Continuing Research and Development of
Linac and Final Doublet Girder Movers

Classification:

Accelerator Science

Institution and Personnel requesting funding:

Colorado State University

David W. Warner, Engineer

Collaborators:

Stanford Linear Accelerator Center:
Gordon Bowden (staff scientist)

Project Leader:

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Project Overview

This proposal is a continuation of the magnet mover R&D which was supported in the 2003 LCRD program. The project was not selected for funding in the 2004 round of LCRD grants, but we were given a no-cost extension to our existing grant and strongly encouraged to apply again in the next round. This extension has allowed us to continue research at a very low level.

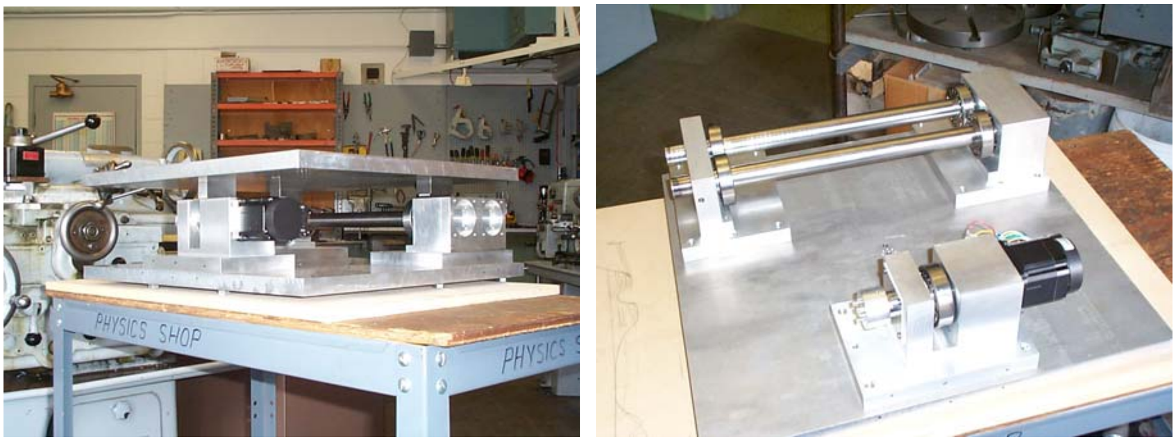
We are requesting funds for a three-year R&D program, which will continue our investigations of the resolution attainable with mechanical movers similar to those produced at SLAC for the FFTB, and our efforts to reduce the costs associated with manufacturing them. We will also mount piezoelectric movers to the FFTB magnet mover to possibly reduce cost and/or improve the precision of the design while maintaining the required range of motion. After selecting the optimal design choice, we will produce production mover designs and a prototype device, with an emphasis on manufacturability and cost reduction. Vibration isolation and temperature control requirements are beyond the scope of this project—we are investigating the feasibility of manufacturing movers capable of meeting the motion precision required by the accelerator.

Two important decisions taken in the last year have had a major impact on magnet mover requirements. First, the selection of cryogenic RF technology for the linac has reduced the number of magnet movers required. Rather than the approximately 10,000 movers which would have been required for the full linac, we are now developing movers for only the warm magnets used in the beam delivery system of the accelerator, which will require approximately 1000 movers. The reduction in the number of movers has lowered the relative importance of cost while increasing the importance of performance. We are in the process of re-evaluating our initial plans in light of this change in requirements. Second, the requirement for 10nm step size for the final focus girder movers has been changed to 50nm, allowing us to use the same basic mover design throughout the beam delivery system.

Basic Mover Requirements

Every magnet and structure girder in the ILC beam delivery system will sit on movers to allow it to be positioned accurately. Depending on the requirements of the component in question, the movers will be required to position the beam components in either three degrees of freedom (two linear positions and one angle) or five degrees of freedom (two linear positions and three angles). Beam delivery system movers will typically be adjusted every few minutes, and must have a resolution or "step size" of approximately 50nm. It is not required that each step be precisely 50nm, simply that the average step size over a series of 10-20 steps achieve this limit. The movement will be relative, with the motion required by the mover and achieved in operation determined by beam position monitors. Since approximately 1,000 movers will be required, cost reduction, manufacturability and reliability are important for this component.

Gordon Bowden has developed and produced movers used in the FFTB which have been demonstrated to meet the requirements for final focus component movers except for resolution (they were measured to achieve a position resolution of approximately 300nm) and cost (a 5-degree of freedom mover would probably cost at least $5000 each to manufacture in their current design, at least in small quantities). These movers are mechanical, utilizing a kinematic support concept providing motion by rotation of bearings mounted on an eccentric shaft, which are in contact with wedge-shaped anvils supporting the linac component (See Fig. 1). Rotation of the shaft is accomplished by means of a 200 step per rotation stepper motor driven through a 100:1 harmonic drive. Mechanical movers such as these have several desirable features, including potentially lower cost (due to reduced requirements for feedback and control circuitry), reliability, and the ability to retain a set point without active compensation. Position monitoring can be accomplished by simply mounting a rotary encoder on the shaft.



Figures 1A and B: Magnet mover prototype built at CSU from modified SLAC drawings

In order to meet the 50 nm step size requirement, the rotation of the eccentric shaft must be controlled in approximately 60 microradian intervals, or about 100,000 steps per rotation. This is challenging. One possibility for achieving the desired position resolution with the existing mover design is to increase the step resolution of the stepper motor to at least 2000 steps per rotation with a micro-step motor controller. This concept remains untried, and testing is required to determine if a purely mechanical mover of this type can provide 50 nm resolution.

The stepper motors and the harmonic drives are the cost drivers for this system. Any cost reduction effort for the mover must begin here. One way to accomplish this is to use stepper motors more efficiently, with less expensive mechanical reduction to replace the harmonic drives. It may even be possible to eliminate the mechanical gear reduction altogether, if it is possible to drive the stepper motor itself with sufficient precision and maintain sufficient stopped torque from the stepper motor. A second option is to use the mechanical mover to achieve rough positioning (with micron-scale precision) and achieve the 50nm precision motion using piezoelectric stacks. A final option is to use other mechanical options for driving the shafts with the required precision, such as DC actuators or combinations of stepper motors with worm gears, vertical wedges, piezoelectric inchworm movers or other systems.

Broader Impact and Student Involvement

This project will involve both graduate and undergraduate students in developing and testing the LabVIEW control software used to actuate the stepper motors and also the motion control software required to change the rotational motion of the shafts into physical motion of the magnet through two linear and three angular degrees of freedom. The precision movers developed for this project may be useful for other accelerator projects, as well as for optics and other high precision applications.

Results of Prior Research

In September 2003 the Technical Design facility at CSU received funds from the Linear Collider R&D program to develop linac magnet movers and final doublet girder movers. At that time, work began on procuring a prototype mover, refining our understanding of metrology techniques which will be used to qualify the mover, and exploring other shaft drive options that might prove more cost-effective. Our request for continued funding as part of the 2004 LCRD program was not supported, although a no-cost extension to our existing LCRD grant was approved allowing us to continue work on this project at a greatly reduced rate.

In the past year we have built a prototype mechanical mover system and are currently working on the stepper motor microstep control system and rotational encoder systems. We have made progress in identifying candidate metrology systems, but are awaiting the results of this funding request before reaching a decision on the extent of the system we will purchase.

Prototype mover system:

Unfortunately it was not possible to get an existing mover from SLAC, so we have replicated a modified version based on the original design and drawings for the SLAC three-axis mover. Our variant initially includes only three motors (as in the original FFTB mover), which will allow us to control two linear dimensions and one angle (X and Y and roll), but our model was designed to be expanded to 5 motors, allowing us to control all three angles (Pitch, yaw and roll) and two linear dimensions (X and Y, not along the beam axis). The prototype mover combines harmonic drive reducers and a micro-stepped stepper motor to drive the mount shafts, which should allow us to achieve the required step resolution.

Stepper Motor & Control System:

We have purchased and are studying the performance of a stepper motor system using Lin Engineering Model 5704M stepper motors, with a resolution of 0.45 degrees per step, or 800 steps/revolution. These motors are driven with Intelligent Motion Systems Inc. IM483 microstep drivers, which have a published resolution of 256 microsteps per full step. The combination of the motor and driver gives us a theoretical resolution of 204,800 microsteps per revolution. Using this motor/driver combination, it may be possible to eliminate the mechanical harmonic drive mechanical step reduction. If we can achieve sufficient precision and torque to drive the system, this would be a great simplification to mechanical assembly and cost.

The rotational position of the drive shafts is measured using a Micro-E Chip Encoder, with a resolution of 163,840 counts/revolution, allowing angular measurement with the required precision.

In preliminary bench-top testing we achieved very nearly the theoretically predicted precision through a small (few hundred) number of microsteps, but the rotation became less accurate as larger numbers of steps were moved. After further investigation it was determined that driver cards were a major source of our difficulties, due to electronic noise generated as the micro step driver crossed a full step boundary for the stepper motor. We are replacing them with a new model recommended by Lin Engineering, and expect better performance from our new system.

In addition to replacing the drivers as mentioned above we plan to acquire a Trinamic TMCM-302 3-axis controller. This controller will act as the interface between the drivers, encoders and a PC running Labview software.

Metrology:

We are investigating a metrology system based on capacitive position measuring, using a system from Lion Precision that will allow measurements with a precision of approximately 10 nm over a range of 50 microns. Additionally, each of the five drive shafts (after harmonic drive reduction) will be read out using rotary encoders with 3mr resolution. Together, this will allow us to measure the entire range of motion of the mover. We are also investigating linear encoder measuring systems such as those available from RSF electronics, which can achieve a resolution of approximately 100 nm.

We have a quote on a one sensor system that we will buy for our initial measurements, and plan to expand to a full 5 sensor system after we have proven the system works.

This metrology is for use in testing our prototype movers, and would not be part of a production design.

Facilities, Equipment and Other Resources

Our proposal is greatly enhanced by the mover prototype already funded by earlier LCRD funds. Our group also has significant experience with PC-based control systems and experienced LabVIEW programmers. We also have sufficient laboratory space with power, internet access etc. and low cost access to a machine shop with precision lathes, milling machines, etc., provided by the university.

This project is an excellent fit to the capabilities of the technical design facility at Colorado State University. The facility has been involved in manufacturing many components for HEP applications that require cost optimization due to the large number of items to be procured, as well as a great deal of prototype development and fixturing work. Through Prof. Wilson, the CSU HEP group has a long history of participation in the Linear Collider Detector development. The group is fully supportive of the technical design facility proposals to contribute to Linear Collider Accelerator development. Additionally, there is a precision measurements group in the department working on laser atom lithography projects lead by Prof. Siu Au Lee, which can provide advice and assistance as required.

Proposed Project

The work already funded by the LCRD program in our first proposal will be completed by the end of the summer of 2005. Our new proposal expands on the work already funded, taking advantage of the FFTB mover and metrology equipment we will build, and the experience we will have gained to move towards final mover designs.

Year one of this new proposal continues the initial project, investigating rotary motion drivers and motion encoders in an attempt to find a cost-effective version of the FFTB mover with sufficient resolution. We now have an operational mechanical prototype, and shortly will have the micro-stepped stepper motors in place and tested. We also hope to have the metrology equipment in place to allow us to measure its motion by early summer 2005. By October 2005, we will have determined if we can meet the step resolution required with a mechanical three-motor microstepped mover, what type of rotation reduction system will be required, and a preliminary indication of the cost per mover and the difficulties in producing this type of mover

A LabVIEW-based control system and motion control software will be developed with student assistance to allow us to move the magnet platform through a specified range of motion.

Additionally, we plan to purchase a full 5-axis capacitive position measuring system (actually an expansion of the system we are ordering for 1-axis measurements under our current grant) in order to be able to fully monitor the 5-axis movement of the stage simultaneously.

Deliverables:

-Measurements of the resolution achievable using the micro-step driven FFTB mover, both for three-motor and five-motor configurations.
-Development of a metrology system capable of measuring the 5-axis motion of the mover with better than 50 nm precision.
-Results from feasibility of alternate shaft driver options.
-Software and hardware for mover control system
-Designs for magnet mounts for a five-motor system

Year two goals are to evaluate the incorporation of piezoelectric movers and active feedback into a reduced-precision mechanical mover, with feedback based on the capacitive metrology system we are investigating for measuring the system performance or strain gauges.

Our experience during the first year of the project will give us a solid understanding of the limitations of the mechanical mover, and based on this platform we will develop a piezoelectric stack to attach to the mover, and begin to investigate the resolution, vibration isolation, and stability achievable with such a system.

Additionally, we will investigate the possibility of using other mechanical movement devices or alternate motor options, such as DC actuators or piezoelectric inchworm devices to try to reduce costs by eliminating the harmonic drive.

Deliverables:

> -A design for a feedback system to stabilize a piezoelectric stack add-on to a mechanical mover capable of achieving 50 nm precision.
> -A prototype mover system including these additions, and measurements of the resolution and stability achievable by such a system.

Year three of the project will move towards manufacturability of the beam delivery system mover at a low price, involving redesign of the components in collaboration with manufacturing firms to reduce price and to determine the most cost effective option for the driver system. Year three will also include development of any special mounts required for the final focus girder cryostat.

Deliverables:

> -An optimized-for-manufacturability design report for the beam line movers, including an optimized shaft driving system, measurements of system performance, and projected costs
> -A design for a final focus element mover.

Budget Justification

There is no HEP base program grant support for Warner. All costs, including travel, associated with this proposal must be provided by the project. Warner's salary is charged through the CSU Technical Design Facility at a flat rate of $50/hour. Fringe benefits charges are included in this hourly rate. Technician support and machine shop labor are also charged at flat hourly rates of $30/hour and $33/hour respectively, with fringe included in these rates as well.

In Year 1 (FY 05) our labor costs include: 2.5 months support for Warner; technical support funds in the form of machine shop and technician time for additional prototype development work; and summer salary support for a one graduate student to assist with control software development and system testing. We are requesting equipment and M&S funding for the metrology system, computer control hardware, and continued stepper motor development costs. We are requesting travel funds to support 3 trips, typically to SLAC and/or FNAL, to consult with LINAC development experts and report results.

In Year 2 (FY 06) our labor costs include: 3 months support for Warner; technician support; and summer salary for one grad student to assist with measurements and metrology software improvements. We are requesting equipment support for the piezo-electric mover; this equipment cost includes labor (including undergraduate student labor), materials and supplies, but will be capitalized as a single piece of equipment at CSU. We are requesting travel funds to support 3 trips, typically to SLAC and/or FNAL.

In Year 3 (FY 07) our labor costs include: 3 months support for Warner; and technician support for testing the mechanical prototype. We are requesting equipment funds to build an industrial prototype mover in conjunction with a local manufacturing firm; as Year 2, this equipment cost includes development and M&S expenses (including undergraduate student labor) which will be capitalized as a single piece of equipment. We are requesting travel funds to support 3 trips, typically to SLAC and/or FNAL.

Three-Year Budget, in then-year K$

Item	FY2005	FY2006	FY2007	Total
Other Professionals	26.8	33.0	28.5	88.3
Graduate Students	4.5	4.5	0.0	9.0
Undergraduate Students	0.0	0.0	0.0	0.0
Total salaries & Wages	31.3	37.5	28.5	97.3
Fringe Benefits	0.2	0.2	0.0	0.3
Total Salaries, Wages and Fringe Benefits	31.5	37.7	28.5	97.6
Equipment	14.0	12.0	16.0	42.0
Travel	1.5	1.5	1.5	4.5
Materials and Supplies	0.0	2.5	2.5	5.0
Other Direct Costs	0.0	0.0	0.0	0.0
Total Direct Costs	47.0	53.7	48.5	149.1
Indirect Costs	10.1	12.7	9.9	32.7
Total Direct and Indirect Costs	57.0	66.4	58.4	181.8