Flexible bearings for high precision mechanisms in accelerator facilities

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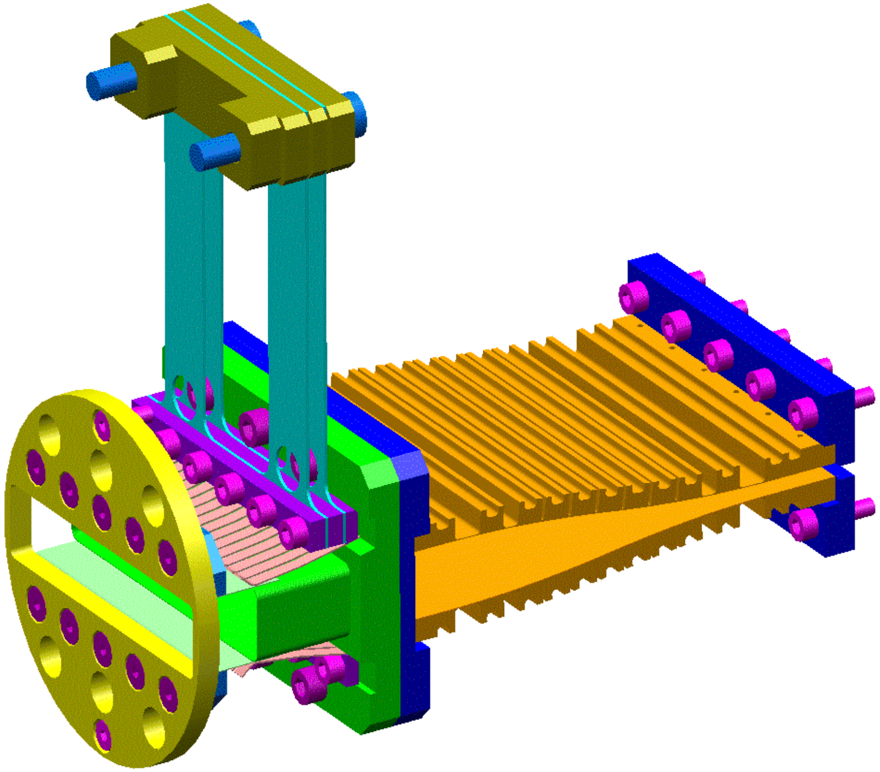
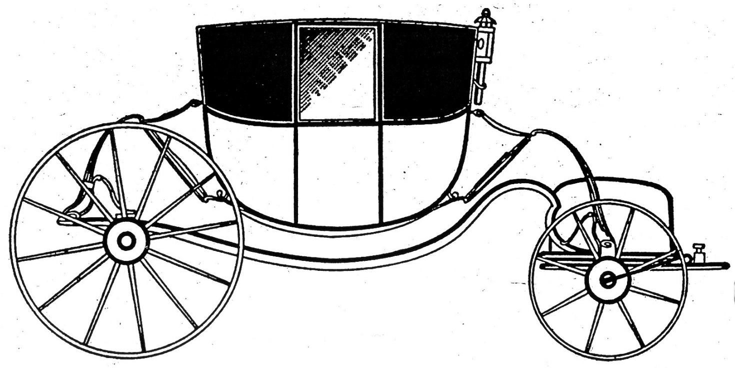


Presentation outline

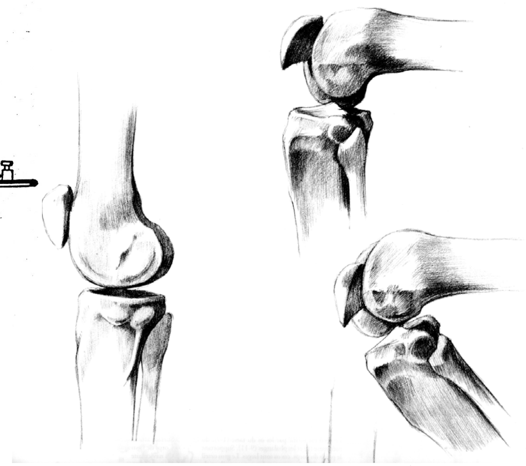
- Introduction
- Flexible bearings design methodology
  - Stroke
  - Parasitic movements
  - Restoring force
  - High precision mechanisms examples (CSEM)
- Compliant mechanisms in accelerator facilities
  - Why compliant mechanisms
  - Examples of use
- Conclusion

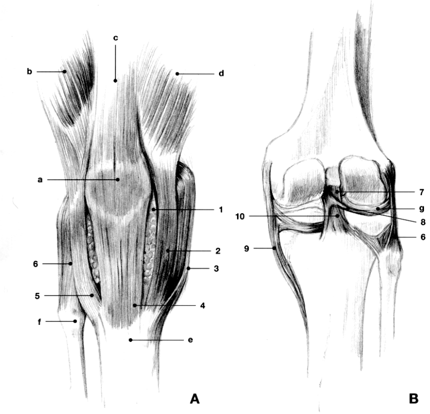
Introduction

- Old approach



Coach with leaf springs 1820

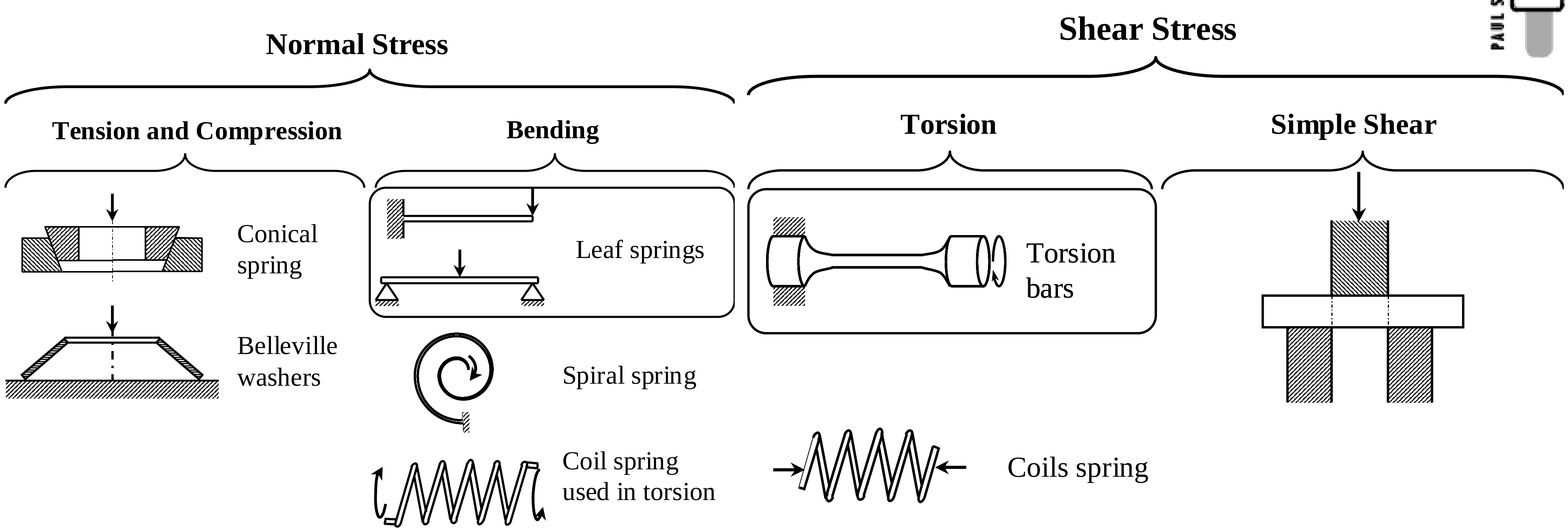




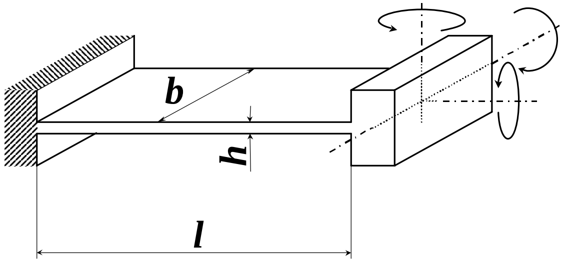
- New needs
  - extreme precision
  - cleanliness
  - hostile environments:

    vacuum, cryogenic, vibrations
- New technologies
  - Electro-discharge machining
  - Silicon technologies, MEMs

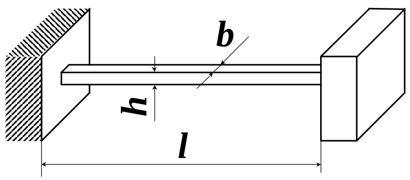
Elementary Articulations



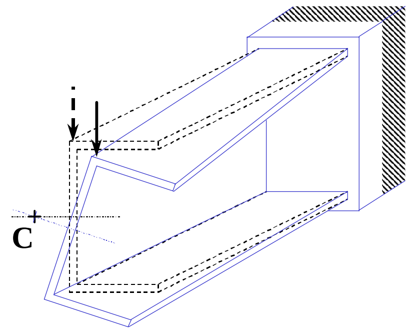
leaf spring



flexible rod



torsion bar



Flexible bearings

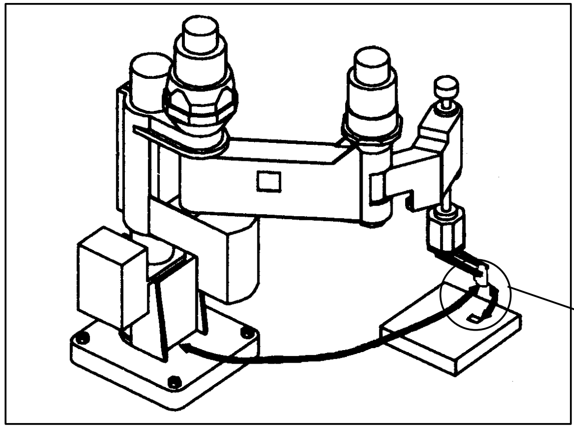
Advantages

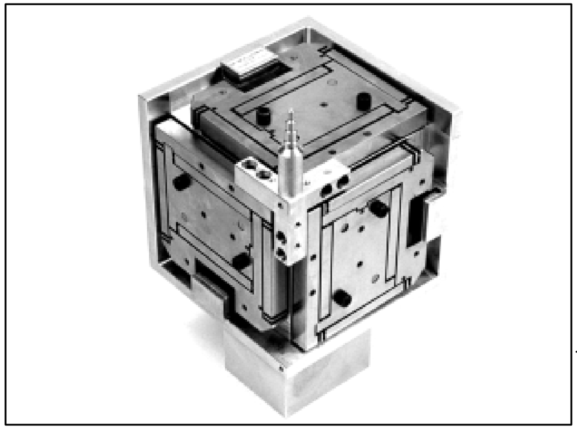
- High precision
- No friction
- No hysteresis
- No wear
- No lubrication
- No risk of jamming
- No backlash
- Monolithic manufacturing ("design for no assembly")
- Main sources of errors are systematic => simple control laws can be used
- Small cost

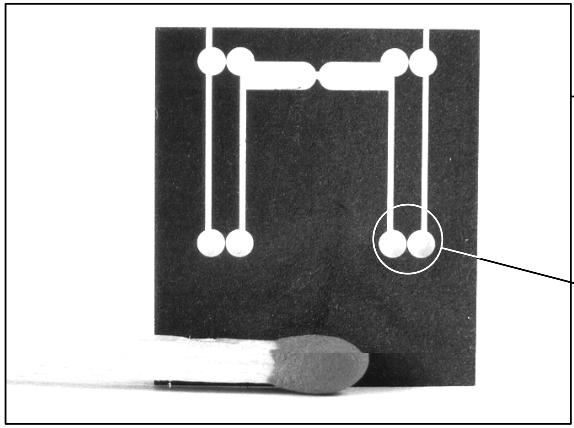
Limitations

- Limited stroke
- Limited load capacity
- Restoring force
- Complex kinematics

Categorisation







Machines
Robots

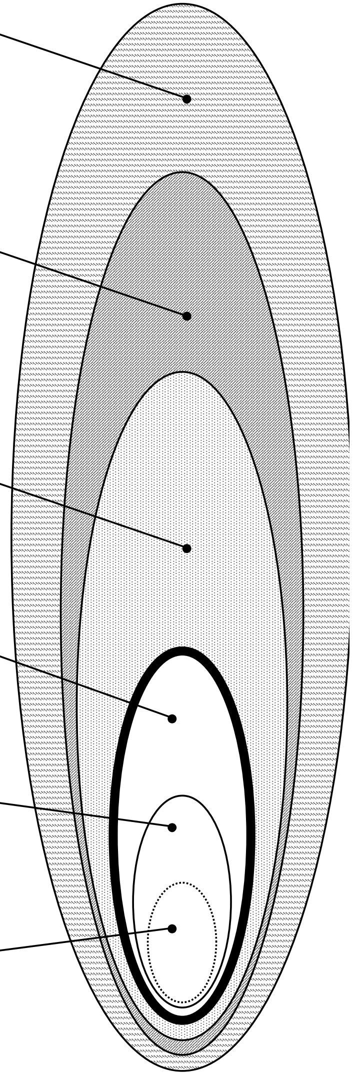
High precision
mechanisms

Mechanical structures

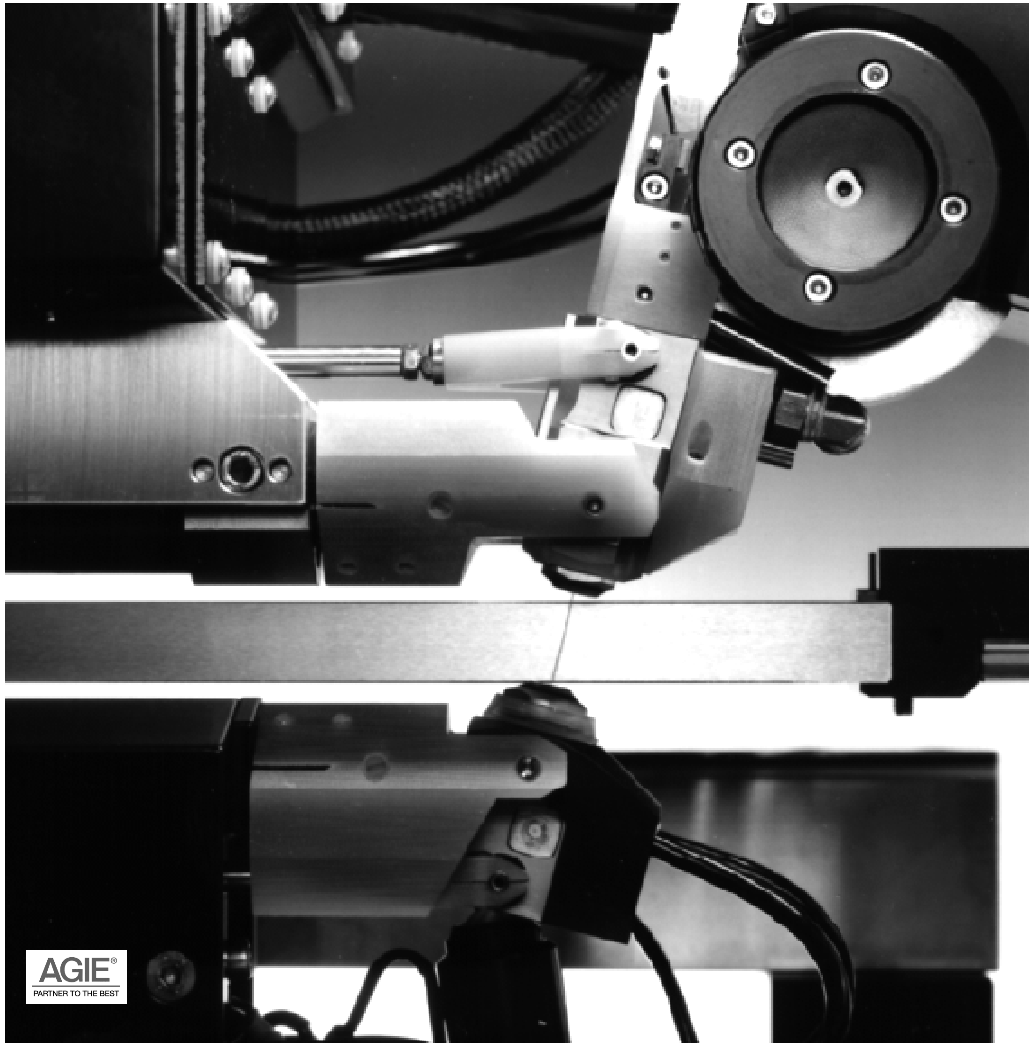
Flexible structures

Flexible bearings

Elementary
flexible articulations

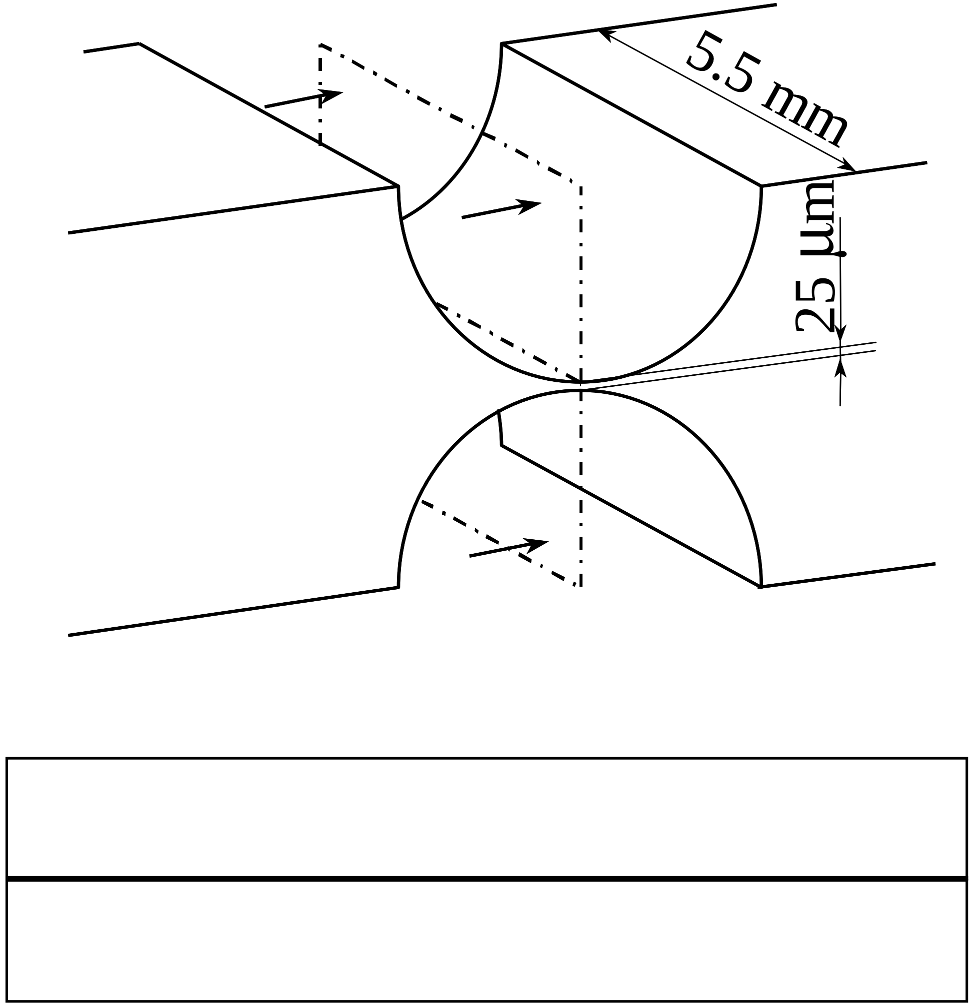


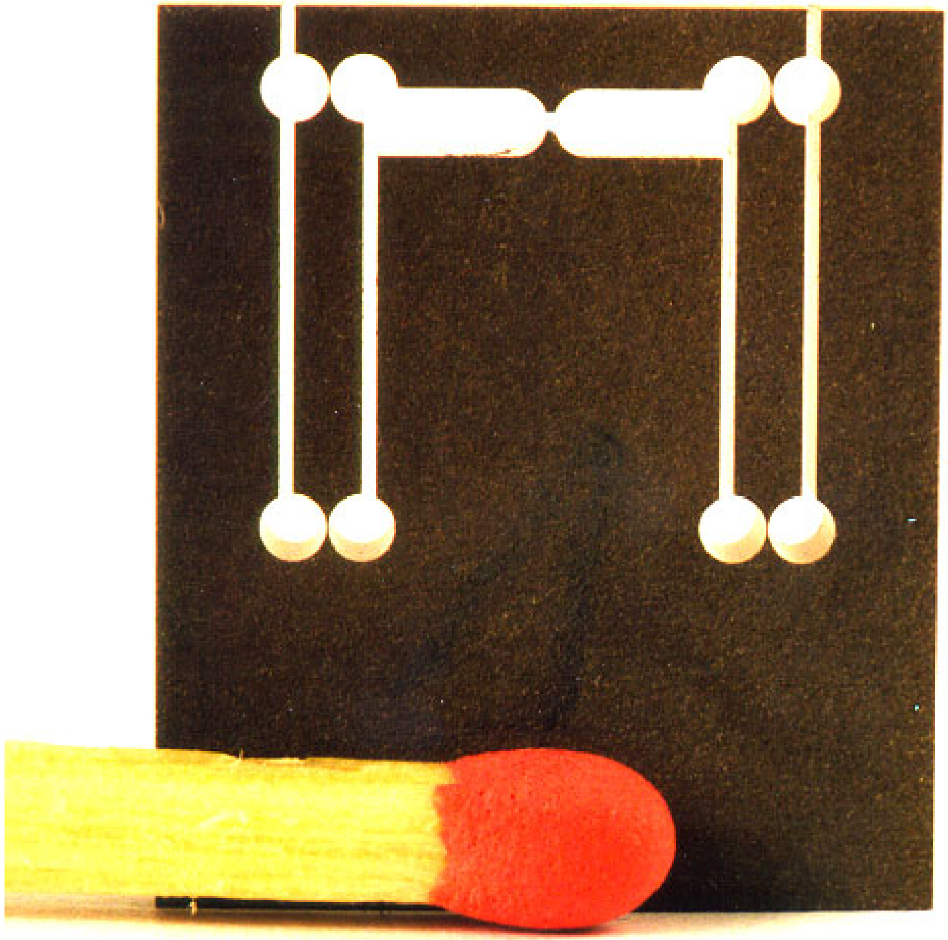
Wire electro-discharge machining



- Very small machining forces
- Insensitivity to hardness
- High aspect ratios
- High precision
- Monolithic machining

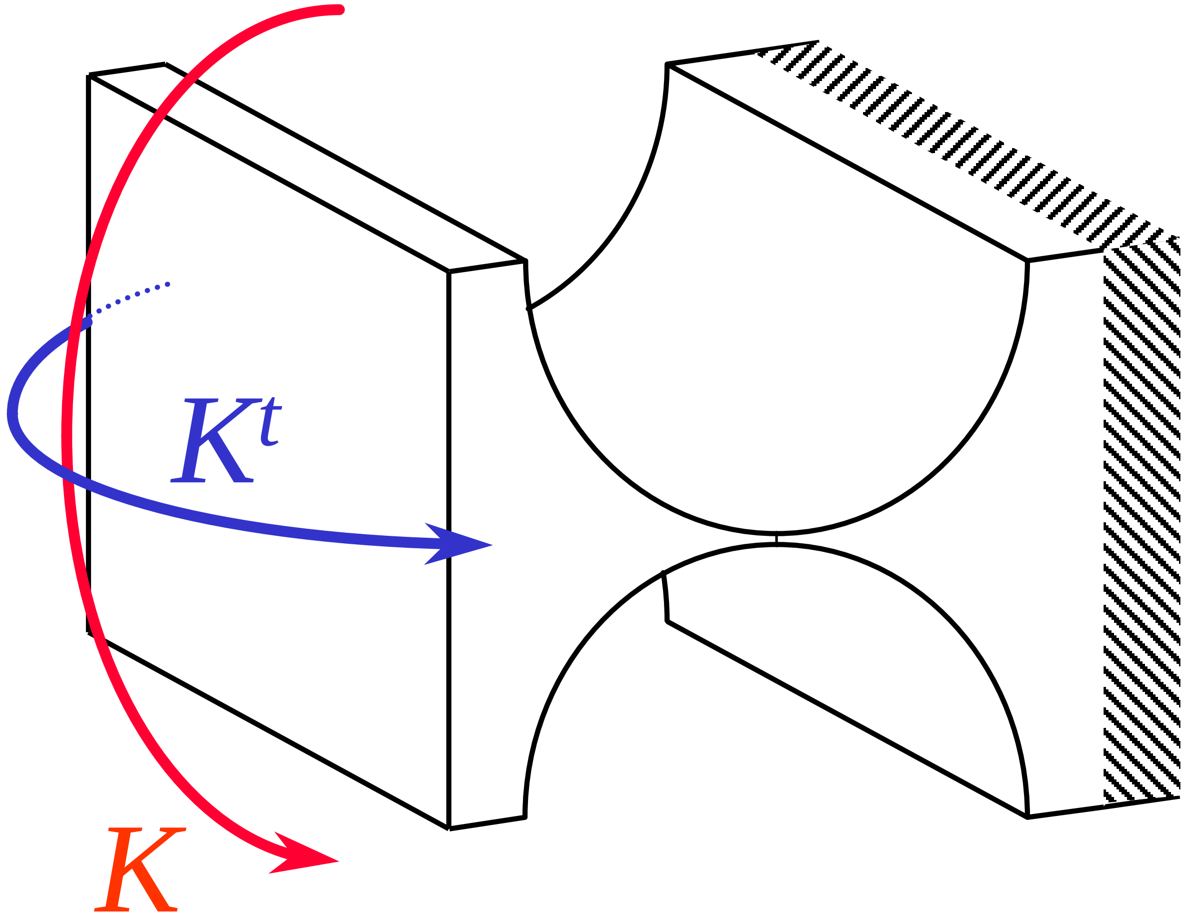
High Aspect Ratios



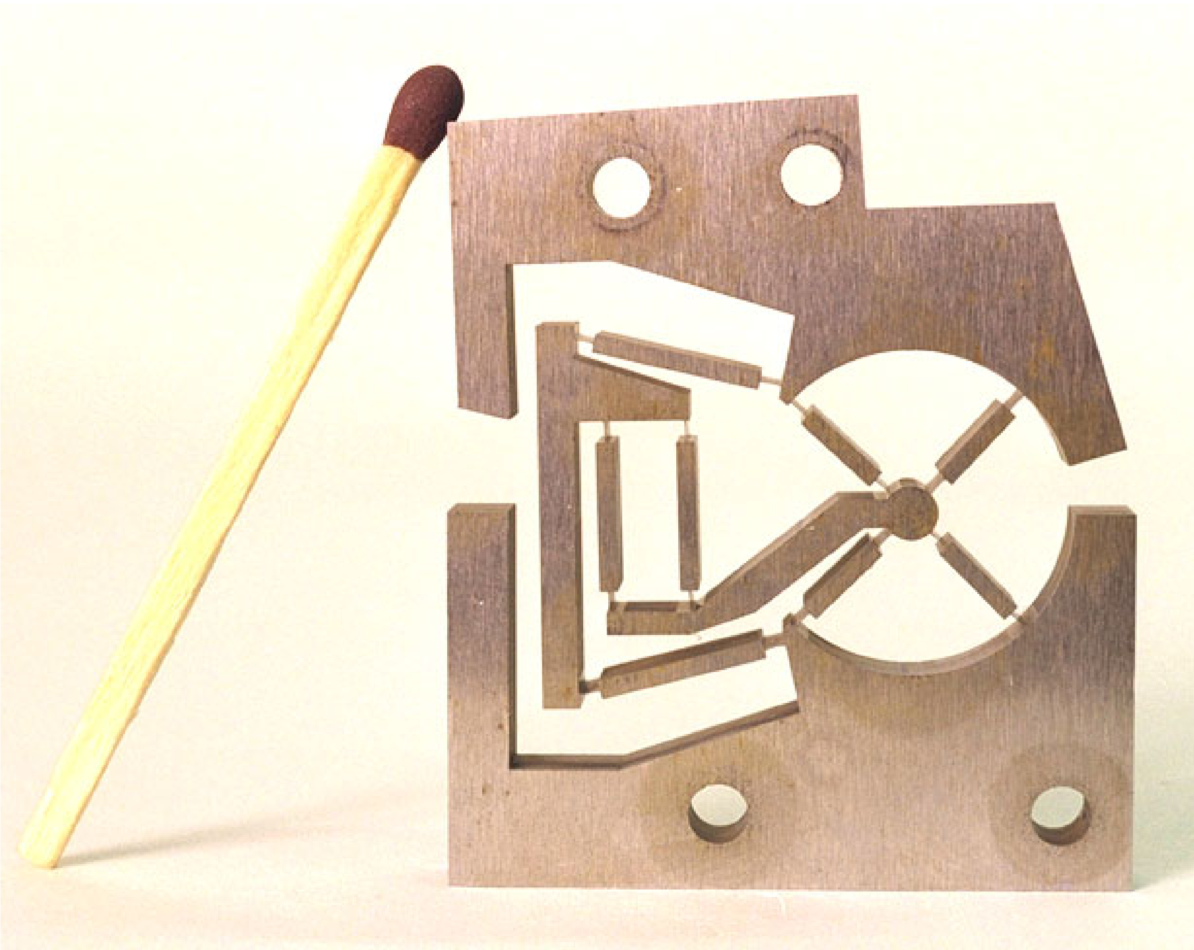


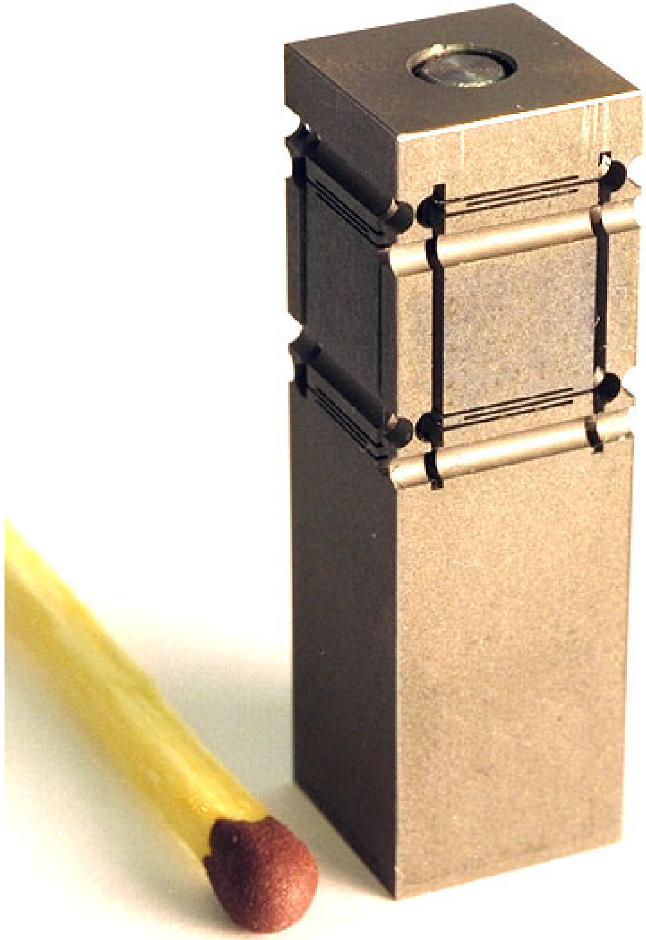
High Stiffness Ratios

$$\frac{K^t}{K} > 20'000$$



Monolithic manufacturing of complex structures



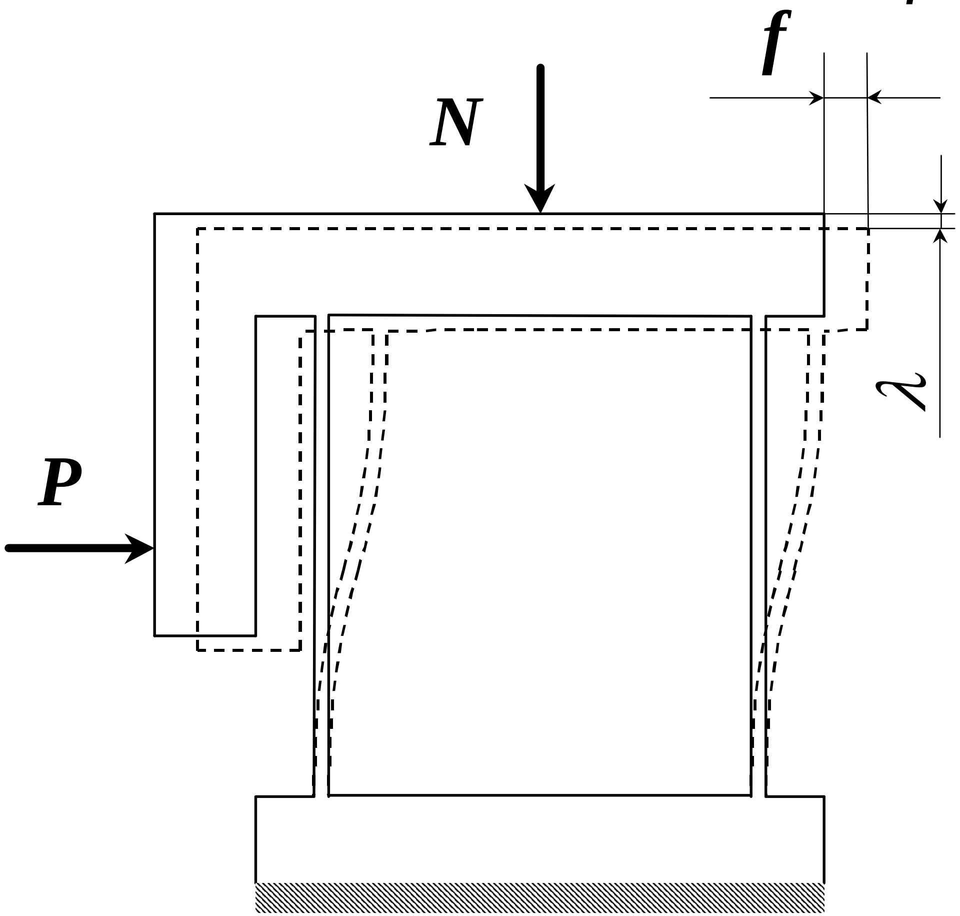


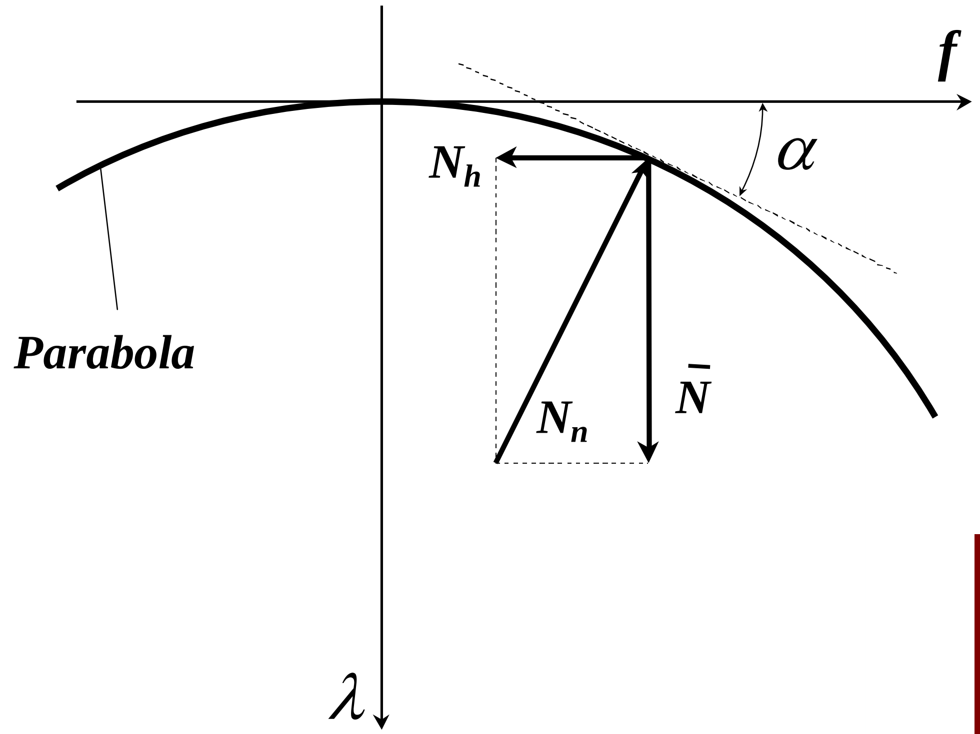
R. Clavel, S. Henein

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

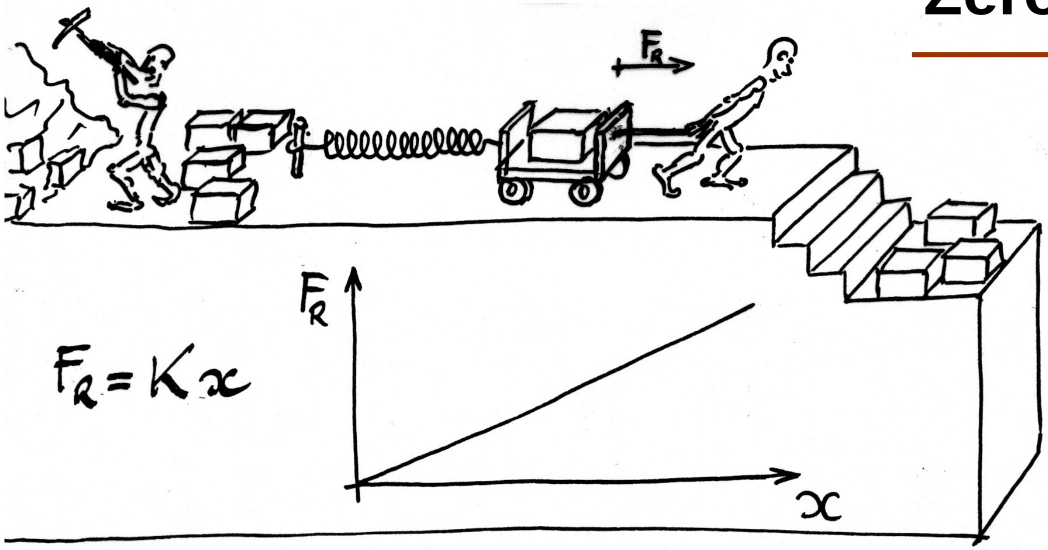
Parallel spring stage

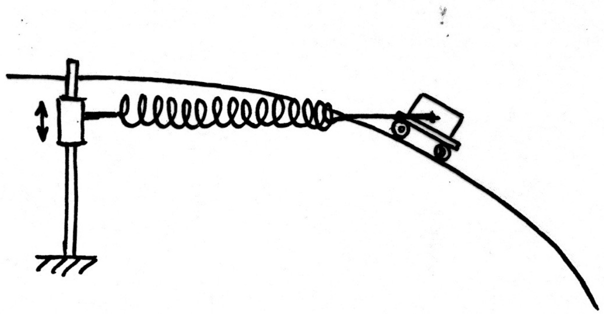
The stiffness $K = \frac{P}{f}$ depends of the load N

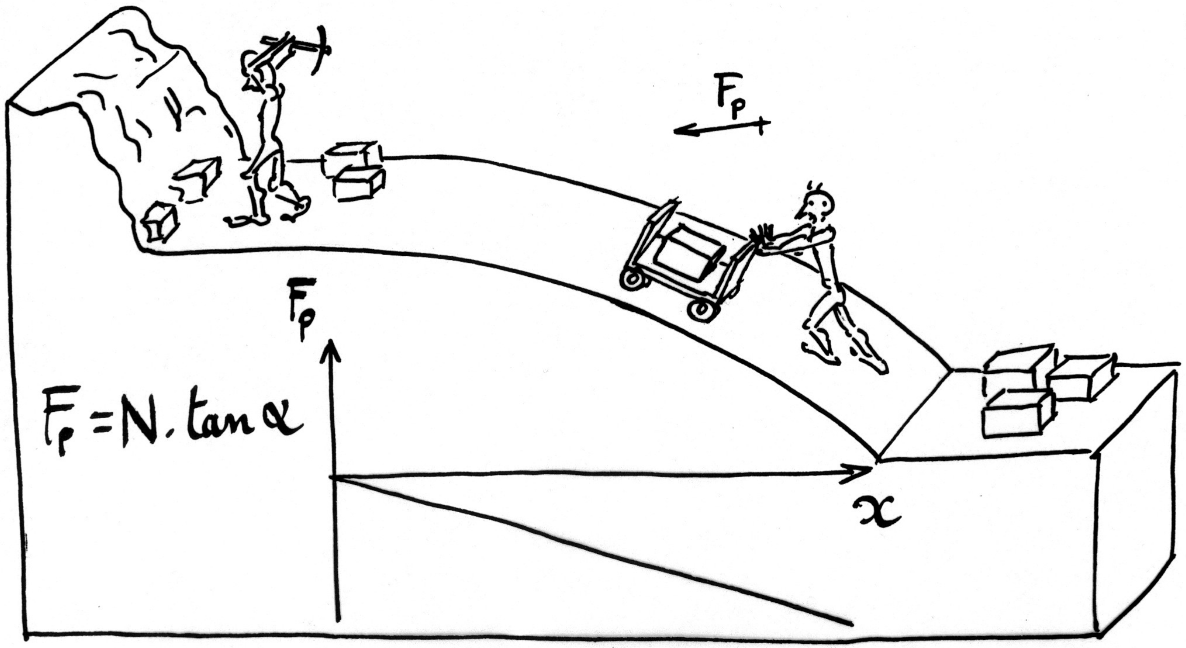


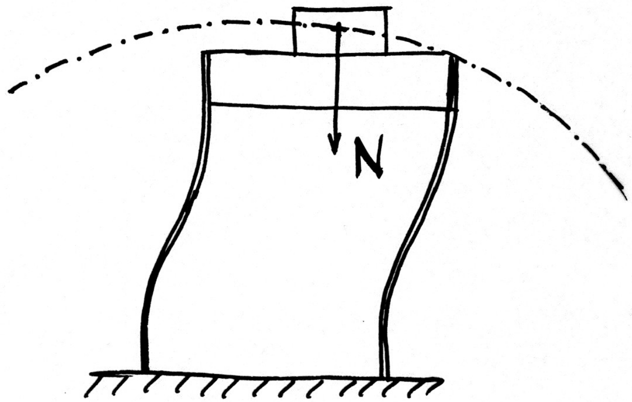


Zero stiffness flexible bearing

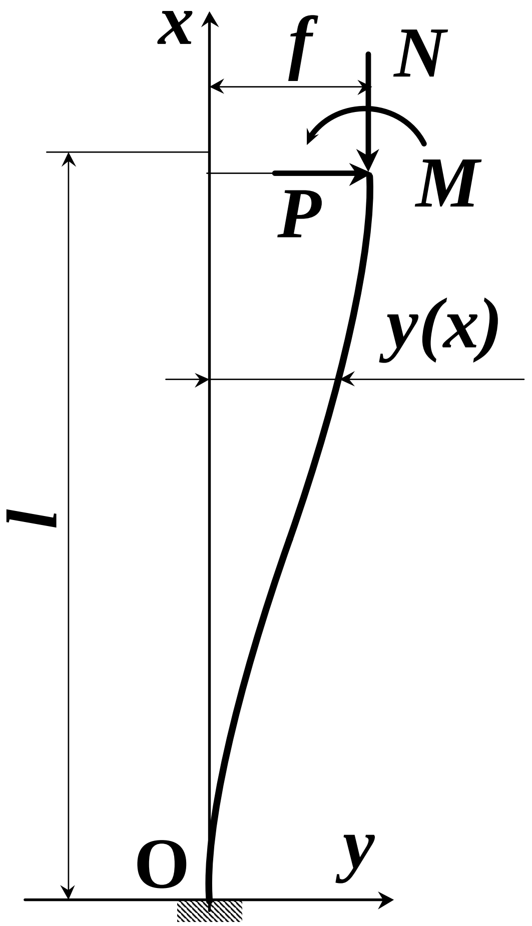


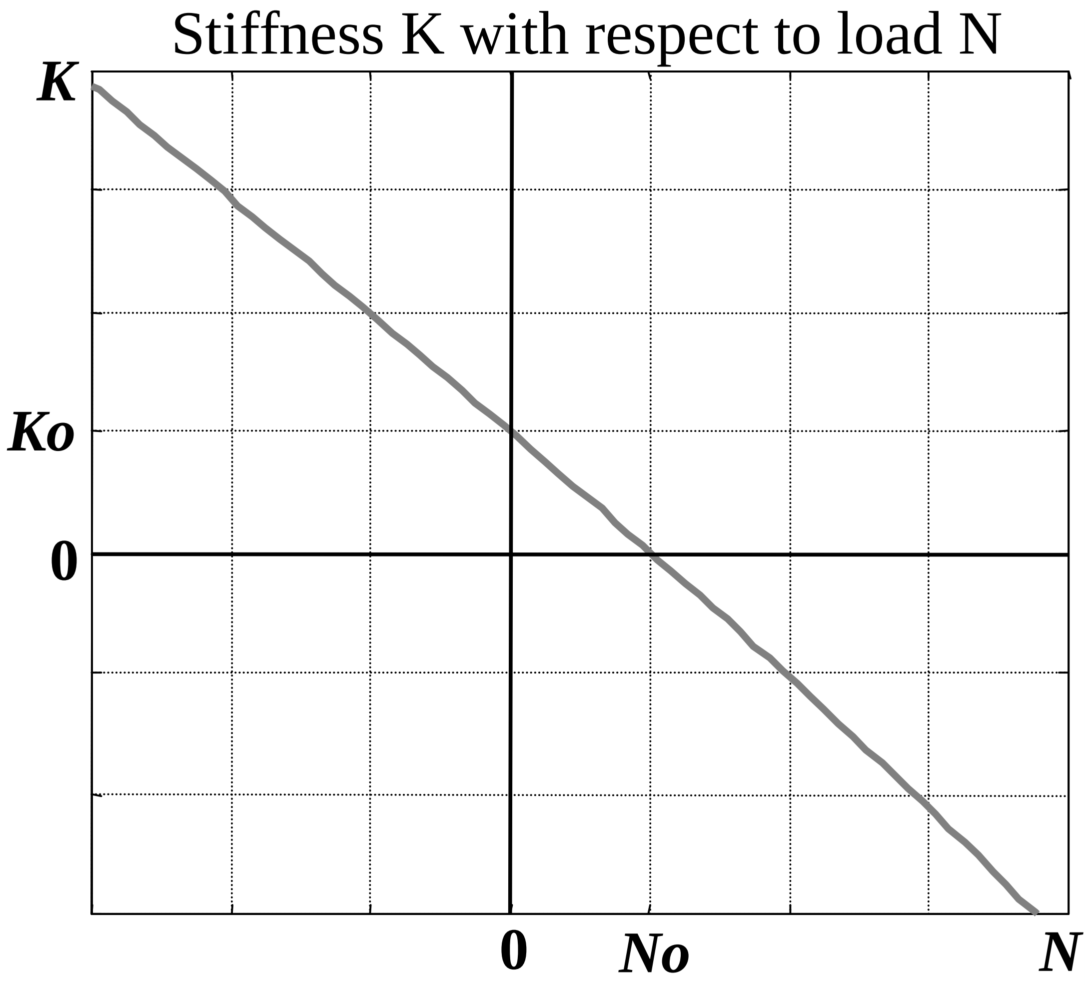




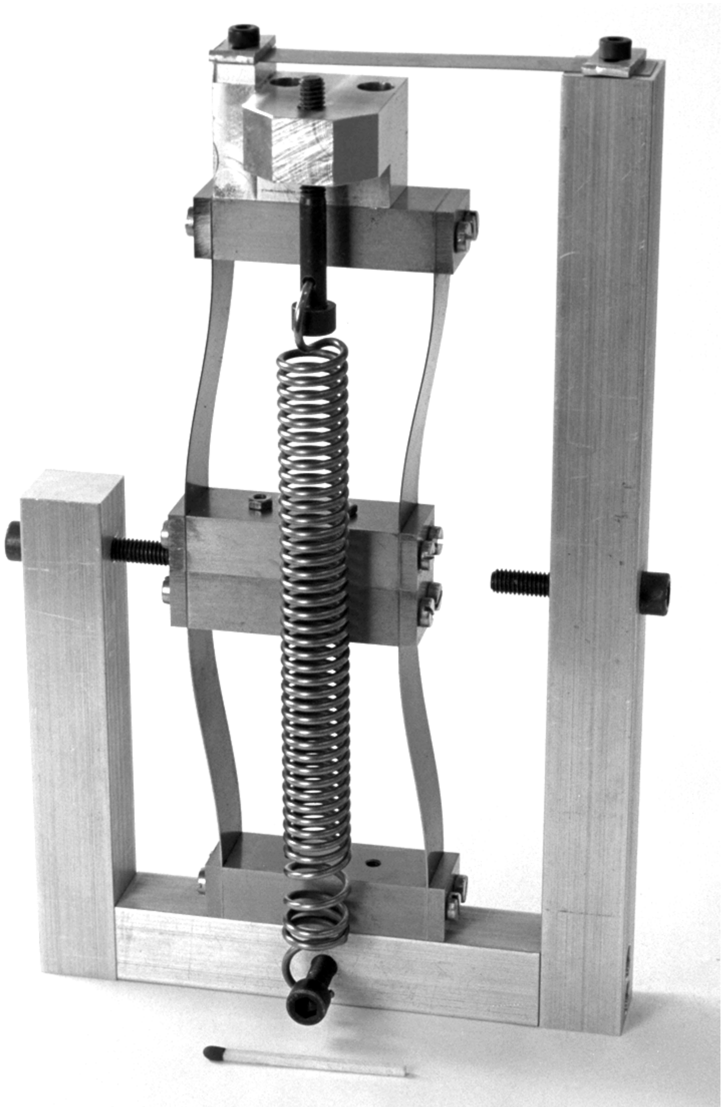


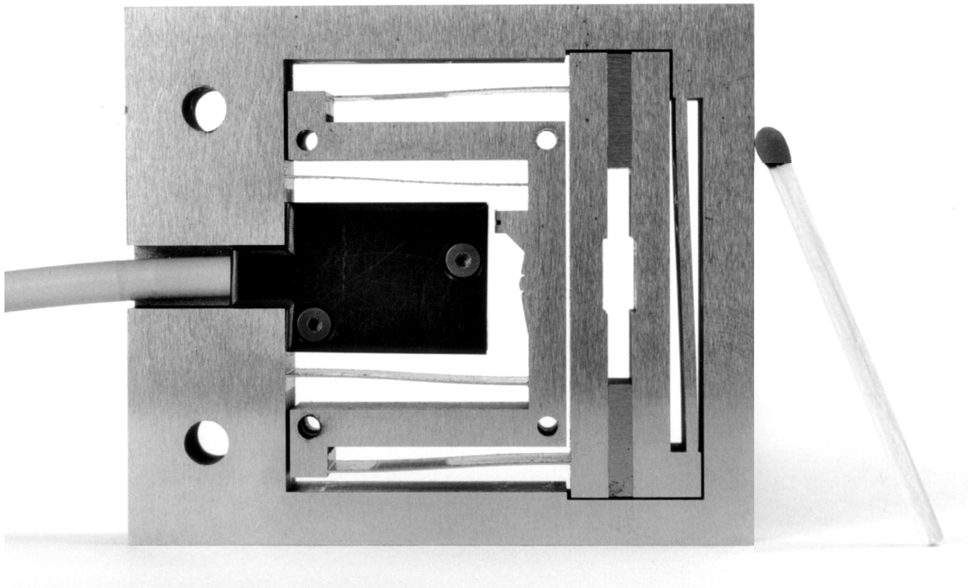
$$K = \frac{N}{\frac{2}{S}\tan\frac{Sl}{2} - l} \quad \text{with} \quad S = \sqrt{\frac{N}{EI}}$$

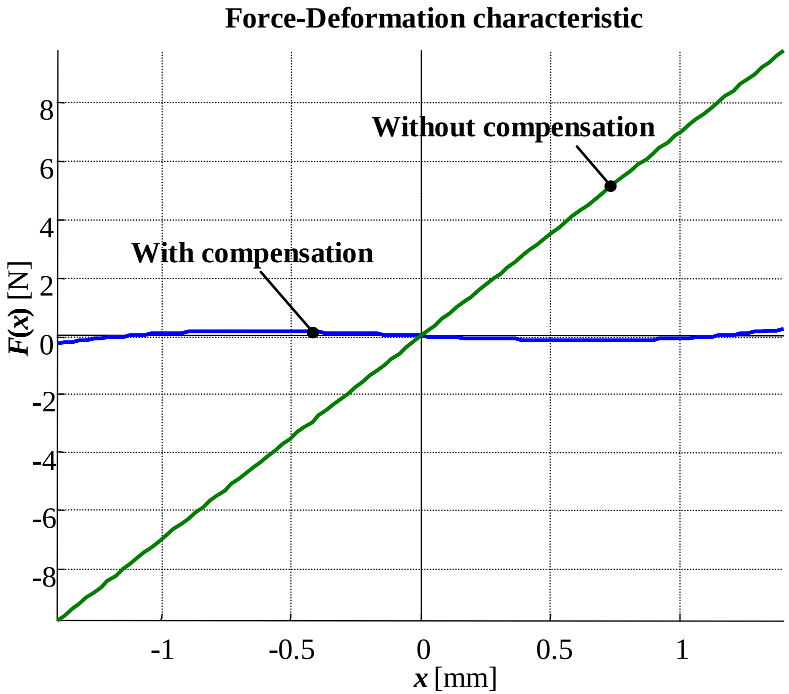




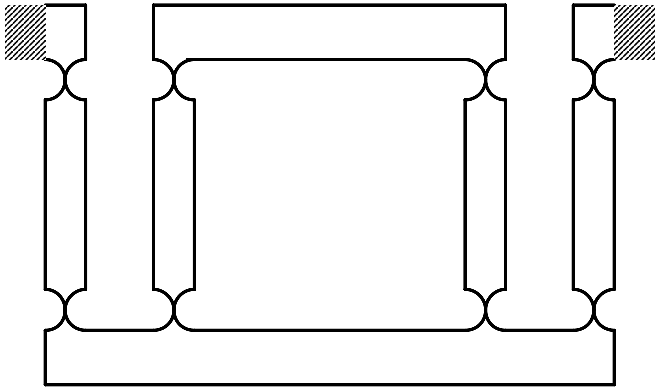
Tuneable stiffness translation bearing

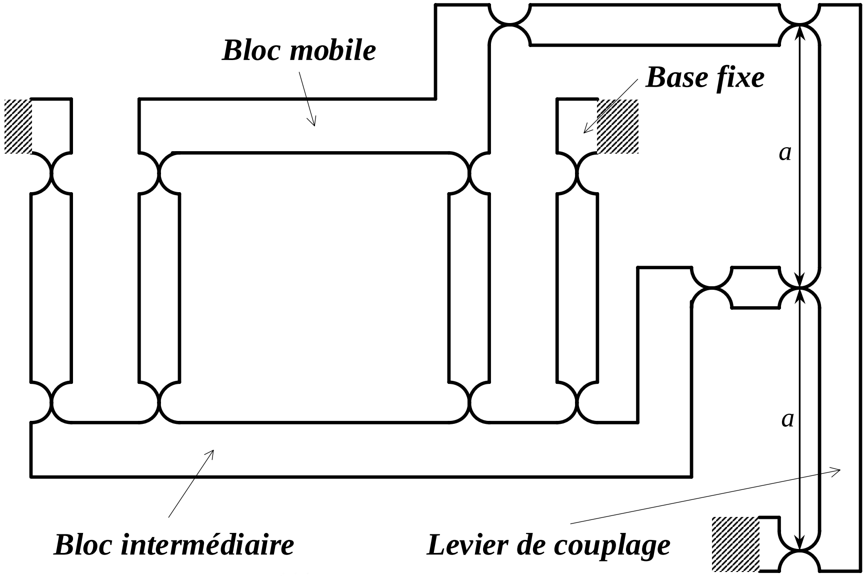


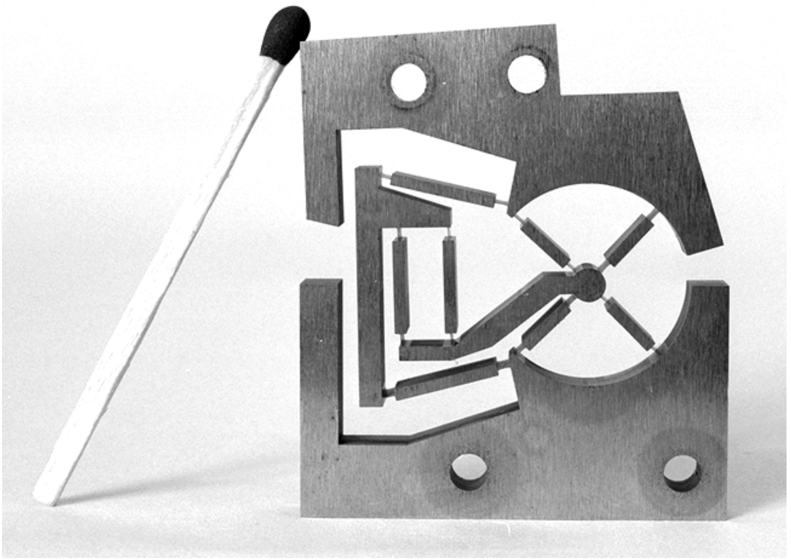




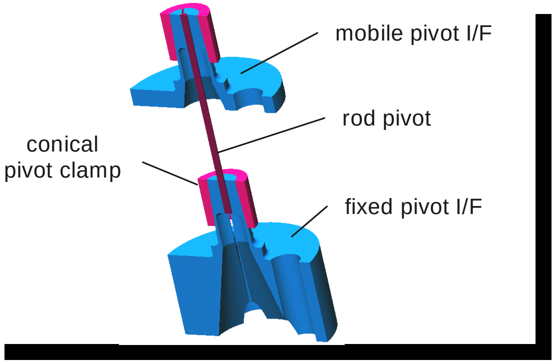
Stroke maximisation and parasitic movement compensation

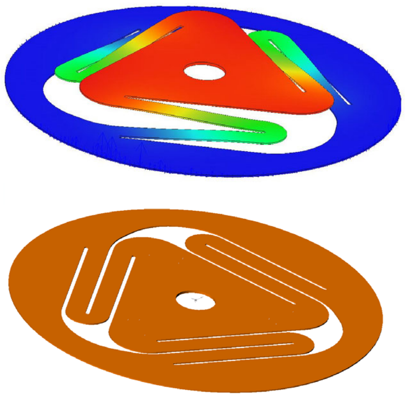


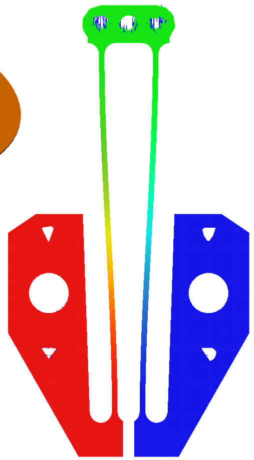


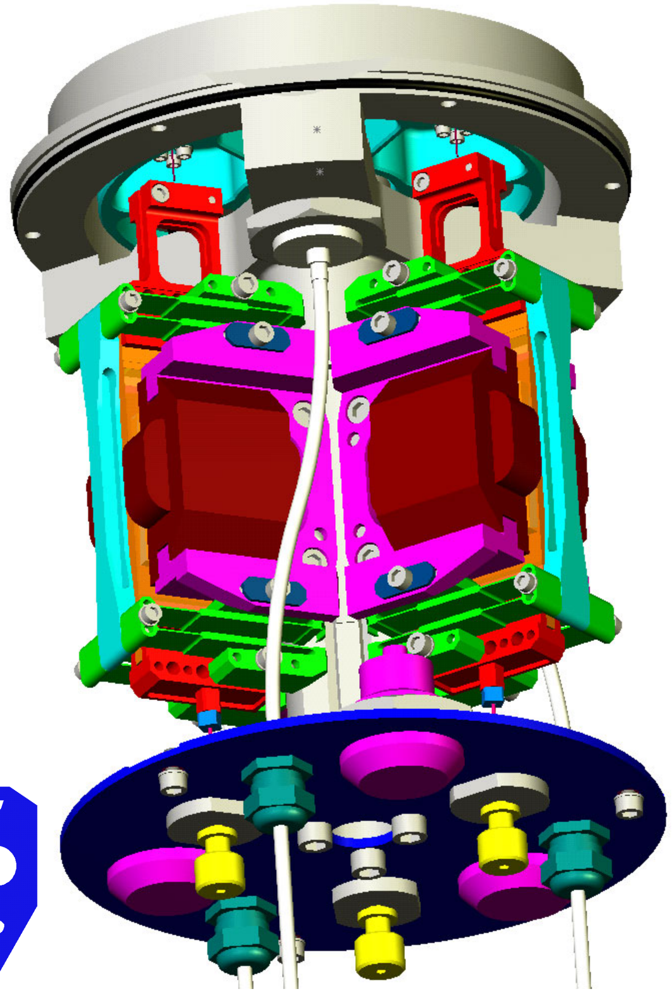


NAOS flexible structure

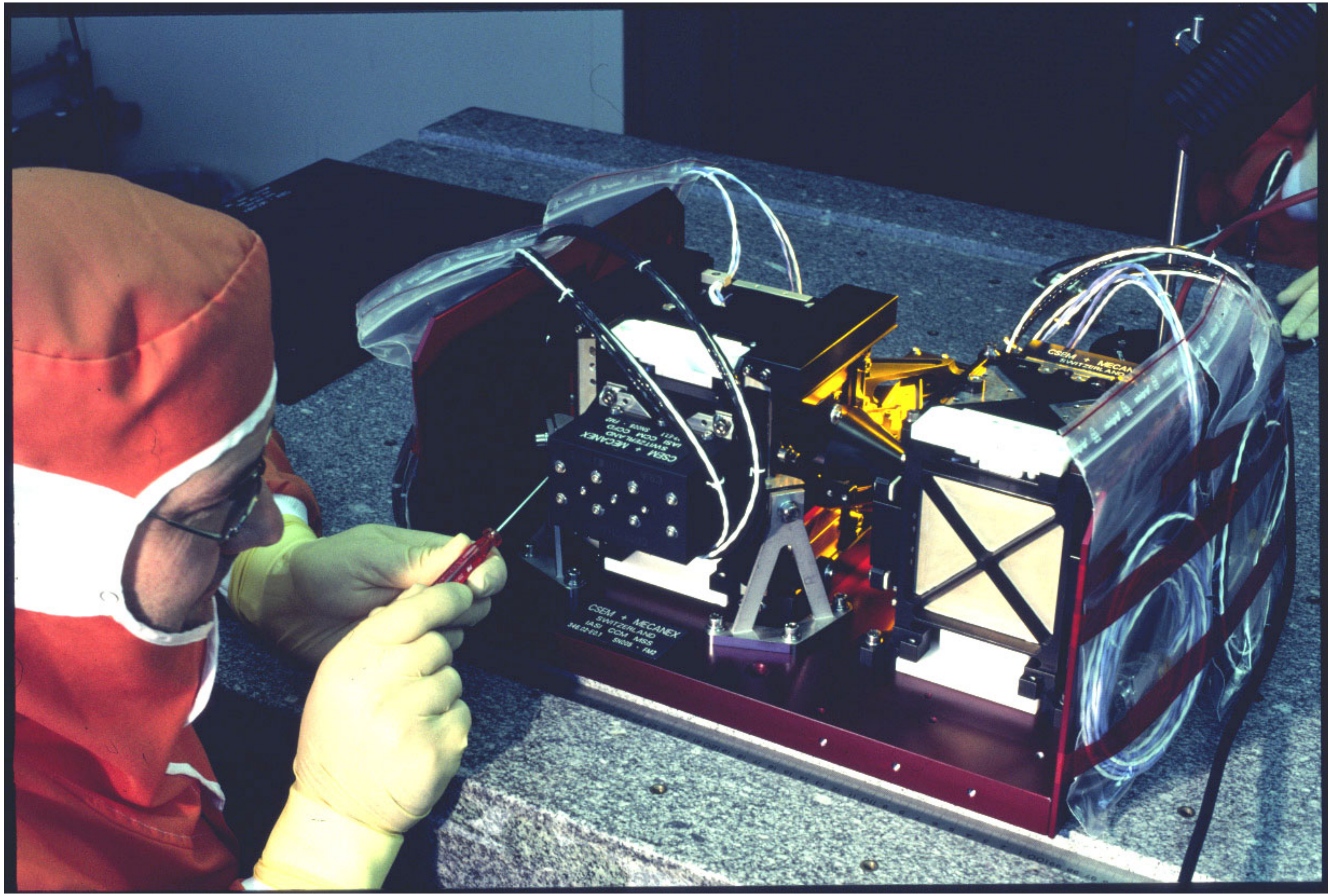






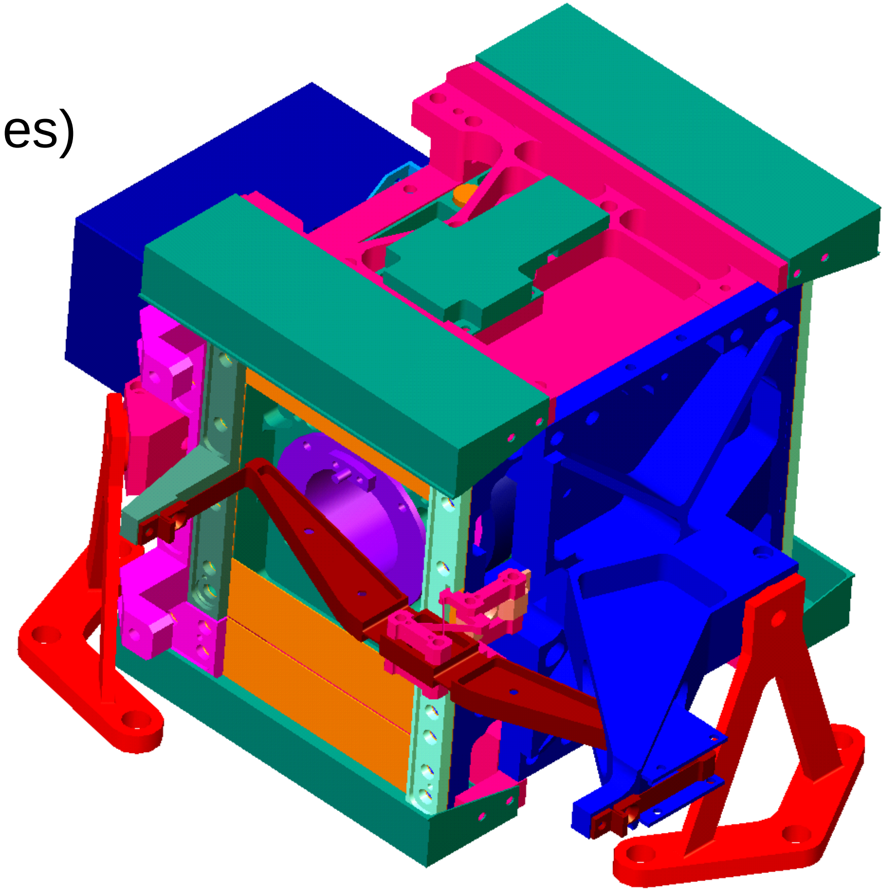


Corner Cube Mechanism
for IASI instrument on METOP



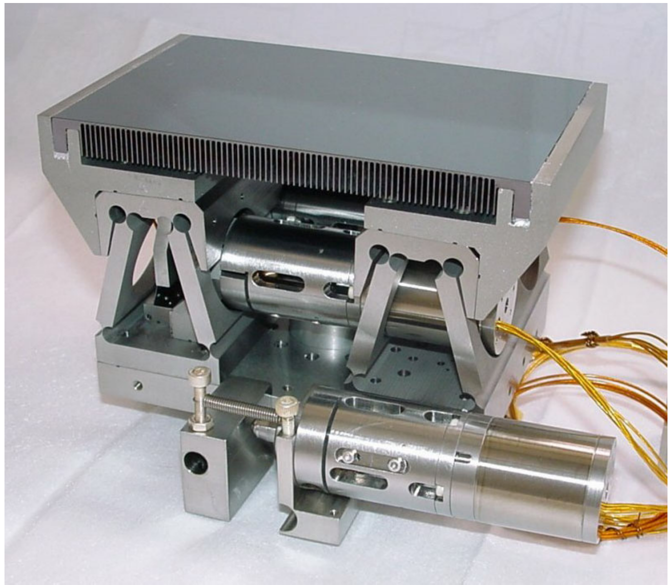
CCM main specifications

- Axial guiding for interferometer linear scanner
- Displacement ± 12 mm
- Lateral error off-axis <1 μm
- 2.5 Hz constant velocity travel
- Lifetime : 5 years non-stop (5.10^8 cycles)



Why compliant mechanisms @ accelerators

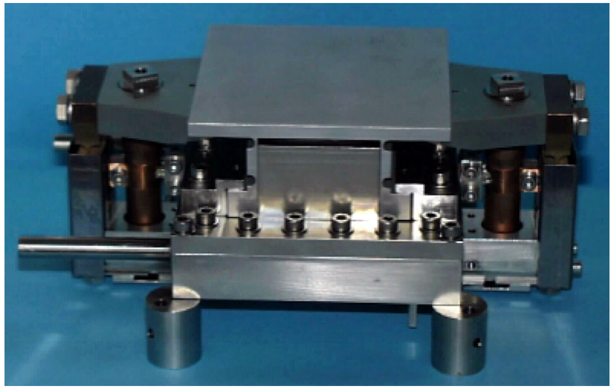
- The technological characteristics of SR and other accelerator facilities pose severe challenges in terms of stability and reproducibility of the beam position => optical elements must be moved with resolutions and accuracies in the nm and μrad region in an UHV environment with “hostile” characteristics (thermal variations, vibrations, …)
- Compliant mechanisms offer the high-precision coupled with UHV, radiation and high- or cryo-temperature compatibility
- They are also characterized by simple, reliable and maintenance free design

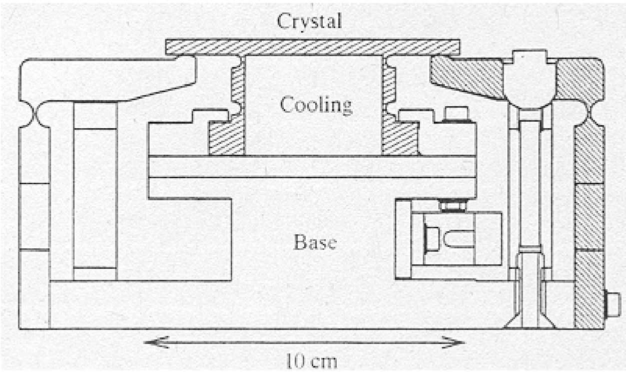


ESRF sagittal bender now commercialised through Oxford Instruments – used also on the SLS Materials Science beamline

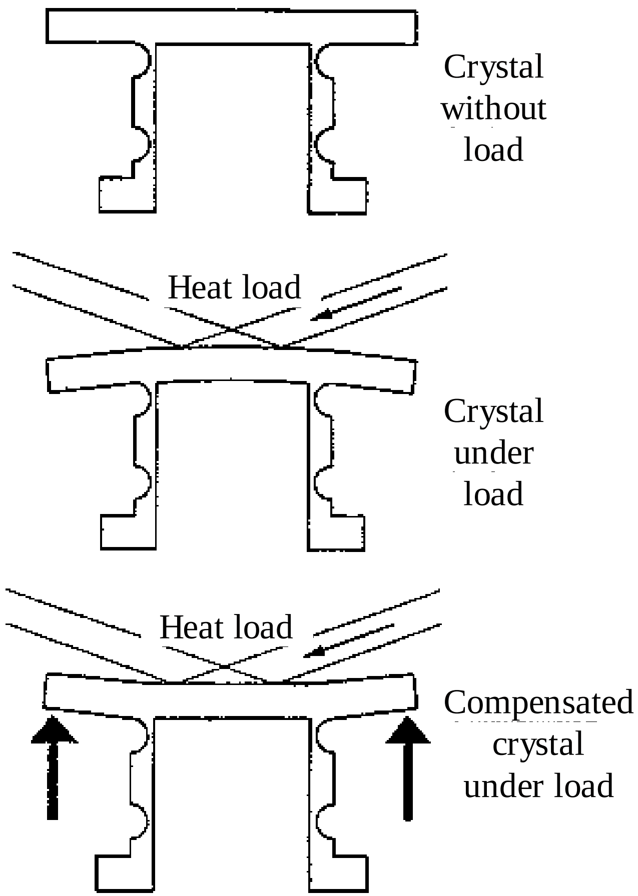
Compliant Mechanisms Used @ SLS (1)

High Heat Load Monochromator Crystal Mount – Materials Science Beamline



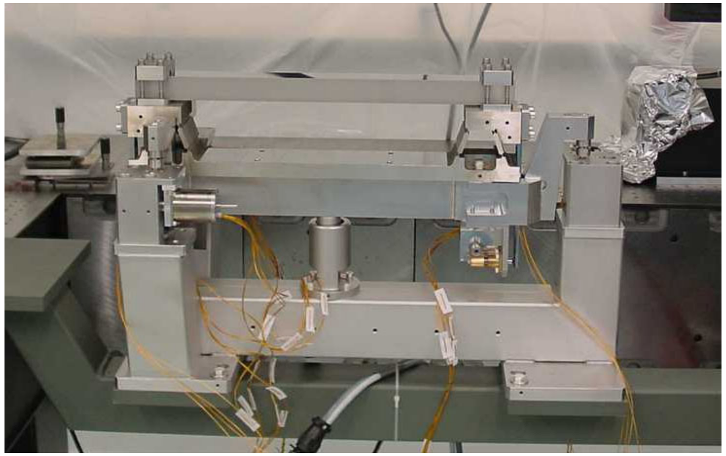


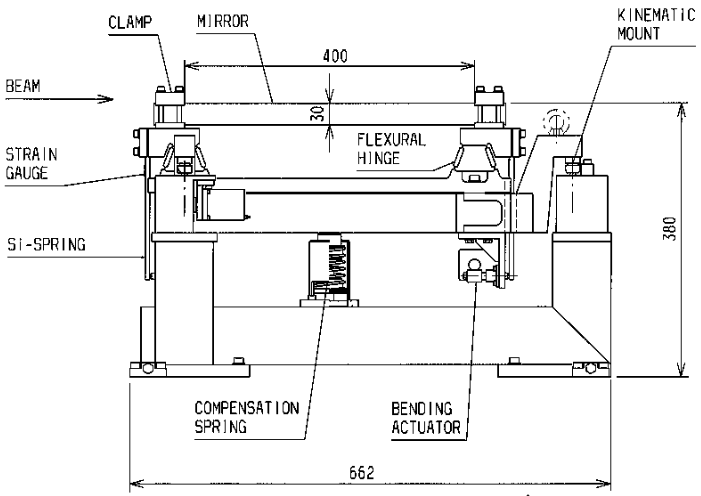
- Collaboration with HASYLAB at DESY, Hamburg (D)
- 1st mono crystal (Si (111)) absorbs up to 1.1 kW of power (up to 3 W/mm^2)
- Elastic hinges in crystal feet decouple it from the support structure and allow the adaptation of its shape
- The compensation of the convex bowing of the reflection surface induced by heat load is achieved by loading the crystal "wings"
- The supports of the lever arms comprise again a set of flexural elements used to achieve their longitudinal and transversal compliance



Compliant Mechanisms Used @ SLS (2)

In-Vacuum Dynamic Mirror Bender – Protein Crystallography Beamline



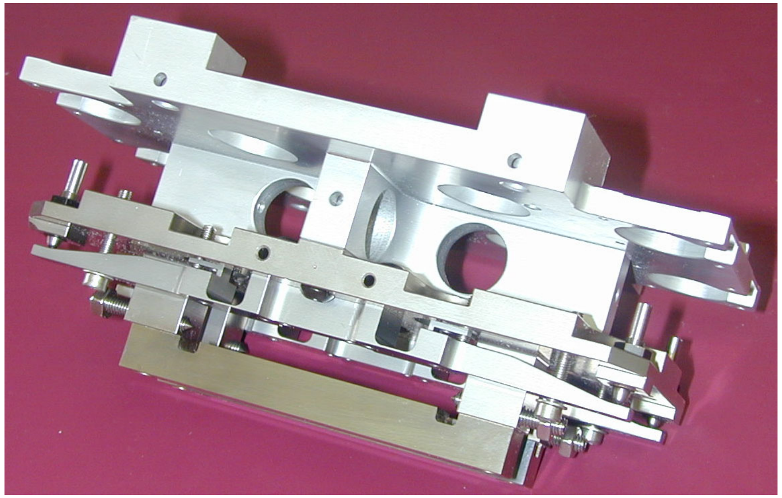


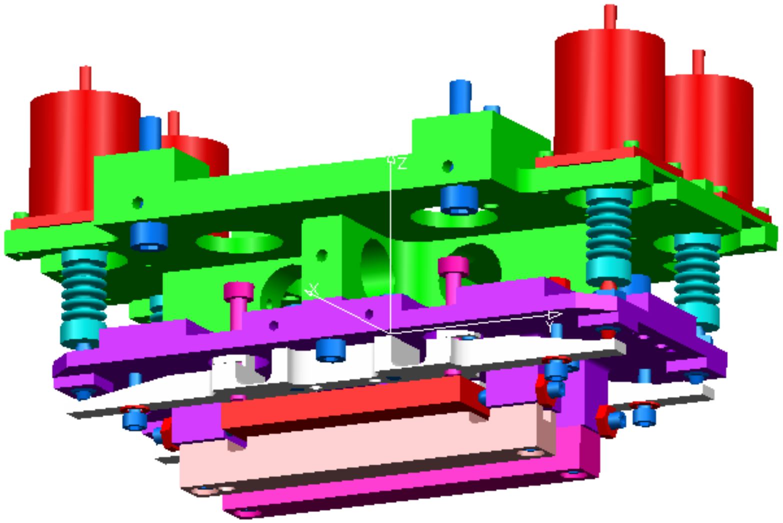
- Collaboration with ESRF, Grenoble (F)
- Vertical focusing rhodium coated fused silica mirror placed on the same optical table and downstream of the double crystal monochromator
- Dynamically bendable providing radiuses of curvature in the 400-12000 m range via 2 independent bending moments at mirror ends through hysteresis-free Si-springs
- The necessary rotational degrees of freedom and the uncoupling of the mirror from its basement are assured through a set of EDM machined flexure hinge based joints
- First experiences show that a sub-µrad bending reproducibility can be obtained

Compliant Mechanisms Used @ SLS (3)

Sagittal Crystal Bender – Protein Crystallography Beamline

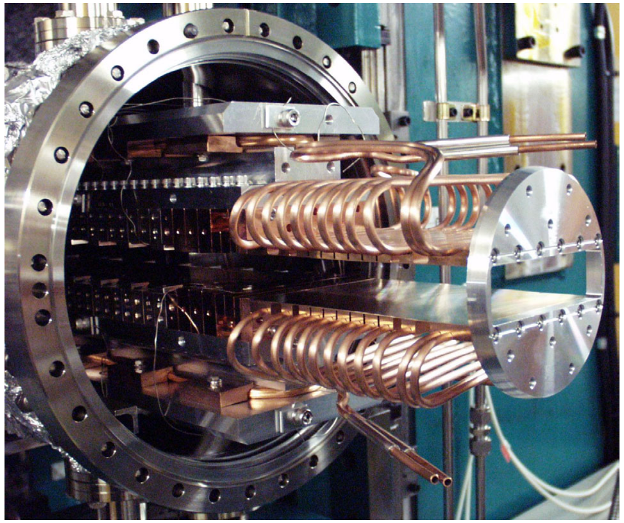
- Sagittal focusing of the second monochromator Si (111) crystal
- Provides an elegant way for dynamical micro-focusing of undulator radiation in the horizontal plane
- Bending achieved by means of 4 motorized micrometer screws and elastic elements-based lever arms
- First tests: at 10 keV a 6 mm beam was focused to 20 μm with an efficiency greater than 90%
- Dynamic focusing was also demonstrated
- Together with the vertical focusing bender, the micro-focusing of the beam to the designed values (10 x 25 μm^2), as well as a 0.1 eV energy reproducibility of the monochromator, were reached
- PSI patented

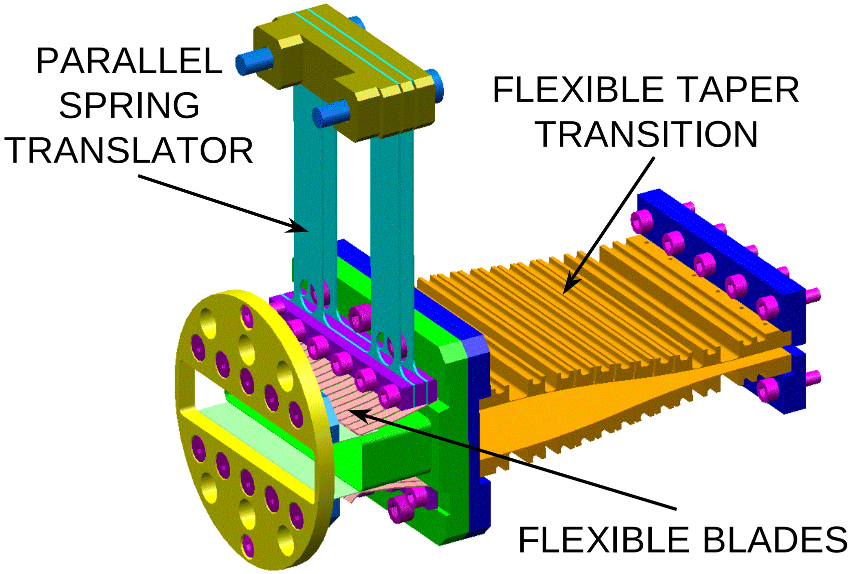




Compliant Mechanisms Used @ SLS (4)

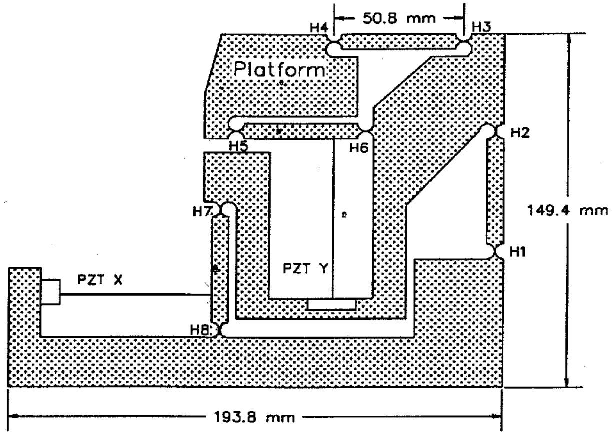
Flexible Taper Transition – In-Vacuum Undulators



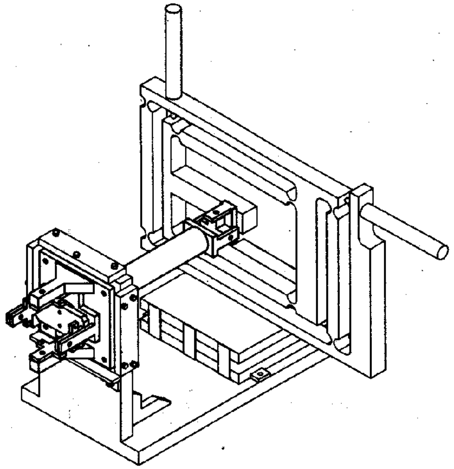


- Collaboration with Spring-8, Japan
- A ribbon cellular CuBe structure provides a smooth transition between the vertical aperture of the adjacent fixed taper section and the in-vacuum magnet carrying beams of the undulator, thus minimizing any impedance discontinuity
- Shape optimized via non-linear FEM analysis to increase fatigue lifetime
- In a further development step longitudinal compliance was assured via a parallel spring translator (+ a flexible-blades based transition) thus avoiding eventual axial-stresses-induced yielding due to the differential thermal expansion of the UHV chamber and the magnet carrying beams during bake-out

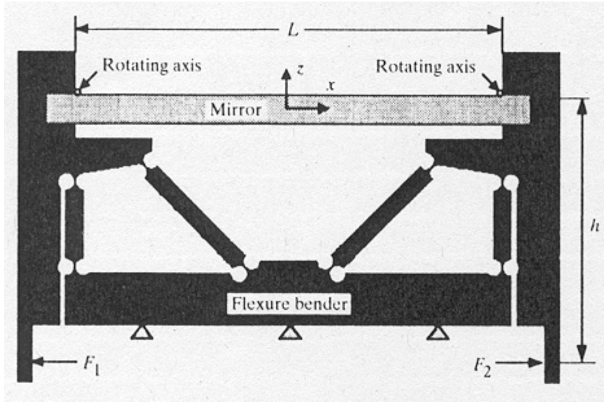
Compliant Mechanisms @ Other SR Facilities



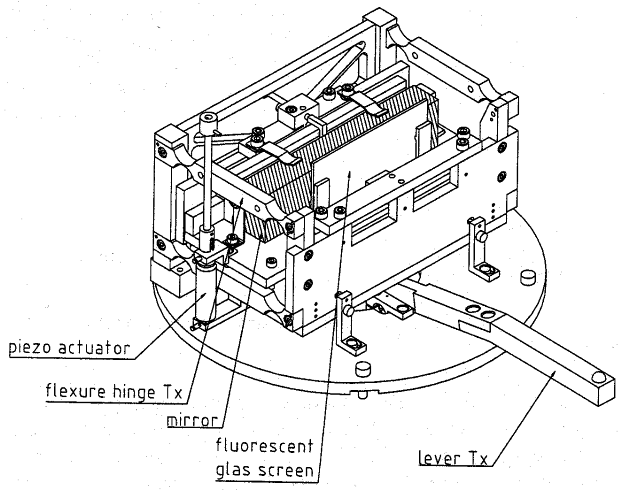
Scanning X-ray microscope micropositioning stage, Wisconsin (USA)



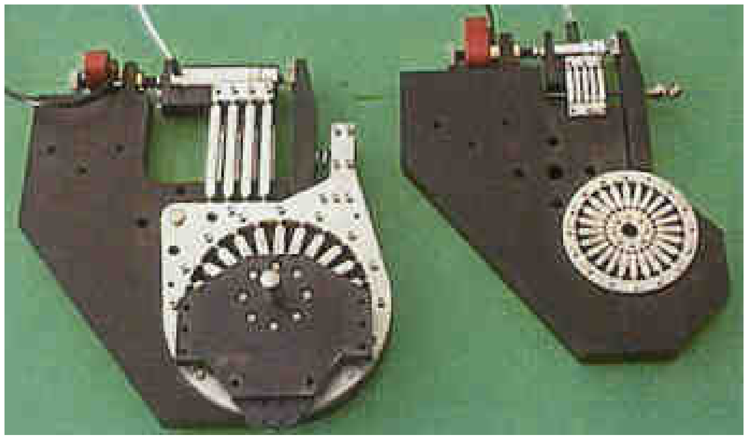
Mirror manipulator, Elettra, Trieste (I)



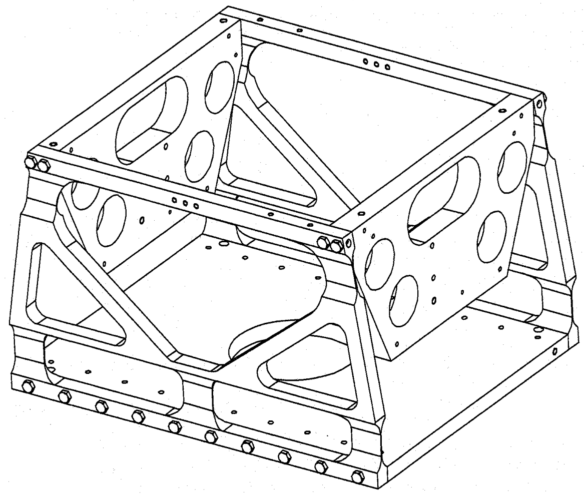
Mirror bender, ESRF, Grenoble (F)



Refocusing mirror holder, Bessy II, Berlin (D)



High-stiffness monochromator weak-link mechanism, APS, Argonne (USA)



Switching mirror flexible parallelogram, Bessy II, Berlin (D)

Conclusion

- Mastering the design of complex flexible structures
- Mastering the interactions at the system level between
  - Mechanical structure
  - Actuators
  - Sensors
  - Electronics
  - Control algorithms

allows to benefit from the compliant mechanisms approach in the design of accelerator equipment and instrumentation.