A high precision mechanical ground rotation sensor

V. Dergachev, R. DeSalvo, M. Asadoor, A. Bhawal, C. Kim, A. Lottarini, Y. Minenkov, C. Murphy, A. O'Toole, G. Pu, A. Rodionov, M. Shaner

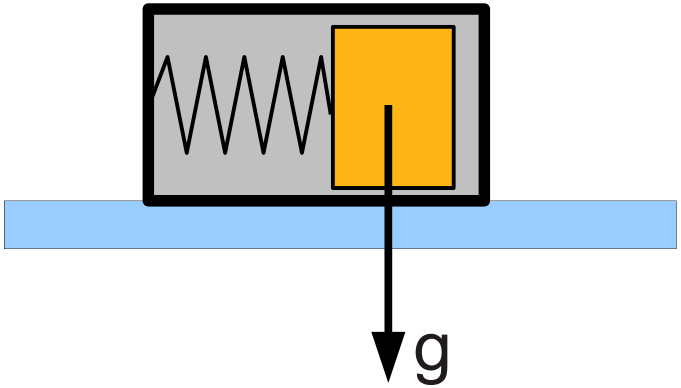
Caltech, April 5th 2013

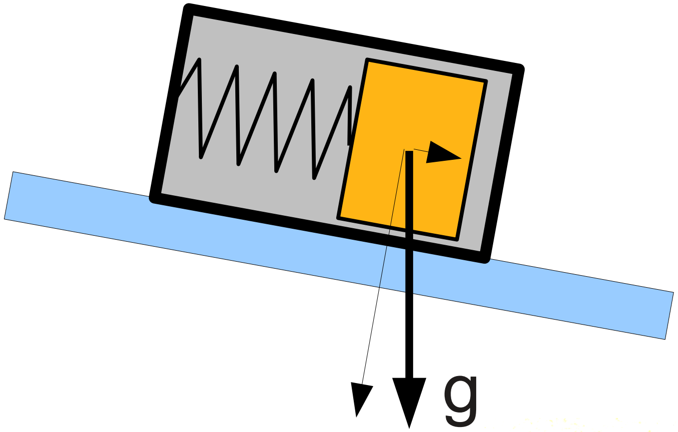
DCC: LIGO-G1300428-v1

Why study tilt ?

- A basic characteristic of an object.
- Accelerometers see tilt as output offset.
- Knowing tilt is useful for seismic isolation systems.
- There is a growing field of rotational seismology.
- For example, a person standing on a concrete pad will compress it by a few microns. This produces tilt of ~1e-7 radians over a few meters.

Tilt can be confused with acceleration





"A linear accelerometer having a full-scale input rating of +/-1g or less is often called an inclinometer. A low range accelerometer used as an inclinometer has relatively high sensitivity to gravitational accelerations of a fraction of a g in magnitude. For this reason inclinometers can be used to measure extremely small angular deviations from plumb or level." - Handbook of Measurement and Control, E.E.Herceg, 1972

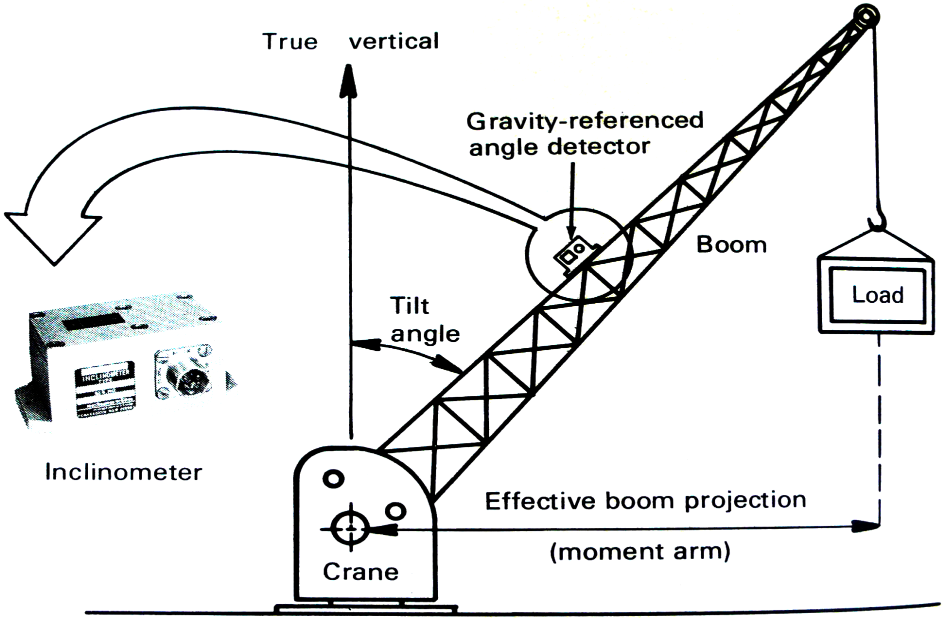
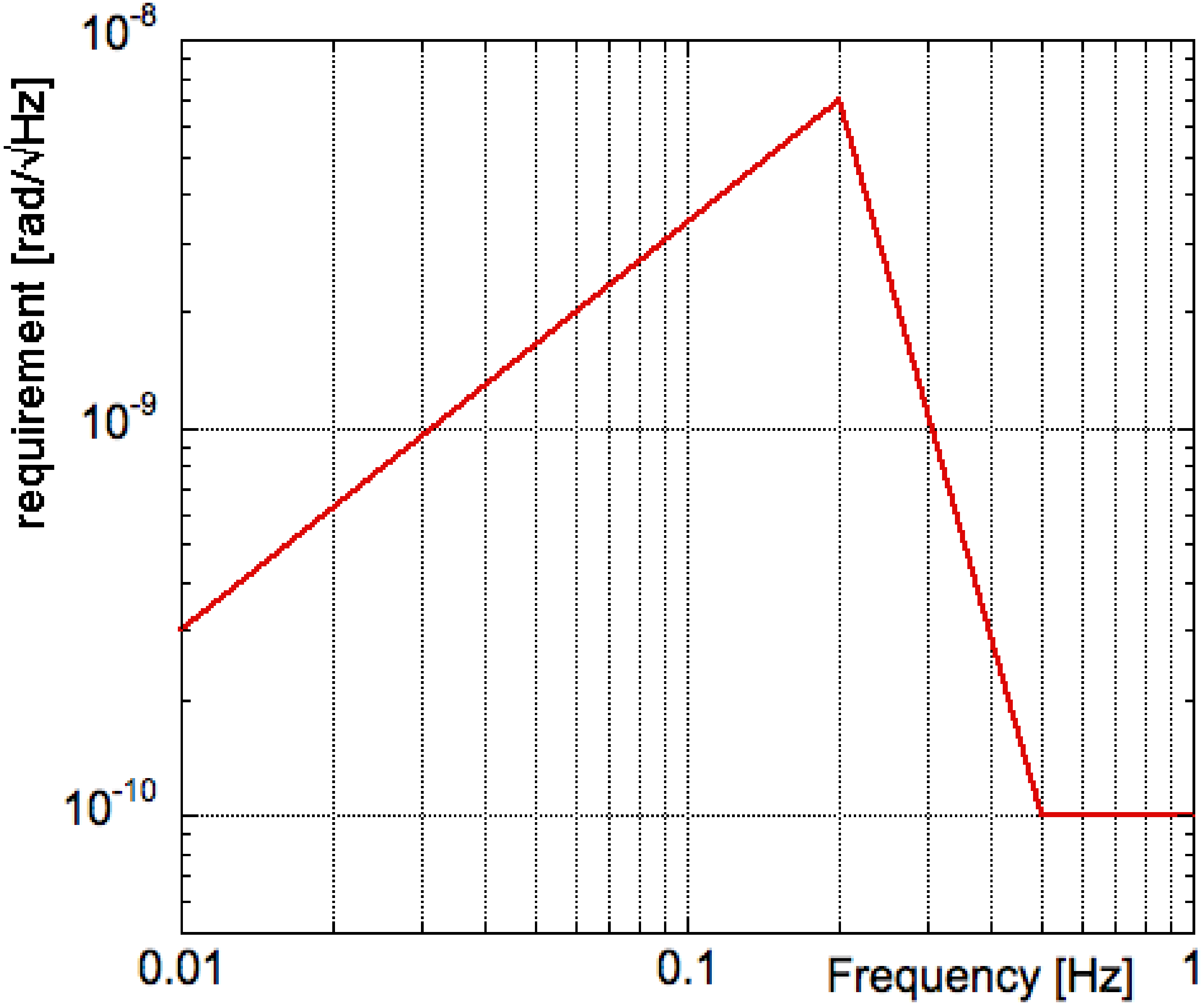


Fig. 12.3 *Application of an inclinometer to crane overturn alarm system.*

Advanced LIGO Active isolation requirements

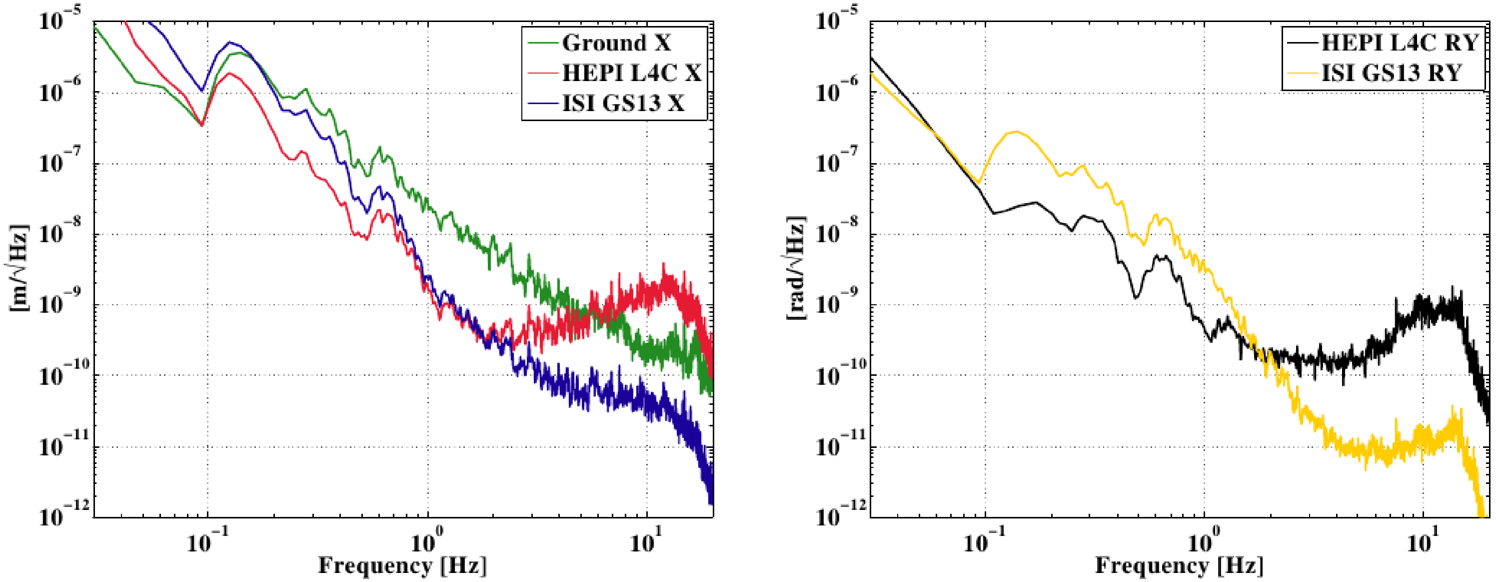


Requirements are more than an order of magnitude more strict than any existing tiltmeter

Lantz, B., et al. (2009). "Requirements for a Ground Rotation Sensor to Improve Advanced LIGO." Bulletin of the Seismological Society of America **99**(2B): 980-989.

Observed tilt coupling

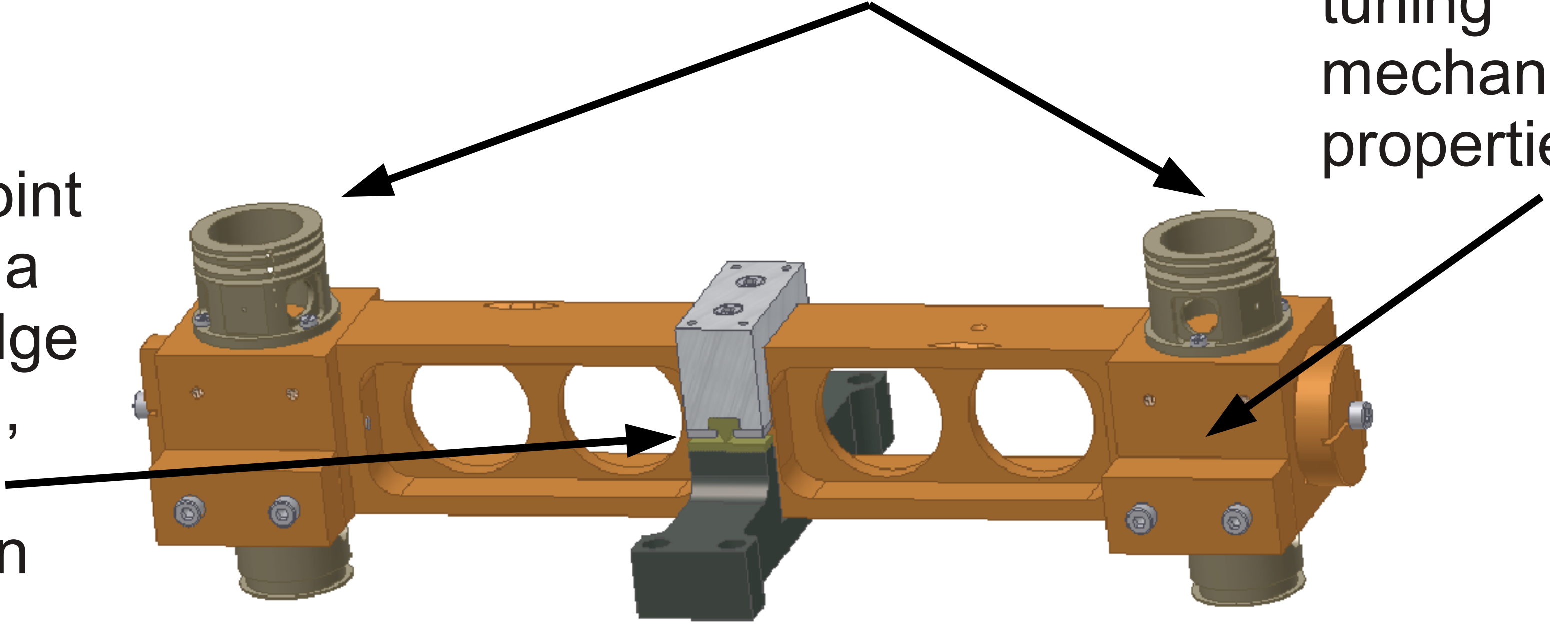
- HEPI's inertial sensors show isolation down to 0.1 Hz
- Inertial sensors on the ISI show isolation which is degrading with decreasing frequency, linked to excess tilt



From “aLIGO Input Mode Cleaner Commissioning Report”, Ryan de Rosa (LSU), DCC #G1300126-v2

Mechanical tiltmeter

- How do you measure tilt this small ?
- Use a *tiltmeter:*



Sensitive position sensors

Adjustable weights for tuning mechanical properties

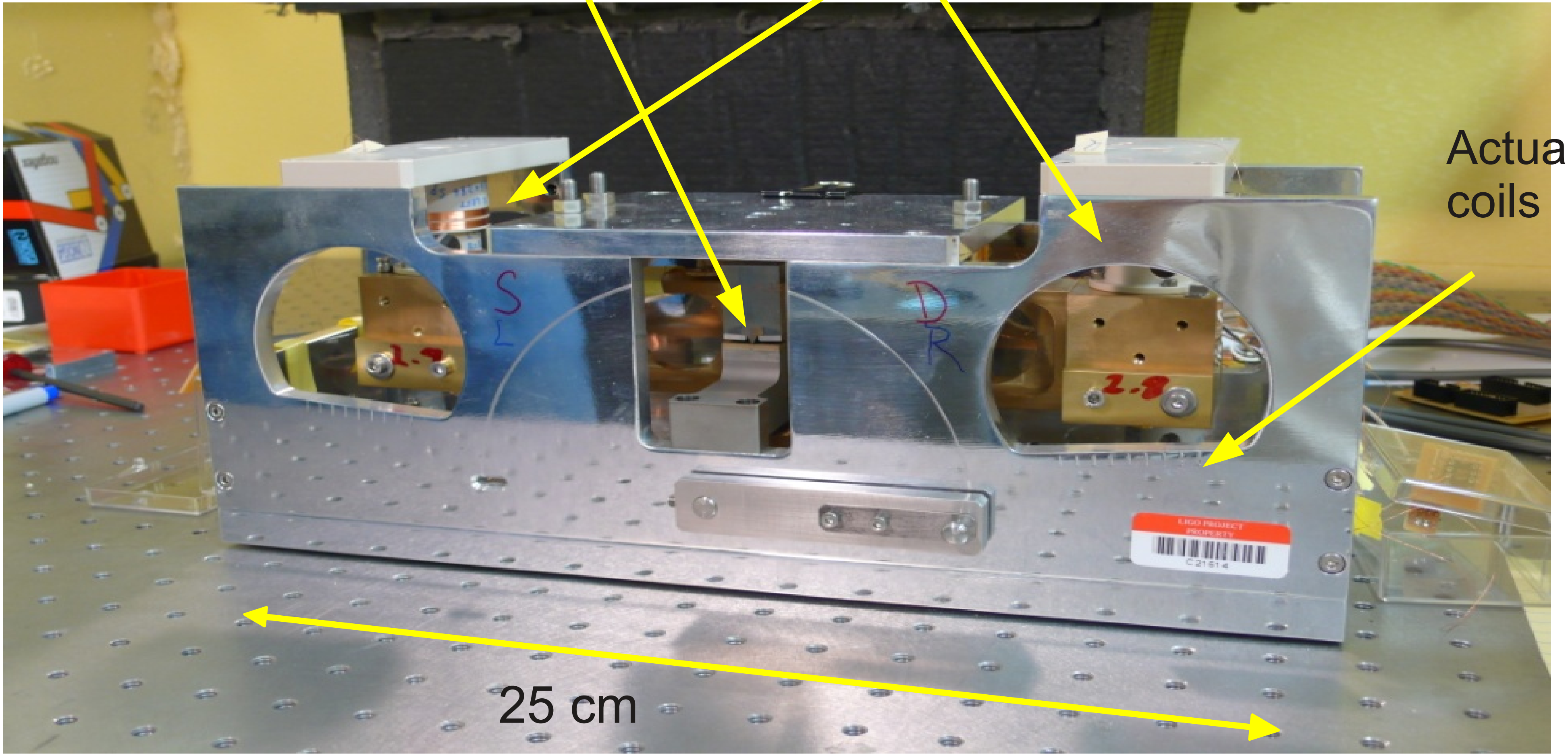
Pivot point built as a knife edge on anvil, both of tungsten carbide

Mechanical tiltmeter

Pivot point built as a knife edge on anvil, both of tungsten carbide

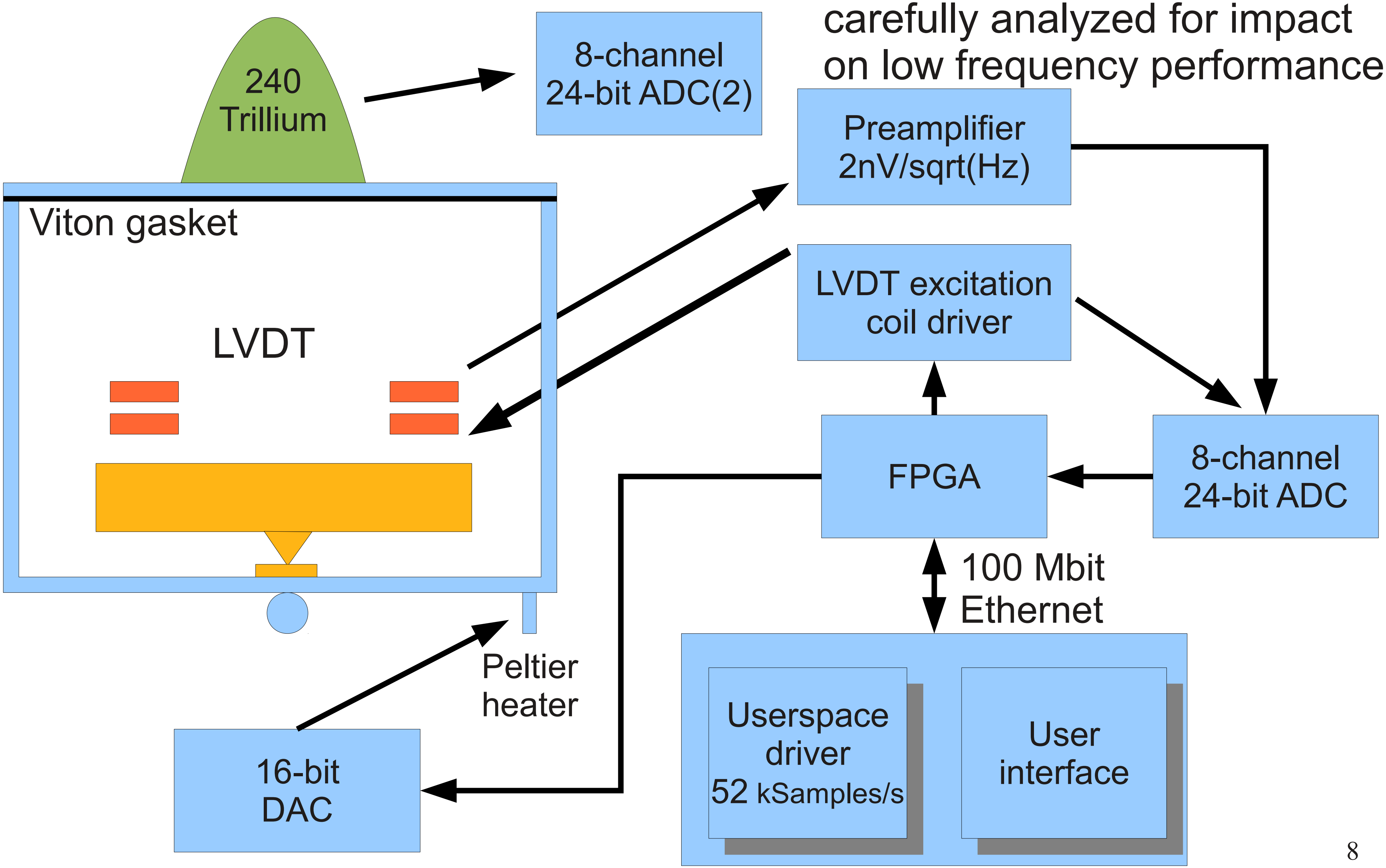
Sensitive position sensors

Actuator coils

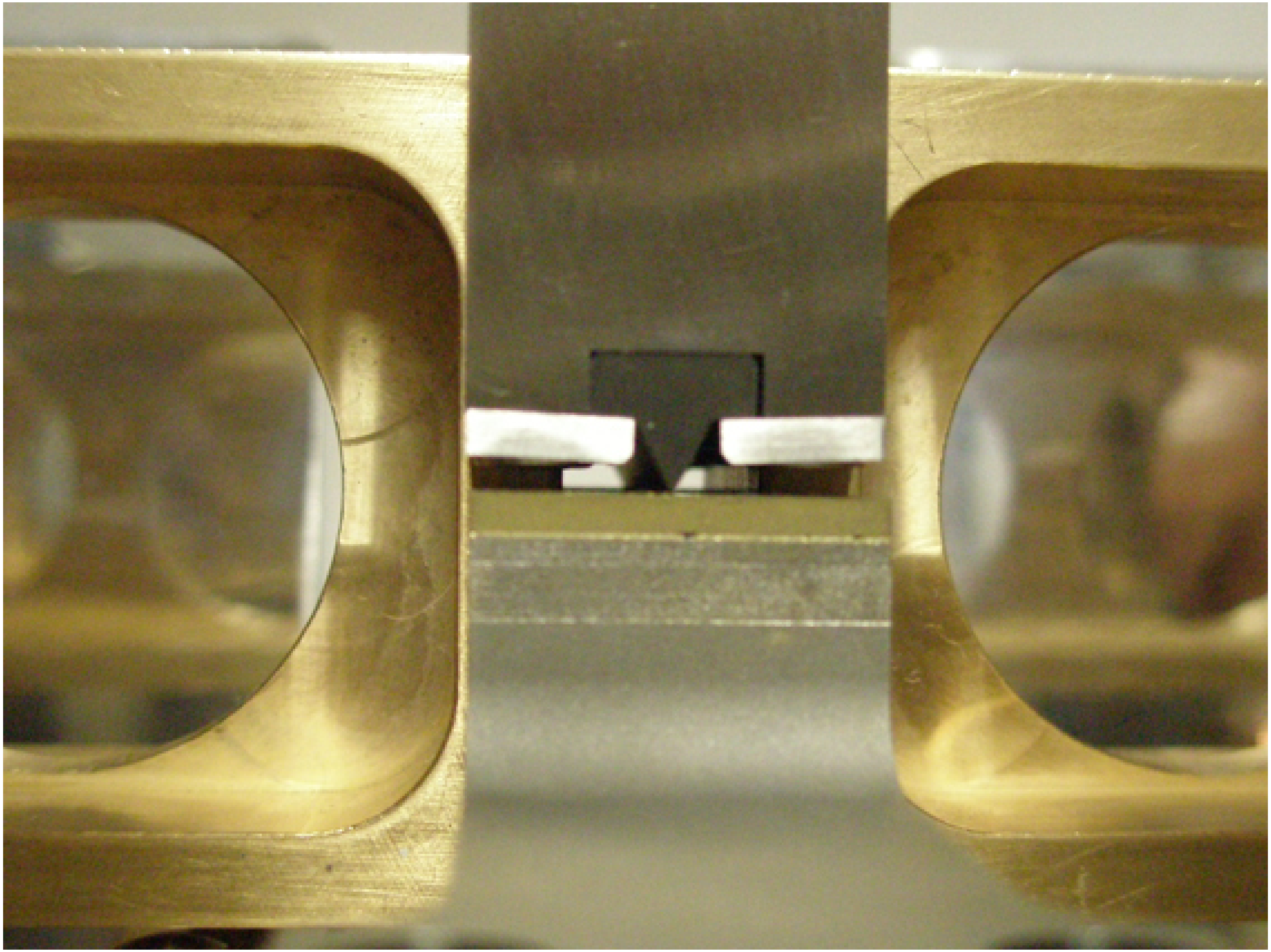


Tiltmeter systems diagram

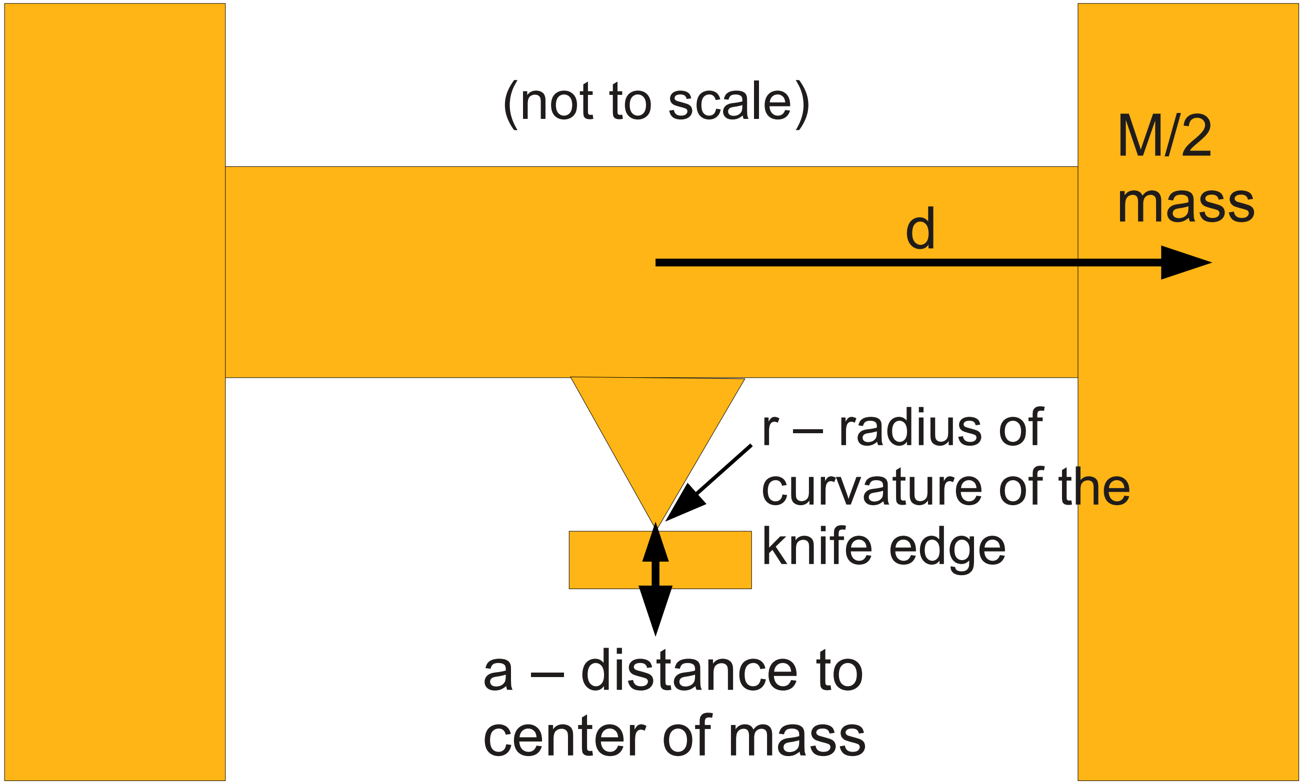
Every analog part needs to be carefully analyzed for impact on low frequency performance



Knife-edge



Principle of operation



(not to scale)

r – radius of curvature of the knife edge

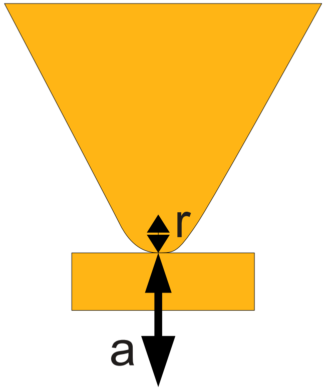
a – distance to center of mass

Proper frequency is tuned by adjusting center of mass:

$$2\pi f = \sqrt{(r+a)g} / d$$

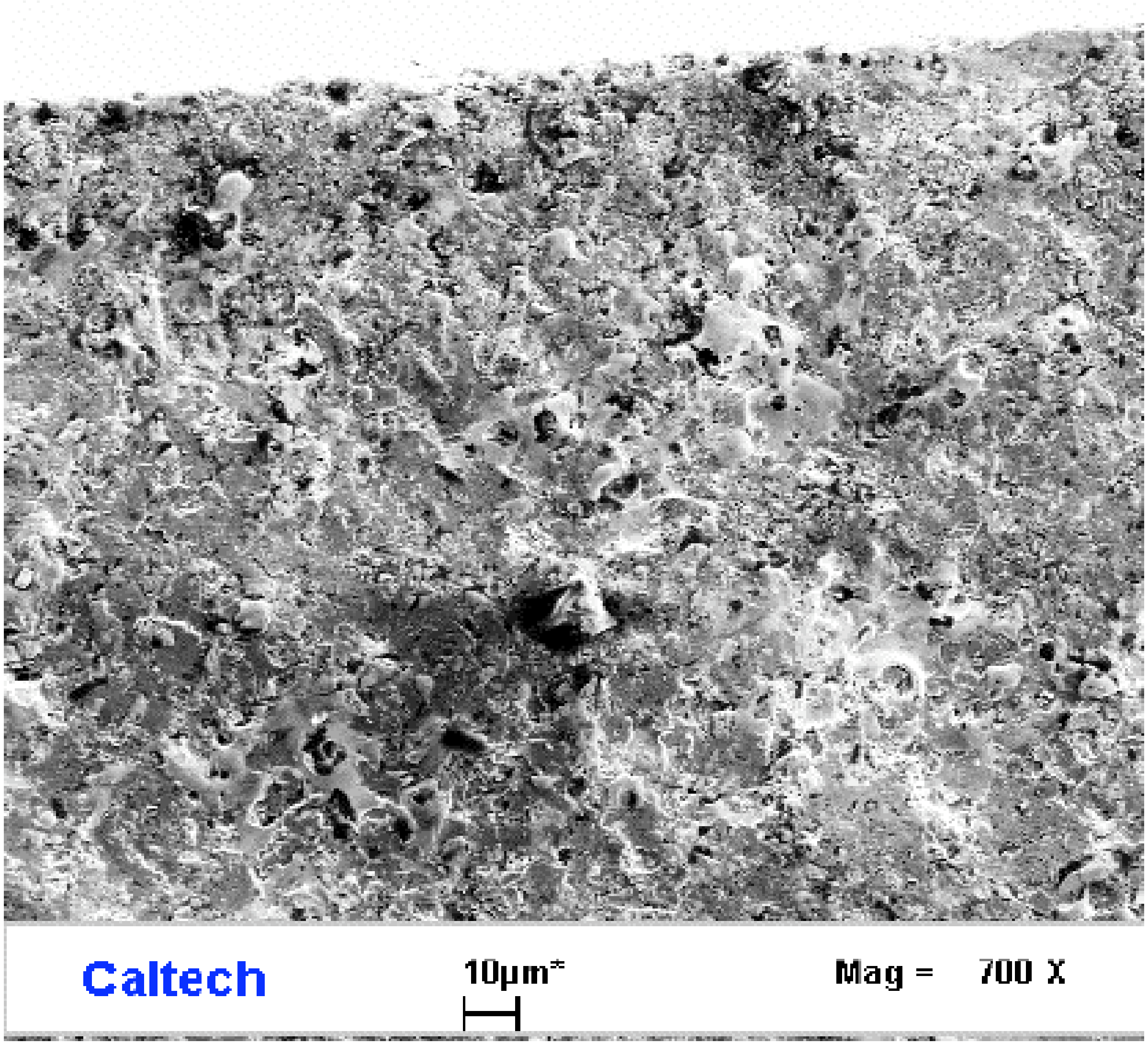
$$r + a = (2\pi f d)^2 / g$$

Influence of linear acceleration is minimized when a =0



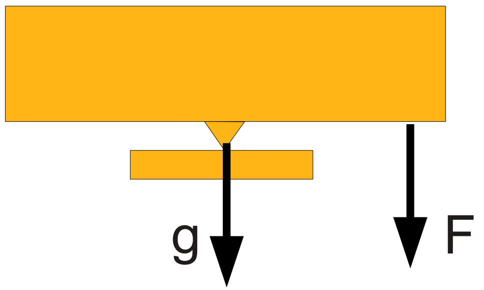
Frequency	r+a for d=12.5cm	r+a for d=50cm
0.1 Hz	0.6 mm	10 mm
0.01 Hz	6 um	100 um
0.001 Hz	60 nm	1 um

Just what is *r* ?



- *r* is the radius of the knife edge tip
- The SEM image of the knife edge shows features a few um in size.
- Do we see noise from this ?
- The very large tilt from hysteresis measurement is 1e-4 radians.
- Even for a 50um tip this is much smaller than grain size.
- Thus we are balancing on a few rows of tungsten carbide grains each around 0.8um in diameter.

Feedback or no feedback ?

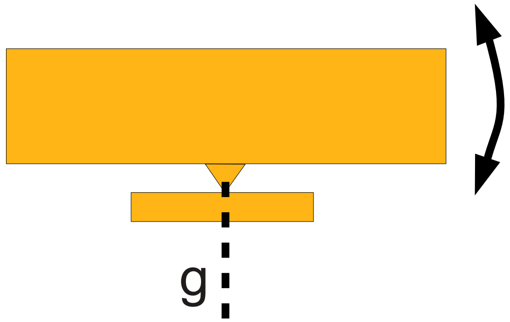


Feedback advantages:

- select and maintain operating point of the instrument, even in unstable configuration
- linearize non-linearities in sensors and electronics

Feedback disadvantages:

- sensor position is given by ratio F/g, and F needs to be known with large precision (1ppm) at 10mHz frequencies.
- magnetic actuation without susceptibility to stray magnetic fields is difficult to achieve



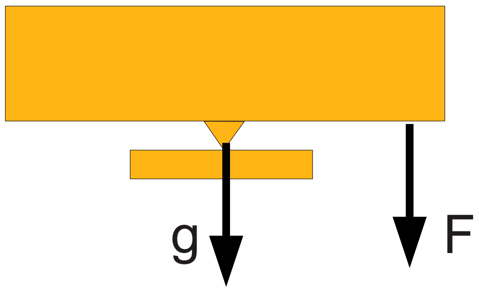
Free motion advantages:

- we are only measuring angles which are dimensionless – purely ratiometric measurement is possible.
- no issues from stray actuation forces

Free motion disadvantages:

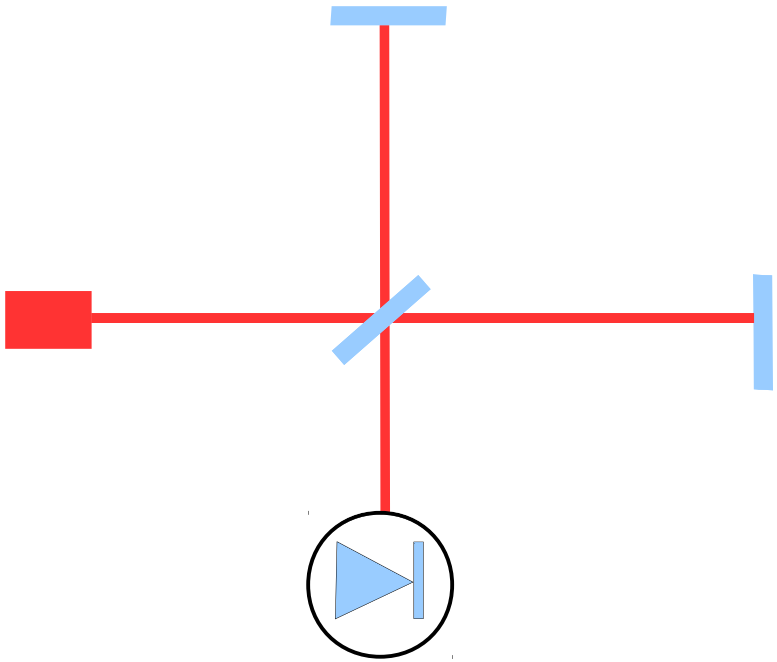
- can only use instrument in stable configuration
- Sensors should have range of at least 10^6

Actuation challenges



- DC magnetic – balance becomes susceptible to external magnetic fields
- AC magnetic – difficult to measure AC current or voltage with required precision.
- Mechanical – additional flexure will decrease Q and contribute internal noise.
- Generally – difficult to apply a force with relative accuracy of 1ppm at 10mHz.

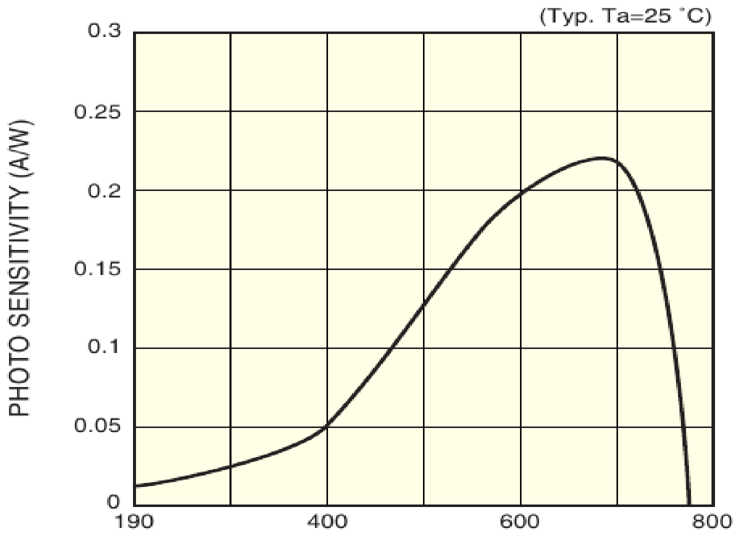
Can we use an interferometer ?



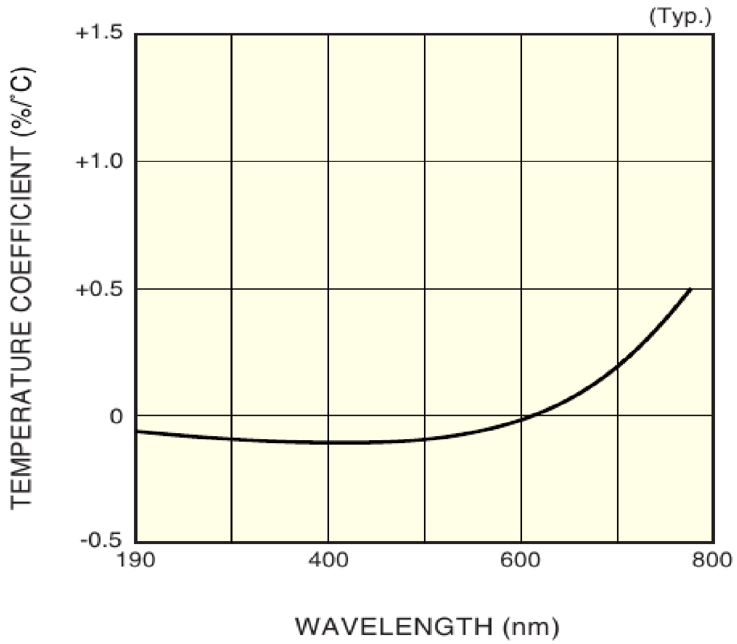
- Need accuracy of 10pm/sqrt(Hz) at 10mHz
- To cope with a possible 1mm mismatch in arm length the laser frequency should be within 4MHz at 10mHz.
- Such lasers exist, but they are not cheap.
- A simple Michelson or Mach-Zender cannot measure absolute position – need extra components, increasing instrument cost and difficulty obtaining good low-frequency operation.

Photodiode stability

■ Spectral response



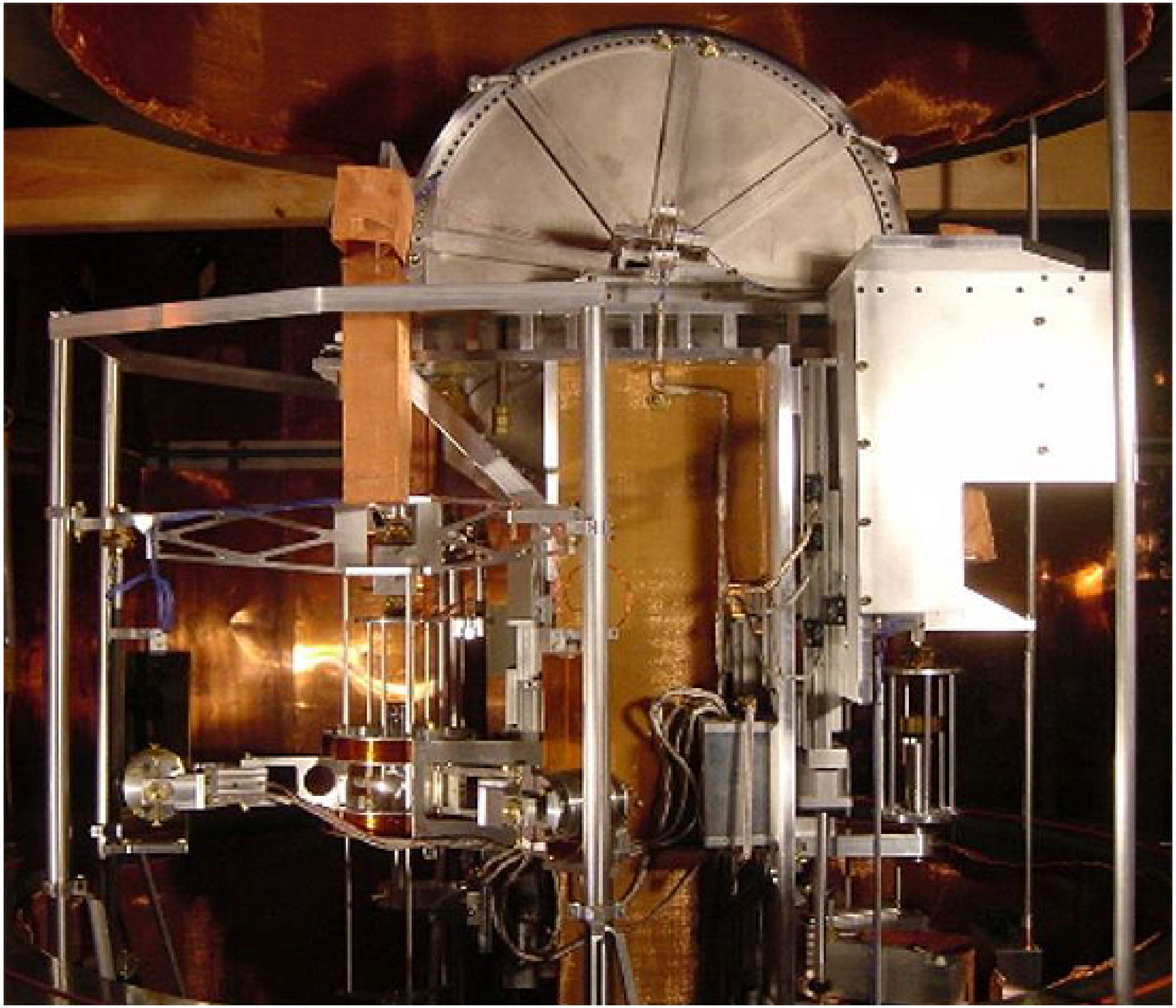
■ Photo sensitivity temperature characteristic



- Free motion operation requires that the photodiode is capable of measuring power with accuracy of 1ppm
- The plots on the left are for Hamamatsu G1746 GaAsP photodiode – one of a few devices with a temperature coefficient plot.
- The steep rise at longer wavelength is due to photon energy becoming less than the energy required to form electron-hole pair.
- What other sources of low-frequency noise are there ?

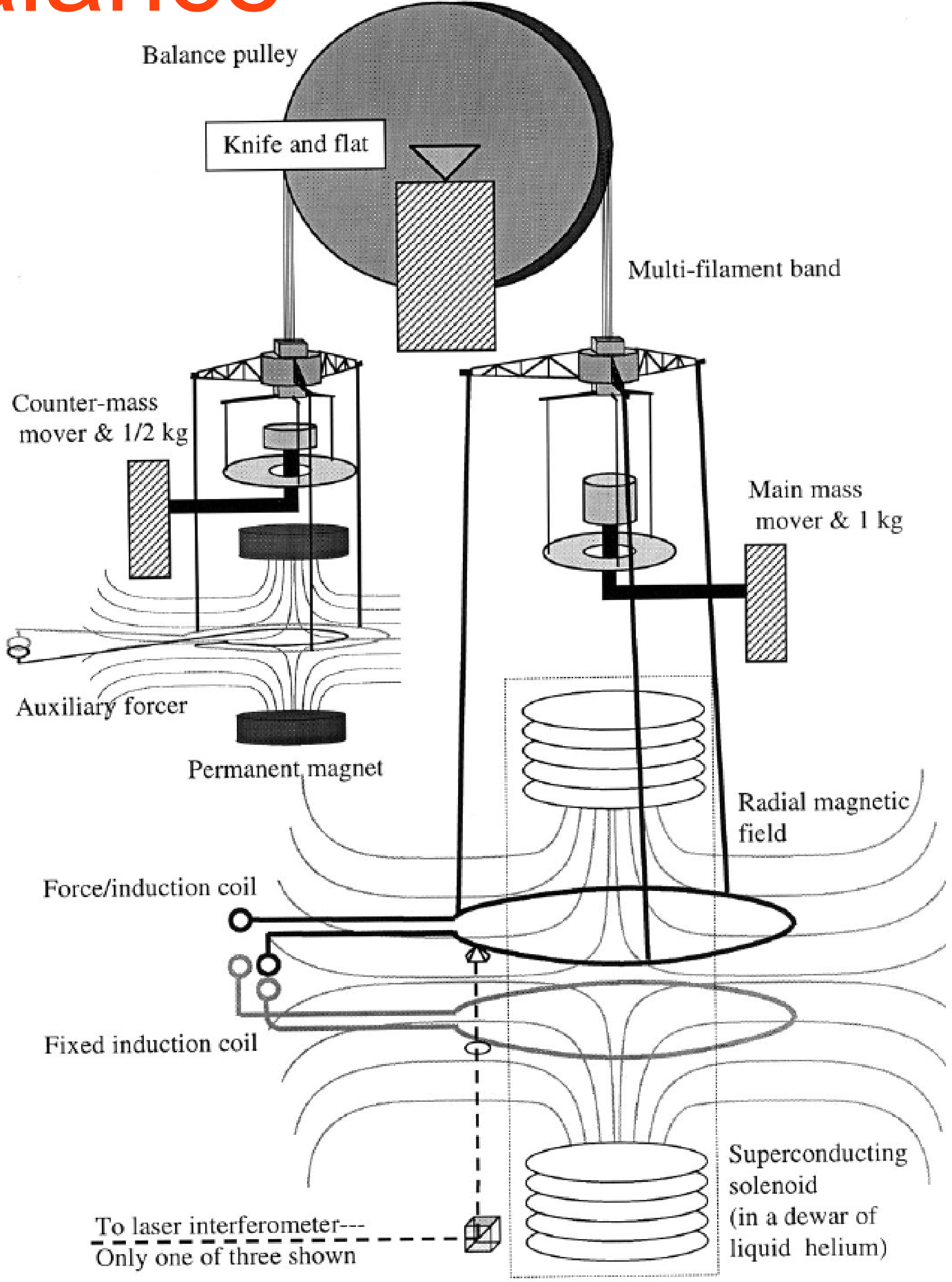
Watt balance at NIST

- Watt balance is a way to relate SI electromagnetic power units to mechanical power units.
- The movement and forces acting on 1kg mass are measured against forces produced by an electrical coil.
- The experiment is located in a building made from non-magnetic materials.

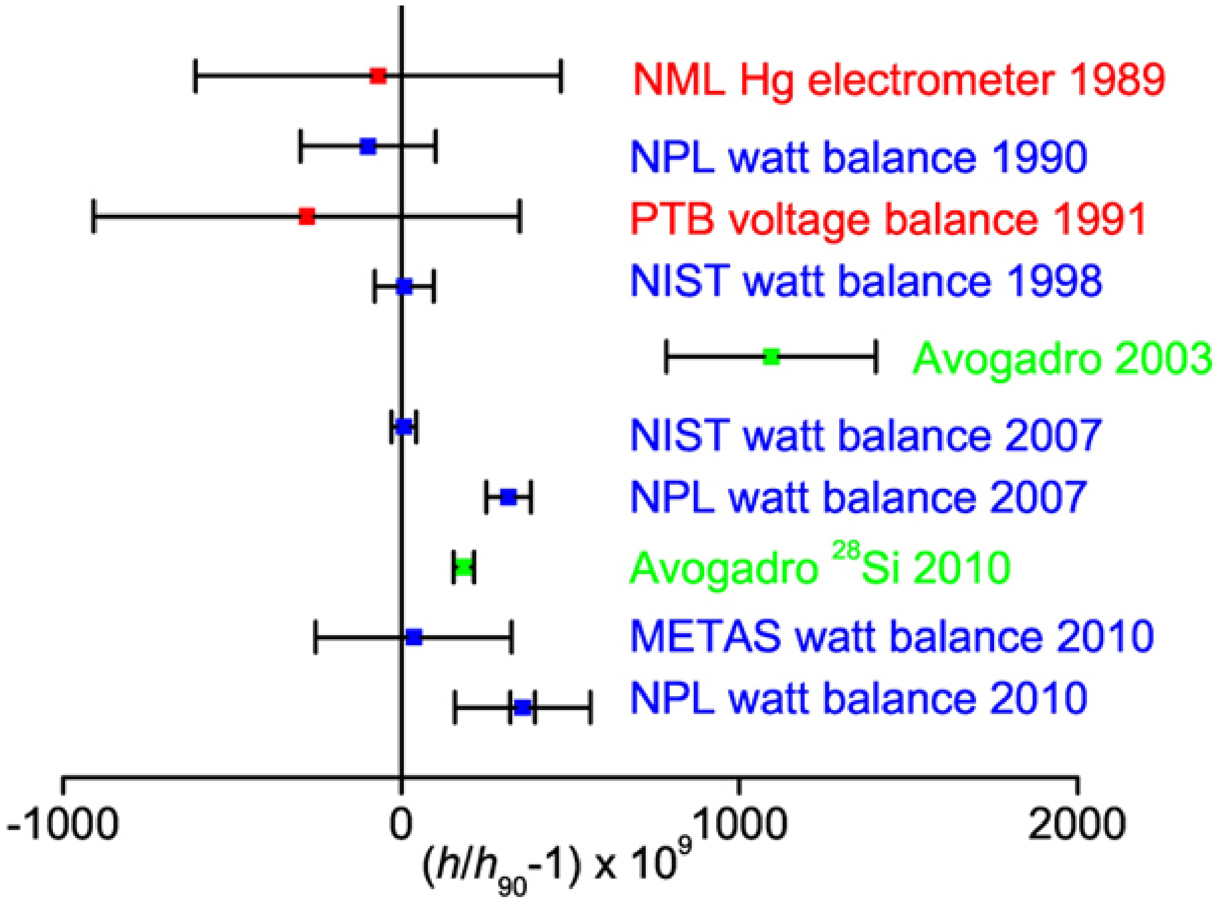


Watt balance

- A scaled up tiltmeter, with all the elements – knife edge, coils
- Voltage is measured using Josephson effect $V=hf/2e$
- Current is related to quantum Hall effect resistor: $R=h/ne^2$
- The interferometer has 1 meter arm length and achieves 10pm/sqrt(Hz) accuracy with the use of iodine standard.
- The measurement of the kilogram done in 1998 had accuracy of 0.1ppm
- Work is underway to improve this by one order of magnitude



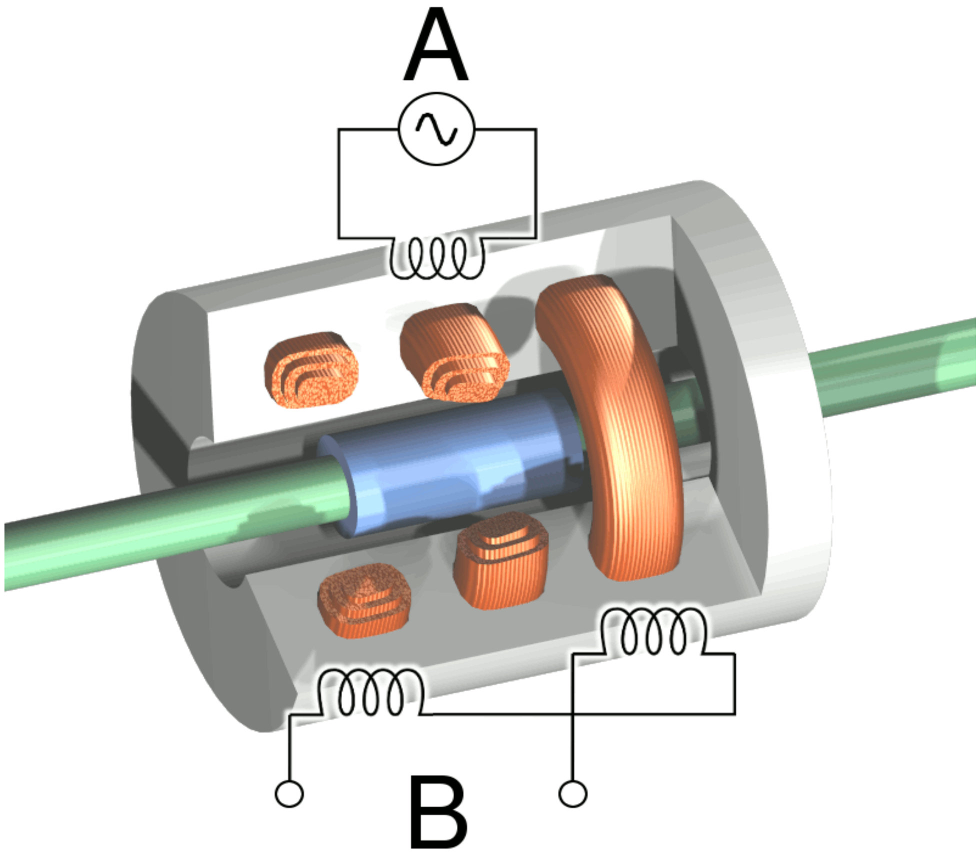
Planck constant measurements



- Watt balance can also be used to measure Planck constant
- The X-axis markings are for 1ppm measurements

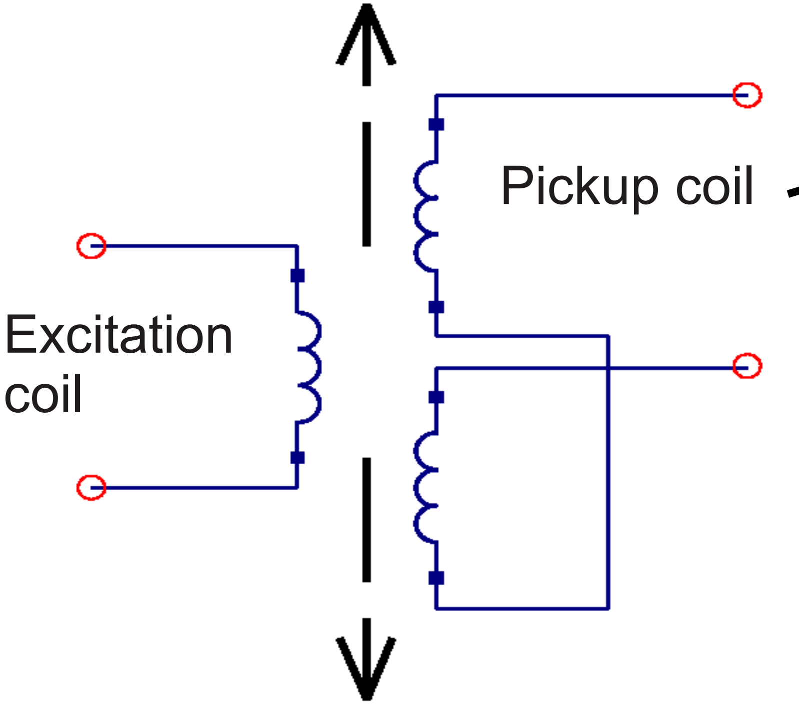
LVDT – linear variable differential transformer

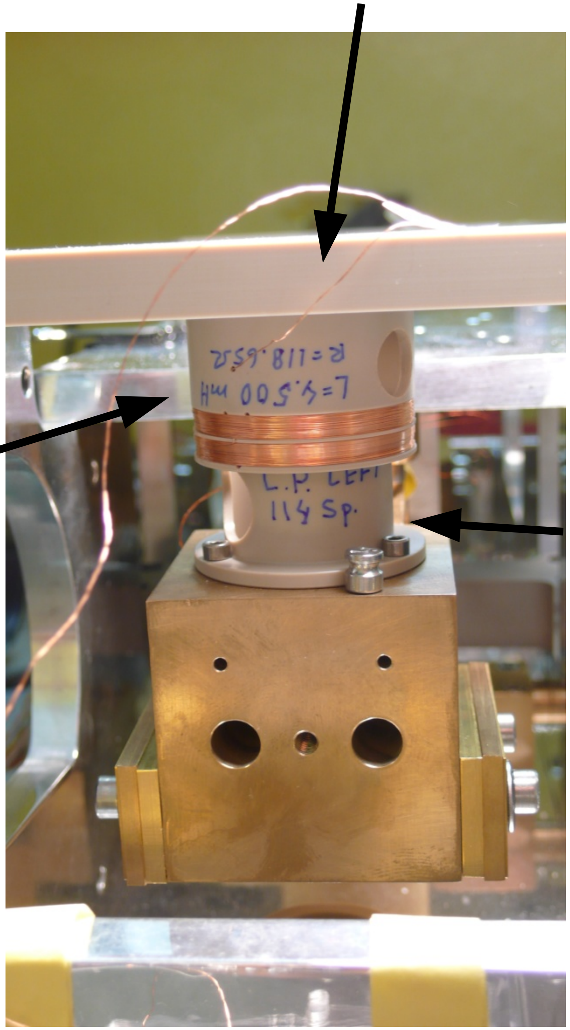
- First LVDT appeared in 1936, started to see widespread use after 1946.
- Most commercial parts use three coils wound on the same bobbin and coupled by movable ferrite core.
- The outer casing confines the magnetic field inside the LVDT.



Air core LVDT

- Tiltmeter uses air core design
- The primary excitation coil induces voltage in differential pickup coil
- Absence of ferrite core eliminates magnetic hysteresis, at the expense of lack of magnetic confinement.
- Also need wires to connect excitation coil mounted on the tiltmeter arm.

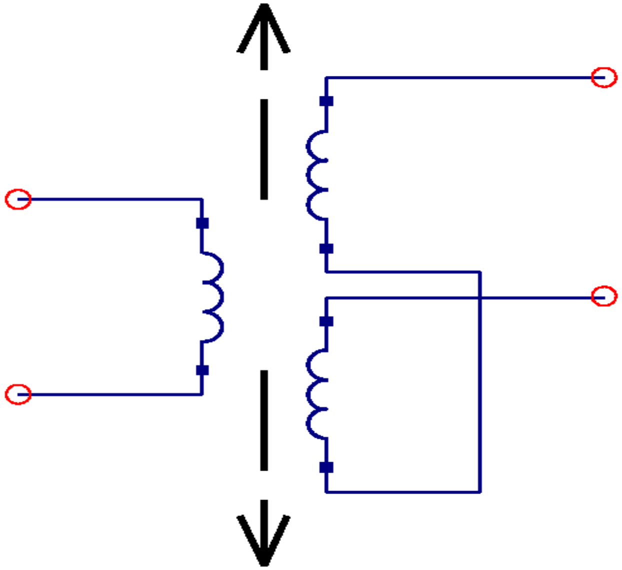




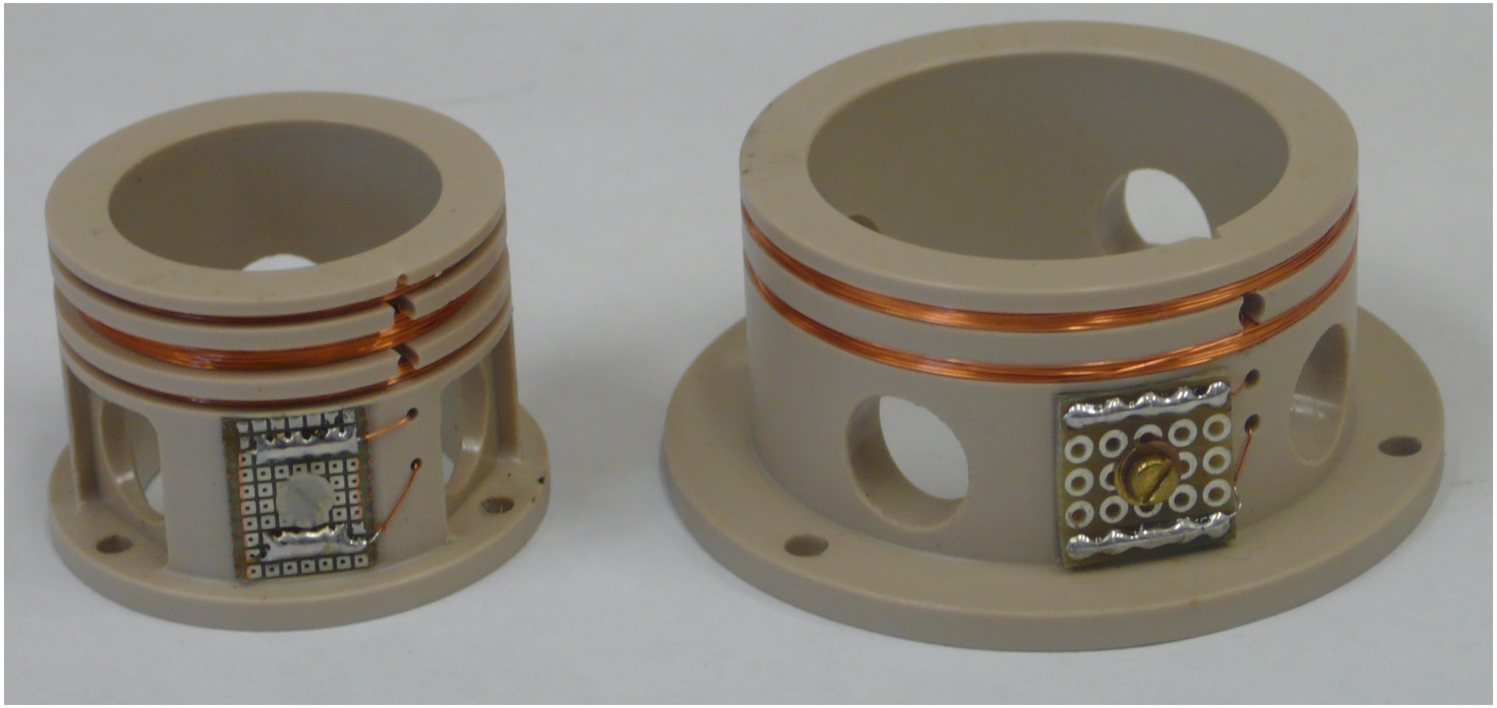
Peek bridge to eliminate eddy currents

Excitation coil

LVDT design

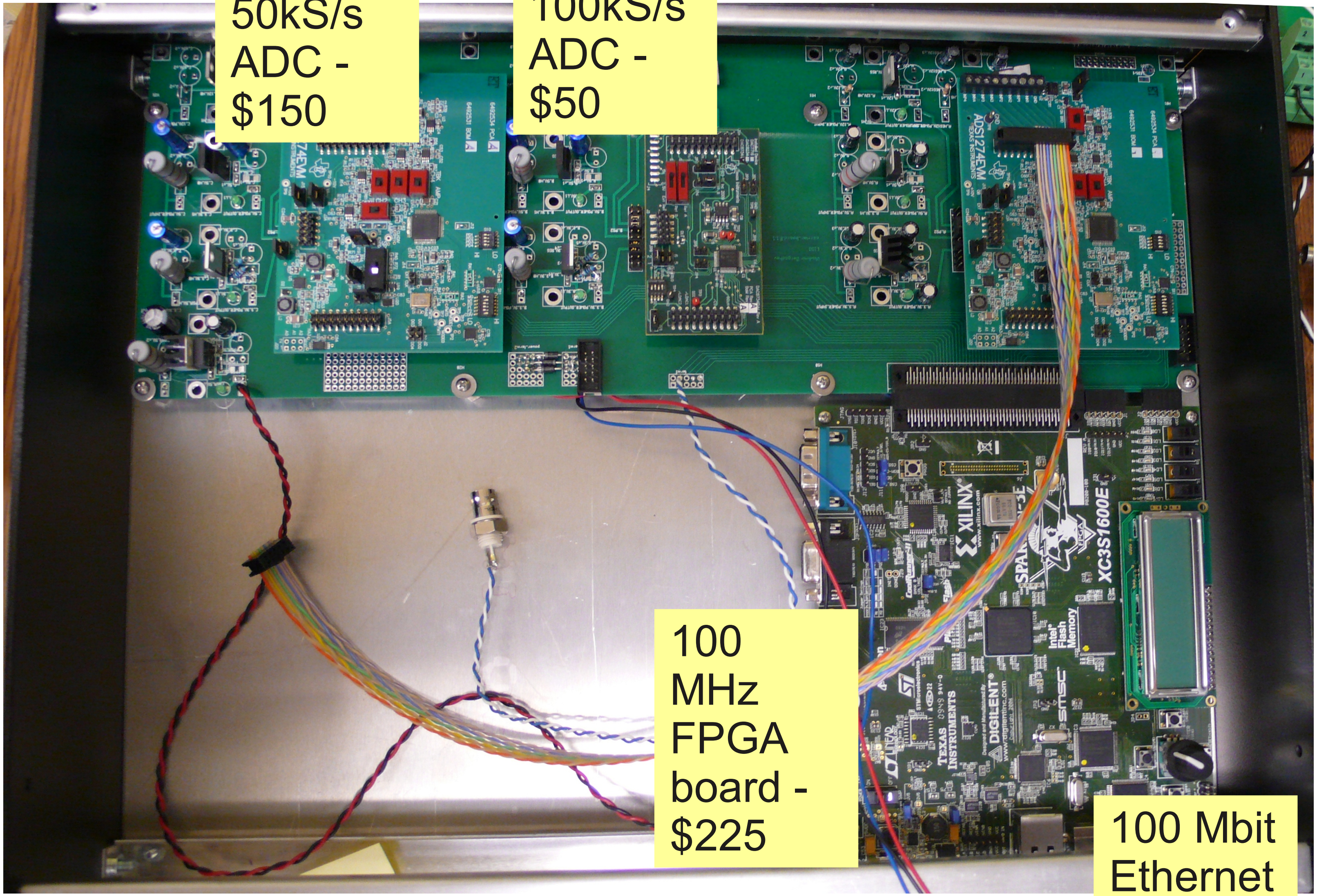


- LVDT coils can exert larger forces than optical methods of measurements.
- This can be mitigated by putting identical coils on each side of the balance, designing the coils to null out external field, stabilizing drive current and using large impedance readout of pickup coils



- We typically drive a few volts into each LVDT coil, with readout electronics of 1nV/sqrt(Hz) sensitivity

Data acquisition and signal synthesis



24-bit 50kS/s ADC - $150

16-bit 100kS/s ADC - $50

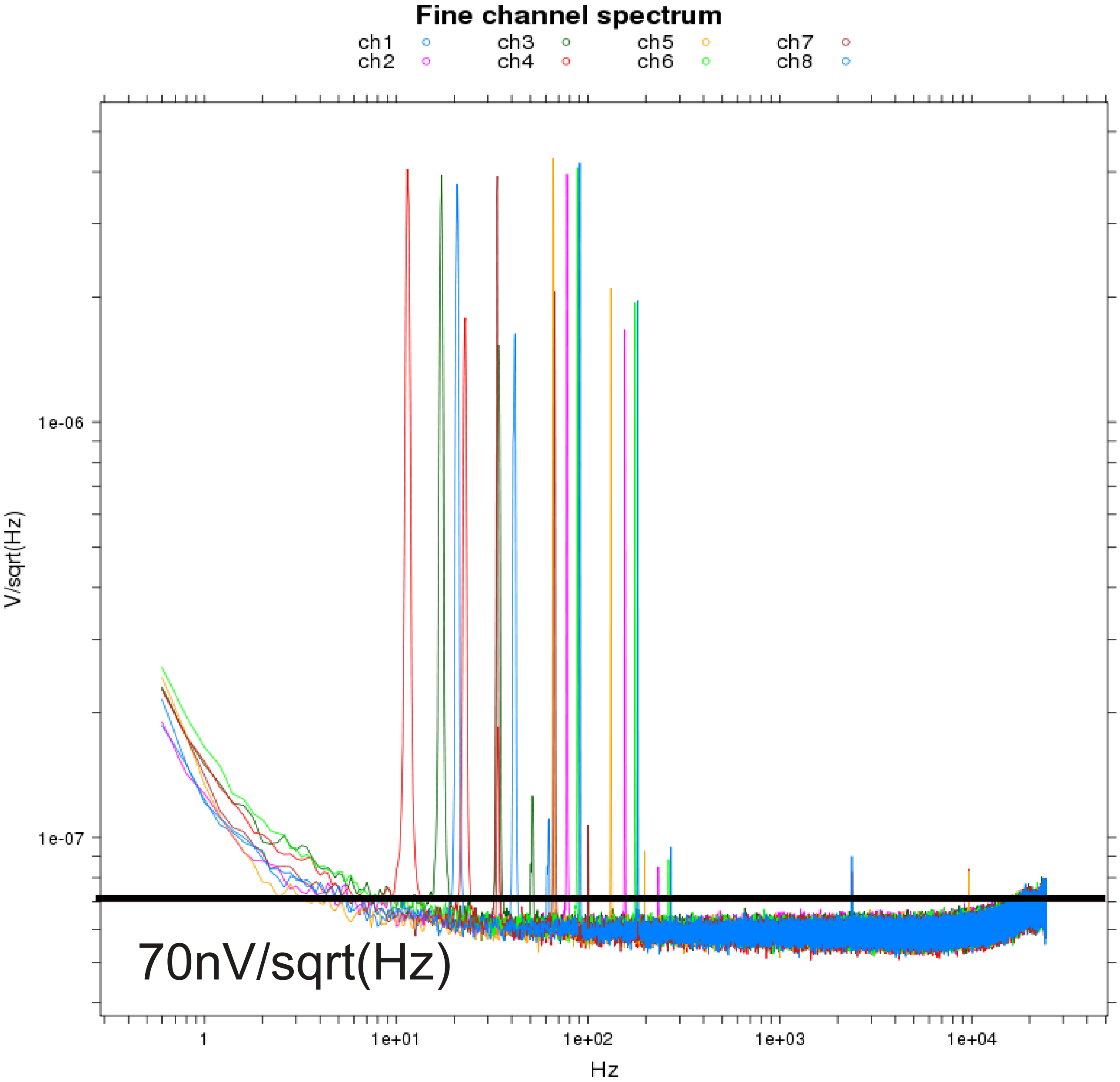
100 MHz FPGA board - $225

100 Mbit Ethernet interface

- Inexpensive high precision data acquisition system
- Easy to assemble
- Connects to TI evaluation boards
- Available boards: 24-bit 4 and 8 channel ADC, 16 and 20 bit DAC
- Communicates with Linux computer over regular Ethernet

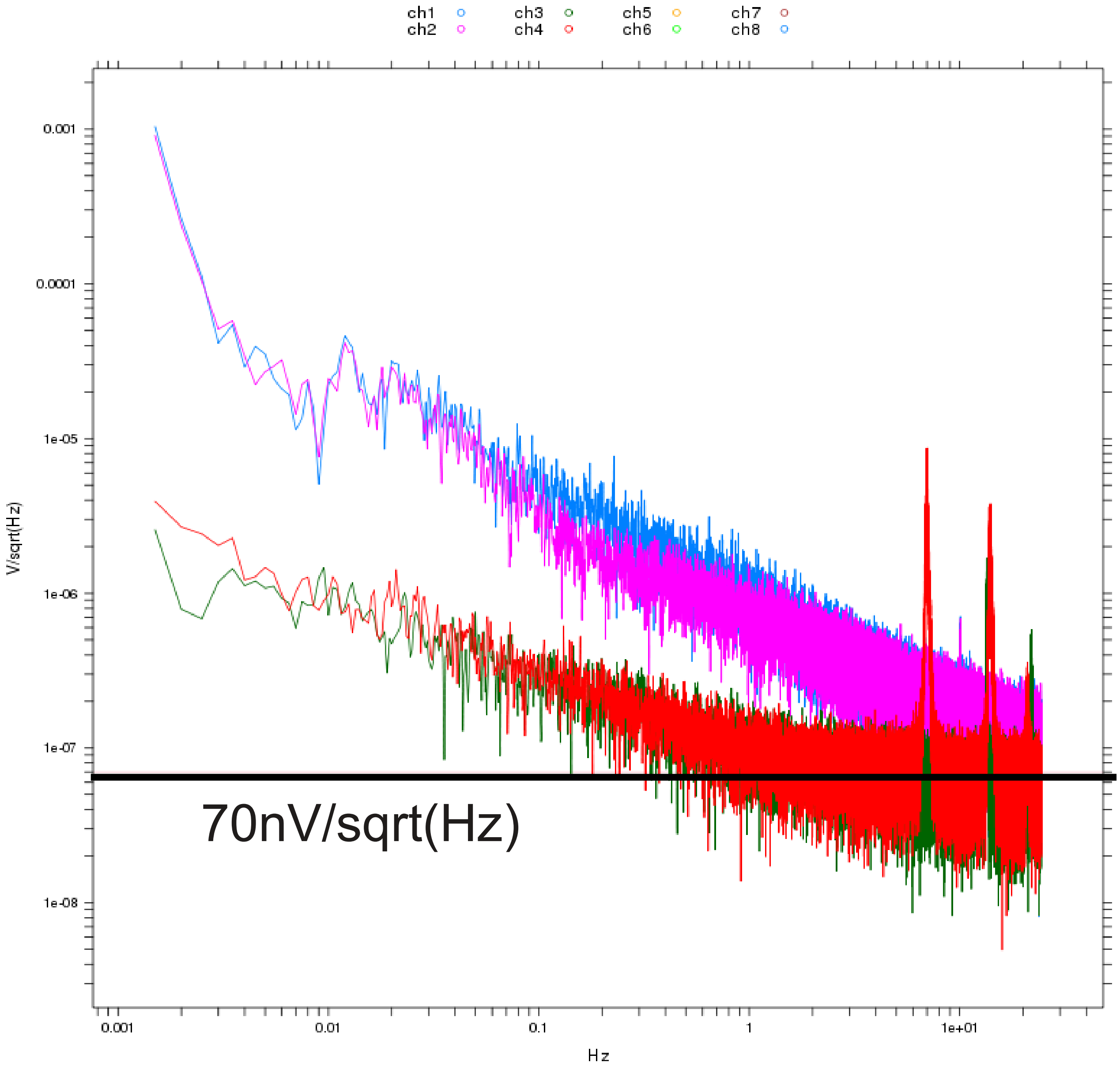
ADC performance

- The upper two curves are spectrum of 2 AA batteries.
- Other inputs were left open.
- The lines between 10 Hz and 300 Hz are EM interference.
- LVDT signal frequency is 6.2 kHz in the safe region on the right.



ADC performance

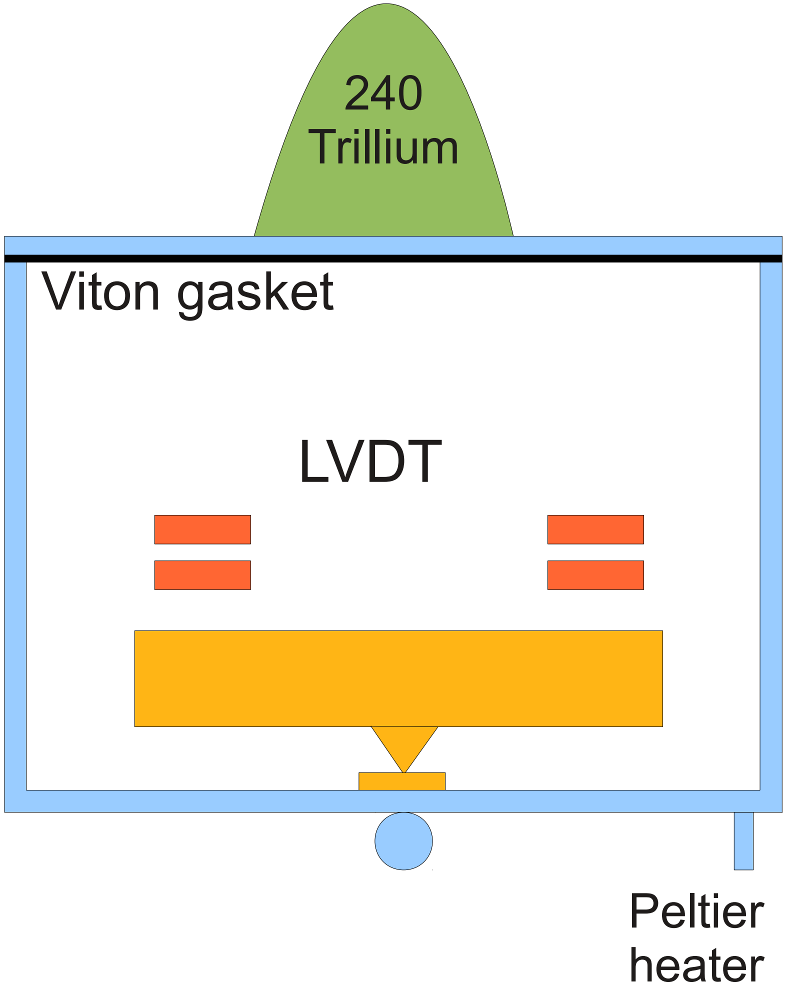
- The upper two curves are spectrum of 2 AA batteries.
- There is a common mode due to voltage reference – adding insulation helps.
- LVDT signal frequency is 6.2 kHz.



70nV/sqrt(Hz)

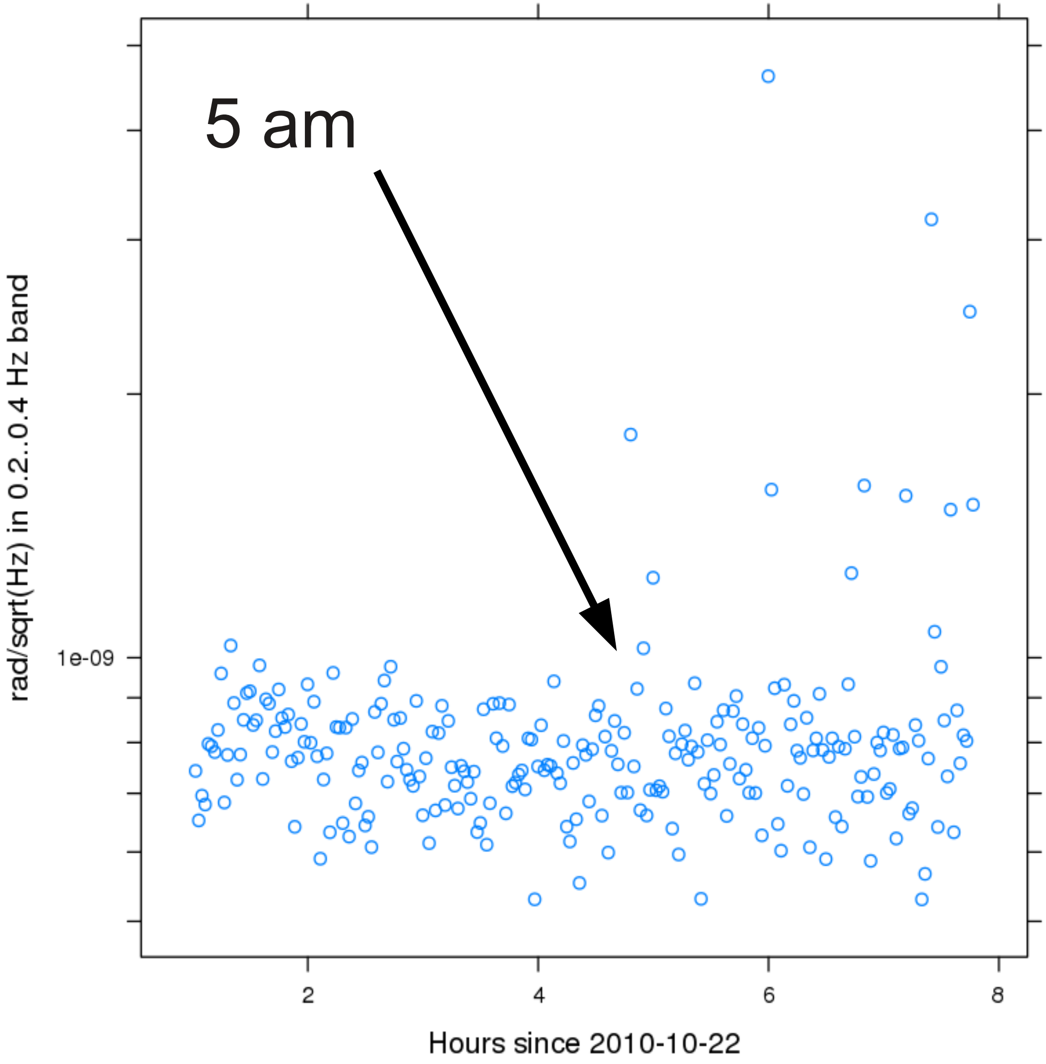
Vacuum operation

- Installed tiltmeter in vacuum chamber, radius 0.25m
- The vacuum chamber is supported by pipe in the middle and an aluminum T at the right end
- Aluminum T is thermally actuated with Peltier elements
- Trillium 240 sits on top of cover, separated by a viton gasket



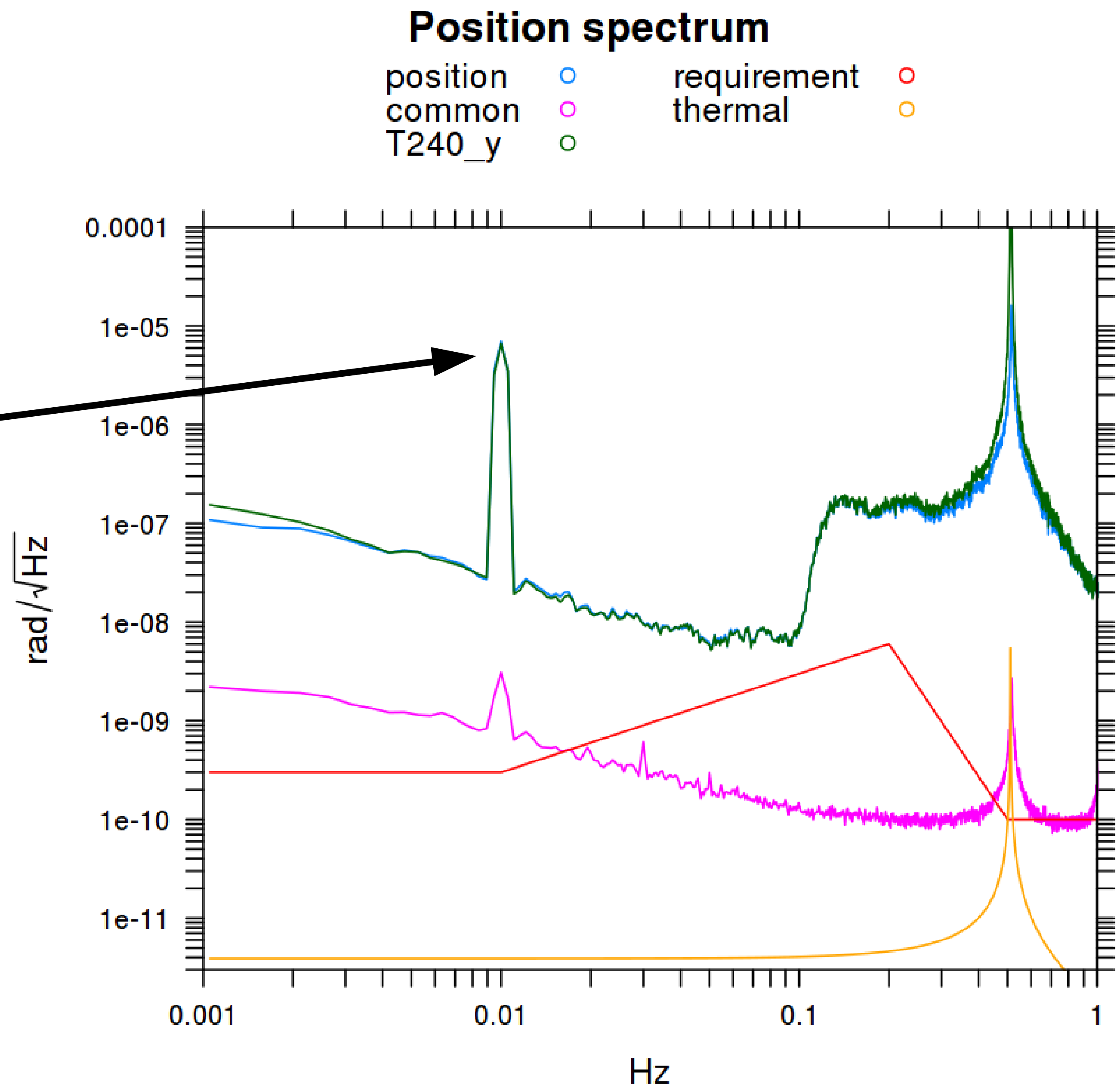
Seismic weather

- The amount of seismic noise changes during the day
- This plot shows integrated noise in 0.2-0.4 Hz frequency band
- Background is an unknown combination of tiltmeter noise and seismic signal
- The day in Caltech starts early !

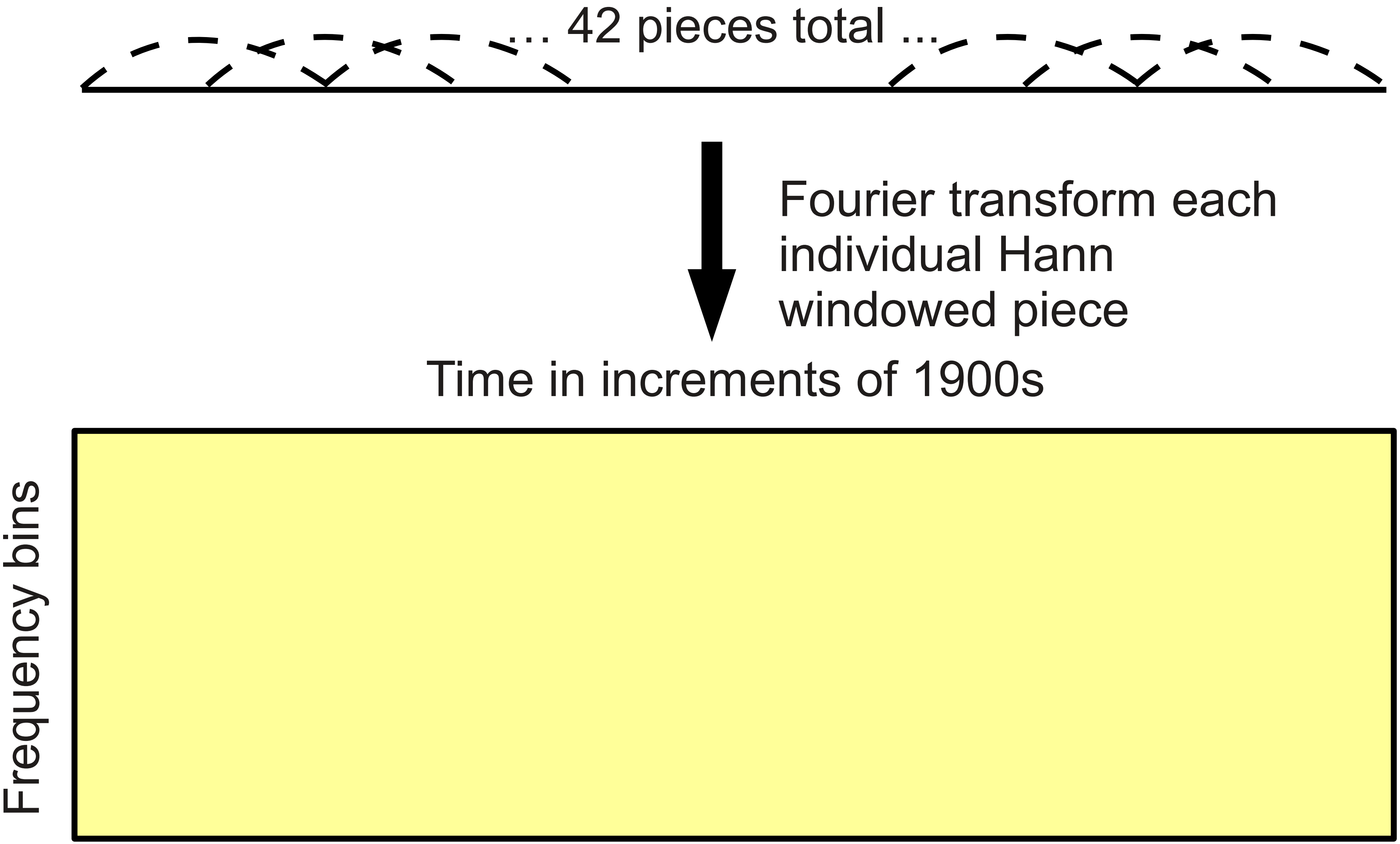


Run 3190, stabilized tank

- Vacuum tank was stabilized by feeding back tiltmeter signal to thermal actuator on tank support
- In addition, a calibration line was injected by varying working point as 10mHz sine wave
- Tiltmeter natural frequency 0.52 Hz, Q=3000



Regression analysis



... 42 pieces total ...

Fourier transform each individual Hann windowed piece

Time in increments of 1900s

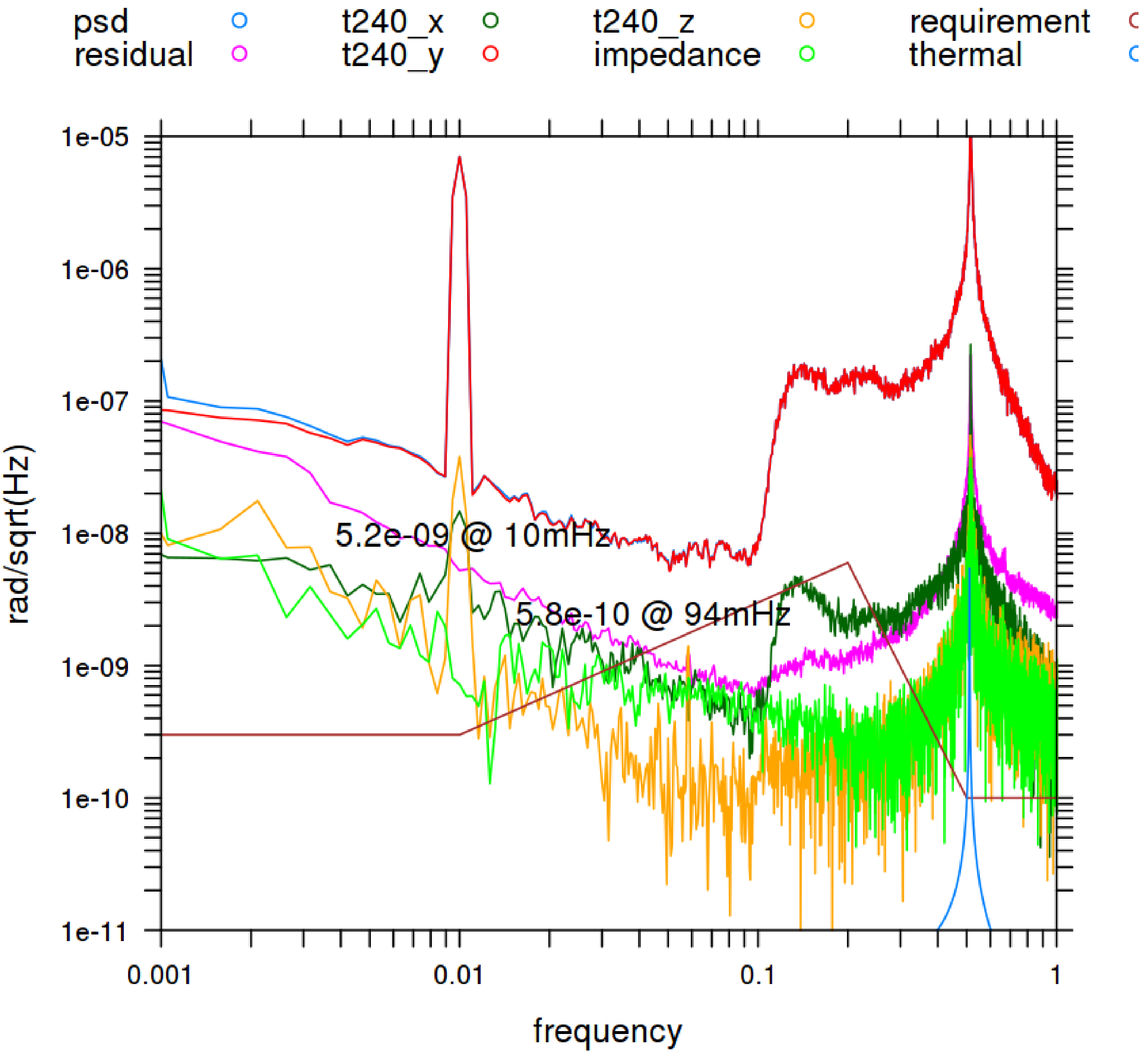
Frequency bins

Regression analysis

- Create time-frequency matrix for tiltmeter timeseries, Trillium 240 x, y, z signals as well as auxiliary signal measuring LVDT coil impedance
- For each tiltmeter frequency bin vector of 42 complex numbers find contributions of Trillium and impedance signals.
- The remainder is the “residual”.

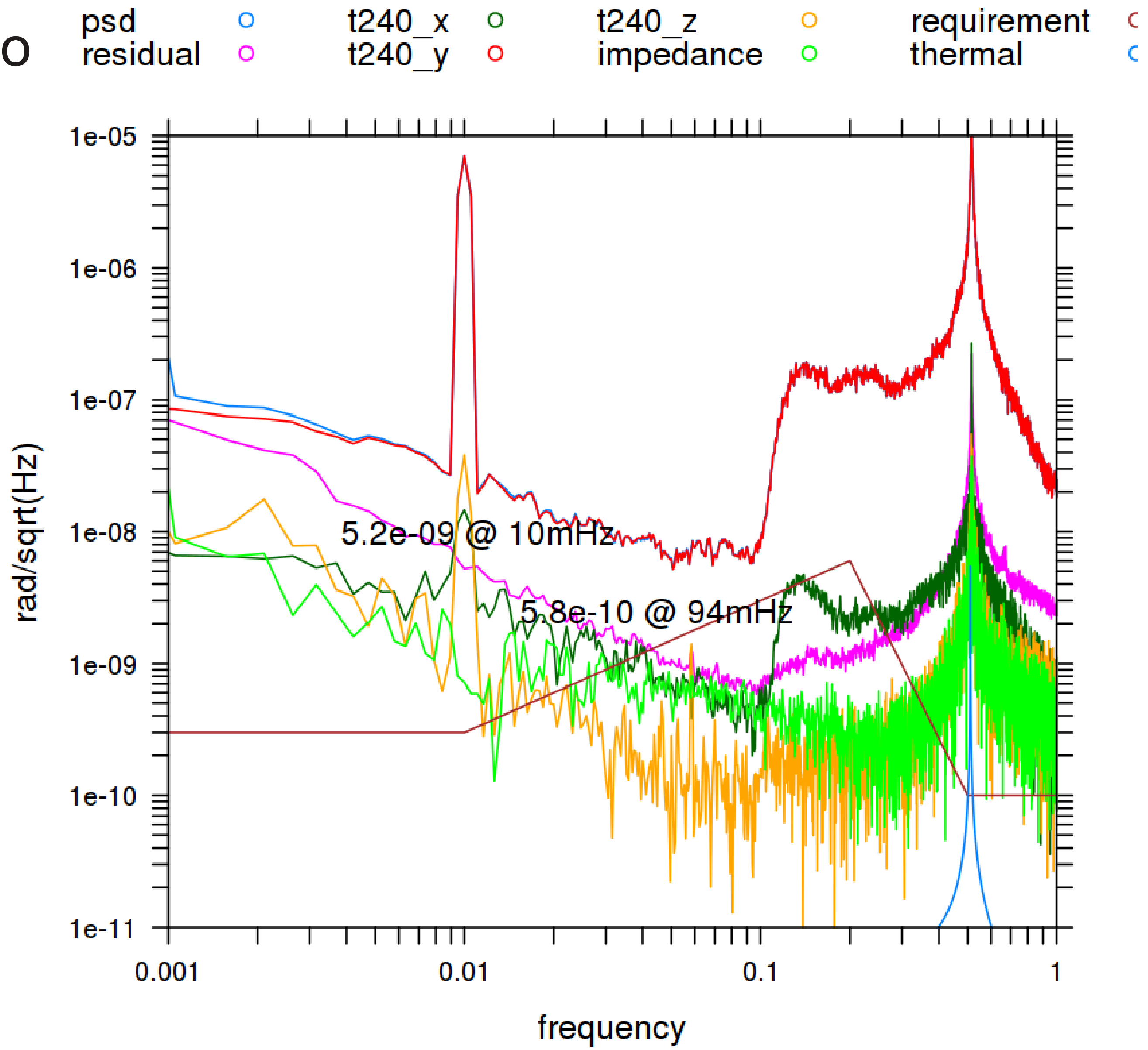
Regression analysis

- Blue (tiltmeter signal) and Red (Trillium Y component) coincide almost everywhere
- Magenta trace is the residual – noise remaining after correlations are taken out
- After statistical corrections, residual 95% CL upper limit at 10mHz is 5.7e-9 rad/sqrt(Hz)
- 6.4e-10 rad/sqrt(Hz) at 94mHz



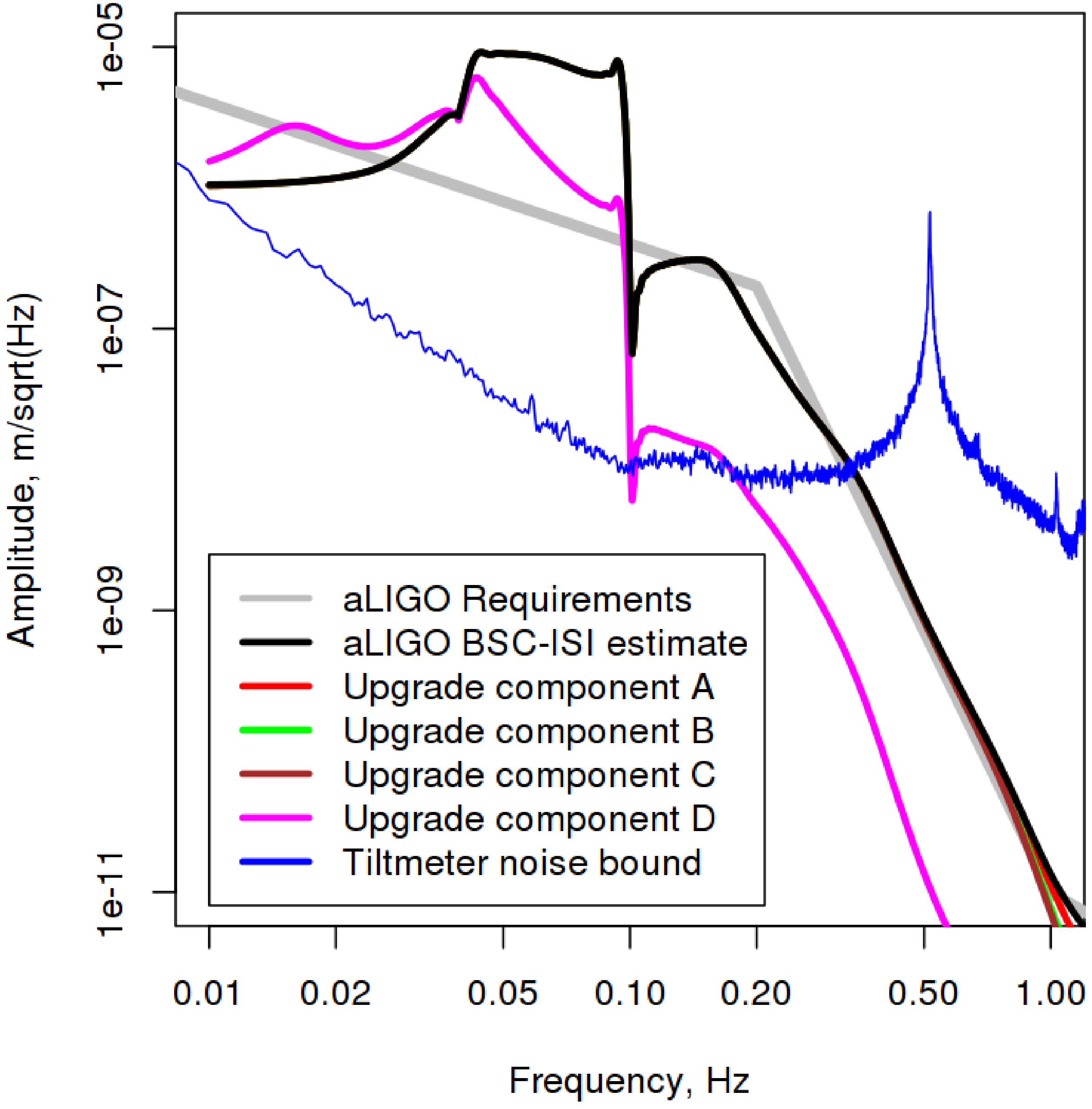
What is needed to achieve requirement ?

- Need two instruments to separate tilt from instrumental noise, designed to be rigidly attached to each other or to a mounting plate
- Study different attachment methods
- And technical details, such as mounting preamplifier closer to the coils, etc.



aLIGO application

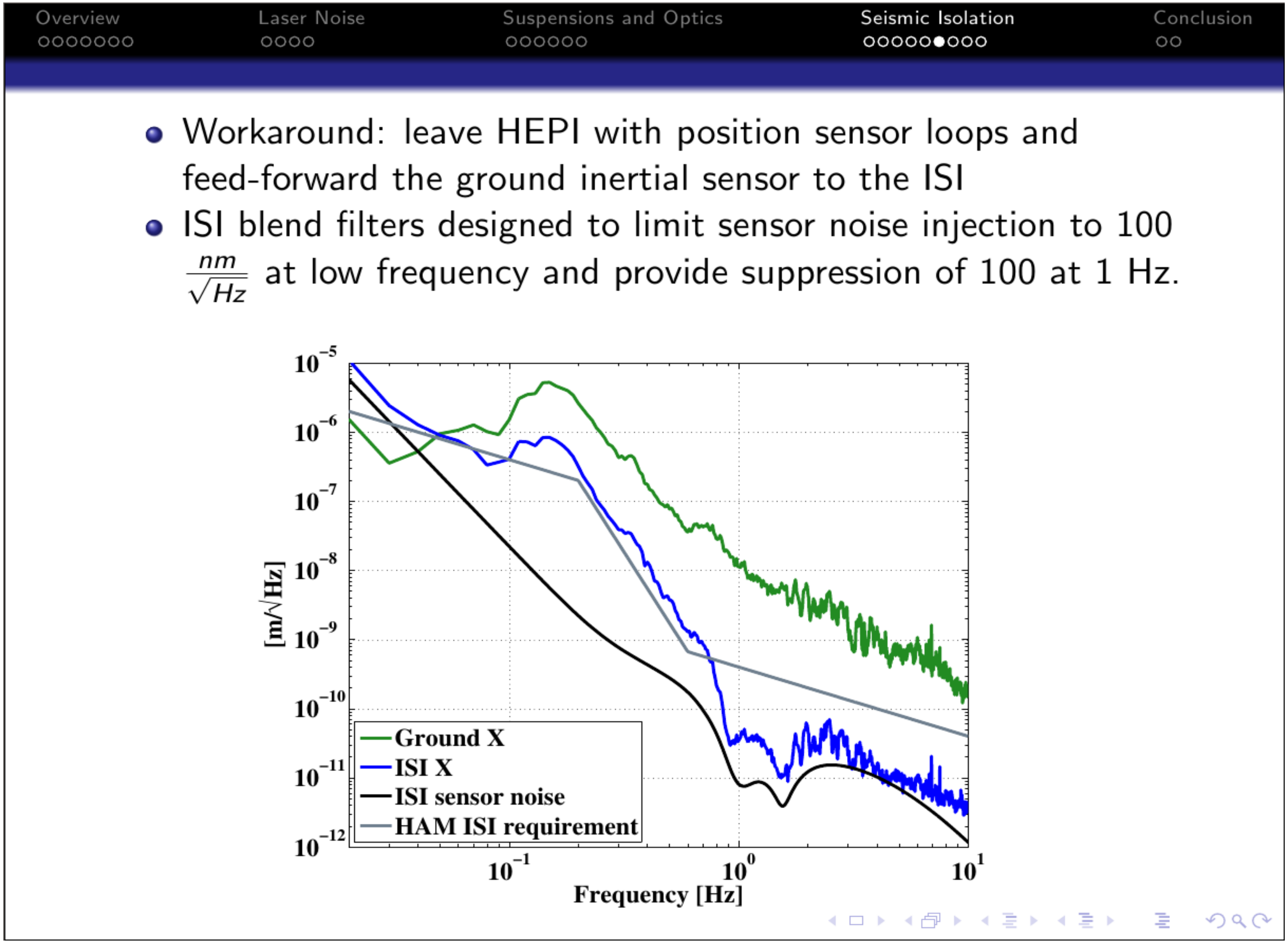
- Blue curve – tiltmeter noise bound (residual) multiplied by g/ω^2
- Black curve – aLIGO BSC-ISI estimate
- **Gray** – requirement
- Other colors show different upgrade paths using tiltfree sensor



End of talk

(supporting slides for questions follow)

Observed tilt coupling (2)

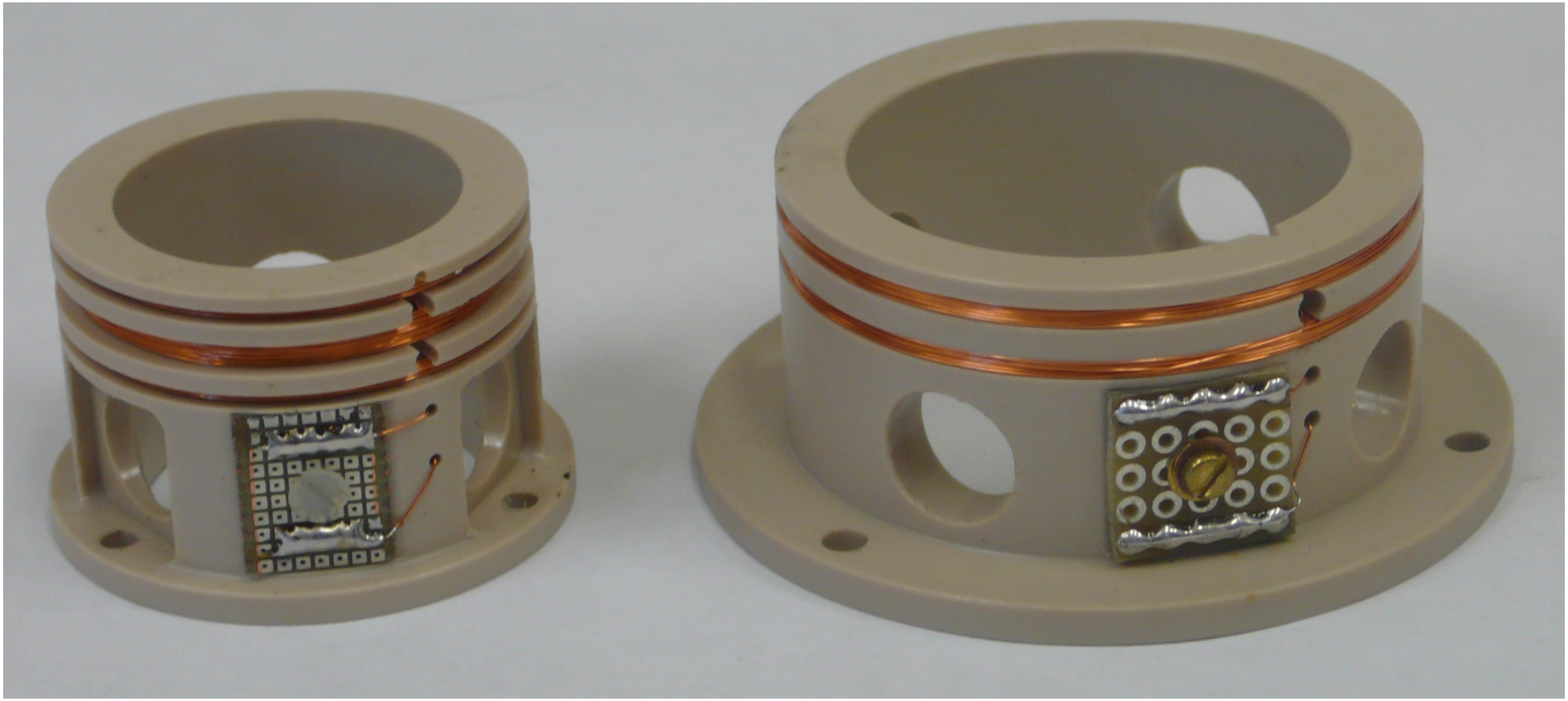


- Workaround: leave HEPI with position sensor loops and feed-forward the ground inertial sensor to the ISI
- ISI blend filters designed to limit sensor noise injection to 100 $\frac{nm}{\sqrt{Hz}}$ at low frequency and provide suppression of 100 at 1 Hz.

From “aLIGO Input Mode Cleaner Commissioning Report”, Ryan de Rosa (LSU), DCC #G1300126-v2

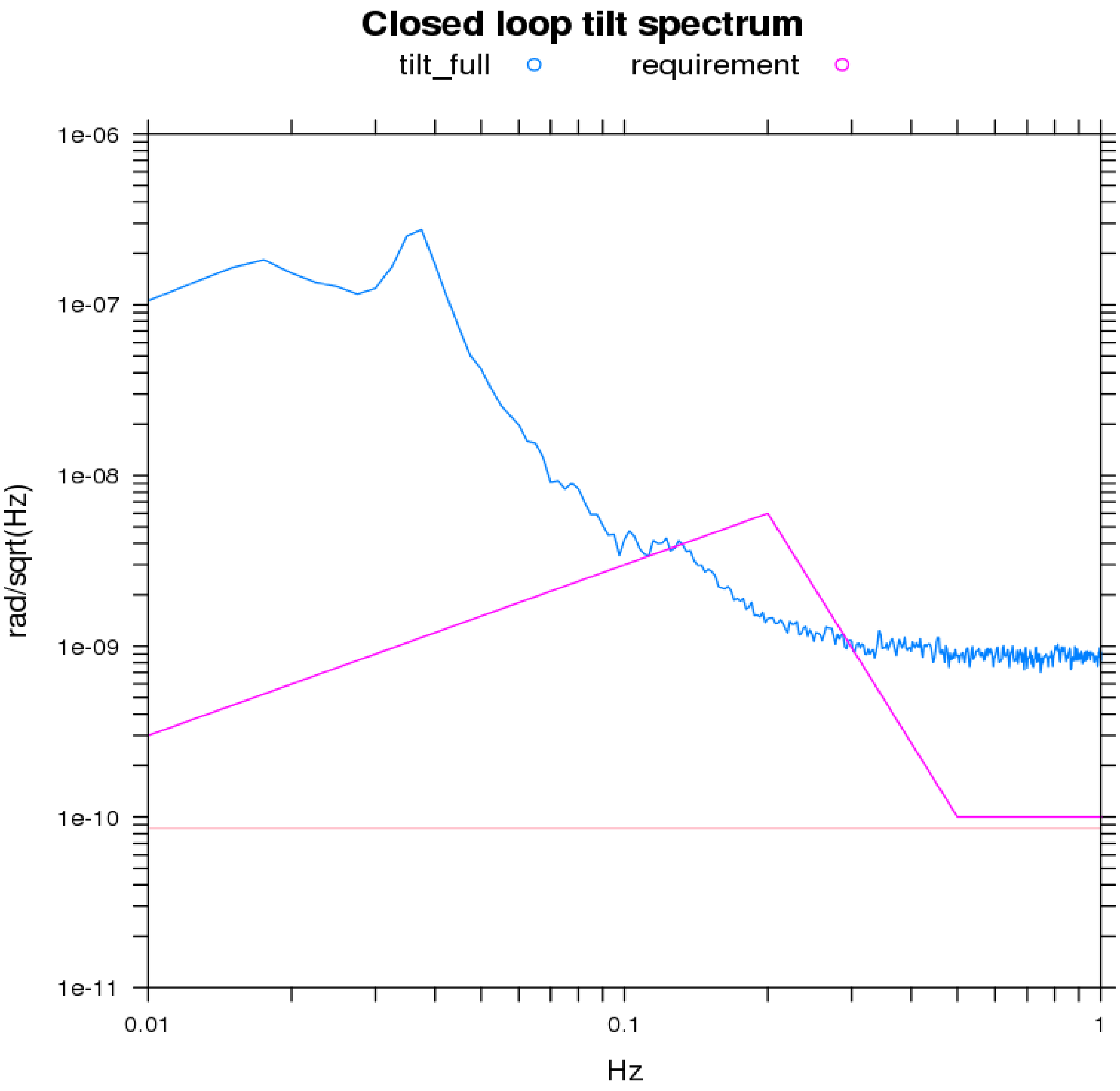
New LVDT design installed

- Differential excitation – designed to reduce external magnetic fields to reduce eddy current effects and self inductance.
- Allows stronger drive currents for increased precision.
- Thicker PEEK walls for better stability (just in case).



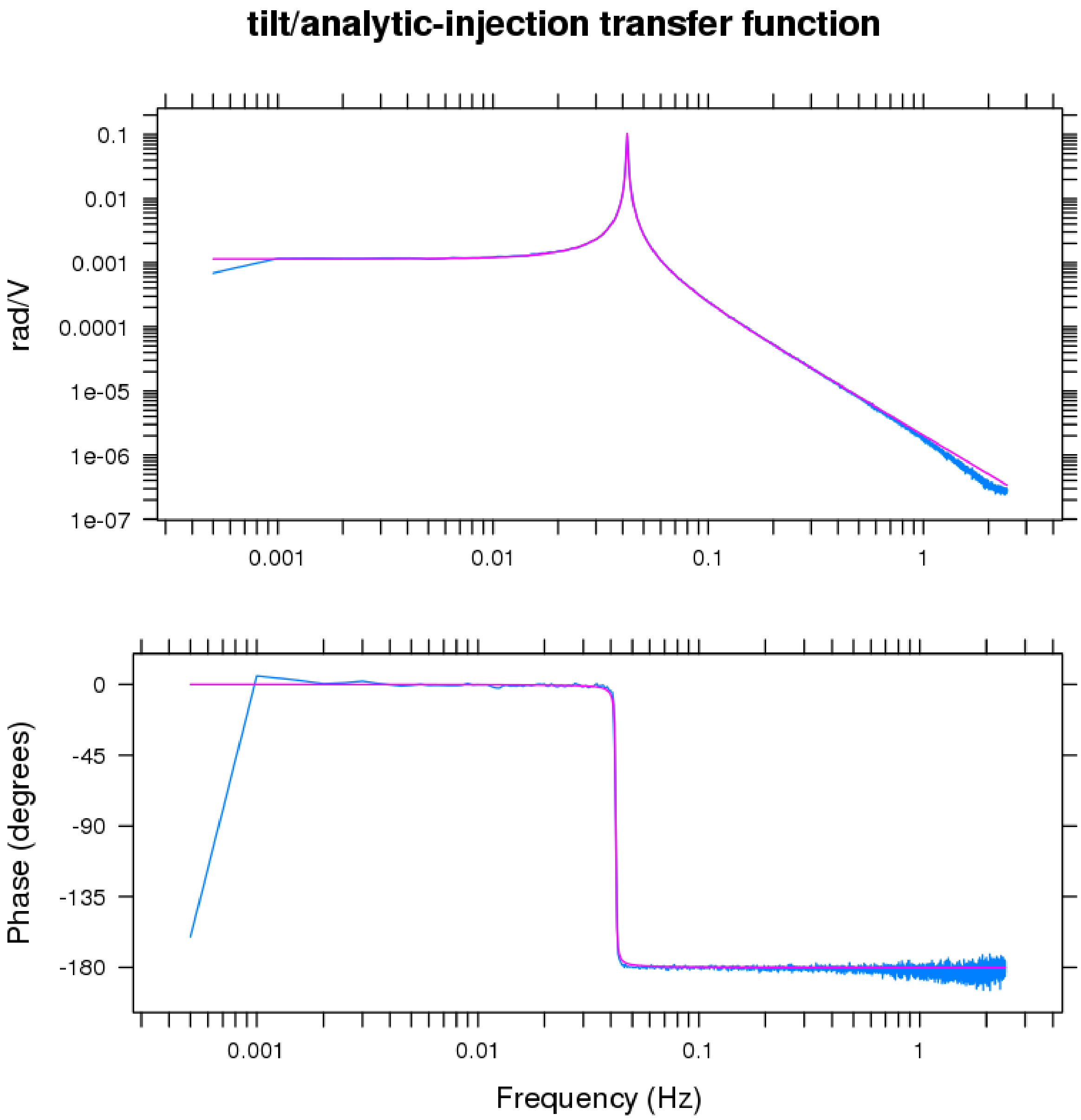
Achieved sensitivity

- For seismic isolation of advanced interferometers we need ~1e-10 rad/sqrt(Hz) (magenta curve)
- Our present sensitivity is below 1e-9 rad/sqrt(Hz) (blue curve)



Actuation transfer function

- f=42 mHz
- Q=90
- Near the resonance peak the actuation is too strong – 20 bit DAC does not have precision to go down all the way to 1e-10.
- Need to shift resonance peak to the left.

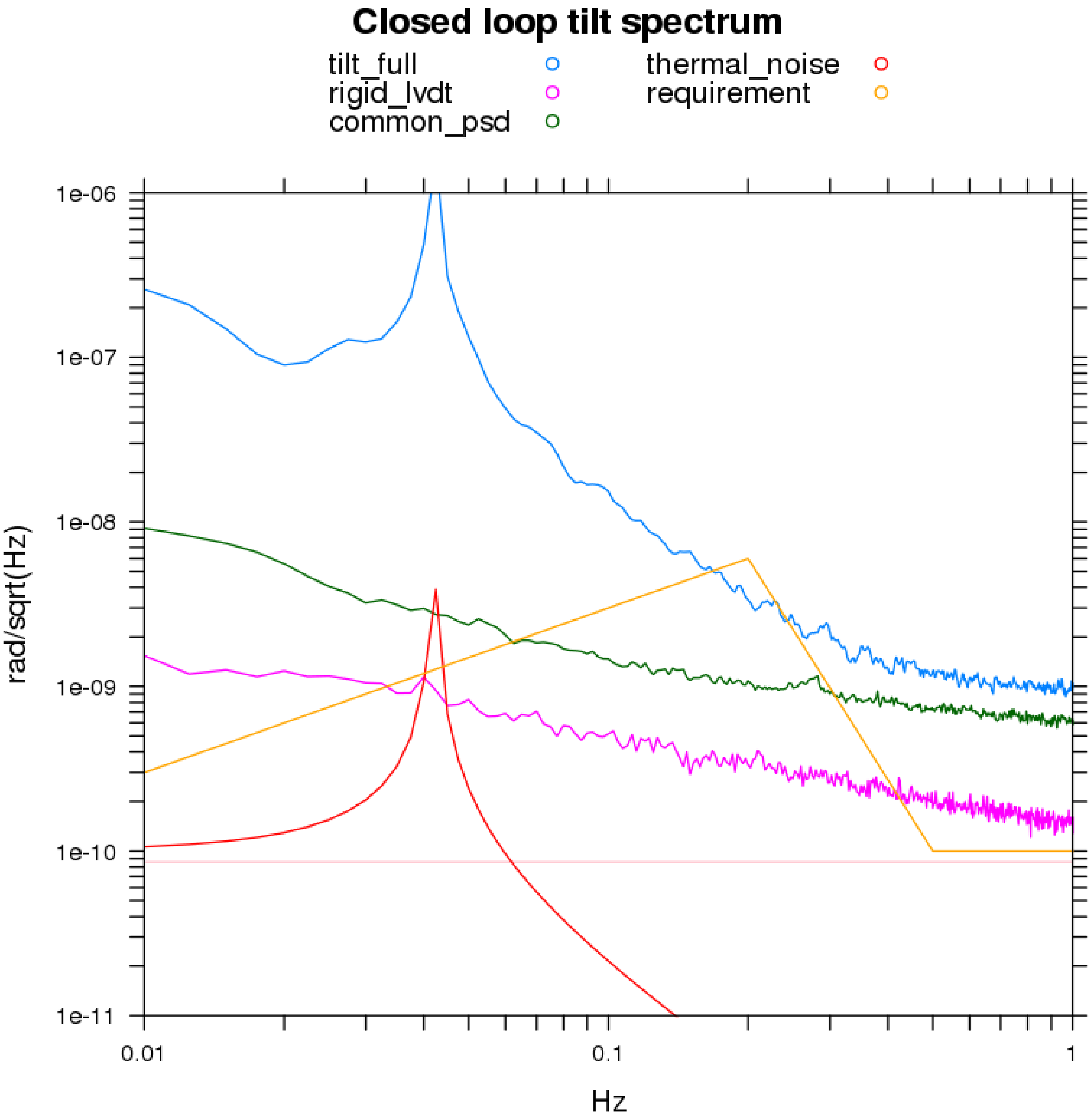


Noise sources

- Electronics
  - readout performs at 9e-11 rad/sqrt(Hz), except for very low frequencies due to known design issue
  - LVDT excitation driver has excess low frequency noise
  - DAC injects noise into actuation coils
  - coupling of LVDT excitation to external objects
- Mechanics
  - Damping due to air
  - Knife edge imperfections
  - Frame stability
  - Thermal noise
- Environment
  - Temperature
  - Air currents

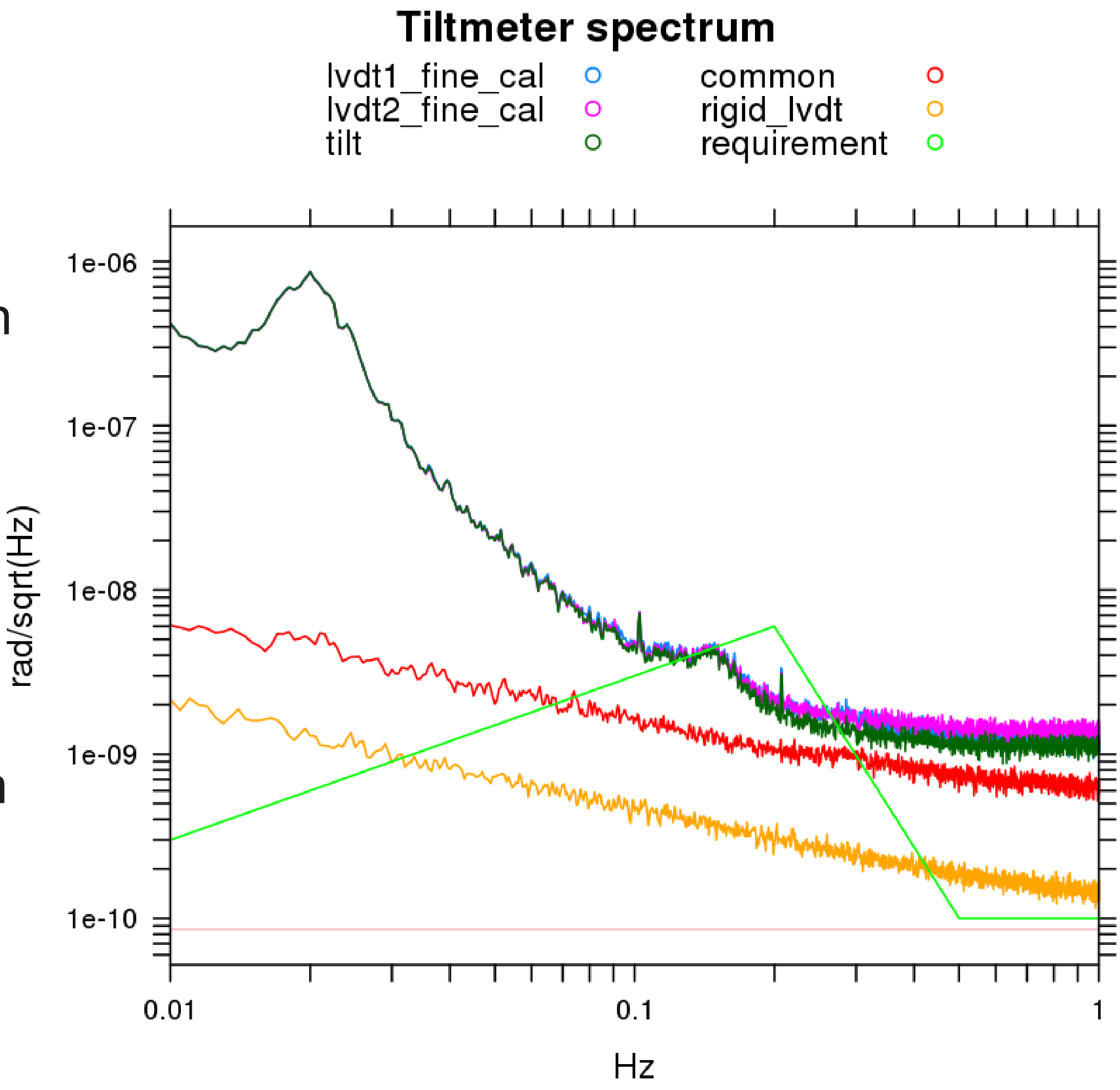
Noise sources

- Blue curve – closed loop tilt spectrum
- Green – common lvdt signal
- Magenta – rigid lvdt
- Red – thermal noise for oscillator with f=42mHz and Q=90
- Pink – readout electronics
- Yellow -requirement

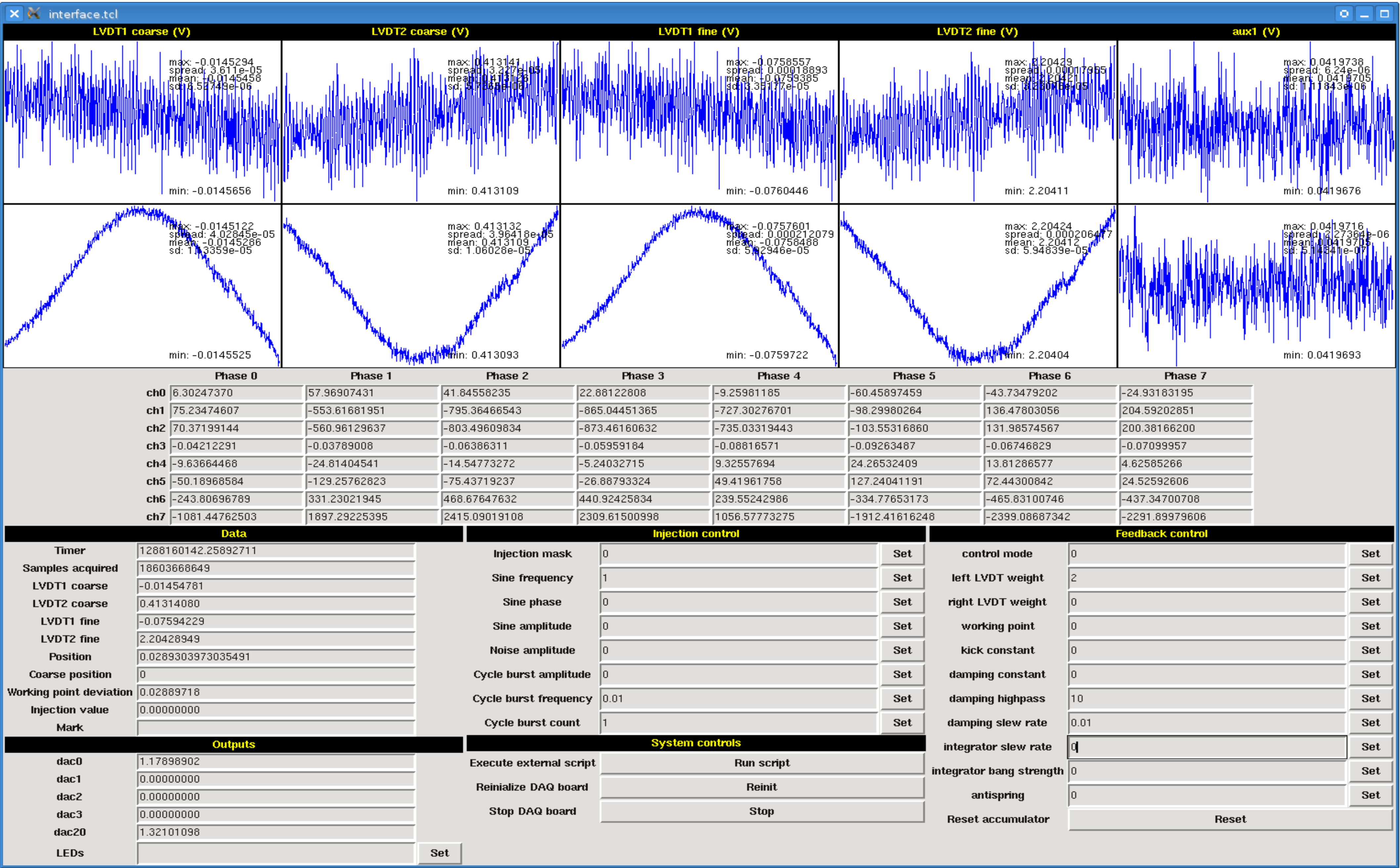


LVDT performance

- LVDT performance can be tested by mounting LVDT on a rigid bracket (yellow curve)
- To obtain performance in meters multiply by arm length of 0.125 m
- Noise level is below 0.02nm/sqrt(Hz) at 1 Hz !
- The "rigid" bracket is not stable enough, can see it settling for a few hours after tightening screws.
- LVDT noise increases when far from null – nonlinearities in electronics ?



User interface



	Phase 0	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6	Phase 7
ch0	6.30247370	57.96907431	41.84558235	22.88122808	-9.25981185	-60.45897459	-43.73479202	-24.93183195
ch1	75.23474607	-553.61681951	-795.36466543	-865.04451365	-727.30276701	-98.29980264	136.47803056	204.59202851
ch2	70.37199144	-560.96129637	-803.49609834	-873.46160632	-735.03319443	-103.55316860	131.98574567	200.38166200
ch3	-0.04212291	-0.03789008	-0.06386311	-0.05959184	-0.08816571	-0.09263487	-0.06746829	-0.07099957
ch4	-9.63664468	-24.81404541	-14.54773272	-5.24032715	9.32557694	24.26532409	13.81286577	4.62585266
ch5	-50.18968584	-129.25762823	-75.43719237	-26.88793324	49.41961758	127.24041191	72.44300842	24.52592606
ch6	-243.80696789	331.23021945	468.67647632	440.92425834	239.55242986	-334.77653173	-465.83100746	-437.34700708
ch7	-1081.44762503	1897.29225395	2415.09019108	2309.61500998	1056.57773275	-1912.41616248	-2399.08687342	-2291.89979606

Data

Timer	1288160142.25892711
Samples acquired	18603668649
LVDT1 coarse	-0.01454781
LVDT2 coarse	0.41314080
LVDT1 fine	-0.07594229
LVDT2 fine	2.20428949
Position	0.0289303973035491
Coarse position	0
Working point deviation	0.02889718
Injection value	0.00000000
Mark	

Outputs

dac0	1.17898902
dac1	0.00000000
dac2	0.00000000
dac3	0.00000000
dac20	1.32101098
LEDs	

Injection control

Injection mask	0
Sine frequency	1
Sine phase	0
Sine amplitude	0
Noise amplitude	0
Cycle burst amplitude	0
Cycle burst frequency	0.01
Cycle burst count	1

System controls

Execute external script

Reinitialize DAQ board

Stop DAQ board

Feedback control

control mode	0
left LVDT weight	2
right LVDT weight	0
working point	0
kick constant	0
damping constant	0
damping highpass	10
damping slew rate	0.01
integrator slew rate	0
integrator bang strength	0
antispring	0

Reset accumulator

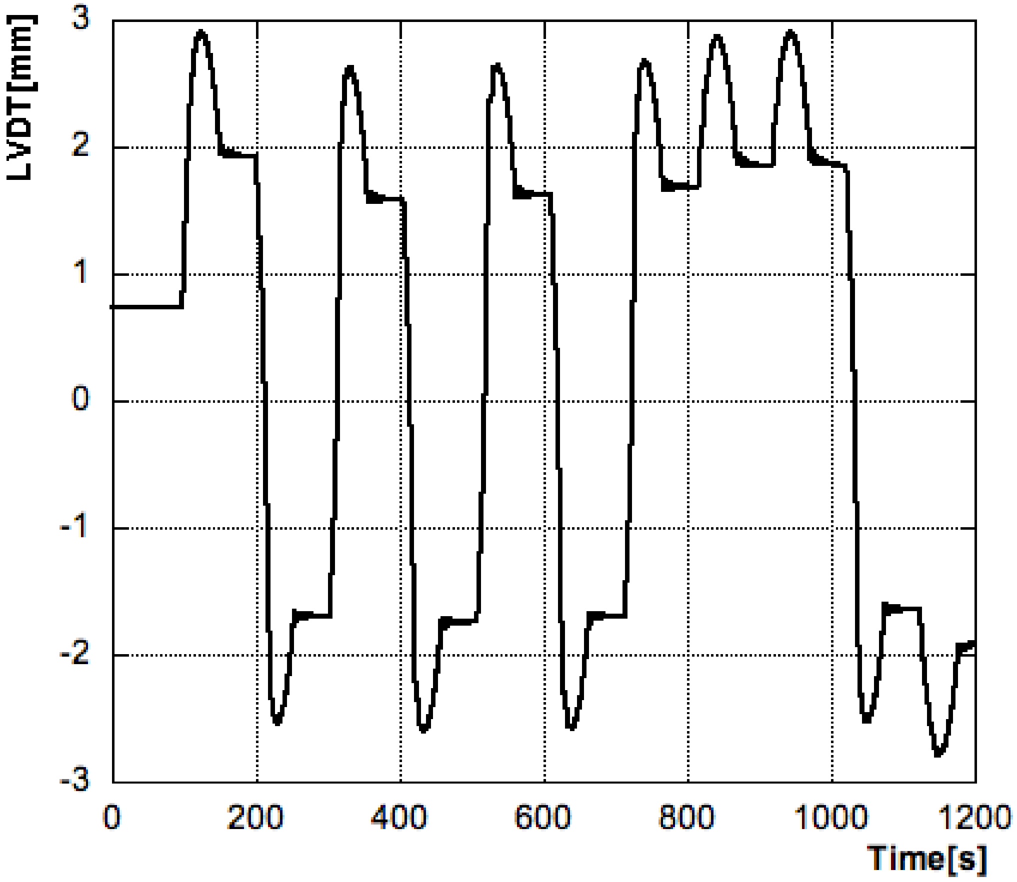
Hysteresis

- Knife edge was implemented to avoid hysteresis

- Example:

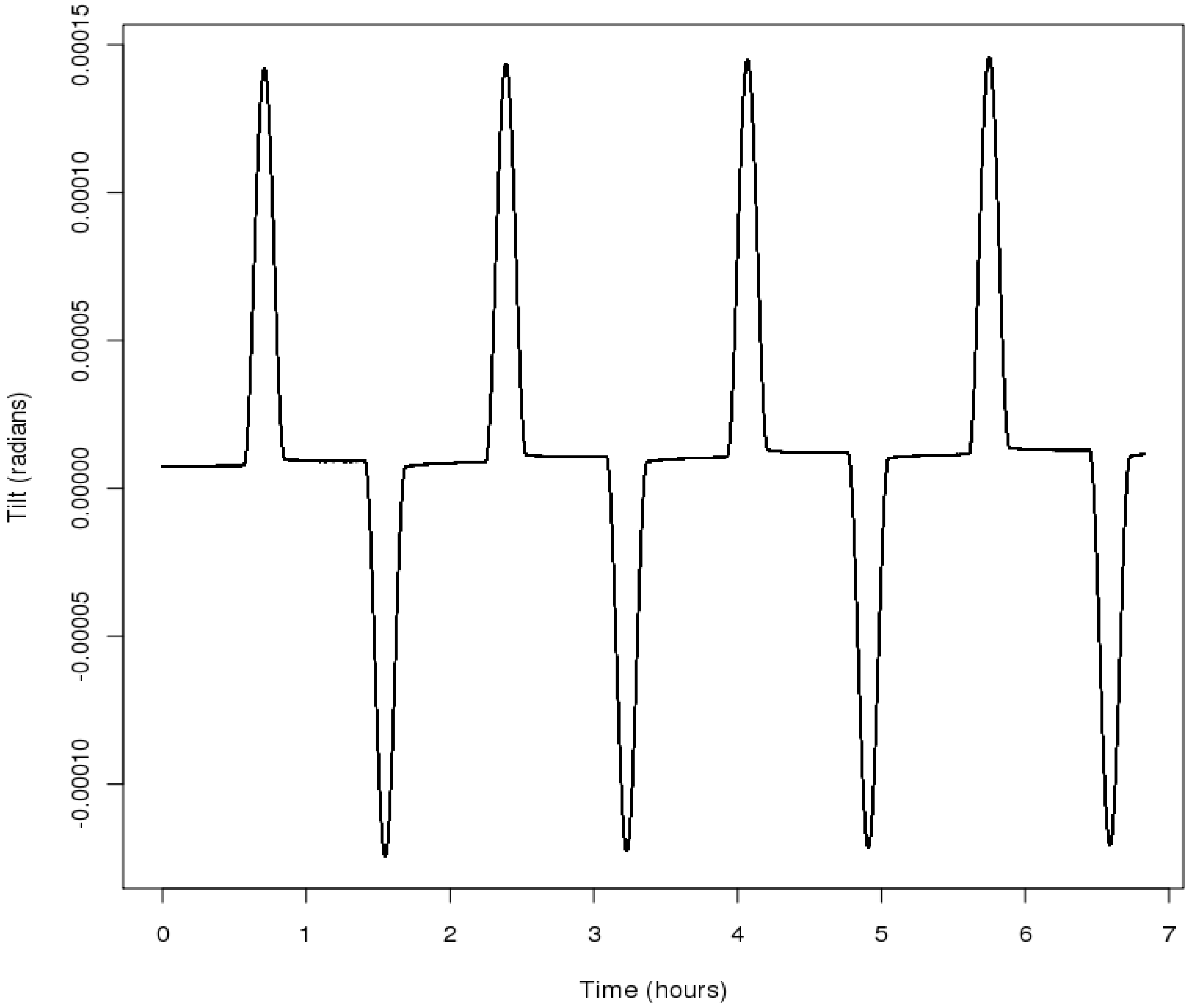
  Hysteresis in a

  Maraging filter



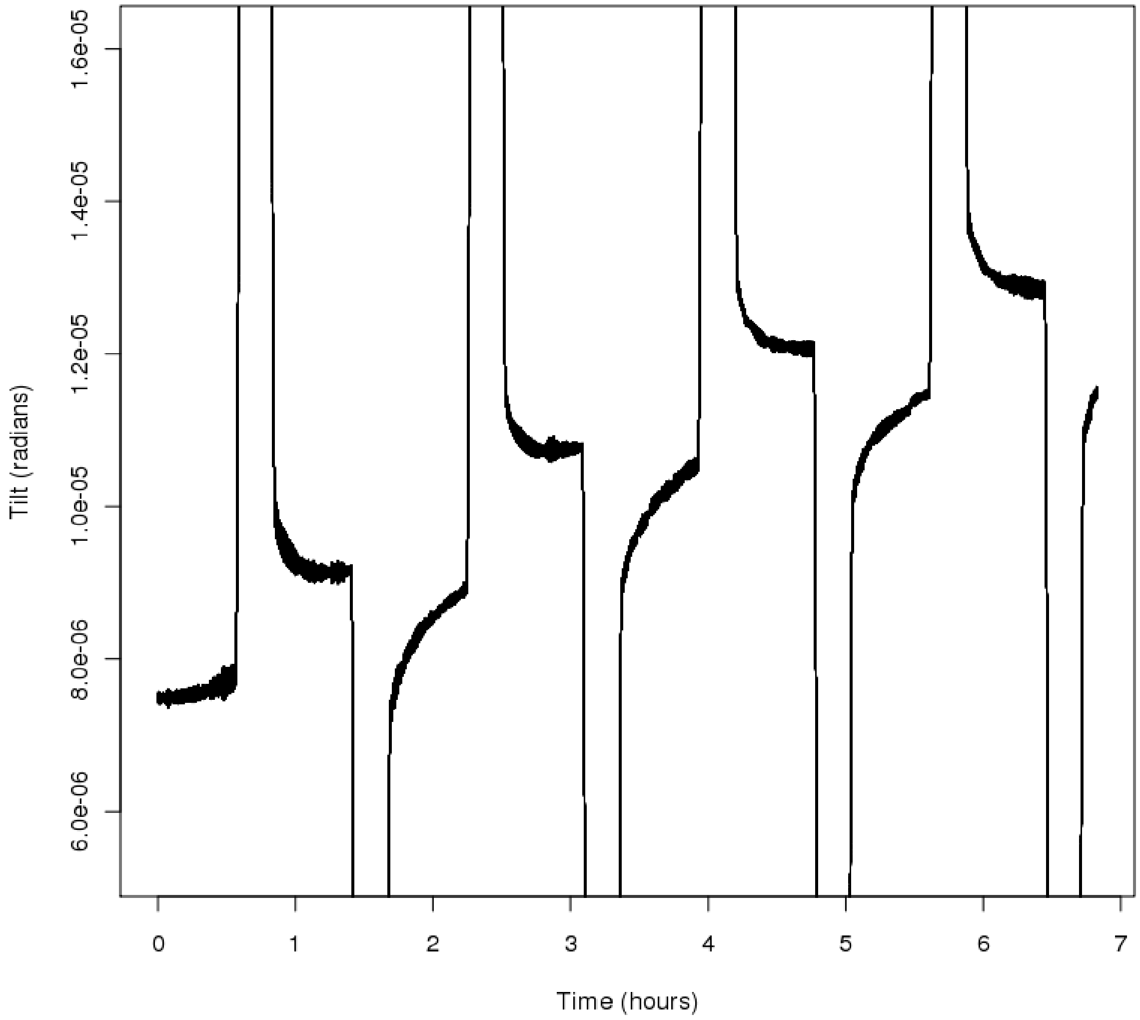
Hysteresis measurement

- Hysteresis in the instrument makes readout depend on past history making measurement more complicated.
- It also serves as a highly non-linear noise source.



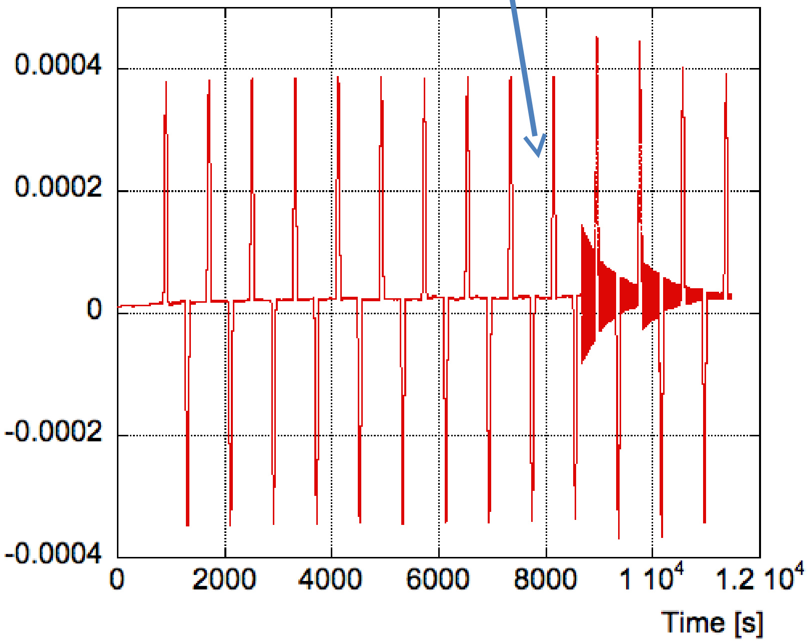
Zooming in

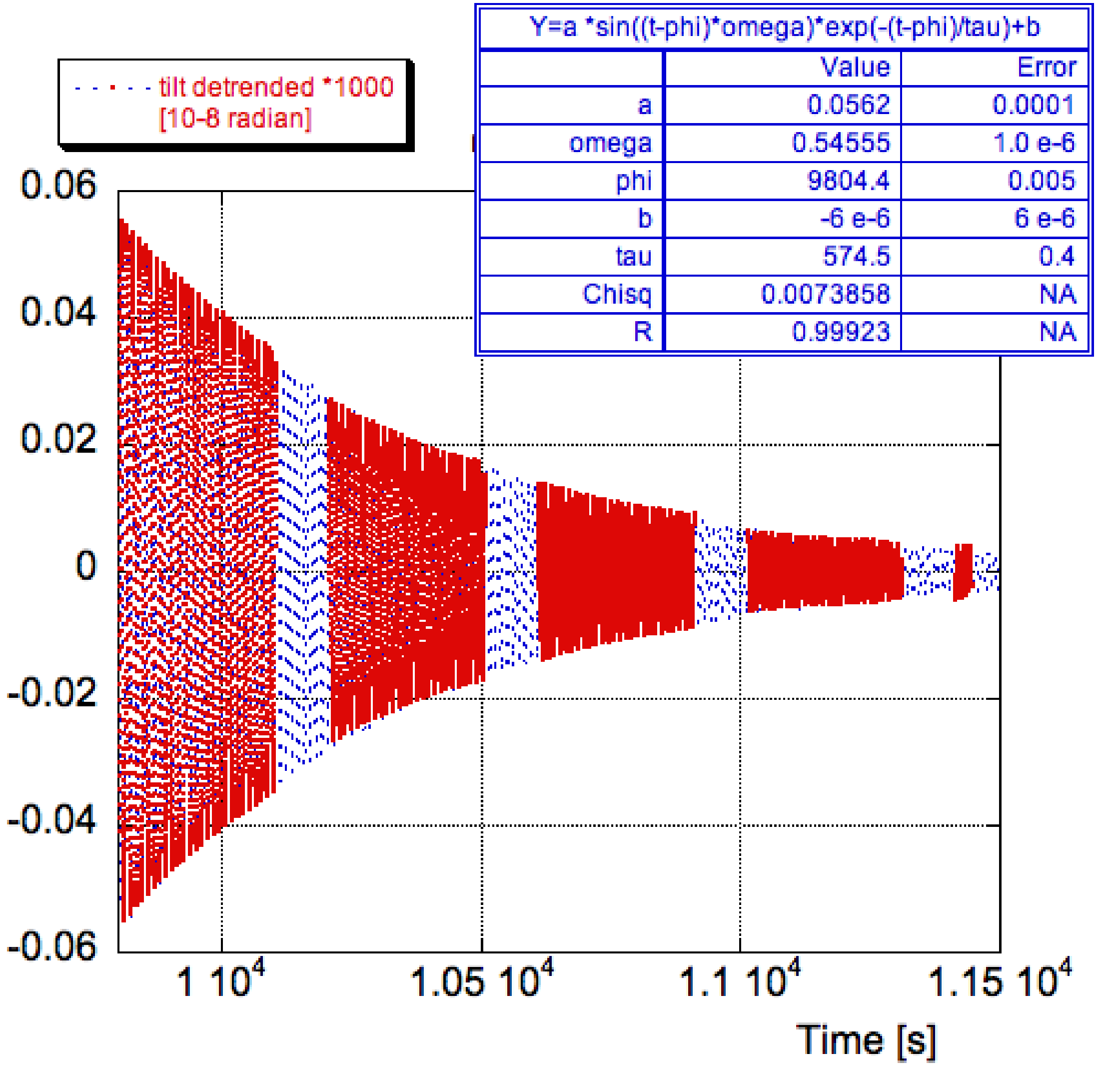
- The tiltmeter proper mode is excited by seismic motion and air currents, so the measurement was done with small amount of viscous friction provided by feedback control. This results in slow exponential decay of 1e-6 radians
- There is also a slow drift that occurred during the measurement
- Subtracting drift and exponential decay we see residual hysteresis of 4e-7 radians (300ppm).
- Primary suspect are resin coated copper wires.



Exponential decay keeps phase through excitations

- Seismic event





Y=a *sin((t-phi)*omega)*exp(-(t-phi)/tau)+b

	Value	Error
a	0.0562	0.0001
omega	0.54555	1.0 e-6
phi	9804.4	0.005
b	-6 e-6	6 e-6
tau	574.5	0.4
Chisq	0.0073858	NA
R	0.99923	NA

Knife-edge manufacturing

- Knife edge made of tungsten carbide, Young's modulus of ≈ 550 GPa.
- Knife edge is cut from tungsten carbide block using wire Electrical Discharge Machining (EDM).

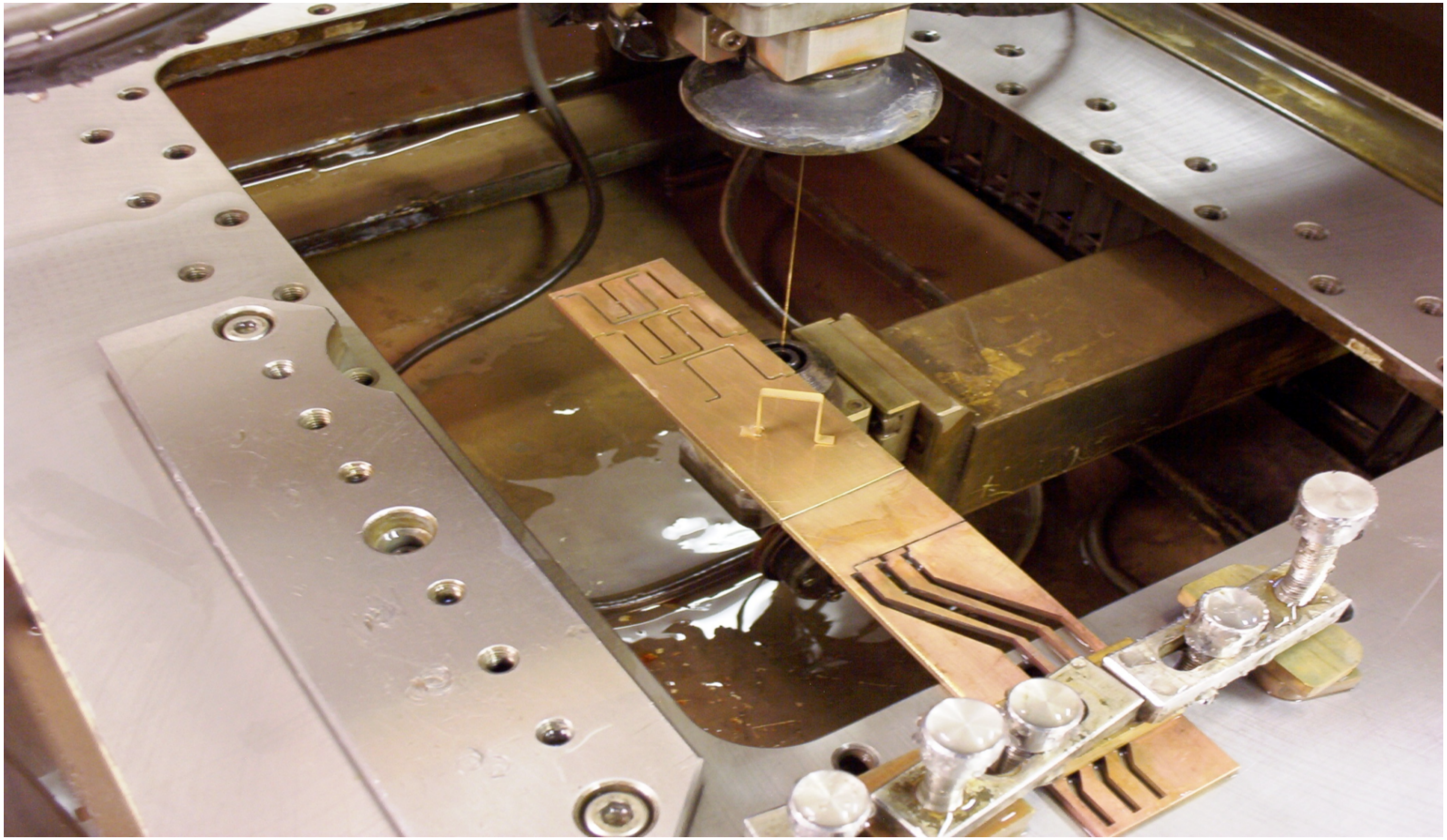
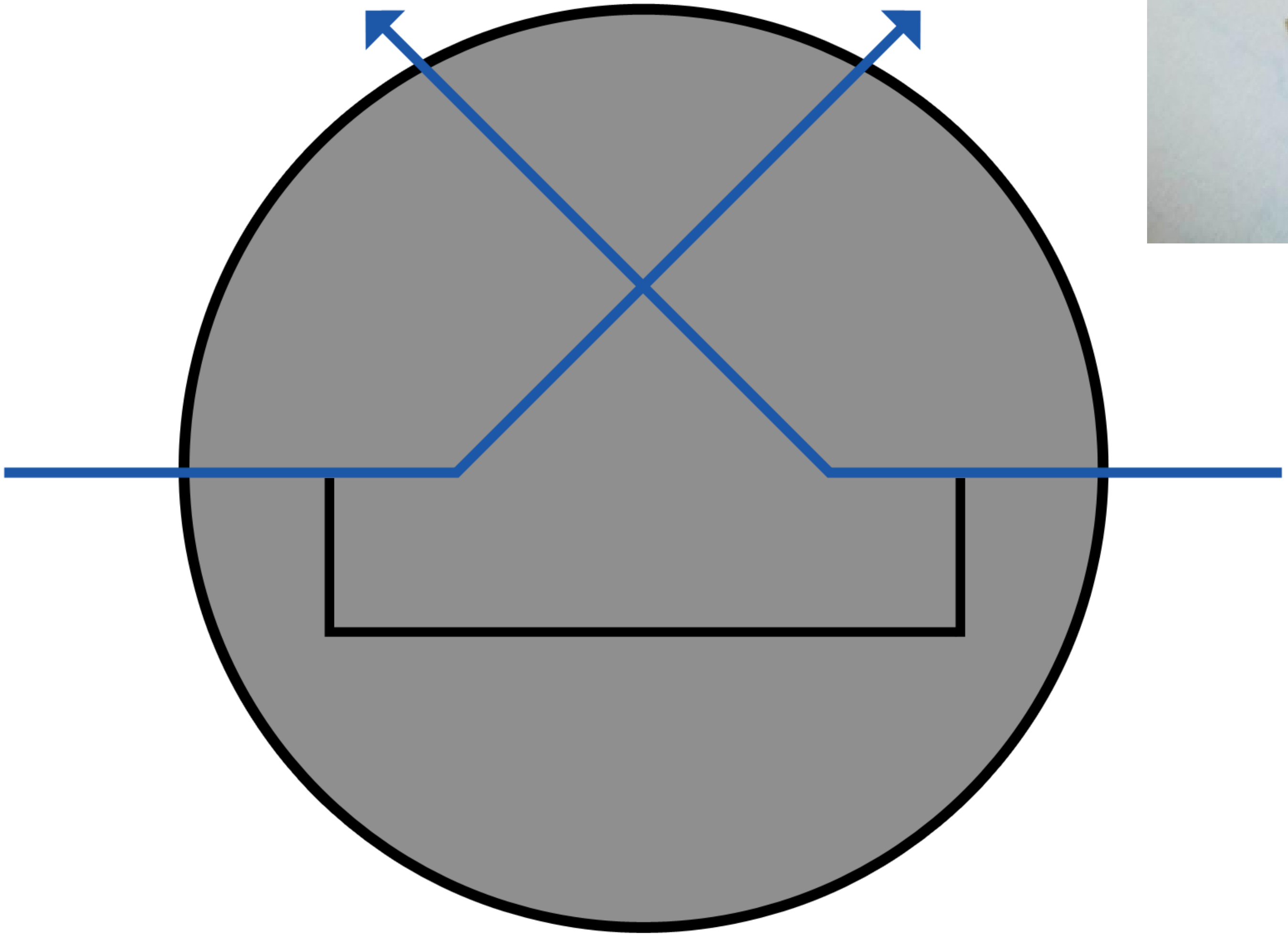
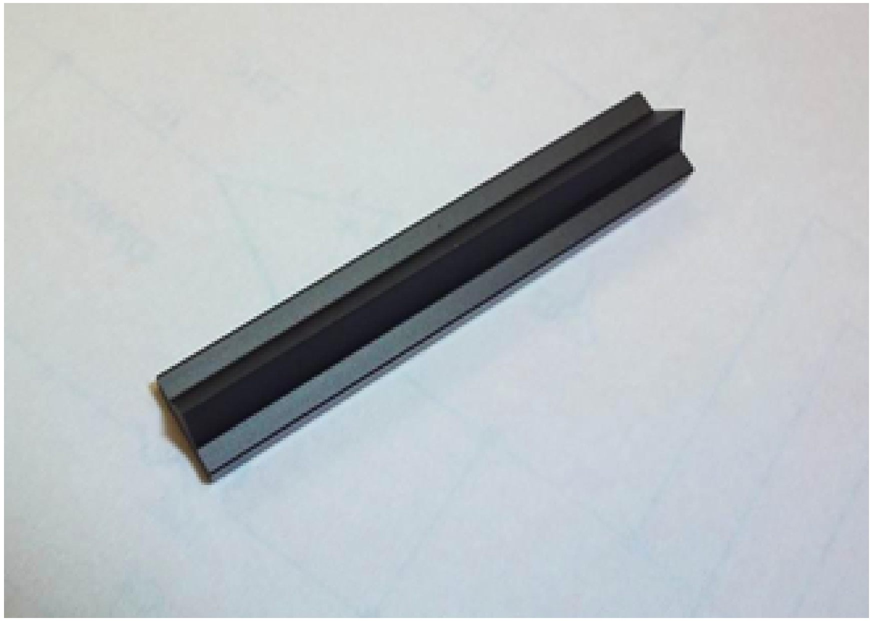


Image source: http://www.cumberlandmodelengineering.com/

Knife-edge manufacturing

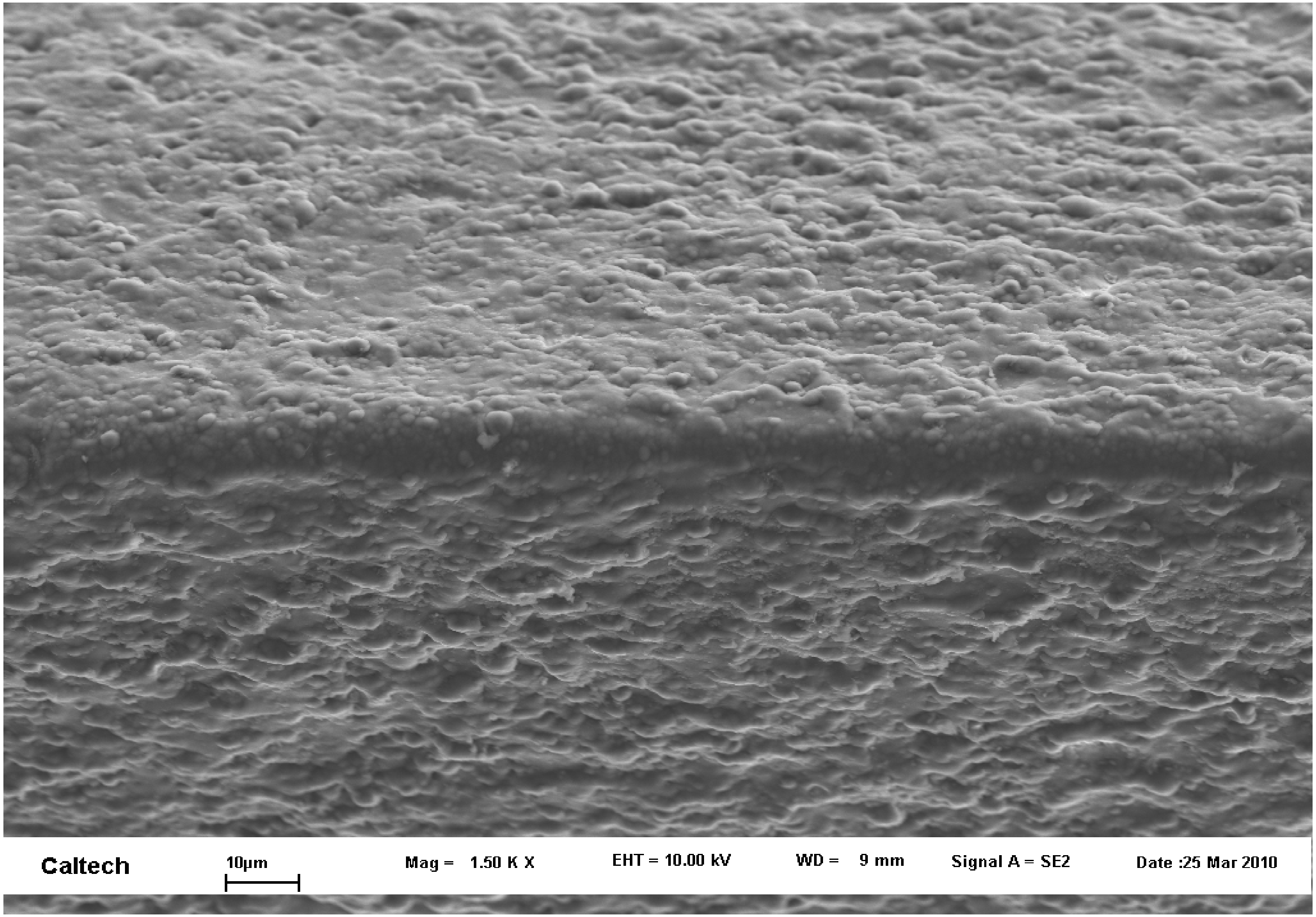
Cutting profile first implemented.





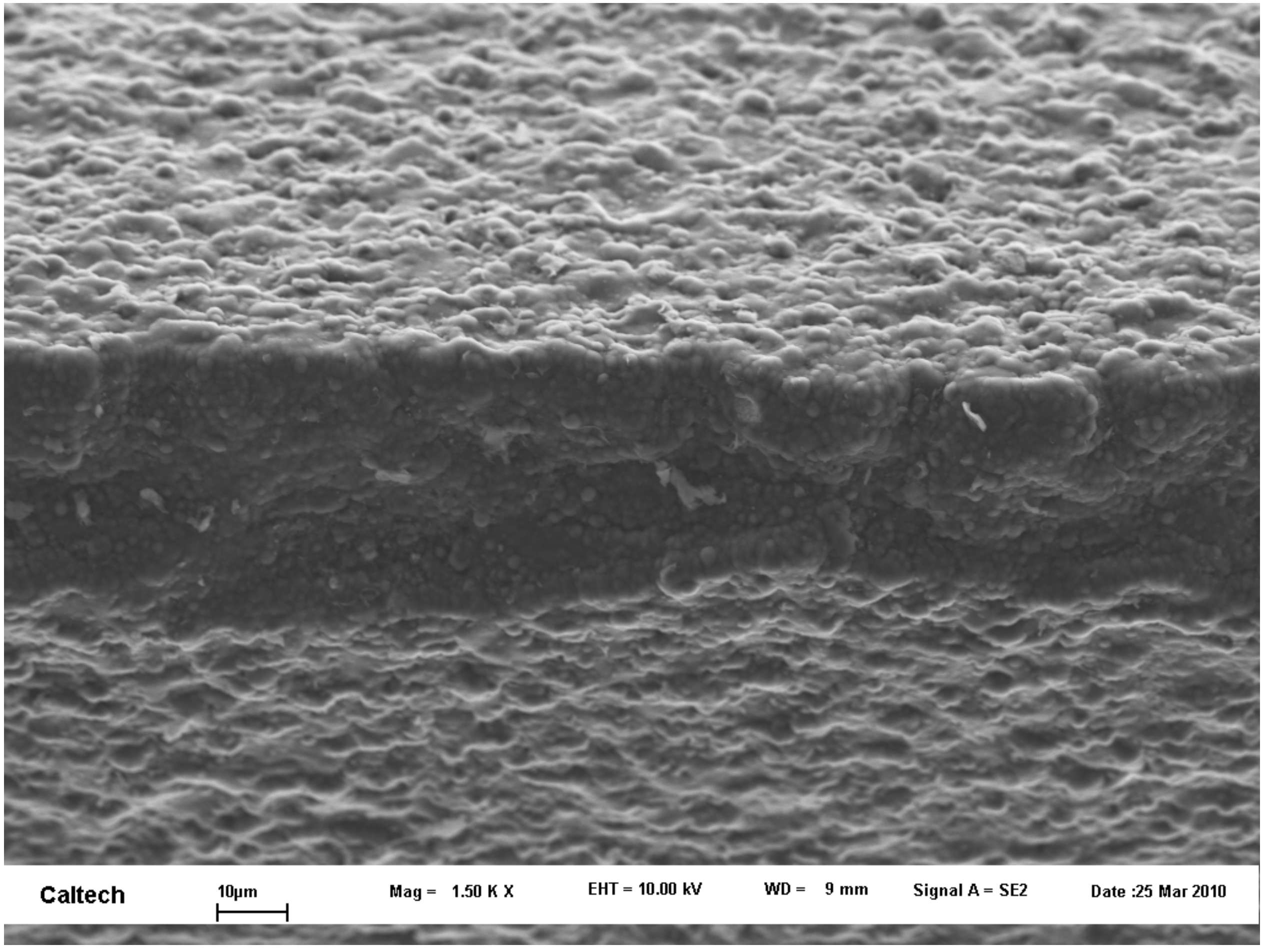
Knife-edge development

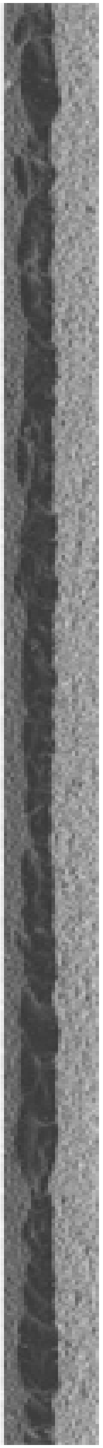
- Need clean sharp edge for low noise.
- Analysis was performed using SEM.



Knife-edge development

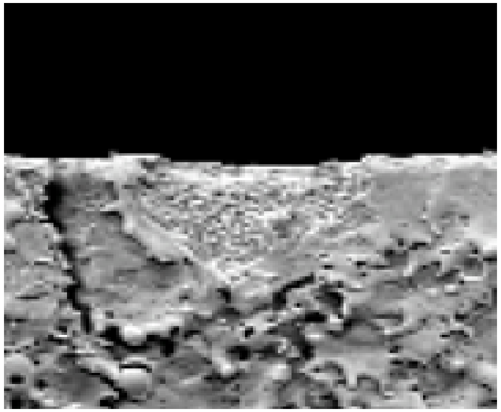
- Major cracks were found on some edges!
- On the worst end only 4.8% of the leading edge was of suitable sharpness.
- Mean crack width: 34 µm

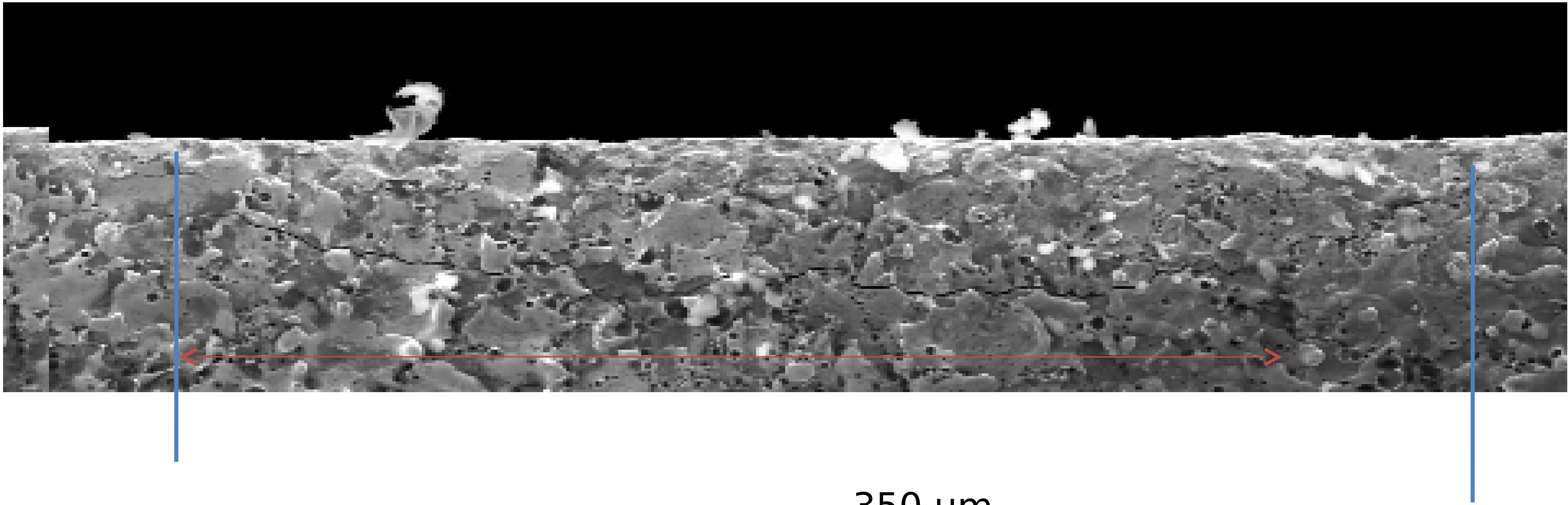




Knife-edge issues

Underlying cracks were also found!

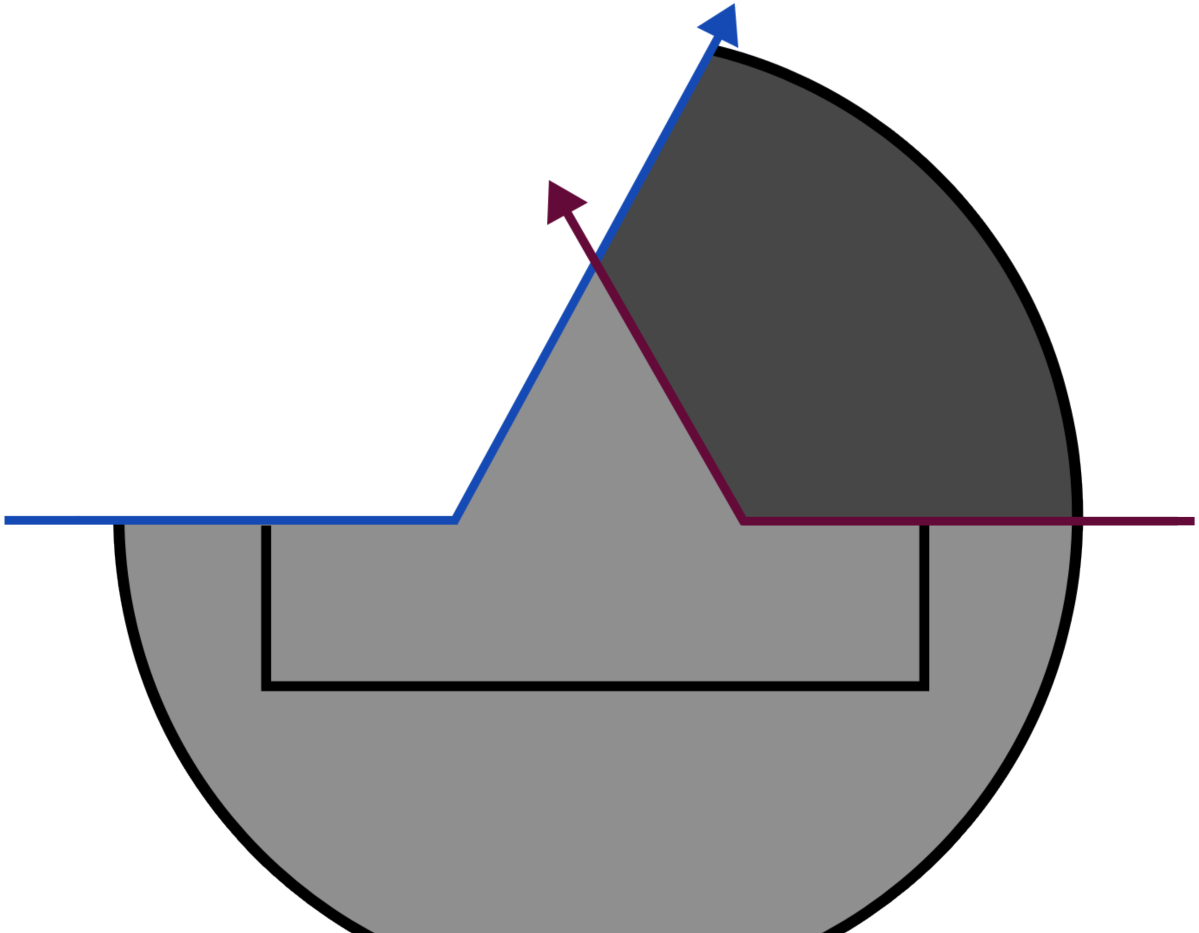




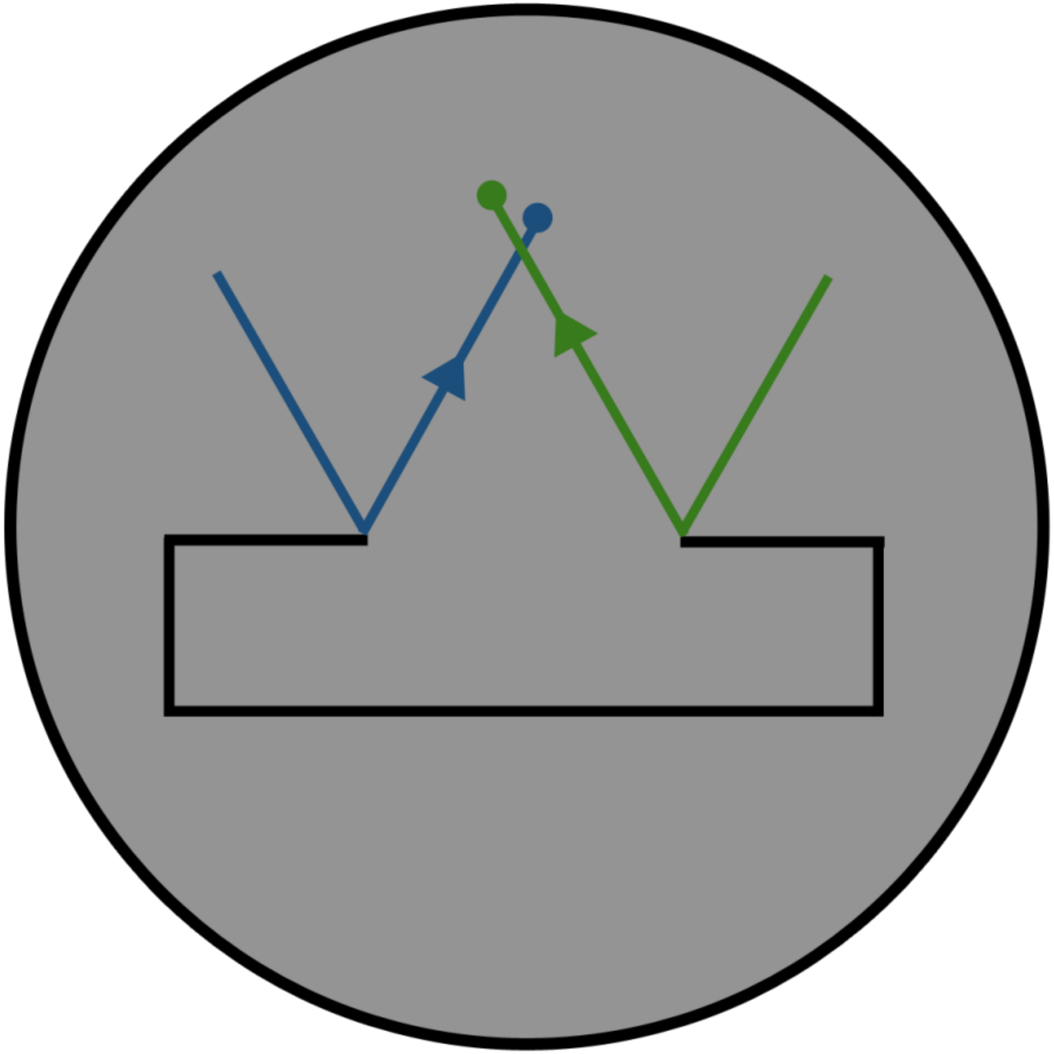
- What happened?

Knife-edge issues

- Cutting scheme first employed is to blame for the crack.
- Huge force concentration on the business end of knife edge when finishing the cut

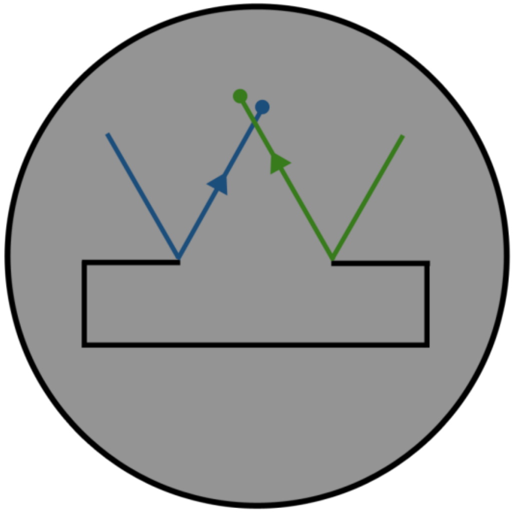


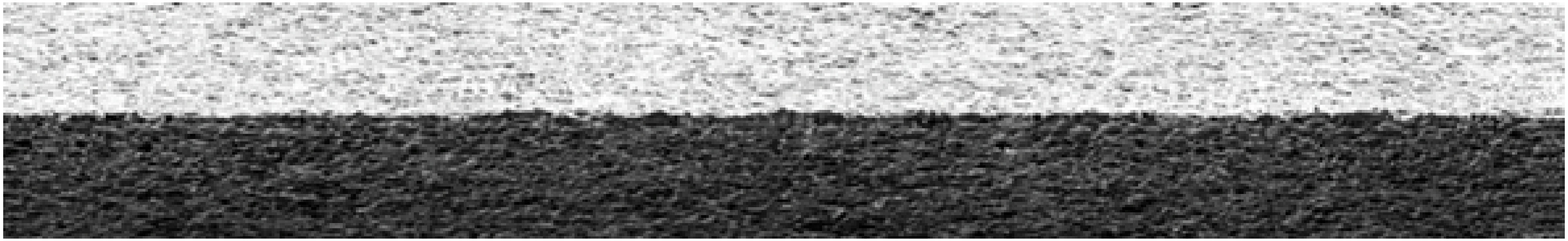
Cutting scheme that avoids the large force concentration on the tip of the knife edge.



Knife-edge development

- Wedge cut with new scheme does not have the crack defect.
- All shown plots were produced with old knife edge.
- Will try the new knife edge when all other improvements are in place.

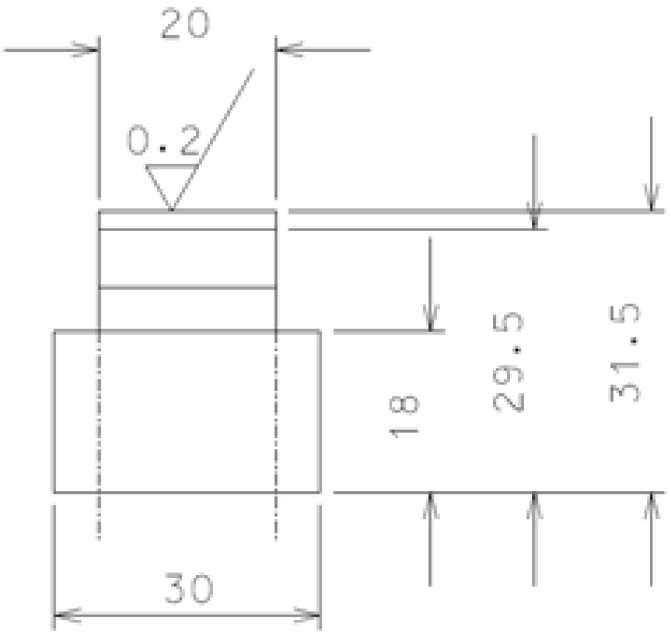


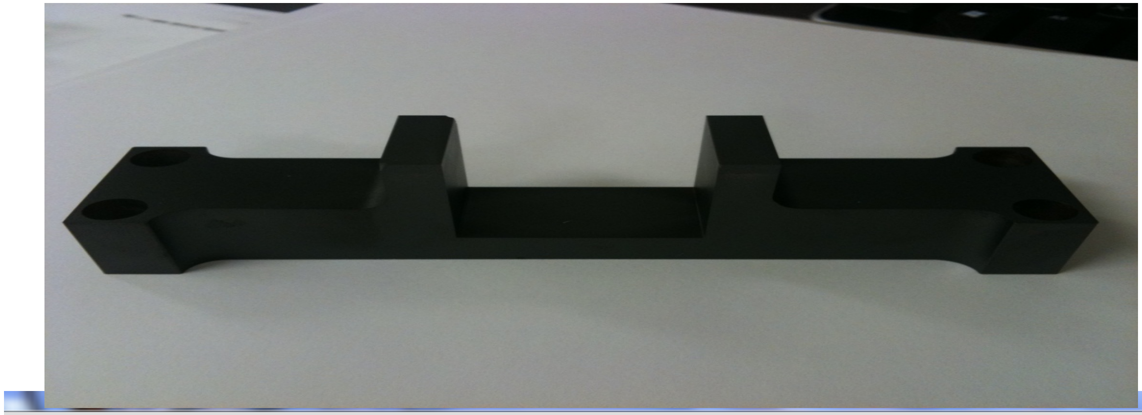


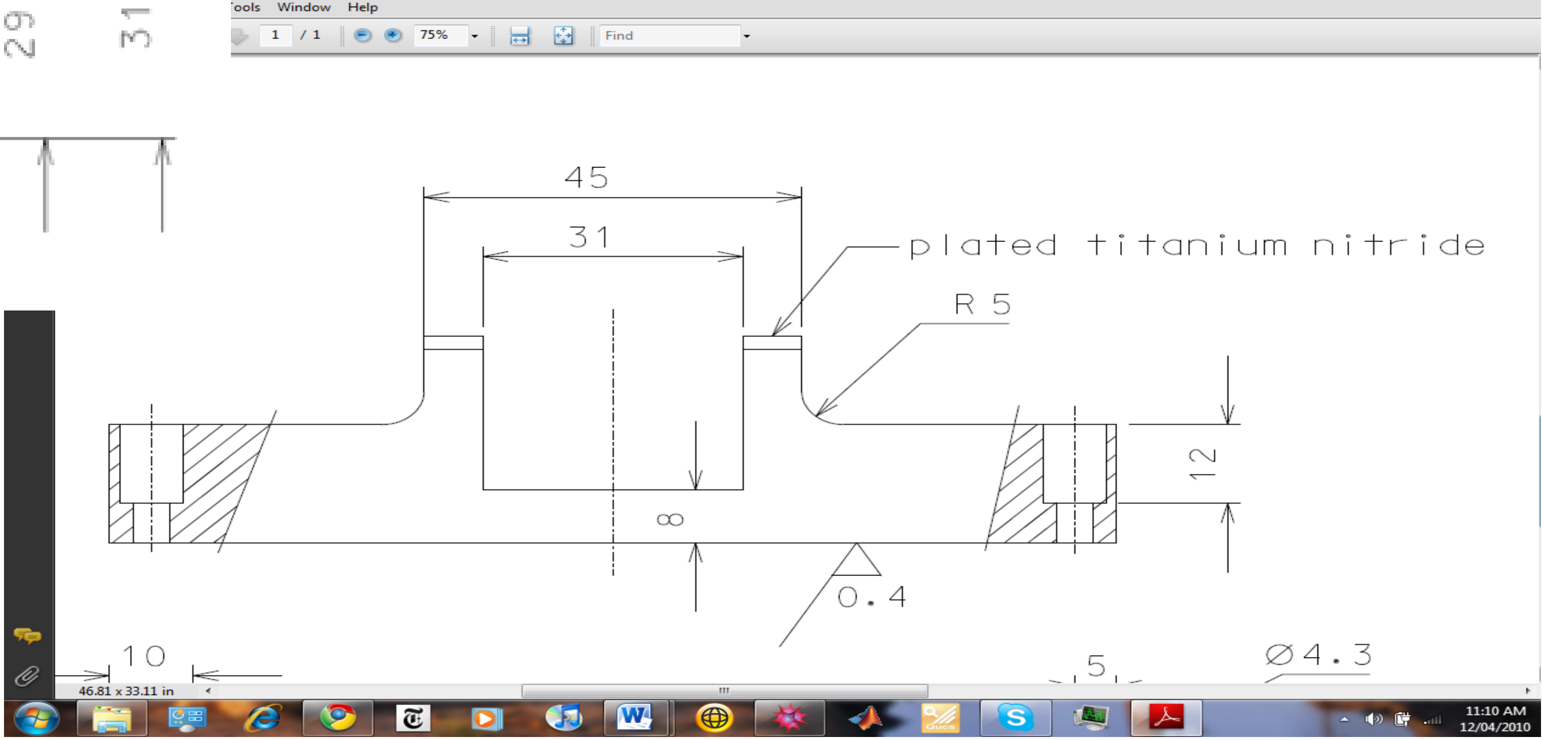
End of Talk

Anvil development

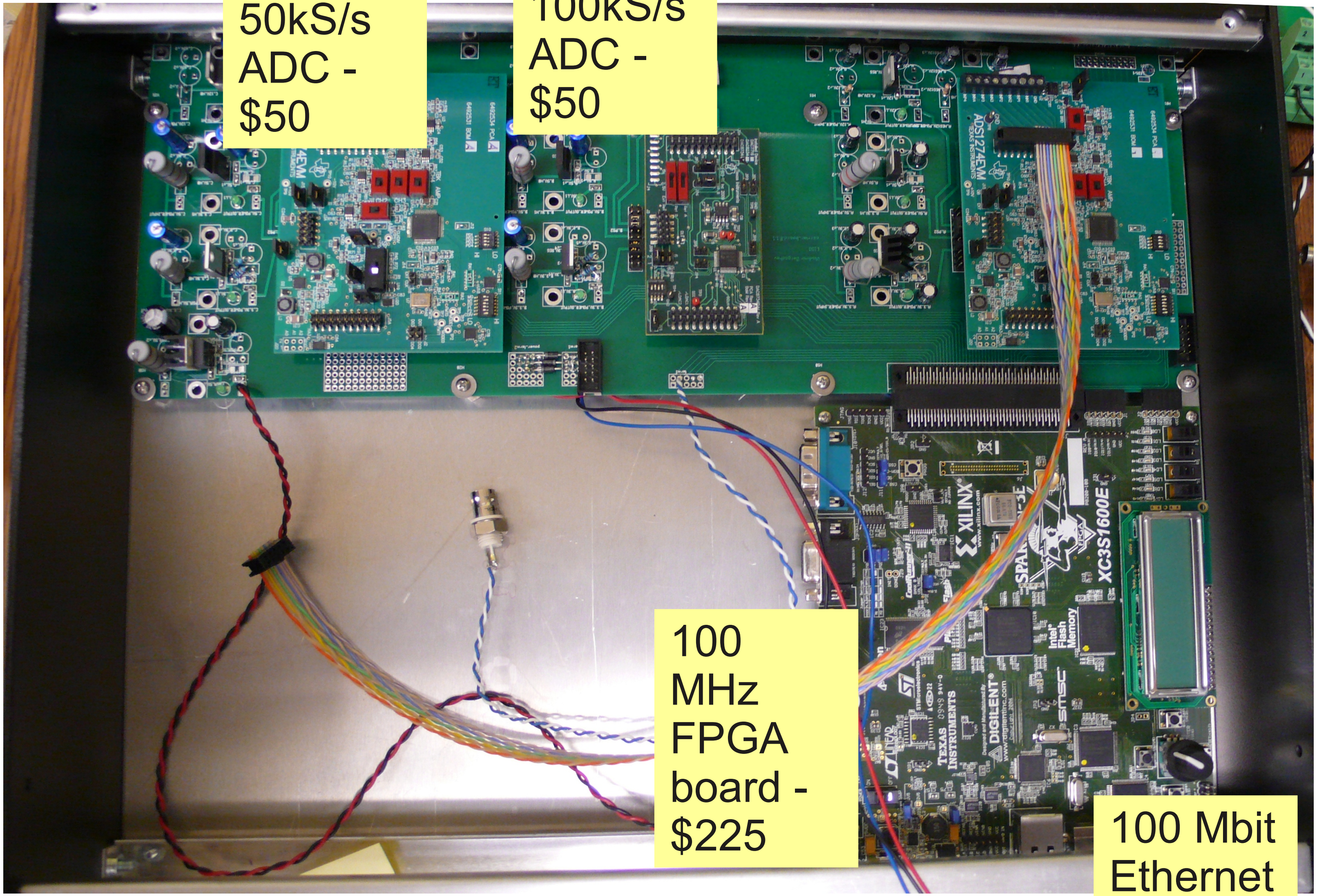
- 16mm of pivot contact on standard anvil
- Tungsten Carbide anvil







Data acquisition and signal synthesis



24-bit 50kS/s ADC - $50

16-bit 100kS/s ADC - $50

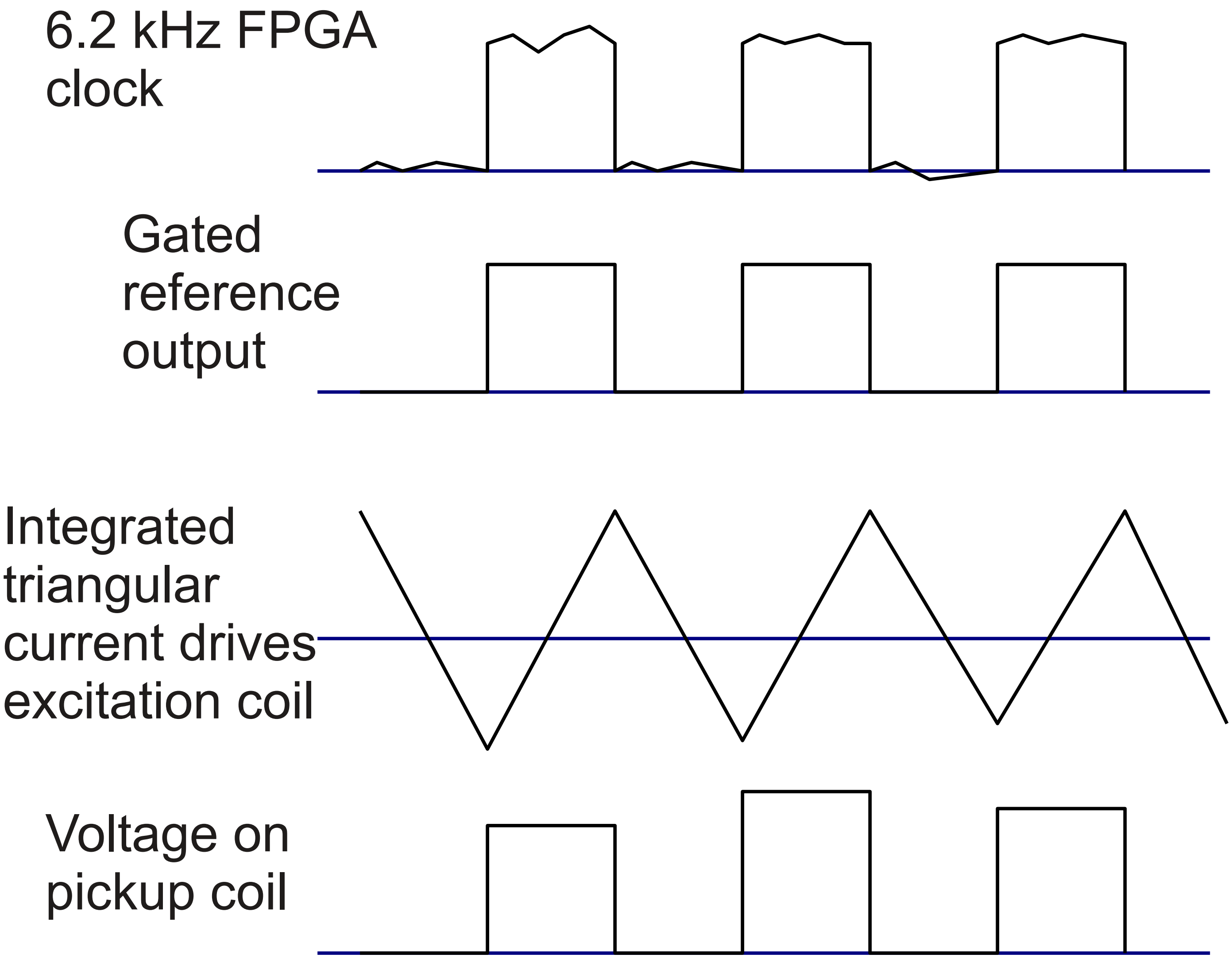
100 MHz FPGA board - $225

100 Mbit Ethernet interface

- Inexpensive high precision data acquisition system
- Easy to assemble
- Connects to TI evaluation boards
- Available boards: 24-bit 4 and 8 channel ADC, 16 and 20 bit DAC
- Communicates with Linux computer over regular Ethernet

LVDT readout

- Conventional LVDT has high inductance
- Usually driven with sine wave, can use phase demodulation for readout
- Air core LVDT has small inductance, readout is always based on amplitude
- Amplitude is proportional to change in magnetic field – triangular excitation current produces easy to sample square wave output
- Triangular excitation current dissipates less power than a sine wave



6.2 kHz FPGA clock

Gated reference output

Integrated triangular current drives excitation coil

Voltage on pickup coil