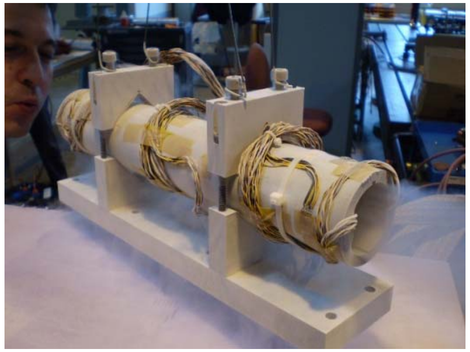
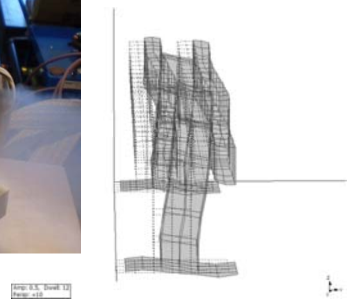
European Organization for Nuclear Research

Engineering Department

Techniques of mechanical measurements
for CERN Applications and Environment

M. Guinchard, A. Kuzmin, EN-MME





Mechanical Measurement Lab, 2010.11.03

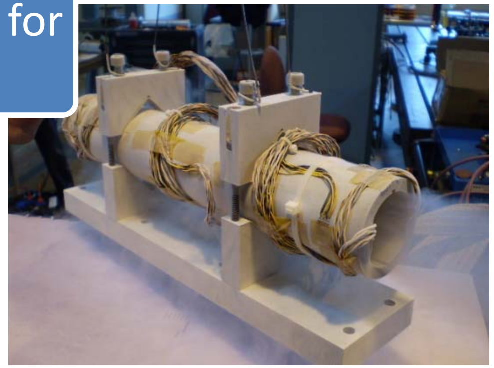
EDMS no. **1064933**

Outline

- Introduction
- Measurements with strain gauges
- Measurements with capacitive gauges
- Other Measurements
- Conclusion

Introduction : Why perform mechanical measurements ?

Generate data for design



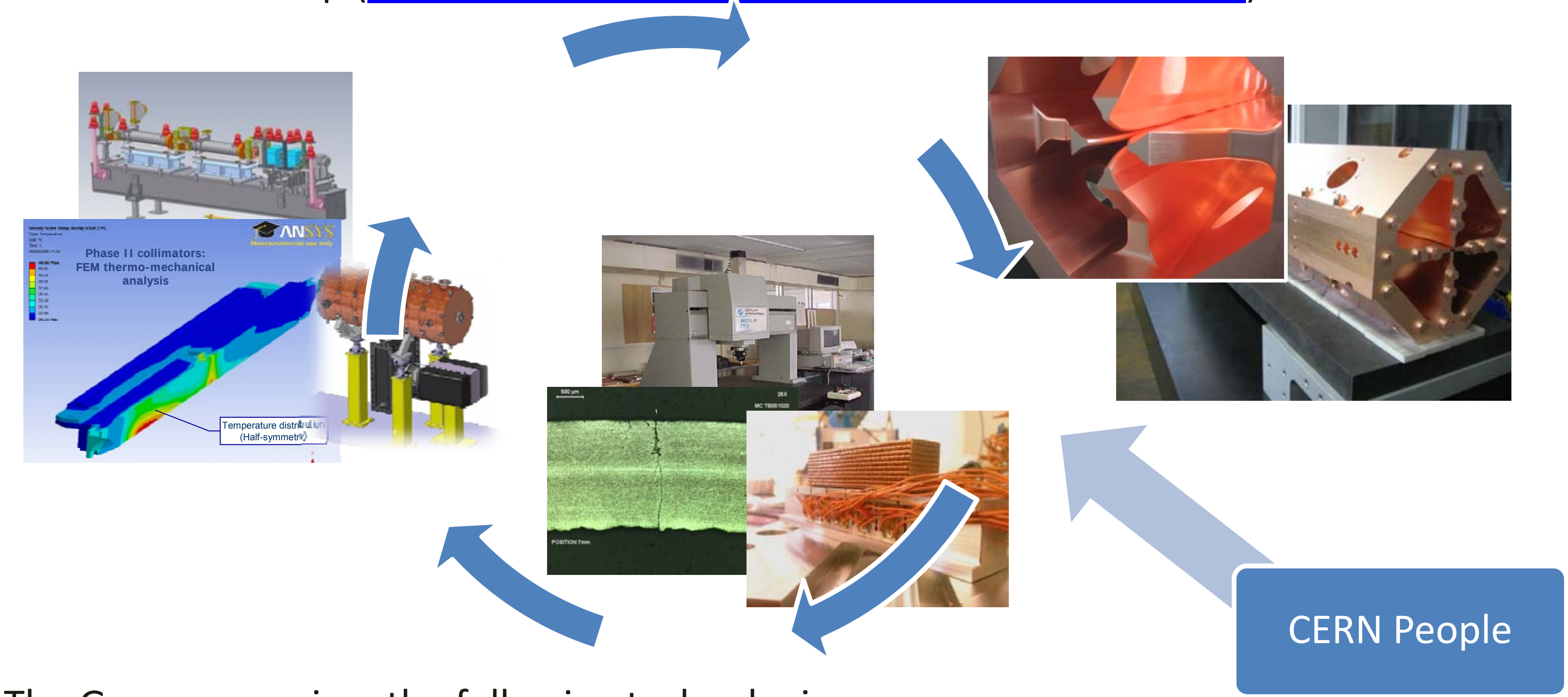
Generate data to validate or propose a theory

Why perform mechanical measurements ?

Maintenance
Safety

Introduction : Mechanical measurements at CERN

- EN-MME Group (http://en-dep.web.cern.ch/en-dep/Groups/MME/)

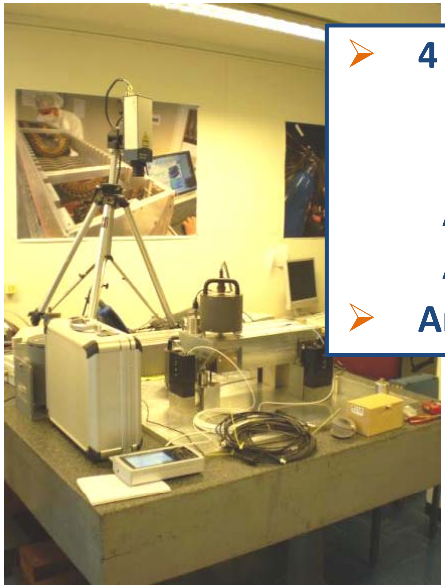


The Group comprises the following technologies:

- Mechanical engineering and design office
- Mechanical workshop with several assembly techniques (welding, vacuum brazing, electron-beam welding, laser, sheet metal work)
- Metrology, Metallurgy and Mechanical measurement lab

Introduction : Mechanical measurements at CERN

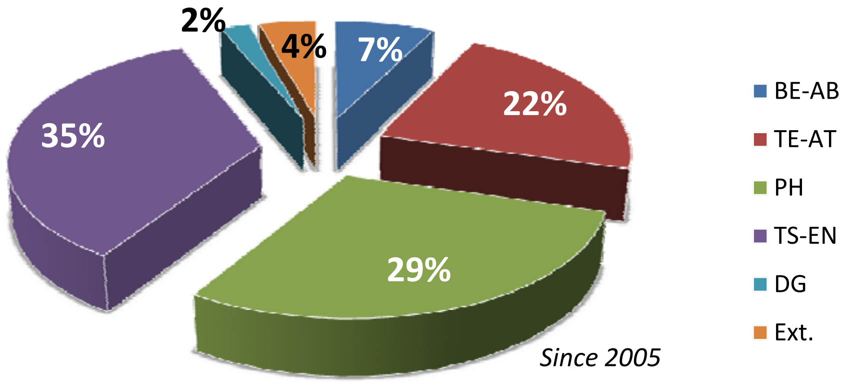
- Mechanical measurements lab :



- **4 people work in the lab :**
  - Frederika De Jaegere (Swedish) - Apprentice
  - Michael Guinchard (France) - Staff
  - Andrey Kuzmin (Russia) - UPAS
  - Ansten Slaathaug (Norway) - TECH
- **Around 40 tasks per year**

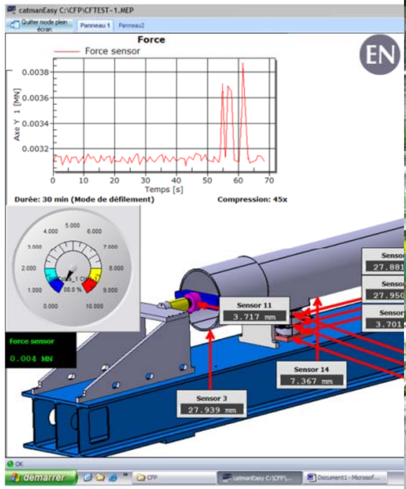
Bdg. 376/R-003

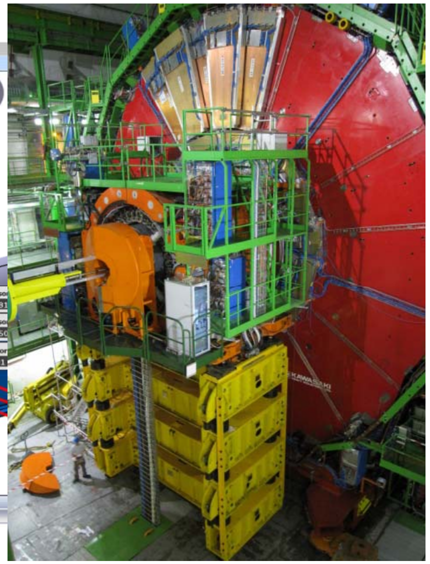
- Mechanical measurements requests by department :

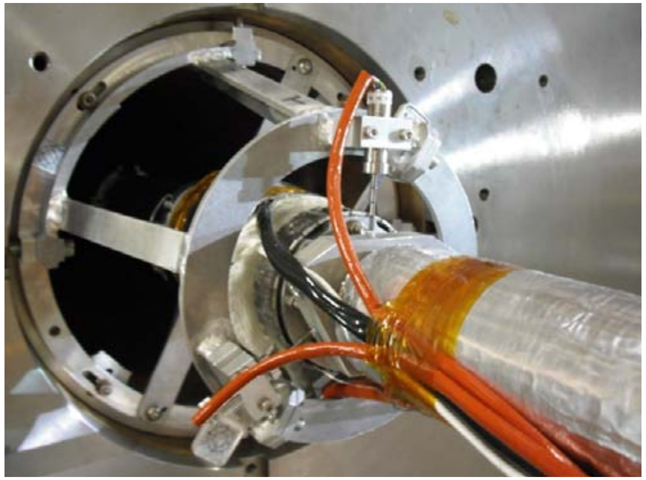


Introduction : Mechanical measurements at CERN

- Recent projects :
  - Vibration control on the PS power generator
  - Load measurements on the brazing machine for the LHC interconnections
  - Force and displacement measurements for LHC magnet cold feet
  - Ground motion measurements at CMS
  - Experimental modal analysis on ”Stave” prototypes for the ATLAS inner detector upgrade - Collaboration UNIGE
  - Monitoring system for the ATLAS Beam pipe alignment on the small wheel







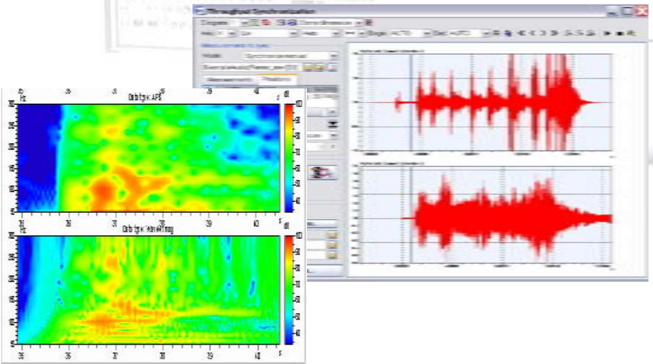
Introduction : Mechanical measurements at CERN

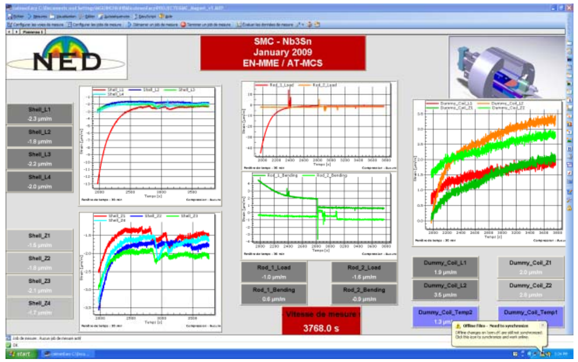
- Equipment :

Displacement Transducers | **Vibration Sensors** | **Load / Tensile Sensors** | **Strain Gauges**

Static and Dynamic Acquisition System

Post-Processing and Analysis





Parameters measured : Force , Stress, Strain, displacement, vibrations, temperature, etc...

Environmental conditions : Magnetic field, cryogenic temperature, radiation

- Stress, Force relation (traction)

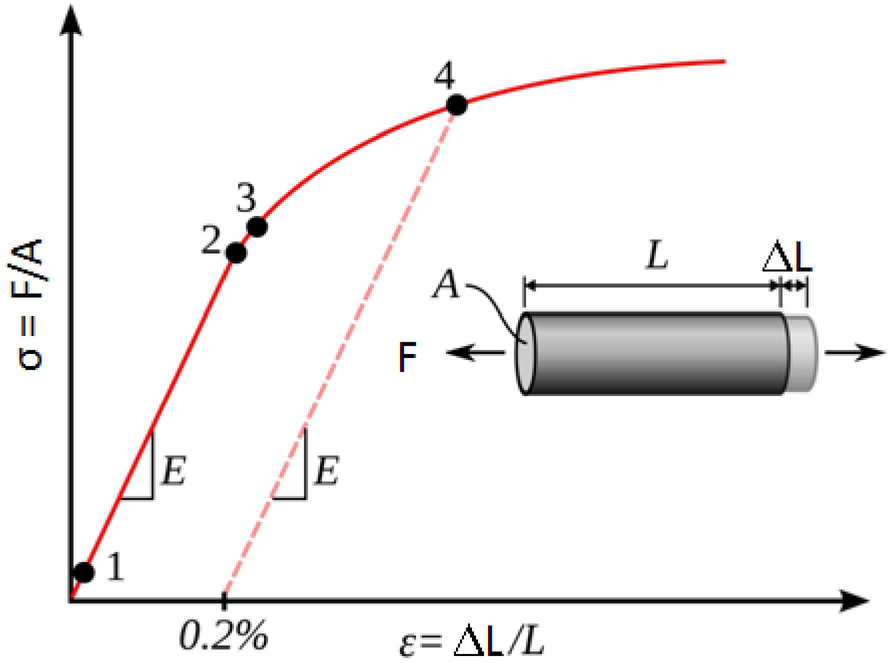
$$\sigma = F / A$$

With :

σ : Mechanical stress (MPa)

F : Force applied (N)

A : Surface (mm²)



- Stress – Strain curve

$$\sigma = E \cdot \varepsilon$$

for the elastic region, with :

σ : Mechanical stress (MPa)

E : Young modulus (MPa)

ε : Mechanical strain (m/m)

- Microstrain

$$\mu\varepsilon = 1 \times 10^{-6}\ m/m = 1\mu m/m$$

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EN

Measurements with Strain gauges

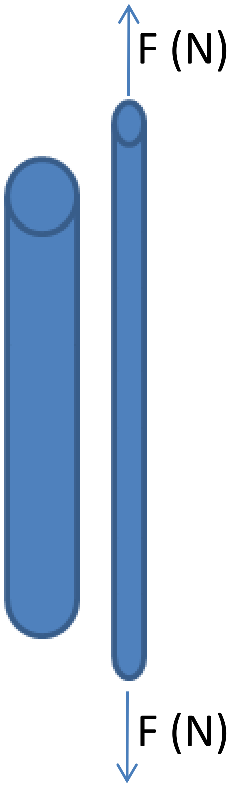
Strain gauges : Introduction

- Historic :
  - **1856 :** Lord Kelvin first reported on a relationship between strain and the resistance of wire conductors.
  - **1938 :** E. Simmons and Arthur C. Ruge invented the strain gauge
  - **After 1952 :** Optimisation period and strain gauge are now used by many industry.

- Applications : All the industry !

Strain gauges : Basic principles

The resistance of a wire (R) is a function of three parameters :



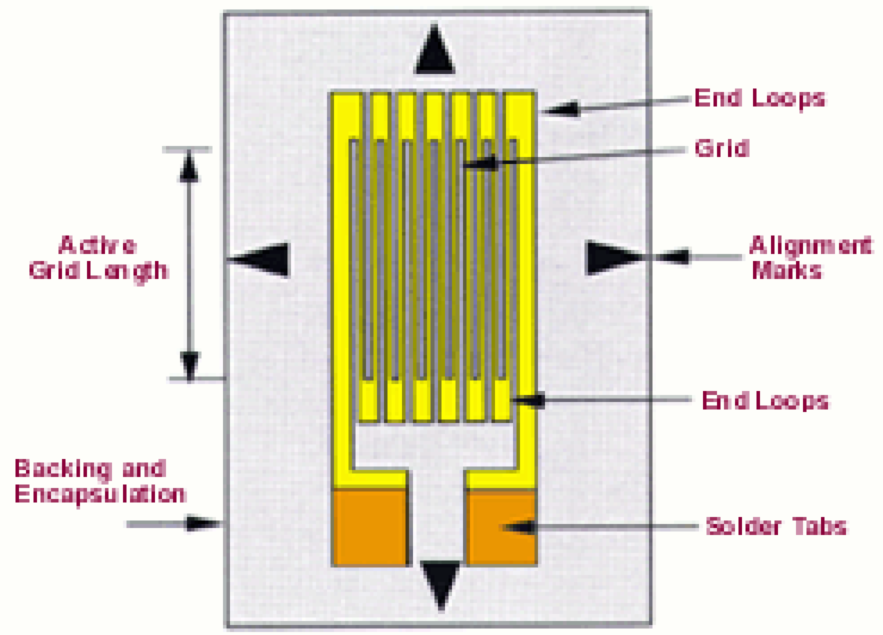
$$R = \rho \frac{L}{S}$$ with R (Ω), Length (m), Section (m²) and ρ (Ω /m)

With an external force, the resistance value increases.

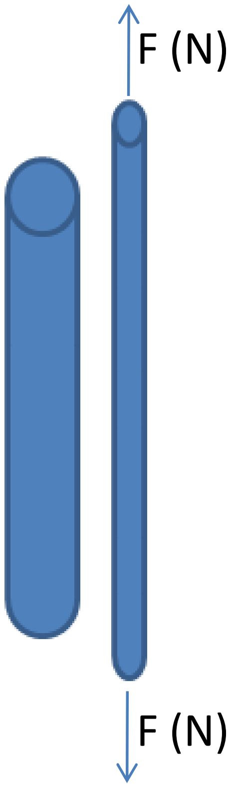
A strain gauge is a long length of conductor arranged in a zigzag pattern on a membrane. When it is stretched, its resistance increases.

$$\frac{\Delta R}{R} = k \frac{\Delta L}{L}$$

with k : Gauge factor



Strain gauges : Basic principles



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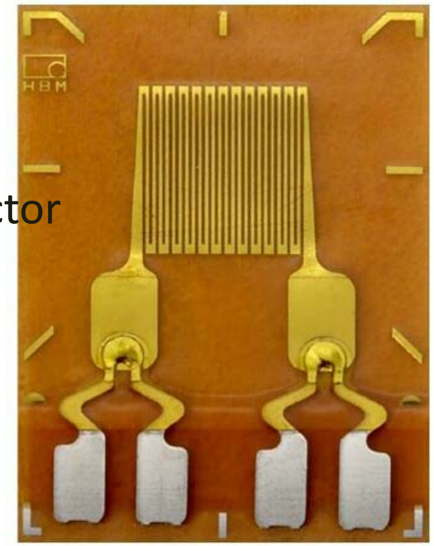
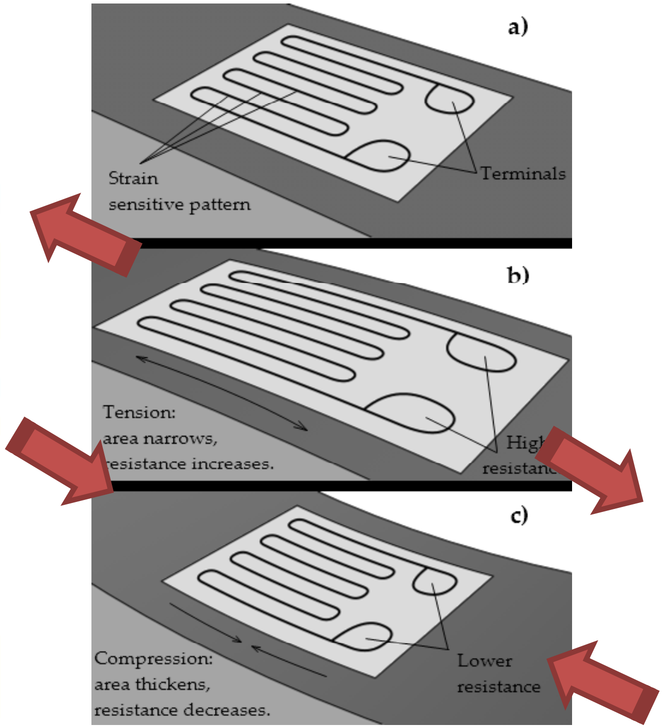
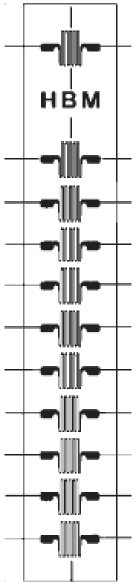
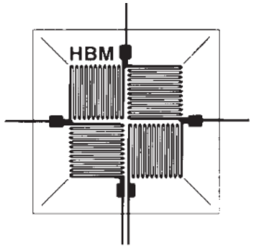


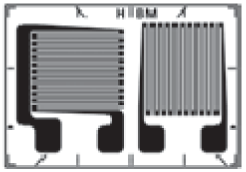


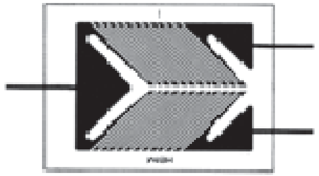
Strain gauges : Basic principles

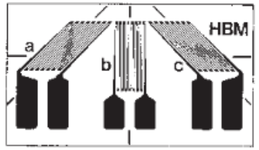


- Materials :
  - Support : Polyimide (≈ 45 µm thickness)
  - Grid : chromium-nickel alloys, copper-nickel alloys
  - Size : Between 0.6 mm and 160 mm for the grid
  - Resistance : 120 Ω, 350 Ω, 700 Ω or 1000 Ω
  - Shape : All type for several applications :







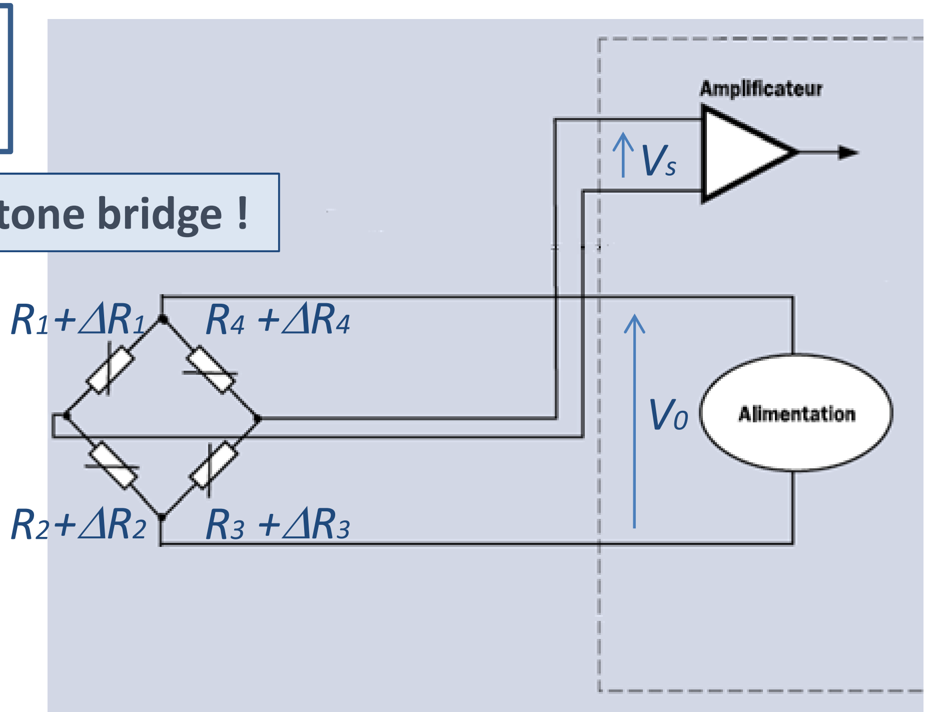


- Adhesive :
  - Requirements :
    - Transmission of the deformations of the test object to the strain gauges
    - Stable behavior across a temperature and strain range which is as wide as possible
  - Products :
    - Hot curing adhesives for cryogenic applications (two components : epoxy resin and adhesive thin liquid)
    - Cold curing adhesives for ambient temperature (Cyano-acrylate thin liquid)

Strain gauges : Wheatstone bridge

Resistance values : 120, 350, 700 Ω
For 2000 µm/m, **ΔR is equal to 11 µΩ**

This very low ΔR is measured with a Wheatstone bridge !



- Wheatstone bridge equation :

$$\frac{V_0}{V_s} = \frac{R_1}{R_1 + R_2} - \frac{R_4}{R_3 + R_4}$$

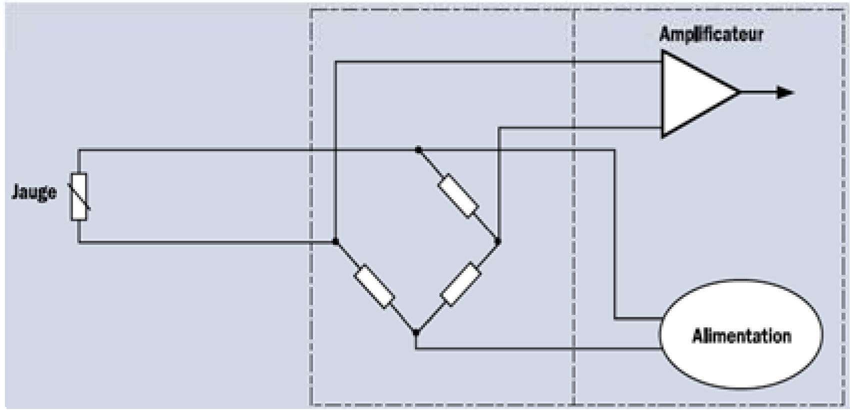
- Application with strain gauges :

$$\frac{V_0}{V_s} = \frac{K}{4}\left(\frac{\Delta L_1}{L_1} - \frac{\Delta L_2}{L_2} + \frac{\Delta L_3}{L_3} - \frac{\Delta L_4}{L_4}\right)$$

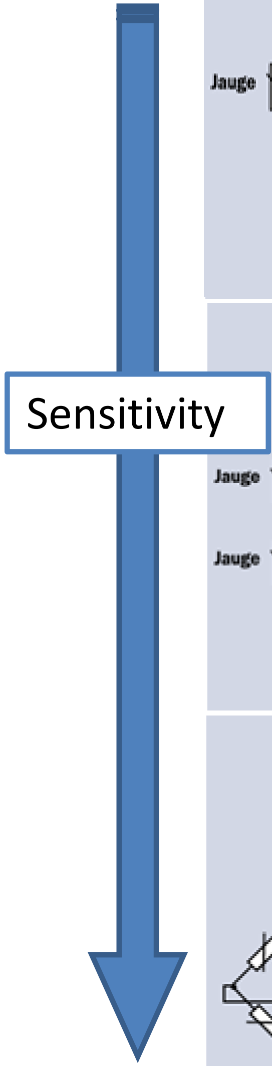
- Configuration :
  - ¼ bridge
  - Half bridge
  - Full bridge

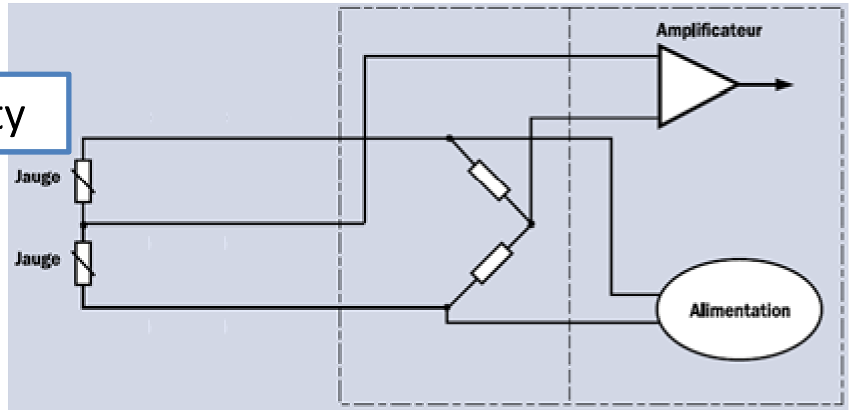
Strain gauges : Wheatstone bridge

- Wheatstone bridge configuration :
  - ¼ Bridge :

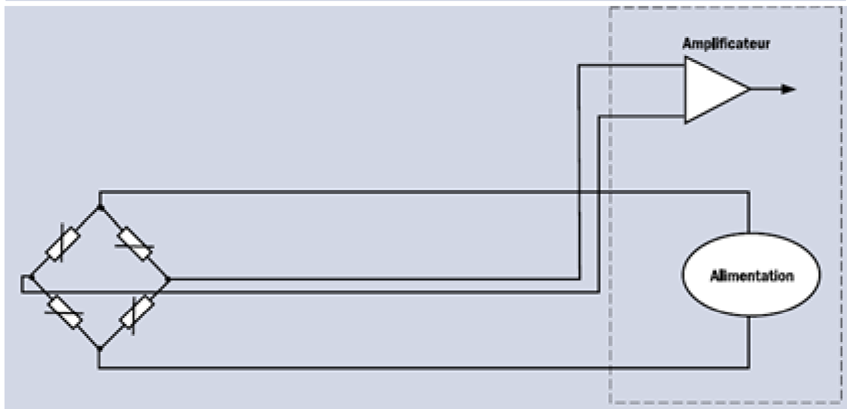


  - Half bridge :



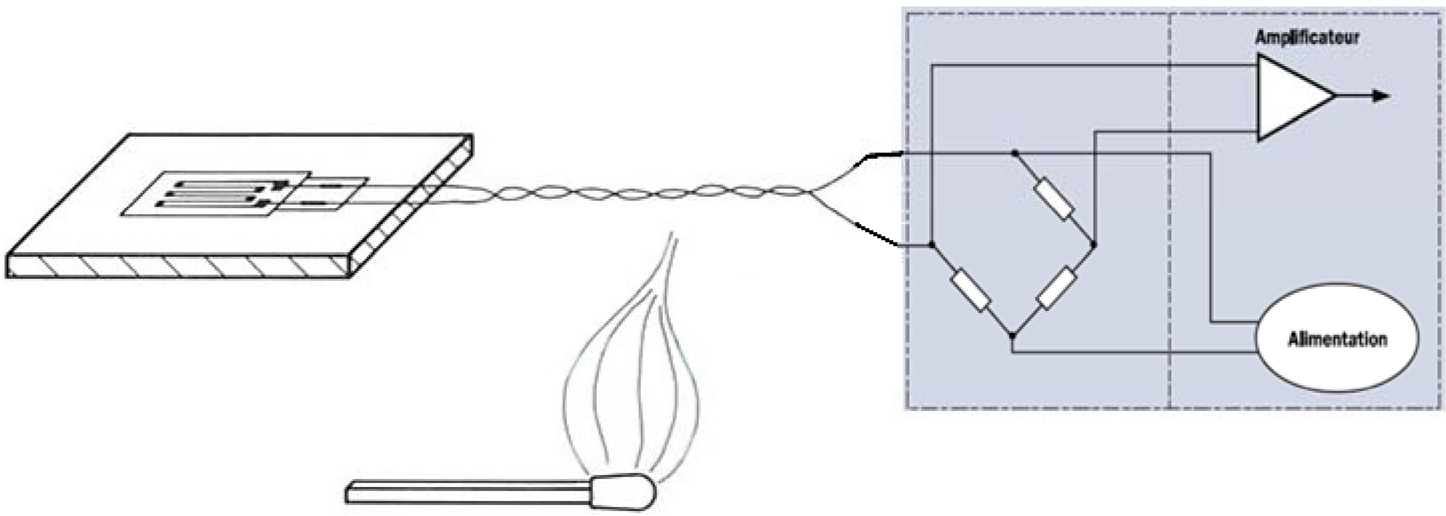


  - Full bridge :



Strain gauges : External disturbances

- Main external disturbances : temperature, magnetic field, …

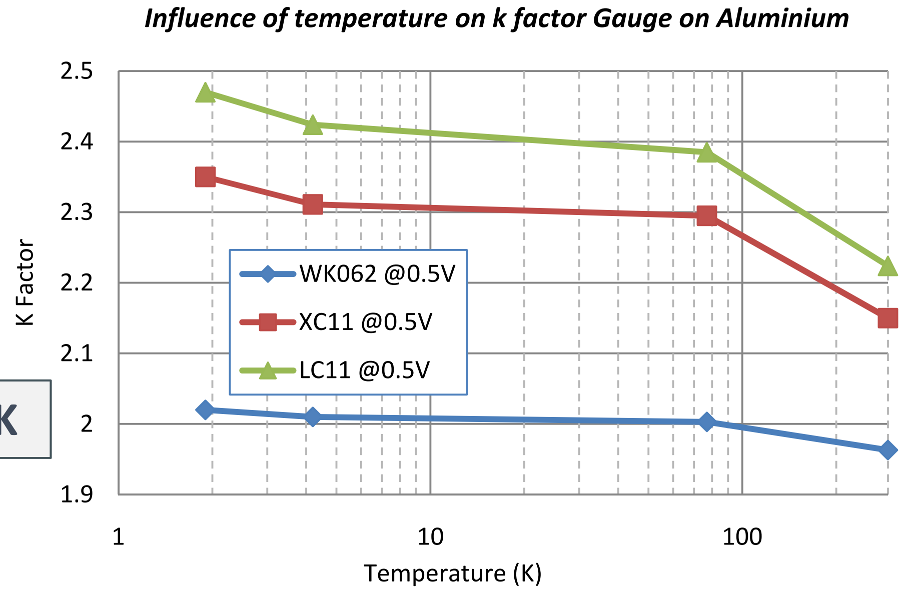


Strain gauges : Temperature effects

- K factor variation :

$$\frac{\Delta R}{R} = k\frac{\Delta L}{L}$$

10 % of variation between 300 K and 1.9 K



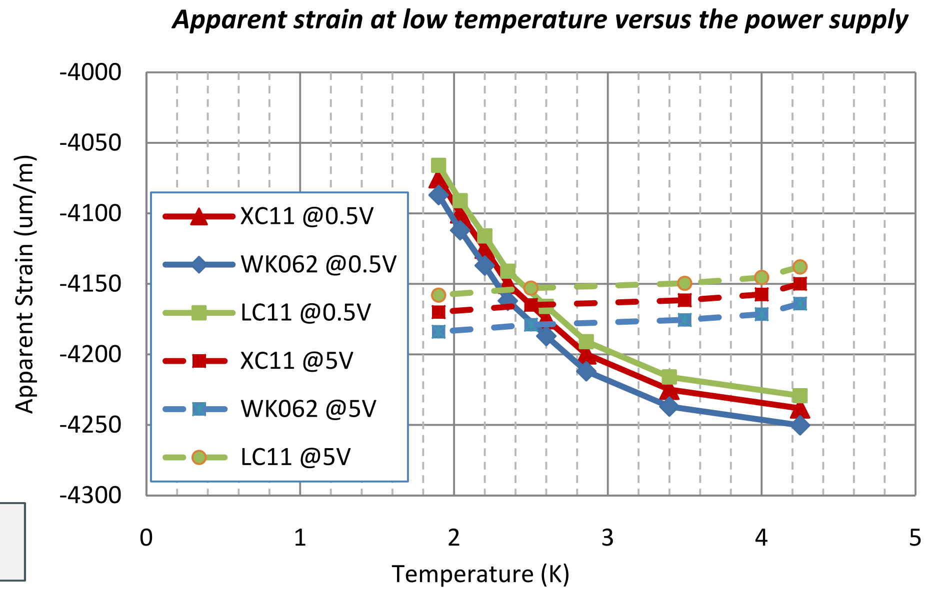
- Apparent strain :

$$\left(\frac{\Delta L}{L}\right)_{Measured} = \left(\frac{\Delta L}{L}\right)_{Real} + \left(\frac{\Delta L}{L}\right)_{ApparentStrain}$$

$$\left(\frac{\Delta L}{L}\right)_{ApparentStrain} = \left[\frac{\beta_G}{k} + \left(\alpha_s - \alpha_g\right)\right] \times \Delta T$$

With :
β_g : Grid resistivity
α_s : Thermal contraction of the support
α_g : Thermal contraction of the grid

≅ 1500 µm/m between 293 K and 77 K



Strain gauges : Temperature effects

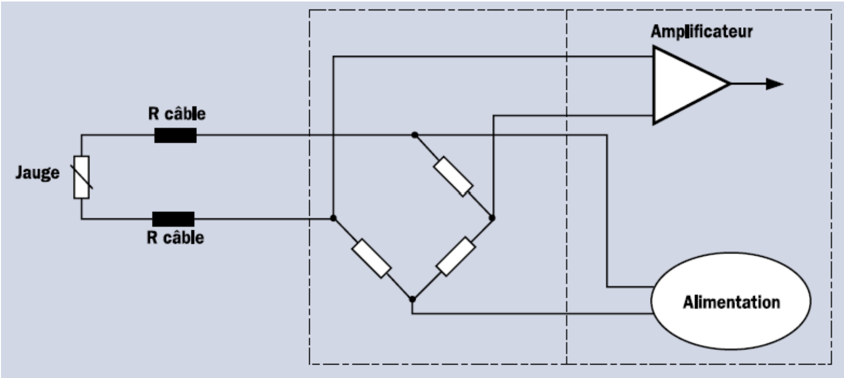
- Resistance of the cables :

  For 10 meters with a section of 0.2 mm²

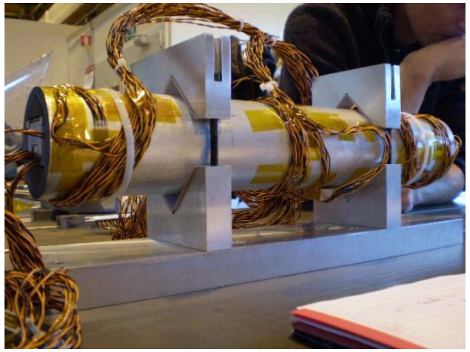
  ≅ 4900 μm/m of apparent strain due to the length of the cables

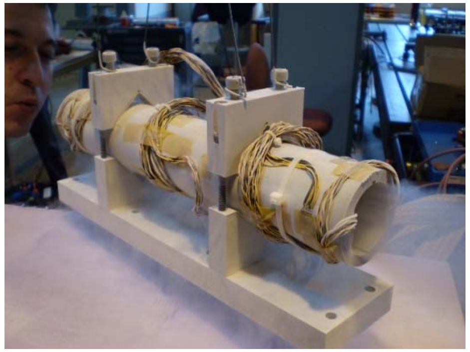
  ⇒ *Compensated by the bridge balancing*

  + ≅ 4200 μm/m between 293 K and 77 K due to the resistance variation



Temperature effects on the strain gauges measurements !



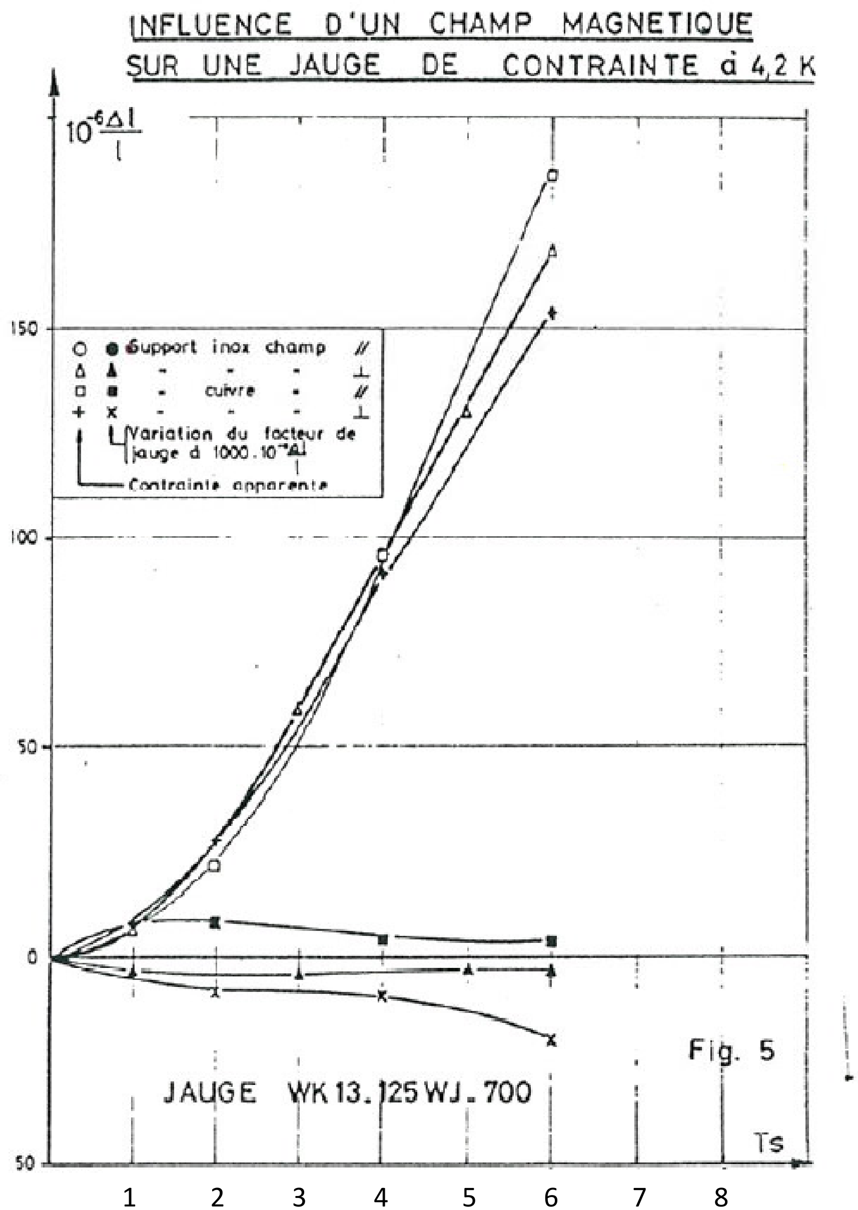


Strain gauges : Other effects

- Magnetic field :
  - Magneto resistance effect
  - Magneto striction effect
  - Induction current

Apparent strain : 200 µm/m @ 6 Ts / 4.2 K
K factor : 5 % of deflection @ 6 Ts / 4.2 K

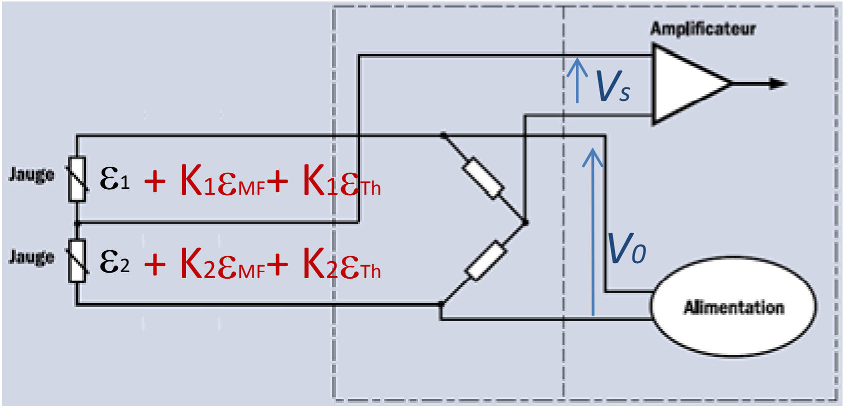
- Radiation effect :
  - Adhesive degradation
  - Zero drift



Strain gauges : Disturbance Compensation

- Bridge Configuration :
  - Use Half or full bridge configuration

$$\frac{V_0}{V_s} = \frac{1}{4}\left(K_1\varepsilon_1 - K_2\varepsilon_2\right)$$



With disturbance :

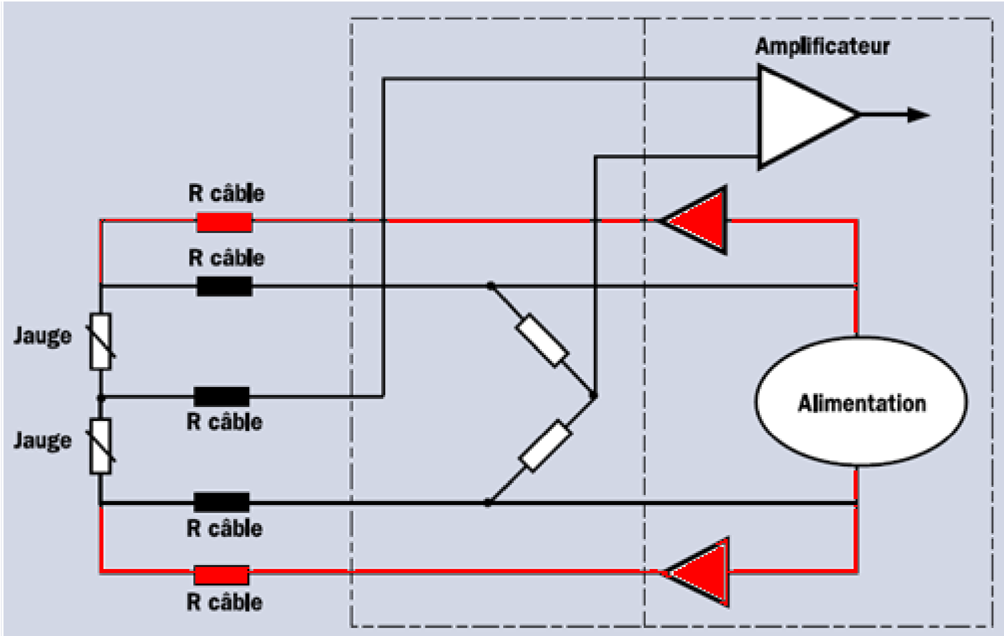
$$\frac{V_0}{V_s} = \frac{1}{4}\left(K_1\varepsilon_1 + K_1\varepsilon_{MF} + K_1\varepsilon_{Th} - \left(K_2\varepsilon_2 + K_2\varepsilon_{MF} + K_2\varepsilon_{Th}\right)\right)$$

If $K_1 \cong K_2 \cong K$ (Same batch or bi-axial strain gauges)

$$\frac{V_0}{V_s} = \frac{K}{4}\left(\varepsilon_1 + \varepsilon_{MF} + \varepsilon_{Th} - \varepsilon_2 - \varepsilon_{MF} - \varepsilon_{Th}\right) = \frac{K}{4}\left(\varepsilon_1 - \varepsilon_2\right)$$

Strain gauges : Disturbance Compensation

- Bridge Configuration :
  - Cable length compensation



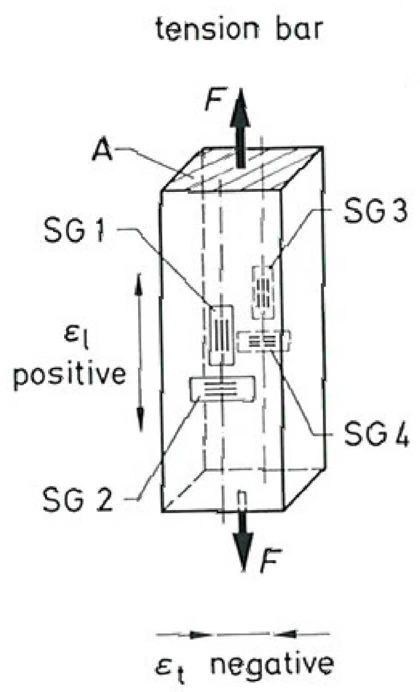
  - Power supply

    - Constant voltage adapted to the strain gauges

    - Carrier frequency method (@225 Hz or 4.8 kHz)

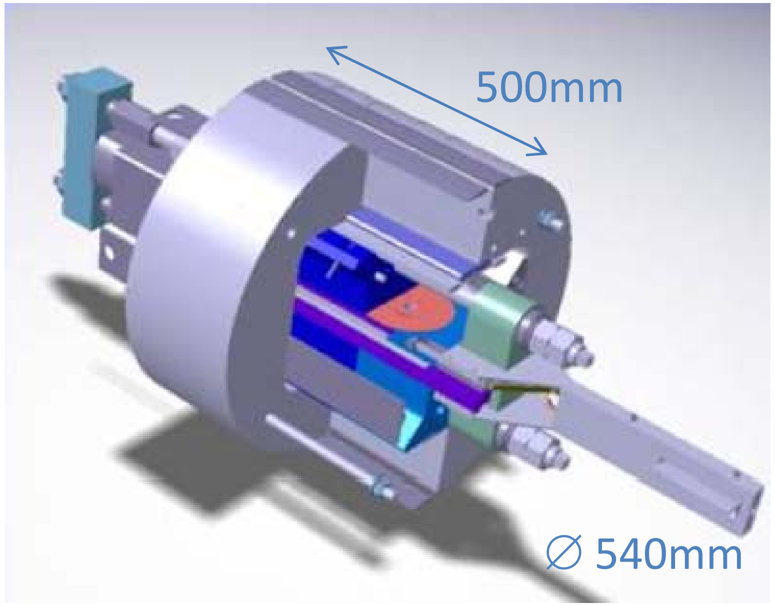
Strain gauges : Examples of disturbance compensation

- Strain gauges installation
  - ¼ Bridge configuration with compensator
    - $\varepsilon_{real} = \varepsilon_{measured} - \varepsilon_{Compensator}$
    - Compensation of the external disturbance
    - Sensitivity to other mechanical load cases
  - ½ Bridge configuration
    - $\varepsilon_{measured} = \varepsilon_{real} - \nu\varepsilon_{real} = \varepsilon real \times (1+|\nu|)$
    - Compensation of the external effects
    - Sensitivity to other mechanical load cases
  - Full Bridge configuration
    - $\varepsilon_{measured} = 2\varepsilon_{real} - 2\nu\varepsilon_{real} = \varepsilon real \times 2(1+|\nu|)$
    - Compensation of the external effects
    - No sensitivity to other mechanical load cases, stress calculation



Applications : Short Magnet Coil (SMC – Eucard)

- Goal : Finite Element Analysis (FEA) validation
- Strain measurements during assembly and cryogenic cool down at 4.2 K
- Dummy-coil, shell and rods instrumented with strain gauges in several configurations



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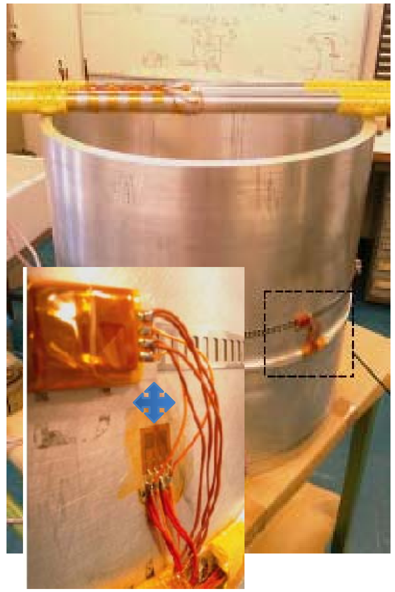
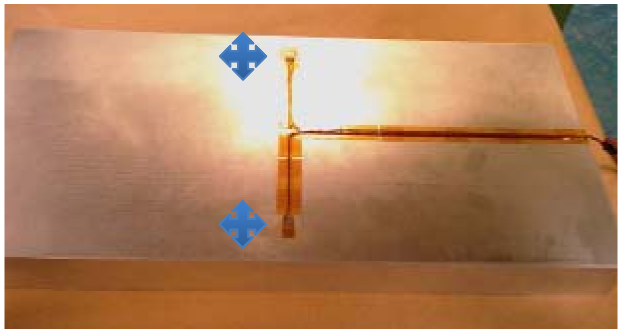
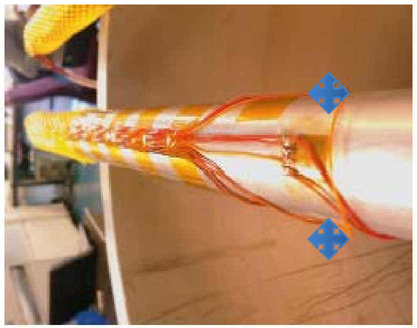
	Dummy Coil	Shell	Rods	
Type of measurements	Local strain values	Local strain values	Traction/Compression stress	Bending stress
Number of measurements	8 (Z direction) 8 (R direction)	8 (Z direction) 8 (Θ direction)	1 for each rod	1 for each rod
Bridge configuration	¼ bridges + ¼ bridges for thermal compensation	Half bridges compensated with thermal compensator	Full bridge	Half bridge
Strain gauges	Chromium – Nickel / Polyimide	Chromium – Nickel / Polyimide	Chromium – Nickel / Polyimide	Chromium – Nickel / Polyimide
Power Supply	2.5 V @4.8 kHz	2.5 V @4.8 kHz	2.5 V @4.8 kHz	2.5 V @4.8 kHz

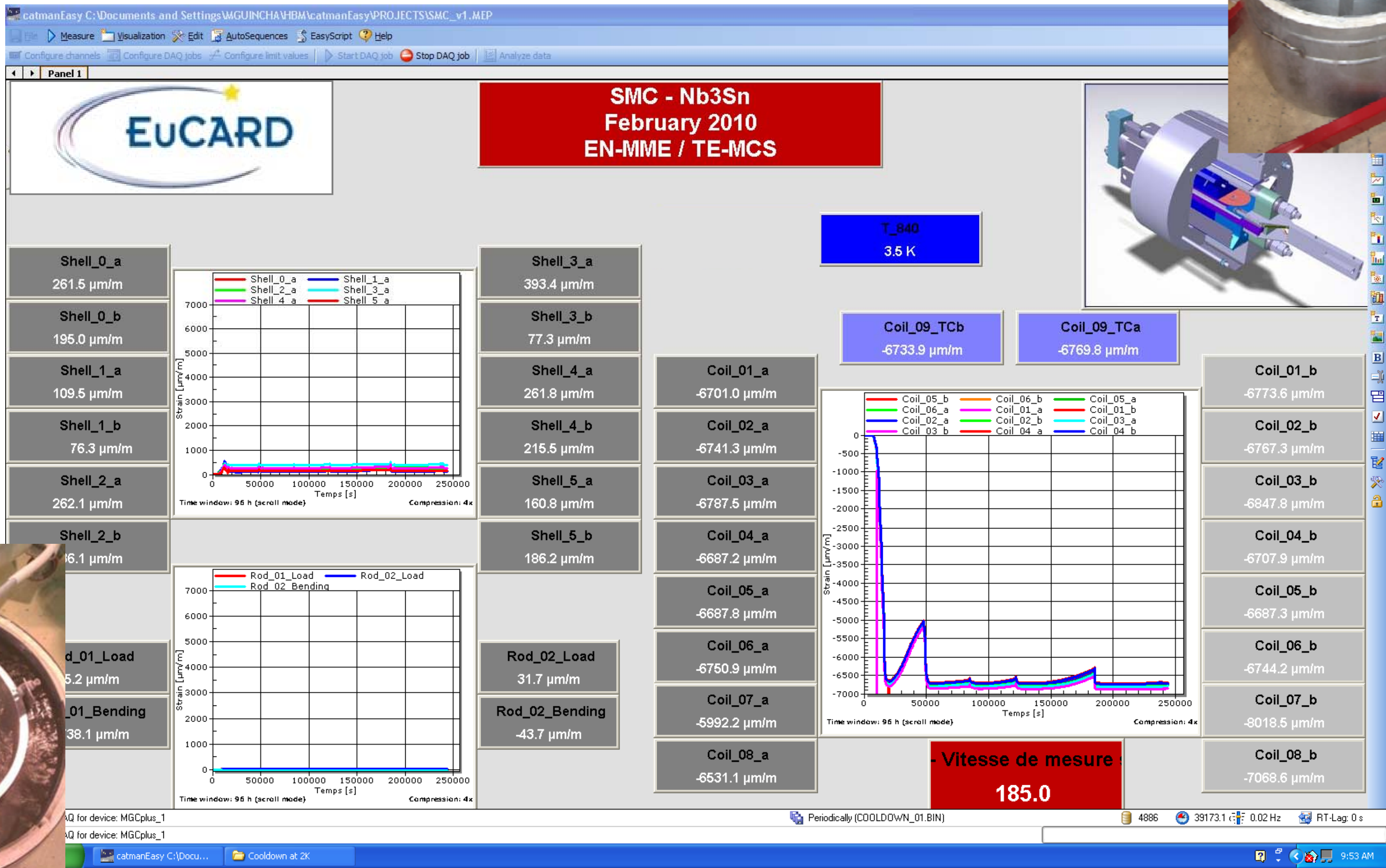






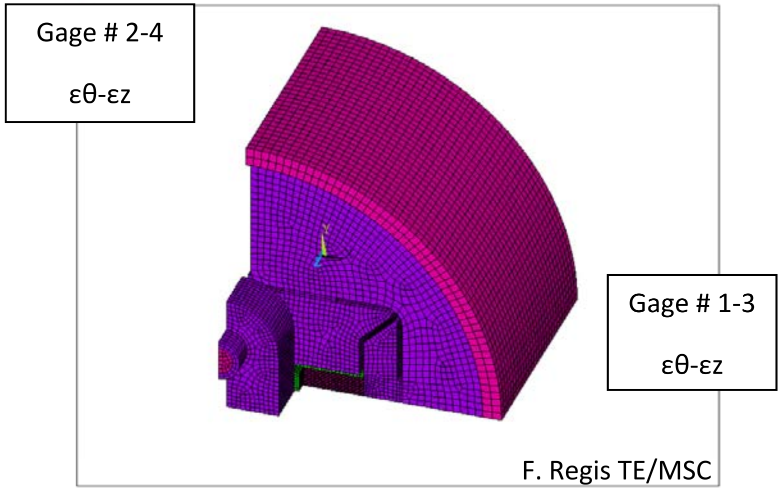
Applications : Short Magnet Coil (SMC – Eucard)

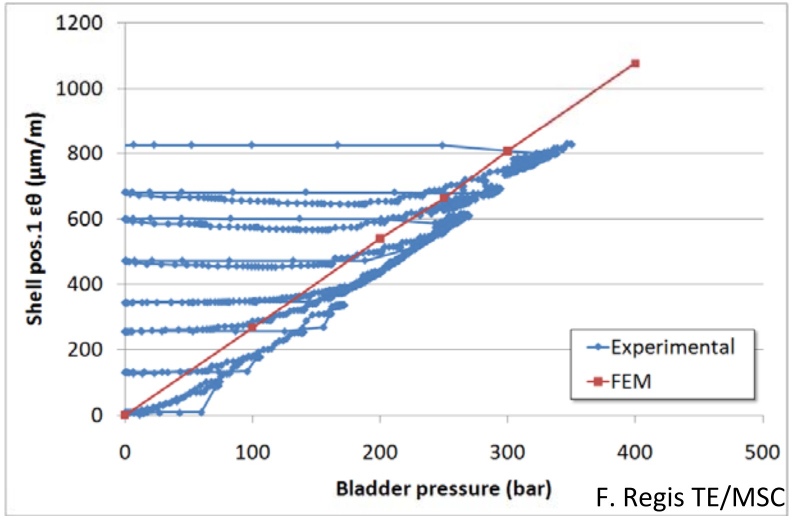
- Cryogenic cycles at 77K
- Cryogenic cycles at 4.2K

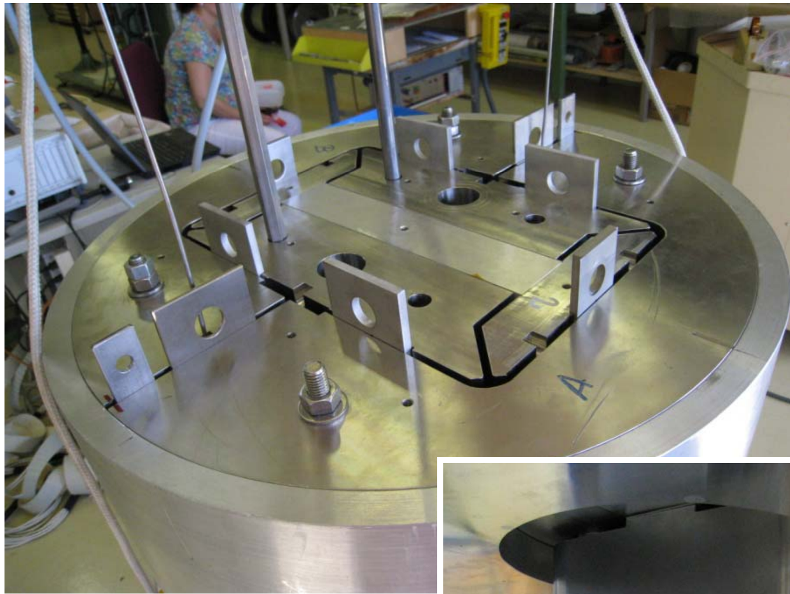


Applications : Short Magnet Coil (SMC – Eucard)

- First Assembly







J.C Perez TE/MSC

Strain gauges : Next developments

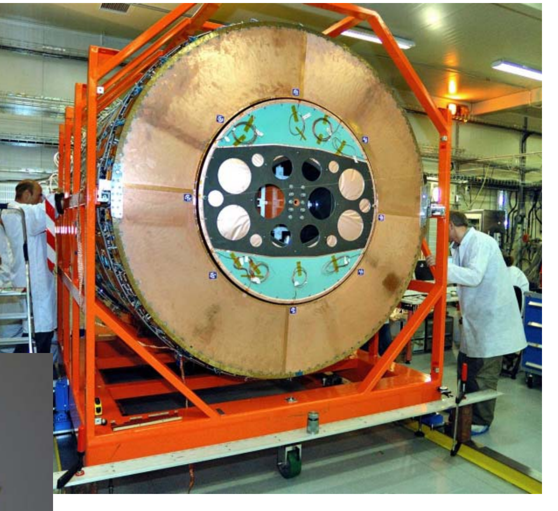
- In 2010, a new phase of characterisation of the strain gauges measurements will be performed at low temperature with a new generation of DAQ ;
- Evaluation of the “hole” drilling method for structure under mechanical load ;
- Evaluation of the new techniques of strain measurements with optical fibre .

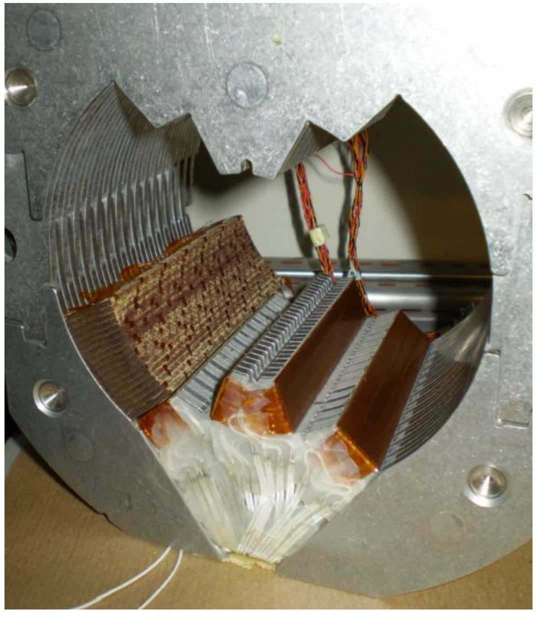
Measurements with Capacitive gauges

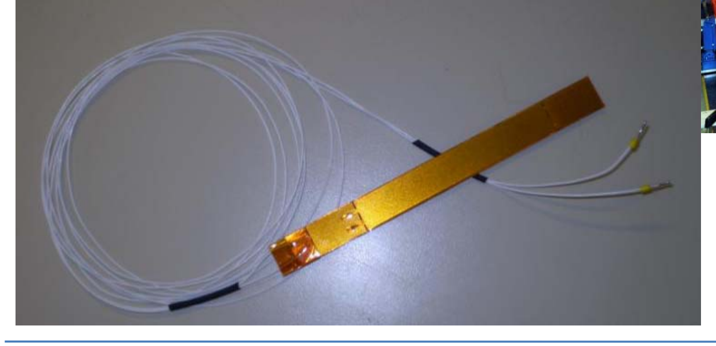
Capacitive gauges : Introduction

- Historic at CERN:
  - **1995 :** Iouri Vanenkov developed at CERN the force capacitive gauges for the LHC magnets prototyping ;
  - **2006** : Technology transfer between I. Vanenkov and the Lab for 10 months ;
  - **2010** : Capacitive gauges are used for the new inner triplets with new DAQ.

- Applications : No industrial applications !







Capacitive gauges : Basic principles

The simplest electrostatic transducer has two parallel plane electrodes of area (S) with a dielectric material of thickness δ and electric permittivity ζ in between. The capacitance C is given by :

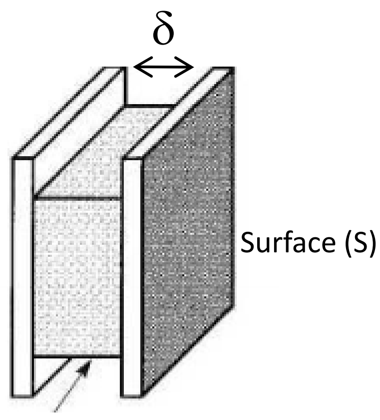
$$C = \frac{\zeta . S}{\delta}$$

with

ζ : Electric permittivity (F/m)

δ : thickness (m)

S : Area (m²)



Application for capacitive gauges :

$$C = \frac{\zeta . S}{\delta\left(1 - \frac{\sigma}{E}\right)}$$

with

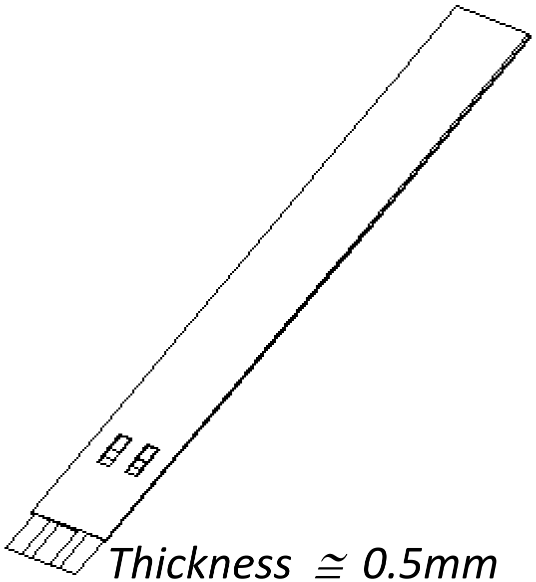
σ : Applied Stress (MPa)

E : Module of elasticity of the dielectric material (MPa)

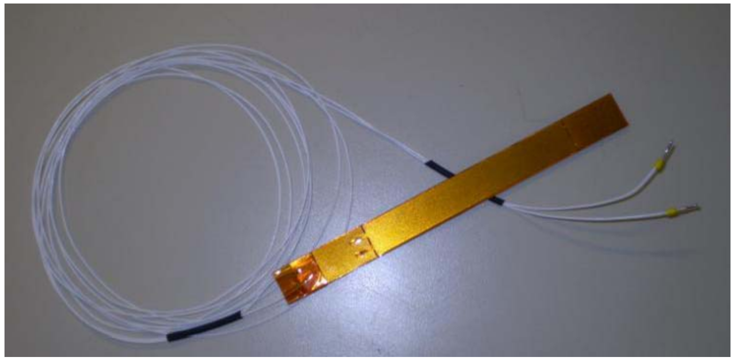
For 200 Mpa, **ΔC is equal to $\cong$ 0.5 nF**

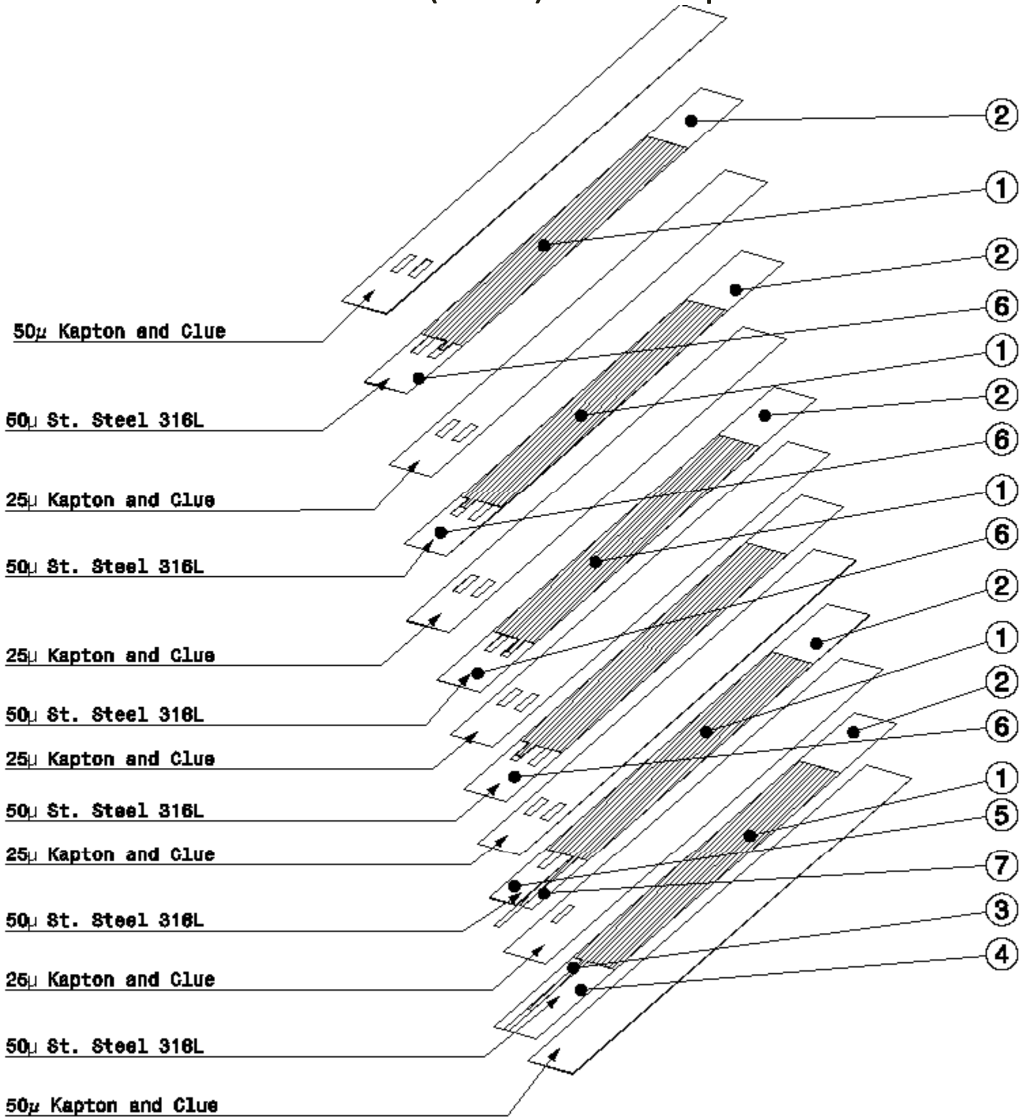
Capacitive gauges : Fabrication

- The gauge consists of a sandwich of stainless steel foils (316L) with Kapton® film



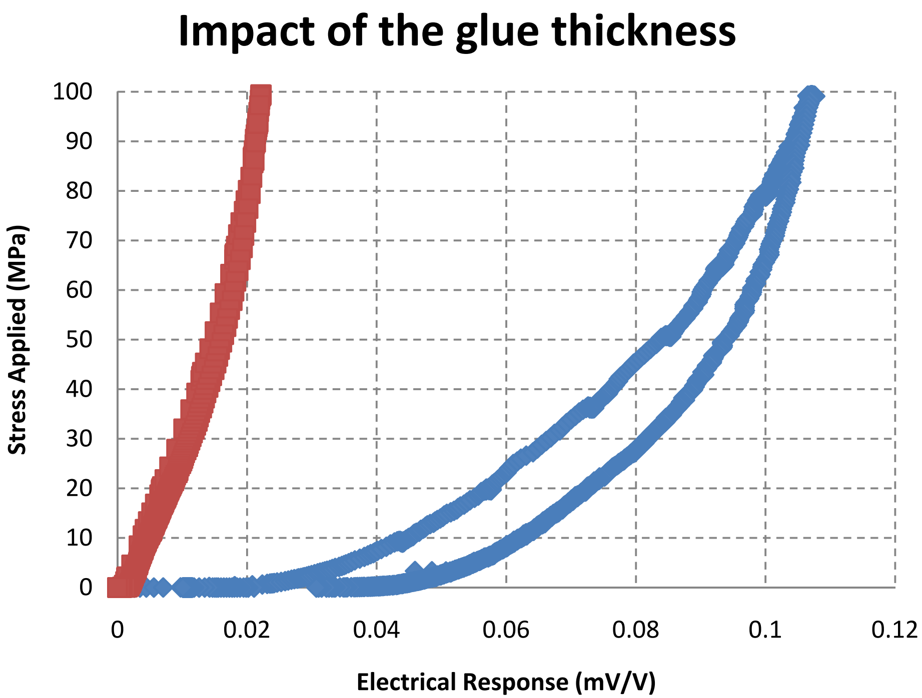
Thickness ≃ 0.5mm

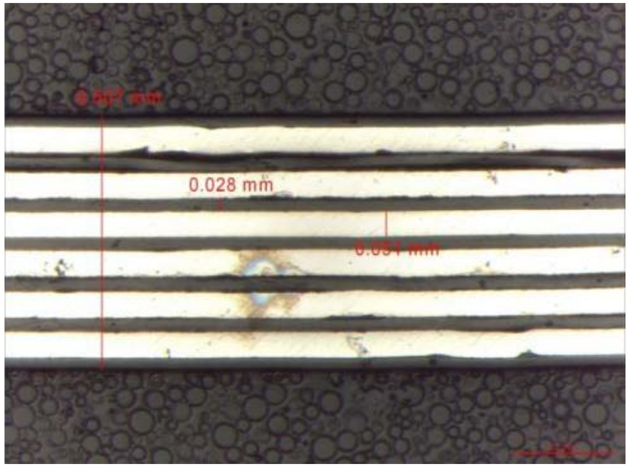


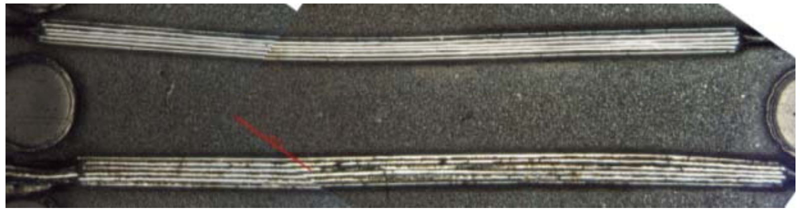


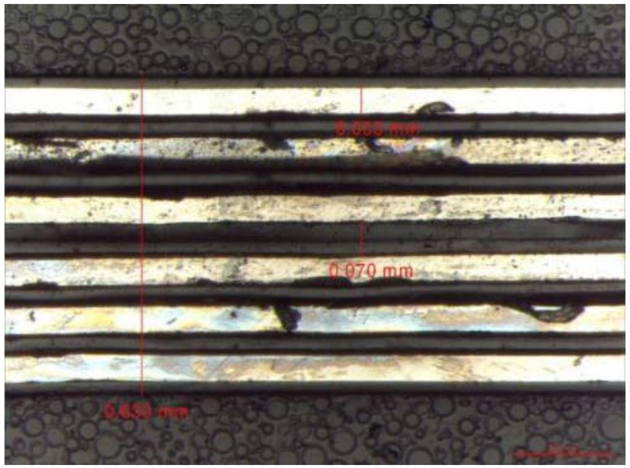
Capacitive gauges : Fabrication

- Impact of the glue on the gauges characteristics :







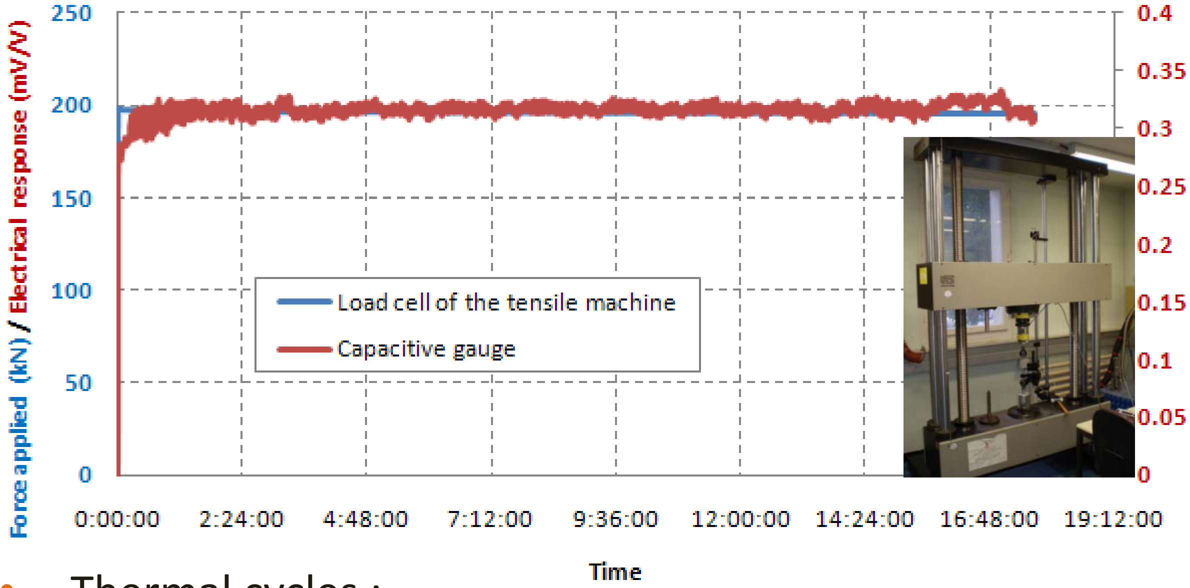


A. Gerardin (EN/MME)

Glue : Two components : epoxy resin adhesive + thin liquid
Conditions : Manual application
Typical glue thickness : few µm

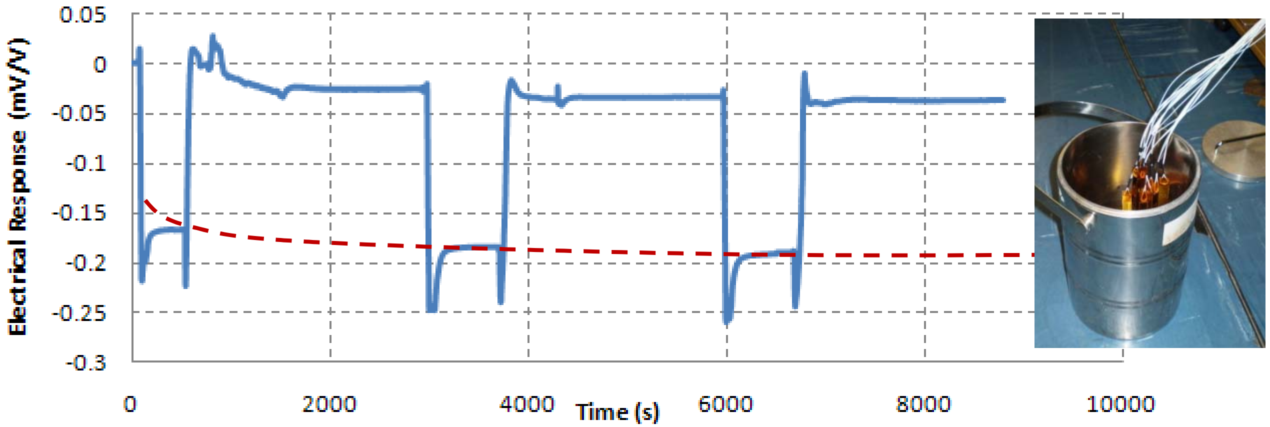
Capacitive gauges : Characteristics

- Stress relaxation test (Displacement fixed) :



Time ≈ 17,5 hours.
Force degradation ≈ 2.5 kN / 200 kN

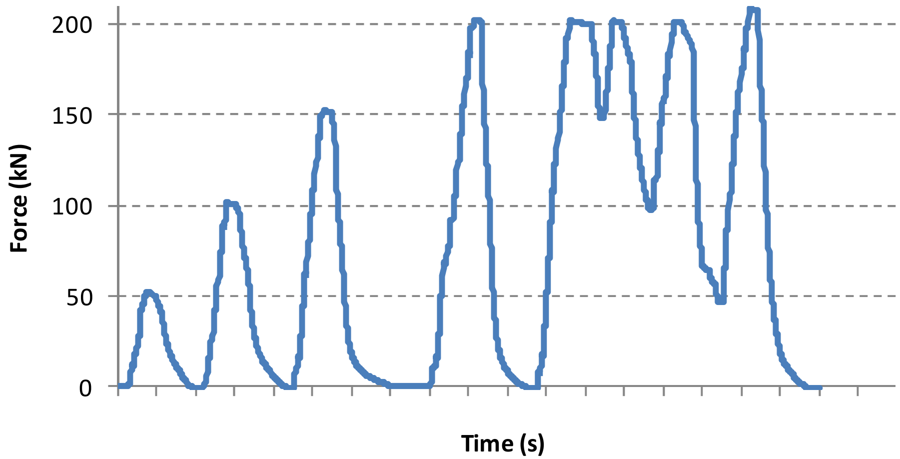
- Thermal cycles :

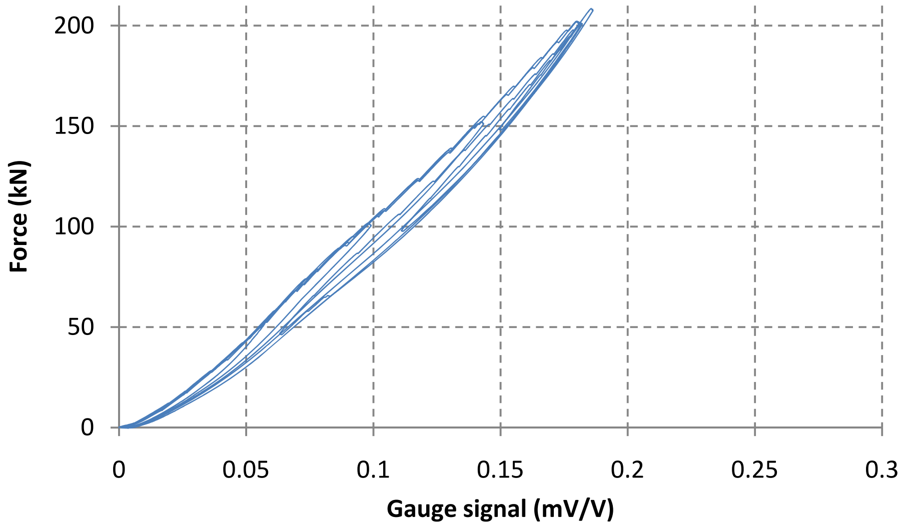


Apparent capacitance stability after 3 cycles

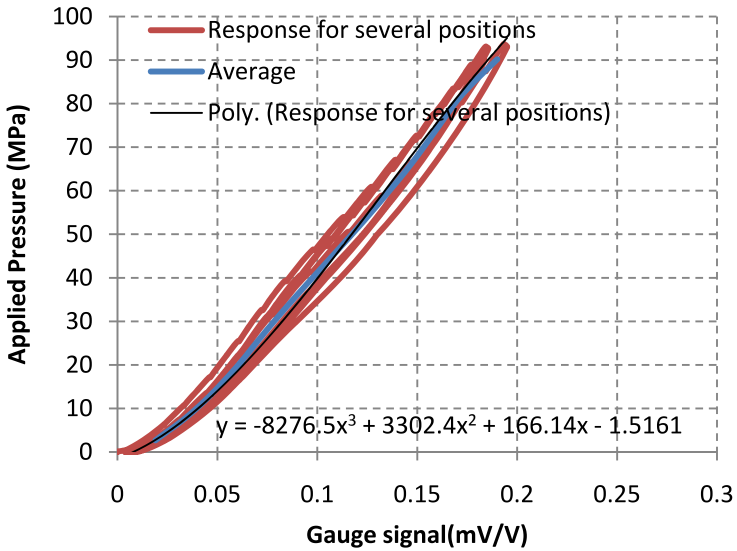
Capacitive gauges : Calibration

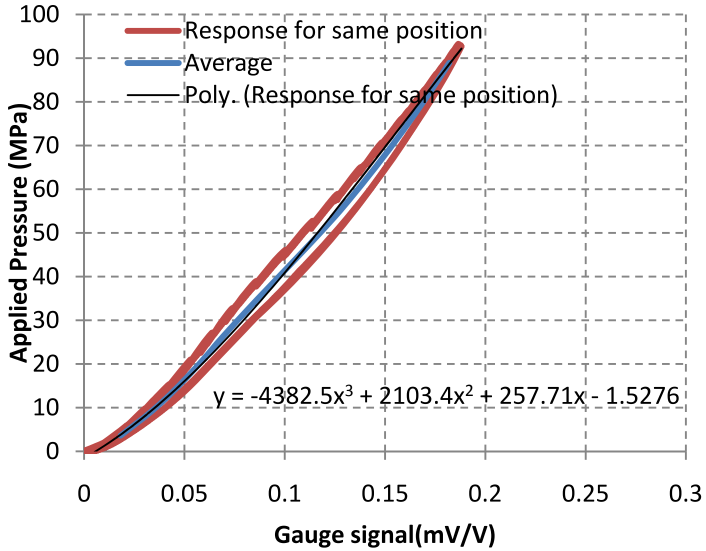
- Cycling tests :





- Calibration :





Capacitive gauges : Results

- Calibration certificate :

CERN — European Organization for Nuclear Research

EN/MME
Laboratoire de Mesures Mécaniques / *Mechanical Measurement*
Certificat d'étalonnage / *Calibration Certificate*

Document Number	015-B04-18	Gauge type	CRNZMML0057
Date	03-10-2010	Gauge serial number	18

Measurement Setup

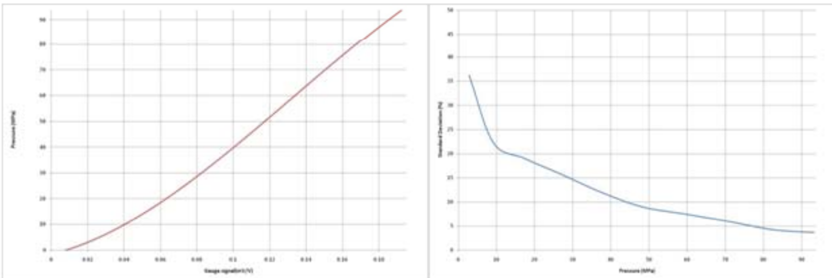
Measurement Device	MGS Plus ML455/AP 455	Measurement Date	10.03.10 15:00:30
Connection Board	04	Measurement program	I-001
Channel on Connection Board	1	Examiner	A. Kuzmin
Acquisition speed	10 Hz		
Temperature			
Air Pressure			
Humidity			

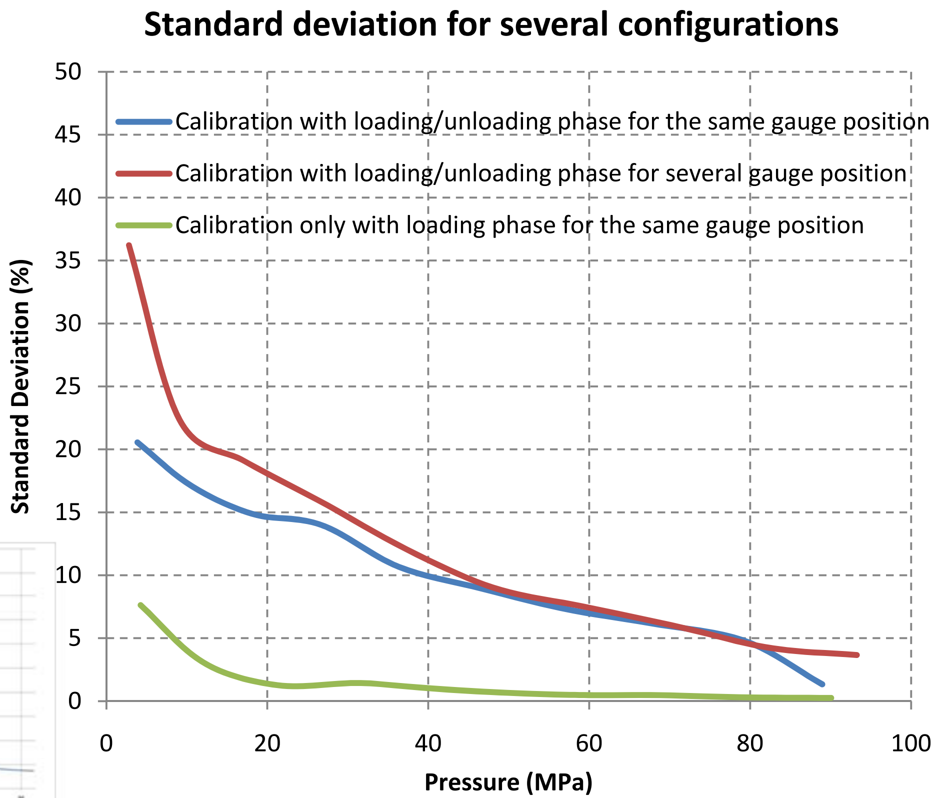
Measurement Results

Gauge signal (mV/V)	Pressure (MPa)	Deviation (%)
0.019	2.67	37.6
0.038	9.35	21.6
0.057	18.15	17.3
0.076	28.70	13.3
0.095	38.74	11.0
0.114	48.25	9.0
0.133	58.31	7.2
0.152	69.17	5.4
0.171	81.30	4.0
0.190	90.16	1.6

Zero balancing	
Zero balancing at ambient temperature	0.307 mV/V
Zero drift at 77K	0.047 mV/V

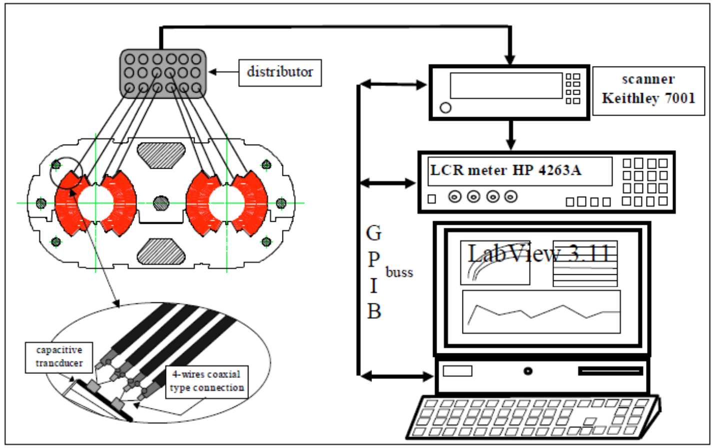
Polynomial function	$y = -8276.5x^3 + 3302.4x^2 + 166.14x - 1.5161$ y - Pressure(MPa) x - Gauge Signal (mV/V)





Capacitive gauges : Data Acquisition System

- Old system :



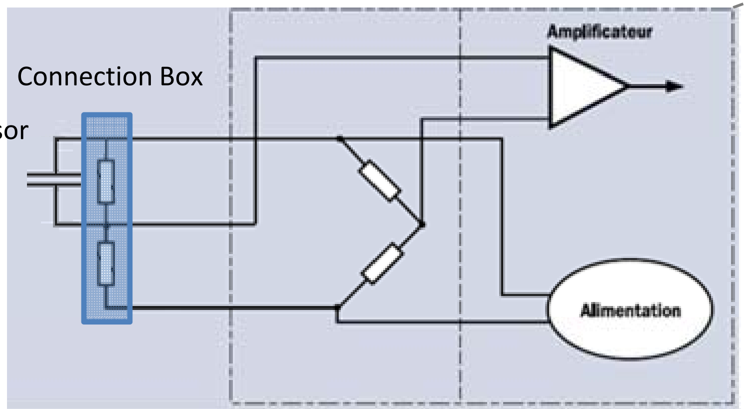
I. Vanenkov

Disadvantages :

-Unsynchronized measurements between channels and with strain gauges ;

- Old electronic without periodic calibration ;

- New system :

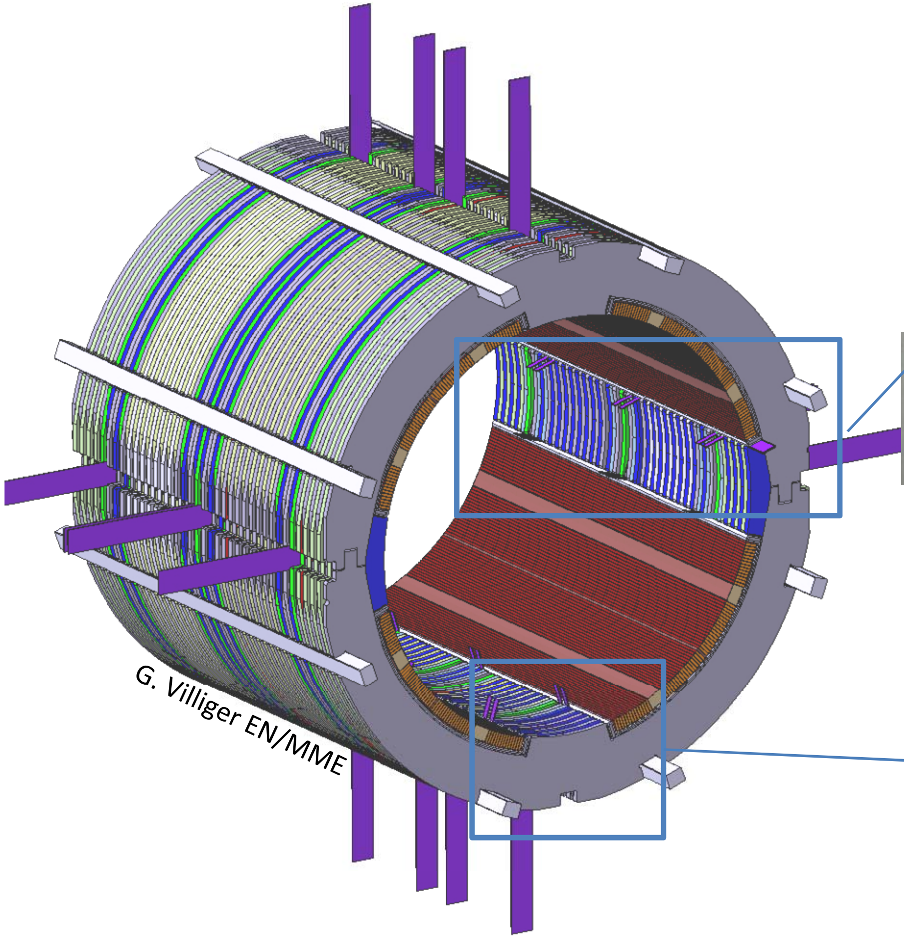


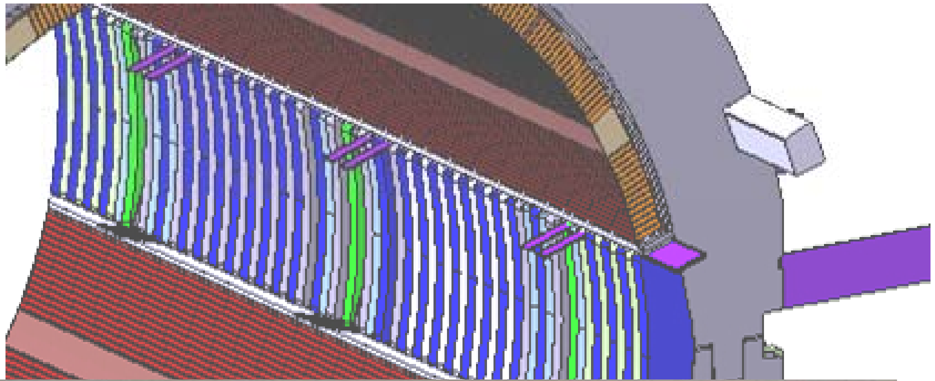
Capacitive Sensor

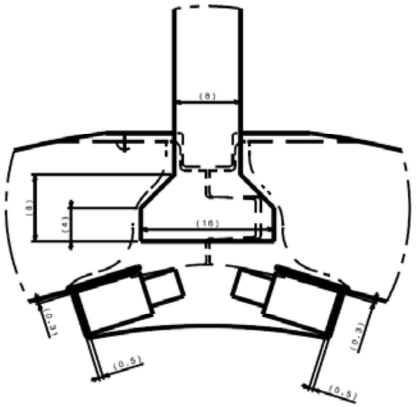
Strain Gauges

Applications : New Inner Triplets

- Goal : Finite Element Analysis (FEA) validation
- Stress measurements during assembly and cryogenic cool down at 1.9K of the 150mm and 2 m models.







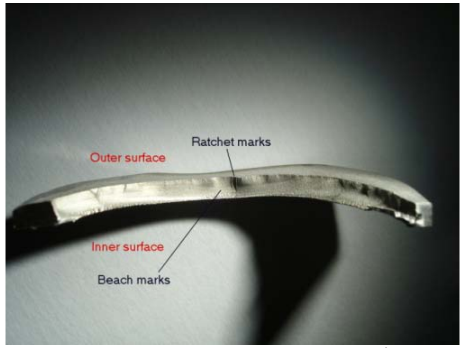
Capacitive gauges : Next steps

- Evaluation of new adhesive ;
- New study concerning the impact of the number of stain steel layers ;
- Collaboration with the industry to produce capacitive gauges ;
- Impact of the magnetic field ;

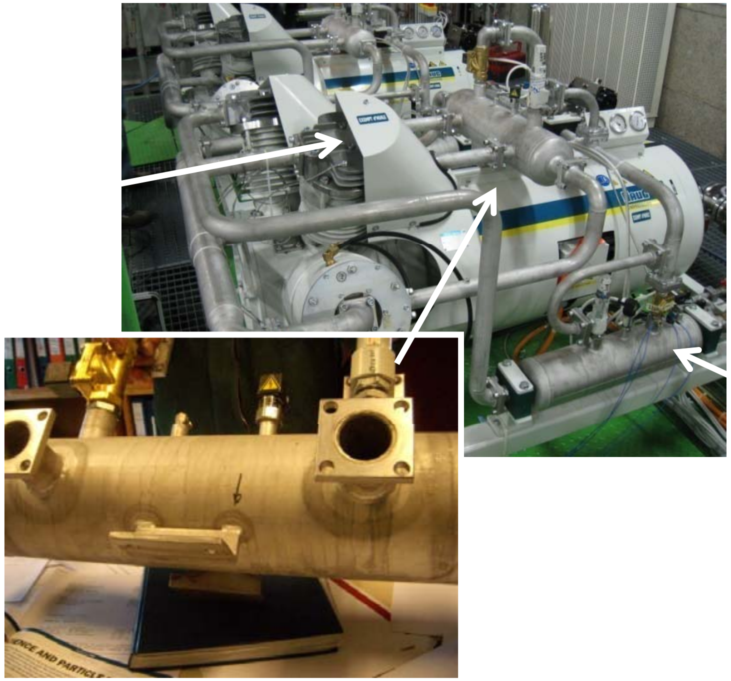
Other Measurements

HAUG Compressors : Introduction

- 6 gas compressors manufactured by HAUG are used in the ATLAS pixel detector cooling system to compress C_3F_8 gas from 1 bar at the inlet to 15 bar at the outlet.
- Cracks have appeared on welded connections at different places of the piping manifold and cover metal sheets. A manometer was also “cut-off” due to vibration inducted wear.



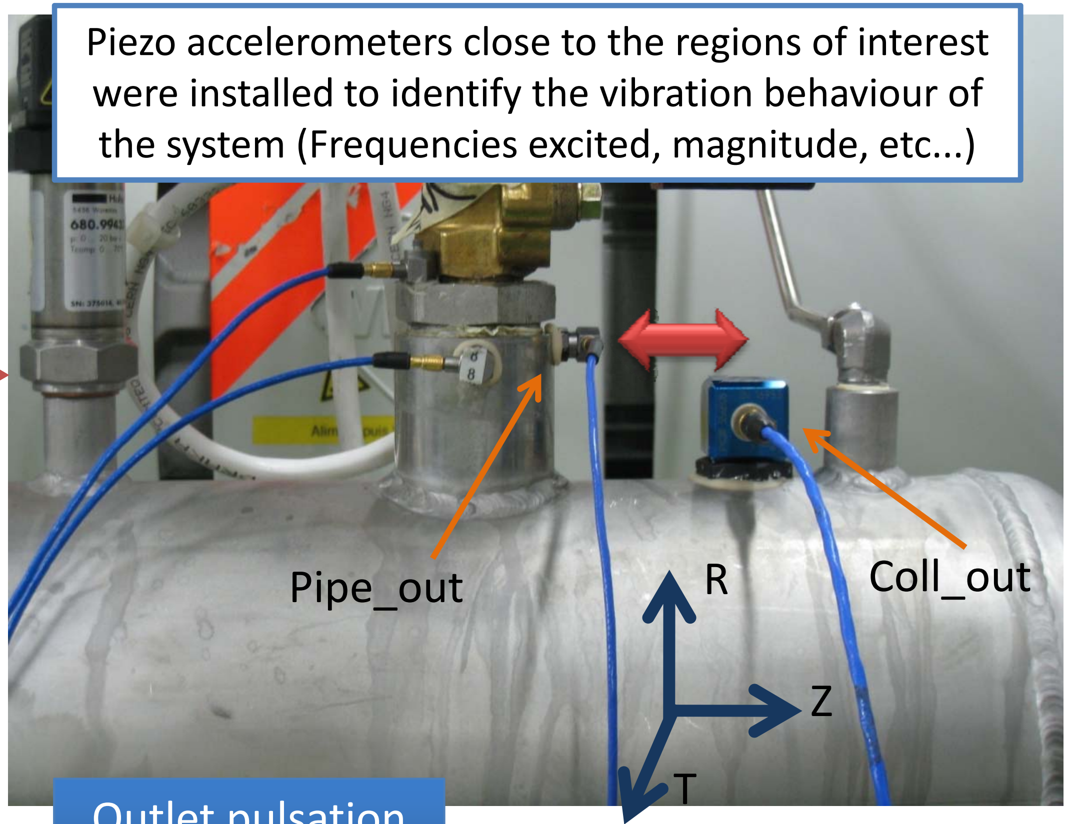
A. Gerardin EN/MME



HAUG Compressors : Vibration measurements

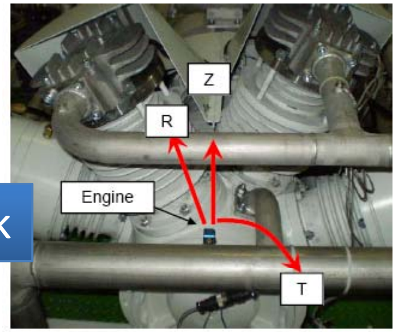
Inlet pulsation dampener

Piezo accelerometers close to the regions of interest were installed to identify the vibration behaviour of the system (Frequencies excited, magnitude, etc...)



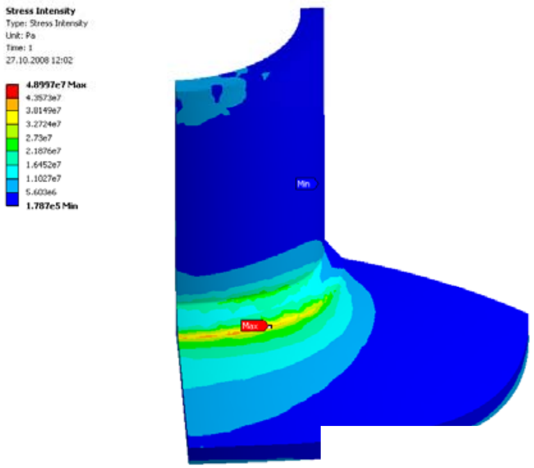
Outlet pulsation dampener

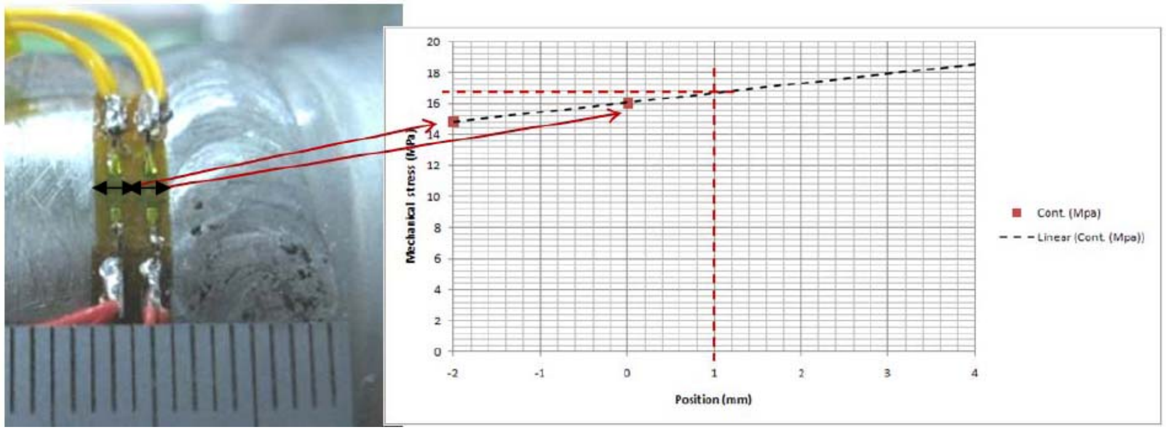
Compressor block



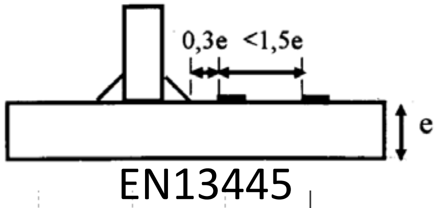
HAUG Compressors : Dynamic stress measurements

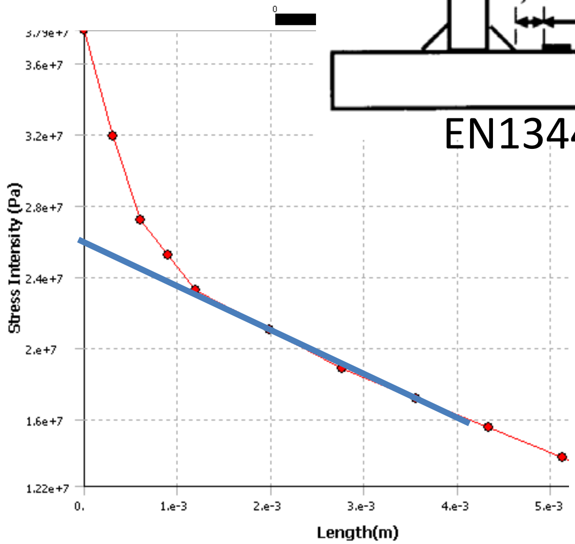
- Goal : Calculation of the notch stress by extrapolation with real stress measurements ;

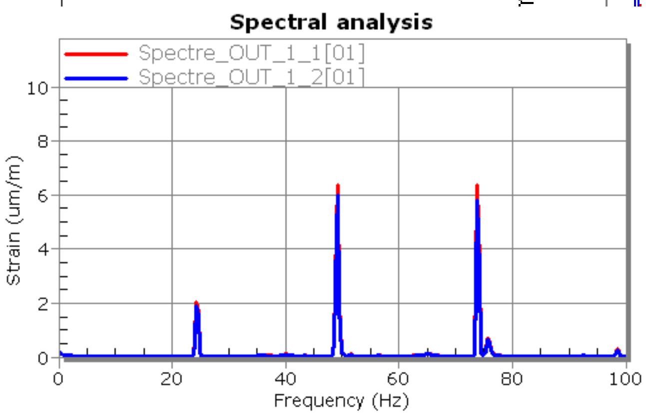


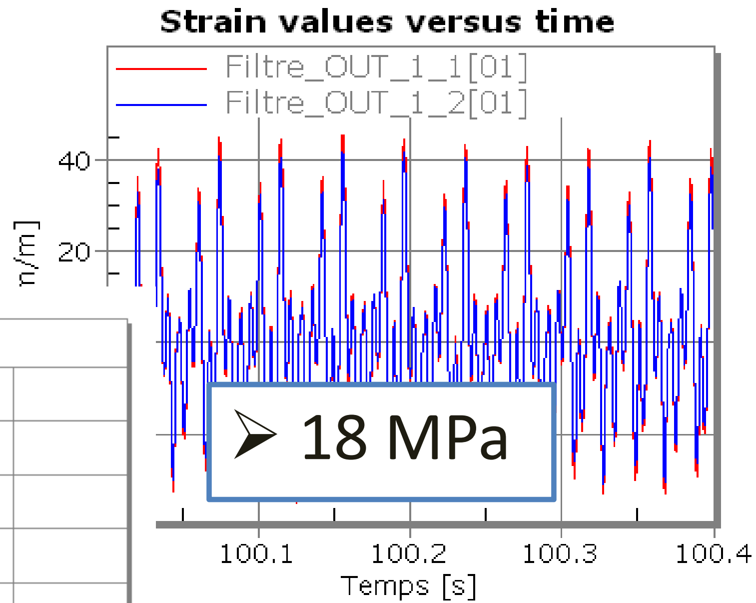


D. Duarte Ramos
EN/MME

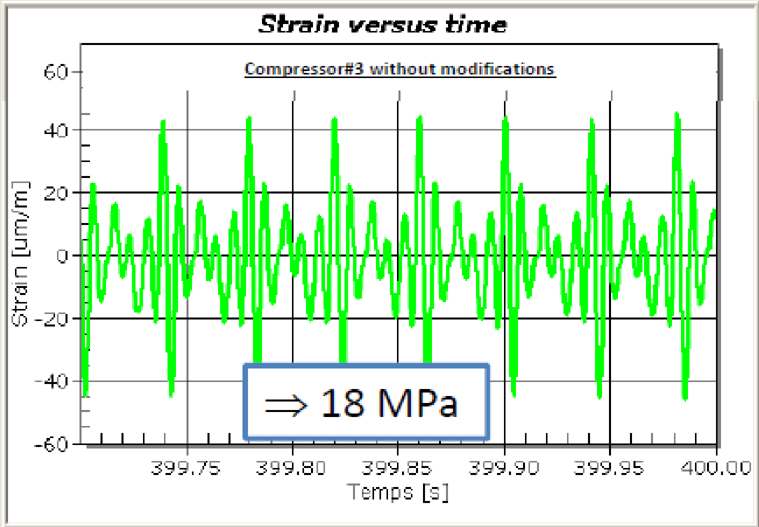


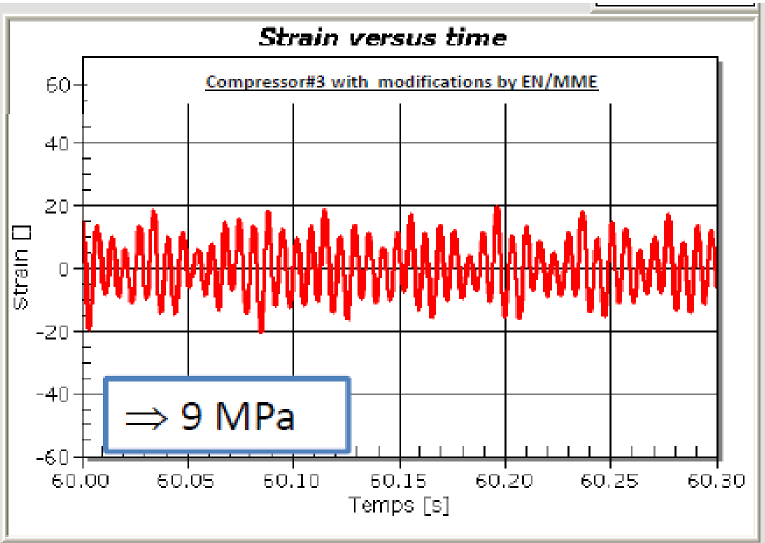






HAUG Compressors : Dynamic stress measurements





Output pressure : 15 bars
Input Pressure : 1 bars

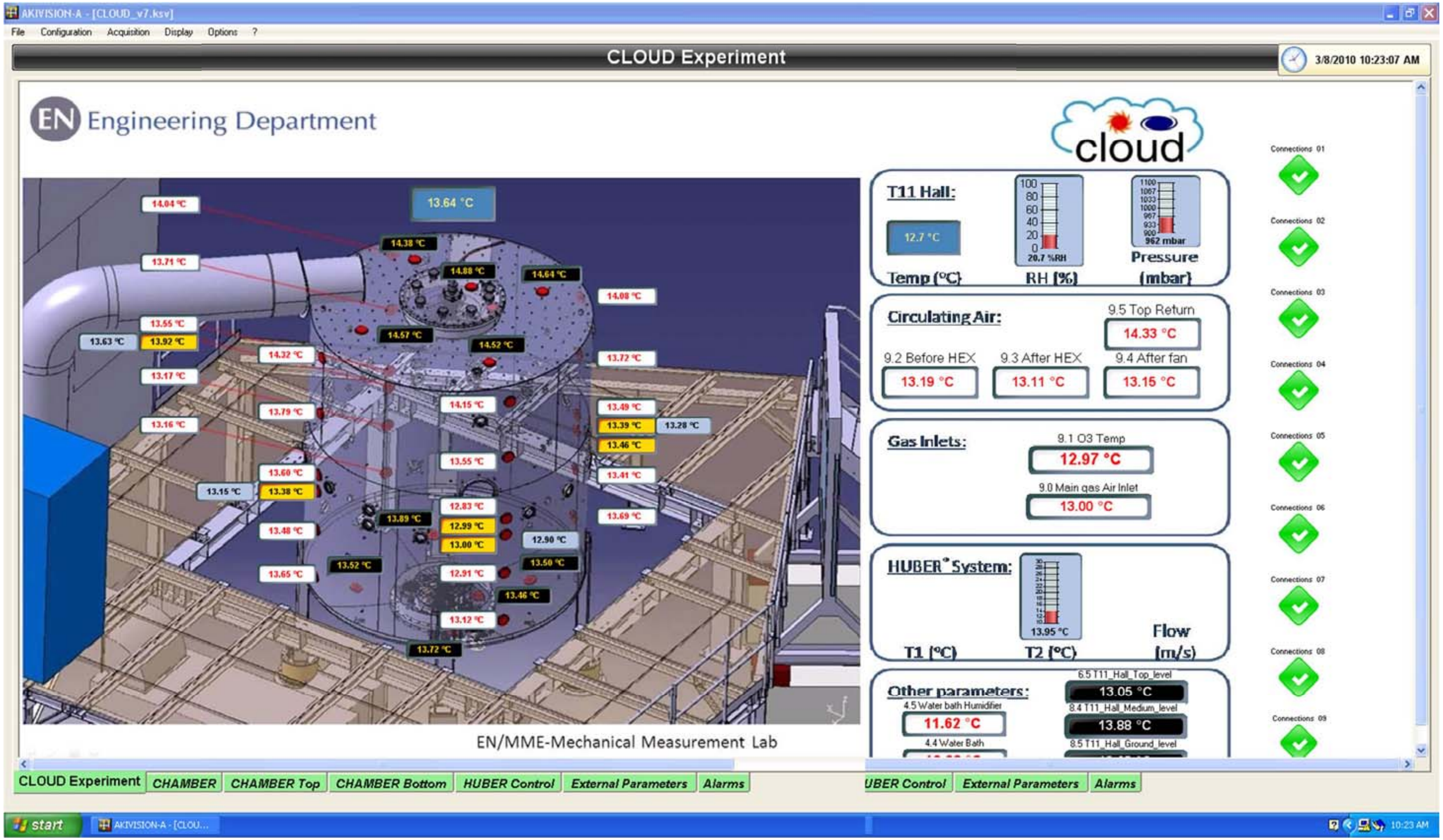
Possible dynamic measurements with strain gauges up to 50 kHz !

CLOUD Experiment : Introduction

- Experience with environmental aim:
  Goal : Simulate the effects of cosmic rays on aerosol and cloud properties

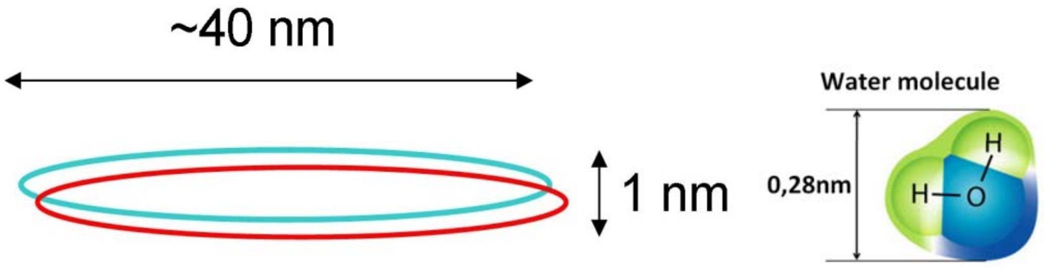
> - Range of temperature:
>   -100°C to +100°C
> - Resolution:
>   ± 0.1°C
> - File export in txt format
> - Environmental conditions :
>   0 to 100% of HR

CLOUD Experiment : First run in November 2009



CLIC nano stabilisation : Introduction

CLIC beam dimensions at the interaction point:

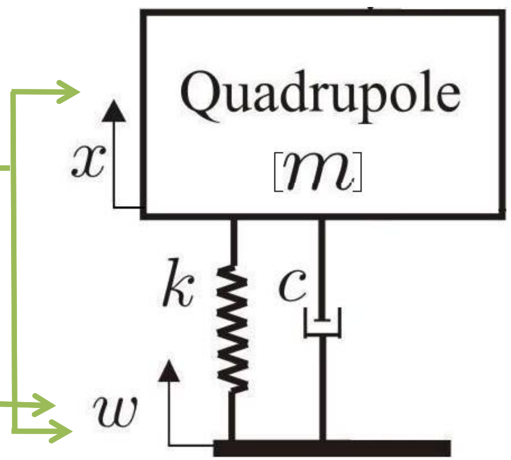


Movement of the CLIC MB quadrupoles must stay below:

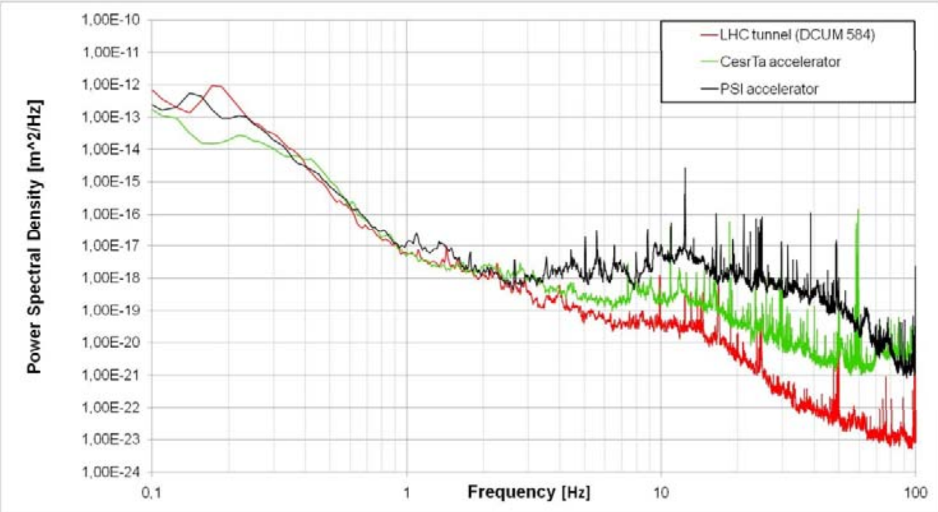
- Vertical: Integrated RMS value of **1nm at 1Hz**
- Lateral: Integrated RMS value of **5nm at 1Hz**

The transfer path characterization

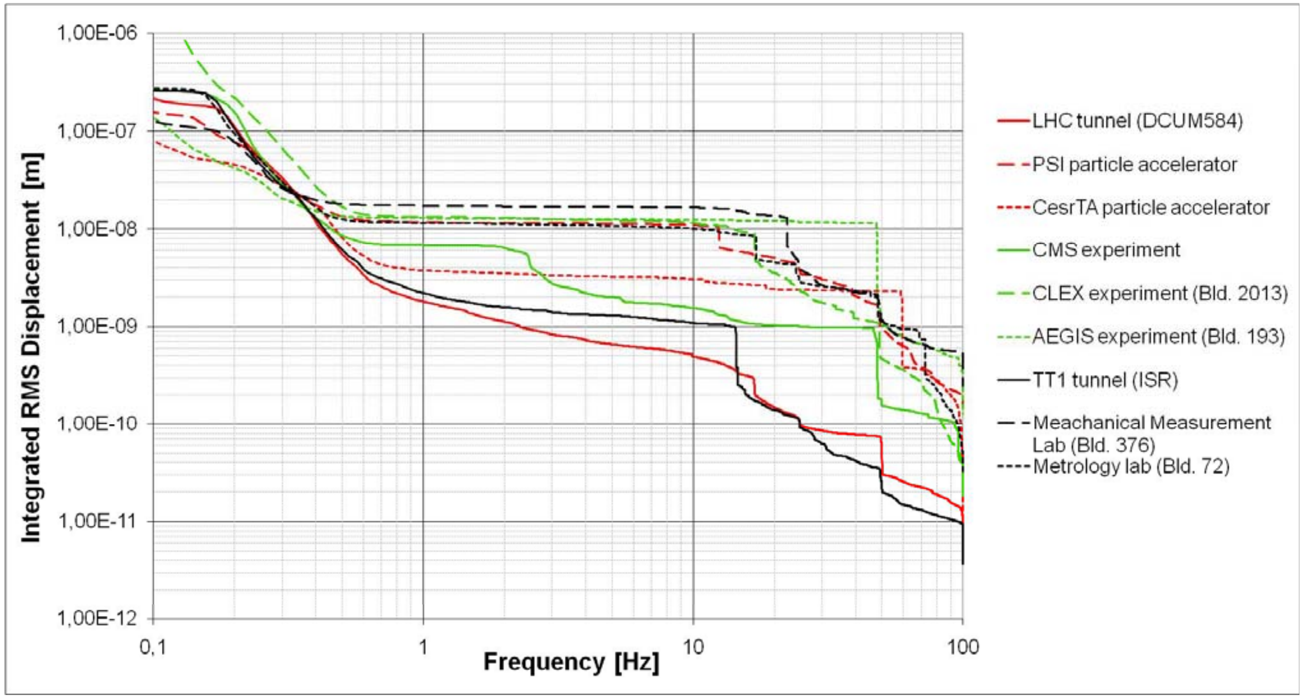
Motion ω characterization



CLIC nano stabilisation : Motion ω characterization

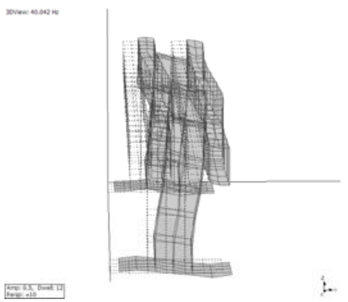


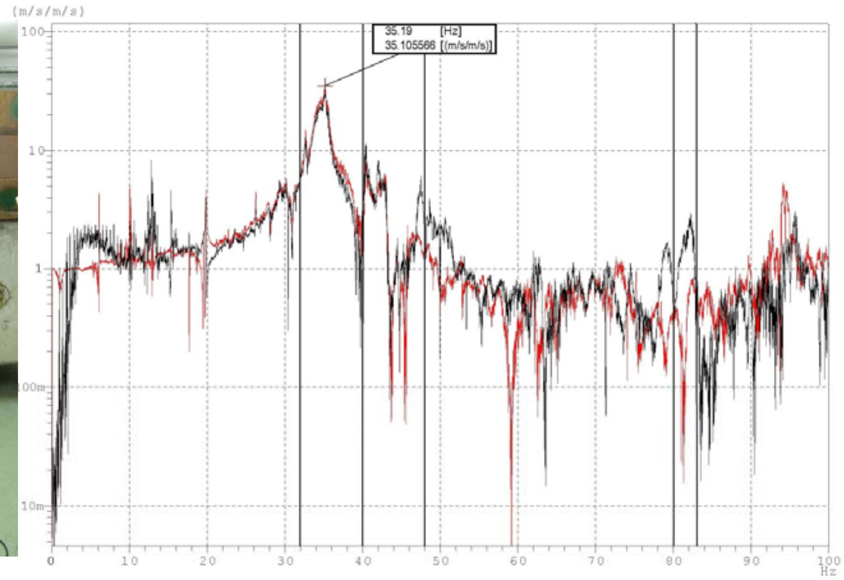
- A significant peak at 1/7 Hz which corresponds to the microseismic peak
- Excitation of ground motion at the electrical line frequency
- Peaks at about 14 Hz are observed between the ground motion at several CERN locations



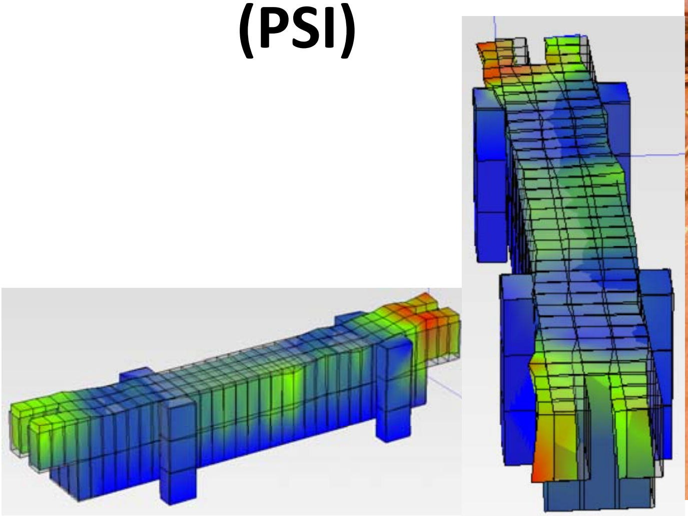
CLIC nano stabilisation : The transfer path characterization

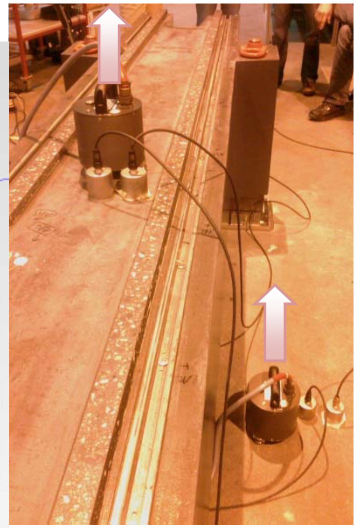
CLEX girder

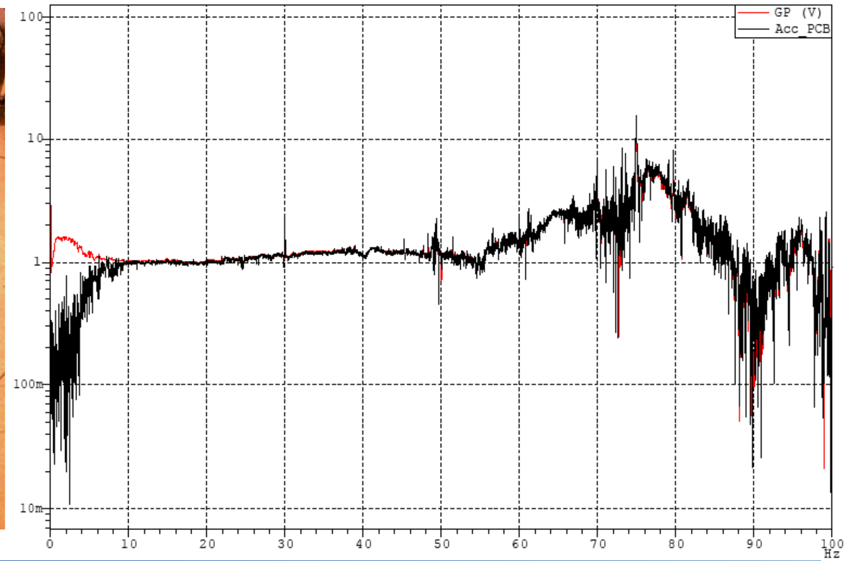




Mineral cast girder (PSI)







Conclusions

Conclusion :

- The mechanical measurement lab of the EN-MME group is able to perform mechanical measurements for CERN applications and environment.
- New studies are in progress to increase our knowledge concerning the behaviour of these measurement techniques in the specific CERN environment according to the new industrial products (DAQ).
- In the lab, each request is a specific development ! The mechanical measurements techniques, knowledge's, equipments and experience are concentrated in the lab of the EN-MME Group.
- For more information you can visit our Web Page at :

http://en-dep.web.cern.ch/en-dep/Groups/MME/DEO/MECHANICAL-LAB/default.asp

Thanks to Alex, Andrey, Delio, Kurt, Ofelia,

Pierre, Ramon, Raphael and Stefano.

Thank you for your attention !

Questions ?