

# PROGRESS REPORT

## Beam simulation: beam transport in the bunch compressor mainlinacs and beam delivery systems, beam halo modeling and transport, and implementation as a diagnostic tool for commissioning and operation

### Personnel and Institution(s) requesting funding

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### Project Overview

This project covers simulations of main beam transport in linear colliders, with an emphasis on integrated damping ring to IP simulations; studies of the sources and transport of beam halo from its origin to the IP; Spin polarization transport from the damping ring to the IP; implementation of modeling tools as a diagnostic for addressing commissioning and operational issues. Each of these topics is discussed in turn in the following paragraphs. Complete and robust simulation and modeling tools are critical to the evaluation of design and commissioning of ILC, and our goal is to develop software with the flexibility to investigate and evaluate design alternatives.

#### *Machine commissioning and operation*

During machine commissioning, interpretation of measurements of beam position monitors, beam size monitors, cavity higher order modes, etc. will be critical to identification of component failures and implementation of correction algorithms. Typically a simulation is used to compute the effects of the guide field on the beam so that the consequence of various field errors, misalignments, etc. can be anticipated. During commissioning, however, we must first measure the guide field errors, so that with the help of the models, appropriate corrections can be determined. We plan to develop the modeling tools to extract information about the guide field from the beam instrumentation, so that we can simulate the diagnosis and optimization of machine performance.

#### *Main beam transport*

One of the essential requirements for a linear collider is the need for the preservation of a very small vertical emittance during beam transport from the damping ring to the IP. The best estimate of what is required to do this comes from integrated simulations of beam transport from the damping ring to the IP. Elaborate simulation programs have been developed

at SLAC, DESY and CERN for the linear collider projects, in which errors can be incorporated, and realistic tuning algorithms can be explored, based on the expected performance of diagnostic systems. The errors are both static and dynamic, and include initial alignment errors, instrumentation resolution, ground motion and mechanical noise. Dynamic stabilization schemes and linac-based and IP feedback can be incorporated.

The worldwide effort in this area could benefit from additional manpower working in collaboration with the existing investigators to refine the simulation tools and develop improved tuning algorithms. We propose to join these ongoing beam simulation efforts, providing additional manpower, as well as fresh perspectives.

We will work closely with our collaborators, who have extensive experience in beam simulation, to identify critical issues which, in the context of the worldwide effort, require attention.

Particular areas of interest to us include the exploration of the tolerance of the baseline emittance preservation schemes to diagnostic faults, realistic modeling of the bunch compressors, and the effects of lattice mismatches. Also, one of our aspirations is to develop the machine model so that it can eventually interact with the control system in such a way that we can use it to diagnose and correct machine errors. Until a real control system exists, we can simulate that as well and begin to understand how the operational problems will become evident and then how they might be addressed.

We would also like to explore the utility of simulations of beam transport from the source to the damping ring. Our group has considerable experience developing computer models to study the properties of stored and accelerated beams, and for the evaluation of machine performance and diagnosis and correction of guide field errors etc. We have done extensive simulation of single particle dynamics, beam-beam interaction, long range interaction of multiple bunch beams, and of the injection process for both CESR (5.3GeV) and for CESR-c (1.9GeV). We also created a detailed simulation of the positron production process in our linac in order to improve efficiency, and a rudimentary model of a superconducting linac to explore the dependence of single and multi-bunch stability on cavity parameters. We are well equipped to contribute to the effort to model beam transport in a high energy linac.

#### *Beam halo modeling and transport*

Understanding and control of beam halo is a crucial issue for linear colliders. The extent of the beam halo impacts the design of the collimation systems and muon spoilers, which in turn determine background conditions at the detector. The collimation systems are also an essential part of the machine protection system, a key issue for machine reliability.

One of the principal open issues in the baseline linear collider designs is the absence of a fully developed pre-linac collimation system. Working with our collaborators, we propose to develop a realistic design for such a system.

Beam halo typically explores regions of the vacuum chamber far from the central axis, where magnetic field nonlinearities, often ignored in main beam transport simulations, may be important. We propose to study the transport of halo particles, represented as longitudinal and transverse beam distribution tails, from the damping ring to where the halo is intercepted, exploring, for example, the effects of nonlinear field errors.

The baseline linear collider collimation systems have been designed to cope with a relatively high level of beam halo, based on previous linear collider experience. This level is typically much larger than simple estimates would indicate. A more basic understanding of the origin

of beam halo would allow a better optimization of the collimation system design. We propose to simulate the sources of beam halo (e.g, due to scattering processes in the damping rings, dark current in the linac cavities, etc.) and track these particles from their sources to the collimation systems, where they are removed from the beam. Comparisons will be made to the assumed halo used for the design of the baseline collimation systems for ILC, and to the SLC beam halo experience.

## Progress Report

### *Machine Commissioning and Operation*

Our simulations are based on an existing object-oriented particle-tracking library, BMAD. BMAD has been extensively tested against an operating accelerator, CESR, since the late 1990's [1]. It was created to enable accelerator physicists to develop programs without the need to code from scratch commonly used functions such as lattice file parsing and particle tracking. Using a subroutine library such as BMAD reduces the time needed to develop programs and reduces programming errors.

To facilitate the efficient development of simulations, an accelerator design and analysis program based on BMAD has been developed called Tao (Tool for Accelerator Optics) [2]. Tao provides an environment for solving many simulation problems, including the design of lattices subject to constraints and the simulation of errors and changes in machine parameters. It provides a single interface for both simulation work and machine control, and allows for the simulation of machine commissioning including the simulation of data measurement and correction. For our ILC beam dynamics studies, we have developed an implementation of Tao called *ILCv* that incorporates the ILC accelerator components. In the first year of this grant, *ILCv* results were checked in detail against those of existing codes [3].

### *Main Beam Transport*

The three beam-based alignment algorithms Dispersion Free Steering [4], Ballistic Alignment [5] and the Kubo Method [6] have been implemented in *ILCv*. We have studied the effects of BPM resolution, beam jitter, stray fields, BPM and steering magnet failure and the effects of various cavity shape wakefields. A parametric study has been conducted in the presence of the above types of errors for all three algorithms. Results were presented at the 2005 Particle Accelerator Conference [7] and at the Second ILC Accelerator Workshop at Snowmass, Colorado [8].

We find that BPM resolution has only modest impact on alignment. In the worst case, 20 micron BPM resolution degraded the emittance by 10 nm (about 30%) relative to perfect BPM resolution. Similarly, vertical beam jitter of 10 microns RMS (the beam size) degraded the emittance by no more than 30%. These studies were done by undergraduate Theodor Brasoveano and a participant in LEPP's Research Experience for Undergraduates Program, Kristin Kopp, and are summarized in their reports [9] [10].

We have found Ballistic Alignment to be very sensitive to stray fields. A 50 microTesla field, comparable to that of the earth, would degrade the emittance by a factor of 20 or more. The problem is most severe for stray fields in the upstream end of the linac. We will be conducting further studies on the extent of stray fields in the machine tunnel and their effects on all three alignment algorithms with particular attention to Ballistic Alignment.

Dispersion Free Steering was found to be very robust to BPM and Steering Magnet failure in contrast to the Kubo Method, and to a lesser extent, Ballistic Alignment, which degrade in performance very quickly with component failure. For the Kubo Method, a single BPM failure can degrade the vertical emittance by a factor of five. Steering magnet failure is equally serious. We have investigated compensation techniques to deal with failed BPMs and steering magnets.

Emittance dilution is insensitive to the weak wakefields, however, we have found some systematic effects due to wakefields in both the Kubo method and Dispersion Free Steering. These effects result in a greater dependence on wakefield strength than simple component alignment error would suggest. The systematic effects are not present in Ballistic Alignment.

We have been working closely with the ILC Low Emittance Transport working group and we have been coordinating our studies through that forum. We have begun a benchmarking study with several other LET simulation groups and have made progress comparing the detailed performance of Dispersion Free Steering algorithms between the various simulation codes that have been developed at Cornell, SLAC, DESY and CERN.

The ILC calls for longitudinally polarized electrons and positrons. With the support of the ILC Low Emittance Transport working group we have begun to investigate the effects of guide fields between the damping ring and the IP on beam polarization. This includes a design study of the spin rotator located after the damping ring.

Few beam dynamics codes have implemented spin transport and none include the components necessary for this study so BMAD and *ILCv* has been extended to perform particle spin tracking. This implementation uses a spinor-quaternion approach [11], which is very CPU efficient. Spin tracking is being extended to study all components between the damping ring and the IP, including RF cavities and the helical undulator. Common wisdom is that beam depolarization is not a problem in lepton linacs. But studies so far have shown that due to the ultra-relativistic energies obtained in the ILC, depolarization will be a concern, especially in the Beam Delivery System.

Our work is being performed in collaboration with the EuroTEV study on ILC spin dynamics. We have given talks on the design of the spin rotator at meetings of the ILC Low Emittance Transport task force [12], and will present our results at the CERN Low Emittance Transport meeting in February, 2006.

#### *Beam halo modeling and transport*

*ILCv* is used to model all accelerators of the linear collider, including injector, damping ring, bunch compressor and main linac and final focus. It is straightforward to link the accelerators together and propagate particles through the entire chain of machines. This capability has been demonstrated and integrated “cradle to grave” simulations are in the plans. This flexibility will also permit a thorough investigation of beam halo beginning with formation in the damping ring, propagation through bunch compressor and main linac to its fate in the beam delivery system.

The Low Emittance Transport working group does not view beam halo studies to be a high priority at this time compared to more basic emittance growth issues and spin transport [13]. After consultation with the collaboration we have decided to defer our study of beam halo to 2007, and will for the next year concentrate on the areas discussed above.

## Next year Project Activities and Deliverables

The most recent results of our studies will be presented at the CERN Low Emittance Transport meeting in February, 2006. At this meeting we will also participate in coordinating the worldwide Low Emittance Transport work for the next year.

In 2006, we plan to exploit the capability of *ILCv* to study the effects of ground motion on beam trajectory and emittance dilution. The simulation will be used to determine how, in the presence of ground motion and environmental noise, emittance degrades with time. The efficacy of alignment feedback algorithms will be tested using the same machinery.

We are working in particularly close contact with physicists at SLAC and will continue to do so throughout the next year. We expect our work to be included in the ILC Reference Design Report (RDR) document to be published at the end of 2006.

In 2007, we plan to propagate beam halo originating in the damping ring through spin rotator, bunch compressor, main linac, and BDS to learn the fate of the large amplitude particles. The study will help to test the design of collimators and identify regions of the machine vulnerable to background and high radiation.

The work will be summarized in internal reports and PAC papers.

### Budget justification:

This work will be carried out primarily by the personnel noted above from Cornell, with help from our collaborators. Graduate students will be supported by Cornell's base grant, and so are not budgeted for here. Funds are provided for additional computing nodes to support the simulations. There is also a travel allowance for meetings with our collaborators and with the world-wide Low Emittance Transport group, and for participation in conferences.

Indirect costs are calculated at Cornell's rate on modified total direct costs of 58% (through June 2007) and 59% (thereafter).

### Budget, in then-year K\$

**Institution:** Cornell University

Item	FY06
Other Professionals	0
Graduate Students	0
Undergraduate Students	5.0
Total Salaries and Wages	5.0
Fringe Benefits	0
Total Salaries, Wages and Fringe Benefits	5.0
Equipment	18.0
Travel	5.0
Materials and Supplies	0
Other direct costs	0
Total direct costs	28.0
Indirect costs	5.9
Total direct and indirect costs	33.9

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