May 17, 2007

To whom it may concern:

The report of the ILC Tracking R&D Review Committee is attached. The review was held during the Beijing ACFA/GDE Workshop in February, 2007. The World Wide Study R&D Panel, chaired by Chris Damerell of Rutherford Appleton Laboratory, UK, organized the review. The review was endorsed by the GDE, the ILCSC, ICFA, and the FALC. The review panel of experts on tracking included several consultants from outside the ILC community. The main goal for the review was to examine the efforts of the tracking R&D teams within the global context, to enhance communication, and to advance the R&D program toward timely completion on a time scale consistent with the ILC accelerator R&D program.

The review was a success, with helpful preparation in advance, and valuable interactions between the committee and the researchers during the meeting in Beijing. The committee recommendations have been given serious and thoughtful consideration by the R&D teams, and are certain to help achieve the goals for the review, namely advancing the R&D program.

Two of the R&D teams have prepared written responses to the committee report, which are attached to the report.

The World Wide Study is grateful to the Review Committee for their conscientious efforts and thoughtful comments and recommendations. The recommendations will now be considered carefully by the World Wide Study, in consultation with the R&D teams.

Sincerely,

WWS co-chairs
Jim Brau, Francois Richard, and Hitoshi Yamamoto

Attachments:
Tracking R&D Review Report
SiD Collaboration Comment
LCTPC Collaboration Comment

15 April 2007

ILC Tracking R&D
Report of Review Committee

Review dates: 5-8 February 2007
ILC Workshop, Beijing

1. COMMITTEE MEMBERS

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2. EXECUTIVE SUMMARY

The Tracking Review Committee studied the programmes of the three large R&D collaborations (LCTPC, SiLC and SiD tracking) plus one new idea (from the CLUCOU group). These cover the two main alternatives for ILC tracking, namely gaseous (central) plus silicon (forward), as opposed to an all-silicon system.

Most of the material presented focused on recent results and details of current R&D work, where impressive progress was reported. The LCTPC collaboration has lifted the TPC technology to new levels of performance by advances in gas amplification and signal detection systems (GEM, Micromegas and CMOS sensors) and is developing novel approaches to the gating grid needed to suppress positive ion feedback. They are making important progress in the *dE/dx* performance of TPCs. The CLUCOU group has revived interest in the large drift chamber approach, based on the very successful KLOE drift chamber. This approach raises the possibility of important reductions in the material budget, and freedom from positive ion feedback issues. However, it is important to study whether the space-time granularity under ILC operating conditions will be sufficient. The SiLC collaboration has drawn together a diverse community of silicon detector experts, and is exploring options of relevance both for an all-silicon system and for the silicon detector components of gaseous/silicon hybrid systems. They are following a rich programme of options for sensor and readout technology, including forward pixels being developed in conjunction with the ILC vertexing community. The SiD collaboration has made impressive progress in defining a comprehensive all-silicon tracking system, including many of the details which are needed to establish an ambitious material budget. Their R&D programme is supported by simulations of track reconstruction which can be expected to refine the design (number of barrel and forward layers really needed, balance between forward strips and pixels, etc).

These R&D programmes are in different ways all addressing the challenge that the ILC tracking system needs to achieve a major improvement in performance compared with all predecessors. Nearly 100% track finding efficiency is needed over the full solid angle, with momentum resolution an order of magnitude better than in previous detectors. Reactions including jets in the forward region will be particularly important, due to multi-jet processes where one or more happens to be directed forward, and to 2-jet processes where this region may be particularly sensitive to new physics. Hence it will be vital that the tracking system should for the first time perform as well in this region as in the central region. Given the excellent R&D work reported, the Committee is satisfied that many of the ambitious goals will be realised. However, there is a serious risk that the forward tracking may under-perform badly, as has happened in all previous energy-frontier detectors (LEP, SLC and the Tevatron), which would do major damage to a broad range of ILC physics.

The Committee recommends that the R&D programme of the ILC tracking community be expanded and focused so as to minimise the risk that the vital physics goals will be missed. Specifically, we consider it essential that large prototypes of both technology options (gaseous and silicon) be evaluated under realistic ILC conditions. By this we mean a test beam with the coarse ILC time structure (1 ms on, alternating with 200 ms off), with close-to-final mechanics, electronics and cooling, including the pulsed power operation that is mandatory to avoid the unacceptable material penalty of liquid cooling. We strongly recommend that these tests be carried out in a 3-5 T magnetic field, in order to avoid the risk of numerous unpleasant surprises in real ILC detectors. These tests should be completed during 2010 or 2011, in order to allow tracking options to be selected that will adequately serve the physics needs. In particular, the goals for material budget for one or both approaches may be too optimistic, so that what proves to be sufficiently robust and stable may need to be so massive that the physics reach, particularly for forward jets, is severely diminished.

The committee believes that some of the current R&D activities (studying fine details of GEM/Micromegas performance differences, studying features of 3-D silicon that are unlikely to be applied in ILC, etc) could be deferred, in order to move forward at full speed to the large prototype system tests.

Building up the infrastructure needed for these tests within the next 3 years will be challenging. Fortunately, the essential components of the expensive infrastructure could be shared by all R&D collaborations. We therefore suggest that they form a *Tracking Coordination Group* (TCG) to plan, implement and manage the use of these facilities. The final output from this group, in around 2011, should be a report of the performance actually delivered, so that a safe extrapolation can be made to what could be achieved by a full sized tracking system built with any of the candidate technologies. This TCG report should provide the input needed to determine how well a given combination of vertex detector, tracking system and calorimetry will address the ILC physics issues.

As well as being responsible for the shared infrastructure, a second important function of the TCG will be to improve the horizontal integration of the work, encouraging a better exchange of information between the different R&D collaborations. This would cover common engineering problems such as pulsed-power operation, support materials, and cooling concepts.

A third function of the TCG would be to encourage the simulations needed for the formulation of the tracker requirements. For example the need for stereo information in an all-silicon tracker, the required material budget in both the gaseous (instrumented endplate) and the silicon tracker and the effect of the expected beam-related backgrounds on the tracker performance are not well determined at this time.

The programmes of the R&D groups, expanded to produce large prototypes by 2010/2011, will require increased resources. The infrastructure to test these prototypes, including the high field solenoid, will further increase the requirements. The committee is convinced that providing these resources will be fully justified by the physics rewards that will result from the successful completion of this programme. There needs to be a concerted and coordinated effort by all funding agencies and labs. It should involve the TCG, since priorities need to be set to assure that the vital problems are investigated and solved.

If it turns out that fortunately one can build an ILC tracking system of comparable performance using either of the main candidate technologies, one can expect the existing R&D groups to lead the construction of the different tracking systems, one in each experiment collaboration. However, if the results strongly favour one technology, this outcome should be respected. For this reason, while the forthcoming detector designs will assume certain tracking technologies, we recommend that *the definitive selection of these technologies be dependent on* the large prototype tests to be completed in 2011, when it will be possible to base the choices on proven performance rather than on incomplete and possibly over-optimistic estimates. Such flexibility can be achieved by the designations 'baseline' and 'alternative' as used in the ILC machine development.

A one-sentence summary of our recommendations: *Form a Tracking Coordination Group to coordinate the completion of the R&D programme, so that the choice of tracking technologies for ILC detectors can be made on the basis of these results.*

3. INTRODUCTION

The WWS-OC asked the Detector R&D Panel to organise regular reviews of Detector R&D, to be held in conjunction with the regional workshops (3 per year). This report documents the recommendations from the first of these, on ILC tracking. We define the 'tracking system' to comprise the combination of central tracker and forward tracker, in other words, the gaseous tracker plus silicon system in one concept, and the all-silicon system in the other. The aim of these reviews is to understand the activities of the numerous groups undertaking ILC detector R&D round the world, and to assist them to follow a timely path to completion of their work. In the case of tracking, for each R&D collaboration, completion of work is defined as:

evaluating the performance of a large tracking prototype with respect to all relevant criteria, in sufficient detail to determine the performance of a full-scale detector constructed with this technology.

- The verb 'evaluate', according to the Oxford English Dictionary, means 'to determine the numerical value of'. It does not mean, as one collaboration member feared, to assign a value judgment as in 'good' or 'bad'.
- 'a large prototype' means of a size sufficient to permit reliable extrapolation to the full-scale detector. Details to be worked out with the collaborations.
- 'all relevant criteria' includes tracking precision, mechanical stability, effects of operation in a 3-5 T field, effects of coarse beam bunch structure (1 ms on, 200 ms off), effects of pulsed power including mechanical vibrations, cooling system, material budget, sensitivity to electromagnetic interference during the ILC bunch train, sensitivity to erratic bunches (so-called 'fliers'), etc. Details to be worked out with the collaborations.

There was unanimous agreement between the committee and collaborations that completion of the work as defined above, should be achieved by 2010/2011. In the mean time, we understand that detector designs based on the two main tracking options are likely to be developed to the level of engineering designs, as is under way for the accelerator. This being the case, these designs should be regarded as 'baseline' tracking options, with the other options being considered as 'alternatives', where the eventual decisions should be guided by the results with the large prototypes.

There is of course the question of obtaining funding for the critically needed infrastructure, but this should be a soluble problem. If the accelerator R&D is to be funded to the level needed to complete the Engineering Design by 2010, it should be possible to find the resources needed to complete the critical tracking R&D on the same timescale. Results of the tracking R&D programme are as important as those for the accelerator, in order to permit the construction of the accelerator and detector systems in phase with one other.

The ILC tracking requirements cannot be considered purely from the viewpoint of the tracking system. The vertex detector on the inside, and the ECAL on the outside, play essential roles. Most tracks will be found and measured with high precision in the vertex detector consisting of concentric barrels and possibly forward disks. With its $\sim 10^9$ pixels, the tracks it finds will be extrapolated outwards with very high precision. For these tracks, the function of the tracking system is mainly to determine precisely their momenta and provide linkage to the ECAL. However, some primary particles (K_s^0, Λ^0 , several percent of *B* and *D* baryons) live long enough to fly through the entire vertex detector, so that their decay products should generally be found in the outer tracker, central or forward. Even if this is unsuccessful, these tracks may be found from the stubs left in the highly segmented ECAL. Viewing the tracking system as a 'momenter' may be a reasonable first approximation, but this is a seriously incomplete picture. For example, low momentum tracks from jets at all polar angles generally leave hits in the vertex detector, then curl into the forward tracking system. Finding these tracks in the vertex detector alone may be excluded for most vertex detector options, since extrapolation uncertainties induced by multiple scattering lead to numerous fake tracks, so a combination of vertex detector with forward tracking will be obligatory for track finding in this region. If the most ambitious vertex detector option with single bunch timing capability can be realised, even these tracks may be found without the help of forward tracking, but at present it would be unrealistic to assume this.

Even disregarding late decays and low p_T tracks, the separate track finding efficiencies of the vertex detector and outer tracker will of course each fall short of 100%, partly due to possible technical failures of parts of these systems. The redundancy provided by two track finding systems operating independently *on the same tracks* provides a powerful diagnostic and a means to compensate for inefficiencies which would otherwise bias the physics.

Simulations of the full track reconstruction are still at an early stage, particularly in conditions of realistic background. For this and other reasons, firm performance requirements for the tracking system are not yet available. There is considerable uncertainty regarding the degradation in physics potential resulting from a given material budget, and this is a particularly serious issue in the forward region, where there tends to be an accumulation of material. It is clear that excellent tracking performance in the forward region is obligatory, since many important physics processes result in multi-jet events, and the probability of one or more jets being in the forward region is high. Furthermore, much 2-jet physics is sensitive to the region of small polar angles, particularly in reactions which depend on the longitudinal polarization of beam electrons. For various reasons, previous e^+e^- collider detectors (LEP, SLD) have performed poorly in terms of forward tracking, so we need a major improvement in performance at ILC. Whether any of the tracking systems currently envisaged will deliver this is an open question. The performance will inevitably be degraded by material, specially since the purpose of the tracking is partly to work with the calorimetry for particle flow. For example, a charged pion which undergoes charge exchange scattering in material at the end of the tracking system, thereby throwing photons from decay of one or more π^0s into the ECAL, is guaranteed to increase the confusion term in the jet energy determination. We need to see plots of the jet energy resolution as function of polar angle, for different tracking systems with different material budgets, in order to evaluate the magnitude of such effects. Groups are currently working towards such simulations, but are not there yet. This is not an unreasonable situation; the R&D collaborations know that they should minimise the material budgets in their large prototypes, and by 2010 we will surely know what is the cost of an additional 0.1 X_0 in material, in different regions of the tracking system. Armed with data from the tests of the large prototypes, and results from these simulations, the ILC community will have the information they need to choose a tracking system that best satisfies the physics requirements.

One concern expressed in the review was that this approach to ILC tracking may push in the direction of one detector rather than two. This is not the view of the committee. Even if the outcome of the R&D eventually favours only one tracking technology, it would be appropriate to use that technology in two detectors, as with ATLAS and CMS. There would remain many areas of potential complementarity, such as vertexing and calorimetry, possibly associated with different classes of physics. In the opinion of the committee, it is dangerously premature to be speculating on the outcome of R&D programmes which are currently in full flow. The results of these programmes are needed in order to have a rational discussion about the optimal design of two ILC detectors, with differences in some but not all subdetector technologies. At present, we are a long way from knowing what these optimal combinations of subdetectors will prove to be. In our review, we aimed to help the tracking R&D collaborations prepare the ground for all essential information to be accumulated by 2010/2011.

4. REVIEW PROCESS

Outline plans for the tracking review were announced to the community at the ILC workshop in Vancouver, in July 2006. There followed a lengthy period of negotiation, in which the WWS-OC was heavily involved, in order to reach agreement regarding the review procedure. This was finally achieved during the ILC workshop in Valencia, in November 2006. Guidelines for participating groups, based on these agreements, were published on 30 November 2006 [1].

According to the survey carried out at the end of 2005, the ILC tracking R&D was in the hands of 3 major collaborations (LCTPC, SiLC and SiD tracking), plus seven disconnected groups. By the end of last year, these separate groups had found shelter within one or other of the main collaborations, which was already a positive development, resulting in a more coherent R&D programme. Meanwhile, a group advocating a new idea has joined the work, the CLUCOU group from Lecce, and they were considered separately in our review.

In the guidelines, we asked all groups to provide written reports covering specific aspects of their work, with a deadline of 28 January; all 4 reports were received within a day or so of this deadline. These reports were uploaded to a password-protected Wiki site [2], accessible only to the Committee members. By agreement with the collaborations, others with a need to know may be given access to these reports. Since they contain possibly sensitive financial information, we agreed not to make them public. The collaboration reports were received in time to be studied before the start of the review, for which the committee was most grateful.

The review was scheduled to begin on the second day of the ILC workshop in Beijing. This gave all committee members, including the consultants who were not ILC 'insiders', the opportunity to follow the plenary talks on the opening day, thereby gaining a valuable overview of the ILC project. The first phase of the review consisted of open session presentations by all the collaborations and the CLUCOU group. The main collaborations were allocated 2 hours for their presentations, to be organised as they saw fit, followed in each case by an hour for discussion. Timekeeping by the speakers was patchy, so that in one case all the discussion time was eaten up by presentations. Slides of these presentations can be found at [3].

The second phase consisted of a closed session in which committee members were able to question representatives of each collaboration in turn. In principle, this gave the opportunity to discuss confidential matters such as funding, but since we were furnished with this information in the reports, and since there were many technical questions left over from the open session, this is how the time was spent. Here we profited enormously from the presence on the committee of an impressive array of world experts in tracking systems, so that valuable dialogues resulted. An important feature was a dinner of the committee with the collaboration representatives, which resulted in continuing informal discussions, in which a number of key issues were resolved between the various experts from both sides.

The open and closed sessions were interleaved with executive sessions, in which the committee formulated plans for our recommendations, some of which were of general applicability, and others were specific to individual collaborations. This needed significant thinking time, and in the opinion of the committee, fully justified the pace of the review, which spanned 4 days in total. The 4th day (morning only) was devoted to a closeout session with each collaboration. We first told them of our general recommendations (see Section 5), and invited feedback. In one case, this resulted in a lengthy discussion, which mainly consisted of our explaining in more detail what was intended, rather than trying to impose an unpopular plan of action on them. The discussion of these general recommendations necessarily took priority, so there was not time to discuss the collaboration-specific issues in detail. This may have been a good thing, since most of those issues needed time for thought on the part of the collaborations. We supplied them with the comments and questions from expert committee members, and gave them a week to respond. The results of this activity are reported in Section 6 of this report.

Since this was the first such review with a fully international composition, we anticipated that there could be problems, and that we might need to revise the procedure significantly in future. However, discussions within the committee and with the collaborations have been extremely positive. Everyone who was closely involved seems to be well satisfied with the procedures, and nobody has proposed major changes in future. It seems that this general format and level of detail is about right. However, we would in future urge all the collaborations to take their time allocations seriously, and resist the temptation to present more material than can be reasonably fitted within these allocations. The committee is of the opinion that 2 hours should suffice for presenting the key points, even in the largest collaborations where a wide diversity of work needs to be reported.

5. RECOMMENDATIONS (GENERAL)

In the guidelines for the collaborations, we asked them to provide an overview of the goals, starting from where they are now, up to the completion of their R&D programme, ready to start construction with a frozen design and proven manufacturers. By common consent, the completion of the R&D to the point where an experiment collaboration could responsibly establish their tracking technology, should occur approximately in phase with the completion of the Engineering Design for the machine, currently planned for 2010. Of course, this date may slip, but in the opinion of the committee, it would be irresponsible to plan on such slippage. Therefore, we were very interested, for each collaboration, to learn how they plan to reach this stage of development on this timescale.

The committee was particularly interested in the *systems engineering*, and considered that urgent consideration now needs to be given to these aspects; see the list of 'relevant criteria' noted in Section 3. We were concerned that some of the R&D goals asserted by collaborations as sufficient to move into detailed design of an ILC detector, were too modest. The currently available resources are mostly in the form of salaries, and are allocated to specifically approved R&D projects, some of which are linked to applications other than ILC. For this reason, there is little flexibility to transfer funds to purchase new equipment such as a large volume solenoid. Furthermore, the geographical distribution of these resources is extremely variable. In particular, the budgets for North America are totally inadequate. Building up the infrastructure will make sense only when the collaborations are being supported sufficiently to sustain their core R&D programmes.

Before thinking about how to provide this infrastructure, it will be necessary to define precisely what is required. For example, if we have a test beam with 1 ms on and 200 ms off, is it acceptable to accumulate 10% of the 'on' flux during the 'off' periods, or should it be 1%, or what? How large do the 'large prototypes' need to be, in order to answer the critical questions before designing the full-scale ILC tracking detectors? The committee is convinced that the large prototypes will need to be tested in beam, within a 3-5 T solenoid, probably of the split-magnet types, so as to allow appropriate beam entry and exit apertures. What solenoid parameters are needed to satisfy both kinds of detectors, gaseous and silicon?

To answer such questions, and to facilitate the realisation of the system tests, the committee decided unanimously to recommend the setting up of a *Tracking Coordination Group* (TCG), with responsibilities along the following lines:

- agree on all the criteria that are of high priority in choosing a tracking detector technology for ILC, setting aside those that are not (here they will need to use information from the concept groups, physics studies etc)
- define the infrastructure needed to carry out the performance evaluation, for each detector technology
- work together to build up this infrastructure (by making joint proposals to their current funding agencies, discussing with directors of host laboratories, and maybe beyond)
- plan the use of these facilities (scheduling, etc) as the critical time period 2010-2011 approaches
- plan uniform procedures for measuring and reporting performance, regarding each of the relevant criteria
- support information exchange on common problems such as pulsed power operation, power and signal distribution, mechanical structures, cooling, shielding etc.
- incorporate other items forgotten from this list

We should emphasise that the infrastructure applies not only to test beam equipment. The solenoid tests will surely be done some with beam and some without. For example, measuring mechanical vibrations under the impact of pulsed power in the solenoid may be adequately (or better) measured with optical monitoring equipment than with beam. Another issue unrelated to test beams is sensitivity of detector systems to electromagnetic interference (EMI) which is likely to be a potentially serious problem during the ILC bunch train. Detector electronics that needs to be active during this time should be evaluated and if necessary modified or redesigned accordingly. Having a calibrated, properly equipped anechoic chamber in which these tests can be carried out objectively, will do a service to both tracking and vertex detector communities, and is hence suggested as part of the TCG responsibilities.

Other opportunities for coordination will surely present themselves, related to cost-effectiveness rather than to explicit R&D challenges, such as the possibility of a common DAQ system, ideally shared between the tracking and vertexing R&D groups.

The functions of the TCG will be similar to those of the 'task forces' which are working so successfully for the ILC accelerator R&D. For the detector community, the term coordination group was preferred, at least by this committee. By analogy with the accelerator task forces, we suggest the composition of this group could be:

representatives from the ILC Detector R&D Panel, for each of the main tracking collaborations (Dean Karlen, Hwanbae Park and Harry Weerts for the LCTPC, SiLC and SiD respectively) two further representatives from each of these collaborations, plus one from CLUCOU

The functions of the TCG have a large overlap with the Vertexing Coordination Group (VCG) which has recently formed with encouragement from the Detector R&D Panel and WWS-OC chairs. To ensure cross-communication between the two groups, it was suggested that the chair of the VCG should be a member of the TCG, and vice versa.

There needs of course to be a close connection with the group currently planning future ILC test beam facilities, and this might also be best achieved by cross-membership between these groups.

In the closeout session, we discussed the formation of the TCG with all the collaborations, and with the CLUCOU group. All except one were immediately enthusiastic, while one started (understandably) by querying the need for 'yet another committee'. During the preparation of this report, they too have offered their support to the TCG. Our Review Committee contained some world experts on the development of large tracking systems such as those needed for ILC, and it is surely significant that the formation of the TCG was considered to be extremely desirable by these experts. One of them expressed the opinion that the R&D collaborations 'will thank us for having pushed it'.

Of course, this can only become a reality if endorsed by the WWS-OC, and if the R&D collaborations decide to make it happen, since the TCG will be composed of 'their' people. Getting such a group to work together at the fully international scale could be a challenge, but one for which the ILC accelerator community has already provided a number of successful examples. Judging from their task forces, meetings at approximately 2 week intervals would seem appropriate, but this is something to be decided by the Tracking Coordination Group when they first meet. The Tracking Review Committee believes that forming the TCG overrides in importance all our detailed suggestions to particular collaborations, since it should lead to a coherent and objective evaluation of large prototypes, under conditions which will allow their potential for ILC tracking detectors to be fully determined.

The Tracking Coordination Group should be largely self-organising, beyond the broad terms of reference suggested above. However, it will need to be linked to a higher authority, for example in situations where it has difficulty obtaining the resources to build up the necessary infrastructure. In the case of the accelerator task forces, this link is provided by regular reporting to the GDE-EC, typically at 3 month intervals. Given the close links between the GDE-EC and the labs and funding agencies, this approach has proved to be extremely effective.

As noted in Section 3, even when the properties and technical performance of a candidate tracking system are well defined, the performance for physics depends on the simulation in an assumed overall detector, including vertex detector, ECAL, etc. Such simulations are the responsibility of the detector concept groups, not the detector R&D groups, but clearly both must communicate closely to ensure that the simulations reflect a realistic configuration, especially as designs evolve. The software is currently under development, and could not yet quantify the physics benefit of (for example) reducing the thickness of the TPC endplate by say 0.1 X_0. However, rapid progress is being made, and we can trust the developers of these tools to have them fully functional well before the studies of large prototypes are completed. Both are essential, and some of the studies (stereo, forward region design) need to be completed before large-scale prototypes are being built.

Finally, the performance of a tracking detector for physics depends on the nature and magnitude of backgrounds to be encountered at ILC. Evaluating these is the responsibility of the detector concepts, in conjunction with Machine-Detector Interface Task-Force S4. This work has been going on for many years, and continues today with an everincreasing degree of realism. With one exception, results are probably adequate for simulating the tracking system. The exception relates to the problem of errant bunches (so-called 'fliers' in SLC) that could trip the main high voltage of a gaseous detector. If these occur too often, they would be a major incentive for an all-silicon tracker. S4 will make a systematic study of this risk. With recent changes to the ILC design, such as central damping rings, some potential sources of fliers can be eliminated. The fast intra-train abort limits the potential damage to one bunch. Seriously errant bunches could be produced for example by failure of a chunk of RF during the bunch train, so one should not be complacent. However, by the end of the ED phase, we can be confident that S4 will be able to quantify the risks, and hopefully give the all-clear for the use of a gaseous tracking chamber at ILC. Furthermore, not all gaseous trackers will be as vulnerable as was the SLD drift chamber, so the probability of damaging events may be significantly reduced by optimised detector design.

6. RECOMMENDATIONS (SPECIFIC)

6.1. LCTPC

We order our comments roughly within the phases defined by the collaboration:

Demonstration phase (ongoing work with small prototypes)

LP1 (2006-2010) [LP = Large Prototype]

LP2 (2010-2011)

6.1.1. Demonstration phase

We congratulate the collaboration on a large and diverse R&D programme which has yielded many interesting results over a number of years. Our main concern is whether the diversity of options will be sustainable all the way through till an experiment collaboration makes a choice between GEMs, Micromegas, CMOS sensors, and numerous lesser options which continue to be studied in parallel, such as the gating grid. We wonder if the chances of a TPC tracker being selected might be enhanced by a more focused R&D programme, but it is for the collaboration to judge in detail when and if some options might be classified as 'alternatives', in the interests of faster overall progress towards the critical goals. Alternatives could still be considered for future upgrades. Some of the open issues for this phase clearly could be of major benefit, such as the resistive anode charge dispersion, if it can reduce the number of channels, while not degrading the 2-hit resolution.

In parallel with the small-scale R&D, an issue that seemed to us to need urgent attention was an outline system design to the level of detail that a preliminary assessment of the buildup of material in the instrumented endplate could be made. We have no idea, from the information reported to us in this review, whether the stated goal of the collaboration 'to keep this well below 30% X_0 ' is even close to being achievable. In the opinion of one experienced consultant, they could easily be off by a factor of 2-3. As just one example, the only safe solution for the gating grid so far identified may be wires. Would the forces associated with such a wire plane be compatible with the requirements for mechanical stability of the ultra-thin endplate? Some basic mechanical engineering studies of such issues seem to be urgently needed. Picture an instrumented endplate of 3.2 m diameter with a high density of stretched wires (gating grid), foils (GEM or other), readout chips, wiring appropriate for 50 kW peak power, adequate cooling, etc. All this needs to be supported with a high degree of rigidity, in the face of the hammering at 5 Hz due to the Lorentz forces from the pulsed power in the 4 T field, plus the thermal shock associated with the peak power dissipation. It is far from clear to us what material budget will be required to do this in a properly engineered system, but some indications from a structural engineering study could be extremely informative.

End-plate design must also accommodate the requirements of the front-end electronics and vice versa. These new designs place much higher demands on the electronics and packaging than previous systems, so the details of the front-end ICs together with the endplate layout must be considered as a system. Initial versions of the readout ICs should be incorporated in TPC prototype tests as soon as possible to address potential surprises early on. Regarding the CMOS pixel option, the system of ~$6x10^9$ pixels would not be outrageous by 2020, judging from the growth of mosaics in astronomy and particle physics tracking detectors, so the main challenge is probably in the non-standard features needed to integrate the required gas gain in front of the silicon pixels. Good progress has been made, and solutions to the breakdown problems are being found. However, once robust small systems are operating, there will remain a major challenge to engineer the full-sized structures, given the constraints of mechanical stability, pulsed power in a high magnetic field, etc. After assessing the overall project challenges, it might be wise to consign this to the 'alternative' category, considered for a possible upgrade beyond the baseline detector for which the proof of principle needs to be established within the next 4 years.

There follows a list of detailed questions which we believe to be critical for the proof-of principle of the TPC tracker. Due to the stringent requirement on position accuracy (100 μm or better throughout the sensitive volume) several major issues should be addressed. Pending an extensive prototype test in realistic emulated conditions (high magnetic field, pulsed beam with ILC time structure, see main recommendations) we suggest the following laboratory measurements and verifications, organized and shared between participating groups. All apply to both the Micromegas and GEM (hereafter named MPGD) approach, and should be organized with a common protocol to allow comparison of results.

1. Pulsed beam: study of the reaction of the MPGD on a sudden surge of ionization. With the intricate HV multi-electrode distribution system in a TPC in the field cage and in the MPGD, with several RC constants, a local pulse-induced discharge could lead to unbalance with irreversible damages, or at least wipe all the burst data, given the typical recovery time of HV power supplies (~1 ms). After defining the expected ionization rate (including background) in “good” and “bad” conditions, the detectors should be exposed to an equivalent pulsed flash of radiation (light? X-rays?) while monitoring their main properties (gain, current, position accuracy with collimated X-ray source,..). As MPGDs are notoriously prone to discharge on high local charge densities, particular attention should be given to the effect of heavily ionizing events, such as n-p reactions. An emulation with a neutron beam or an alpha-emitter (for example ^{220}Rn gas in the detector) is highly advisable.

2. Positive ions:

2A: Gain and/or position resolution changes due to charge built-up in the MPGD; this can be an outcome of the previous point, and/or verified separately flooding the detector with a source while monitoring gain and position of a collimated beam/source.

2B: Track distortions induced by positive ions backdrift. Although there is general agreement that they will be unacceptable without gating, a (simple) electrostatic simulation of the effect should be done to confirm the need of this complication. Concurrently, a dedicated prototype to measure the effect and test gating structures should be made. As foreseeable gating structures (wires, grids, GEM) affect also transmission and positioning of the drifting electrons, affected by magnetic field, the measurement should be done in a magnet with strength as close as possible to nominal. DC transmission can be measured easily from currents, while for pulsed gating some pulsed source should be made (see point 1).

3. Medium and long-term stability: verification of main detector performances and operating parameters (drift velocity, gain) as a function of expected variations of temperature and pressure. Together with simulation of track distortions due to field misalignment, the data can be used to define the required tolerances (e.g. in the temperature gradient over the volume) and the calibration and monitoring protocols.

4. Response uniformity over large areas: gain as a function of position, with particular attention to the edges in composite end-plates. This should include a realistic estimate of the response changes due to external factors (pad surface and capacitance, amplifiers gain, temperature gradients on the readout boards….) and is a combination of measurements and simulation.

6.1.2. LP1 (2006-2010)

Preparations for this Large Prototype phase are well under way. The DESY test beam, 1 Tesla PCMAG solenoid, and endplate connected by cables to bulky remote electronics, represents a significant but very partial step towards the essential demonstration system.

6.1.3. LP2 (2010-2011)

This is the prototype that should determine whether a TPC central tracker can satisfy the ILC physics requirements. For the first time, performance will be evaluated in a high energy hadron beam (Protvino and Fermilab are both mentioned, but the latter seems more probable given the other infrastructure required, which should best be shared between collaborations). Furthermore, we hope that the Fermilab beam will provide the coarse ILC time structure which will be needed to truly demonstrate the stability of the TPC under these conditions. Tests in a higher field solenoid are mentioned, which harmonise with the general recommendations of this committee. The collaboration proposes to construct LP2 with lightweight materials and with miniature electronics integrated onto the endplate, as will be needed in the production version. In order to satisfy the material budget goals, avoiding liquid cooling systems, the electronics will need to be operated with pulsed power. The instrumented endplate and other components of LP2 should be weighed prior to assembly, in order to establish the actual material budget for this tracking system. This should then allow a plausible extrapolation to the full-sized TPC that would be needed for ILC. [This suggestion applies to all large prototypes. There are numerous examples in real experiments where the material budget in the simulations proved to be a serious under-estimate, due to engineers needing to add strengthening ribs, glue, metal screening plates, etc, in order to build a working detector.]

A major concern of the committee is that the current plans for LP2 could well prove to be too little too late. There could be many problems associated with this very large step in the R&D programme, even if only pursued with one option of gas multiplier technology, whereas three are envisaged. Leaving time for only one attempt at this phase, to be followed immediately by the final design of the TPC in one of the real ILC detectors, seems too optimistic. We suggest bringing the start of the LP2 phase forward, so as to design, construct and test some of the critical elements of a lightweight instrumented endplate during the LP1 phase.

6.2. CLUCOU

This group offers an interesting option for a gaseous central tracker, should technical problems such as positive ion feedback or the thickness of the instrumented endplate prevent a TPC tracker from achieving the performance goals. This is not the first collaboration to consider a large drift chamber, an option which was explored with considerable success over a number of years by the GLD collaboration. Currently all concept studies which prefer gaseous trackers (LDC, GLD and 4th) favour the TPC approach, and the CLUCOU group forms a subset of the 4th Concept.

What is particularly new is that this option is based on the very successful KLOE drift chamber, one of the largest, highest performance and most transparent tracking chambers ever constructed. Use of helium as the chamber gas reduces the material and (because of the low drift velocity) opens the door for cluster counting, which might improve the space-point precision from ~120 μm down to 50 μm, as well as providing enhanced *dE/dx* performance, mainly at low momenta. Even without cluster counting, the momentum resolution is calculated to be similar to that of the TPC option.

The KLOE chamber construction suggests that a thickness of instrumented endplate of 15-20% X_0 may be possible, which might prove to be a considerable improvement over a TPC.

Against these possible advantages, this approach will be more vulnerable to high background than the TPC, with its high density of voxels, whereas the drift chamber integrates background over the full length of the chamber. Even here, the comparison is complicated, because the TPC integrates background over about 150 BX, as the voxel drifts towards the end of the chamber, whereas the background in the DC is restricted to a single bunch crossing. Estimates currently made by the group suggest about 15% occupancy using small cells (4 mm hexagons) for the inner part of the chamber, which sounds promising. However, simulations are needed to see how bad the situation may be in the core of high energy jets, where some tracks could be unresolvable over the inner region. Even so, as with the TPC, it is the overall performance in conjunction with the vertex detector which really matters, so simple calculations tend to give misleading results. It will be very interesting to see what emerges from detailed simulations within the next year or so. One should also remember that a very high density of information from the central detector tends to come at a price in terms of the material in the instrumented endplate, thereby degrading the forward tracking performance. Striking the right balance between central tracking and forward tracking is one of the key unexplored areas in the optimisation of the ILC detector system.

All the possible weaknesses of this approach identified by our committee are on the to-do list of the CLUCOU collaboration for simulations and/or experimental study, much of it for other application areas. Over the next year, they hope to establish in detail the viability of this approach. They welcomed the opportunity to join the coordinated tracking efforts for ILC, and looked favourably on the possibility of building a large prototype and testing it under ILC conditions, should the necessary infrastructure become available.

In summary, the CLUCOU group has only recently started to explore this approach to ILC tracking, in the light of a potential requirement which could prove to be serious. This review was obviously too early for an in-depth study of this approach, but the committee supports the scientific case, and looks forward with interest to the future evolution of this R&D programme.

6.3. SiLC

This collaboration provides a very broad programme of R&D in silicon detectors. Much of their work fills important and unique requirements, such as exploring precisely what silicon tracking system will be needed in conjunction with a gaseous central tracker, and the beginnings of an in-depth study of the requirements for forward silicon tracking, whether in conjunction with gaseous or silicon central tracking systems. Here, in parallel with the SiD collaboration, they are entering new territory. As previously commented, forward tracking has never been made to work properly. This work will need large scale prototypes in appropriate beam tests, to establish a viable solution to this most important problem. A few aspects of their R&D programme appear to the committee to go beyond the likely areas of relevance to ILC; specific examples are mentioned below.

6.3.1. Mechanics, cooling and alignment

For the gaseous central tracker, they consider a silicon envelope comprising barrel SIT and SET, respectively inside and outside the TPC radial coverage. Since a major issue with the TPC alone is the material budget, and since the vertex detector provides superb pointing accuracy for tracks emerging from the IP, the need for these additional barrels should be considered carefully. Similarly, they consider a large forward disk (ECT or endcap tracker) behind the TPC. Since this will be followed immediately by the highly segmented ECAL, and since this detector would sit in the shadow of all the material of the TPC instrumented endcap, the usefulness of this detector also needs careful justification. Extensive simulations by the SiLC collaboration have already provided some of this. Issues such as improved momentum resolution, improved angular coverage, calibration of the TPC, and redundancy in case of partial failure of a region of the gaseous detector, are all valid reasons in favour. The eventual balance of arguments for and against this envelope will be decided by their ongoing simulations and R&D studies.

The SiLC collaboration also has a strong interest in an all-silicon tracker, where much of their R&D on sensors, mechanical supports and electronics complements that of the SiD collaboration, and hence strengthens the overall programme. This is most apparent in the vitally important forward tracking detector (FTD), where they are making important contributions to the design of this complex system of inner pixel disks followed by disks of strip detectors. Material budget is very important, mechanical support structures are challenging, and it is a major task to establish a system that will achieve efficient track reconstruction in this region of high background, and unfavourable orientation of solenoid field with respect to jet directions. For the pixel sensors, they are keeping closely in touch with the developments for ILC vertex detectors, which should eventually provide the best available solution for their inner disks. For the strips, they are following a systematic approach of exploring different strip pitches, lengths and orientations.

For a central silicon tracker, they are exploring a variety of options, including the interesting case of long ladders with thin sensors having electronics only at the outer ends, taking advantage of the relatively relaxed bunch timing at

ILC, aiming to reduce the material budget below what is achievable with more conventional approximately square modules. This is opening the field to more innovative mechanical support structures. It is in the interests of the silicon tracking R&D to have these studies pursued in parallel with the contrasting SiD approach, since at this stage it is unclear which is more likely to provide the higher performance system. Their systematic exploration of different substrate materials and adhesives is of general benefit to the community.

Their work on alignment is also breaking interesting new ground. They will characterise the well-developed frequency-scanned interferometry approach (FSI) for the ILC environment, where the pressure on material budget implies that solutions that worked elsewhere (notably in ATLAS) would be disfavoured. Furthermore, their study of the hybrid approach pioneered for AMS-1, which promises to avoid mechanical transfer problems that limit the precision of FSI, is particularly interesting for all-silicon tracking systems at ILC and elsewhere.

Some of their programme is devoted to R&D on water cooling, which should not be needed if pulsed power is adopted. Should this approach fail, the tracking system would need a complete redesign, so it was not clear to us that there would in any case be a role for the current all-silicon layout with water cooling tacked on. If this is to be taken seriously, it would be important to produce a simple comprehensive thermal model that supports this scenario, before working on details of a water-cooled design.

They list work on push-pull operation among their mechanical R&D topics, and this is certainly important. Lessons can be learned from SLD, where repeated door openings provided experience in the sort of mechanical disturbances to be encountered. This is an example where the SiLC studies should be relevant to the mechanical design of all ILC tracking systems that will be subjected to this mode of operation, should it be finally adopted by ILC. Establishing mechanical design principles which are sufficiently robust, and which avoid badly degrading the material budget, is an important and urgent goal, since the move towards push-pull operation is already far advanced.

6.3.2. Sensors and modules

This collaboration has an impressive diversity of links to numerous foundries for sensor production, including ETRI in Korea, which is exploring novel approaches to sensor processing. However, the collaboration should keep in mind that at the end of the R&D phase, they will need to have an established fabrication programme with a major commercial supplier who can manufacture, QA and test the required number of wafers (20k?) in a timely manner. The current concerns about double-sided sensors are based on a body of experience which may be less relevant in 5 years when construction begins. The ongoing work of this collaboration will ensure that when the time comes, the ILC tracking community will be well positioned to build the silicon systems with optimised sensor designs.

The approach of long shaping time electronics, which is particularly explored by this collaboration, has major implications for the sensors, which are investigated as part of a coherent overall package. The relationship between strip resistance and noise sets fundamental limits on ladder lengths, but longer shaping times offer flexibility beyond what is possible with shorter bunch crossing intervals, so conditions at ILC are considerably more favourable than at LHC.

The work on reduced thickness sensors, could pay dividends in terms of the material budget of the final system, although the reduced signal-to-noise has to be evaluated. The contacts with high-volume manufacturers about production on 8 inch wafers should be continued, to find out soon if this is a viable alternative. The work on IR-transparent sensors is particularly interesting, in order to make the most of the hybrid alignment option. The committee was less convinced of the relevance for ILC of the work on 3-D and active edge sensors, but understands that this is a by-product of R&D for other applications. Similarly, we had difficulty understanding the interest in DC coupled sensors, since the additional costs of AC coupled devices would pay dividends in terms of robust functionality, unless used for a specific function, such as the charge-division concept tried within SiD.

Regarding the pixel sensors that will be needed for the inner forward tracking disks (number still to be defined), they wisely leave the R&D to the vertex detector community, with which they are closely linked. They have fortunately broken free of the mindset of hybrid pixel sensors which for some time was considered to be a natural default by one of the concepts. Such sensors would impose an unwelcome material budget in a region where layer thickness will be of paramount importance (given that low momentum tracks from jets at *all* polar angles are funneled into this aperture).

Overall, the SiLC R&D work on sensors is providing a broad link between possible ILC needs, the wider community, and a range of commercial companies. Many of their ideas are likely to pay off when the time comes to make firm choices of ILC tracking systems.

6.3.3. Electronics

This collaboration is pursuing two approaches to silicon readout electronics, the evolution to deeper and deeper submicron designs on one hand (DSM), and the design of long shaping-time front-end electronics (LSTFE) on the other. Furthermore, the SiD collaboration has again a different approach. Given the special features of the ILC environment, and remembering the different approaches to silicon detector electronics investigated in the LHC R&D programme, this multiplicity of approaches is considered healthy, particularly since they are exploring the problem in significantly different ways.

The LSTFE approach uses a long shaping time (~1 μs), which is permitted because of the long time between ILC bunches, to reduce noise from long ladders (up to ~1 m) to acceptable limits. Measuring the time over threshold of the signal could permit the particle position to be measured with 7 μm resolution, by cluster centroiding. To avoid the material overheads of active cooling, they plan to run the chip with pulsed power.

So far, they obtain promising results with their first prototype. They have an energetic program to continue the developments, including a variant for short sensors, either of the type developed by the SiD collaboration, or those still to be developed for forward tracking.

The DSM approach has similar aims, as regards low mass, high channel density, and low average power dissipation by using pulsed power. As well as a long shaping time signal, they use a second signal with fast shaping time (10-30 ns) to provide a measurement of the hit position along the strip with a few cm precision. Since there was considerable skepticism within the committee that this approach would work, a thorough simulation is warranted before investing in any hardware effort. They have designed and built prototypes with 180 nm and 130 nm processes. Results are promising, with a similar noise performance achieved with these two processes. They now plan to investigate a 90 nm process, but 130 nm is the current baseline. They also plan, but have not yet implemented, pulsed power operation.

As well as the chip development, this collaboration is studying various options for low mass electrical connections, notably bump bonding (technology transfer from pixel detectors), tape automated bonding (TAB), which is widely used in industry, micro-coax cabling and fibre optic links. Closer analysis of these technology options is necessary to determine the trade-offs in real ILC tracking detectors.

6.3.4. Simulations

As with many others, the SiLC collaboration has drawn together considerable expertise in sensor modeling, device simulation, chip design and so on. In addition, they maintain and develop the fast simulation program SGV from the LEP era. This continues to provide a robust framework for physics studies and for detector optimisation, at a time when the new ILC tools are at a relatively early stage of development and debugging. They also contribute to the development of the powerful new tools. While not really the subject of this review, these activities are proving influential in studies of ILC tracking detectors in two or more design concepts. The close link between this work and the detector R&D is focusing attention on previously neglected key areas, such as the forward tracking, where it is good to see the real detector requirements beginning to emerge from these studies. Given the complex problems associated with forward tracking (photon conversions, secondary interactions) the SGV studies will need to be extended to Geant 4-based simulations in order to explore the problems in sufficient detail.

6.3.5. Long term R&D goals

The SiLC collaboration is pursuing essentially three parallel goals for the phase of final system tests, before design of the complete tracking system within an experiment collaboration, circa 2010-2011. One is to provide whatever support (envelope) turns out to be needed with a gaseous central tracker. Another is to help provide an all-silicon tracker, should this be selected for use by one or both experiment collaborations. A third is to establish the needed forward tracking system based on disks of pixels and strips, that will be needed by both experiment collaborations.

Their current plans for long term testing include ladders in an assembly with the LP1 TPC prototype. Looking forward to the time period 2010-2011, they intend to participate in using the common infrastructure (test beam with ILC time structure, hopefully large field solenoid, etc). They will test large-scale prototypes of their ladders with different lengths of sensors and different electronics options, as well as prototype forward disks. Details will depend on the outcome of their current R&D work. In the most optimistic scenario, their long ladders may perform satisfactorily, and win the competition for minimal material, and their forward disks may also prove to be optimal. The fact that their R&D programme is naturally linked to both the silicon and gaseous options is another argument for enhanced horizontal integration between the collaborations, completing their R&D by working together in the same test beam with shared resources, that forms the main recommendation of this review.

6.4. SiD

This collaboration is pursuing an R&D programme that is focused on an all-silicon tracking system for ILC. While this approach is likely to satisfy the requirements of homogeneous tracking quality over the full solid angle range, there is the risk that its performance might be uniformly sub-standard. Such concerns arise because of the phenomenal precision (better than 10 μm) needed in each measurement point, coupled with the thin layers and delicate supports needed to satisfy the material budget, exacerbated by the Lorentz forces associated with the pulsed power at 5 Hz, inducing vibrations of unknown amplitude. However, there are good reasons to hope that these challenges can be overcome. There is already good experience with mechanical stability of tracking systems built with sensor modules mounted on stiff carbon fibre support systems. The current R&D programme takes this to new performance levels, and given the necessary resources, this may well prove to be achievable.

In their presentations in Beijing, they emphasised their policy of 'vertical integration', being embedded neatly within the overall SiD design concept. The immediate reaction of the committee was to recommend a higher level of 'horizontal integration', including collaborative activities with colleagues in the SiLC groups regarding sensor and chip designs. In the very helpful 'answers to questions' from the SiD collaboration after the review, they expressed similar sentiments, so we are in the fortunate position that this approach is agreed by everyone.

6.4.1. Mechanics, cooling and alignment

This collaboration has made impressive progress with developing a coherent outline design for an all-silicon tracker which respects the important requirement of providing access to the innermost detector systems (vertex detector, forward calorimetry, etc). Many details remain to be worked out, but the level of engineering thought that has gone into this design is impressive. As they explain, there has been good success in building small silicon detectors with low mass, and also large area systems where however the material budget would be damaging to physics at ILC. Their ambitious goal is to provide a large area system of low mass (0.8% X_0 per layer) which will also respect the physics requirement for equally efficient tracking in the forward region as in the central region.

The design is based on tested principles (carbon fibre support shells, to which sensor modules are attached with lightweight clips). The main differences with the past are in the module design (discussed below), the avoidance of liquid cooling, and advances in available materials.

The committee is impressed that the collaboration had good answers for most of our difficult questions. However, the goal is to make point measurements on tracks with precision better than 10 μm. They are well aware of the risks associated with building such a lightweight structure, and operating it with pulsed power (50 kW peak!) in an unusually high magnetic field. Minor stresses could distort the assembly, and the impulses at 5 Hz due to the Lorentz forces could induce vibrations of unacceptable amplitude. The brisk flow of gas needed for cooling could also induce vibrations of micron amplitude, and possibly much larger. Fortunately, their FSI alignment system will respond to high frequency vibrations (typical frequencies around 60 Hz expected from their simulations), so this system will provide an effective monitor. Measurement of residuals in beam tests with oblique tracks will provide an independent direct indication, if the studies are carried out with pulsed power in a high field solenoid.

The SiD collaboration is at a relatively advanced stage of design that could soon lead to prototype modules and sub-structures. They acknowledge the need for testing a mechanically complete barrel, and the committee urges that this should be done early enough for improvements to be made in time for a second round of prototyping to be completed before the community needs to select the ILC tracking systems. If for example the needed mechanical stability can be achieved, but only by significantly stiffening the structure, the extra material will count against the selection of this technology. For these reasons, full system tests under realistic ILC-like conditions will be obligatory.

6.4.2. Sensors, modules and electronics

As they explain, the plans for sensors are generally conservative (300 μm thick single-sided), but they do include within their collaboration efforts for thinner devices (down to 150 μm) and they would be open to double-sided sensors (which might be most useful for their forward disks) should these become commercially available from a reliable source. So in this respect, they cover all reasonable options.

The bump-bonded KPiX chip, which eliminates the need for an intermediate hybrid, was considered certainly worth exploring by the experts on our committee, but it might prove to be too daring, so they made some suggestions for reducing the risks. They also had some specific concerns regarding possible noise due to non-optimal ground return paths, and other issues. In subsequent discussions between these experts and collaboration members, much progress has been made. In their 'answers to questions' received on February 27, there is now a high level of agreement.

The collaboration envisages a wire-bonded fallback option. Furthermore, they informed us of recent developments in bump-bonding ('stud bumping') which could satisfy their requirements at low cost and would be appropriate for small volume prototyping of individual dies. In addition, they are open to possible use of the other chips being developed for ILC tracking, both the LSTFE chip from UCSC and the DSM chip (0.13 μm or below) from the Paris group. Therefore, they are well placed to take advantage of all the readout chip design options.

Power delivery and power pulsing is acknowledged by all to be a major issue, which could severely impact on the material budget. In their answers to questions, the collaboration provided interesting suggestions for exploring this as the detector design matures. It is of course understandable that this system aspect has not yet been addressed, but the impact could be so severe that it should soon become a focus of study, not only from the point of view of prototyping, but also in terms of defining the infrastructure needed to eventually verify the performance of whatever solution is developed over the next few years. This issue is mentioned again in Section 6.4.4

6.4.3. Simulations

We welcome and are impressed by the enthusiastic involvement of this tracking group in the key issues which will shape the design of the detector. Extremely high track reconstruction efficiency, as required for ILC physics, has been demonstrated in simulation for high momentum particles that originate within the beampipe and traverse the multi-layer vertex detector as well as the central tracker. However, there is a greater challenge associated with tracks from decays beyond the vertex detector, some of which are low p_T tracks seen only in the forward disks. Maintaining excellent efficiency for finding these tracks is important for physics, and this will require unprecedented detector performance.

Regarding the material budget of any potential tracking system, as they comment: 'Electromagnetic showers should start in the ECAL, not in the tracker, while the confusion that results from additional tracker/calorimeter hits created by charged particle interactions and delta rays should be minimized'. While it is true that simulations are not yet telling us precisely how damaging the material will be in regard to (for example) reconstructing forward jets, it is clear that the confusion term which drives the jet energy resolution will be degraded progressively by material in front of the ECAL.

As a result of the excellent work being done by members of these R&D collaborations and others, the ILC community is moving close to answering these questions. However, most of the studies are so far restricted to the measurement of track finding efficiencies as function of angle and momentum. The extension to quantify the impact of tracker material on benchmark physics processes remains to be done.

6.4.4. Long term R&D goals

The SiD collaboration rightly considers that most of their early R&D studies can be made with bench tests, moving to a test beam only for the later development. However, they envisage a 'sizable test beam effort', firstly in FY2008, and subsequently for a large-scale system test in FY 2010, the latter to include a large disk as well as a barrel prototype. They also 'anticipate the need for a 5-6 T magnet to study detector performance and vibration issues associated with pulsed power', agreeing with the committee's opinion that this could be a major issue, with potentially severe adverse effects on the material budget. Whether these tests are best done with beam or with optical monitoring is an open question, but the need for a large volume solenoid is apparent in either case. For gaseous detectors, the issues go well beyond mechanical vibrations, so the opinion of the committee is that this magnet should form part of the test beam facilities, to be used by the different R&D collaborations according to their specific needs. Seeing a large gas-cooled prototype that meets the material budget goals, operating stably with ILC-like pulsed beam and pulsed power when embedded in an appropriate magnetic field, will provide the assurances needed that this is indeed a viable tracker technology for ILC physics. Currently, all groups are very far from achieving these goals. The risks of not providing the infrastructure, and hence of not establishing whether these goals can be met, are in the opinion of this committee unacceptable.

7. FUNDING ISSUES

We asked all collaborations to report in confidence on the state of their funding, and they supplied us with a considerable amount of valuable information. Since this report is likely to become semi-public, we do not include the figures here. In fact, as with so much of ILC funding, the situation is currently viable, but the prognosis is unclear. All the R&D groups (including CLUCOU) are hoping to be allocated the resources needed in order to progress to their large prototypes by 2010/2011. This optimistically assumes ongoing expansion of their manpower and equipment budgets in phase with the buildup of the accelerator Engineering Design activities over the next 3 years. There remain significant regional variations, with support in the USA in urgent need of expansion. Just as the accelerator R&D resources in the ED phase will be allocated strategically so as to reduce the most serious risks to the machine, the same should apply to the detector R&D. Since highly efficient and precise tracking over the full solid angle has never before been achieved in any HEP detector, and this unprecedented performance is required for ILC physics, the committee believes that R&D towards these goals merits as high a priority as any other in the ILC programme, though the timescale can be extended slightly beyond the ED phase of the machine. The committee strongly encourages the funding agencies to provide the support, both to the collaborations to build their large prototypes, and for the infrastructure needed for their full evaluation.

Regarding the infrastructure, EUDET has already provided vital support, and we hope this will continue. However, this needs to be augmented by contributions from other regions. What will make the R&D goals particularly challenging are the environmental issues - better than 10 µm point measurement precision over the full solid angle in a 3-5 T field, with massive pulsed power currents during the 1 ms train, and so on. We have recommended that a Tracking Coordination Group be formed to build up the necessary infrastructure for these tests. But they will be able to do nothing without new resources. They will need ongoing help from EUDET, and similar support from labs and agencies in the other regions, if they are to achieve their goals. Precisely how to develop this support is an issue for them to work on, in conjunction with the WWS-OC, the GDE and direct contacts with labs and funding agencies. This should form part of a coordinated strategy for achieving the most critical R&D goals over the next few years.

In their 'answers to questions', the SiD collaboration said 'Ultimately, the greatest R&D risk is that insufficient resources will be directed towards achieving the goals of this plan.' This statement could be echoed for all the ILC tracking work, and it is the job of this review to propose procedures which will ensure that this avoidable risk is eliminated. There is a great opportunity here - we should work together not to lose it.

Acknowledgements

We owe a considerable debt of gratitude to the external consultants Their authority, insight and wisdom have been essential in arriving at objective recommendations, which we are confident will be of long term value to the ILC project. In addition, we are thankful to the RDB chair, regional representatives and local experts, who generously gave their time and advice to this review. Professor Li Weiguo, the chair of the ACFA workshop, gave us a great deal of help throughout the review, for which we are particularly grateful. Naomi Nagahashi provided constant help from the start of the planning phase, through each day of the review, and was particularly helpful in sorting out some difficult and urgent problems. We are also grateful for administrative support given by Maxine Hronek, Maura Barone and Xu Tongzhou, all of whom helped to make the review a success. We gratefully acknowledge help and financial support from the FALC (Funding Agencies for Large Colliders).

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SiD Observations on the Tracking Review

We would first like to express our appreciation for the significant effort expended by the members of the review committee and to thank them for the excellent tracking review. Since this was the first such review, we thought it would be useful to incorporate in the report the following observations that we feel would be helpful for future reviews.

We found the technical advice provided during both formal and informal discussions with members of the R&D panel to be the most beneficial aspects of the review, and believe the review report would have benefited from an executive summary that highlighted these technical challenges and issues. We encourage future R&D reviews to include in the executive summary an overview of the current R&D status and to comment on future plans, whether those plans are appropriate and sufficient, whether their time scale meets the committee's expectations, and whether resources, including funding, are adequate.

We appreciate the committee's recognition of the need for greater coordination and communication among the tracking R&D collaborations. However, we don't think that the creation of a Tracking Coordination Group (TCG) with a long list of responsibilities and biweekly meetings is the way for tracking to proceed. We also don't believe that it is in the purview of the review committee, or the TCG, to tell detector collaborations how and when to make their definitive selections of technologies. We suggest that future reviews provide more general, and less prescriptive, encouragement for the goals of improved cross communication and coordination.

Finally, we agree with the committee that it is important to understand the issues of mechanical stability, effects of power pulsing, and sensor performance in the presence of large magnetic fields. However, we are not convinced that a large scale prototype test in a big magnet on the suggested time frame is the most cost-effective way to address these issues. Furthermore, there is a test beam working group charged by the WWS with planning and coordinating the test facilities that will be required. We suggest that future review committees coordinate with the test beam working group on issues relating to test beams and other large test facilities.

LCTPC Comments to the Tracking-Review Report, version of 15 April 2007

We have general and TPC-specific comments.

●The **general comments** relate to the proposed Tracking Coordination Group (TGC).

We think the TGC will be useful as long as it only serves for the exchange of information. It should not have the power of decision and create yet another level of bureaucracy. For information exchange, bi-monthly meetings are adequate at the moment.

In our opinion, the TGC should not be charged with defining the overall tracking philosophy since this is the responsibility of the detector collaborations.

The main job of the TGC would be to set up a large ~4T magnet for R&D at the ILC test-beam facility at Fermilab with start of operation around 2010. The TGC would help coordinate the schedule of the data-taking for the various measurements.

●The **TPC-specific comments** are as follows.

Most of the TPC issues listed in the report are covered in our written document which was submitted to the Beijing review and is available at http://mppmu.mpg.de/~settles/trackingreview05022007-21.pdf, where the R&D needed is also discussed.

Addressing p.6, we would like to emphasize our tracking philosophy which goes further than the concept written there. The advantage of having excellent TPC track recognition together with excellent tracking by the vertex detector is mainly related to the particle-flow measurement. PFA resolution is best if all details of an interaction are well measured; if particles and energy are missed or poorly measured, the PFA resolution becomes worse. Redundancy of TPC and vertex detectors will give better overall efficiency since fewer tracks will be missed (e.g. from long-lived particles) or poorly measured.

At the top of p.10, we do not agree that "errant bunches" are only a problem for gaseous tracking. Any subdetector will have HV problems with beam losses if it is not designed properly, as also happened at LEP.