STATUS REPORT
Linear Collider Tracker Alignment System R&D and Simulation Studies

Classification (subsystem)

Detector (Tracking)

Personnel and Institution requesting funding

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Project Overview

The University of Michigan group has a long-term interest in helping design and construct the central tracking system for a linear collider detector. This interest is driven not by a particular favorite technology, but by the critical importance of charged-particle tracking to the physics processes we wish to investigate, which include Higgs production and decay, along with certain Supersymmetric channels.

This project has two thrusts: 1) R&D for a silicon tracker alignment system based on frequency-scanned interferometry; and 2) detailed simulation and evaluation of key physical processes that govern the design of the tracker. The research proposed here builds on extensive work by our group in both areas. While the R&D work is most closely relevant to the SiD detector, where silicon tracking will be pervasive, it is also relevant to the forward angle silicon disks envisioned for the other proposed Linear Collider detectors. The simulation work and benchmarking is relevant to all proposed detectors.

More detail is provided below under "Research Plan" and in the description of deliverables.

Broader Impacts

Riles has worked closely with undergraduates for many years, both in high energy physics and in LIGO-related research. Two undergraduates (Tim Blass and Sven Nyberg) have worked on the alignment R&D work described below. Blass has graduated and is now a graduate student in mathematics at UT Austin. Nyberg is now writing a senior thesis based on the work described here. Nyberg has received partial support from the NSF Research Experience for Undergraduates (REU) Program. Five other undergraduates, Jennifer Lindahl, Tim Bodiya, Phil Szepietowski, Peter Troyan, and Ramon Armen, have worked with Riles in the same laboratory on LIGO-related research. There is considerable cross-fertilization (and sharing of equipment!) between the two research teams working on different interferometers on optical tables only five meters apart. Undergraduates provide essential contributions to the PI's research.

More generally, Riles has served for many years as a physics department adviser to majors, has participated in high school recruiting programs, including helping organize Physics Olympiads and rewriting a handbook for physics majors used in recruiting. As an adviser, he also meets with most of the entering freshmen with calculus-based Advanced Placement Exam physics credit and advertises to them the opportunities open to physics majors. Riles has given frequent presentations on frontier physics to a variety of student groups and delivered a pair of "Saturday Morning Physics" lectures to the general public in spring 2005. These lectures were videotaped for web archiving[1] and are shown repeatedly on a local community cable television channel.

Results of Prior Research

Since 1998, we have contributed extensively to linear collider simulation studies, both in technical tracking reconstruction issues and in evaluating physics analysis demands upon tracker performance. Riles has served as a co-convener of the American linear collider central tracking working group since 1998, sharing leadership responsibilities in different years with Dean Karlen, John Jaros and Bruce Schumm.

Assistant Research Scientist Haijun Yang began linear collider studies in fall 2000. He has carried out several related studies: 1) Studies of Higgs and Supersymmetry physics capability and 2) influence of central tracking performance on Higgs and Supersymmetry physics. As a member of the Higgs working group, he has evaluated the precision with which the Higgs mass and cross section can be evaluated at 350 GeV and 500 GeV center of mass energies. This study has used both the JAS fast Monte Carlo and the full simulation packages. Yang has independently confirmed and improved upon preliminary findings by European groups with the use of a more sophisticated and powerful fitting technique, based on Monte Carlo event interpolation.

In parallel, Yang has examined the influence of central tracker parameters on the precision of Higgs and slepton mass determination. In addition, he has assisted the SLAC simulations group in comparing the tracker's performance in full Monte Carlo simulations *vs* performance in parametrized fast Monte Carlo simulations. He has given numerous presentations on Higgs physics, Supersymmetry and tracking at various linear collider workshops[2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13] and at the Snowmass 2001 & 2005 meetings[14, 15, 16]. Yang's studies of the Higgsstrahlung process found that previous baseline tracker designs in the U.S. were close to where improved resolution does not yield comparable improvement in Higgs recoil mass resolution, because of expected intrinsic beam energy spread in the X-band accelerator designs, but that further improvement could be attained with the smaller beam energy spreads of S-band accelerators. More recent work on slepton and neutralinos[8] indicated that in large regions of sparticle mass parameter space, measuring lepton spectrum end-points to determine sparticle masses is less sensitive than was previously believed to degraded momentum resolution[17].

At the Stanford Linear Collider Workshop in March 2005, Yang presented[12] updated studies of the Higgsstrahlung and slepton processes, incorporating new ILC beam parameters with much smaller energy spread than had been used in earlier warm-technology simulations. *Consistent with earlier studies, he found[12] that with the smaller spread, one can gain significantly in Higgs mass precision with improved track momentum resolution over present baseline detector designs.* In contrast, slepton mass precisions benefit little from improved tracking resolution, thanks to intrinsic smearing from beammstrahlung and initial-state radiation. In addition, Yang presented a new study on the effects of improved momentum resolution on measurement of Higgs branching ratios. As he had found earlier for Higgs cross section measurements, the precision of Higgs branching ratio measurements are quite insensitive to tracking resolution.

The unprecedented excellent track momentum resolutions contemplated for linear collider detectors demand minimizing systematic uncertainties in subdetector relative alignments. At the same time, there is a strong desire for a very low-material tracking system (see discussion below). In the case of a silicon main tracker and in the case of silicon forward disks (envisioned in all linear collider detector designs now on the table), the low material budget may lead to a structure that is far from rigid. The short time scales on which alignment can change (e.g., from beam-driven temperature fluctuations) probably preclude reliance on traditional alignment schemes based on detected tracks, where it is assumed the alignment drifts slowly, if at all, during the time required to accumulate sufficient statistics. A system that can monitor alignment drifts "in real time" would be highly desirable in any precise tracker and probably essential to an aggressive, low-material silicon tracker. The tradeoff one would make in the future between low material budget and rigidity will depend critically upon what a feasible alignment system permits.

During the last $2\frac{1}{2}$ years, we have investigated the capability of a novel precise alignment scheme based on Frequency Scanned Interferometry (FSI), first developed by the Oxford group for the Atlas Detector[18]. The FSI system incorporates multiple interferometers fed by optical fibers from the same laser source, where the laser frequency is scanned and fringes counted, to obtain a set of absolute lengths. In order to explore this technique, we have set up a bench test in our laboratory at Michigan. We have purchased, installed and commissioned the components of a self-contained FSI system that operates at optical wavelengths. These components include a Newport RS4000 optical table, two New Focus Velocity 6308 tunable lasers (λ = 665-675 nm – one laser is borrowed), a high-finesse (>200) Thorlabs SA200 F-P Fabry-Perot spectral analyzer, a Faraday isolator, several photodiodes with amplifiers, a femtoWatt photoreceiver, retroreflectors (both prism and hollow), a National Instruments data acquisition card with 4-channel analog/digital conversion, steerable mirrors, beamsplitters, optical choppers, optical fibers, fiber couplers, a microscope for inspecting fibers, and an array of thermistors.

With this apparatus, we have reached and extended the state of the art in precision distance measurements at DC over distance scales of a meter under laboratory-controlled conditions. We have attained precisions better than 100 nm, using a single tunable laser when environmental conditions are carefully controlled. Precisions under uncontrolled conditions (e.g., air currents, temperature fluctuations) were, however, an order of magnitude worse with the single-laser measurements. Hence this year we commissioned a dual-laser FSI system (with a 2nd laser borrowed from New Focus) that employs optical choppers to alternate the beams introduced to the interferometer by the optical fibers. By using lasers that scan over the same wavelength range but in opposite directions during the same short time interval, we are able to eliminate major systematic uncertainties, a technique pioneered by the Oxford ATLAS group.

A number of significant technical complications had to be overcome in implementing the dual-laser system, primarily the reduction by half of the light seen by the interferometer photodiode from each chopped beam, the reduction of useful Fabry-Perot transmission peaks, and the difficulty in handling "edge effects" at chopped-beam transitions, all leading to increased statistical uncertainties in FSI distance determinations, despite the decrease in systematic uncertainties. With refinement of our beam-chopping method and with improved analysis software, however, we were able to overcome these hurdles. *As a result, we recently achieved precisions of 200 nm under highly unfavorable conditions, using the dual-laser scanning technique. This achievement marks a major milestone in our R&D plans[16].* Results from our alignment studies have been presented by Yang at four linear collider workshops[9, 10, 11, 13], and an article concerning our single-laser benchtop FSI appeared recently in *Applied Optics*[19]. An article on the dual-laser results is in preparation.

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- NSF Subcontract 43422-7323 (Cornell U.) "Tracker Simulation Studies and Alignment System Research and Development," 9/15/03-8/31/04, $9,702 (Linear Collider)
- DOE Grant DE FG02 04 ER41345 "Linear Collider Tracker Simulation Studies and Alignment System R&D," 9/1/04-8/31/05, $45,000 (Linear Collider)
- NSF Subgrant 206381B - 5.8 (U. Oregon) "Linear Collider Tracker Simulation Studies and Alignment System R&D," 8/15/05-7/31/06, $40,2500 (Linear Collider)

Research Plan

With the international decision on ILC technology[20] and efforts underway worldwide to create conceptual design reports for at least two detectors (using large gaseous or silicon central trackers), it is appropriate to narrow the focus of our work in two ways. In our detector R&D, we will address overall detector constraints on alignment system design, including detailed layout of sensors and lines of sight, along with the material budget. In our simulation studies, we will confront specific tracking system designs with ever more realistic detector and event reconstruction imperfections.

1) Alignment System

Now that we have achieved several key milestones in our alignment research and development, using off-the-shelf commercial components, we plan to move on to out next goals. In the very near future we will explore and better quantify the conditions under which the dual-laser FSI system achieves adequate and better-than-adequate precision. We will introduce more extreme environmental disturbances, including multi-component vibrations. Soon afterward we plan to start addressing a major milestone in this research: miniaturization of the FSI optical components, as preparation for building a partial prototype of the alignment system.

It should be noted that we have temporarily borrowed from the manufacturer a second scanning laser for our current studies. We cannot retain this "demo" model indefinitely and are concerned that its performance has degraded significantly over the last six months, with increasing frequency of mode hopping during scans. In order to carry out long-term development, we will need to purchase a second laser, and we request funds for this purpose in year 1.

At the same time, we wish to begin confronting the technical issues in constructing multiple interferometers fed by common lasers through an optical fiber fanout. We will need to purchase fiber splitters and additional optical and photodiode components, along with more DAQ channels, for these multiple interferometers. Once we have multiple fiber interferometers, we can verify with a benchtop movable-stage test that 3-D reconstruction of positions of tracker element mockups can be achieved.

For now, we have chosen to work with optical lasers and corresponding optical components. For development of techniques on a benchtop, that choice has proven wise in dramatically shortening the turn-around time on configuration changes, in allowing us to exploit existing laser/optics infrastructure in our laboratory, and in fostering a safer work environment. In the long term, however, in building a full alignment system for a Linear Collider Detector, we expect signficant cost reductions to be possible by using mass-produced infrared lasers and beam components, because of the prevalence of infrared devices, including scannable lasers, in the telecommunications industry. Late next year we expect to make a decision on whether to continue working at optical frequencies or to switch to infrared. The decision will depend not only on the relative speeds of commercial technology improvements at those frequencies, but also on the status of the Linear Collider development itself and the availability of funds to move to infrared technology. The faster the ILC effort moves, the sooner we will have to confront this important technology decision.

It should also be noted that the methods we develop for central and forward tracker alignment may also prove useful for a vertex detector, where again, there is a strong desire for thin detector material that may be subject to short-term position fluctuations. Similarly, our methods may prove useful for alignment monitoring of accelerator components far upstream of the detector (e.g., in the main linacs). Given the natural wide distribution of accelerator components *vs* a relatively compact tracker system, however, it's not clear that a tracker solution will be cost effective for the accelerator. In any case, we will stay cognizant of vertex detector and accelerator needs and explore these possibilities, as the tracking alignment system design evolves.

2) Simulation Studies

In the coming years we wish to extend the ongoing slepton/neutralino studies to additional Supersymmetry final states to understand quantitatively whether they impose more or less stringent requirements than Higgsstrahlung on tracking resolution. We will begin by exploring a larger parameter space in sparticle masses in the slepton production channel. The sharpness of the spectral end-points is governed in part by track resolution. We have already shown that for large regions in sparticle parameter space, track momentum resolution is not critical because of more dominant degradation from initial state radiation and beamsstrahlung. But it has been argued that the case of near degeneracy between very massive sleptons and neutralinos deserves more attention. We propose to quantify, in the context of specific detector designs (gaseous and silicon trackers), the influence of tracking resolution on sparticle mass resolution, including examination of corners of parameter space previously ignored.

A longstanding question in the Linear Collider Detector community is the importance of material burden in the central tracking system. One naturally wishes to avoid introducing unnecessary material in the tracker because it creates multiple scattering, affecting momentum resolution for low-momentum tracks, and because it leads to photon conversions and electron bremsstrahlung, causing confusion in event reconstruction. On the other hand, as discussed above, going to the extreme of an ultra-lightweight silicon tracker, to avoid material burden, invites mechanical support and alignment troubles. We wish to quantify this tradeoff. Our earlier work on slepton spectral endpoints indicates that one can, in fact, tolerate relatively large material in the tracker, but the not-yet-addressed case of nearly denerate sparticle masses could lead to final states of very low momenta, where the effects of multiple scattering are more pronounced. We will carry out our Supersymmetry studies with a careful eye on this issue.

We also propose to carry out more realistic analysis studies of a variety of Higgs and Supersymmetric final states, using information from both the central tracking system and the calorimetery in the new detector designs. Yang has developed with colleagues on the Mini-Boone Experiment at Fermilab a new general-purpose analysis technique called "boosting,"[21] which allows the effective use of a large number of input variables for signal/background discrimination. Unlike a neural net approach, boosting is highly deterministic (minimal dependence on arbitrary starting paramters), fast, and able to make good use of many dozens of variables. Yang and collaborators in the Mini-Boone Experiment[22] have recently shown that boosting gives better than a 50% improvement in signal detection efficiency (fixed background fraction) compared to a mature neural-net algorithm that had been developed over several years for that experiment. We believe the boosting method can be applied quite effectively in Linear Collider studies too. As a pioneer in applying the boosting method to high energy physics data analysis, Yang is well positioned to implement this powerful new method.

Facilities, Equipment and Other Resources The University of Michigan provides strong support for high energy physics reseearch. Within the last decade the University opened up a new 70,000 square foot Physics Research Laboratory within which our group occupies a large 5-bay area. Our group has optical tables, a variety of lasers, and many optical components (lenses, mirrors, polarizers, Faraday rotators, electro-optic modulators, photodiodes, etc,) useful in interferometry. The department's high energy physics electronics lab is a state-of-the-art electronics facility, allowing in-house design of multi-layer printed circuit boards and of application-specific integrated circuit (ASIC) chips. Its facilities include regular and double-density, surface-mount assembly and test stands. The department maintains a machine shop (and separate student shop) with computer-controlled machine tools. The department Computer Services Group provides maintenance support for Windows PC's, for our group's small linux cluster, and for our high-speed access to the internet. The Michigan High Energy Physics group includes 15 faculty members working on accelerator-based experiments at CERN, Fermilab, DESY, and Protvino.

FY2006 Project Activities and Deliverables

We will continue tracker alignment R&D. Specifically, we will quantify our robustness with the dual-laser FSI system against environmental disturbances. We will also start the key tasks of miniaturizing the optical components of the system and demonstration with multiple interferometers of 3-D position reconstruction. In parallel, we will come up with a conceptual design of an alignment scheme for the new silicon detector baseline tracker design and the silicon forward disk trackers for both the gaseous and silicon central trackers. We will write a general simulation program that allows the performance evaluation of various layout schemes. It is envisioned that hundreds of absolute length measurements between pairs of reference points would be used in a global fit to determine the local and global alignment parameters of the tracking subsystems. An article describing findings with our dual-laser system will be submitted for publication to a refereed journal (probabably *Applied Optics*), and presentations will be made at Linear Collider Workshops.

During the first year we will also carry out simulation studies of the tracking performance requirements imposed by measurements of slepton production, specifically imposed by desired precision on sparticle masses in the near-degenerate realm. We will write a detailed technical report on our findings in which the new gaseous and silicon tracker designs are compared quantitatively. Presentations will be given at Linear Collider Workshops. Our work will focus on the SiD detector design, but we expect to address gaseous detectors in part too.

FY2007 Project Activities and Deliverables

We will complete a multi-interferometer, dual-laser demonstration FSI system on our benchtop to address remaining critical technology and methodology issues, with incorporation of miniaturized optical components. Specifically, we must design and prototype tiny mounts for optical fiber beam delivery and return, including beam splitters and retroreflectors. We will take full advantage, however, of the considerable R&D already carried out by the ATLAS FSI groups. An article describing this work will be submitted for publication to a refereed journal (probabably *Nuc. Inst. Meth.*), and presentations will be made at Linear Collider Workshops.

Simulation studies in the second year will depend on findings from the first year on slepton production. We expect, however, to investigate other supersymmetry channels involving isolated leptons whose precise measurement imposes stringent performance requirements on the tracker. Chargino production is a natural channel to investigate. We will deliver a technical report on our findings and make presentations at Linear Collider Workshops.

(FY2008 Project Activities and Deliverables)

(For completeness and reference we describe here our plans and resource needs beyond year 2, in preparation for technology decisions to be made near the end of FY2008.)

We hope by the start of the third year to have a concrete design in hand for a full alignment system and to have evaluated singly the primary issues affecting that design. At that point we would wish to build a partial prototype of the system to test system integration issues, including the critical miniaturization. There is considerable uncertainty at this point, however, since we may wish to switch to infrared lasers in Year 3, as discussed above. We assume for the sake of budgeting that we will *not* make that switch in Year 3. A technical report will be written on our design and prototyping work, and presentations made at Linear Collider Workshops.

We anticipate that our supersymmetry/tracking simulation studies will have been completed to satisfaction by the start of the third year, but depending on what has been learned, we may wish to pursue certain specific topics in further detail. If so, another technical report will be written on our findings and presentations made at Linear Collider Workshops.

Budget justification:

In the following budget, we request in all years half-time support for Assistant Research Scientist Haijun Yang, half-time support for a graduate student, and part-time employment of two undergraduates. In addition, we request travel funds for Riles and Yang to attend two Linear Collider Workshops per year. We also request funding for laboratory equipment; in Year 1, we request funds to purchase a second scanning laser and additional optical and electronic components. In Year 2, we request funds for optical and electronic components needed to commission a multi-interferometer benchtop system. (In Year 3, we expect to request funds for prototyping a system with many miniaturized elements appropriate for the inner regions of a Linear Collider Detector, along with funds for quarter-time technician support.)

Three-year budget, in then-year K$

Institution: University of Michigan

Item	FY2006	FY2007	Total	(FY2008)	(Grand total)
Other Professionals	0	0	0	15	15
Asst. Research Scientist (0.5)	25	26	51	27	78
Graduate Student (0.5)	11	12	23	13	36
Undergraduate Students	8	8	16	8	24
Total Salaries and Wages	44	46	90	63	153
Fringe Benefits (@27%)	12	12	24	17	41
Total Salaries, Wages and Fringe Benefits	56	58	114	80	194
Equipment	25	15	40	10	50
Travel	6	6	12	6	18
Materials and Supplies	2	2	4	2	6
Other direct costs (tuition)	7	8	15	9	24
Total direct costs	96	89	185	107	292
Indirect costs (@53%)	51	47	98	57	155
Total direct and indirect costs	147	136	283	164	447

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