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 contains a progress report on the magnet mover research funded in the 2005 LCRD accelerator research program, and a request for continued funding at a level slightly higher than that proposed in our 2005 3-year request, to cover reductions in our 2005 award. Our initial request for support in 2005 totaled $57,000, and assumed that the funds would be available for our use in July 2005. The actual 2005 award for the project was $46,333, and arrived in October 2005. This resulted in a reduction in scope for year 1, and a delay to the schedule. Despite these changes, however, we can report significant progress, and preliminary measurements on our prototype, which meet requirements.

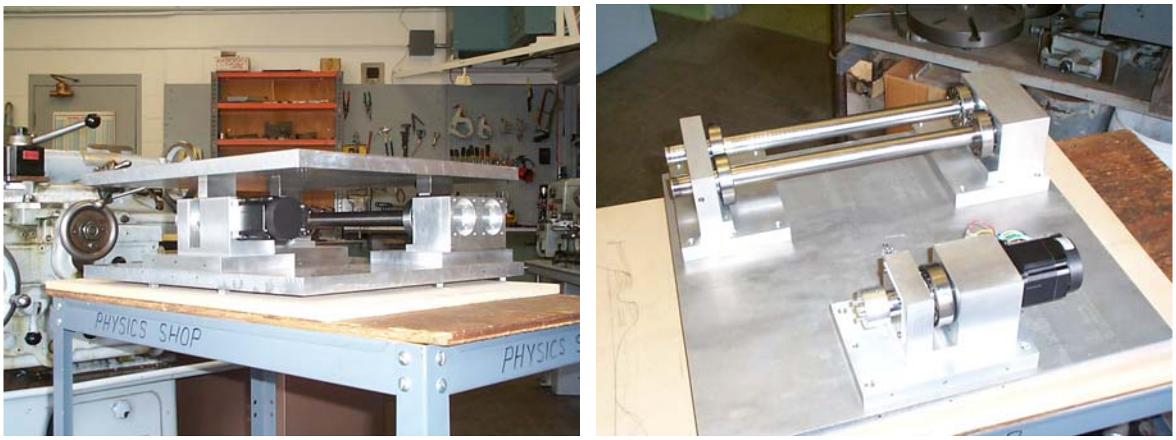
We are requesting funds for the remaining 2 years of our R&D program, which will continue our investigations of the resolution attainable with mechanical movers similar to those produced at SLAC for the FFTB, and our efforts to reduce the costs associated with manufacturing them. We will also mount piezoelectric movers to our modified FFTB magnet mover to investigate the possibility of reducing cost and/or improving 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.

Basic Mover Requirements

Every magnet and structure girder in the ILC beam delivery system will sit on movers to allow them to be positioned accurately. Depending on the requirements of the component in question, the movers must 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 average. 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 developed and produced movers used in the FFTB while not achieving the required precision (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) have provided the fundamental design concept for our mover. These FFTB 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.

We have developed a similar mover at CSU, slightly modifying the SLAC design, principally by removing the harmonic drive 100:1 mechanical reducer and directly driving the eccentric shaft with a high-precision micro-stepped stepper motor This change was made to remove the complications involved in the harmonic drive installation, to increase the precision of motion achieved, and to bring the system cost down (See Fig. 1 A and B).



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

In order to meet the 50 nm step size requirement for a shaft with 1.5mm eccentricity (3mm total motion), the rotation of the shaft must be controlled in approximately 33 microradian intervals, or approximately 188,000 steps per rotation. In our initial testing with Year 1 funds, we have demonstrated that we can achieve greater than 200,000 steps per rotation with a micro-stepped motor, sufficient to meet this requirement. Our initial measurements using a capacitive metrology device indicate we are achieving linear motion of approximately 40 nm per step using this direct drive system.

A second option is to use a mechanical mover to achieve rough positioning (with micron-scale precision) and achieve the 50nm precision motion using piezo-electric 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 2005 LCRD funding for the project resumed. We have completed a prototype mechanical mover system and have demonstrated a stepper motor micro-step control system and rotational encoder systems capable of achieving the desired precision. We are testing a candidate capacitive metrology system, and expect to place an order for a three-axis measurement system shortly.

Prototype mover system:

Due to reductions to our proposed 2005 budget, our mover curently 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). It was designed to allow expansion 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). We plan to expand the system to the 5 degree of freedom model with 2006 funding.

Stepper Motor & Control System:

We purchased and have demonstrated the performance of a stepper motor system using Lin Engineering Model 5704M stepper motors, with an intrinsic 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 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 (~30 microradians per step). Using this motor/driver combination, it appears to 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 (38 microradians), allowing angular measurement with the required precision.

In preliminary bench-top testing we achieved very nearly the theoretically predicted precision of rotational motion from the stepper motors as measured by the chip encoder.

We have also acquired a Trinamic TMCM-302 3-axis controller to act as the interface between the drivers, encoders and a PC running LabView software.

Metrology and Monitoring:

We are investigating a metrology system based on capacitive position measuring, using a system from Lion Precision that should allow measurements with a precision of approximately 20 nm over a range of 500 microns.

In December 2005 we received a one-axis evaluation system from Lion, and are testing this system on our prototype mover. We plan to purchase a 3-axis system in January 2006, and plan to expand to a full 5 sensor system after we have proven the 3-D system works.

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

One impact of the removal of the harmonic drives from the system is that the stepper motors are required to provide holding torque to maintain the set position under load. This results in a constant heat source from each motor, when moving or stationary. To monitor temperature effects from this heat, we have mounted thermocouples to the motors, motor mounts, and platform of the mover and monitor them using a LabJack U12 DAQ board read out through the LabVIEW program controlling the stepper motors.

Preliminary Results:

As noted above, the data presented here represent very preliminary measurements, taken in the first 2 weeks after receipt of our metrology system in December, 2005. The initial results are very promising, however. Figure 2 shows the linear motion of one edge of the mover platform as a function of the number of micro-steps requested by the software. As can be seen, the motion is very linear over the range measured, approximately 40 nm per step. Several data sets are shown, moving 100 steps in one direction, then back to the origin, then 100 steps forward again, demonstrating the system has reasonable backlash and repeatability of motion. These measurements were taken with the shaft eccentricity at 90 degrees to the direction of motion, where the motion per step should be greatest. A load of approximately 30 kg was resting on the mover during these tests.

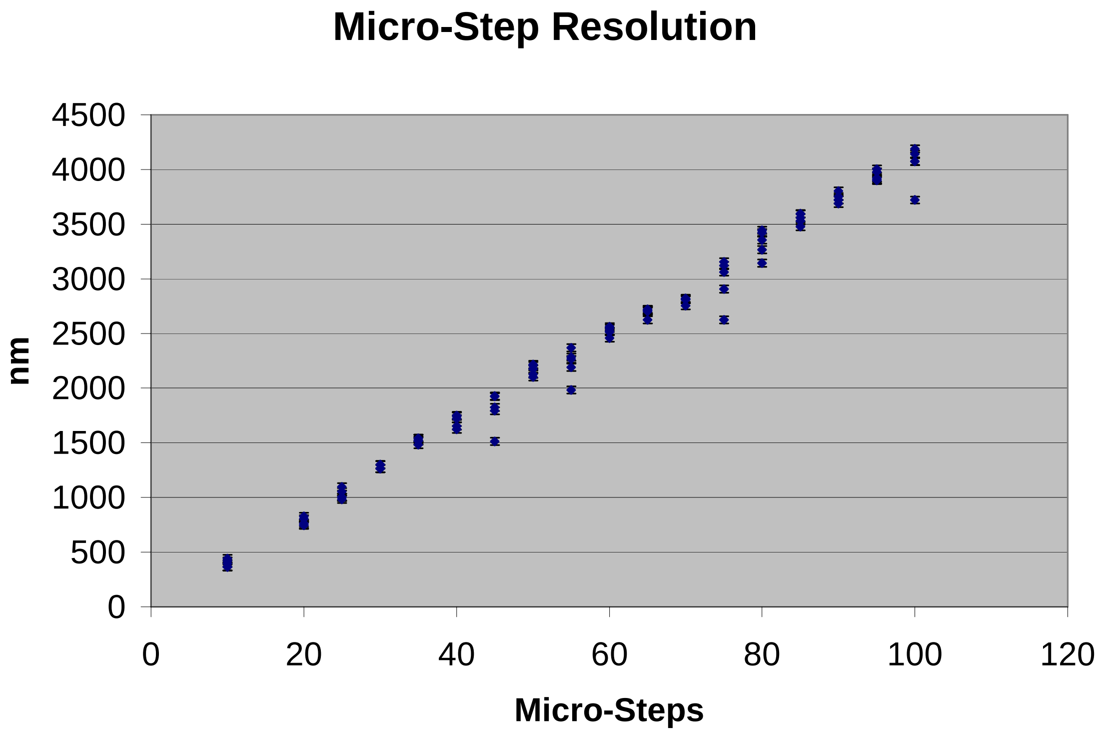


Figure 2: Motion control precision, shown as distance moved per microstep, of approximately 40 nm per step resolution

Figure 3 shows the long-term stability of the system. The data show the motion of the system when parked in a fixed position overnight, as measured by the capacitive sensor on a minute-by-minute basis. As can be seen from the plot, short-term position variation appears to be on the order of 50nm, while in approximately 700 minutes of monitoring the mover support platform shifted by approximately 250 nm. The cause of this gross motion is unknown, and may be due to relaxation of the bearings, thermal effects, or other causes. The chip encoder measured no rotation of the shaft during this measurement, so insufficient breaking torque of the motor seems not to be a cause.

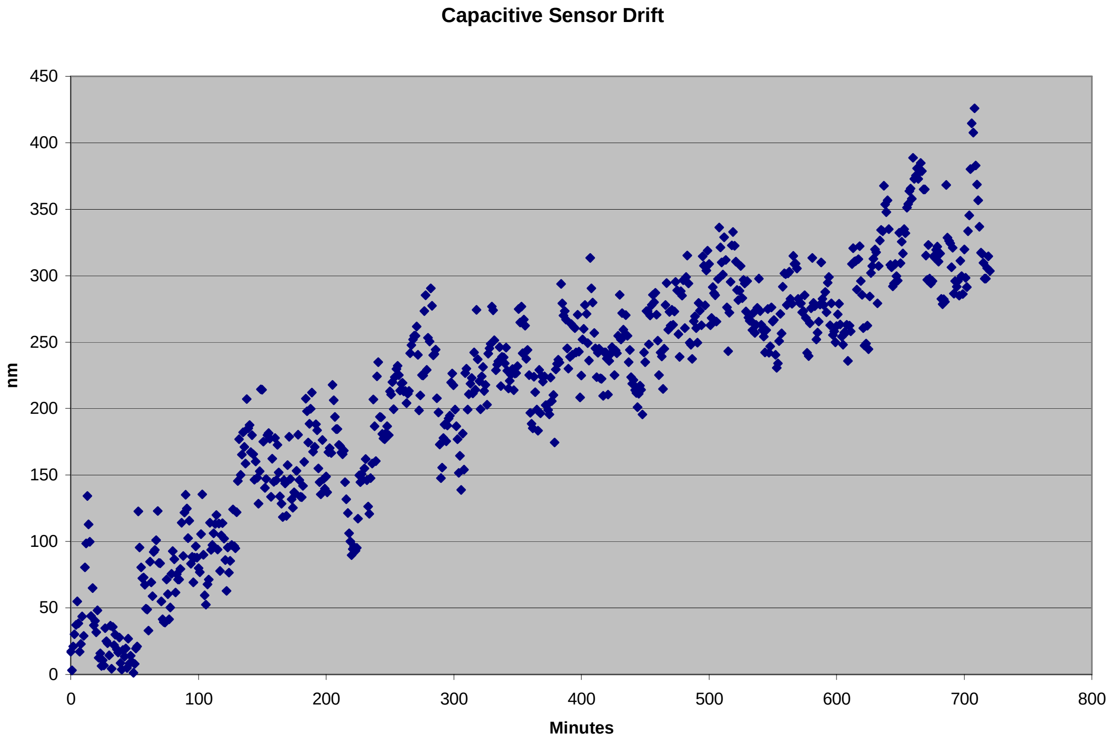


Figure 3: Overnight stability of mover platform in parked position

Initial measurements of the operational motor temperature seem quite stable with time. Figure 4 shows the temperature of one motor as a function of time. This measurement was taken under breaking torque conditions, with the mover supporting a 30 kg load.

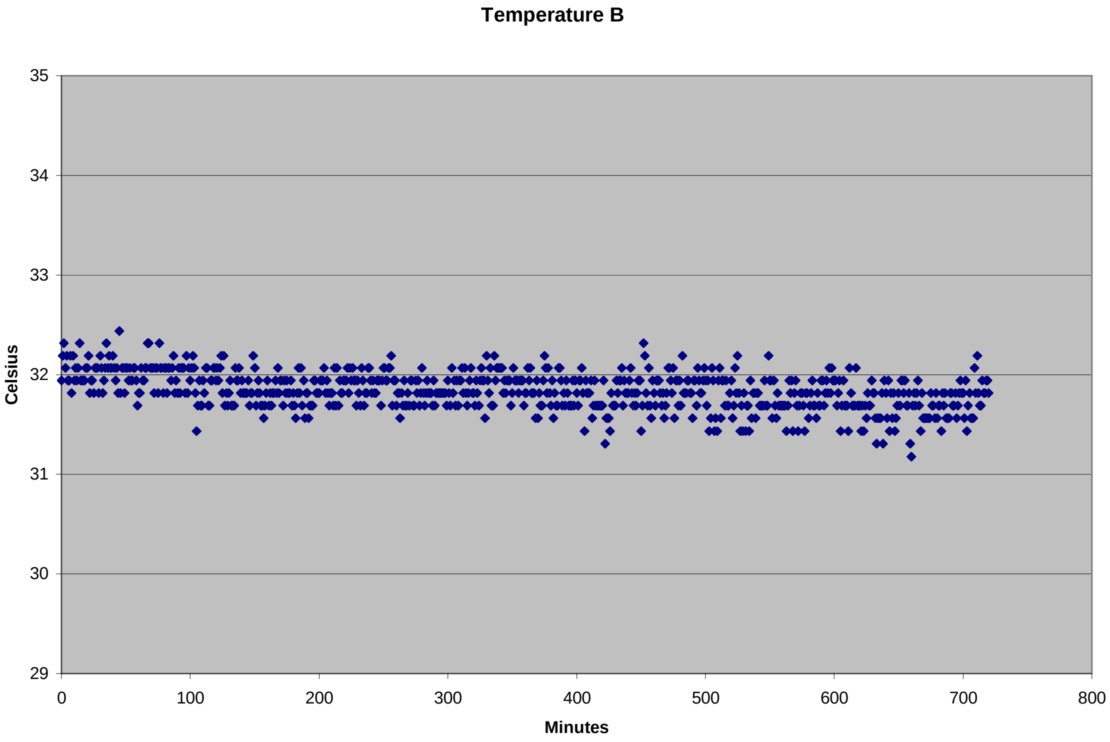


Figure 4: Temperature stability of activated stepper motor with time.

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 HEP 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 beginning of summer 2006. Our new proposal expands on the work already funded, taking advantage of the FFTB mover and metrology equipment we have built, and the experience we have gained to move towards final mover designs.

With our existing funding, we expect to complete the following:

-Measurements of the resolution achievable using the micro-step driven FFTB mover for a three-motor configuration.
-Development of a metrology system capable of measuring the 3-axis motion of the mover with better than 50 nm precision.
-Results from feasibility of alternate shaft driver options.
-Software and hardware for motor control system

Year two goals are to:

- Upgrade the mover to a 5 stepper motor configuration, controlling motion through 3 angles and 2 linear motions, including designs for shaft mounts for a five-motor system

- Develop software to control the motion of the mover to desired angle and position (as opposed to simply rotating the shafts through a specified angle, as in year 1)

- Evaluate the incorporation of piezoelectric movers and active feedback into a less-precise 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.

Deliverables:

-Upgrade mover prototype to 5 motor configuration.
-Motion control software for mover
-A design for a feedback system to stabilize a piezoelectric stack add-on to a mechanical mover capable of achieving 50 nm precision.
-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, with no explicit fringe associated.

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 to avoid overhead costs. 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.

Remaining Two-Year Budget, in then-year K$

Item	FY2006	FY2007	Total
Other Professionals	36.3	36.3	72.6
Graduate Students	5.3	0.0	5.3
Undergraduate Students	0.0	0.0	0.0
Total salaries & Wages	41.6	36.3	77.9
Fringe Benefits	0.2	0.0	0.2
Total Salaries, Wages and Fringe Benefits	41.7	36.3	78.0
Equipment	15.0	16.0	31.0
Travel	2.0	2.0	4.0
Materials and Supplies	4.0	3.0	7.0
Other Direct Costs	0.0	0.0	0.0
Total Direct Costs	62.7	57.3	120.0
Indirect Costs	14.6	12.6	27.1
Total Direct and Indirect Costs	77.3	69.9	147.2