



**National Physical Laboratory**

# Low Force Metrology at the National Physical Laboratory, UK

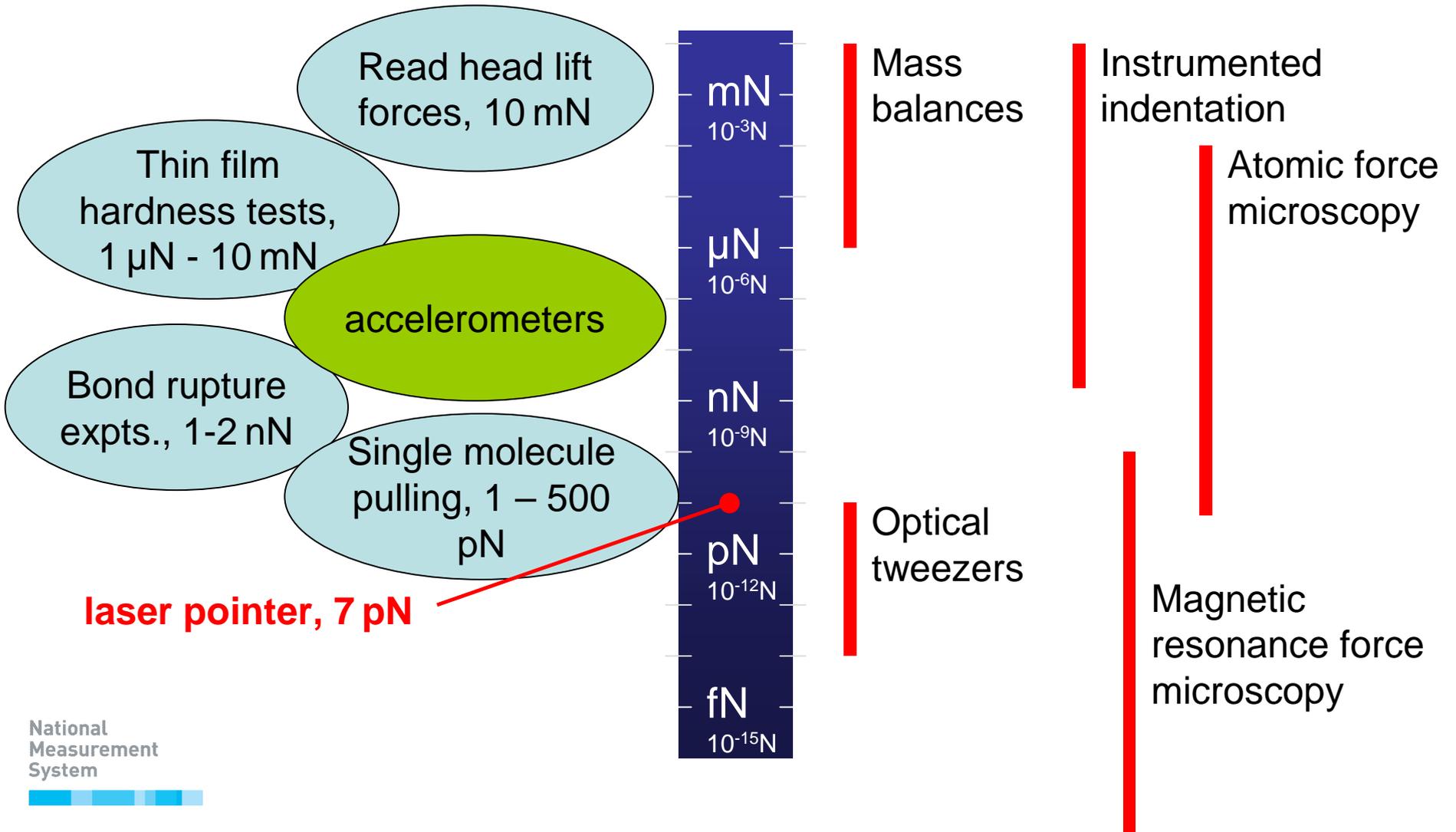
**Christopher Jones**  
**24 November 2010**

**Workshop on Now and Future of Small Forces**  
**IMEKO 2010 TC3, Pattaya**

**National  
Measurement  
System**



# The force scale...and some applications



## Overview

- Background
- Current capability
- Future plans

## The National Physical Laboratory

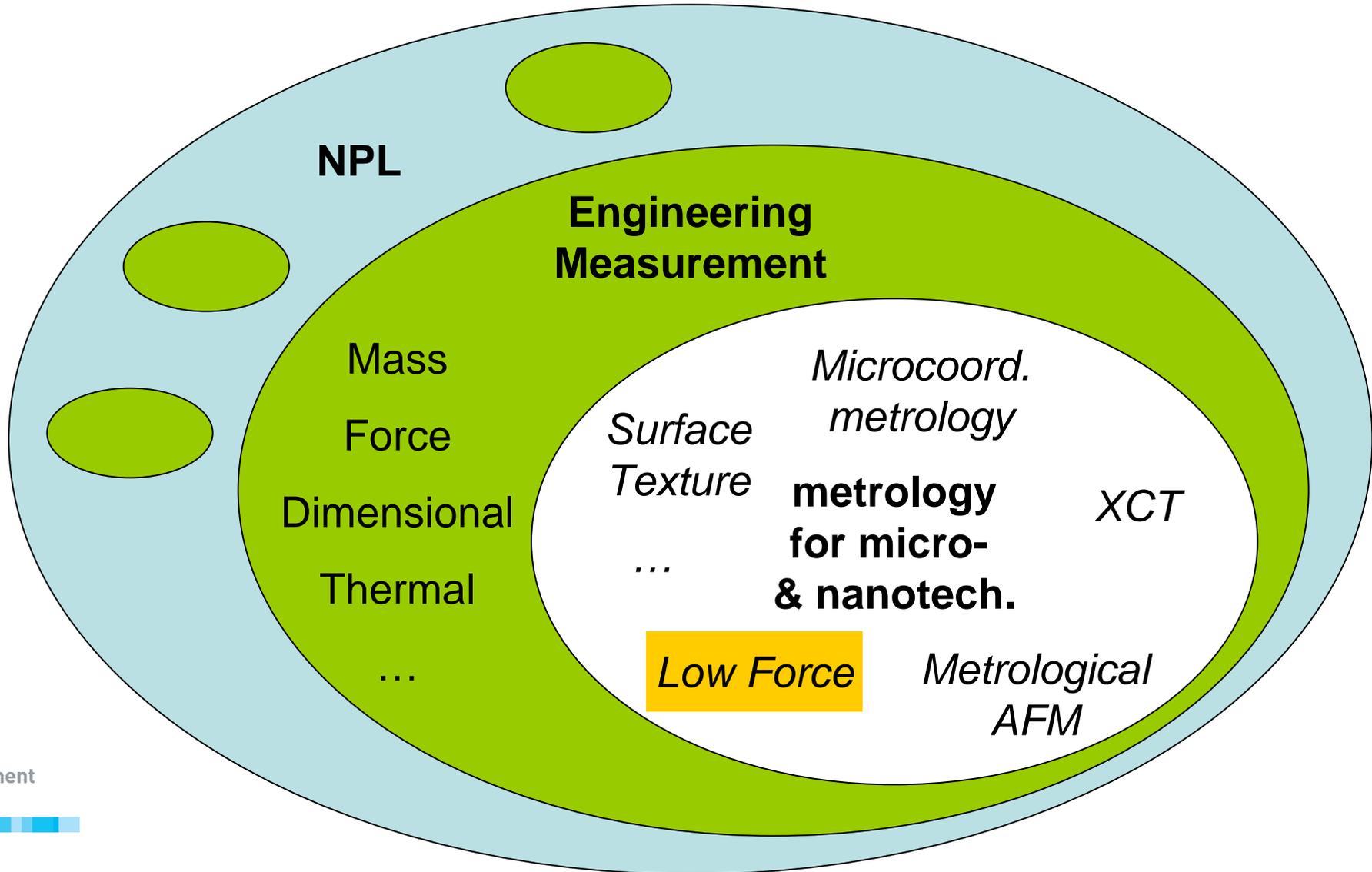
- The UK's NMI
- Commercially operated – 30% won
- Metrology research
- Commercial services



[www.npl.co.uk](http://www.npl.co.uk)



# The National Physical Laboratory



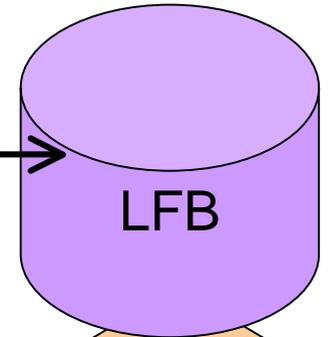
## History of low force measurement at NPL

- Macro force metrology
- $\mu$ -thrusters
- Traceable  $\mu\text{N}$ - $\text{nN}$  force measurement infrastructure
- Local collaboration e.g. materials



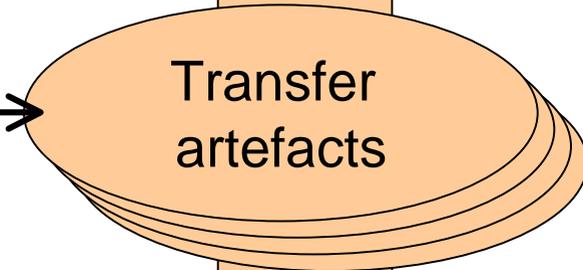
## LF traceability at NPL

Primary standard: best possible  
small force realisation

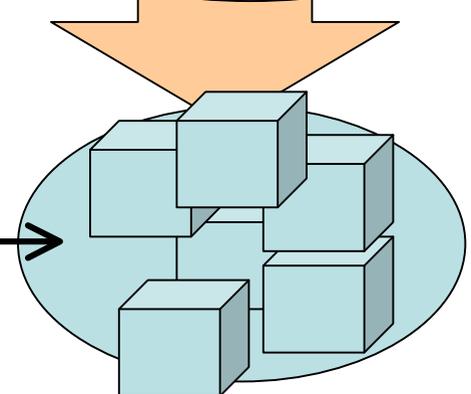


Goal: much-improved  
traceability route for  
low force  
measurement

interface

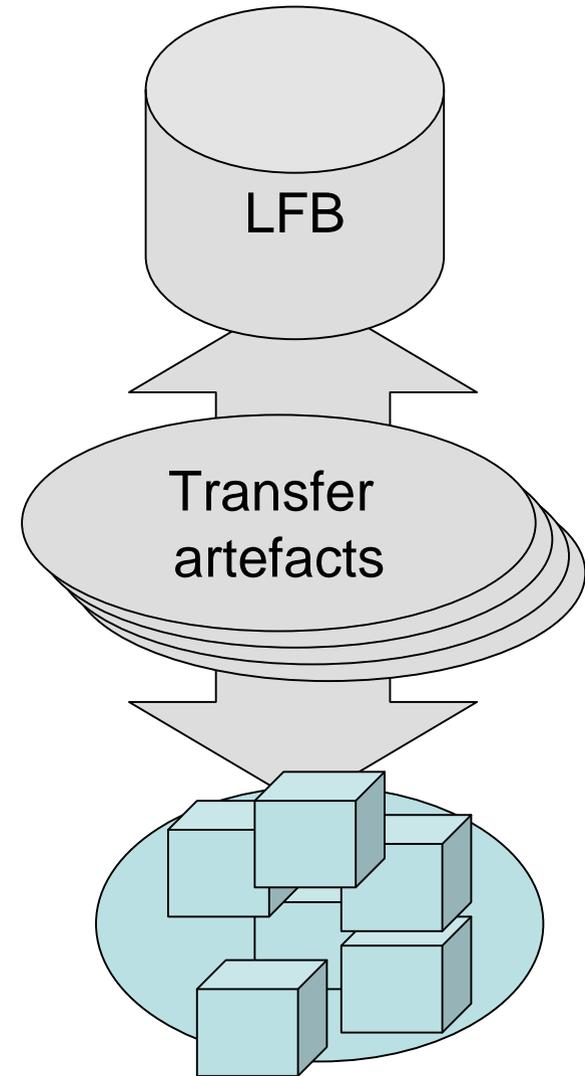


Target instruments in  
industry (and at NPL)

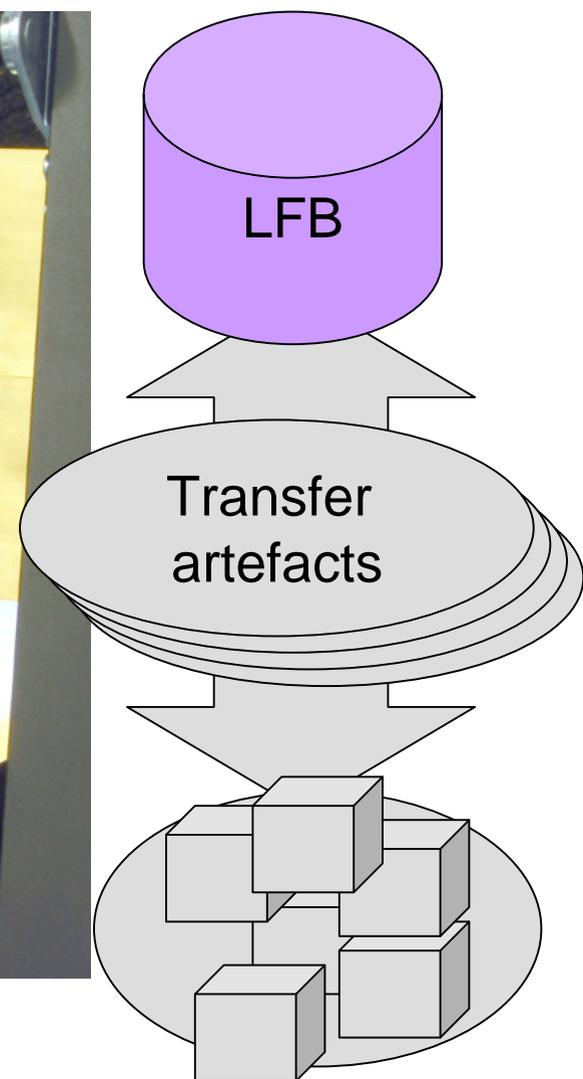
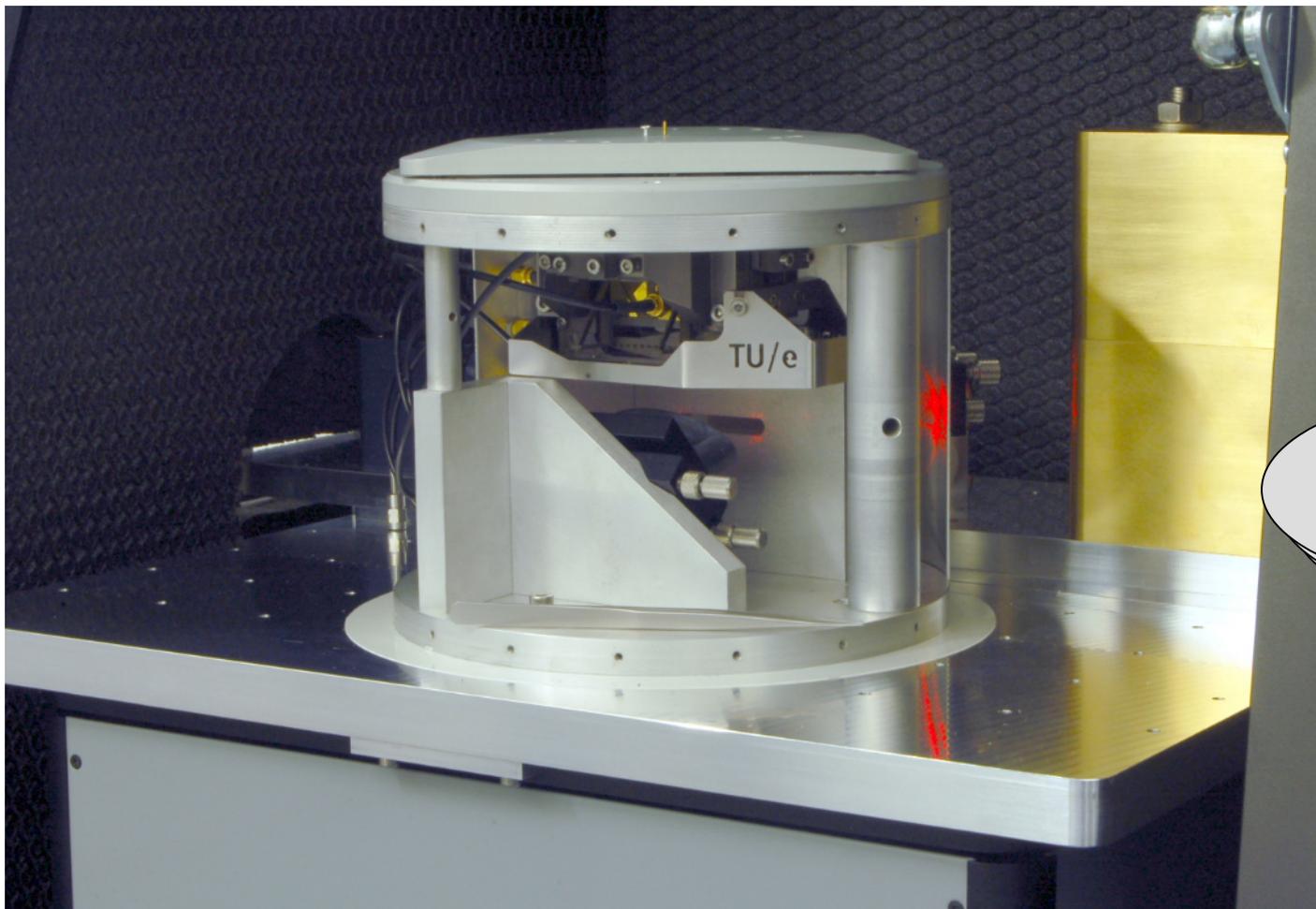


## Initial applications at NPL

- Micro- and nanodimensional metrology
- Atomic Force Microscopy
- Nanoindentors

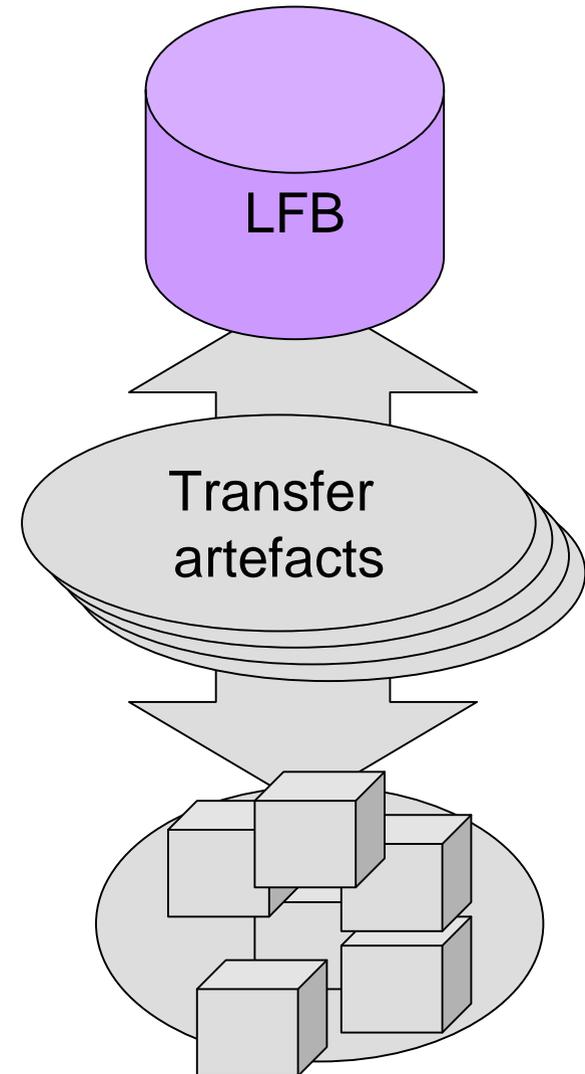


## The Low Force Balance (LFB)



## The Low Force Balance (LFB)

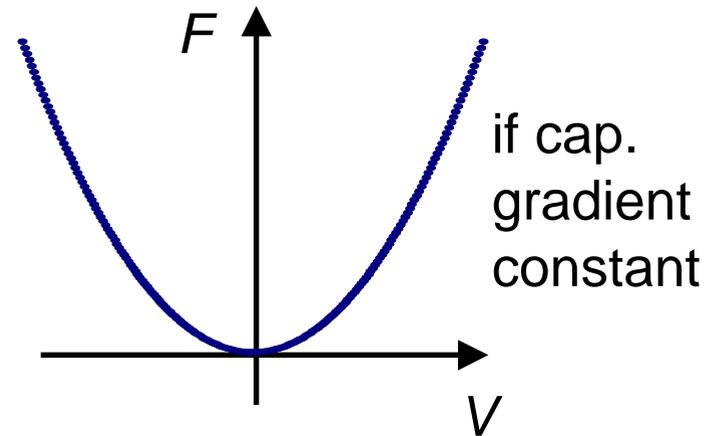
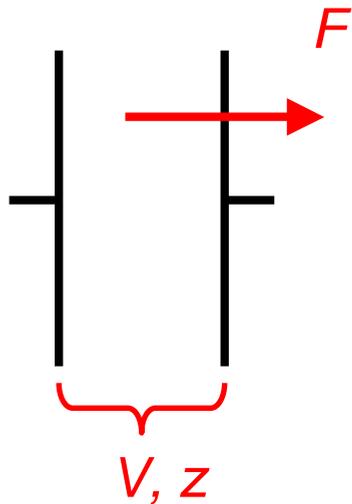
- Electrostatic balance principle
- 10  $\mu\text{N}$  to 1 nN range
- 30  $\mu\text{N} \equiv 3 \text{ mg} \equiv [1 \text{ cm fine gauge wire}]$
- Air operation
- Vertical interaction via platen



## The electrostatic force balance principle

- Electrostatic force in parallel-plate capacitor is:

$$F = \frac{1}{2} \frac{dC}{dz} V^2$$



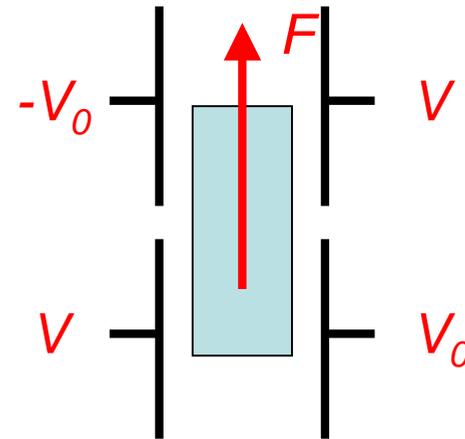
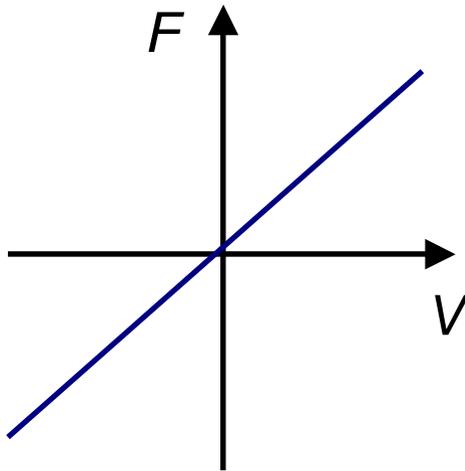
$$F \propto V^2$$



## Electrostatic force generation for the 4-plate LFB

- For four plates, with a bias voltage  $V_0$  and dielectric vane (blue):

$$F = 2 \frac{dC}{dz} V_0 \cdot V \quad \text{i.e.} \quad F \propto V$$



N.B. AC modulation required!

(troubleshooting credit to Dr Jon Pratt at NIST)

## Electrostatic force generation for the 4-plate LFB

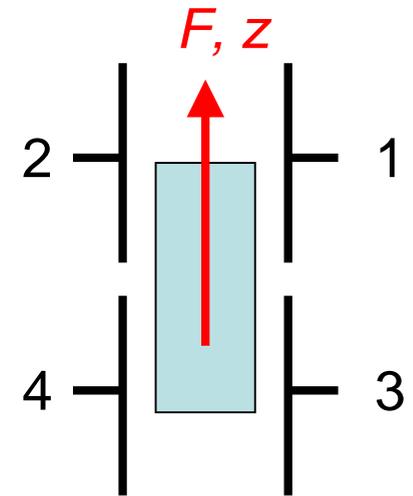
$$F_{\text{el}} = F_z = \frac{1}{2} \mathbf{V}^T \cdot \frac{d}{dz} \mathbf{C} \cdot \mathbf{V}$$

where

$$\mathbf{V} = \begin{pmatrix} V_{14} \\ V_{24} \\ V_{34} \end{pmatrix} = \begin{pmatrix} 0 \\ -V_0 - V \\ V_0 - V \end{pmatrix}$$

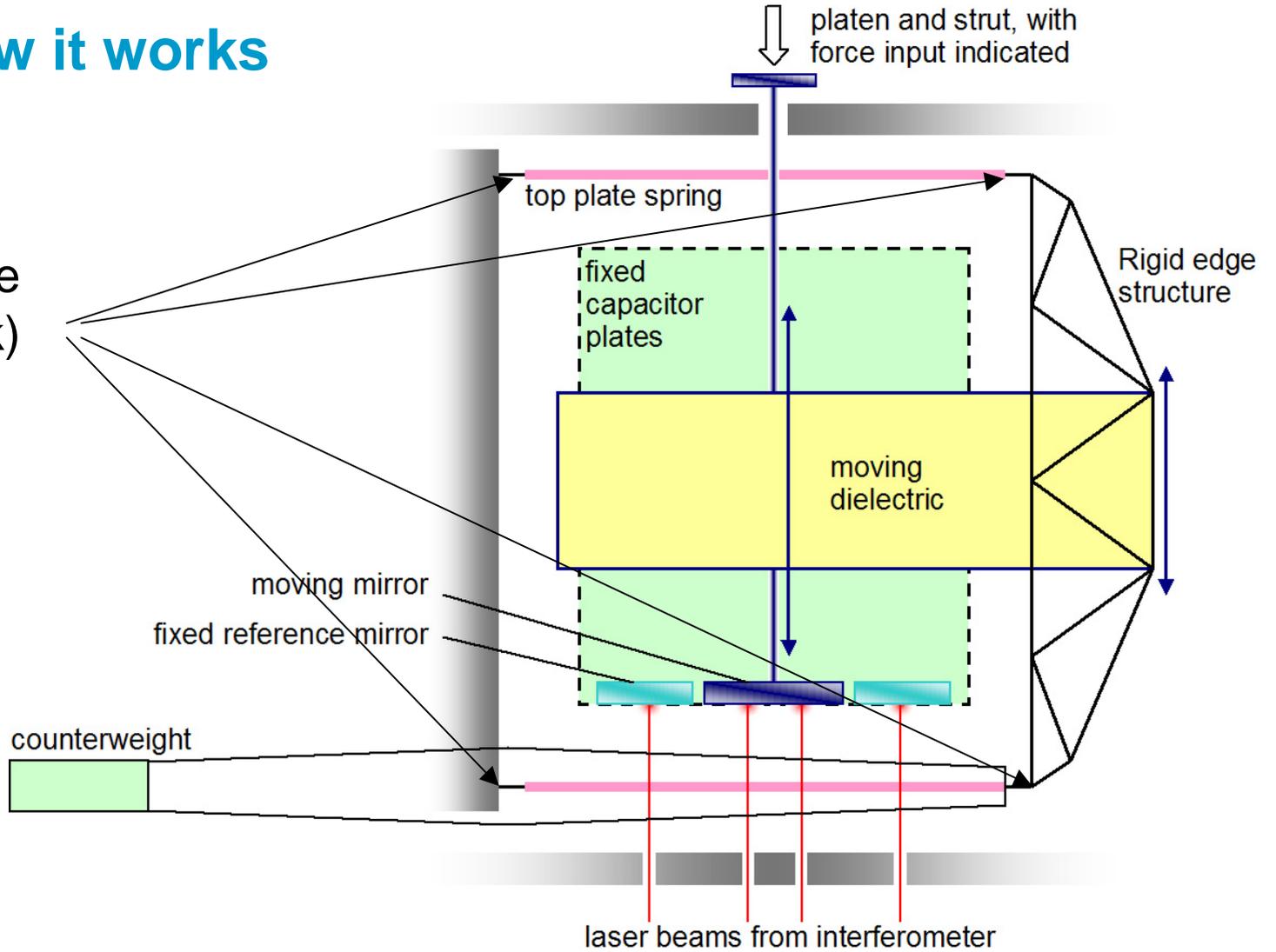
and

$$\mathbf{C} = \begin{pmatrix} C_{12} + C_{13} + C_{14} & -C_{12} & -C_{13} \\ -C_{12} & C_{12} + C_{23} + C_{24} & -C_{23} \\ -C_{13} & -C_{23} & C_{13} + C_{23} + C_{34} \end{pmatrix}$$

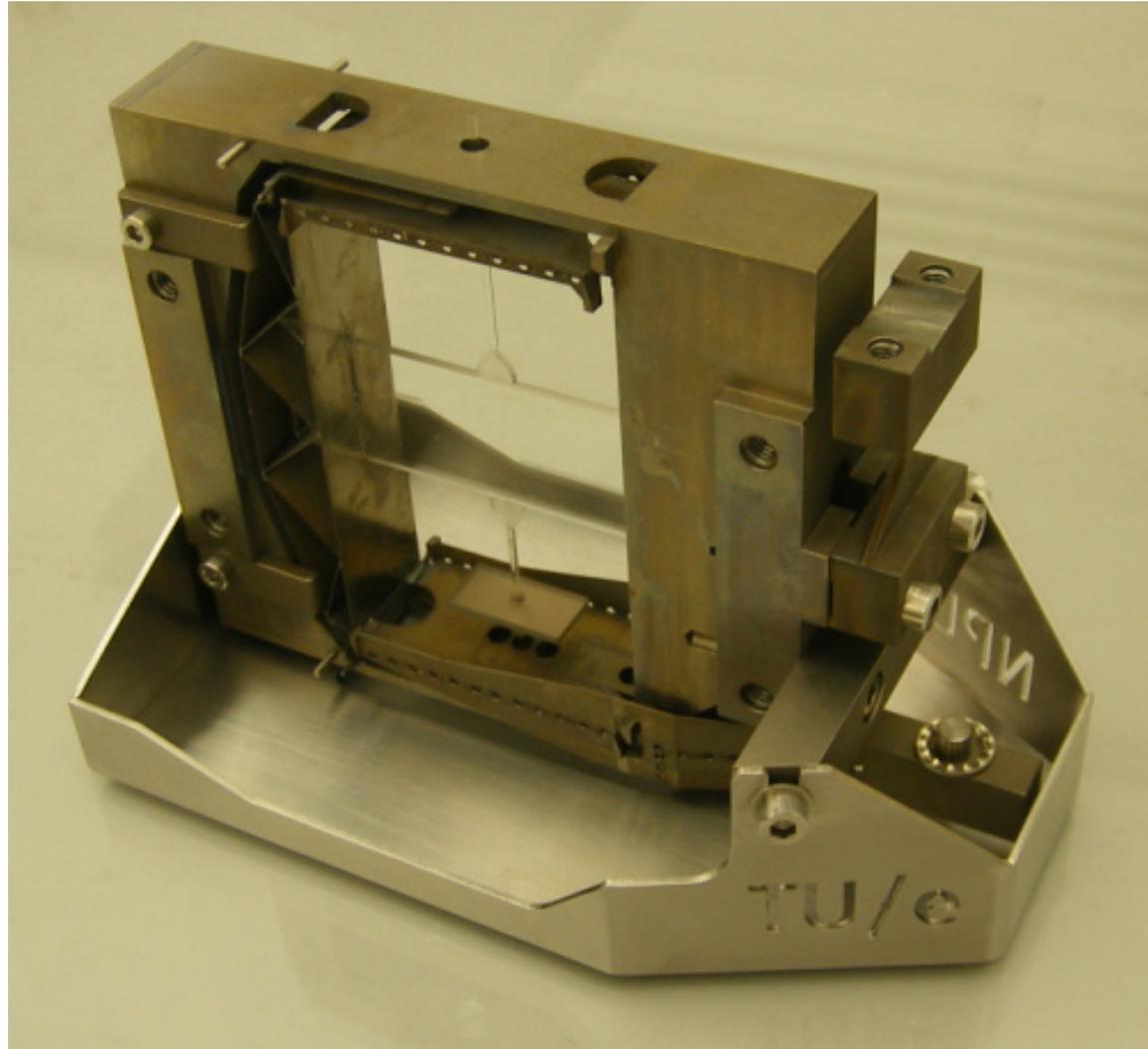


# LFB: How it works

leaf flexure  
(4-bar link)



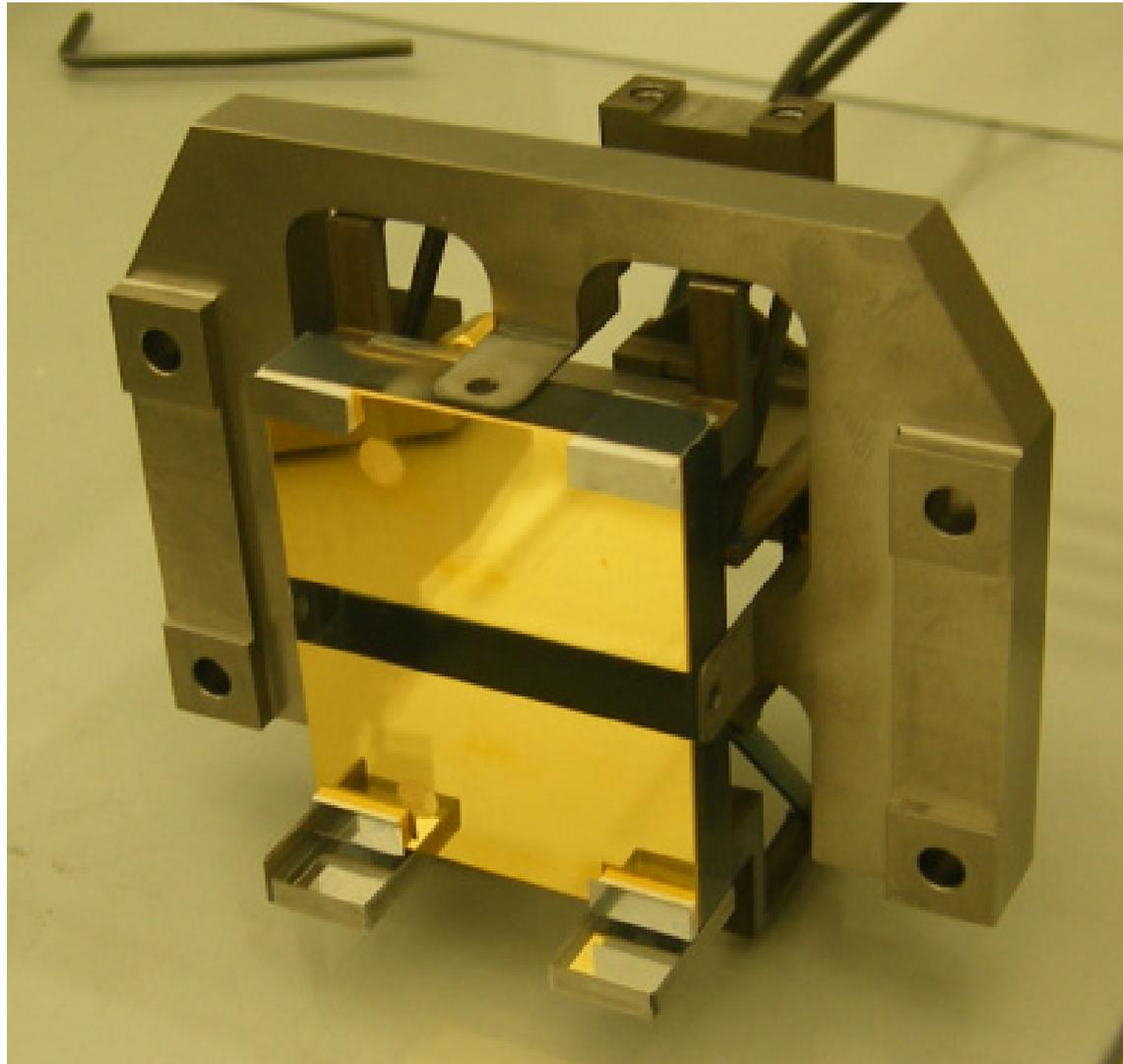
## LFB: How it works



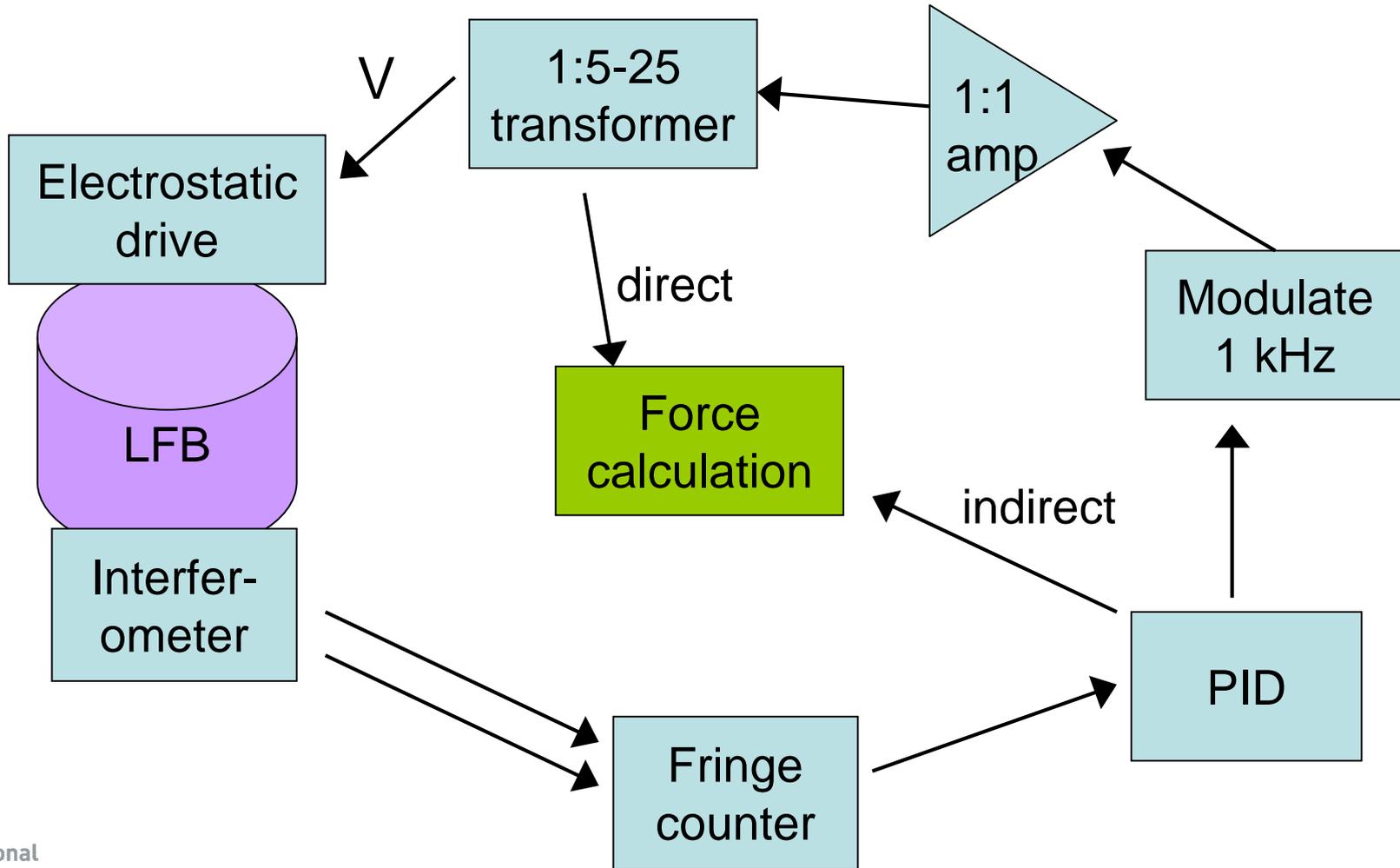
## LFB: How it works



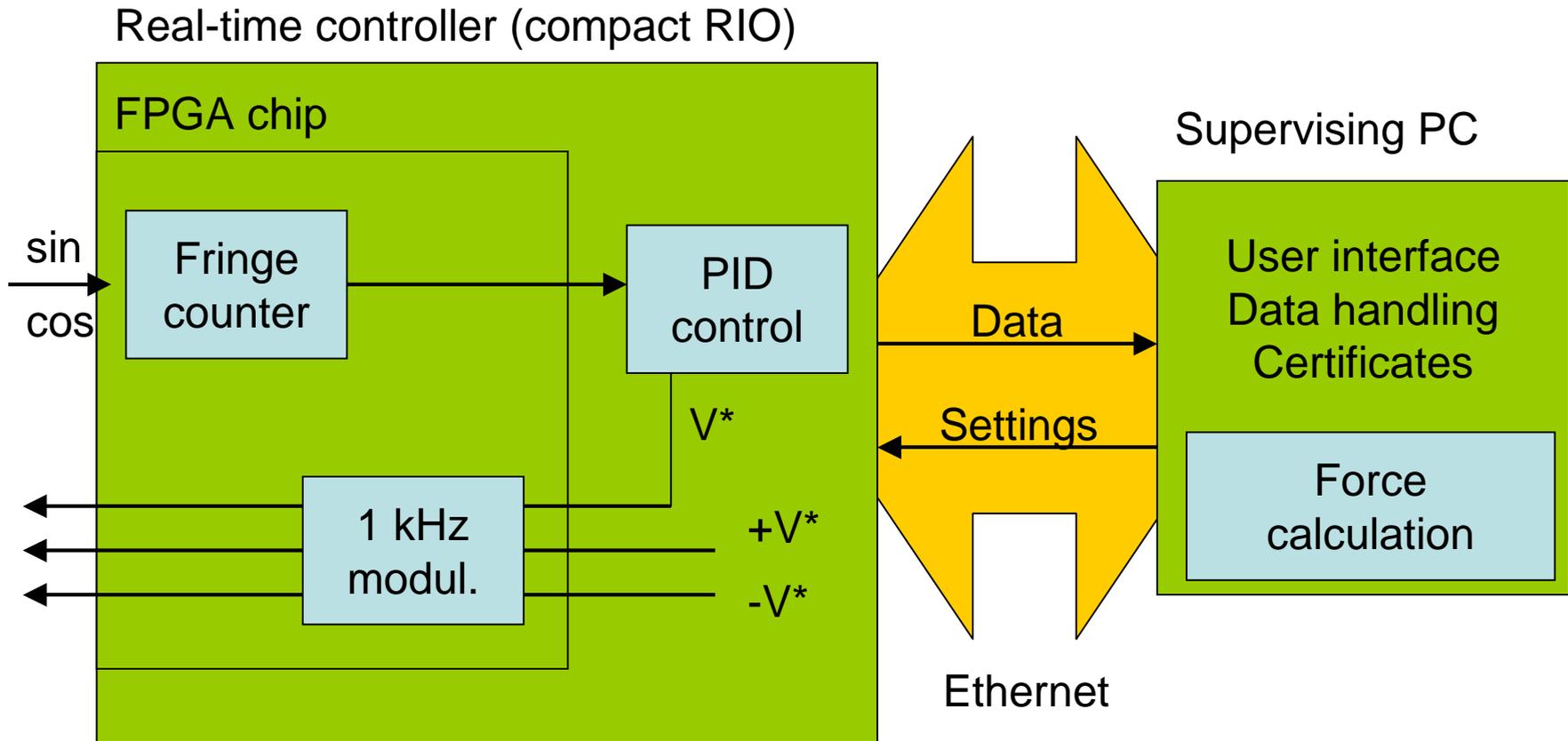
## LFB: How it works



## LFB: How it works: electronics in control loop



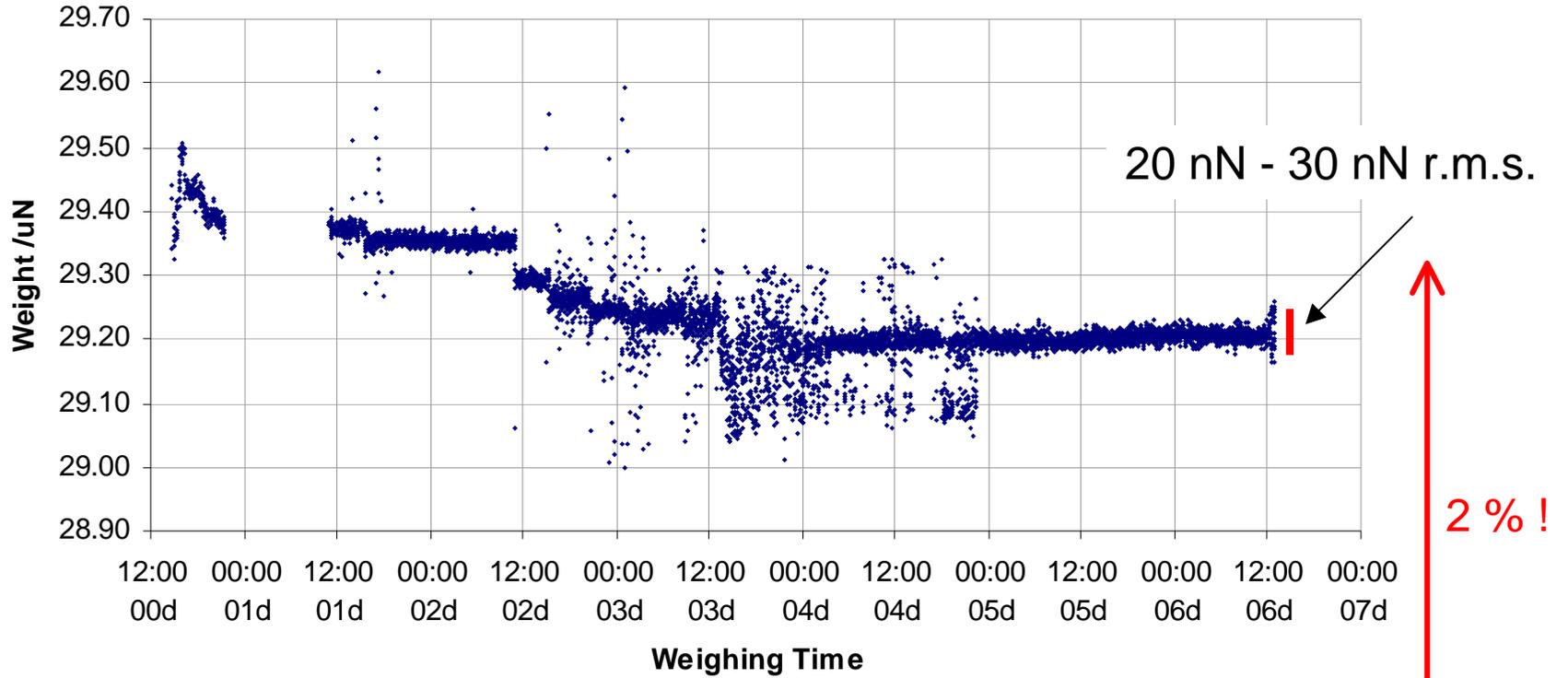
# LFB: How it works: overview of control software



## LFB: control loop noise and isolation

- Active vibration isolation table and enclosure
- Displacement control noise 10 nm rms max
- Force noise around 20 nN rms
- Low frequency drift tradeoff

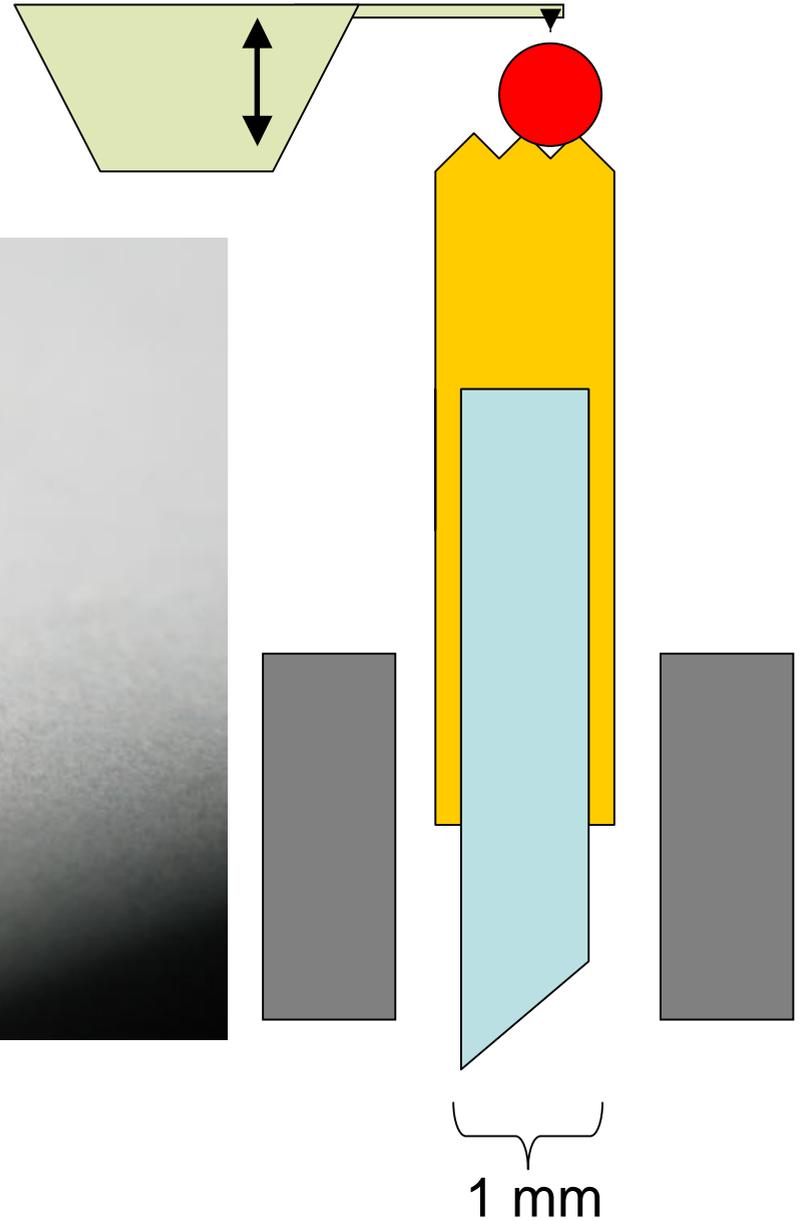
# LFB: mass comparison – indirect V measurement



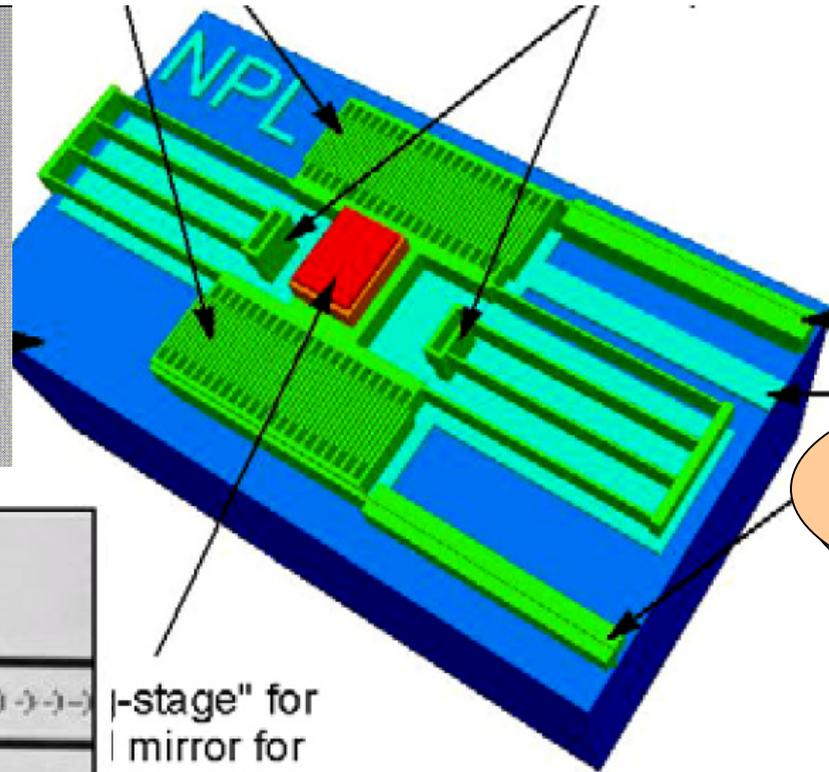
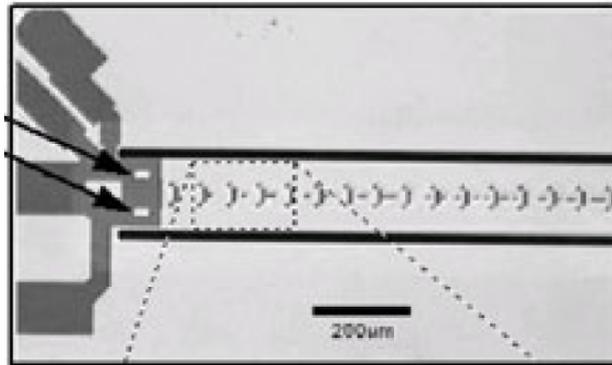
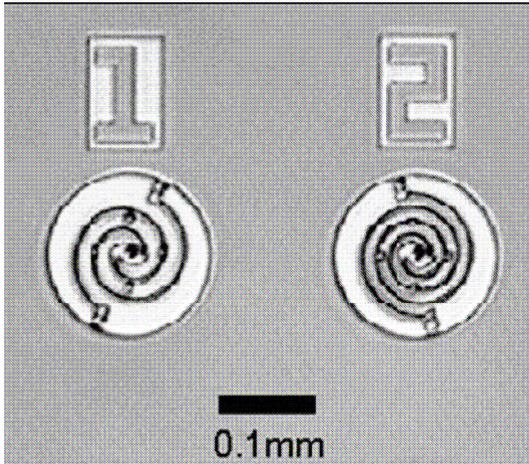
Mass:  
28.52  $\mu\text{N}$



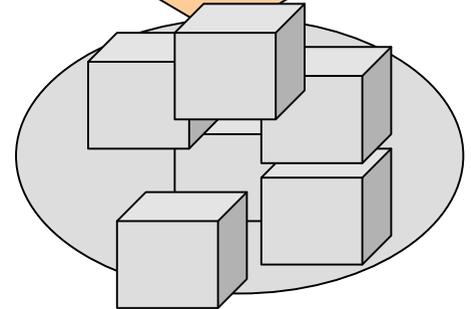
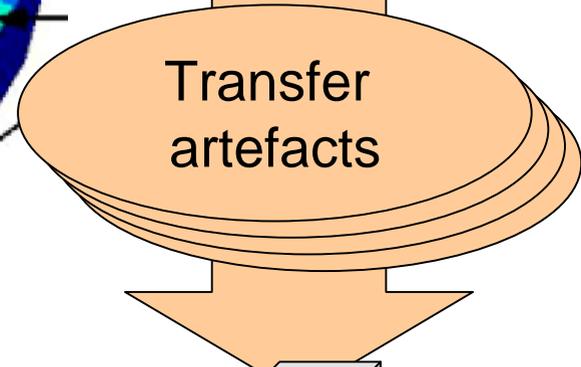
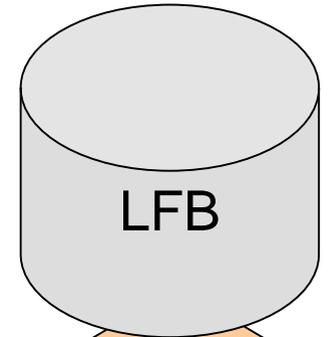
# LFB platen design



# History of LF artefact development at NPL

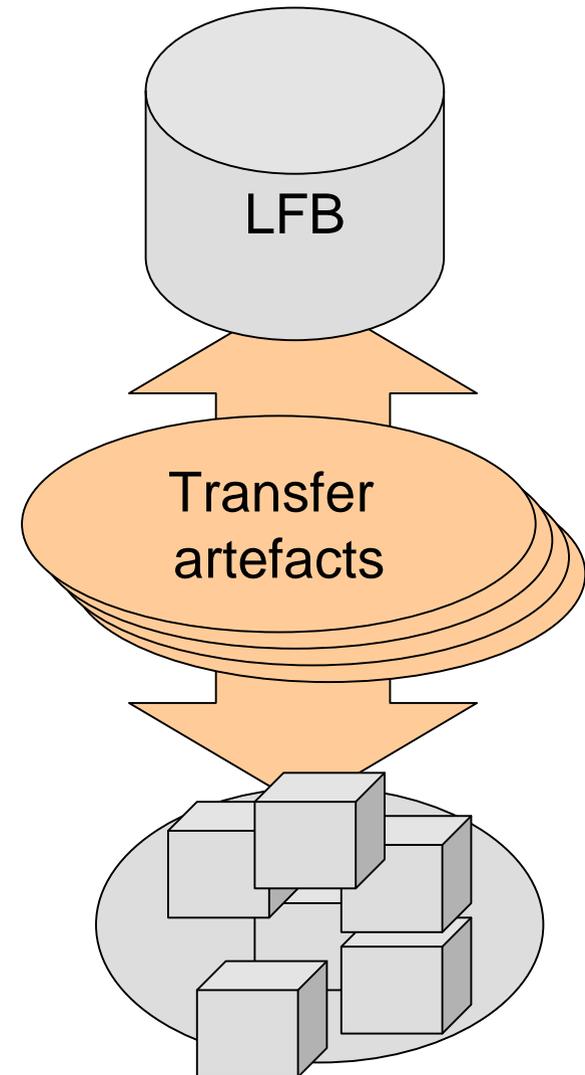


"-stage" for  
mirror for

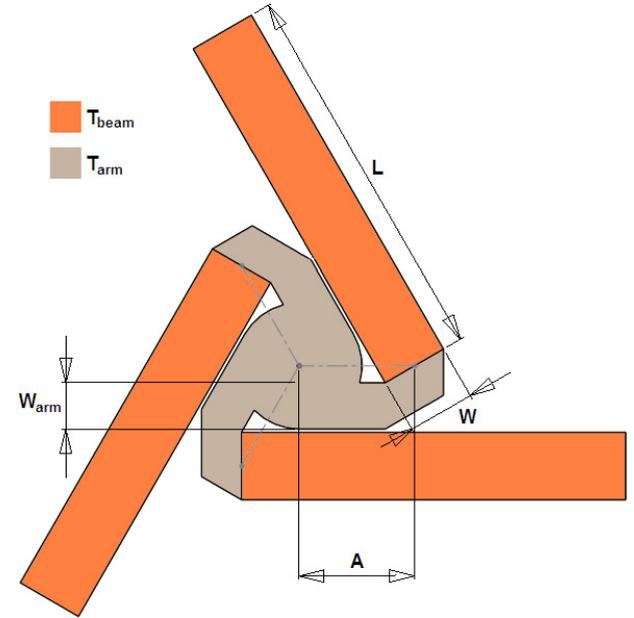
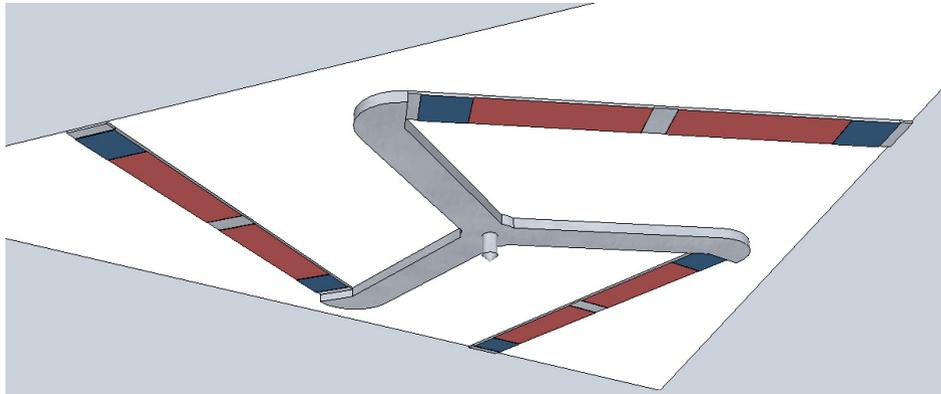


## Requirements for successful artefact

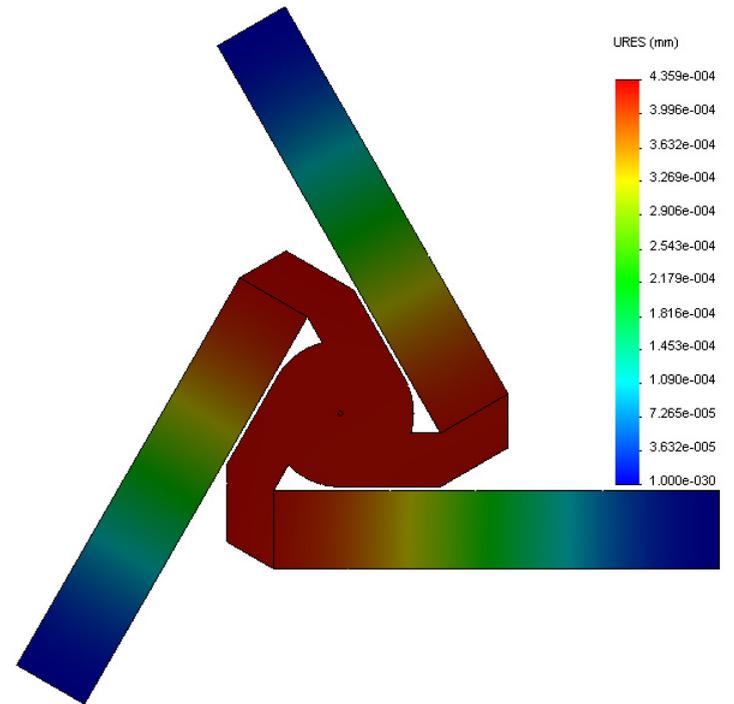
- Outputs repeatable analogue to an input force ... and vice versa
- Self-contained metrology
  - ✓ c.f. spring constant calibration devices
- Robust, yet compact
- Balance interface
  - ✓ Invertible
  - ✓ Tip design
  - ✓ No crosstalk
- Acceptable production cost



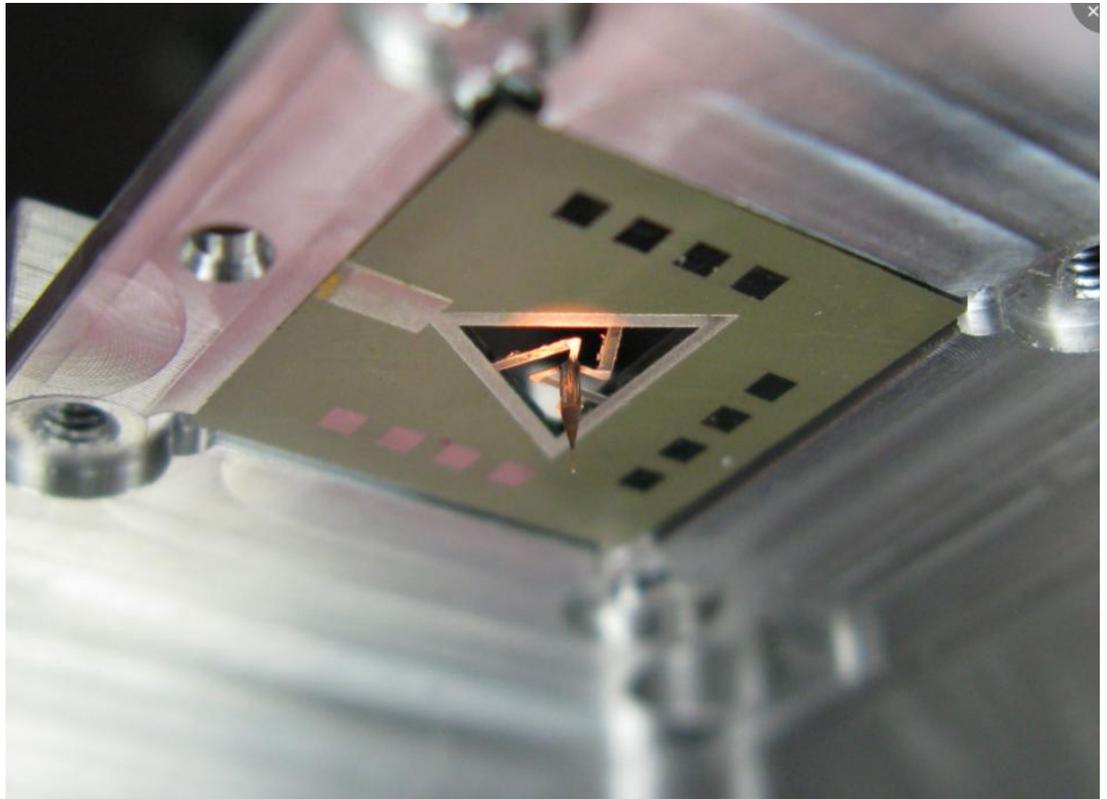
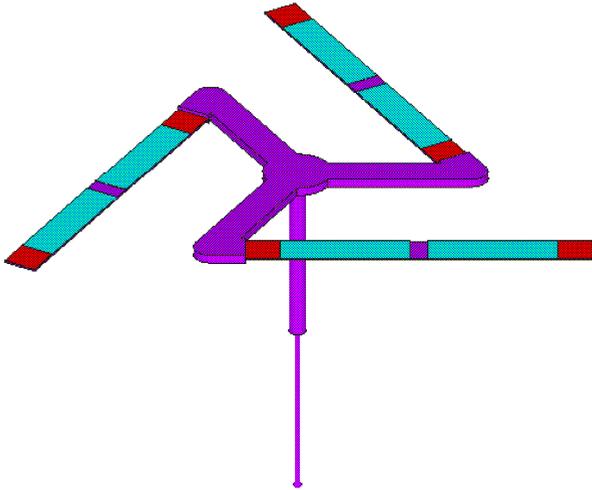
## The triskelion concept



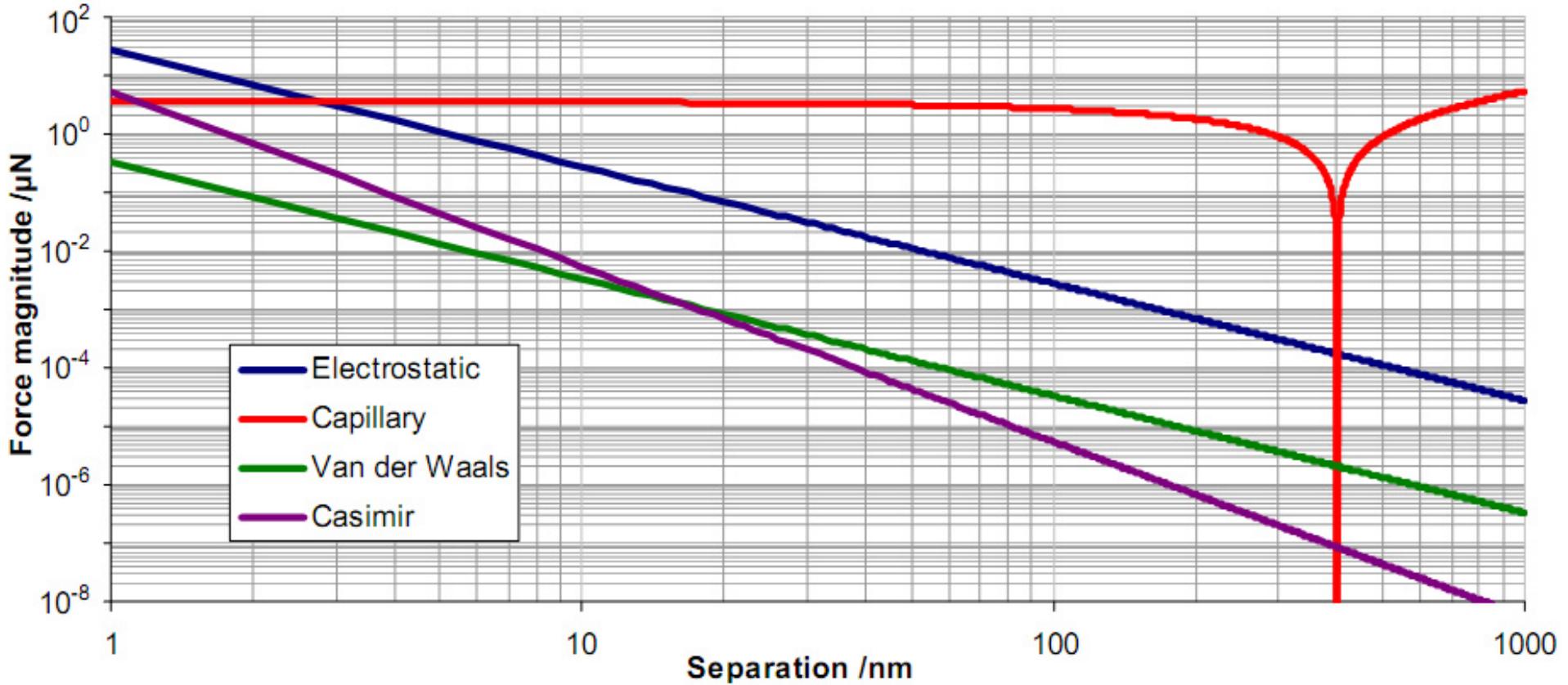
- Modes of operation
  - ✓ Strain sensor
  - ✓ Strain generator
  - ✓ Null-deflection artefact



# Diversion – vibrating microprobe heritage and motivation



# Microprobe contact forces

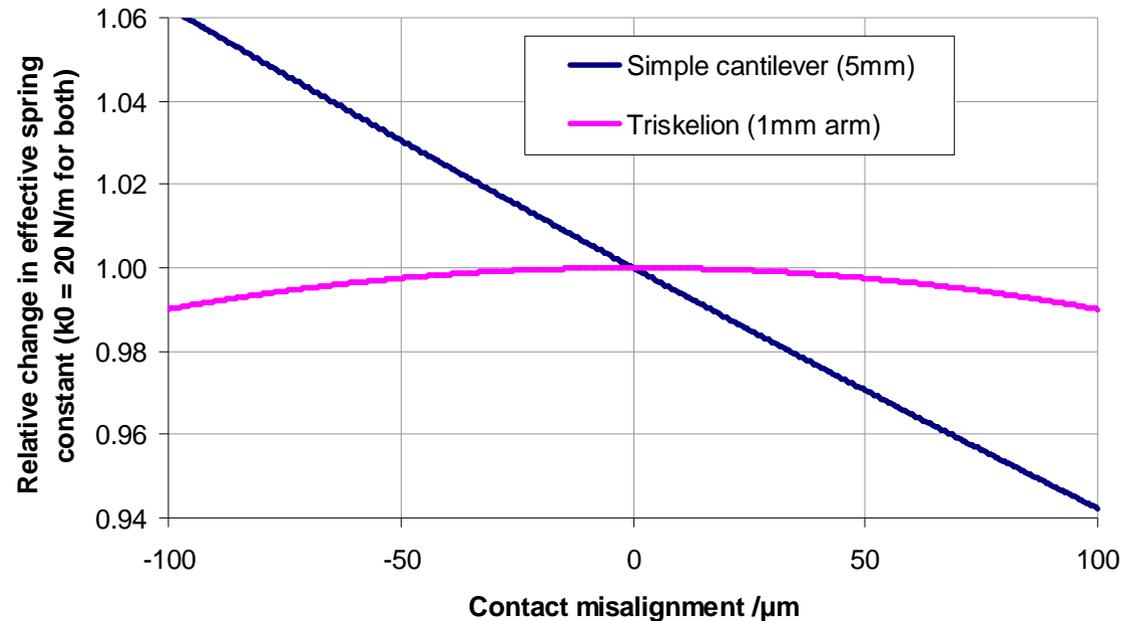


(compiled from various sources)



## Alignment insensitivity bonus of triskelion flexure

- Rectangular cantilever stiffness uncertainty:  $dk/dL \sim L$  for small axial misalignment
- Triskelion artefacts stiffness uncertainty:  $dk/dL \sim -L^2$  for small misalignment from centre



(1<sup>st</sup> order model!)



# Modelling for artefacts

Analytical  
(Warwick University)  
1<sup>st</sup> order for fast computation

```

%% NUMERICAL EVALUATION
%% Create trial input displacement(s) $X_0$
X0 = [1e-6, 1e-6, 1e-6, 0, 0, 0]';
%% Derive tilt $A_{Ii}$ and translation $A_{IIIi}$ to arm ends
% redefine arm length and alphas numerically
ap = [ap1 ap2 ap3];
for i = 1:3
    AI{i} = [ 1 0 0 0 0 0; ...
             0 1 0 0 0 0; ...
             0 0 1 a*cos(ap(i)) a*cos(ap(i)) 0; ...
             0 0 0 1 0 0; ...
             0 0 0 0 1 0; ...
             0 0 0 0 0 1]; ...
    AII{i} = [ a*cos(ap(i)); ...
              a*sin(ap(i)); ...
              0; ...
              0; ...
              0; ...
              0];
end
%% Derive rotation into beam coords $B_{i}$
% redefine beam angles numerically
be = [be1 be2 be3];
for i = 1:3

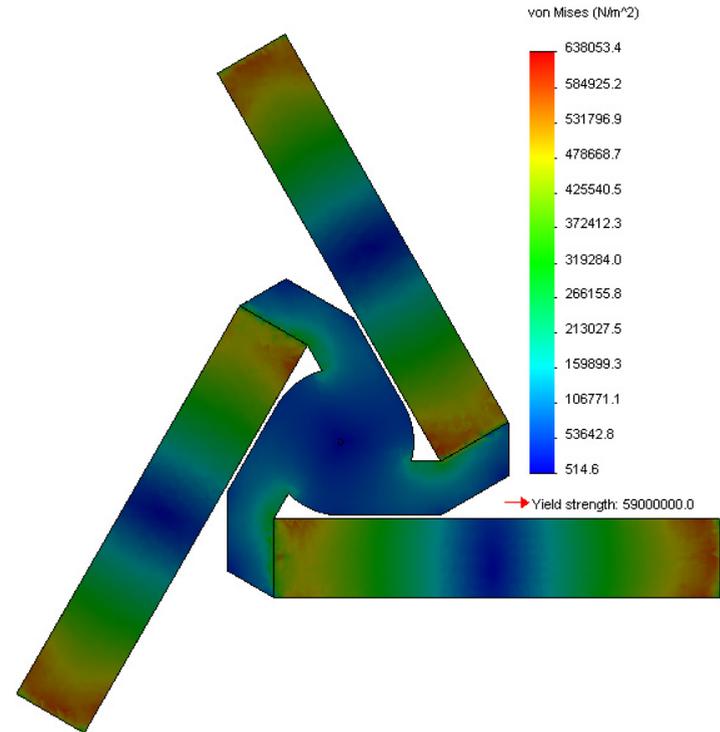
```

```

B{i} = [ cos(be(i)) sin(be(i)) 0 0 0 0; ...
        -sin(be(i)) cos(be(i)) 0 0 0 0; ...
        0 0 1 0 0 0; ...
        0 0 0 cos(be(i)) sin(be(i)) 0; ...
        0 0 0 -sin(be(i)) cos(be(i)) 0; ...
        0 0 0 0 0 1]; ...

```

Finite Element  
(Greenwich University)



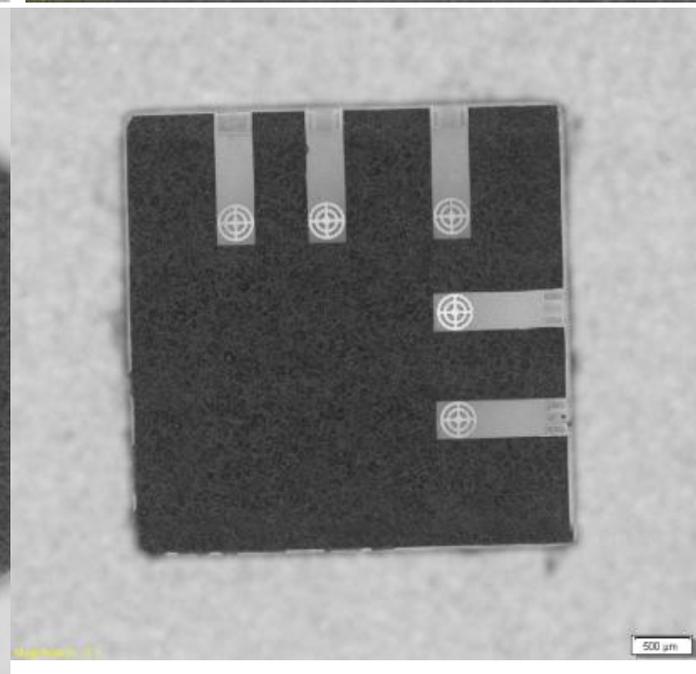
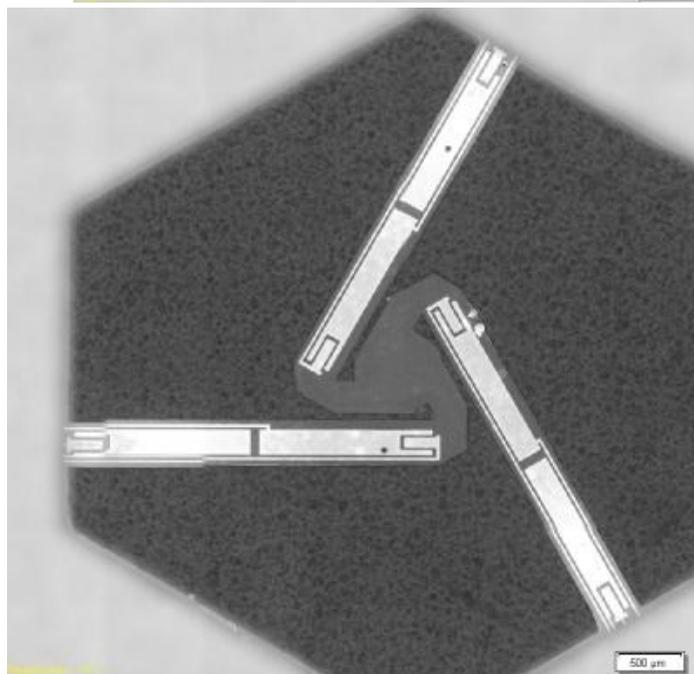
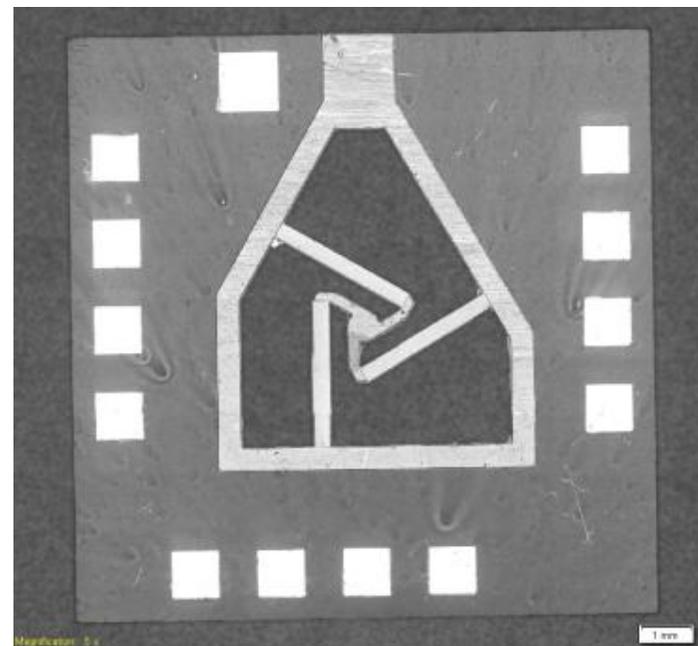
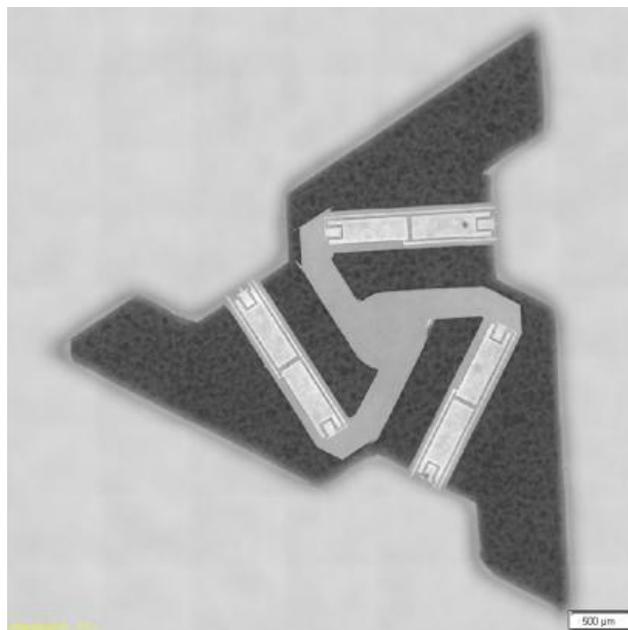
## Challenges of piezoelectric sensing and actuation

- Challenge of move from AC to DC non-trivial
  - ✓ Non-standard usage
  - ✓ Stable charge integrator needed
  - ✓ Minimise noise and crosstalk

## Some prototype artefacts

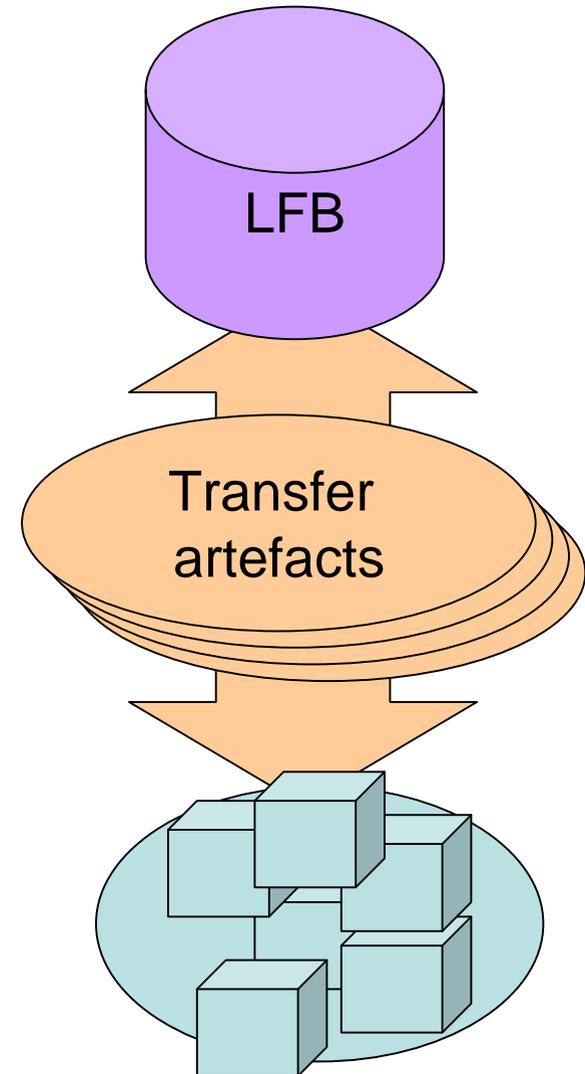
Piezoelectric  
thick film on  
nickel flexure  
(silicon base)

Fabrication  
partner:  
Cranfield  
University



## The future for low force at NPL

- Measurement service
  - ✓ Internal MNT users
  - ✓ Case studies of bespoke measurements
- Further artefacts
  - ✓ Smaller
  - ✓ Better value
  - ✓ Good practice recommendations



## Our Collaborators

THE UNIVERSITY OF  
**WARWICK**

*Cranfield*  
UNIVERSITY

**TU/e**

**NIST**

 *the*  
UNIVERSITY  
*of*  
GREENWICH

**KRISs**  
한국표준과학연구원

**PTB**

