line magnet', this approach offers the possibility of dramatically reducing the magnet costs per Tesla with a highly efficient use of superconductor and a simple magnet structure with most of the magnet warm. Since the field strength in a superferric magnet is limited, a long machine circumference is unavoidable (~600 km) and during the workshop low cost tunneling and magnet installation techniques were examined with both geological and tunneling experts. Other issues associated with a very large machine size involve the stored energy in the circulating beam arising from the large number of bunches, beam stability problems driven by the high impedance, and unit costs associated with the non-magnetic arc elements (instrumentation, vacuum, corrections etc..). Many innovative approaches were presented and discussed on these and other topics.

The high-field option follows a different line of attack from the low-field one. Based on an as yet unproven magnet operating at 12.5 T, this design relies on exploiting the emittance damping resulting from synchrotron radiation. With damping times in the 2-4 hr range the integrated luminosity during a 10-20 hr store is essentially independent of the initial beam parameters. Since the low field performance requires little more than getting the beam to 'stay in the pipe', cost savings are therefore hoped to arise from tolerance reduction in the emittance preservation requirements, field quality requirements, the use of a lower injection energy, and the shorter tunnel. Issues associated with this approach involve handling the radiated power into the bore tube (~1 W/m), ensuring acceptable vacuum in the presence of desorbed gases, and, of course, the dominant fact that there is no accelerator magnet capable of achieving the necessary 12.5 T field. The desired field strength and synchrotron heating lead naturally to a magnet approach based on high temperature superconductor (HTS) technology, but lower temperature approaches based on existing superconductors are possible though probably much too expensive.

A major topic of discussion throughout the meeting involved the potential use of HTS technology for future hadron machines. During the last several years great progress has been made in this area, and the possibilities of R&D efforts to develop these materials for magnet uses, received much attention. The low-field magnet design could potentially use a BSSCO material in a relatively straightforward way. This material is starting to become available in engineering quantities and is well matched to the lower fields and current densities in the superferric environment. A different material, YBCO, has promise for the high field magnets but is less advanced than BSSCO at this time and to date has only been produced in very thin films. The use of HTS technology is compelling. In addition to the increased cryogenic efficiency arising from a higher operating temperature, these materials have less sensitivity to operating temperature variations which can be exploited to greatly simplify the cryogenic system. The increased Carnot efficiency could also be exploited to simplify cryostat designs by tolerating a higher heat leak. The area of HTS was certainly identified as a key technology within the charge to this sub group for future efforts.

In addition to work focused on the two machine options, other more generic topics were worked on which would be suited to either approach. An analysis of interaction regions indicated that beta-star values lower than the normally assumed 20 cm appear feasible with a free space of ± 25 m and a quadrupole gradient of 300 T/m. With the inclusion of crab crossing schemes beta-star's as low as 5 cm appear possible with second order chromatic correction. Machine lattices with long arc cells have potential advantages including cost savings. During the workshop it was concluded that adequate beam dynamics performance could be achieved with cell lengths of the order of 500 m with the optimum length determined primarily by systematic rather than random field harmonics in the magnets. Beam stability appears to be a problem for the low-field option where the small bore tube and large circumference result in rapid resistive wall growth times. Single bunch stability may also prove to be an issue. One of the more interesting aspects of the machine parameters involves bunch spacing and intensity. For a given luminosity the machine design would prefer fewer bunches with more intensity to minimize stored energy and synchrotron radiation power. For reasonable parameter sets, the number of interactions per crossing varies in the range of 40 - 100, with the accelerator preferring the latter and the experiments presumably preferring the former. At this point in time there has been no consensus reached on the optimum values.

Various options for the vacuum system were investigated. Distributed pumping is needed in all cases but acceptable vacuum performance can be achieved. The warm bore tube of the low-field option simplifies this system. In the high field case cryo-pumping is needed for the synchrotron desorbed gas which limits the operating temperature to 20K or below. In the absence of HTS technology large cryogenic systems are unavoidable. While there does not appear to be any technical problems with very large cryogenic facilities the fundamental issue is, once again, cost. Other aspects of the machine design such as power supplies, quench protection, beam handling, and installation are covered in the sub group report.

In conclusion, one can say that while no technical problems have been found which would preclude the construction of a 50 x 50 Tev Hadron Collider, present day techniques are simply too expensive to be deemed viable in today's cost cutting climate. Fortunately there appears to be no shortage of ideas on potentially cheaper approaches which would benefit from R&D support. The single most important R&D topic at this time is the use of HTS technology in the area of accelerator magnets.

VI. ADVANCED ACCELERATOR TECHNOLOGIES SUMMARY REPORT

The advanced technology working group was charged with discussing and evaluating concepts for achieving 5 TeV center-of-mass e+e-g collisions with luminosity 10^{35} $cm^{-2}sec^{-1}$. The concepts were studied with particular attention to the gradient, emittance, efficiency & collective effects. From the discussions, promising R&D directions were identified and are reported in the summary paper for the subgroup. It should be emphasized the purpose of the group was to study the state of the field and discuss research directions and requirements. The level of maturity of the concepts and associated technologies varied greatly. None of the schemes was presented as, nor considered to be, at present, a candidate for a collider. Another goal of the group was to provide the opportunity for workers in the advanced accelerator areas to gain an appreciation of the requirements and concerns for the high energy collider, and, of course, for the more mainstream accelerator scientists to become acquainted with the exciting developments in the advanced accelerator field. We believe a sound basis for further collaborations between these groups was established.

Much of the motivation for re-examining the potential of advanced concepts at the 5 TeV energy scale arises from new results such as high-power, short-pulse, efficient lasers, phase, amplitude, and jitter control of T3 lasers, plasma channel guiding of laser pulses, demonstration of high gradient acceleration in Raman Forward Scatter experiments, microfabrication and wakefield instrumentation.

The areas examined were lasers and beams, laser wakefield acceleration, gamma-gamma colliders, RF sources (klystrons and gyrotrons), short-bunch wakefields, superconducting linacs and technology, THz radiation for accelerator applications, dielectric accelerators, and millimeter-wave accelerators and associated microfabrication technologies.

The discussions began with an examination of a variety of 5 TeV parameters. Among the consequences of this discussion was the conclusion that any approach to the 5TeV collider (that uses a "realistic" emittance and average beam power) pushes the IP parameters towards high Upsilon (intense Beamstrahlung at the IP) and pushes the accelerator towards short wavelength. Reports were heard on accelerator concepts ranging from conventional and two-beam accelerators at 30GHz, matrixed linacs at 90GHz, short pulse THz acceleration, plasma wakefield and electron beam wakefield accelerators, and dielectric accelerators from 100GHz to laser frequencies. Roughly, the gradients under consideration increase with decreasing wavelength of the accelerating structures. The 30GHz schemes envisioned gradients of order 80GV/m- 250GV/m, the 90GHz schemes, as well as the laser-dielectric schemes had 1GV/m, the plasma-based ideas envisioned around 10GV/m. The potential of high gradient superconducting structures and plasma-based injectors was also examined.

The concepts are at a different level of development and have a different set of near and medium term problems to address. For example, the high-frequency rf schemes have to study fabrication, breakdown and heating limits, while the laser wakefield schemes, which have achieved high field gradients in a plasma, must demonstrate the ability to accelerate a low emittance beam, to excite wakes in plasma channels over distances much longer than diffraction lengths, to couple efficiently to the plasma, etc. The power sources, rf and laser, also need substantial development to reach the simultaneous requirements of power, repetition rate and efficiency. The details of the suggestions for R and D can be found in the working group summary. Important themes were the desire for high luminosity without backgrounds from the beamstrahlung, and reduction of the enormous site power-levels. To compensate space-charge at the IP, neutral beam collisions were proposed, and plasma compensation was reconsidered. To reduce the site power requirement, beam-combining was considered, in conjunction with matrixed linacs. These techniques appear promising for short-wavelength linacs.

VII. REFERENCES

[1] NLC ZDR Design Group, SLAC Report 474 (1996).

[2] NLC ZDR Design Group and the NLC Physics Working Group, SLAC Report 485

[3] D. Burke, *Next Linear Collider*, Proceedings. of the 1996 DPF/DPB Workshop: New Directions for High Energy Physics, Snowmass, CO (1996)

[4] *The TeV2000 Committee Report*, Fermilab Internal Report, W. Bardeen, Chair.

[5] *Recycler Ring Technical Design Report, Revision 1.1*, Fermilab Internal Report, August 1996

[6] *The Muon Collider Feasibilty Study*, BNL-52503,Fermi-Conf.-96/092,Lbnl-38946, and on the CD of these Proceedings.

[7] R. Palmer and A. Tollestrup, these proceedings

[8] *SNOWMASS96 Session on Acceleration Systems for the Muon Collider*, D. Neuffer, these proceedings

[9] A. Garren and C. Johnstone, these proceedings.

[10] *Muon Collider Background and Detector Working Group Contribution*, Muon Collider Detector Sub-Group, these proceedings