LIGO tiltmeter development

LIGO-G1000989

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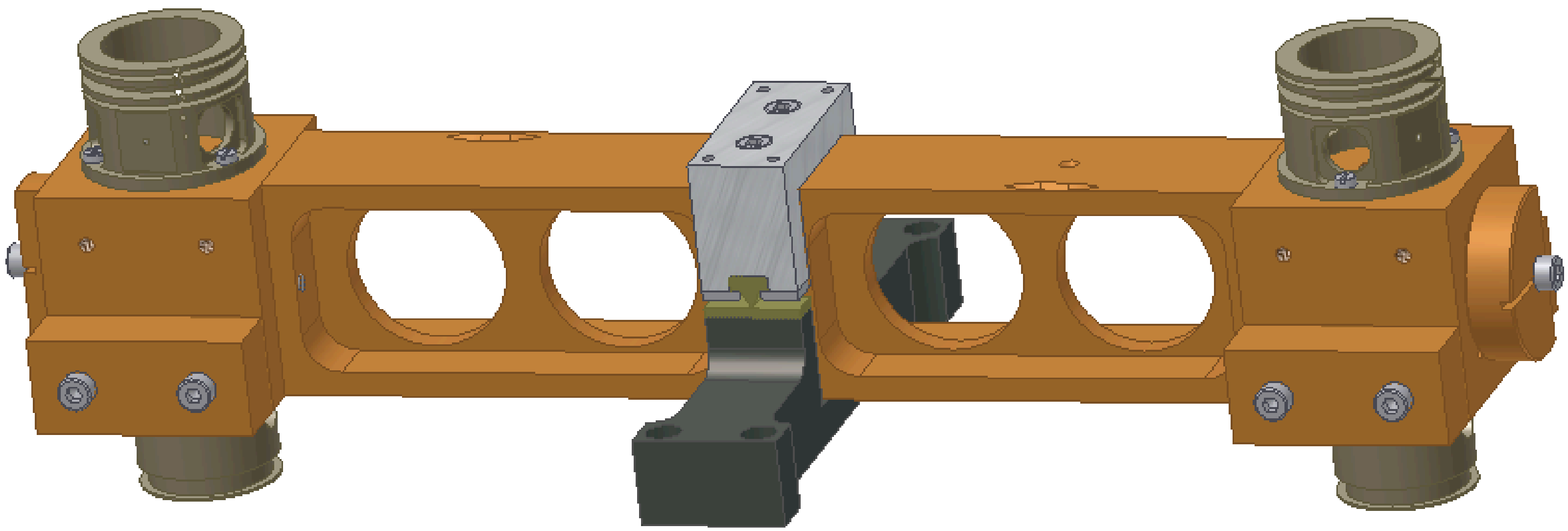
Introduction



What is a tiltmeter for

- High precision tiltmeters are:
  - useful for passive seismic attenuation systems

    and
  - necessary for active ones

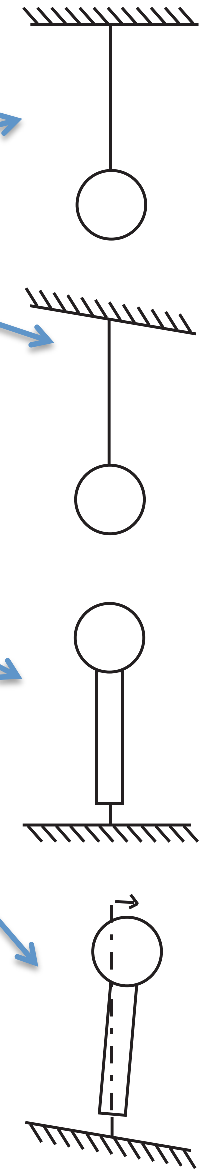
- Tilt seismometers of sufficient precision would allow the development of rotational seismology

LIGO

Use for passive attenuation

- Most of a passive seismic chain unaffected by tilt, no need
- The first stage is an inverted pendulum

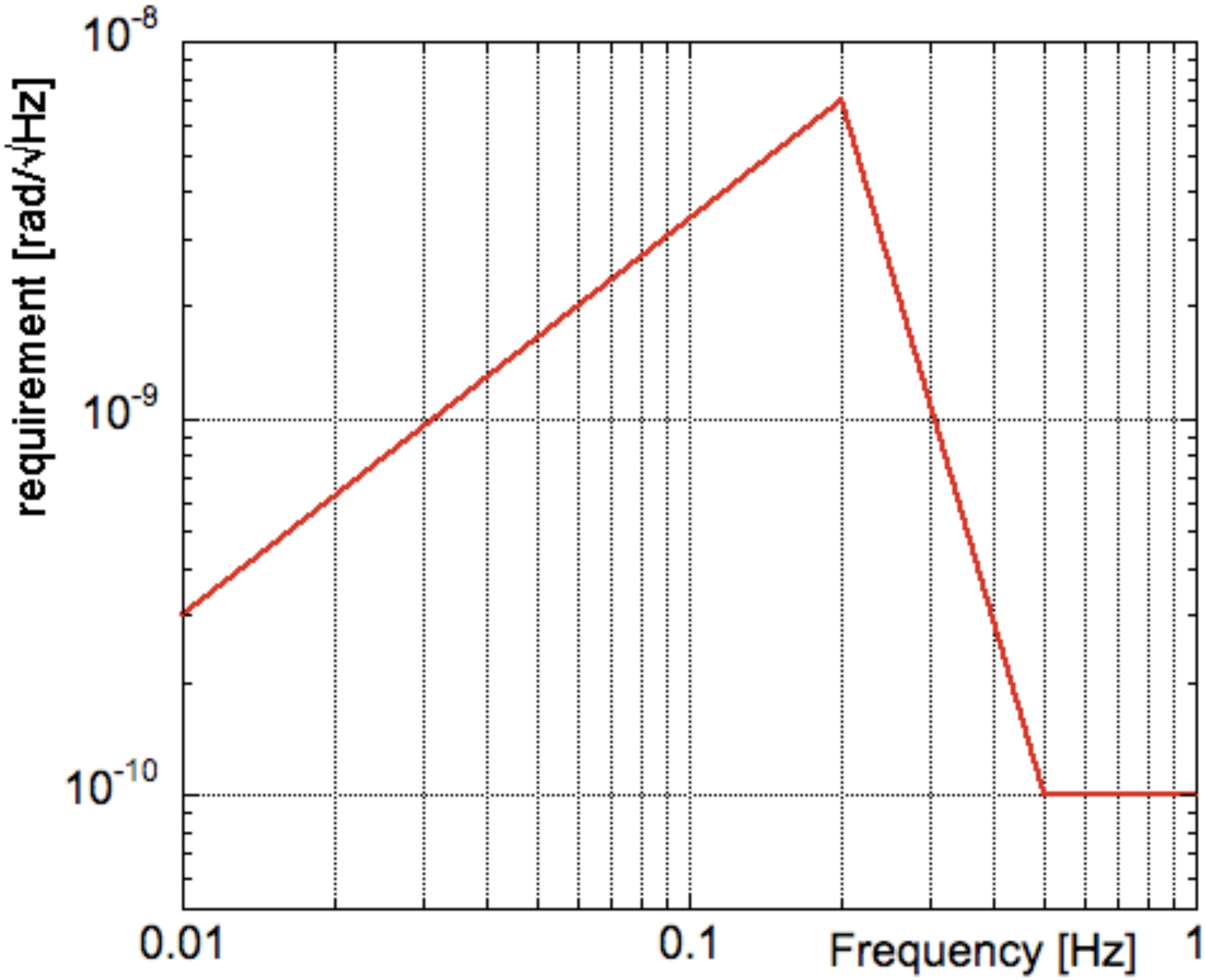
  like a horizontal accelerometer
- Sensitive to tilt through θ g
- Sufficient performance with position sensor correction but . . .
- Better performance correcting with a tiltmeter feed-forward loop



Use for Active attenuation

- Horizontal accelerometer signal fooled by θ g
- Impossible on Earth to distinguish a tilt from an acceleration (Equivalence principle)
- Signal pollution proportional to $1/\omega^2$
- Position correction negates attenuation performance
- Active attenuation impossible at low frequency without a high sensitivity tiltmeter

AdLIGO Active attenuation requirements



- Requirements are more than an order of magnitude better 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.

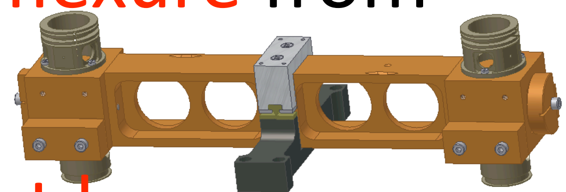
Uses for rotational seismology

- Surface waves are transversal waves
- Rotational behavior not trivial at surface or near other discontinuities
- Rotational accelerometers complementing the linear ones would make better sensor suites.

LIGO

Tiltmeter performance limits

- All recent mechanical tiltmeters are based on a bar suspended by a thin metal flexure from its center of weight



- All failed to satisfy expectations at low frequency, mainly with 1/f noise
- Recent discovery of Self Organized Criticality noise in dislocation movement
  explains this excess noise

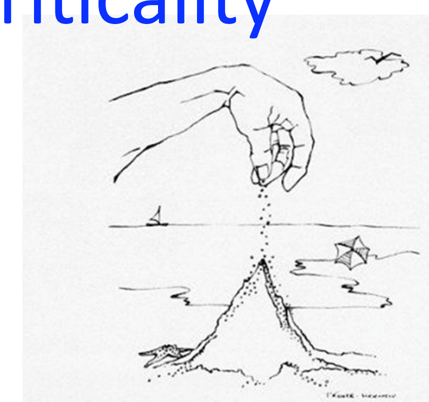


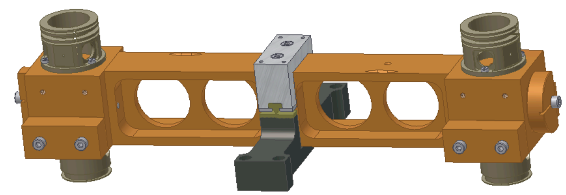
Figure 1. Sandpile. (Drawing by Ms. Elaine Wiesenfeld.)

•**R. DeSalvo** (2010) "The Role of Self Organized Criticality in Elasticity of Metallic Springs; Observations of a new Dissipation Regime." LIGO–P1000105

Per Bak 1996, How nature works: The Science of Self-Organized Criticality

How to avoid the limitation

- The identified noise derives from dislocation collective movement in the flexure.
- Solution:
- replace flexure with
  a non metallic hinge

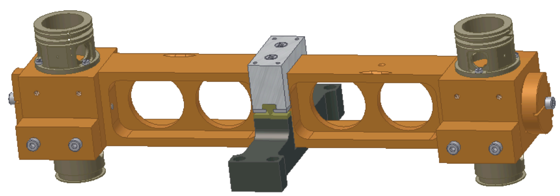


- Back to the future, return to the

knife edge design of precision scales

Beyond the old knife edge design

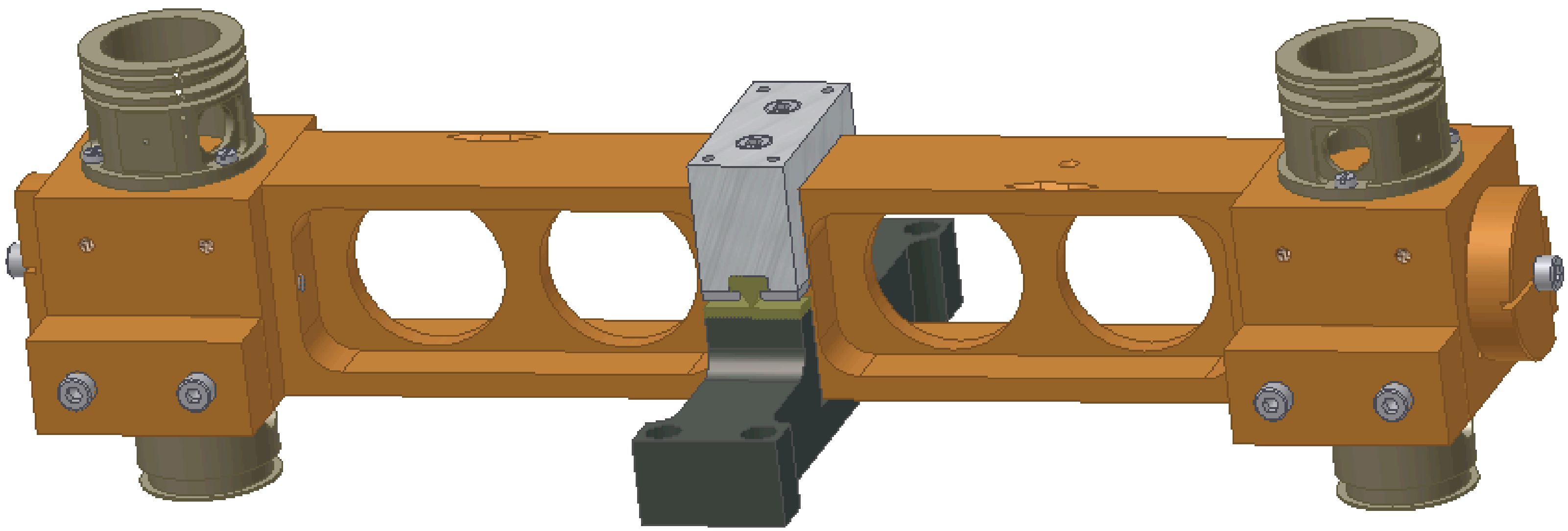
- Old design based on natural hard stones to manufacture low loss knife edge hinges



- We are past the stone age
- Tungsten carbide (WC) is a high tech, precision machinable, very hard stone
- Advanced coating (TiN, DLC, Diamond, et c.) allow for even harder stones and less losses

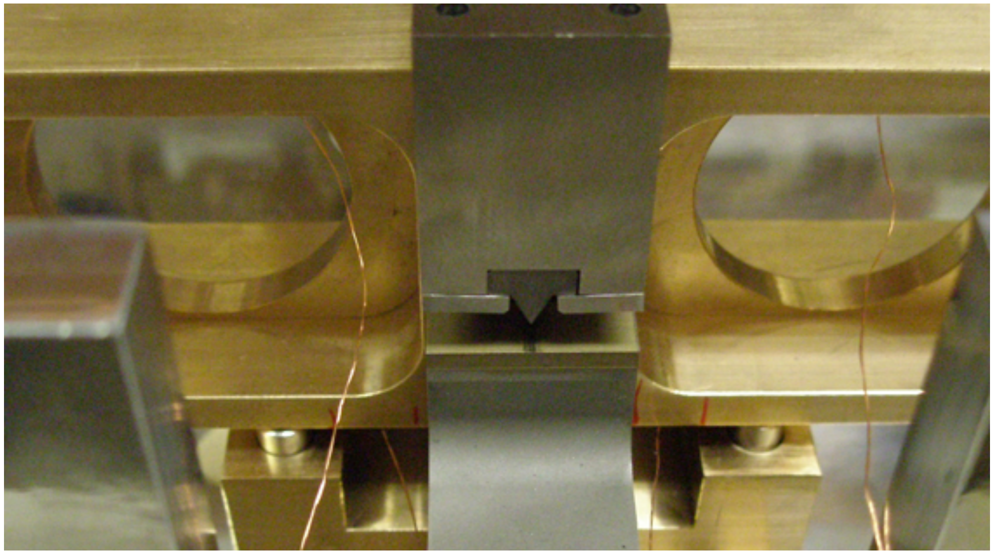
Tiltmeter design

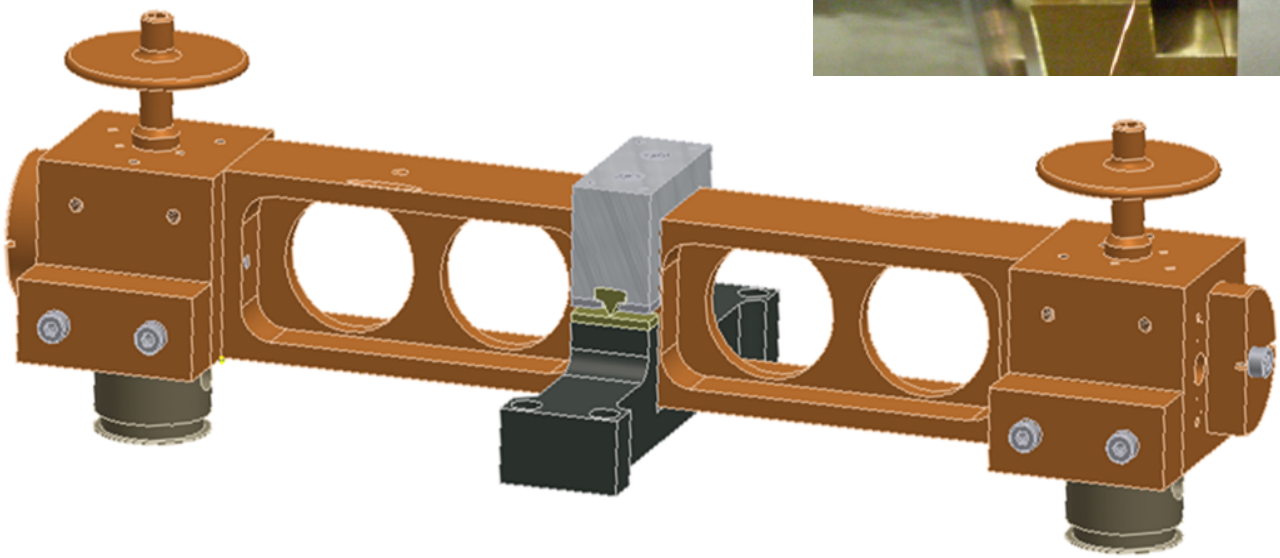
- Pivot and arm
- Differential displacement sensor
- Differential actuation
- Gravitational frequency tuning



Features of LIGO tiltmeter

- Pivot: Knife edge
  - Implemented to prevent SOC noise*.
  - Wedge & Anvil
  - Both precision machined WC





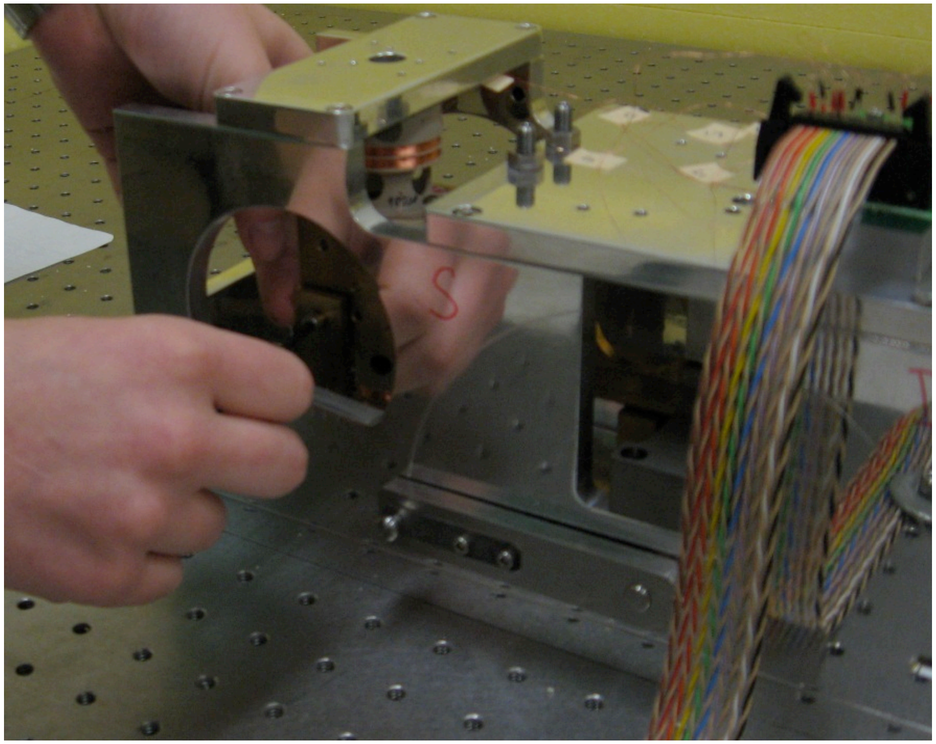
•**R. DeSalvo** (2010) "The Role of Self Organized Criticality in Elasticity of Metallic Springs; Observation of a new Dissipation Regime." LIGO-P1000105

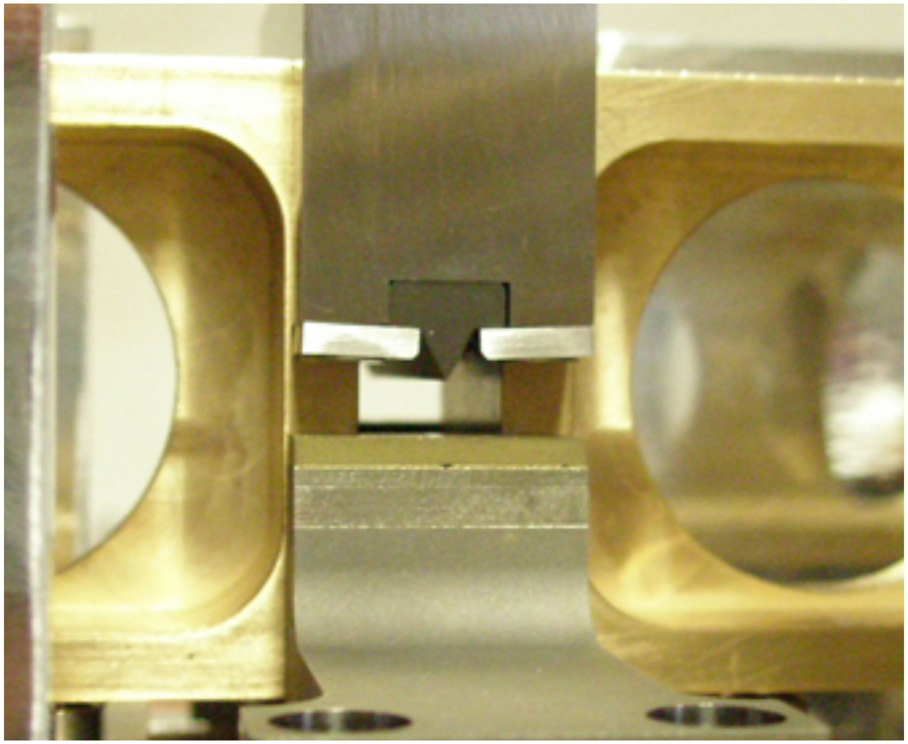
Features of LIGO tiltmeter

- Rigid case: Aluminum

Features of LIGO tiltmeter

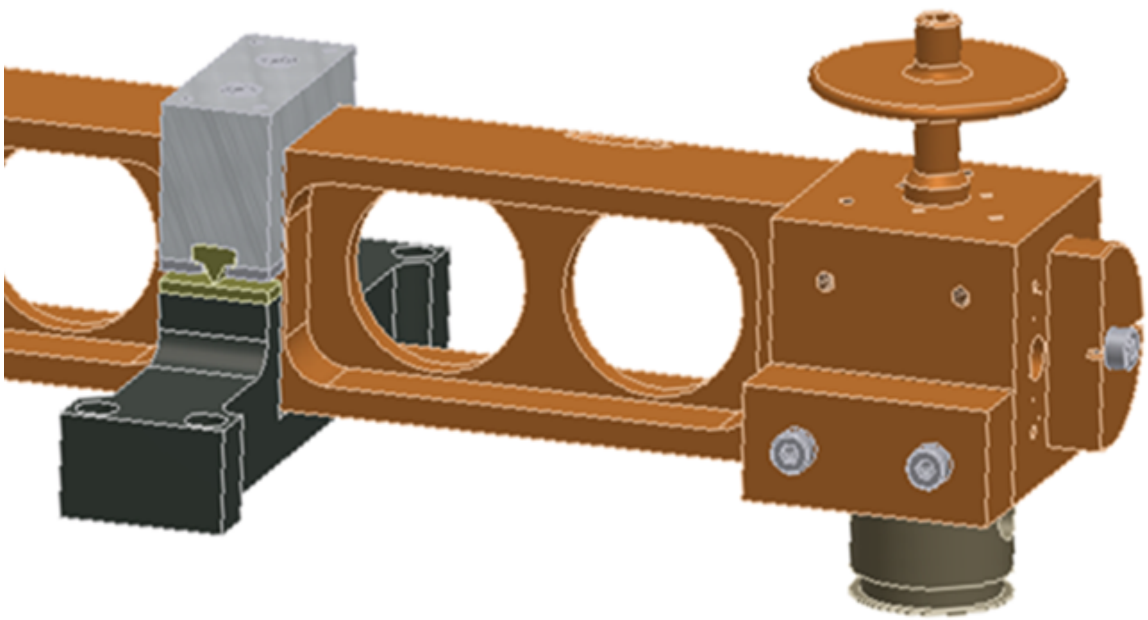
- Compact and portable design for easy implementation.
- Ultra-high vacuum (UHV) compatible including those implemented in LIGO.
- Balance arm can be lifted and locked for transport.

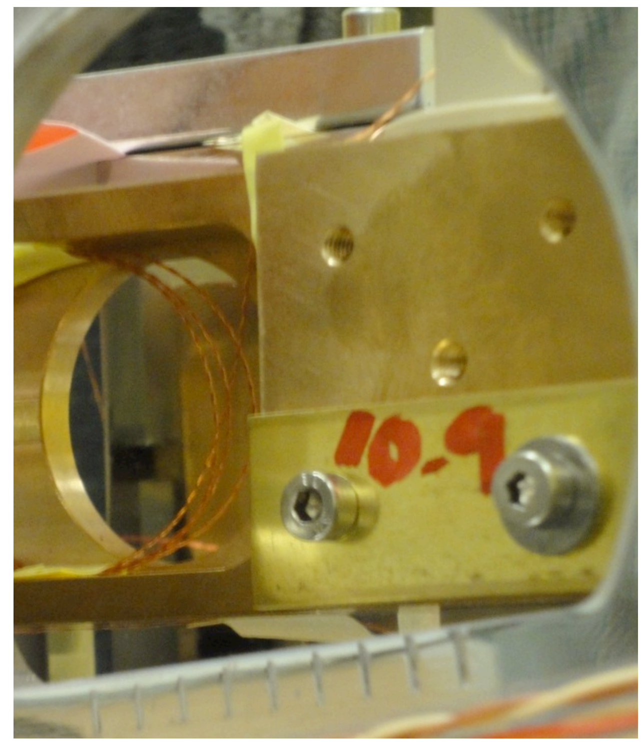




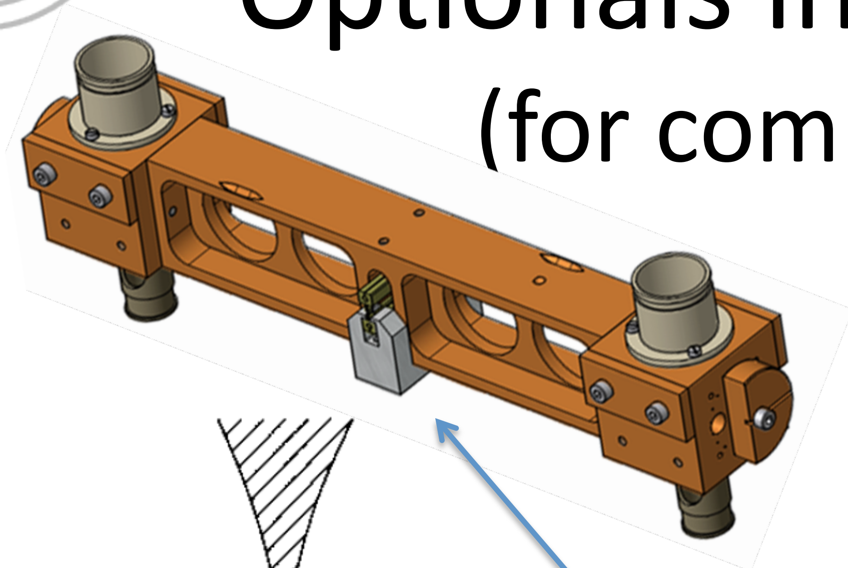
Features of LIGO tiltmeter

- Frequency can be tuned by positioning masses in eight locations on either end and above and below the center of mass.
- Tuning to zero frequency means insensitivity to horizontal acceleration

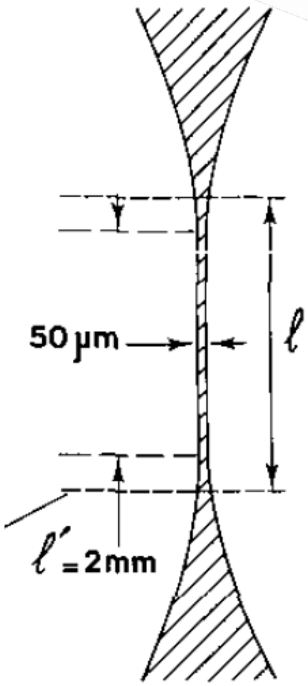


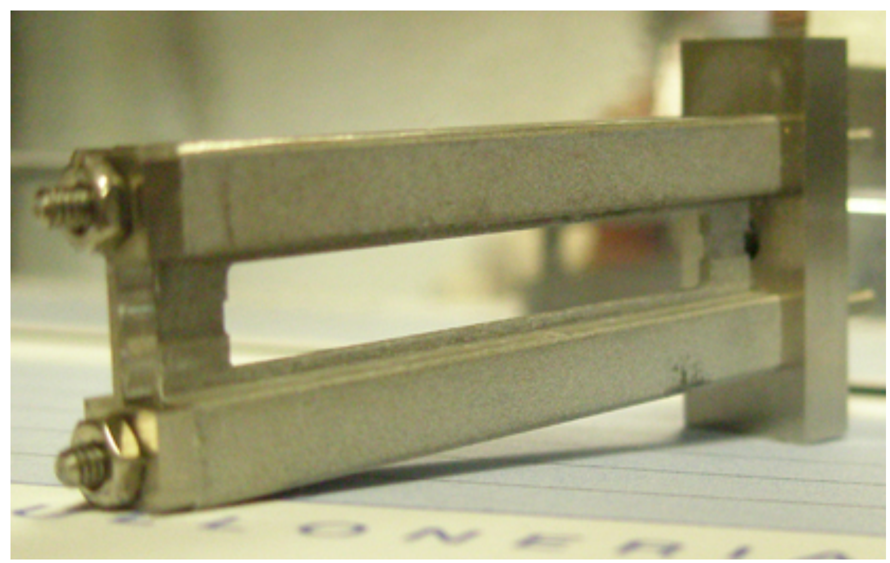


Optionals in LIGO tiltmeter (for comparative studies)



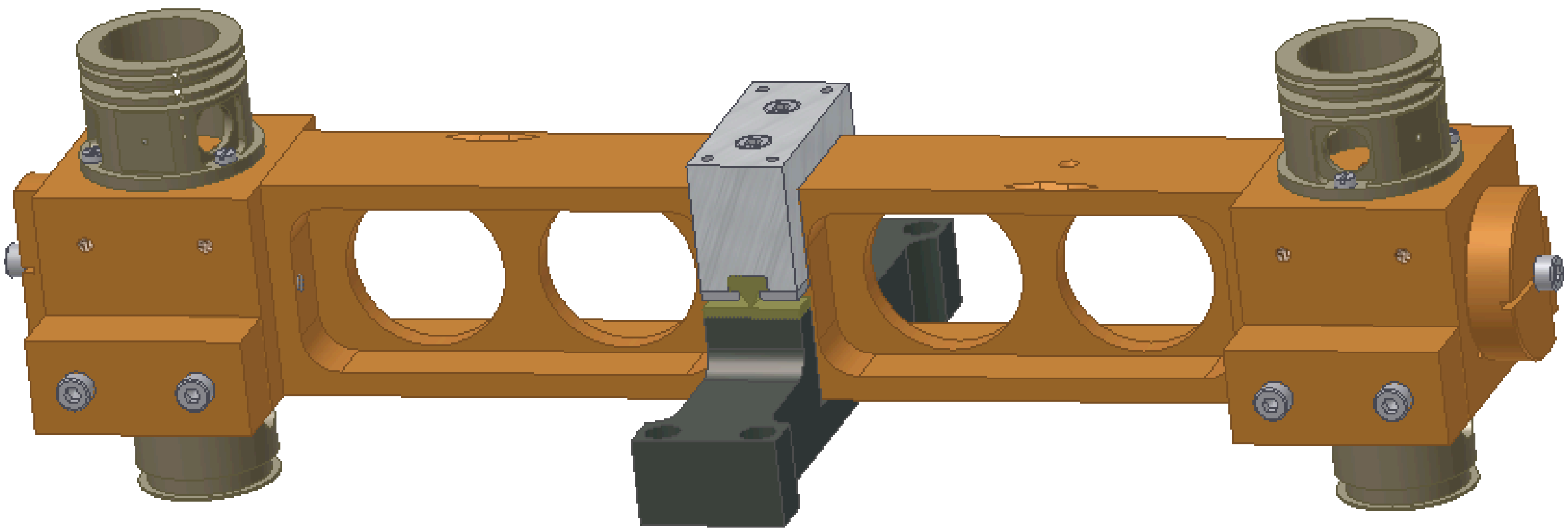
- Pivot: Flexure hinge
- Allow study of SOC





Quinn, T. J. (1992). "The beam balance as an instrument for very precise weighing." Measurement Science and Technology **3**(2): 141.

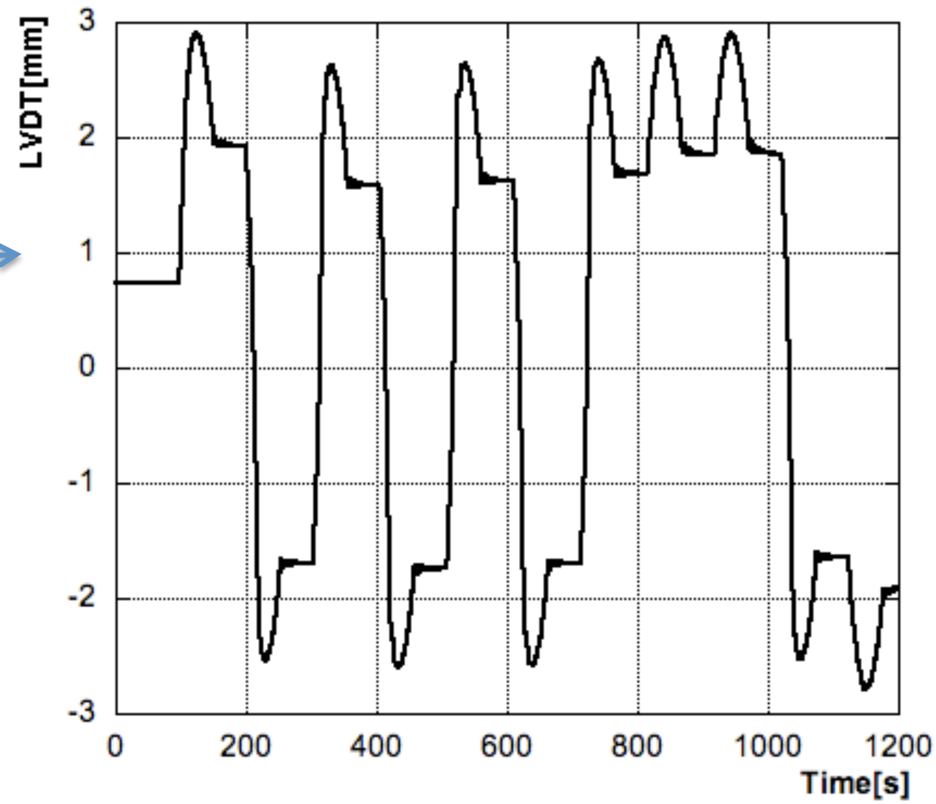
Experimental Results



Results

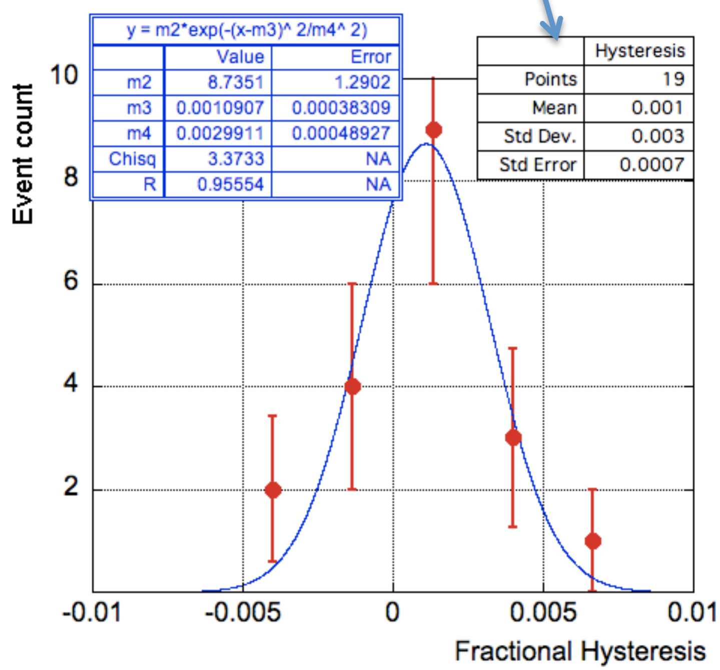
- Knife edge was implemented to avoid hysteresis

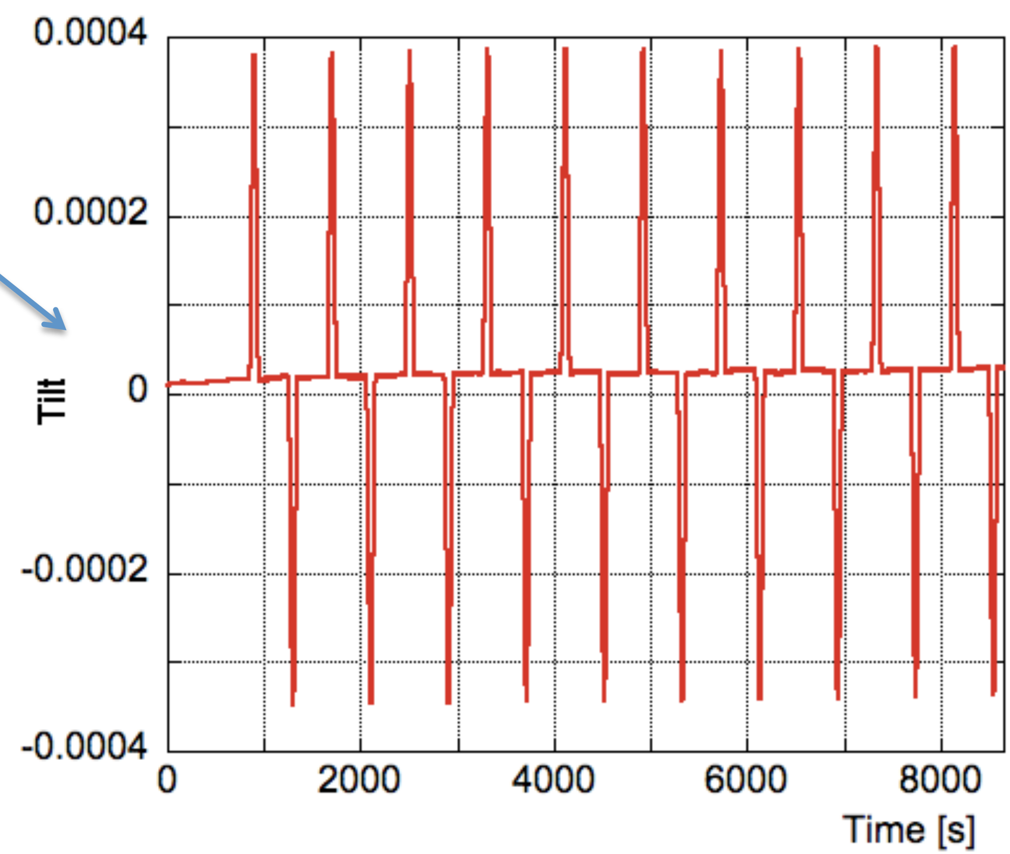
- Example:
  Hysteresis in a
  Maraging filter



Results

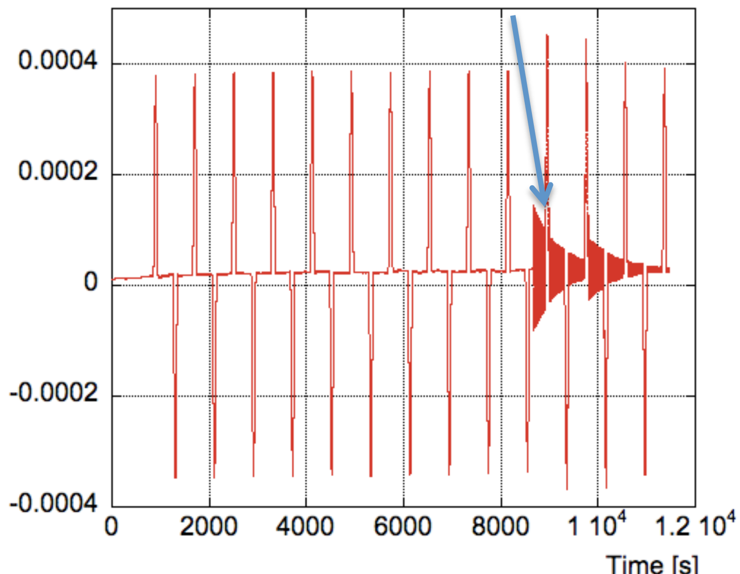
- Knife edge implemented to avoid hysteresis
- ~ No Hysteresis in tiltmeter





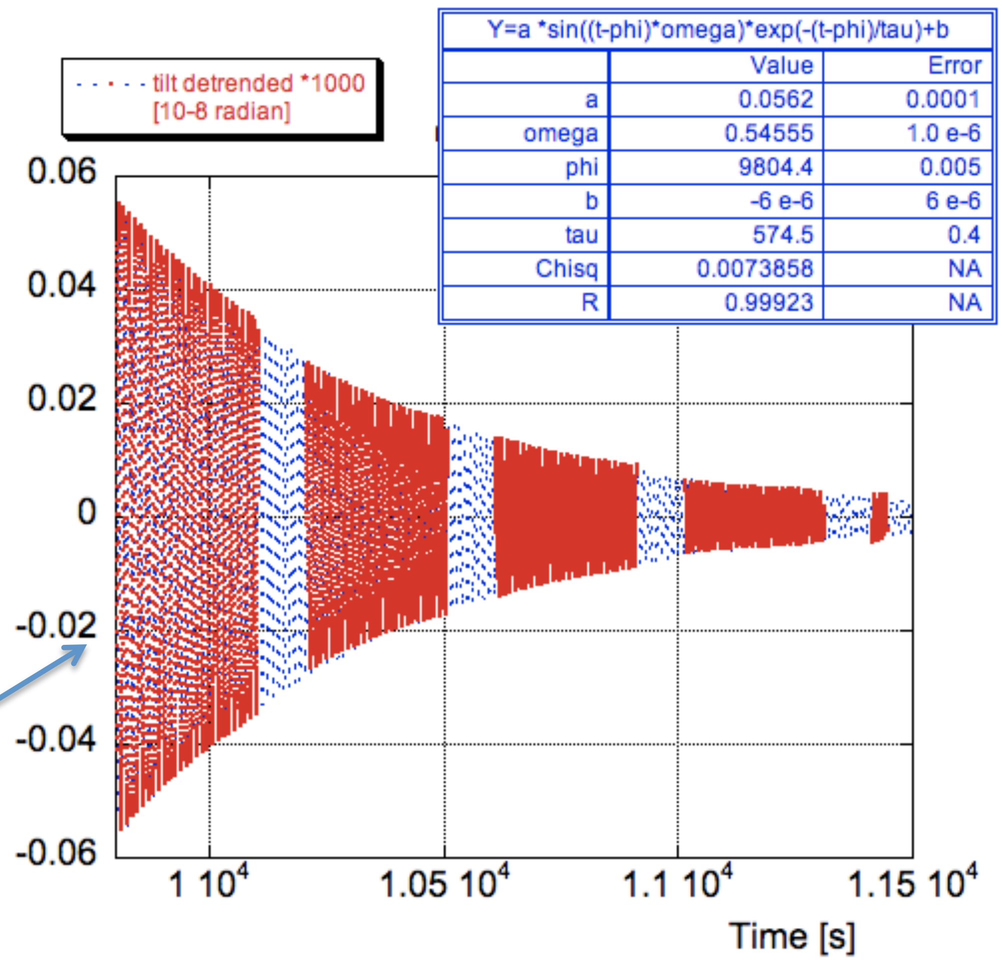
Quality checks

- Seismic event



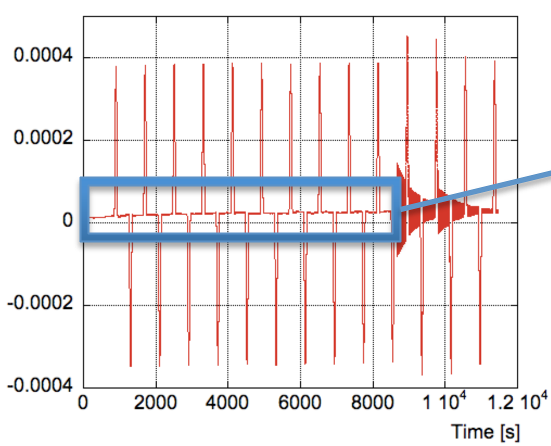
- Very good fit
- Coherent decay

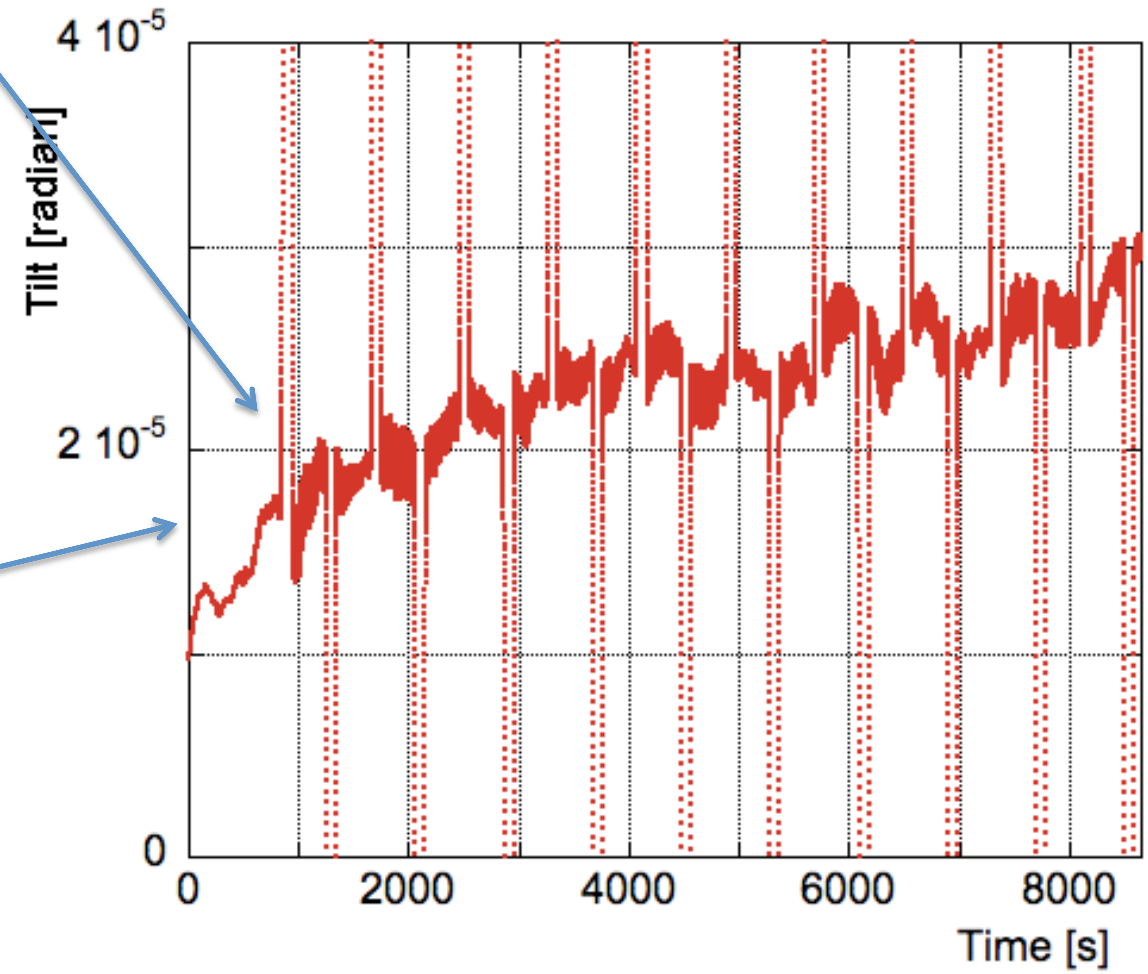
Through excitations



Quality check

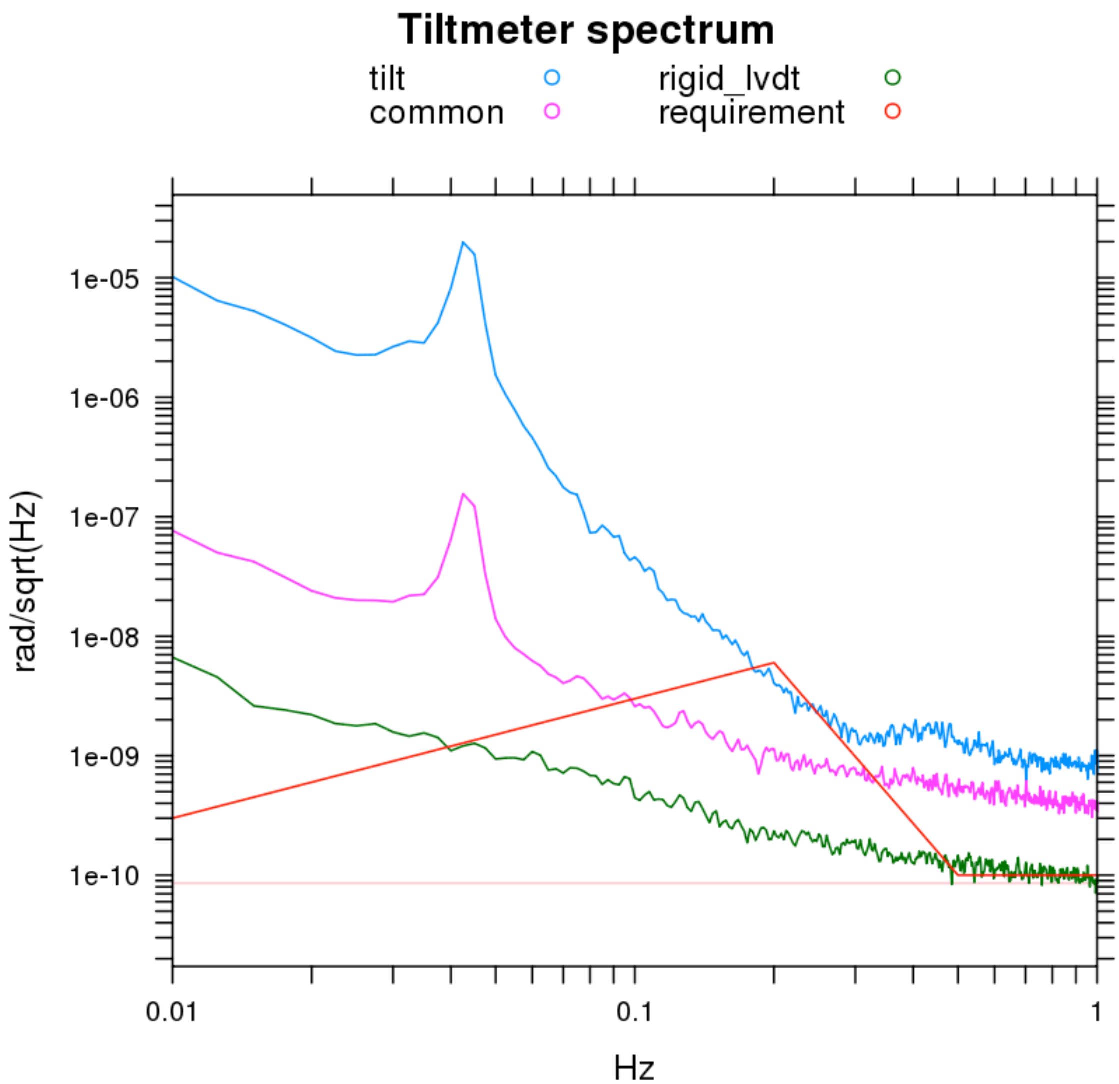
- Real table tilt





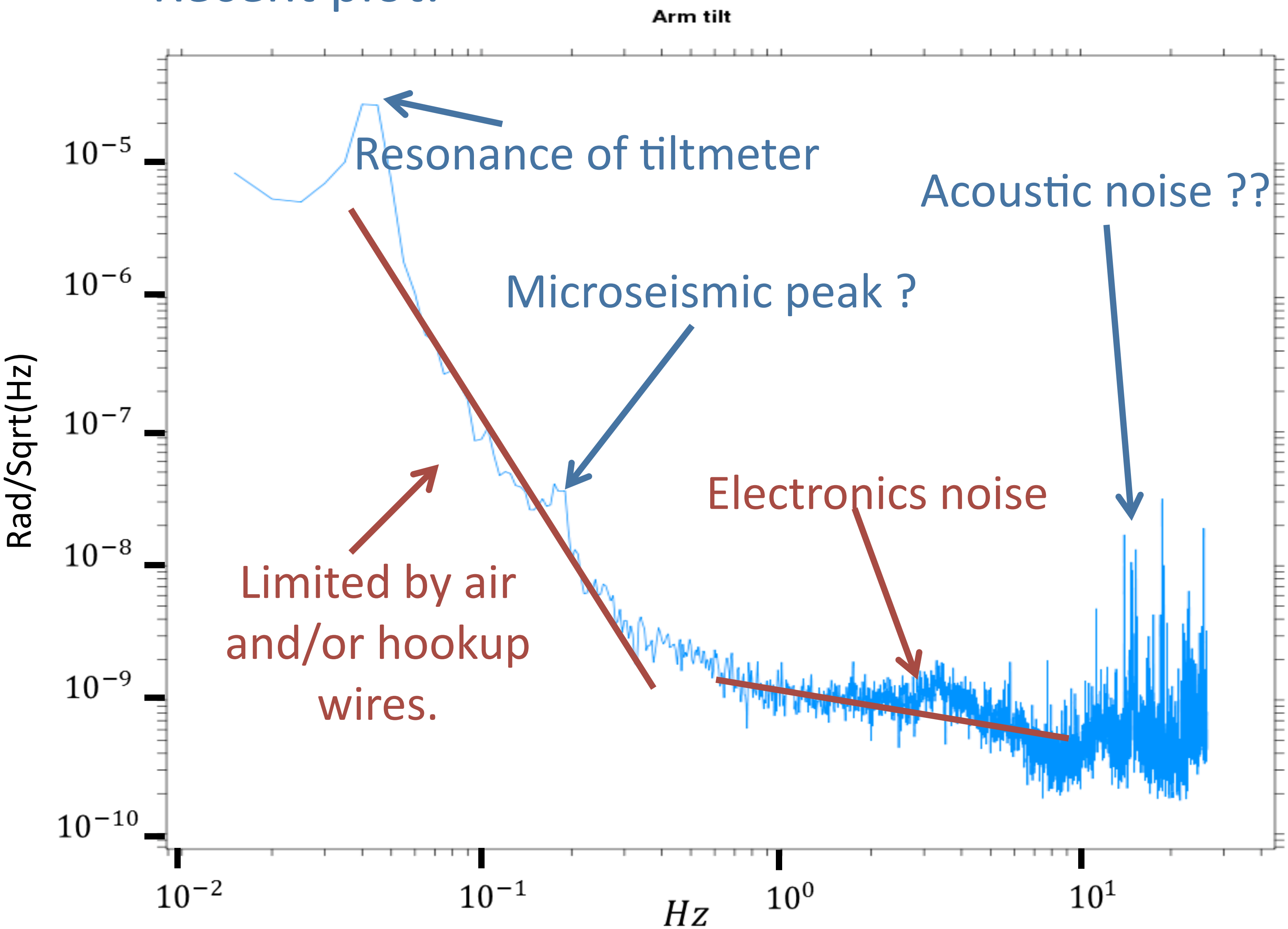
Preliminary performance

- Rough hinge
- In air
- On table with rubber feet
- Copper wires

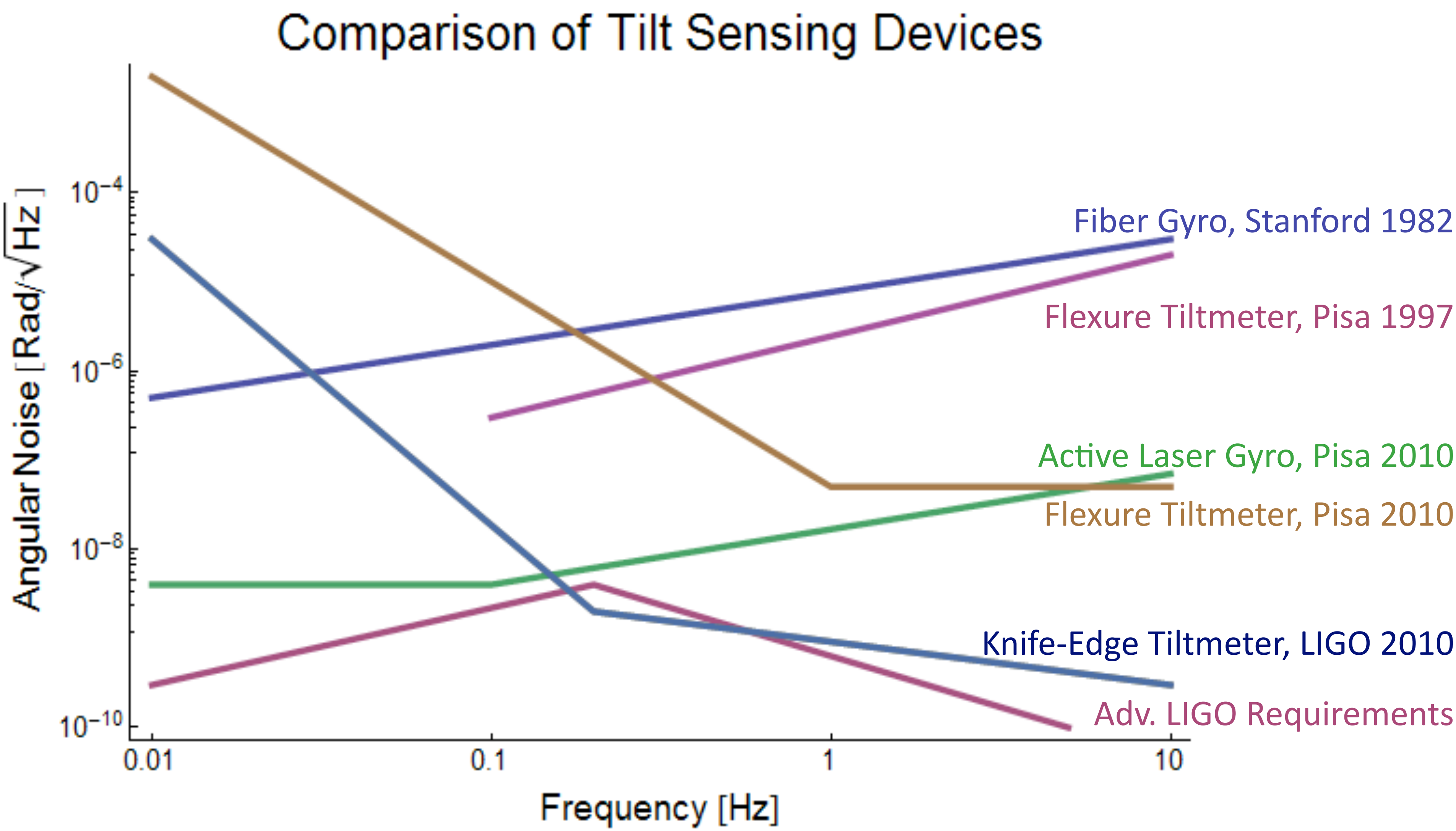


4. Current tilt sensitivity

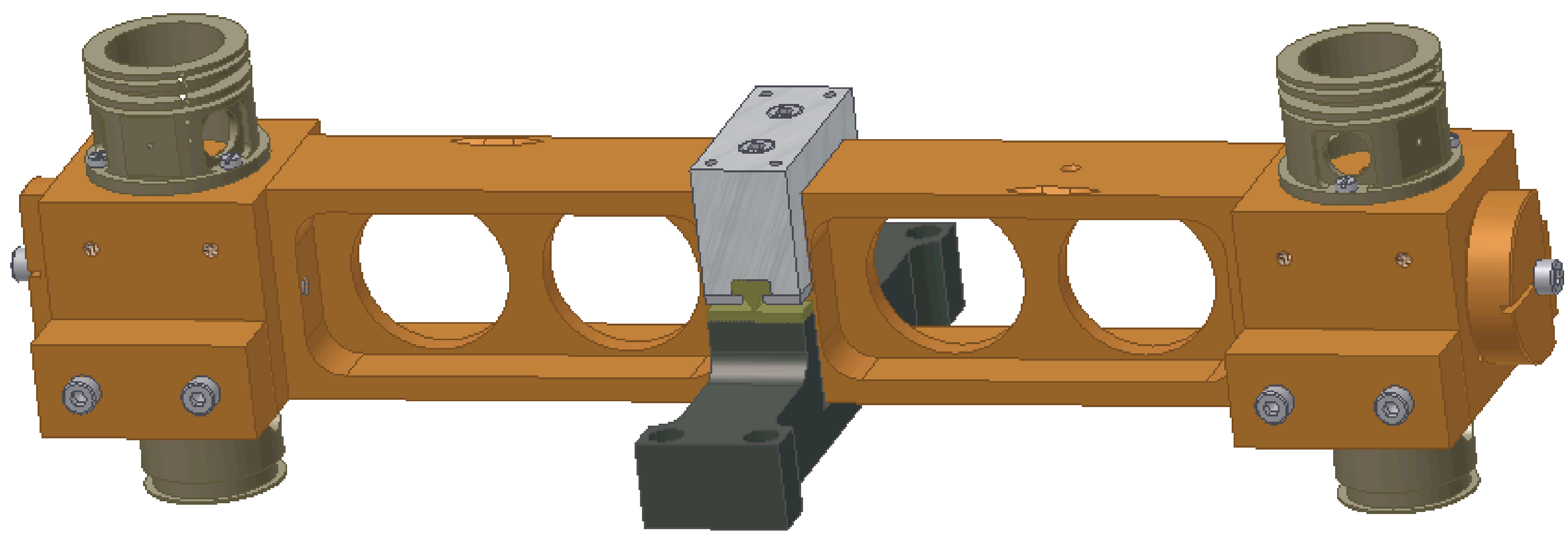
- Recent plot:



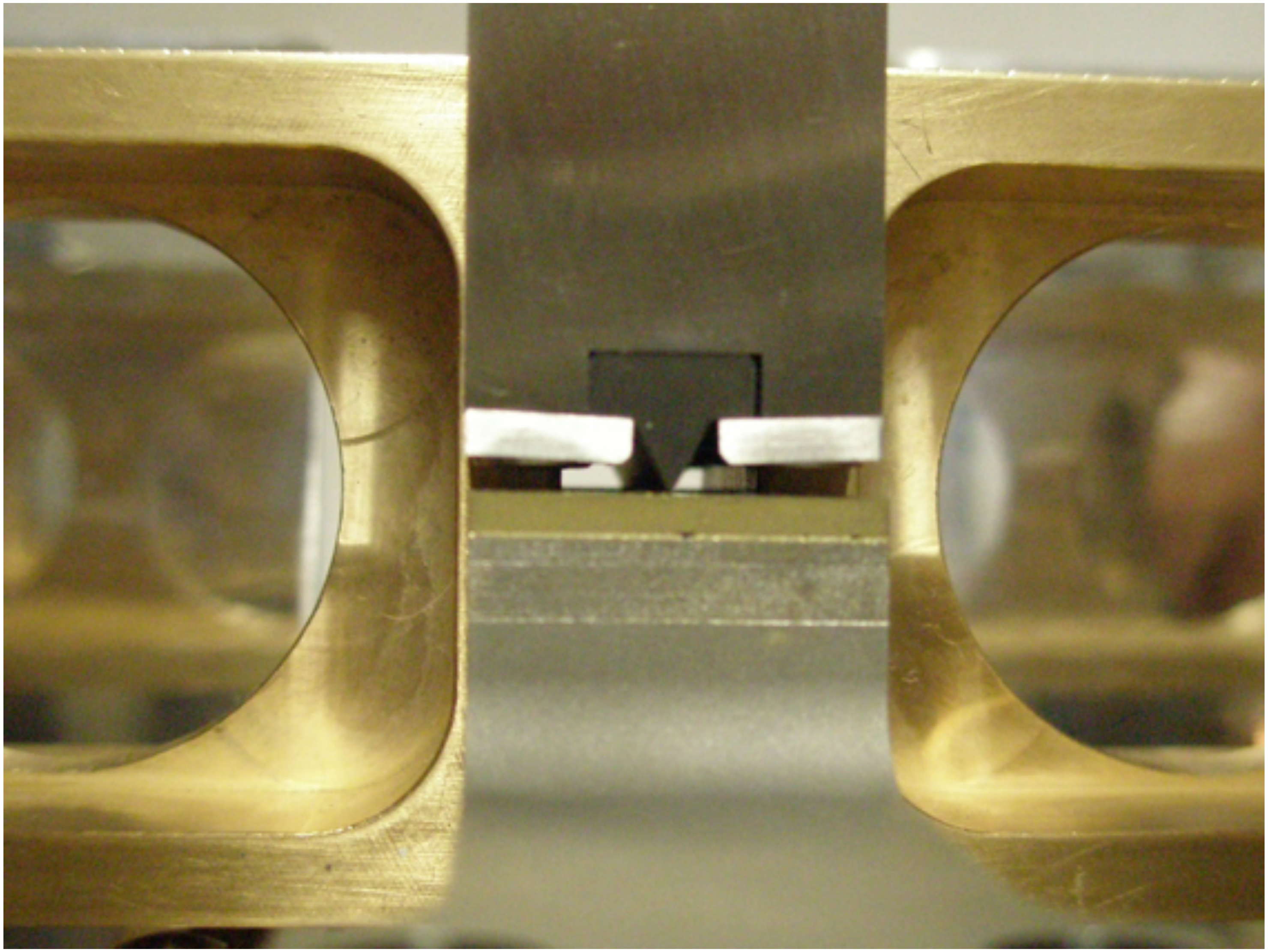
Other rotation sensing devices



Instrument development



Knife-edge development



Knife-edge manufacturing

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

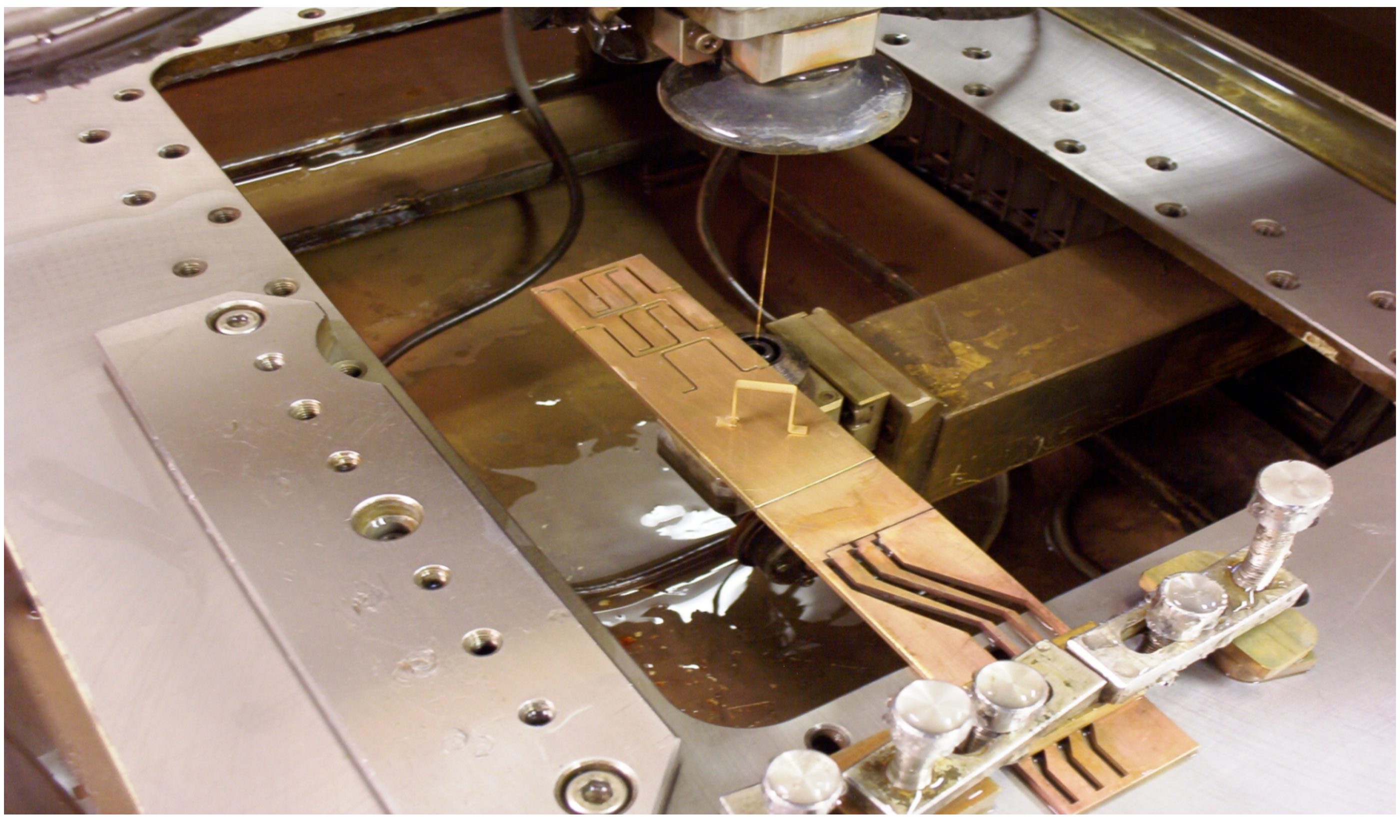
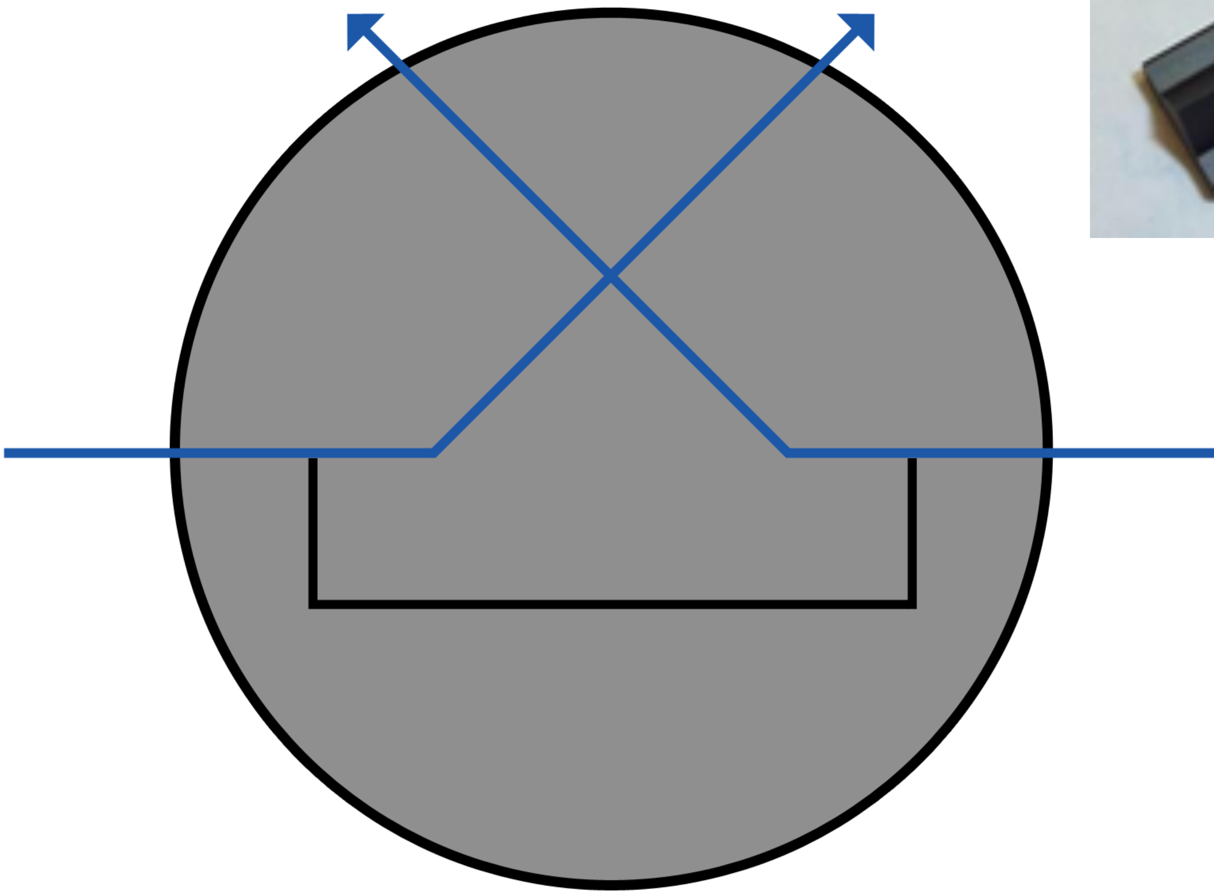
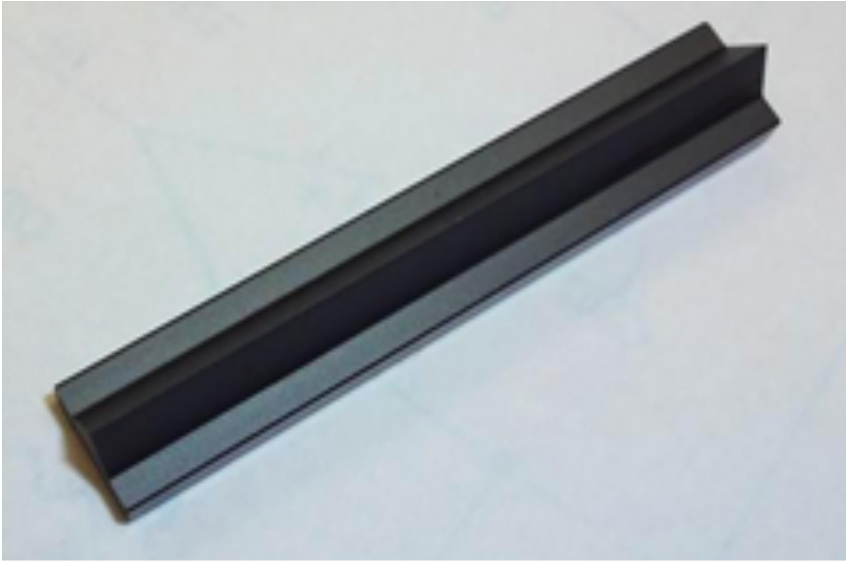


Image source: http://www.cumberlandmodelengineering.com/

Knife-edge manufacturing

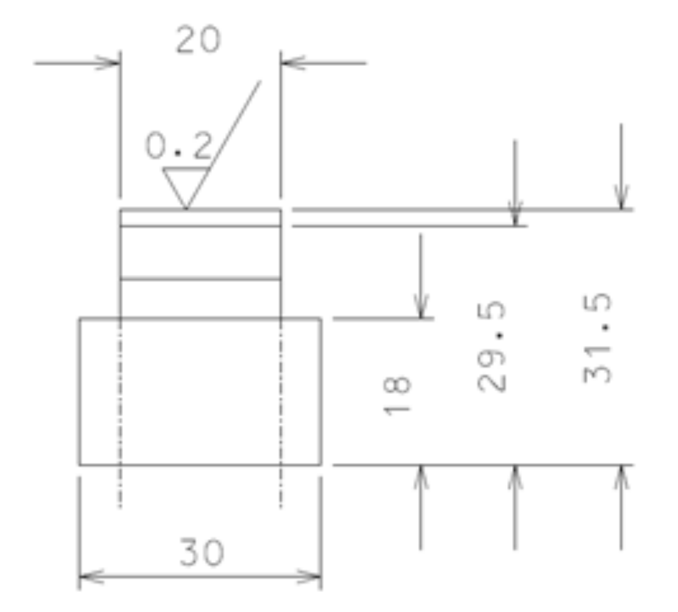
- Cutting profile first implemented.

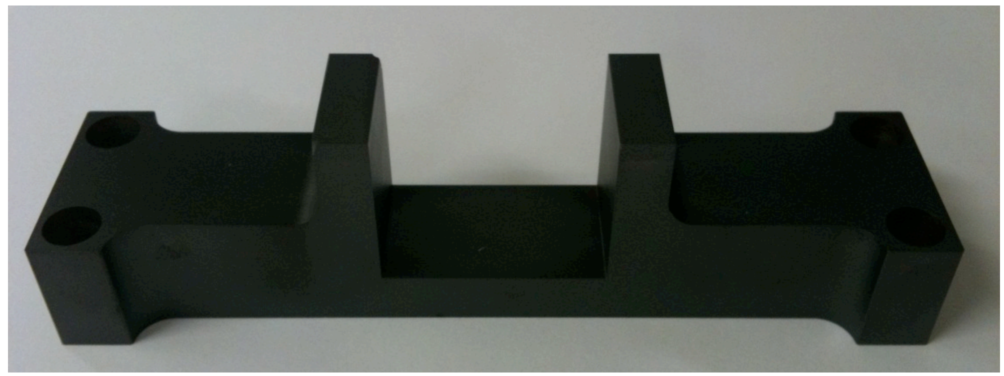


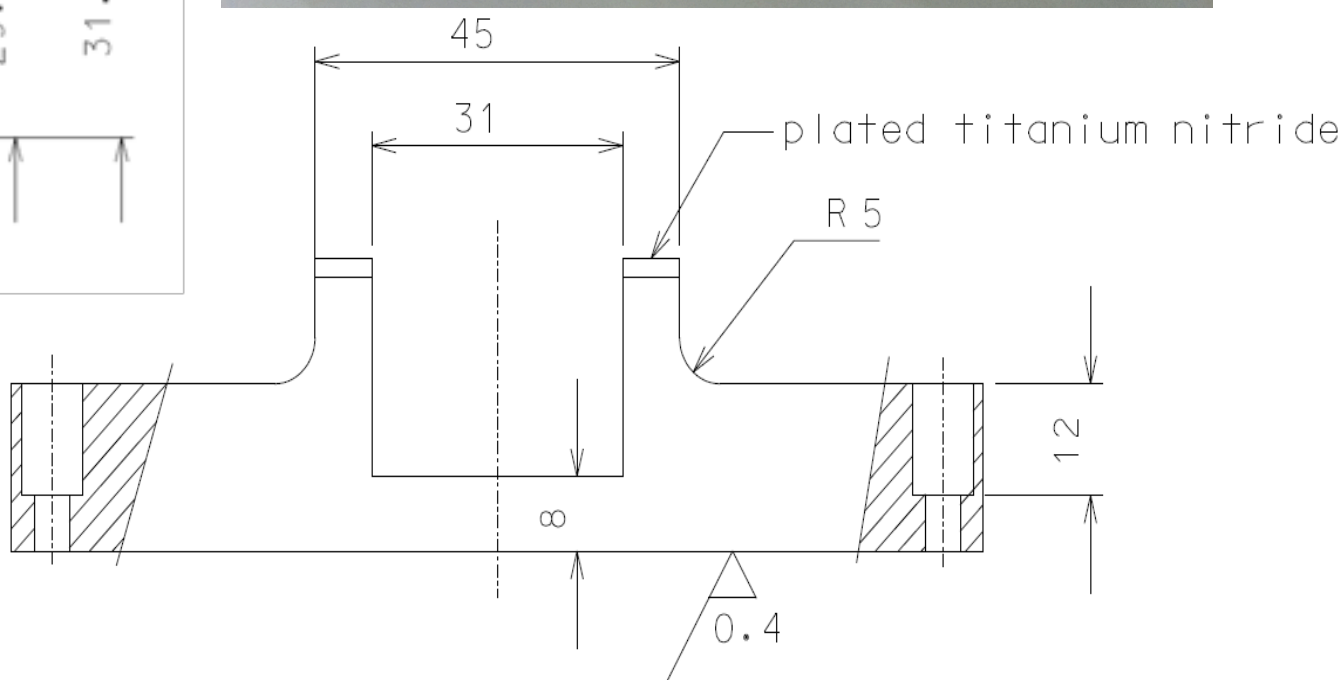


Anvil development

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

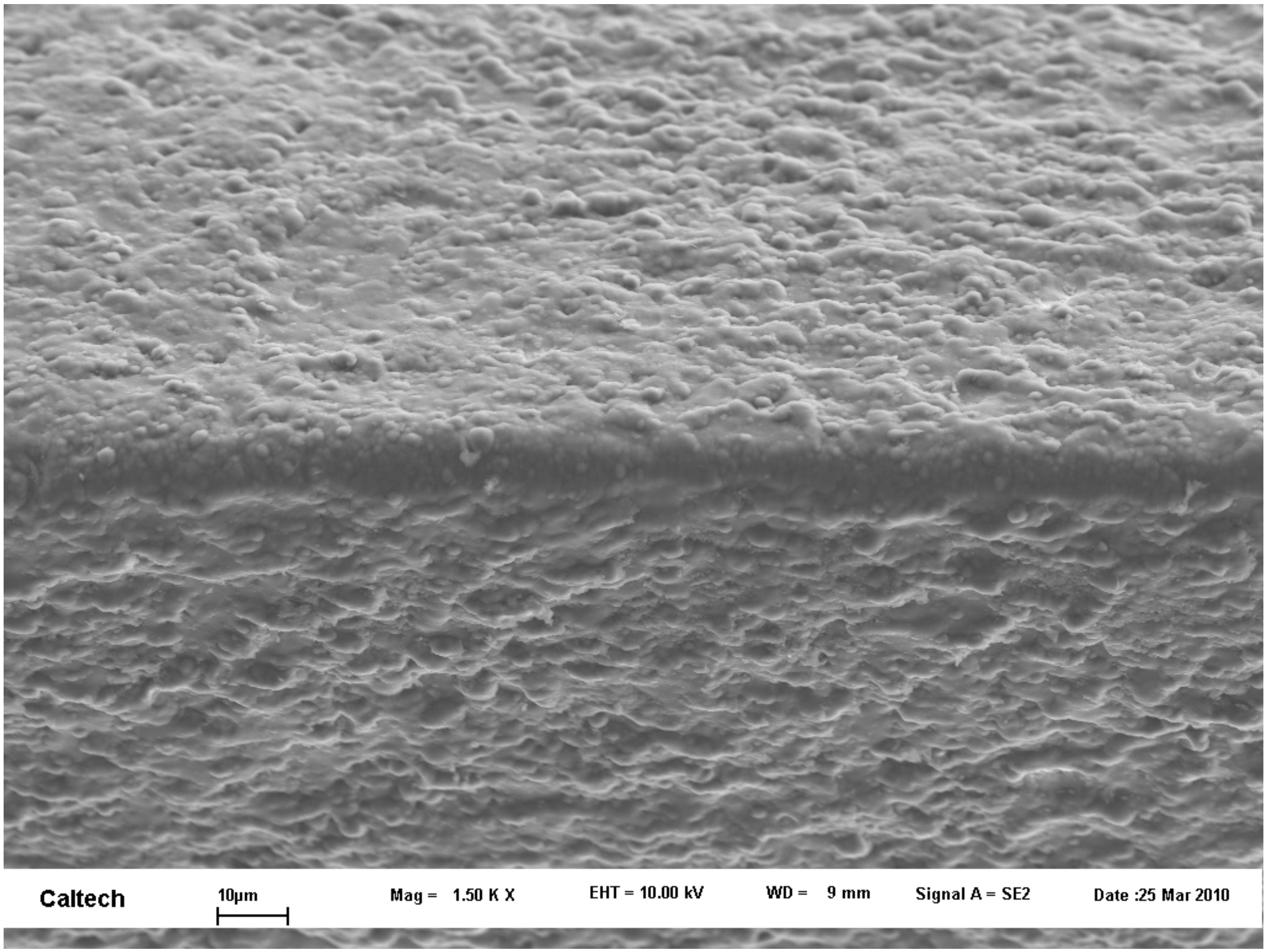






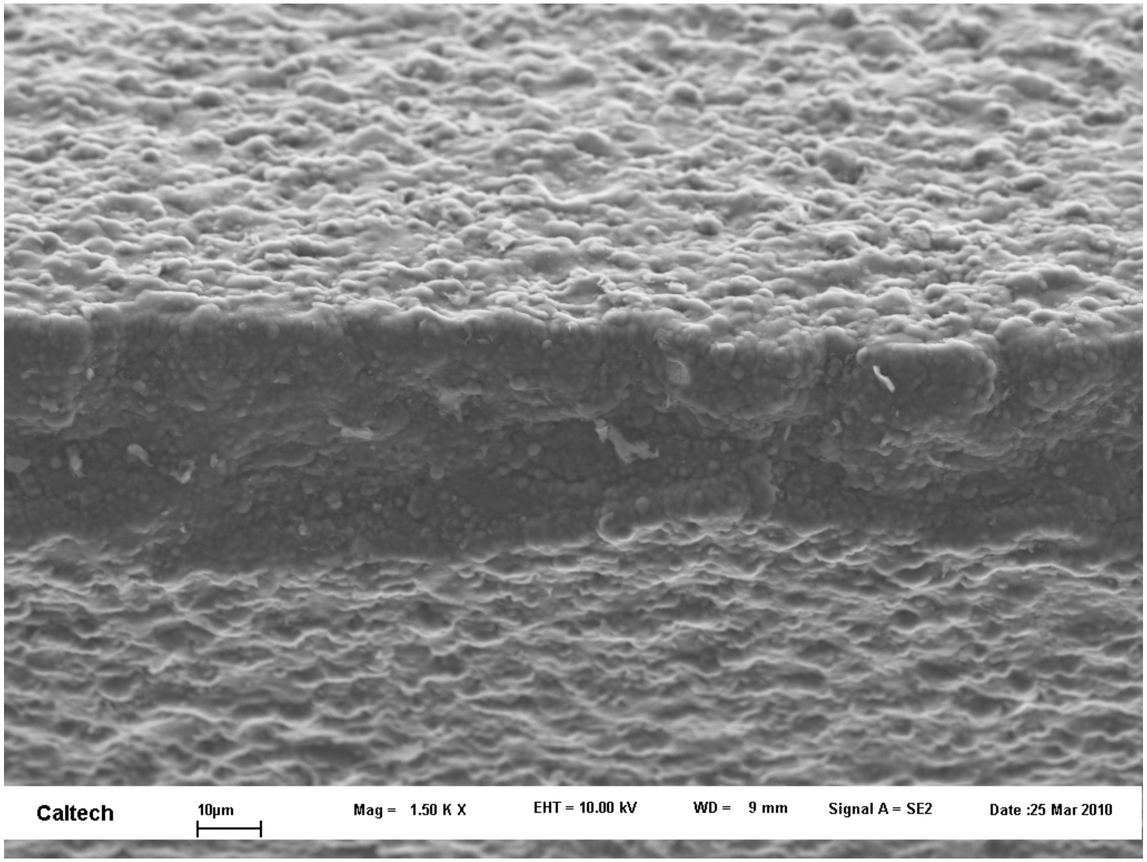
Knife-edge development

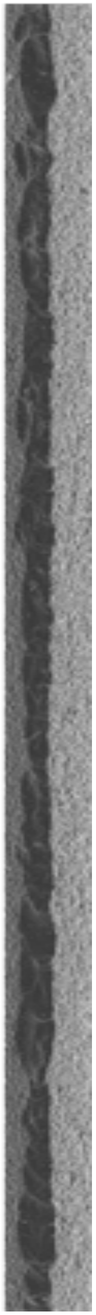
- Clean even sharp edge should give low noise.
- Analysis was performed using SEM.



Knife-edge development

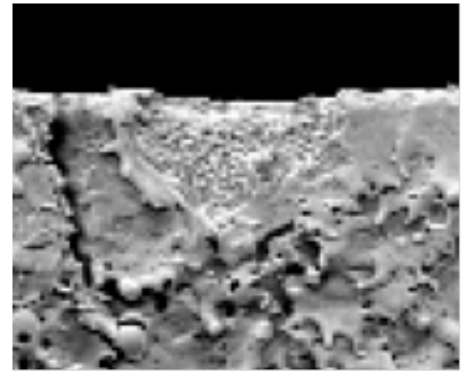
- Major cracks were found on some edges!
- On the worst end only 4.8% of the leading edge was of suitable sharpness.
- Mean crack width: 34 µm

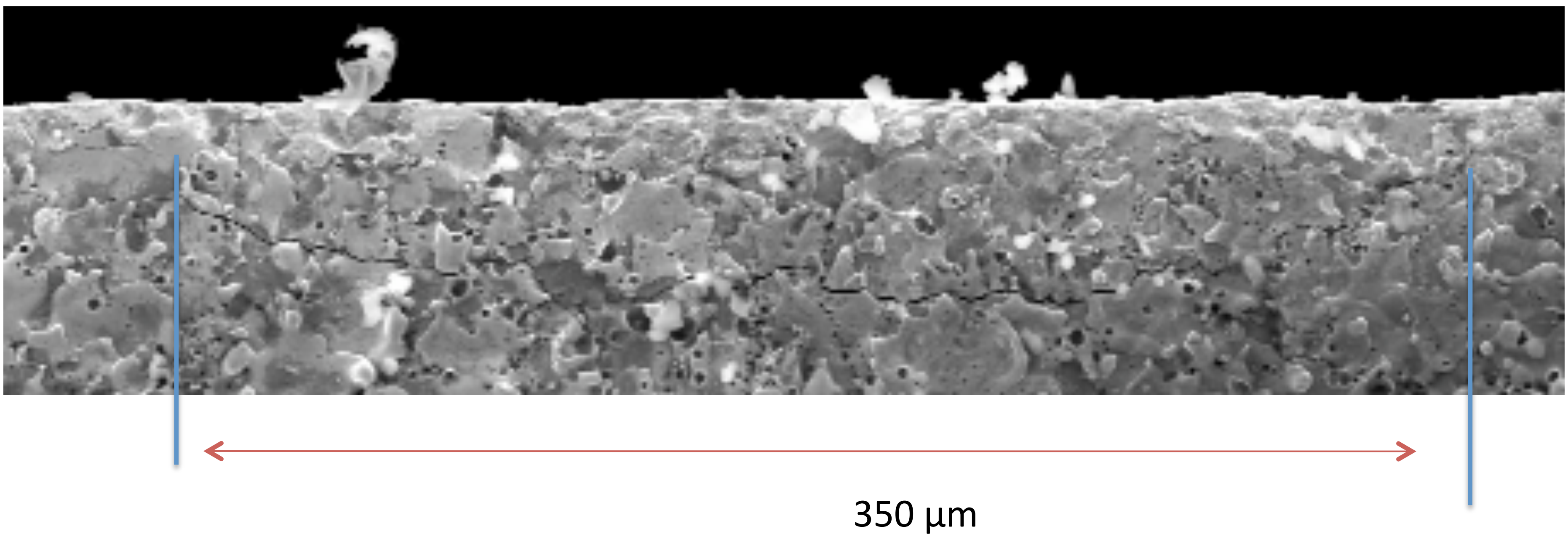




Knife-edge development

- Underlying cracks were also found!

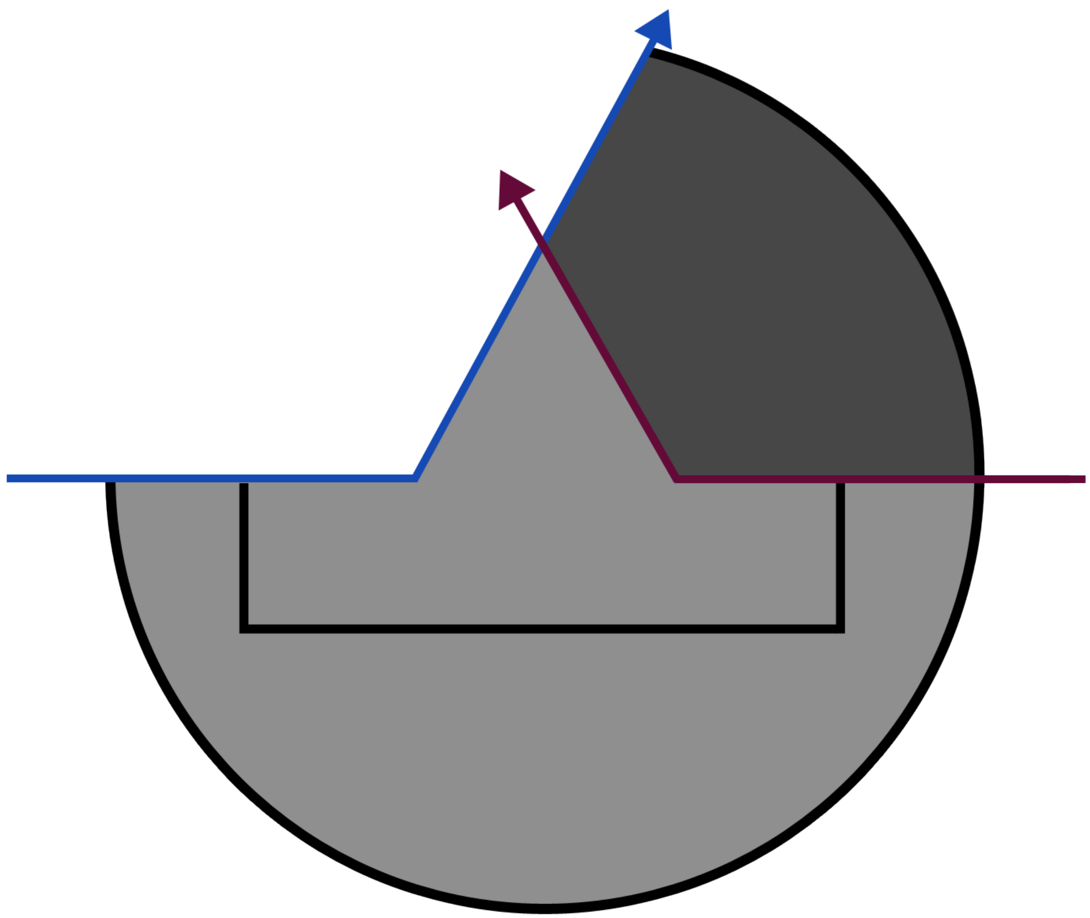




- What happened?

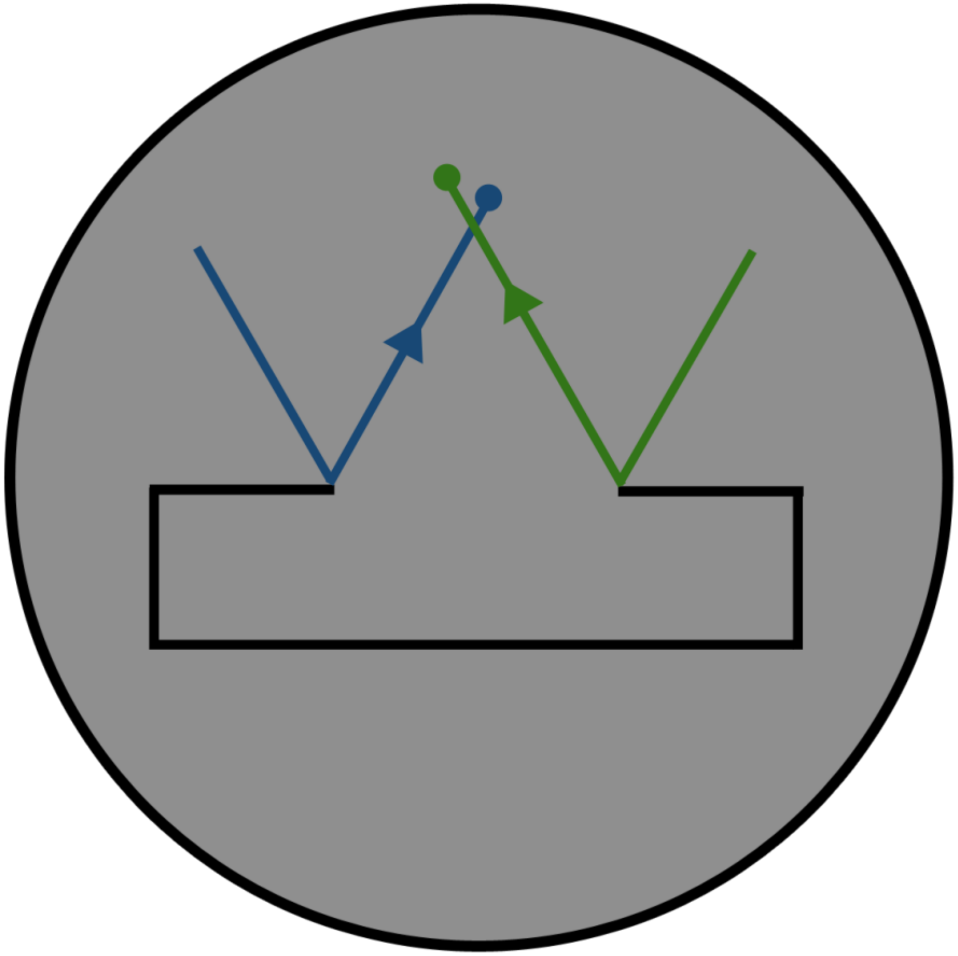
Knife-edge development

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



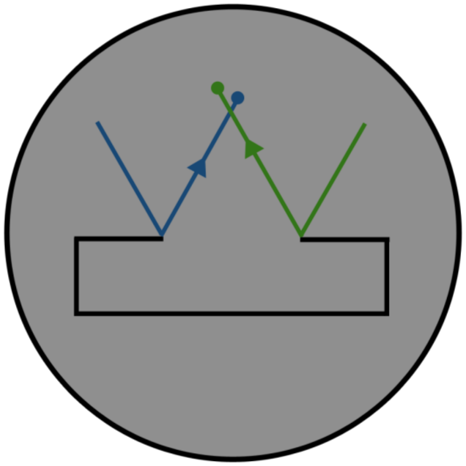
Knife-edge solution

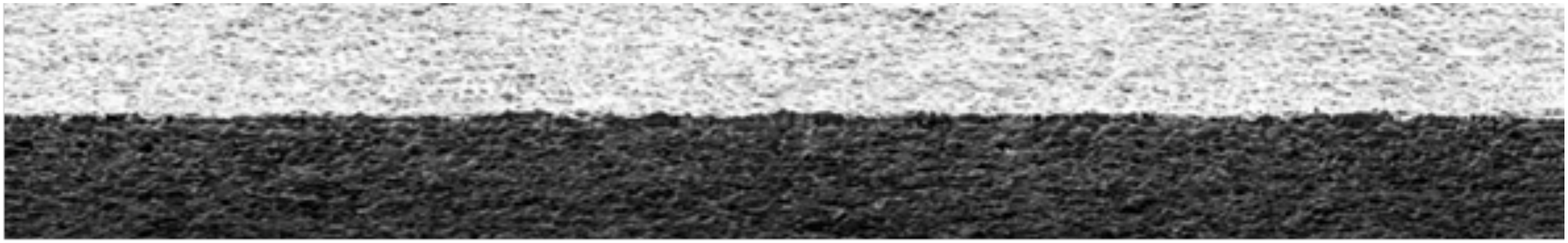
- Cutting scheme that avoids the large force concentration on the tip of the knife edge.



Knife-edge development

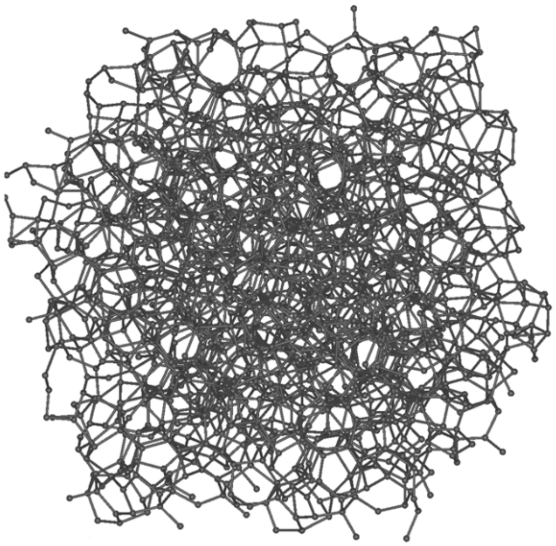
- Wedge cut with new scheme was found to not contain the crack defect .



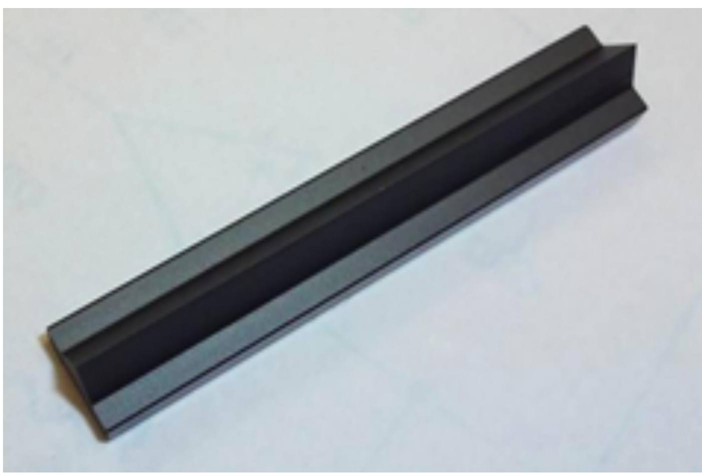


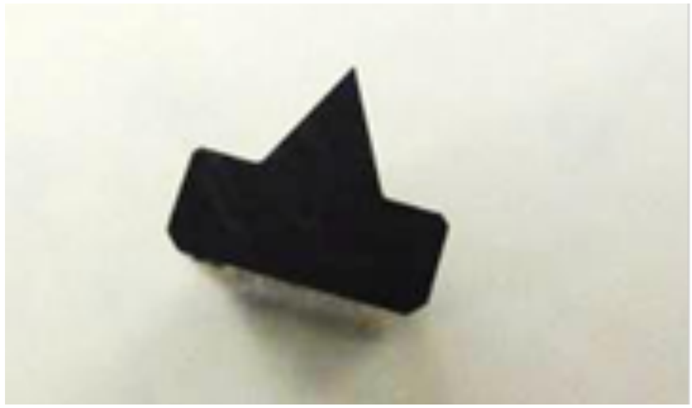
Knife-edge further developments

- Currently implemented 45mm WC blade is uncoated "naked
- Future coating options:
  - PVD Diamond Like Carbon (DLC)
  - CVD DLC
  - Tungsten carbide (Glass)
  - Titanium Nitride
  - Diamond



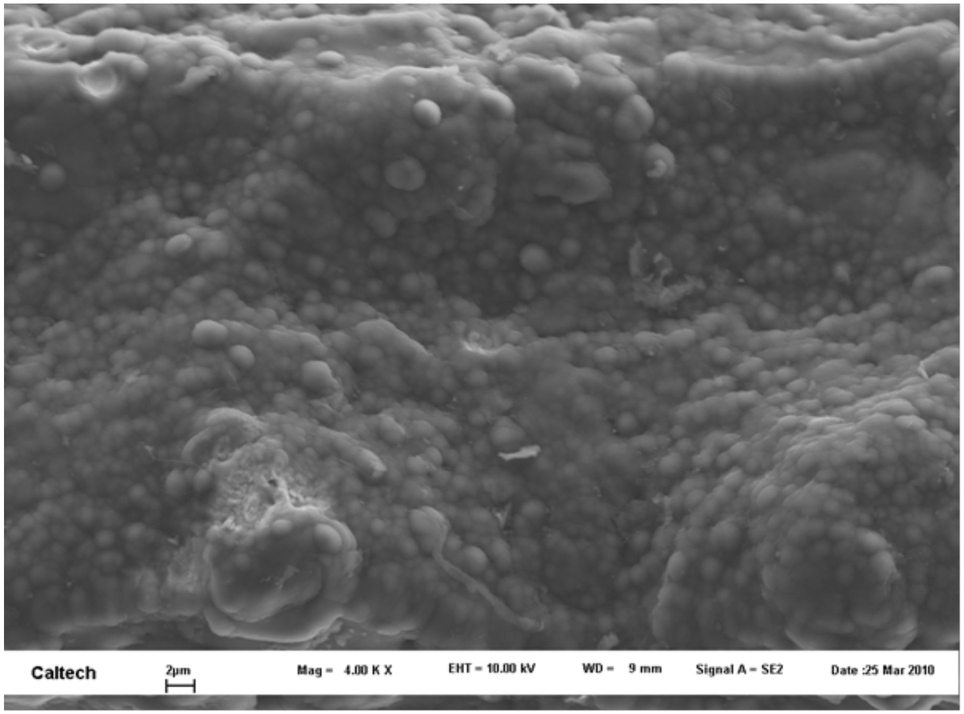
Source: Wikipedia- Amorphous carbon

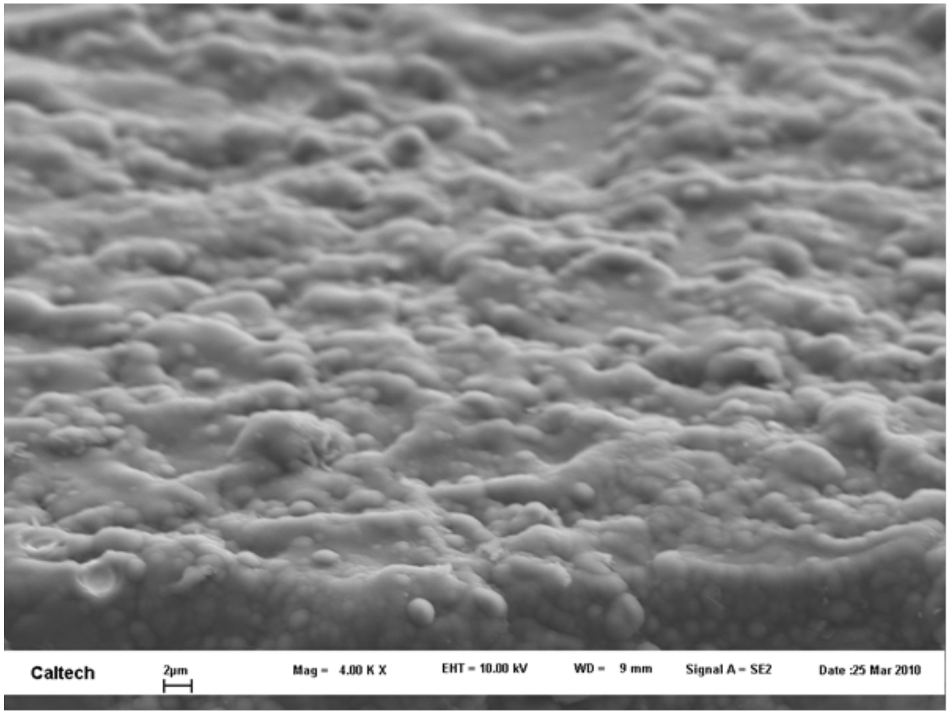




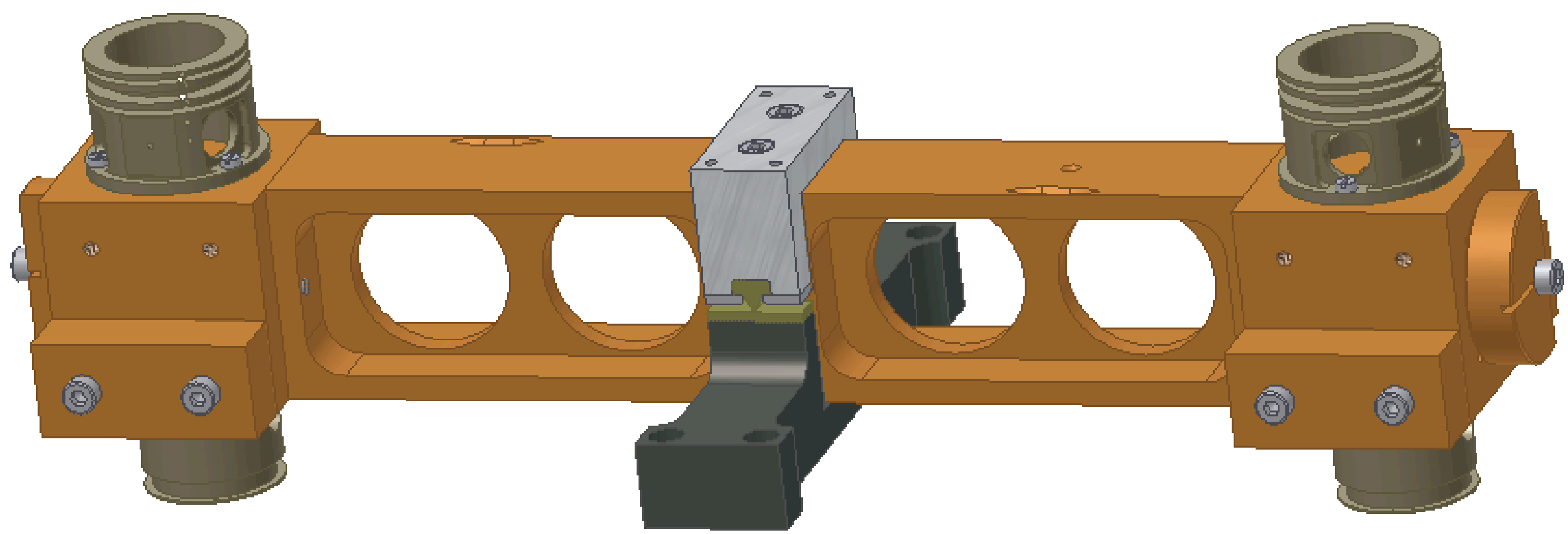
Knife-edge material details

- 0.8 µm diameter WC powder balls.
- ~8% cobalt binder





Position redout

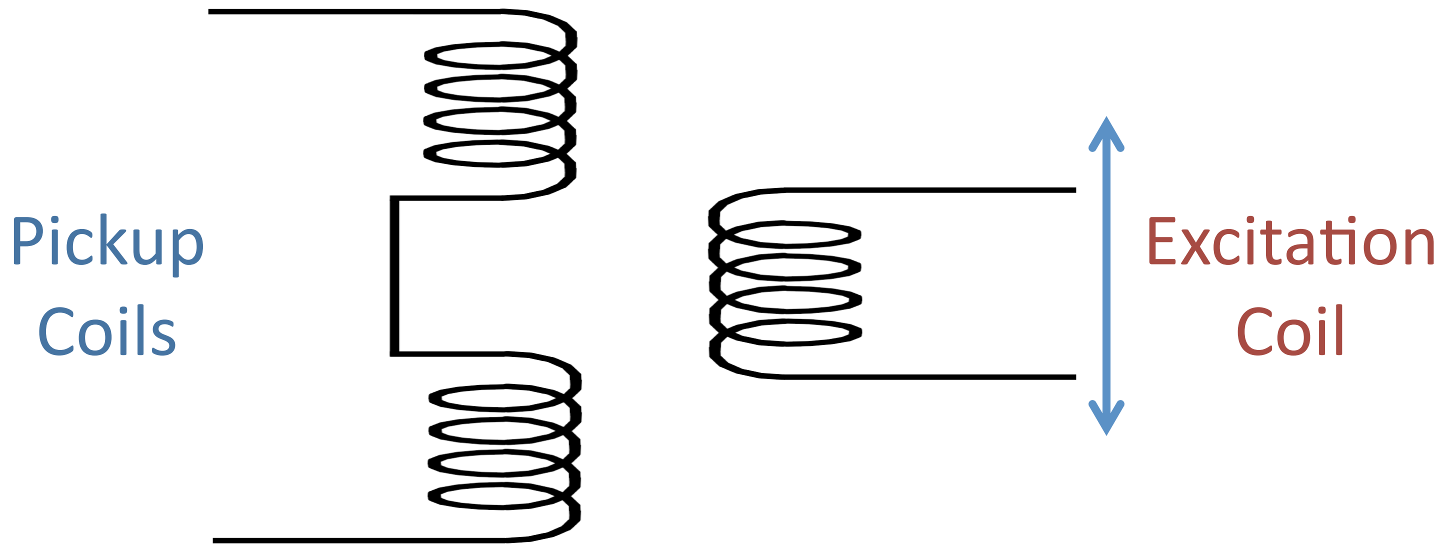


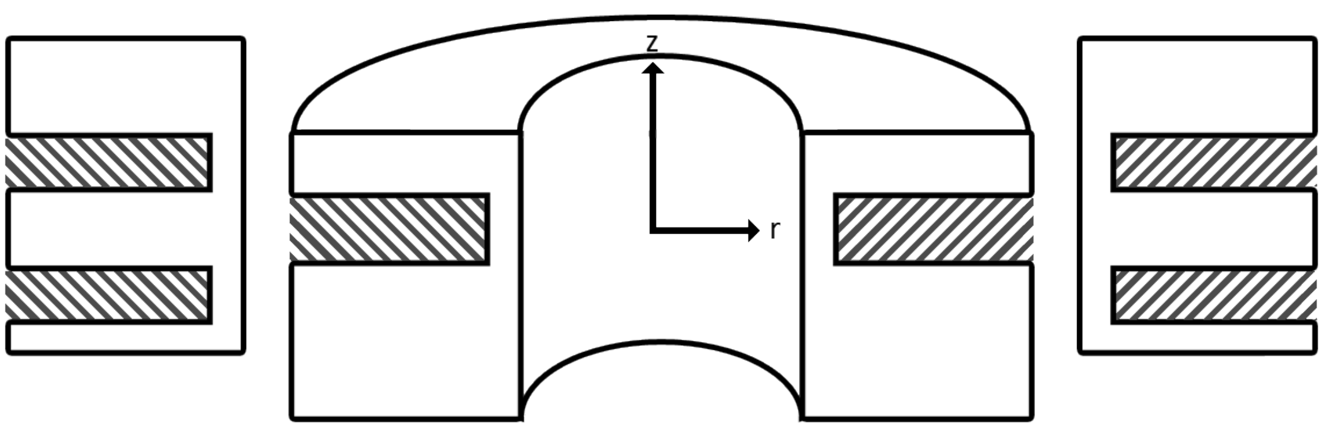
Current design: LVDT measurement

- Easiest UHV implementation
- Moderate Eddy current forces
- Three coil design
- Sufficient sensitivity

Position measurement

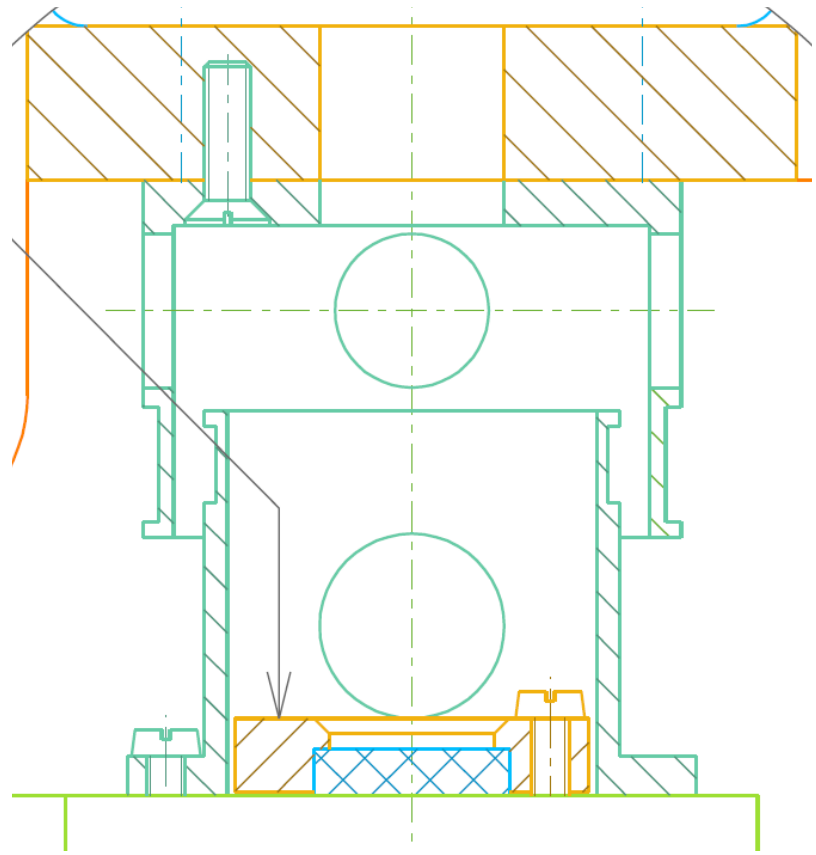
- Differential measurement.
- Linear variable differential transformer (LVDT)





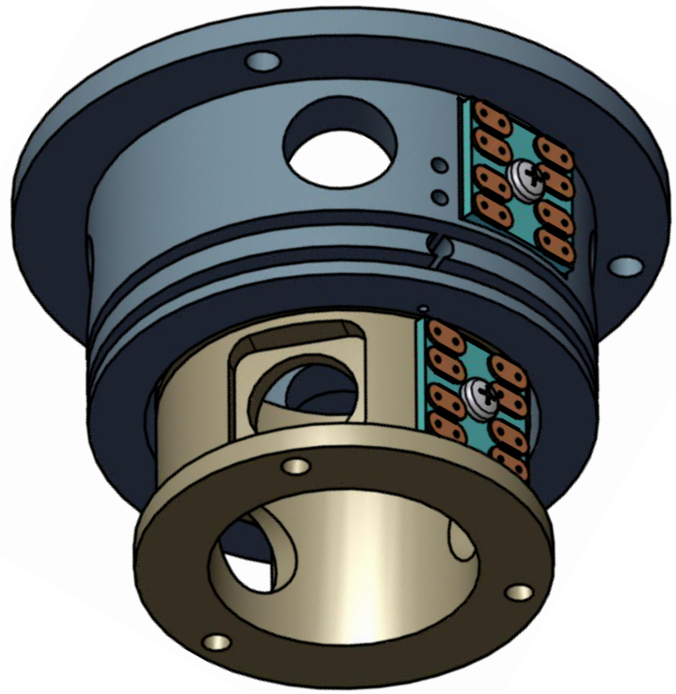
LVDT development

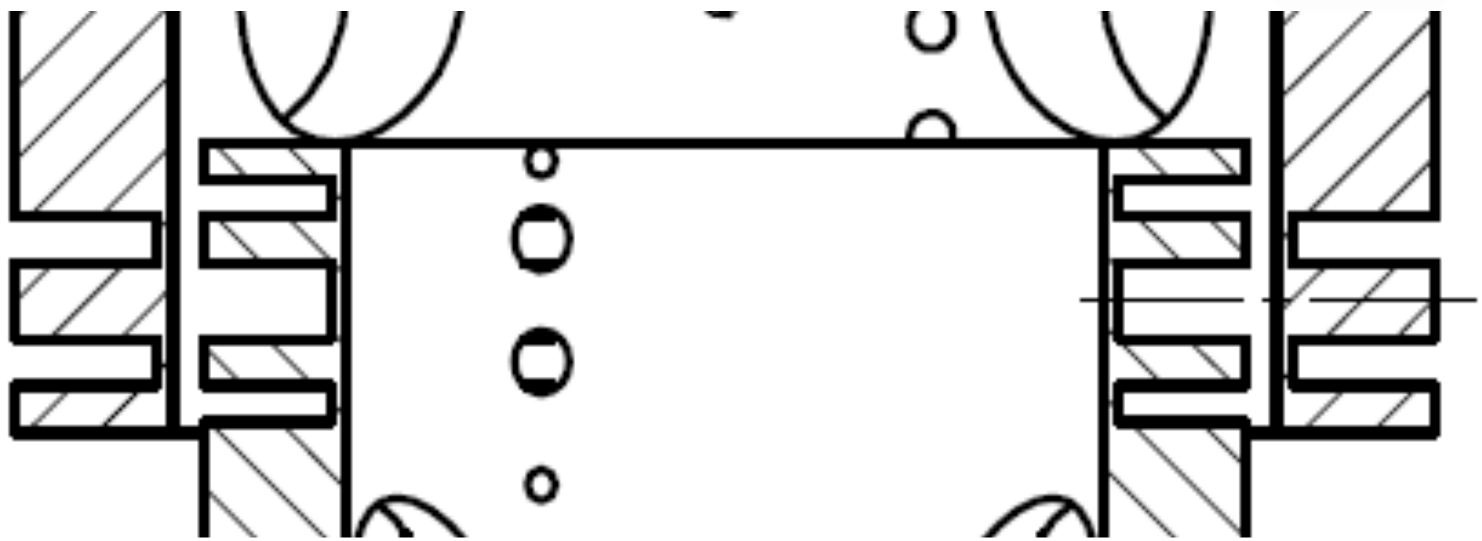
- Excess forces occurring, correlated with emitter strength
- Coupling between the LVDT and aluminum case was suspected: Eddy currents
- Peek bridges were introduced to reduce non-linear forces.
- Noticeable reduction in excess forces



LVDT development

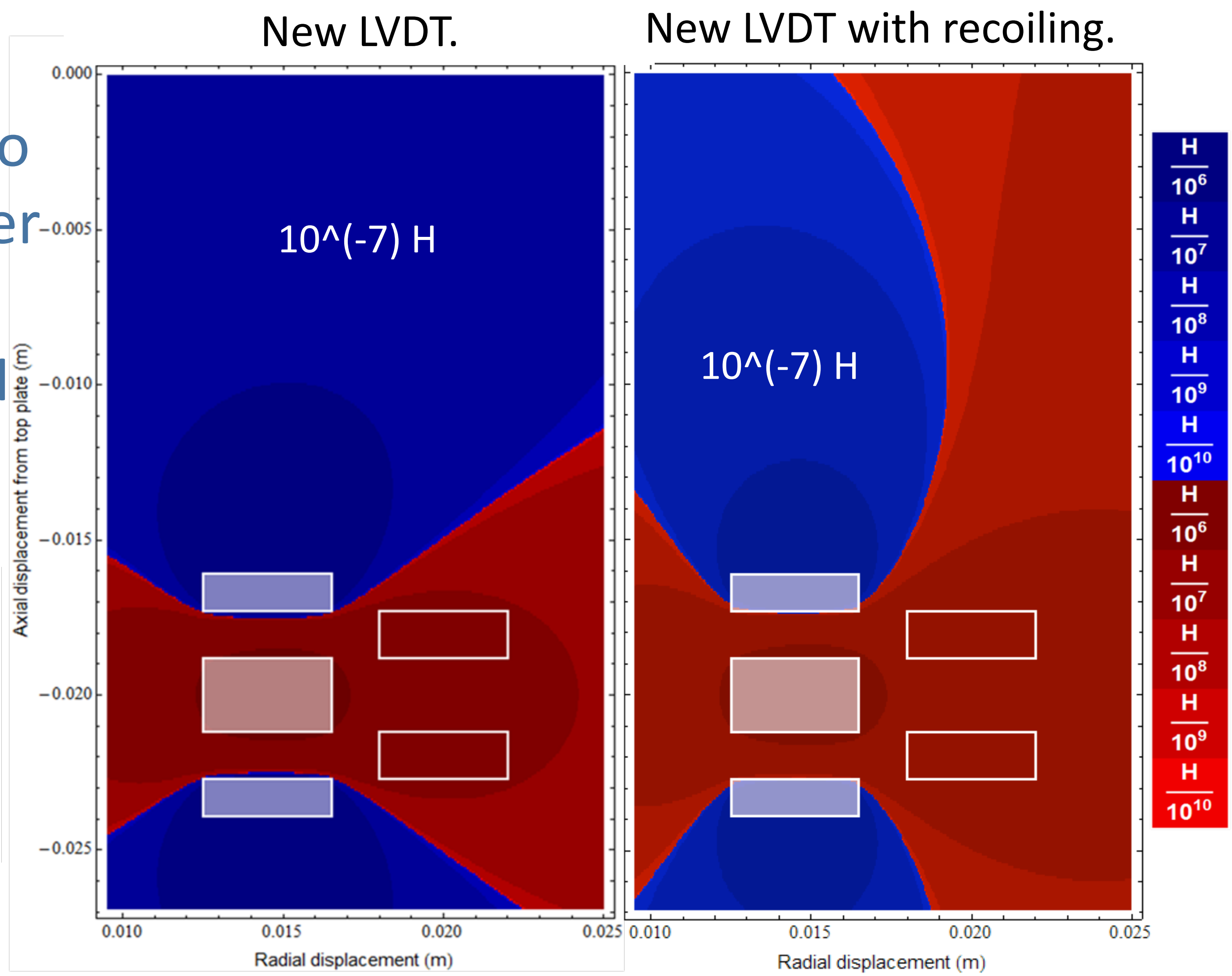
- Cancel magnetic field into top plate to reduce eddy currents.
- Three coil design.

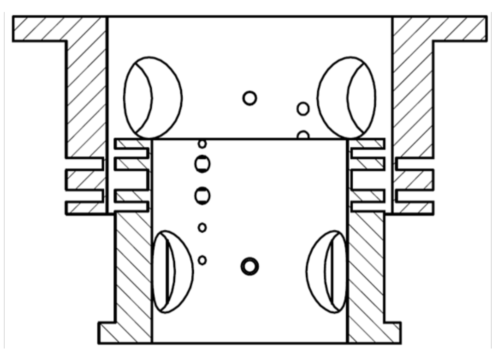




LVDT optimization

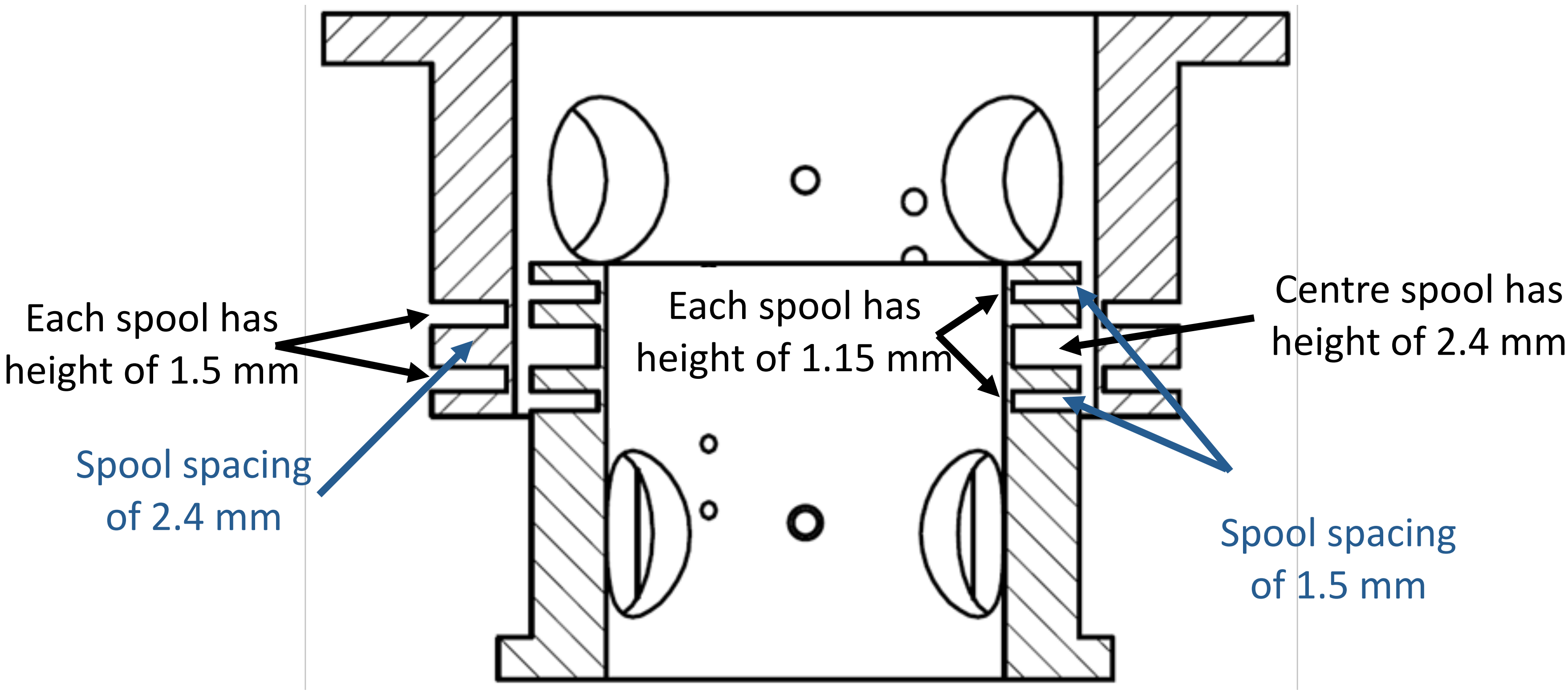
- Optimization is achieved through unequal coiling
- Coiling: (167,-351,167) Ratio:(1:-2.0989:1)
- Total mutual induction into top plate after optimization is 5 10^(-9) H





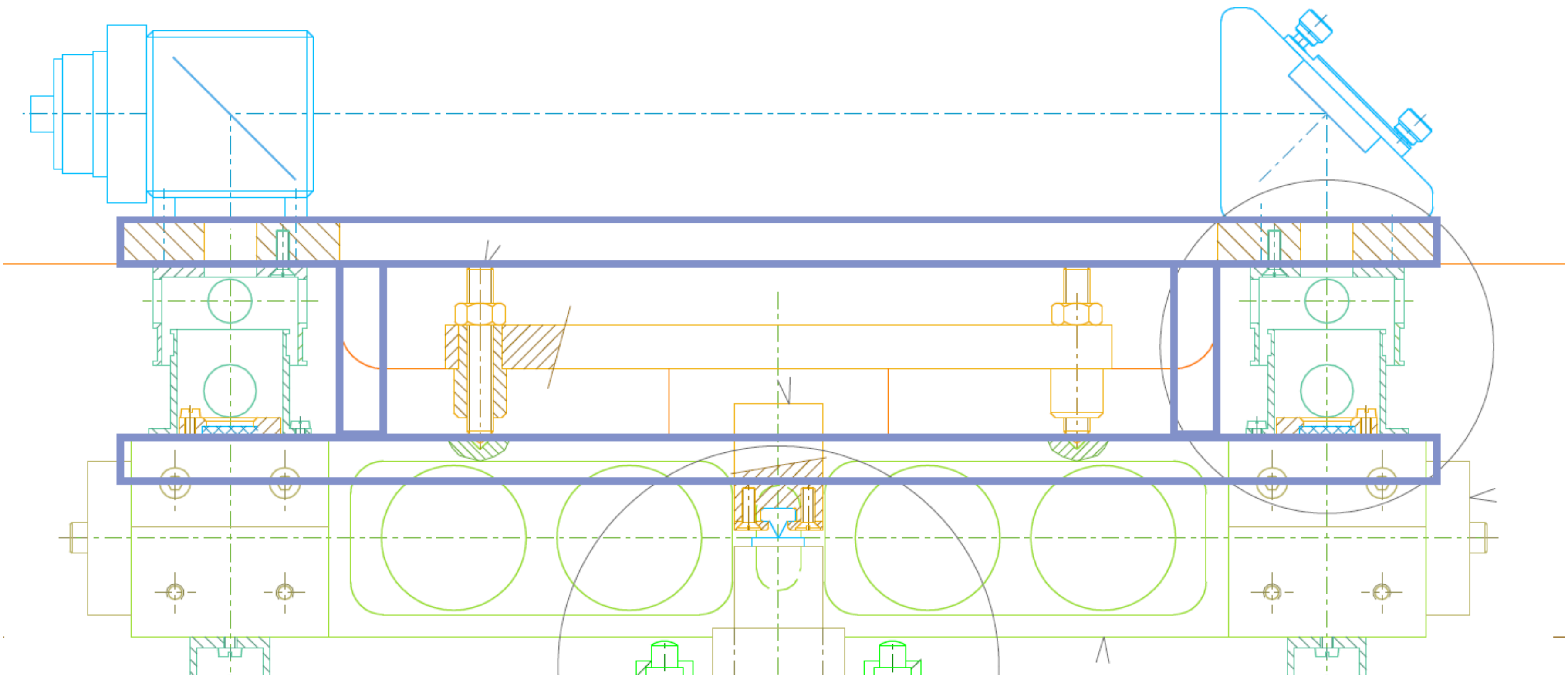
LVDT development

- With optimization inductance to top plate is reduced by
- Total reduction factor of 500!

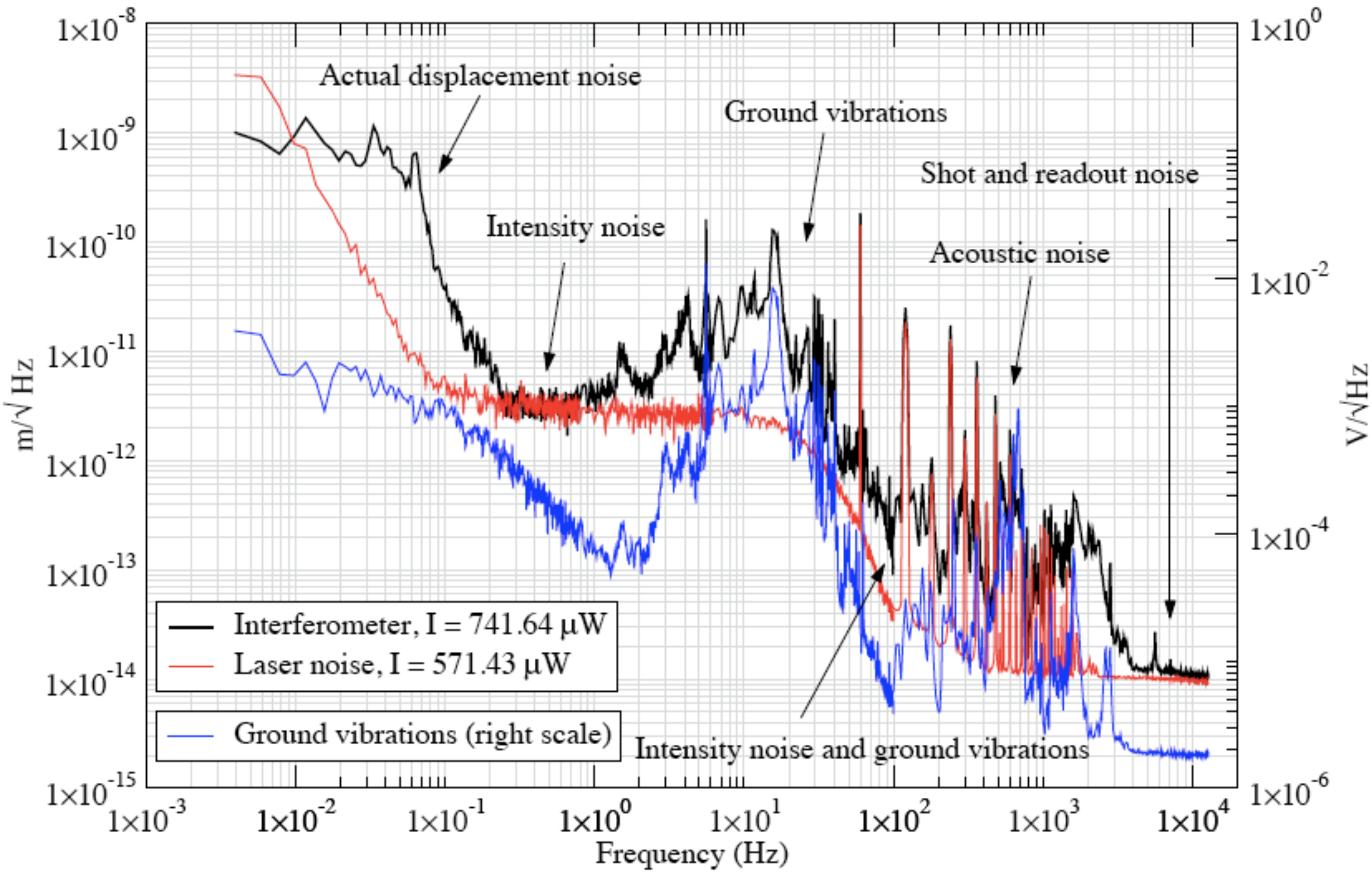


Interferometric Displacement measurement

- Differential measurement.
- Highest sensitivity
- Self calibrating
- Difficult UHV implementation

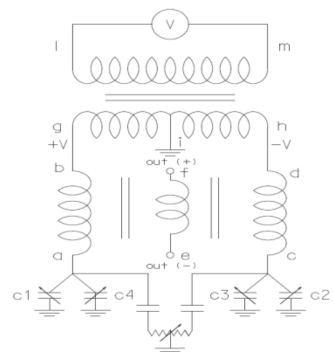


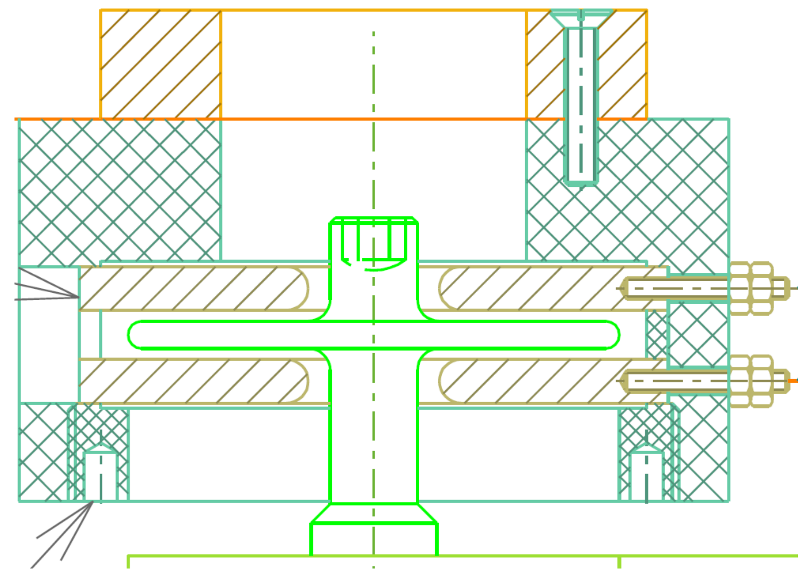
Potentiality with interferometer

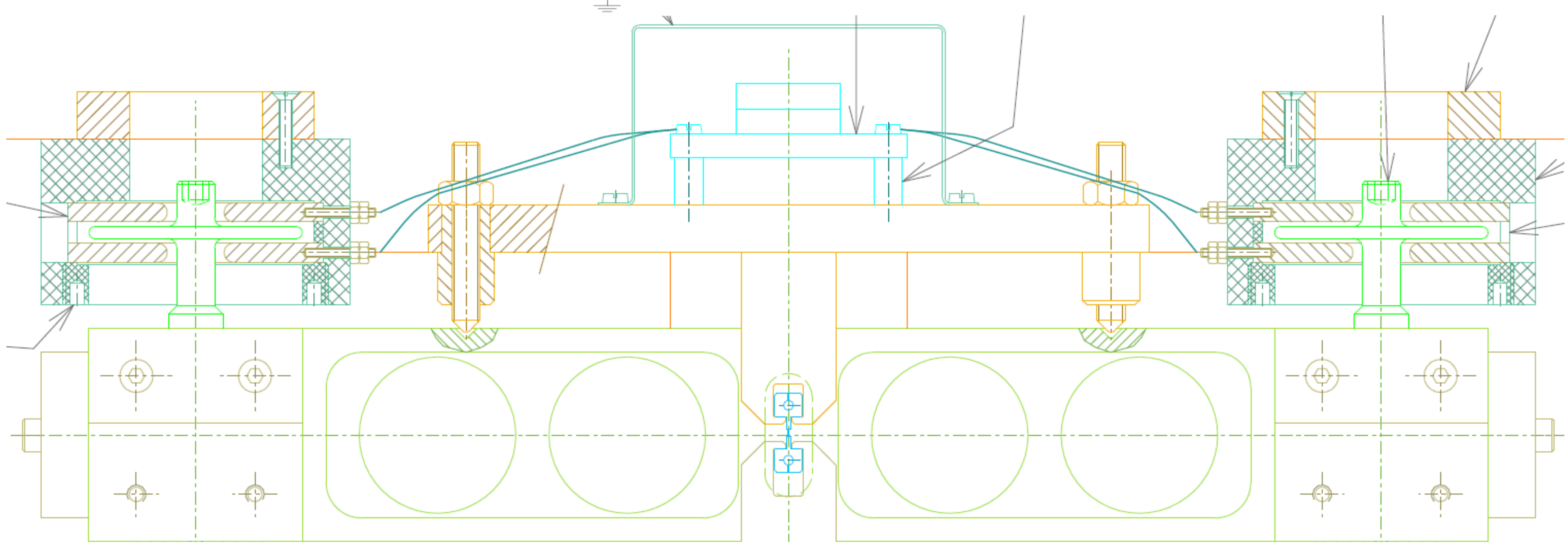
- 

Capacitive Displacement measurement

- Possibel better sensitivity
- Problem with stray forces







Future developments

- DLC coating
- Place two tiltmeters in vacuum!
- Michelson interferometer in combination with LVDT
- Diamond coating
- Quadrupole actuator
- Optical only position recording

- Flexure for SOC study!!

End of talk.