Active Vibration Stabilization for the NLC Final Focus Quads

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Vibration Requirements

- Linear Colliders operate with nanometer scale beam sizes at the IP, and require nanometer beam position stabilities.
- This translates to nanometer stability requirements on the final quads, and 10s of nanometer stability on the linac and beam delivery quads.
- This sounds hard: Nanometers are small!!

Nanometers: Why isn't this crazy

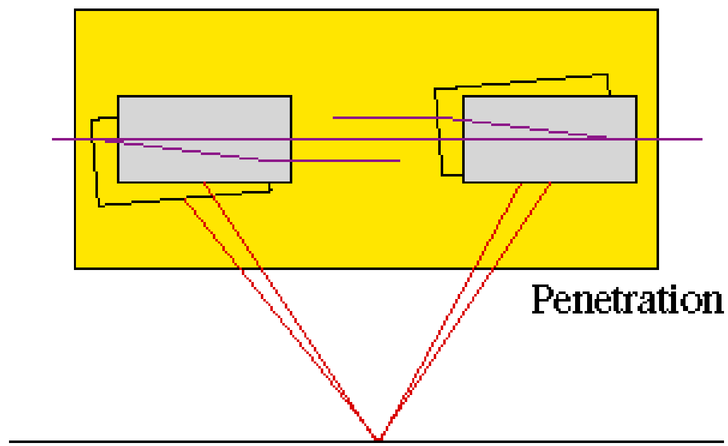
- Only the differential positions of the magnets are important (the earth's motion around the sun is not a problem). We are only concerned with variations over short spatial periods.
- The beam-beam deflection provides a measurement of the relative beam positions at 120Hz (for NLC). Feedback can (and must) be used. We are only concerned with high vibration frequencies.

Requirements

- At quiet sites, with magnets rigidly mounted to the ground, the natural vibration spectrum (spatial and temporal) is within tolerance.
- Accelerator sites are noisy: cultural noise may be too large.
- The final focus magnets must be suspended within the physics detector – difficult to avoid amplification of the ground motion.
- Would like to use magnet stabilization technology.

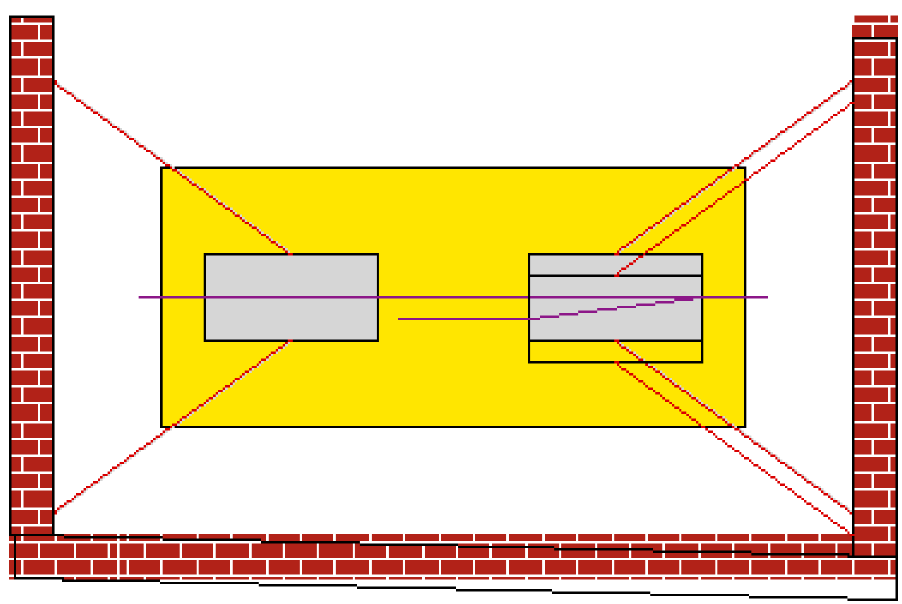
Stabilization Technologies
Optical Anchor

- Use a laser interferometer to measure the relative positions of the magnets. (Early work at SLAC now ongoing at UBC).
- Nanometer measurement noise over meters demonstrated.
- Acts as an "infinitely rigid" connection to the ground.
  - Good: causes final quads to move correlated to the rest of the machine
  - Bad: Difficult to find a good reference point.



Longitudinal translated to vertical (can be fixed with very deep anchor point).

Penetration through detector required.



Differential motion of the pit walls is not corrected

Stabilization Technologies Feed Forward

- Measure the position of the ground or magnet with an accelerometer (or possibly interferometer)
- Steer the beam to correct for the predicted effect of the motion
- Eliminates the need to put fast actuators on the magnet
- The accelerometer may not be a good indication of the motion of the magnetic center
  - Axis coupling
  - Structure resonances.

Stabilization Technologies Intra-train Feedback

- Use the beam beam deflection to measure the beam offset and correct within a train
- Difficult for NLC due to short train length – but simulations indicate considerable improvement.
- Timescale easy for Tesla
- Uncertainties about the “banana effect”.

Stabilization Technologies
Inertial Feedback

- Use accelerometers to measure the magnet position
- Apply force to the magnet to prevent it from moving.
- Avoids feedforward problem of needing to know the exact gain.
- Requires mechanical pushers, and may have stability problems if there are phase delays.

Subject of the remainder of this talk

Optical Anchor vs. Inertial

- Feedback loop easy (reads down to DC)
- Locks quads to ground – correlated with remainder of machine

- Locks quads to "fixed stars"
- Does not rely on ground motion correlations
- No interference with detector

May be used in combination

PM vs Super Quads

- No additional vibration
- Compact (high first resonant frequency design)
- Tunability: either awkward mechanical, or magnet replacement

- Energy Tunability
- Complex, flexible design.
- Flowing helium possible source of additional vibration

Soft vs Stiff Support

- Low forces coupled to the magnet
- High frequency vibrations attenuated by suspension
- Low frequencies fixed by feedback
- Used by LIGO

- Motion amplitude small.
- May not need to use feedback.
- Resists magnet forces

Inertial Feedback System Sensors

- Cannot sense absolute position or velocity
  - At low frequencies has “acceleration noise”
  - Position noise goes as $1/\omega^2$
- Piezoelectric accelerometers typically operate below resonance
  - Poor sensitivity at low frequencies
  - Certain manufactures lie about performance
- Standard geophones have very good low frequency noise (<1 nm at <1 Hz) but are sensitive to magnetic fields.
- Are developing our own sensor

Feedback Actuators

- Coils can provide large forces, but will not work in magnetic fields
- Piezoelectric actuators are standard – but have high stiffness. Cannot be used with soft suspensions
- Electrostatic actuators can provide small forces with low stiffness, and fast response times.

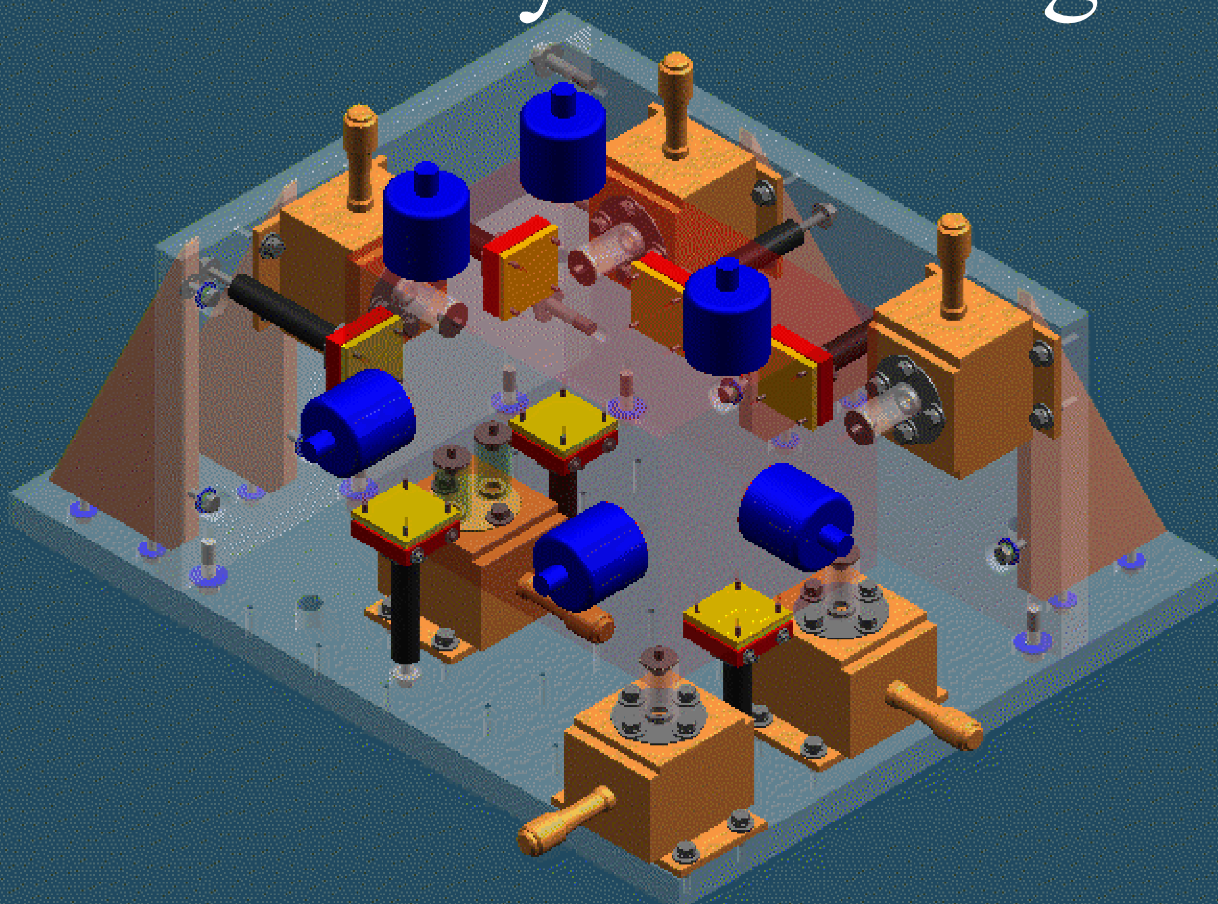
Stabilization R+D Concept

- Exact ground motion not known
  - Site not selected
  - Unknown conventional facilities impact
- Final magnet and detector design not yet done.
- Investigate / develop technology, not try to meet specific specification
- For now, focus on (difficult) final doublet problem.

Stabilization R+D Program

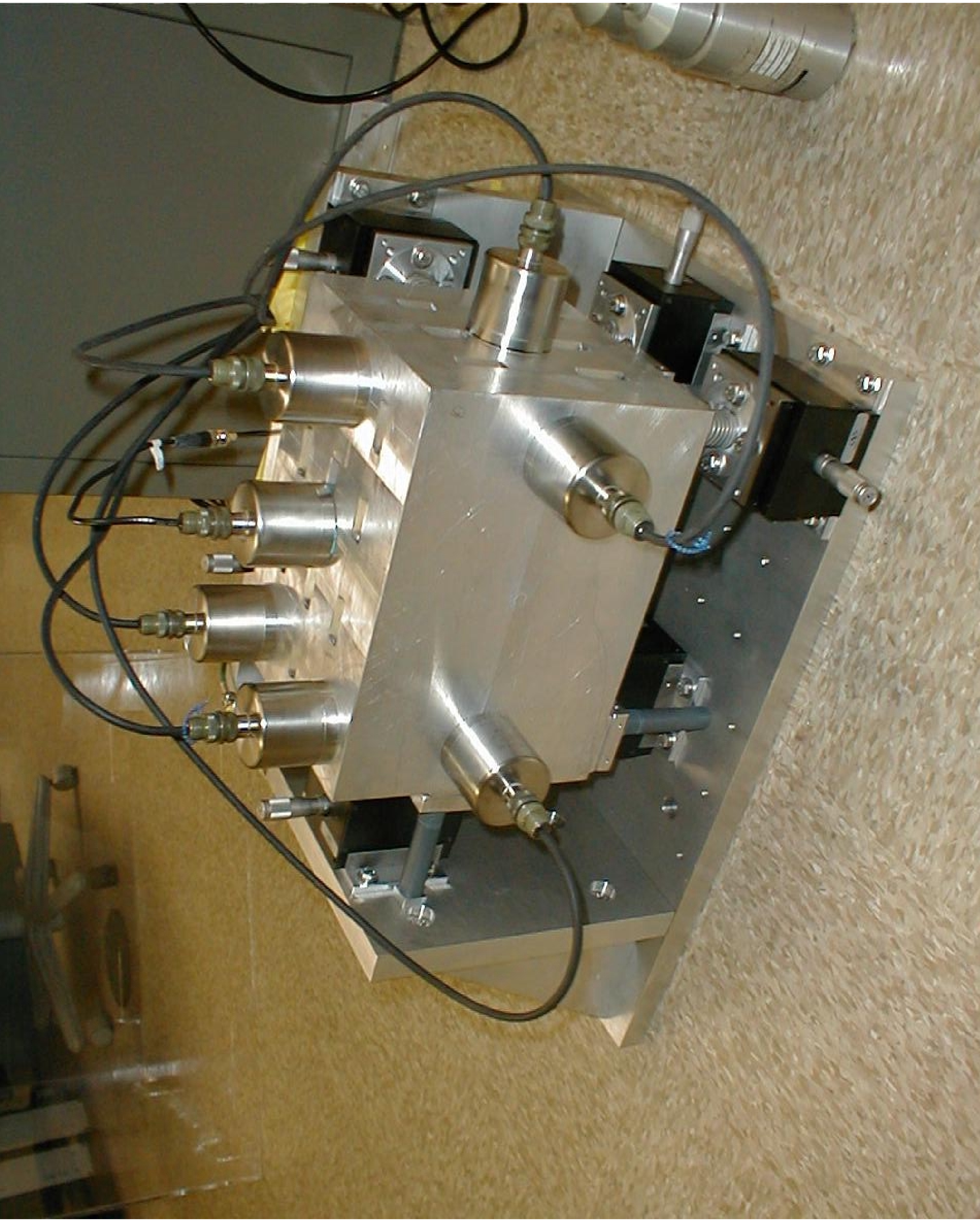
- Construct simple block on springs.
  - Measure and control all 6 solid body modes with accelerometer sensors
  - Replace accelerometers with compact geophones
  - Design electrostatic accelerometers to replace geophones.
- Construct pair of blocks
  - Investigate differential motion
  - Test dual rate (accelerometer / beam) feedback
- Construct extended object with similar mode frequencies to a FF quad.
- Construct a realistic simulation of a FF quad.

Test System Design



Test System Hardware

- Sensors: Start with accelerometers
  - High Noise
  - Simple Frequency Response
  - Will replace with compact geophones (now)
- Actuators: electrostatic
  - 1kV across ~1mm gap, 5x5cm
  - Provide sufficient force
  - Note: force is proportional to v^2



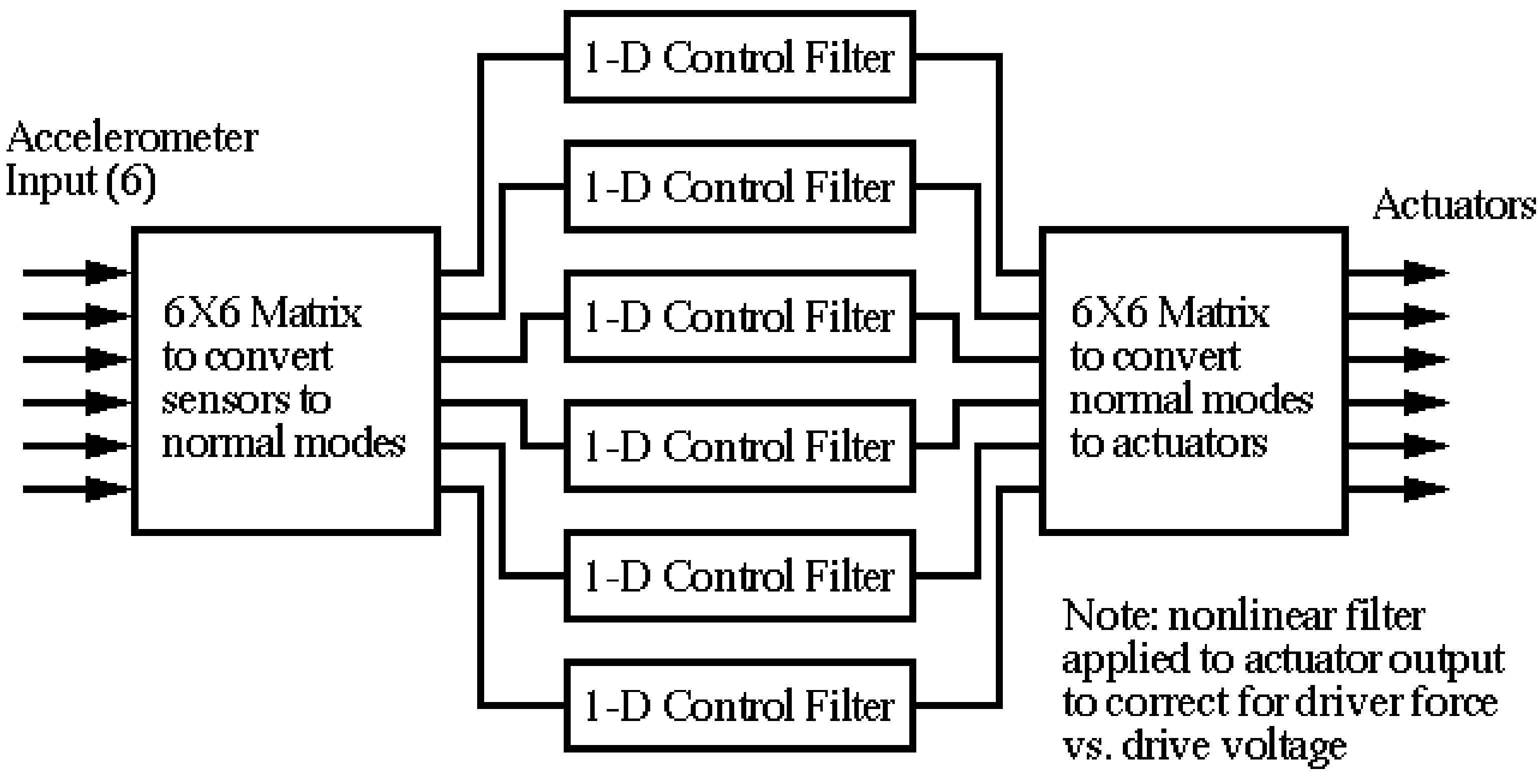
Test System DAQ

- System constructed in VME format
  - Allows future compatibility with EPICS at SLAC
- Use TMS320C40 (~40 MFLOPs)
  - Old, but we know how to program it
- Use “over specified” ADC, DAC
  - Both 250KHz, 16 bit
  - Communication through DSP using private ‘C40 ports
  - VME backplane not used for real time

Test System Software

- DSP runs real time data acquisition, feedback, and "first level" processing.
- Data can be transmitted to Matlab for complex processing.
  - DSP talks to the VME controller through dual port memory
  - VME controller talks to Unix (Matlab) through ethernet (NFS)

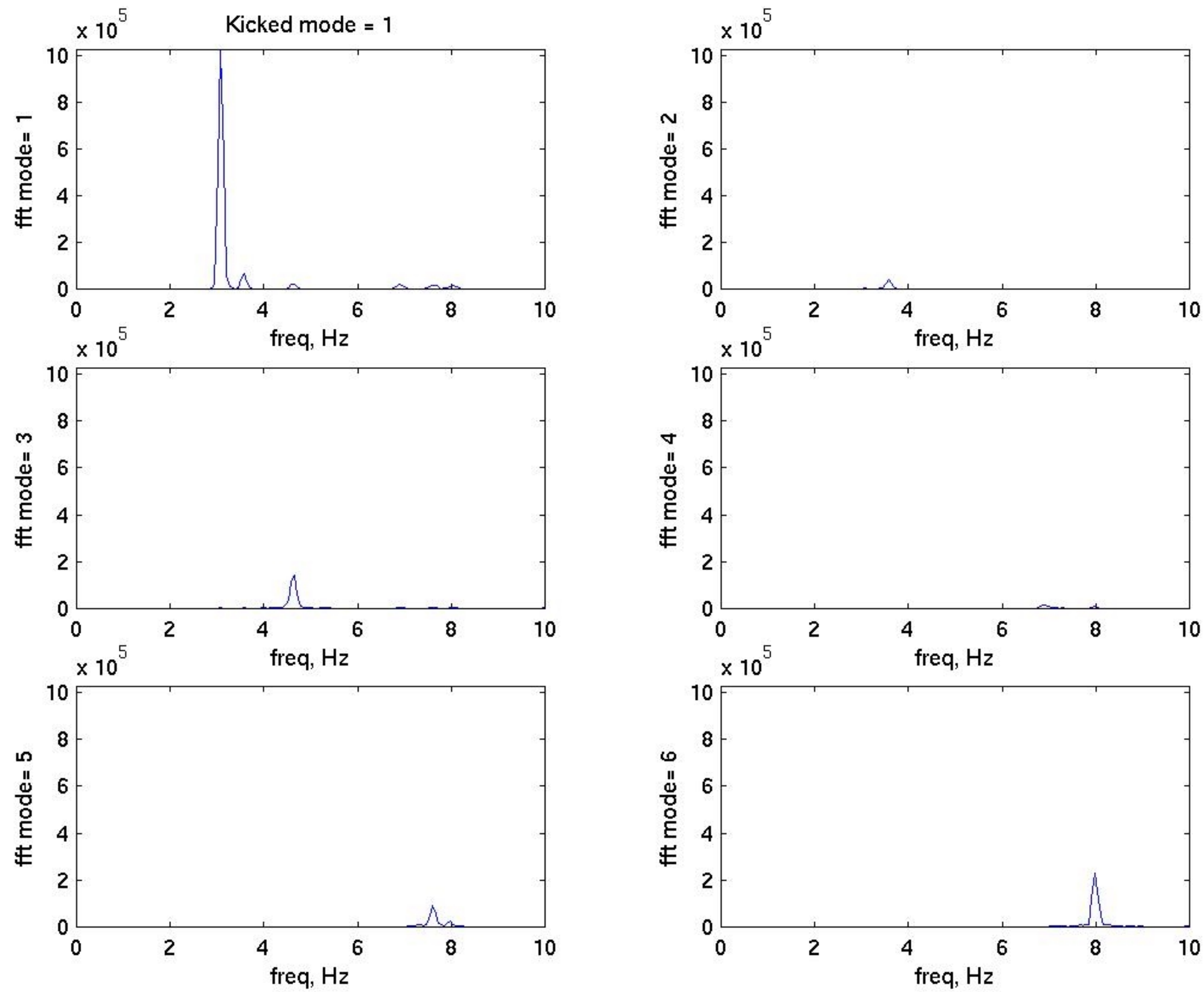
Algorithm


Accelerometer
Input (6)
6X6 Matrix
to convert
sensors to
normal modes
1-D Control Filter
1-D Control Filter
1-D Control Filter
1-D Control Filter
1-D Control Filter
1-D Control Filter
6X6 Matrix
to convert
normal modes
to actuators
Actuators
Note: nonlinear filter
applied to actuator output
to correct for driver force
vs. drive voltage

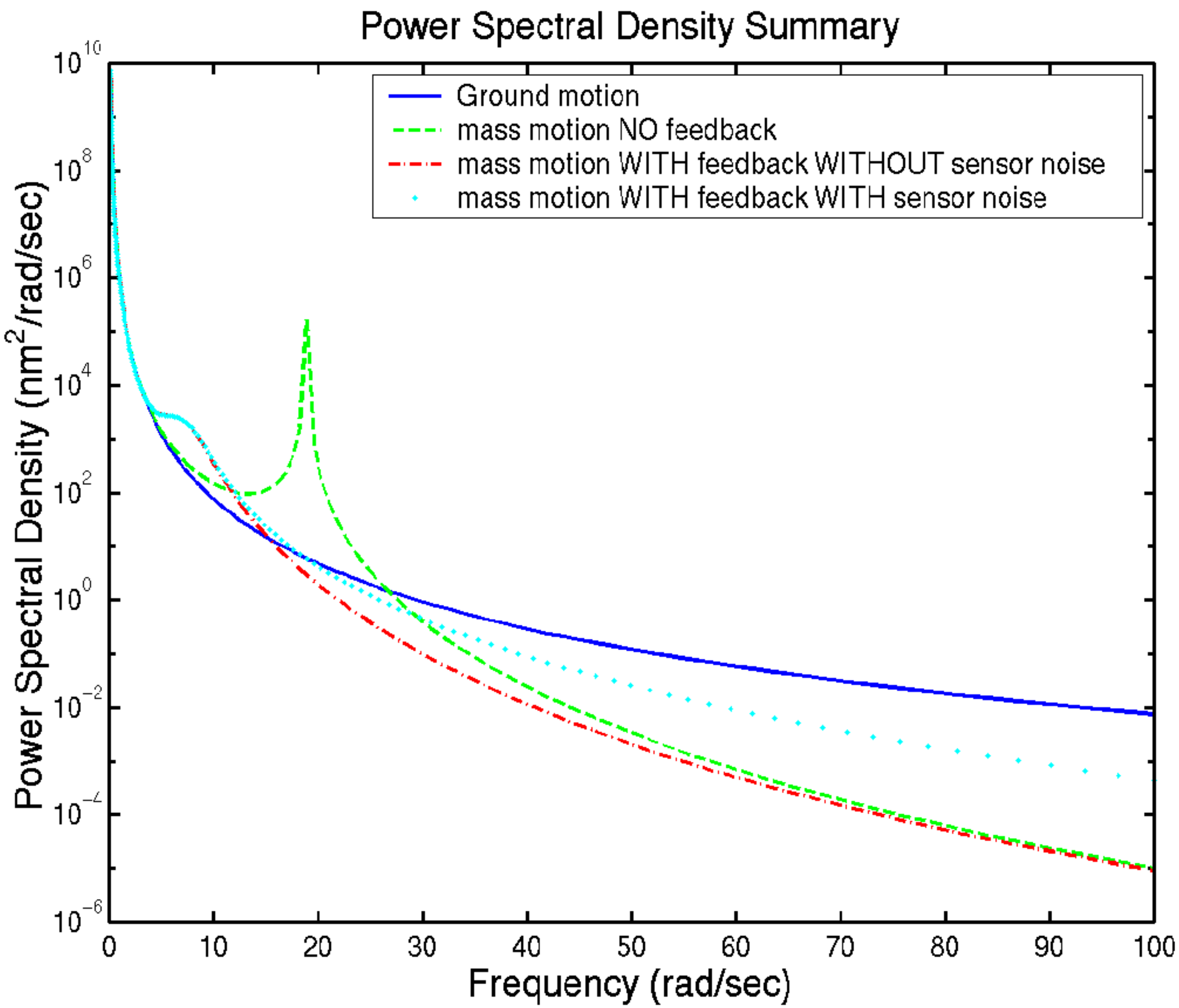
Orthogonalization

- Measure 6 mode frequencies by driving actuators with broadband noise
  - Easy due to high Q
- Drive actuators near resonance
  - Measure exact frequencies
  - Measure actuator to mode couplings
  - Measure mode to sensor couplings
- Test orthogonalization
  - Drive actuator vector for mode N at frequency of mode $M \neq N$
  - Measure amplitude of mode M.

Orthogonalization result for mode 1



1-D simulation results

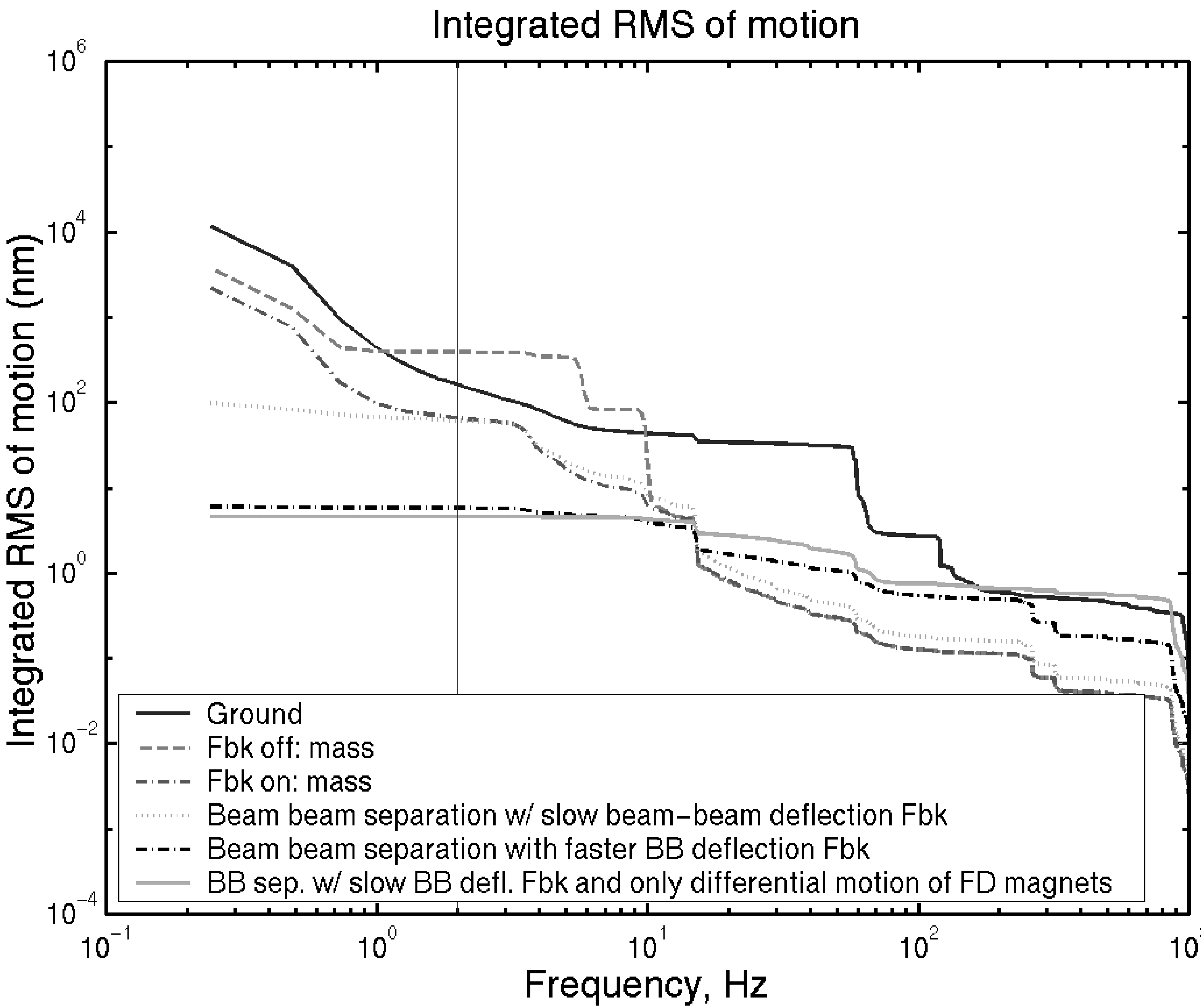


Test Conditions (excuses)

- Noisy Laboratory
  - Integrated noise from 2 Hz to ∞ > 100nm
  - Nominal for SLAC "quiet" conditions ~1nm.
- Noisy Sensors
  - Accelerometers 30X specified noise
  - Significant limit below ~10Hz.
  - Better sensors installed – not yet operated
- Geophone used for evaluating performance

How to Interpret Data

- Data below ~2Hz not reliable
- Integrated motion is infinite!
  - Earth's orbital motion around sun is large!
- Apply conservative beam / beam feedback model
- Apply aggressive beam / beam feedback model
  - Assumes low incoming beam jitter at 5-20Hz
- Apply (VERY POOR) estimate of reduction in motion due to differential motion.


Integrated RMS of motion
Integrated RMS of motion (nm)
Frequency, Hz
Ground
Fbk off: mass
Fbk on: mass
Beam beam separation w/ slow beam−beam deflection Fbk
Beam beam separation with faster BB deflection Fbk
BB sep. w/ slow BB defl. Fbk and only differential motion of FD magnets

Comments on Results

- Beam noise at high (5-20) Hz frequencies has a strong impact on performance at low (1-5) Hz noise.
- High frequency cultural noise strongly attenuated
- Overall noise still ~10X too big
  - Need quieter sensors
  - Need quieter Lab

Sensor Improvements

- Compact Geophones (4.5Hz resonance) installed.
  - Resonance "in band" requires modification to feedback – believed to be straight forward.
- Electrostatic (non-magnetic) geophone development:
  - Sensor electronic noise of 0.01nm/sqrt(Hz) demonstrated.
  - Mechanical design starting – expect prototype by end of 2001.

Overall NLC FF Vibration Strategy

1. At a quiet site, with good supports, beam / beam feedback is sufficient.
2. If site is not quiet, add inertial and / or optical anchor to reduce vibration
3. Add feedforward to correct residual motion
4. Intra-train feedback fixes whatever is left