Final Focus Vibration Control in the NLC

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Requirements

Differential motion of the IP Quads must be less than ~1 nanometer -> Feedback Required

In order to control aberrations, the common mode motion of the IP quads relative to the rest of the machine must be less than ~500 nanometers (much easier).

The electron beam is the only available reference for long term feedback.

Beam - beam deflections provide information on the relative positions of the beams. BPMs can be used to measure the common mode motions of the IP Quads relative to the beam.

The gain of a feedback loop varies approximately as the ratio of the data rate to the disturbance frequency being corrected. For a 120 Hz data rate, the maximum frequency disturbance which can be corrected is about 20 Hz. The feedback will only be useful at frequencies below a few hertz.

If ground motions in the >1Hz range exceed the limits of beam based feedback correction, an additional source of quad position data is required.
Non-beam based quad position sensors.

**Optical Anchor:** Measure the quad position relative to the pit floor. (Interferometer)

**Inertial:** Measure the quad acceleration relative to the fixed stars. (Accelerometer)

**Commercial equipment: Interferometer** - Conventional heterodyne interferometers provide 0.3nm resolution, and >10KHz data rates.

**Experiment: Interferometer** - Mike Woods constructed an interferometer with <1nm noise, and sufficient stability in air for use in the final focus.

**Commercial equipment: Inertial** - A combination of Accelerometer and Seismometer can provide sub nanometer noise from about 1 Hz to >10KHz.

Seismometer will not work in a strong magnetic field.

**Experiment: Inertial** - Capacitive sensor based electronics suitable for use in a seismometer gave sub nanometer noise in a 10KHz bandwidth.
Optical Anchor

The optical anchor (with feedback) acts as a wire with infinite longitudinal stiffness, but attached by torque free joints. A stable structure can only be constructed using multiple anchor points.

Below some frequency, the differential motion of the quads must be stabilized relative to the beam - beam deflection scans.

The optical anchor is useful when the differential ground motion is small, but where the quad supports would otherwise amplify this motion.

The function of the Optical Anchor is to improve the performance of the supports.
Inertial Anchor

The inertial anchor (with feedback) decouples the quads from ground motion for frequencies above some roll off frequency. Below that frequency the differential motion of the quads will be stabilized relative to the beam - beam deflections. The common mode motion will be stabilized relative to either the ground or the beams.

Inertial sensor

Support spring (soft)  Electrostatic pusher

Feedback is used to damp rigid body modes (6), and possibly first several bending modes

Does not correct for large scale angular errors

The Inertial Anchor is useful when the differential ground motion is too large, but where the combined motion relative to the rest of the accelerator is not too large.
Inertial vs. Optical Anchors compared

**Low frequencies (<~5Hz):** both use the beam - beam deflections to control the differential quad motion.

**At high frequencies (>~5Hz):**

Optical Anchor: Matches the quad position to the ground - ideally an infinitely rigid support.

Inertial Anchor: Quads kept motionless - ideally an infinitely soft support.

Choice depends on the ground motion $F(\omega,\nu)$ spectrum.

Optical anchor requires modifications to the detector design to allow light paths.

Inertial sensors will use more space on the IP Quad supports than the corner cubes / mirrors for the interferometer.

Inertial sensors will require more sensor R+D. The inertial sensor feedback algorithm will be more complex due to the low frequency roll off of the sensor sensitivity.
Support Options

1. Use a rigid support. This will minimize the quad motions in the absence of feedback but will tend to increase high frequency motion that is difficult to control with feedback.

2. Use a soft support. This will result in large quad motions in the absence of feedback, but improve the performance of the feedback system.

For the Inertial anchor, #2 is clearly superior, as the goal is to de couple the quads from the ground vibration.

For the optical anchor, the situation is more complex, as the goal is to strongly couple to the ground at high frequencies.

For both systems, a stiff support will cause internal resonances of the quad structure to be excited. These “hidden” modes will greatly complicate (may render impossible) the feedback system.

Note that “soft” supports will sag under gravity by $g/\omega^2$. For $f=10$Hz this is 2.5mm. Large amounts of sag (low frequency support) will complicate the design of the supports.
**Actuator Issues**

Piezo-electric elements are generally considered for the short range / high frequency actuators for the quads. They have the advantage of smooth motion at the sub-nanometer level, and of simplicity.

Piezo-electric actuators are stiff (~$10^7$ N/m), so they will couple ground motion to the quads. For the “soft” support scheme, this is unacceptable.

The required forces are very small:

- Assumed quad mass = 200 Kg.
- Assumed resonant frequency = 10 Hz.
- Support stiffness = ~$10^6$ N/m.
- Required force for a 30 nanometer (worst case) motion = 0.03 Newton.

Can use an electro-static pusher. With 10x10cm plates, 1mm separation, need about 1 kV drive voltage. This system will have very low stiffness.

May also be able to use “bending” mode piezo actuators.
Optical Anchor R+D Plans

Work being done by Tom Mattison at University of British Columbia.

Plans to construct a 10 Meter interferometer similar to the Mike Woods interferometer. This system operates slightly off axis to produce a fringe pattern on an array detector. A fit to the phase of the fringe pattern is used to measure the arm length.

Will use long (horizontal) support paths for the test mass. This will allow modeling of the thermal expansion, and vibrational modes of a long support system.

Will close the feedback loop for the 1 dimensional system.

Later will set up a multi-dimensional stabilization system.

Later - set up an absolute distance measuring interferometer. This technology exists (using variable wavelength lasers, etc.), but existing systems do not have sufficient resolution.
Inertial Anchor R+D plans - DAQ system

Real time box functions

On every cycle (~10KHz): Acquire data, Record data, Apply feedback algorithm, Set control outputs.

At the end of a specified number of cycles: upload the recorded data to the control box. Download new feedback parameters.

PC / Unix station control functions:

Cross compile code for real time box, Measure loop performance, calculate new loop parameters. Download new parameters to real time box.
Inertial Anchor R+D plan (continued)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Initial</th>
<th>Final</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-D inputs</td>
<td>6</td>
<td>16</td>
<td>6 for all modes of solid body, more for a beam</td>
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<tr>
<td>A-D resolution</td>
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<td>16 bit</td>
<td></td>
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<tr>
<td>D-A resolution</td>
<td>12 bit</td>
<td>16 bit</td>
<td></td>
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<tr>
<td>Digital IO</td>
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<td>16</td>
<td>Generic Input and Output digital channels</td>
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<td>Loop speed</td>
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<td>30KHz</td>
<td>Fast as possible, limited by internal modes.</td>
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<tr>
<td>Calculations</td>
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<td>2000</td>
<td>N X N transform (X2), PID loop</td>
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<tr>
<td>Mips</td>
<td>8 Mips</td>
<td>240 Mips</td>
<td>Assumes 1/4 time for calculations</td>
</tr>
<tr>
<td>Data memory</td>
<td>1.2MByte</td>
<td>10MByte</td>
<td>10 second record length</td>
</tr>
<tr>
<td>Bus Bandwidth</td>
<td>0.9 MB/s</td>
<td>8 MB/s</td>
<td>Assumed 1/4 time for transfer, 50% efficient</td>
</tr>
<tr>
<td>ADC / DAQ time</td>
<td>25 µs</td>
<td>8.3 µs</td>
<td>Assume 1/4 time for ADC, 1/4 for dac</td>
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Inertial Anchor R+D plan: Inertial Sensor

We need an inertial sensor with sub nanometer noise in a frequency range from ~5 Hz to ~10KHz. In addition the sensor must operate in the high magnetic field of the detector.

The high frequency part of the problem is easy. Compact conventional accelerometers meet our requirements at frequencies above ~100Hz.

At low frequencies, seismometers have sufficient sensitivity, but will not work in magnetic fields.

We have demonstrated a capacitive motion sensor with sub nanometer noise in a 10KHz bandwidth.

Standard accelerometers operate below the resonant frequency of the test mass. Improved low frequency noise can be obtained by operating above the resonant frequency. (seismometer).

Need to design a support system for the test mass with a resonant frequency <5Hz, but with no higher frequency modes below 100Hz.
Inertial Anchor R+D: Inertial Sensor Concept

The slow centering feedback reduces the sensitivity to variations in source amplitude.

It may also be possible to use feedback to reduce the dynamic stiffness of the spring in a manner similar to that used in magnetic seismometers. This will lower the frequency of the low frequency roll off of the system.
Inertial Stabilization R+D plan: Simple test mass feedback

Supports and sensors will control and measure all 6 solid body modes of motion.

Internal block resonances should be > 10KHz, above the frequencies of interest

Feedback loop (based on DAQ system) will orthogonalized the problem, and control all degrees of freedom.
Inertial Stabilization R+D Plan: Complex test mass feedback

This system will test stabilizing an extended object with mechanical properties similar to the final focus support tube and quad (test mass).

Both inertial sensors and interferometers will be used.

Optionally a second unit will be constructed, and the differential motion measured.
Final focus stabilization system: Issues

**Support Stiffness:** If the support system is analyzed in the absence of feedback, a higher stiffness support seems desirable. Unfortunately this will reduce the performance of the feedback. *Need to consider the feedback system when designing the supports.*

**Optical Anchor vs. Inertial Anchor:** The preferred system depends on the vibration spectrum. Probably desirable to continue development of both systems.

**Mechanical Design / System Integration:** The final IP support structure is in a very space constrained location. Any feedback devices must be designed into the overall system - they cannot be added as an after thought.

**Ground Motion:** We need to determine (preferable through experiment) the expected performance of stabilization systems. This will make it possible to specify the allowable vibration for the accelerator site.