Vibration Suppression R&D
at University of British Columbia

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on
Ground Motion in Future Accelerators

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Overview

Approaches to the final quad stability problem

The “Optical Anchor” concept

Results from the SLAC Optical Anchor program

The UBC vibration stabilization R&D program

Future possibilities
The Final Quad Stability Problem

Linear collider luminosity requires nanometer beam sizes in one dimension, conventionally the vertical.

Transverse motions of the final quadrupole move the focal point essentially nanometer to nanometer.

Even at a good site, e.g. Aurora IL dolomite mine, ground motion exceeds this at frequencies below about 10 Hz.

The IP quads will be about 10 meters apart.

Natural ground motion correlations will be large at low frequencies.

Rigid supports to bedrock for both quads would probably be good enough.

But the supports for the quadrupoles will be a compromise between the physics acceptance requirements of the detector and the mechanical requirements for stability.

Unless there is discipline in the design of the detector, and of the IP services, there will be substantial local vibration sources. Perhaps even inside the quads!
Relief from Beam-Beam Feedback

Beam-beam deflections can be used to steer the beams into collision, so the absolute alignment need not be good to nanometers.

Beam-beam-deflection feedback can keep the beams in collision, but the data rate is limited by the bunch rate.

With low-latency feedback, deflection of the first bunches can be used to steer later bunches in the train "easy" for TESLA, plausibly helpful for X-band.

Even with high latency, feedback works well for frequencies much lower than the macro pulse rate. but is it a factor of 2 lower, or 6, or 20?
Choices for Final Quad Position Feedback

Reference point
“Bedrock:” fiducial outside the detector
“Fixed stars:” inertial frame (no DC feedback)

Quadrupole Position Sensor
Interferometer
measures position directly at long range
Geophone
inertial detector above internal resonance
signal proportional to velocity
not compatible with detector solenoid field (?)
Accelerometer
inertial detector below internal resonance
signal proportional to acceleration
Capacitive displacement
measures position directly, but short range
useful as cross-check in laboratory

Quadrupole Position Actuator
Piezoelectric
large force, short distance, stiff
Electrostatic
small force, low stiffness
Electromagnetic (voice coil)
large force, low stiffness
not compatible with detector solenoid field (?)
Don’t move the quad, just steer the beam

Algorithm and implementation
Optical Anchor Concept

Measure quad positions with interferometer(s)

Correct quad positions with piezoelectric(s)

Idea is to artificially stiffen the quad supports to simulate true rigid connection to bedrock

Needs light paths through detector to “bedrock” (also some external interferometer legs not shown here).

Idea originated at SLAC, developed by Mike Woods.
Interferometer

Classical Michelson configuration is fine:

Change in length of either interferometer arm shifts the interference pattern

Tilt one end mirror slightly to make fringes on the photodiode array plane

Put one end mirror on the quad to be stabilized, put beam splitter and other end mirror outside of detector.

HeNe laser wavelength is about $2\pi \times 100$ nanometers, so 1 nanometer is very close to 10 milliradians of phase.

Counting fringes isn’t enough, we need to look for small shifts in the interference pattern.
Interferometer Issues

At the half-intensity points, 1 nanometer gives about 2% fractional change in intensity. Not hard to measure, and not very demanding on laser intensity stability.

For air, n-1 is about $3 \times 10^{-4}$ and proportional to density. A 10 meter path in air is about 4500 wavelengths slower than a 10 meter path in vacuum, so a difference in air density between the two light paths of 0.35 parts per million would look like 1 nanometer.

Obviously it’s preferable to have vacuum light paths. But air is not out of the question if the paths are carefully matched.

If the path lengths are not equal, the light at the photodiodes comes from the laser at different times. If the laser frequency also wanders, this shifts the interference pattern by an amount proportional to $\Delta \omega \Delta t$ times the path length difference.

This is another reason to match the arm lengths.

This can be turned into a virtue: by intentionally sweeping the laser frequency, we can measure the path length difference. This could be used to measure the quad position in situ, and works even if the power has been turned off and back on.
SLAC Optical Anchor R&D

Mike Woods et al, 1996-1999, at SLAC

1 meter baseline in air on optical table in lab building
Stabilized HeNe laser, 1mm-pitch photodiode array
  • demonstrated sub-nanometer resolution

Add piezo mover on one end mirror with feedback loop
  • demonstrated sub-nanometer drift in signal

100 kg simulated quad, 3 piezo movers
  • not interfaced to interferometer
  • measure motion with geophones
  • demonstrated piezoelectric position control
  • saw expected internal quad resonances

10 meter interferometer
  • in Sector 10 alignment lab (quiet, thermally stable)
  • horizontal folded configuration for convenience
  • vacuum-capable

10 meter interferometer results
  • demonstrated 0.2 nm RMS at 256 Hz for 100 s
  • demonstrated drift of 300 nm over 15 hours
  • works OK in air, if light paths are enclosed
  • demonstrated frequency-sweep measurement of difference of arm lengths

Next step was to be integration of the interferometer and piezo controlled quad, but Mike got involved in other things.
SLAC Optical Anchor Test Configuration

- Laser
- Endstation Vacuum Vessels
- Laser Beam Vacuum Pipes
- 45° mirrors
- Beam splitter
- Photodiode Array
“Optical Anchor” Test Setup at SLAC
UBC Optical Anchor R&D

The integration of the 10 meter interferometer and piezoelectric control of a 100 kg test mass is being undertaken by UBC in cooperation with SLAC.

We have an MOU between SLAC and UBC

SLAC is shipping the interferometer to UBC, and will fund some additional equipment

I have a lab in the UBC Physics basement ready for the interferometer to be installed, plus data acquisition computer, etc.

I have an NSERC grant for support of students.

My first engineering physics co-op student came with me to SLAC last spring and operated the interferometer before it was dismantled for shipping.

He also set up the DAQ computer, did calculations of the optimal parameters for interferometer like the spatial frequency of the interference pattern, and made a simulation of a 3-parameter fit for the amplitude, spatial frequency, and phase (arm length) in LabView.

New student is doing detailed design of test platform, and writing fast-feedback software.
UBC Optical Anchor Feedback Test

Goal is to stabilize a 100 kg mass to a nanometer in one degree of freedom relative to a reference 10 meters away.

Interferometer for feedback signal, piezoelectric in series with spring for actuator.

Spring simulates finite rigidity of quad mounts inside detector.

Design initial test platform to have a single degree of freedom and a single dominant resonance

Allow mass, spring constant, and piezo preload to be varied independently and relatively easily.

Stabilize horizontal rather than vertical (for convenience)

Use Michelson interferometer, arms folded parallel, laser at one end, fixed and moving mirrors at other, photodiode array sees interference pattern.

Easy to change interferometer baseline, can start with short baseline for convenience, low drift, then lengthen to full 10 meters later.

The goal is to have initial results for the summer 2001 Snowmass meeting.
UBC Feedback Test Platform

Payload-table mounted to the floor by flexures

• bear the test-mass load in y (vertical)
• stiff in x (normal to interferometer axis)
• flex in z (along interferometer axis)
• can lock to baseplate for reference tests

Position control

• feedback-piezo between tie-rod and payload-table
• exciter-piezo between tie-rod and end anchor

Instrumentation

• one interferometer mirror tied to payload-table
• capacitive position sensor (relative to baseplate)
• can put geophone or accelerometer on table, floor

Computing hardware

• PC with 100 kHz multiplexed ADC/DAC card
• Card can self-trigger for digitizing, and do DMA

Computing software

• Writing feedback code as Linux “driver”
• Feedback wakes up, takes over CPU
• Calculates position from ADC data
• Updates state feedback, writes to control DAC
• Re-sets its alarm clock and goes to sleep

Initial experiments

• Measure open, closed-loop response to exciter piezo
• Vary mass, tie-rod spring-constant, piezo load
UBC Nanometer Vibration Stabilization
Test Platform Design

- Flexures
- Mass Platform
- Capacitive Displacement Sensor
- Interferometer Mirror Mount
- Anchor for setup
- Replacable Spring
- Feedback Piezo
- Drive Piezo
- Preload Springs (1 shown)
- Flexures
Future Plans

Feedback engineering
• optimization of feedback parameters
• investigate algorithms beyond PID
• calibration schemes
  (blocking one or both beams; piezo pulsing)
• dedicated microcontroller implementation

Interferometer non-invasiveness engineering
• corner reflector to minimize remote adjustments
• two laser colors for air density correction
• sealed/inflated gas-volume along light paths

Stabilize more degrees of freedom
• extended platform and two beams

Simulate internal resonances of support structure
• second platform and spring in series with first

It is possible to use an interferometer for “absolute” position measurements by frequency scanning, which would be useful for in-situ micron-alignment checks.

Participate in future IR stabilization exercises