

Linear Collider Tracker Simulation Studies and Alignment System R&D

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) detailed simulation and evaluation of key physical processes that govern the design of the tracker; and 2) R&D for a silicon tracker alignment system based on frequency-scanned interferometry. The research proposed here builds on extensive work by our group in both areas. While the R&D work is most closely relevant to a 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 Impact

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 will be completing a senior thesis on the work described here next year. Nyberg has received partial support from the NSF Research Experience for Undergraduates (REU) Program. Two other undergraduates, Jennifer Lindahl and Tim Bodiya (who have also received partial REU support), work 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 provided 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 will deliver a pair of “Saturday Morning Physics” lectures to the general public in spring 2005. Although these lectures will focus on LIGO research, his research group’s activity in linear collider research will also be discussed. In recent years, the Saturday Morning Physics lectures have consistently attracted 300-500 persons each week. The lectures are videotaped for web archiving and shown repeatedly on the local cable television channel set aside for the University of Michigan.

Results of Prior Research

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-convenor of the linear collider central tracking working group since 1998, sharing leadership responsibilities in different years with Dean Karlen, John Jaros and Bruce Schumm. Riles has shared responsibility for organizing working group meetings, evaluating baseline tracker designs, coordinating tracking simulations, creating & maintaining the group web site, and assembling annual joint R&D proposals.

As part of the baseline tracker design optimization, Riles wrote a stand-alone Monte Carlo hit generator and 3-d helical track fitter to study the effects of multiple scattering on particle momentum resolution *vs* momentum and *vs* polar angle for various tracker configurations. This work served as an independent cross check of the resolution studies carried out by Bruce Schumm using an analytic Billoir approach.

Postdoctoral Fellow Haijun Yang began linear collider studies in fall 2000. He has been carrying 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[1, 2, 3, 4, 5, 6, 7, 8, 9, 10] and at the Snowmass 2001 meeting[11, 12]. 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. His more recent work on slepton and neutralinos[7] indicates 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[13].

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.

Within the last 18 months, we have begun investigating the capability of a novel precise alignment scheme based on Frequency Scanned Interferometry (FSI), first developed by the Oxford group for the Atlas Detector[14]. 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, a New Focus Velocity 6308 tunable laser ($\lambda = 665\text{-}675$ nm), 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 air temperature is carefully controlled. Our preliminary results have been presented by Yang at three linear collider workshops[8, 9, 10], and an article concerning our single-laser benchtop FSI will appear soon in *Applied Optics*[15].

The research and results described above have been partly supported by the following NSF and DOE grants:

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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)

Research Plan

With the recent international decision on ILC technology[16] 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 simulation studies, we will confront specific tracking system designs with realistic detector and event reconstruction imperfections. 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.

1) 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 degenerate 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 calorimetry 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,” [17] 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 parameters), fast, and able to make good use of many dozens of variables. Yang and collaborators in the Mini-Boone Experiment [18] 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.

2) Alignment System

Now that we have commissioned a single-laser FSI system in our laboratory and achieved better than 100 nm accuracy in position determination for distances of order (1 meter) under carefully controlled conditions, we wish to proceed to address distance measurement under poorly controlled conditions, such as we expect to hold in a Linear Collider Detector environment. Following the lead of the Oxford ATLAS FSI group, we have begun to study a dual-laser FSI system that employs optical choppers to alternate the beams introduced to

the interferometer by the optical fibers. By using lasers that scan over different wavelength ranges in the same short time interval, we hope to identify and eliminate systematic uncertainties due primarily to temperature fluctuations of the air in the interferometer beam path. We have temporarily borrowed from the manufacturer a second scanning laser for these preliminary studies, but will need to return this “demo” model soon. In order to carry out long-term development, we will need to purchase a second laser, and we request funds (\$20K) for this purpose in year 1. Our early studies already indicate significant technical complications in implementing the dual-laser system. The need for two different scanning ranges, the reduction by half of the light seen by the interferometer photodiode from each chopped beam, the reduction of usable Fabry-Perot transmission peaks, and the difficulty in handling “edge effects” at chopped-beam transitions, all lead to increased statistical uncertainties in FSI distance determinations, despite the decrease in systematic uncertainties. We believe we can overcome these problems with more sensitive and higher-bandwidth photodiodes, more sophisticated beam chopping, and improved analysis software, but much work will be needed.

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.

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 significant 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 in year 2 or in year 3 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. The faster the ILC effort moves, the sooner we will have to confront this important technology decision.

It should 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.

Facilities, Equipment and Other Resources The University of Michigan provides strong support for high energy physics research. 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 PC's 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.

FY2005 Project Activities and Deliverables

During the first year we will carry out simulation studies of the tracking performance requirements imposed by measurements of slepton production, specifically imposed by desired precision on sparticle masses. 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.

We will also continue tracker alignment R&D. Specifically, we will finish acquiring the components for and building a demonstration dual-laser frequency-scanned interferometer on an optical bench. 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 (probably *Applied Optics*), and presentations will be made at Linear Collider Workshops.

FY2006 Project Activities and Deliverables

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.

We will develop a multi-interferometer, dual-laser demonstration FSI system on our benchtop to address remaining critical technology and methodology issues and begin work on miniaturization of the interferometer 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 (probably *Nuc. Inst. Meth.*), and presentations will be made at Linear Collider Workshops.

FY2007 Project Activities and Deliverables

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.

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 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.

Budget justification:

In the following budget, we request in all years half-time support for Postdoctoral Fellow 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 request funds for prototyping a system with 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	FY2005	FY2006	FY2007	Total
Other Professionals	0	0	15	15
Postdoctoral Fellow (0.5)	24	26	28	78
Graduate Student (0.5)	10	11	12	33
Undergraduate Students	8	8	8	24
Total Salaries and Wages	42	45	63	150
Fringe Benefits (@27%)	11	12	17	40
Total Salaries, Wages and Fringe Benefits	53	57	80	190
Equipment	25	10	10	45
Travel	6	6	6	18
Materials and Supplies	2	2	2	6
Other direct costs (tuition)	7	8	9	24
Total direct costs	93	83	107	283
Indirect costs (@53%)	49	44	57	150
Total direct and indirect costs	142	127	164	433

References

- [1] “Measurement of Higgs Mass at NLC”, H. Yang, Presentation at Workshop on Higgs Physics at a Linear Collider, University of California, Davis, January 27-28, 2001, <http://tenaya.physics.lsa.umich.edu/~hyang/talks/nlc-higgs.ps.gz>.
- [2] “Measurement of Higgs Mass and Cross Section at NLC”, H. Yang and K. Riles, Presentation at Workshop on Future e^+e^- Linear Colliders, Johns Hopkins University, March 19-21, 2001, <http://tenaya.physics.lsa.umich.edu/~hyang/talks/higgs-mass-xs.ps.gz>.

- [3] “Impact of Tracker Design on Higgs Mass Resolution”, H. Yang and K. Riles, Presentation at Workshop on Future e^+e^- Linear Colliders, Johns Hopkins University, March 19-21, 2001, <http://tenaya.physics.lsa.umich.edu/~hyang/talks/trackres-jhu.ps.gz>.
- [4] “A First Look at Track Reconstruction with High Random Backgrounds”, H. Yang and K. Riles, Presentation at American Linear Collider Workshop, University of Chicago, January 7-9, 2002, <http://tenaya.physics.lsa.umich.edu/~hyang/talks/trackeff.pdf>.
- [5] “Measurement of Higgs Mass and Cross Section at NLC” H. Yang and K. Riles, Presentation at Santa Cruz Linear Collider Retreat, June 27-29, 2002, <http://tenaya.physics.lsa.umich.edu/~hyang/talks/higgs-ucsc.pdf>.
- [6] “Impact of Tracker Design on Higgs Mass Resolution and Cross Section”, H. Yang and K. Riles, Presentation at Santa Cruz Linear Collider Retreat, June 27-29, 2002, <http://tenaya.physics.lsa.umich.edu/~hyang/talks/trackres-ucsc.pdf>; see updated report at <http://tenaya.physics.lsa.umich.edu/~keithr/LC/HiggsTrackSummer2002.pdf>.
- [7] “Search for Neutralino and Smuon”, H. Yang and K. Riles, Presentation at American Linear Collider Workshop, University of Texas, Arlington, January 9-11, 2003, <http://tenaya.physics.lsa.umich.edu/~hyang/talks/smuon-uta.pdf>.
- [8] “Frequency Scanned Interferometer for Tracker Alignment”, Presentation at American Linear Collider Workshop, Cornell University, July 13-16, 2003, <http://tenaya.physics.lsa.umich.edu/~hyang/talks/fsi-july-14-2003.pdf>.
- [9] “High-precision Absolute Distance Measurement by using Frequency Scanned Interferometry”, Presentation at American Linear Collider Workshop, Stanford Linear Accelerator Center, January 7-10, 2004, <http://tenaya.physics.lsa.umich.edu/~hyang/talks/fsi-slac-2004.pdf>.
- [10] “High-precision Absolute Distance Measurement by using Frequency Scanned Interferometry”, H. Yang, S. Nyberg, and K. Riles, Presentation at North American Linear Collider Workshop, University of Victoria, July 28-31, 2004, <http://tenaya.physics.lsa.umich.edu/~hyang/talks/fsi-victoria-july-28-2004.pdf>.
- [11] “Measurement of Higgs Mass and Cross Section at a Linear Collider”, H. Yang and K. Riles, P112 in *Proceedings of Snowmass 2001*, Snowmass Village, Colorado, June 30 – July 21, 2001, ed. Norman Graf, SLAC-R-599. Proceedings.
- [12] “Impact of Tracker Design on Higgs Mass and Cross Section Resolutions”, H. Yang and K. Riles, E3040 in *Proceedings of Snowmass 2001*, Snowmass Village, Colorado, June 30 – July 21, 2001, ed. Norman Graf, SLAC-R-599. Proceedings.
- [13] “Linear Collider Detector R&D”, J. Brau *et al.*, Report of International Linear Collider Detector R&D Committee, August 28, 2002, [tt http://blueox.uoregon.edu/~lc/randd.pdf](http://blueox.uoregon.edu/~lc/randd.pdf).
- [14] “Frequency Scanned Interferometry (FSI): The Basis of a Survey System for the ATLAS ID using fast automated remote interferometry”, A.F. Fox-Murphy *et al.*, *Nuc. Inst. and Meth.* **A383**, 229 (1996).

- [15] “High-precision Absolute Distance Measurement using Frequency Scanned Interferometry”, H. Yang, J. Deibel, S. Nyberg and K. Riles, to appear in *Applied Optics*, <http://xxx.lanl.gov/pdf/physics/0409110>.
- [16] Final Report of the International Technology Recommendation Panel (ITRP), http://www.ligo.caltech.edu/~skammer/ITRP/ITRP_Report_Final2.pdf.
- [17] “Experiments with a New Boosting Algorithm”, Y. Freund and R.E. Schapire, Proc COLT, 209-217 ACM Press, New York (1996).
J. Friedman *et al.*, *Annals of Statistics* **28** 337 (2000); **29** 1189 (2001).
- [18] “Boosted Decision Trees, an Alternative to Artificial Neural Networks”, B.P. Roe, H. Yang, J. Zhu, Y. Liu, I. Stancu, and G. McGregor, submitted to *Phys. Rev D.*, <http://xxx.lanl.gov/pdf/physics//0408124>