Mechanical Measurements for Accelerator and Detector components

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CERN
Engineering Department

MECHANICAL & MATERIALS ENGINEERING
FOR PARTICLE ACCELERATORS AND DETECTORS

“Mechanical measurements?”

Sensor Transducer	Cable, Transmission	Signal Conditioning	ADC Data recording and storage	Data analysis
pressure, force, stress, strain, displacement, velocity, elasticity, mass, acceleration, momentum, temperature, friction, thermal conductivity, thermal contraction, contact pressure, emissivity,…	voltage, current, light, signal, … cables, twisted, coaxial, screening, impedance, feed-throughs, contacts, soldering, slip rings, antenna …	power supply, filter, amplifier, electronics, LASER, photodiode, receiver		

variables

Oscar Sacristan De Frutos (CERN)
Digital Twins for Accelerators and Detectors
8 Jun 2024, 12:00

Technology evolution: IC, TEDS, SMART sensors, networks, Digital twins, …

Calibration

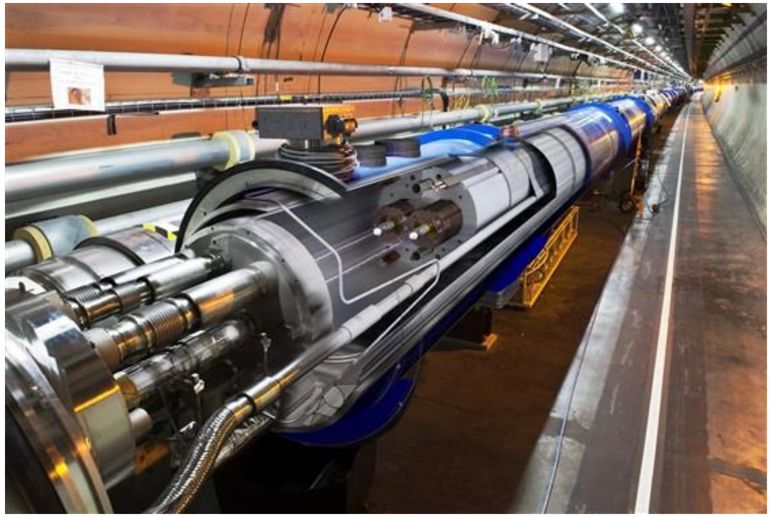
References: Theory and Design for Mechanical Measurements, R. Figliola, D. Beasley
Mechanical Measurements, T. Beckwith, R. Marangoini, J. Lienhard

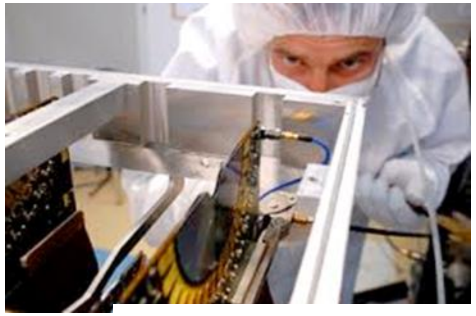
Fair: Sensor and test Nurnberg 11.06-13.06! https://www.sensor-test.de/welcome-to-the-measurement-fair-sensor-test-2022/

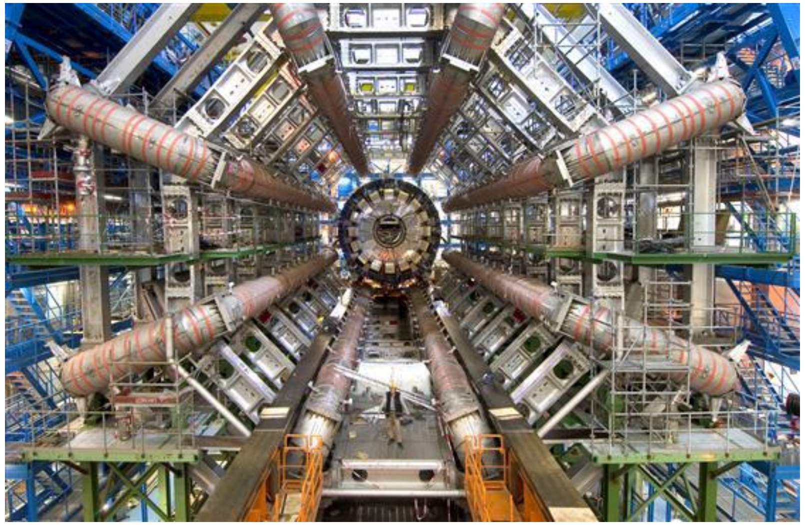
For accelerators and Detector components»?

Specific measurement conditions:

- Vacuum
- Long lead cables, embedded cables
- Large number of channels
- Long term measurements (zero stability)
- Non-standard materials
- Vacuum feedthroughs
- Very light structures
- Very large or very small
- Clean room
- Embarked measurements
- ….



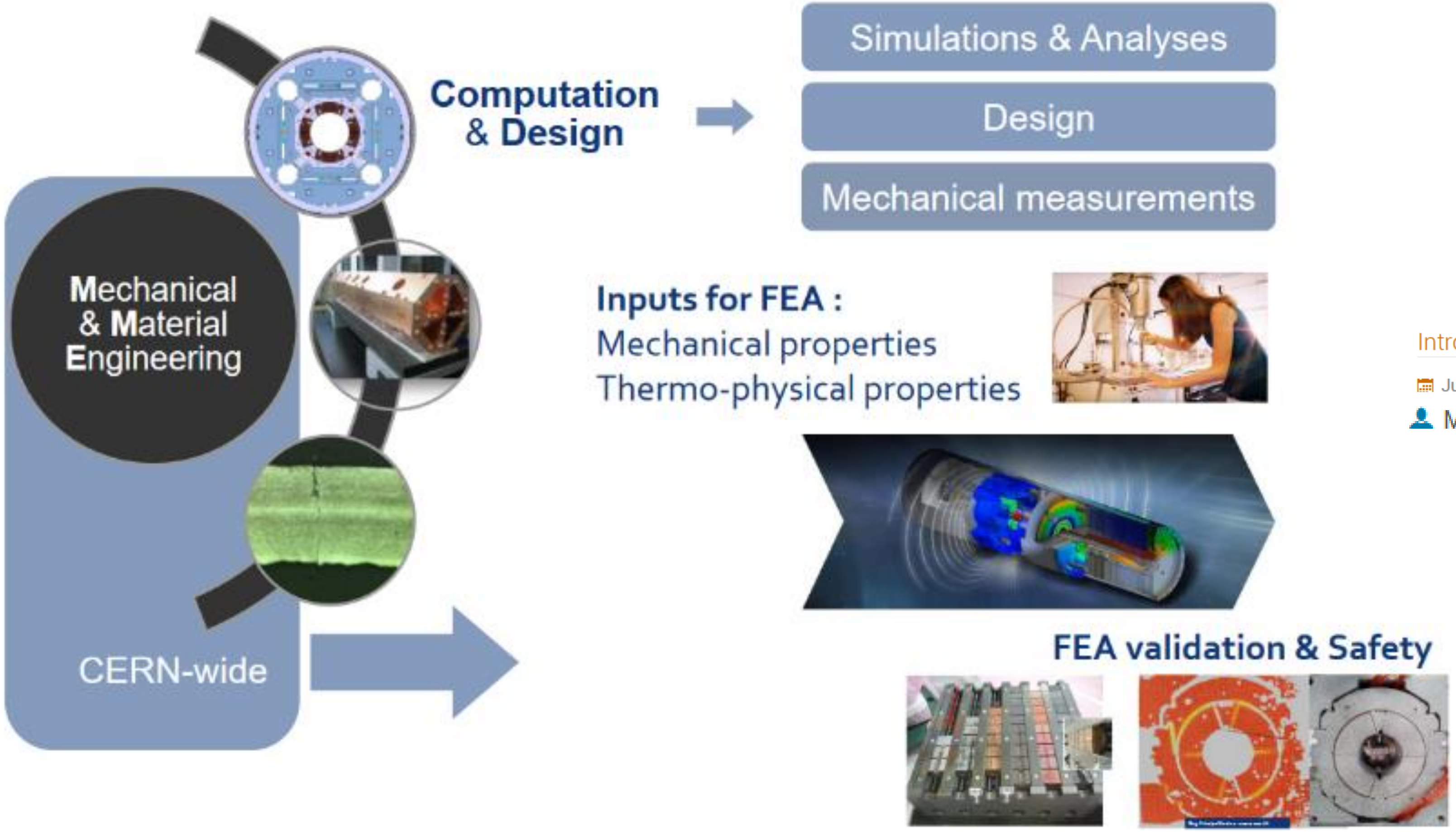




Objectives

- <u>Short</u> introduction to the field
- Some examples in challenging measurement environments
- Give you some references, books, articles
- Some focus as preparation for the hands-on session
- Networking !

CERN MME Mechanical Measurements Lab



Remark to designers:
Will you need measurements?

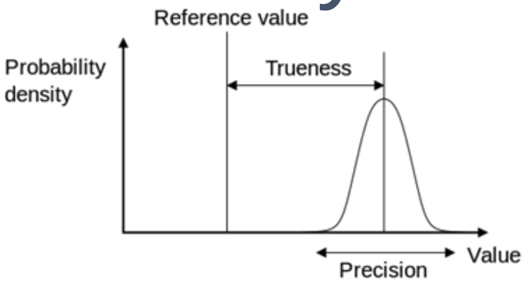
Introduction to Design for Accelerators

Jun 3, 2024, 2:30 PM

Marc Timmins (CERN)

New 360° virtual lab visit available : [here]

Precision, Repeatability, Reproducibility, Accuracy



The measured value you will report (with a unit) will have an error (difference from the real, unknown value).
That estimated error shall be part of your reported value.
Think about significant numbers.

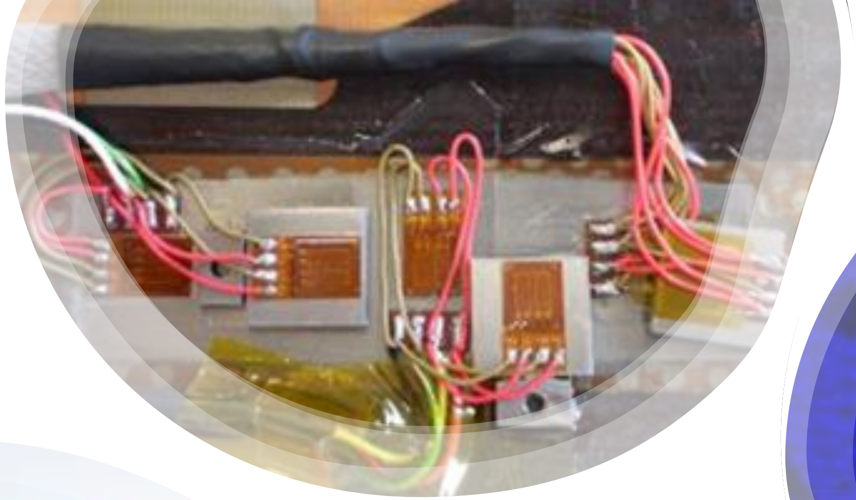
Make a measurement strategy: how will you verify, validate, calibrate

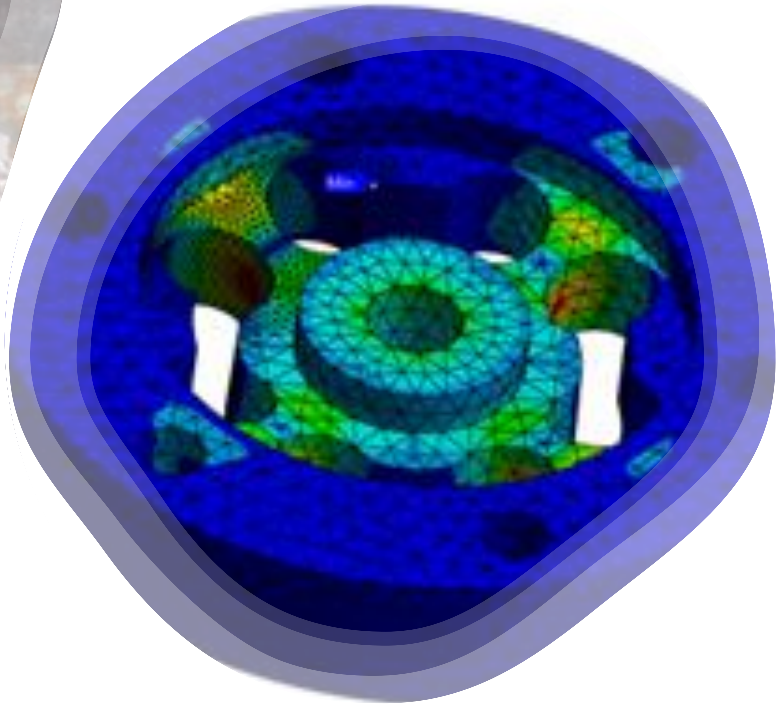
Measurement Uncertainty Speaker

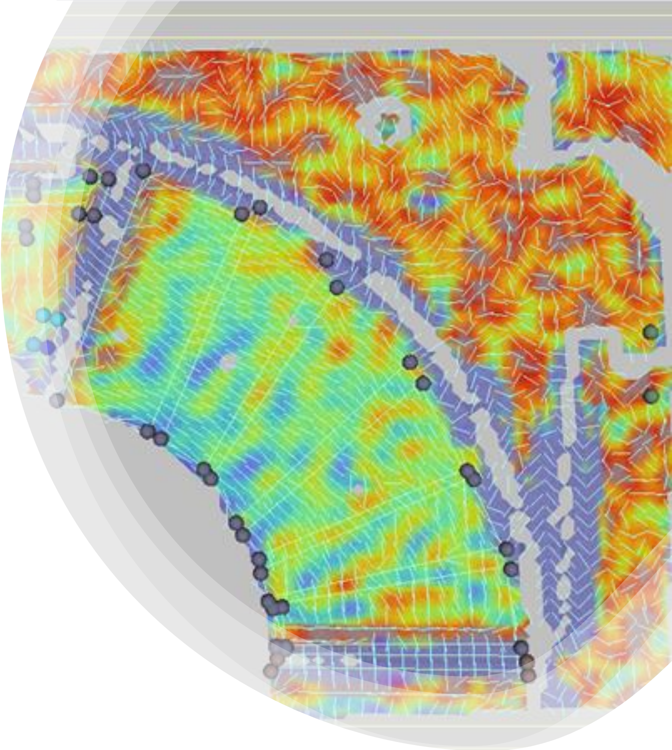
Jun 11, 2024, 11:00 AM Samanta Piano

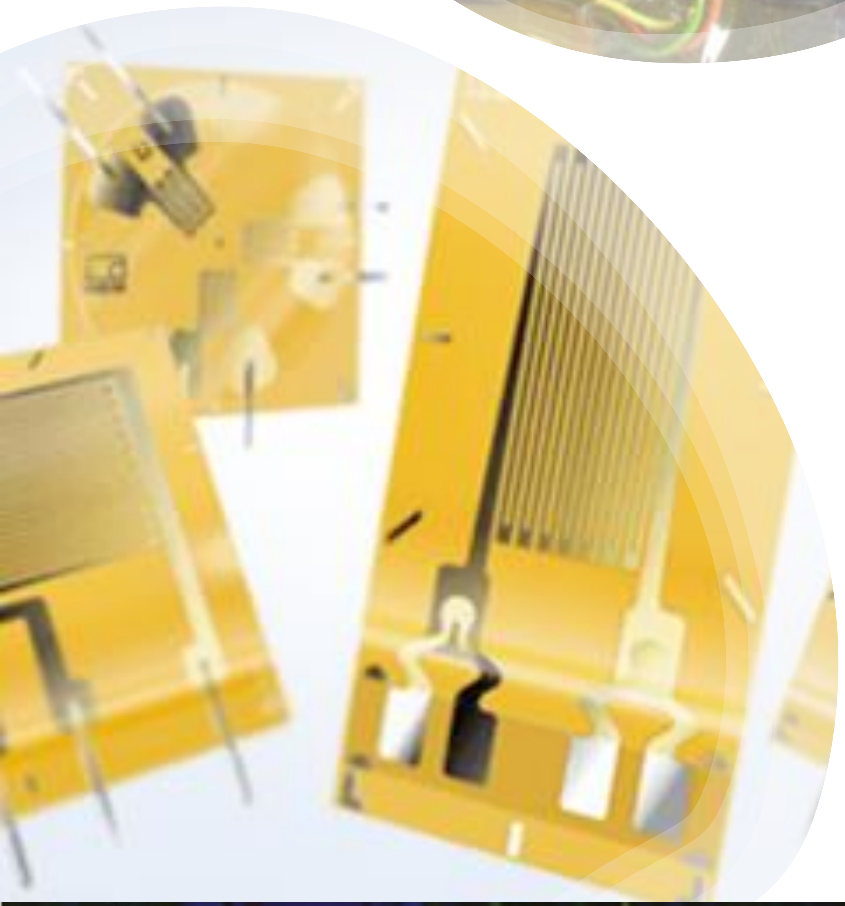
ISO 5725 international standard

Accuracy: trueness + precision
Precision: repeatability + reproducibility
ISO 5725-2: method determination repeatability and reproducibility
ISO 5725-4: method determination of trueness









Strain measurements

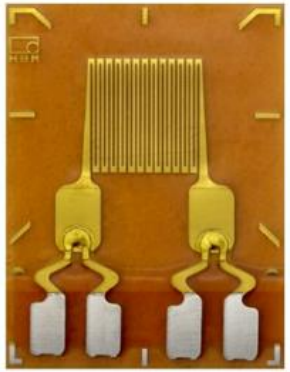
Resistive strain gauges

$$\frac{\Delta \boldsymbol{R}}{\boldsymbol{R}} = \varepsilon(1+2\upsilon) + \frac{\Delta\rho}{\rho}(\varepsilon)$$

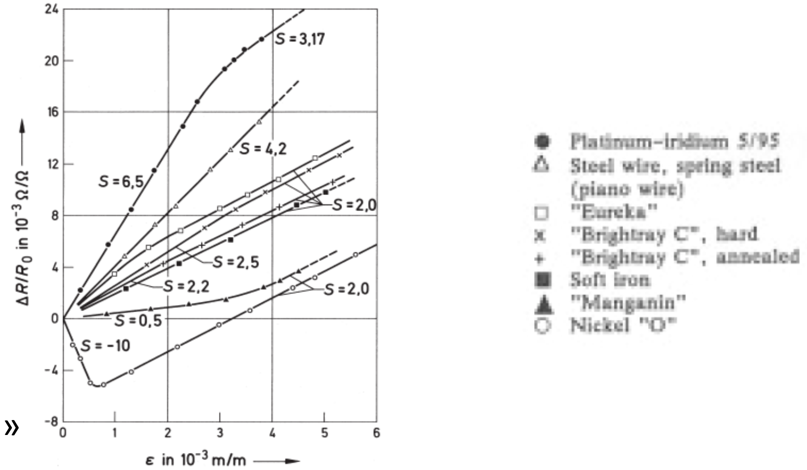
ε strain (m/m)
ρ resistivity (Ohm.m)
ν poisson ratio

$$\boxed{\frac{\Delta \boldsymbol{R}}{\boldsymbol{R}} = \boldsymbol{k\epsilon}}$$

Strain factor or k-factor
k is provided with the gauge (typically around 2)
Typically “unit” « micro-strain »



« Uni-directional gauge »



Influence of temperature on the gauge « Apparent strain » (A.S.)

$$\left(\frac{\Delta R}{R_0}\right)_T = k_{(\Delta T)}\varepsilon_{ax} + \left[\beta_G + k\left(\frac{1+K_t}{1-v_0 K_t}\right)(\alpha_s - \alpha_G)\right]\Delta T$$

β_G = Temperature coefficient of resistance of grid conductor
k = Gauge factor of strain gauge
K_t = Transverse sensitivity of the strain gauge
$(\alpha_s - \alpha_G)$ = Difference of thermal expansion coefficients between the substrate and grid

«Work horse» for:

- Experimental strain and stress analysis
- Transducers:

Force, weight, pressure, deformation, displacement, …

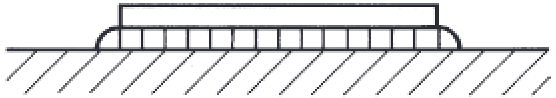
Gauge selection for material support: « self – temperature compensation » at room temperature but this is limited

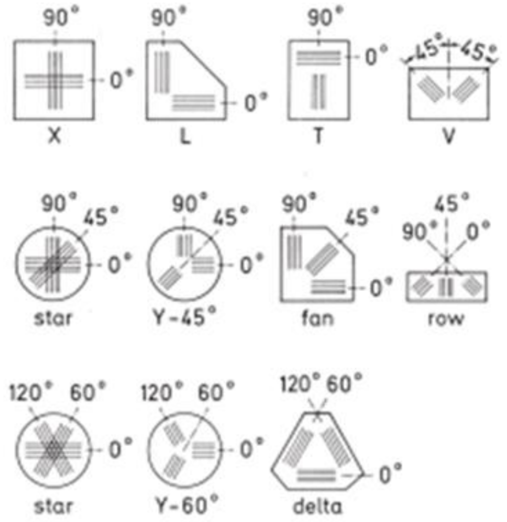
Link to Hoffmann book HBM:
https://mpe.au.dk/fileadmin/www.ase.au.dk/Filer/Laboratorier_og_vaerksteder/Instrument_Depotet/Udstyr/Strain_gauges/HBM_Karl-Hoffmann_An-Introduction-to-Stress-Analysis-using-Strain-Gauges.pdf

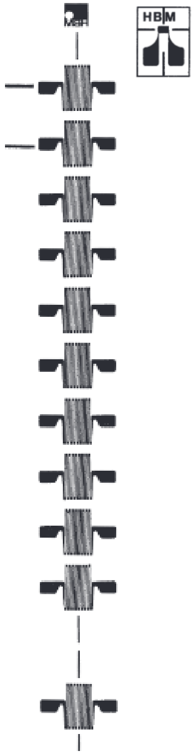
Strain gauge selection and installation

- Strain gauge selection: type,
  material of resistive grid and support
- **Glueing** (cold and warm curing)
- Soldering

Requires a training



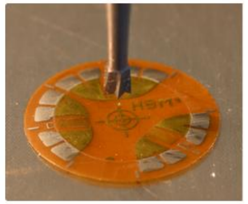


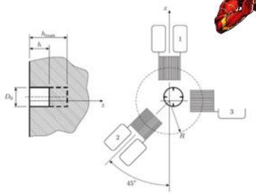


Selection strain gauge type: adapt it to the strain to be measured:

- Strain averaging and length of a strain gauge
- For measuring a gradient : strain gauge chains
- Strain direction: “uni-directional” strain and lateral strain sensitivity of a strain gauge.
- Strain direction: principal strain and stress directions, shear gauges, Rosette gauges
- Transducer design: adapt the measured object to the strain gauge

Residual stress measurement: hole drilling method





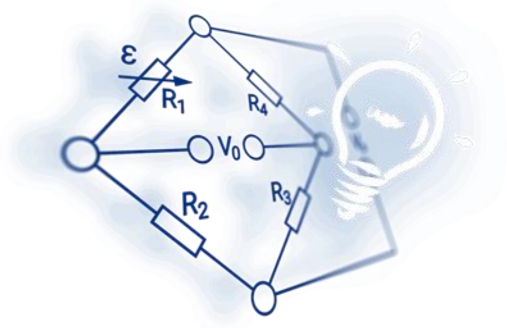
Important to have a good idea of the strain distribution on the measured object!
You (can) only measure strain that is on the surface of the measurement object

Wheatstone bridge

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

ΔR : <μΩ to mΩ range

Wheatstone bridge!



Wheatstone bridge equation :

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

If R1=R2=R3=R4, Vs= 0

For R1≈R2≈R3≈R4 and small ΔR:

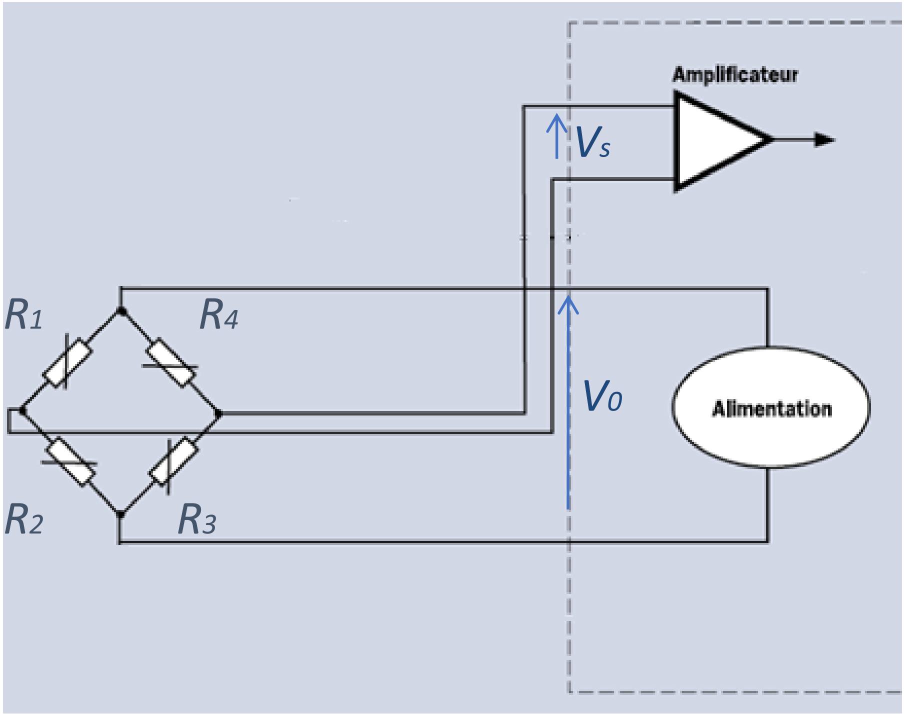
$$\frac{V_0}{V_s} = \frac{1}{4}\left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4}\right)$$

For strain gauges: $$\frac{\Delta R}{R} = k\varepsilon$$

$$\boxed{\frac{V_0}{V_s} = \frac{k}{4}\,(\varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4)}$$

Bridge factor:

$$\frac{V_0}{V_s} = \frac{k}{4}\,\mathrm{B}\varepsilon$$ With B depending on the bridge configuration (see next slides)

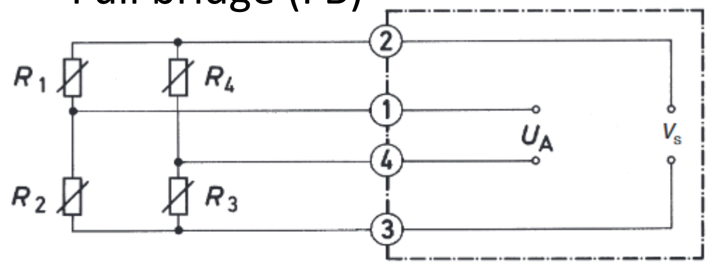


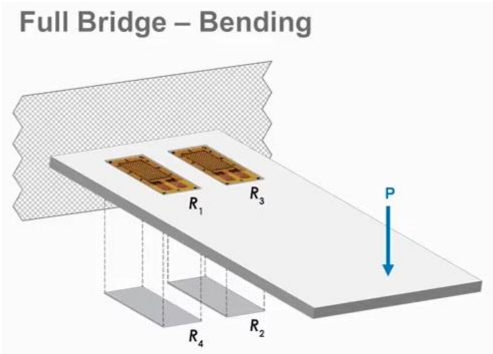
Bridge configurations

$$\frac{V_0}{V_s} = \frac{k}{4}\left(\varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4\right)$$

$$\frac{V_0}{V_s} = \frac{k}{4}\,\mathrm{B}\,\varepsilon$$

Full bridge (FB)



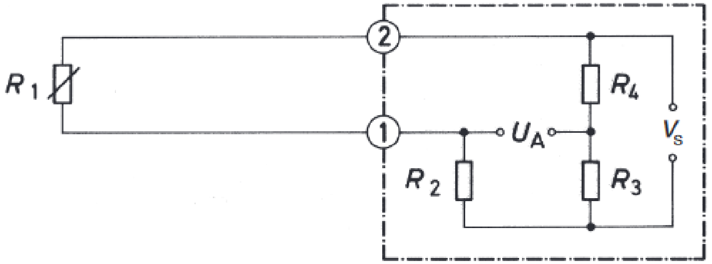


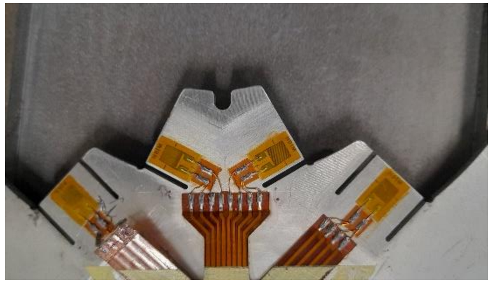
- B=4
- Temperature compensation

«Poisson full bridge»

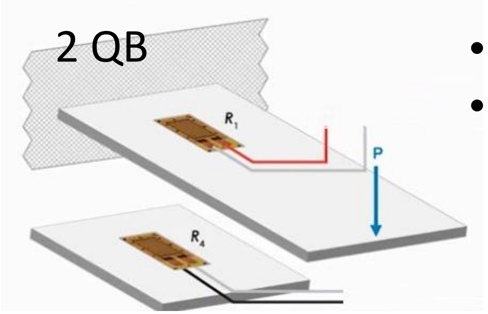
- B=2.6
- Temperature compensation
- Bending compensation

Quarter bridge (QB)



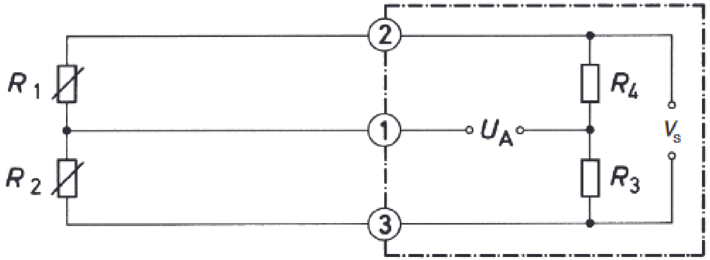


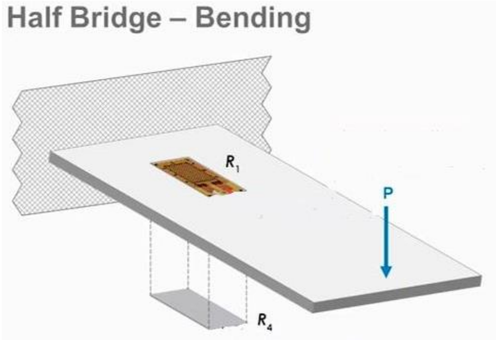
- B=1
- No Temperature compensation



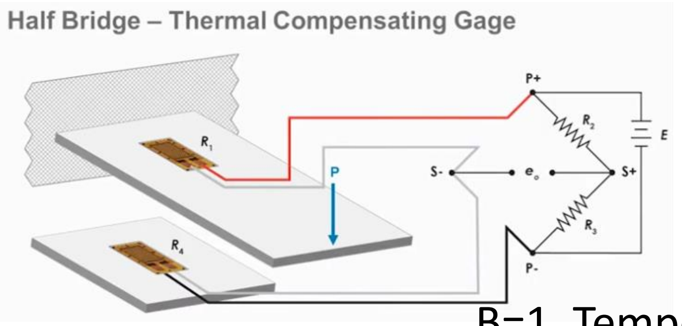
- B=1
- Temperature compensation

Half bridge (HB)





- B=2
- Temperature compensation

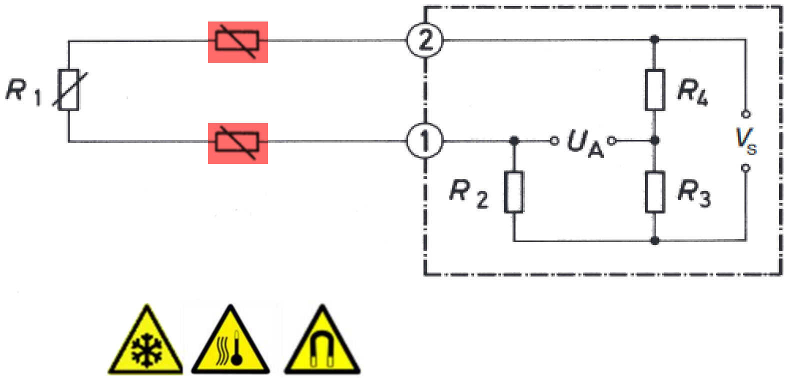


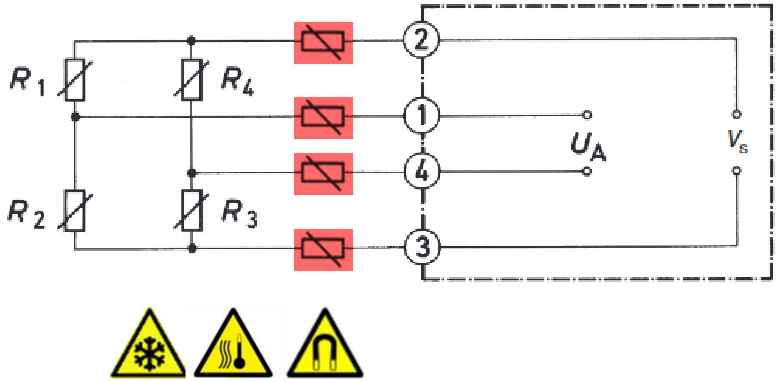
Support without strain

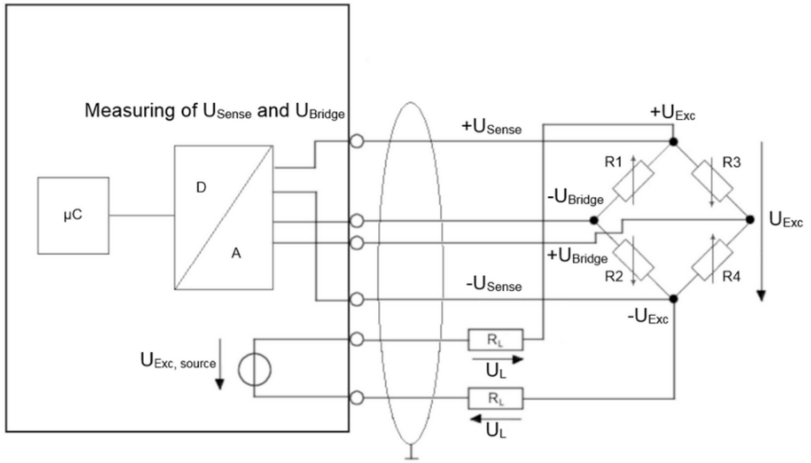
B=1, Temperature compensation

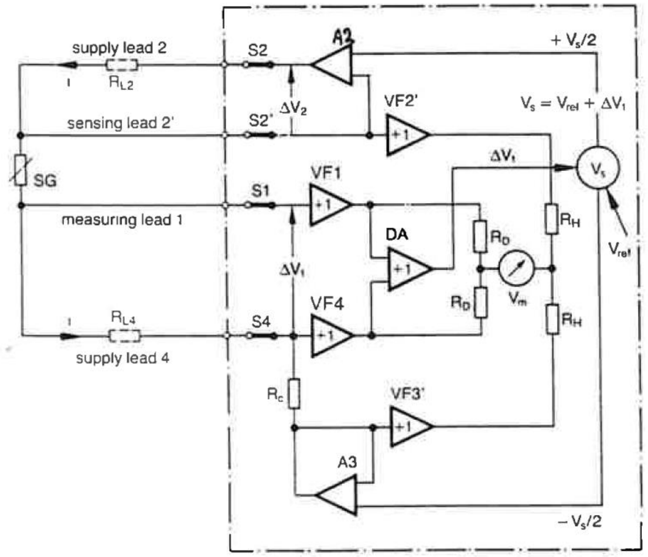
External circuit *Completion circuit*

Lead and conditioner configurations









- Lead resistance NOT negligible with long leads, high temperature changes (cryo), high magnetic fields, low strains, moving leads, feedthrough, slip rings,…
- List of possible mitigations possible by some cabling tricks, but:
- Commercial strain gauge conditioners available with separate supply and sense leads (QB 4, HB 5, FB 6 wires, ~ 0 current in sense leads)
- Regulated DC or AC gauge supply voltage, continuous or short supply (self-heating gauge)
- AC supply : carrier frequency (some kHz) with cable impedance compensation
- Best to use twisted pair cables, where possible shielded per pair

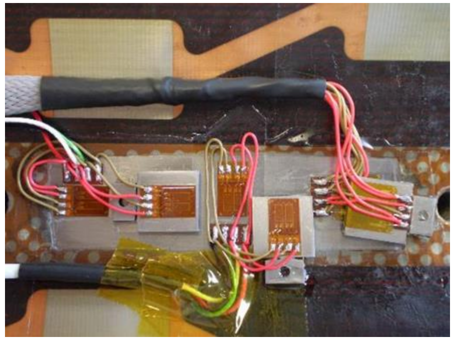
Strain gauges for super conducting magnets

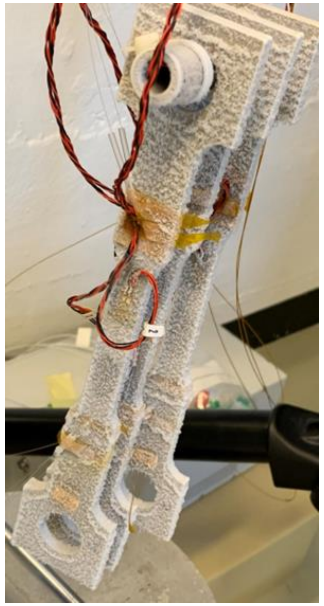
- Strain gauges: modified Karma Alloy (Cr, Ni) with polyimide gauge support +cover
- Glueing: certain commercial epoxy glues, with and without hot curing
- Soldering and cables: certain commercial solders, twisted strand Teflon or polyimide cables

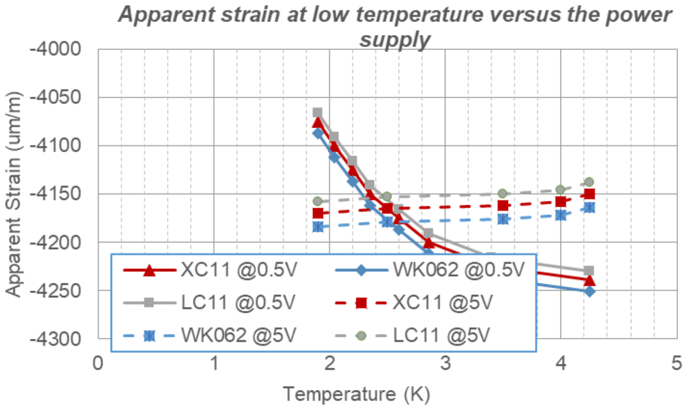
- “training” or cold cycling gauges 77 K for a stable zero

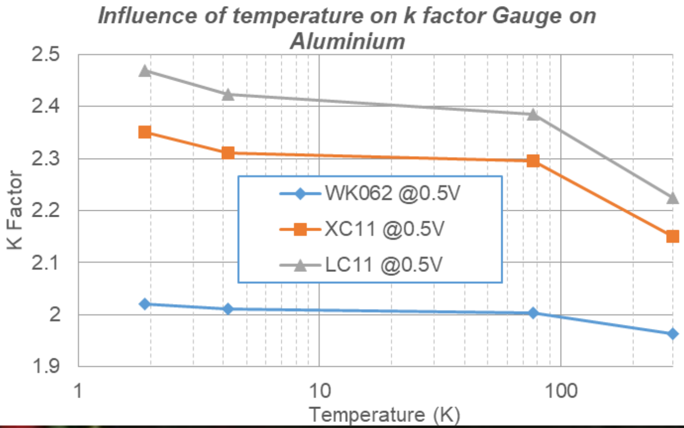
- 4, 5 or 6 wire connections
- Preferred FB and HB for A.S. compensation but also QB with prior strain-less T calibration
- “Kondo effect” (strong inversion of AS in liquid Helium)
- Short Carrier frequency supply voltage 0.5 to 5 V (heating of gauge)
- K-factor correction (~ -10% for 2 K)
- Young modulus (+ 8-10 %)

Contact us









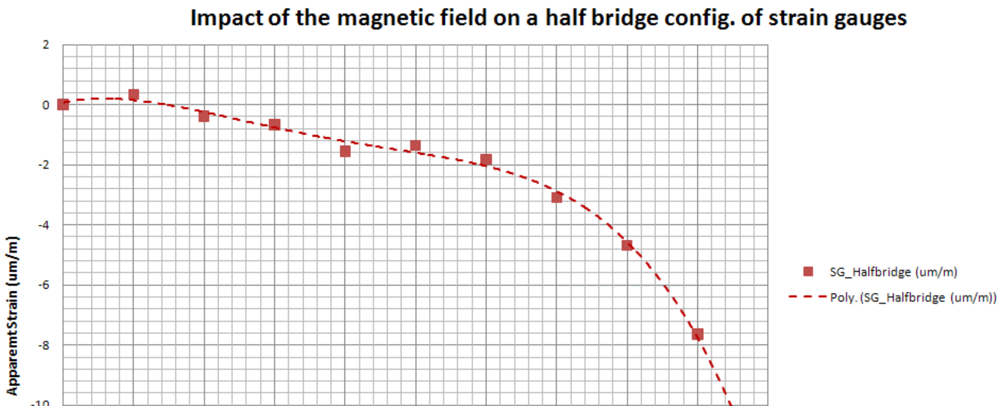
References: P.L. Walstrom, Strain gauges for superconducting magnet testing, Cryogenics 1980 ; C. Ferrero, Thermal and magnetic correlation in apparent strain down to 1.53 K and up to 6 T on strain gauges; K. Artoos et al., Performance of Strain Gauges in Superfluid Helium, Technical note EST-ESI/97-1, T. Dijoud et al. Caractérisation du facteur k des jauges de contrainte à basse température, CERN note EDMS 1150596

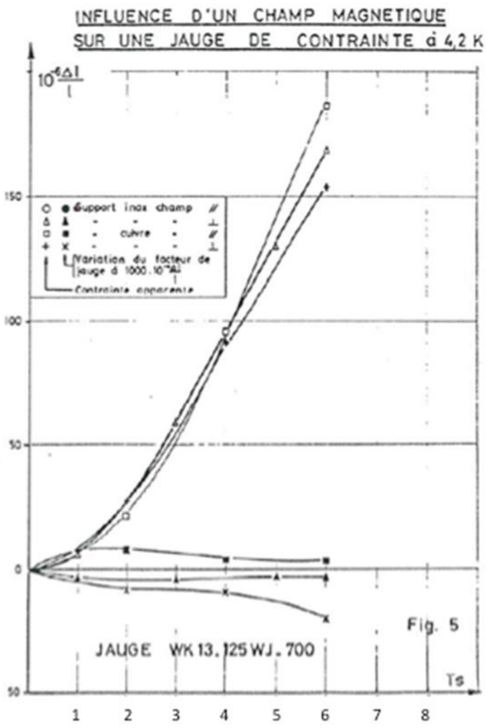
Strain gauges for super conducting magnets

<u>Effect magnetic field:</u>

- (Magneto-striction: mostly support)
- Magneto-resistance
  - * Strongly increases below 10 K
  - * Depends on orientation gauge
  - * Mod. K alloy well adapted
- FB and HB configuration to compensate

- Lead induction : limit by twisted pairs (attention with what you twist!)





Magnetic field influence can be limited but never zero, foresee a way to validate/ evaluate (e.g. strain less support)!

<u>Effect Radiation:</u>

Degradation glue, materials, oxidation of the grid

Creates in the first place a **zero drift**. This can be reduced with full bridges but not eliminated.

Can completely destroy the gauge

Literature nuclear industry

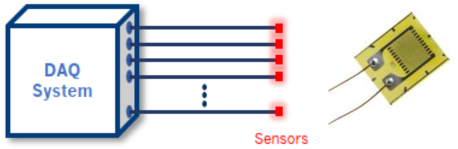
Info in Hoffman book; N. Noppe et al., Strain gauges in a nuclear environment, Materials & Design Volume 14, Number 6, 1993

Strain Sensing Techniques Evolution

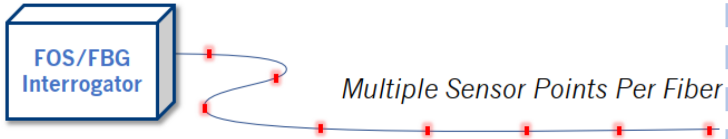
80's — 2011 — 2021

Electrical Strain Gauge (ESG)

Multiple Copper Wires Per Sensor



Fiber Bragg Grating (FBG)



Discrete

Rayleigh Backscattering (RBS)

Distributed

ESG:

- Robust well proven technology
- Bulky sensors and multiple cabling
- Sensitive to temperature and magnetic field
- Gauge small heat dissipation

FBG:

- Single optical fiber for multiple meas. points
- Challenging bonding process for cryogenic temperatures
- Sensitive to temperature
- <u>Not sensitive to magnetic field</u>
- ~ 0 heat dissipation on measurement point

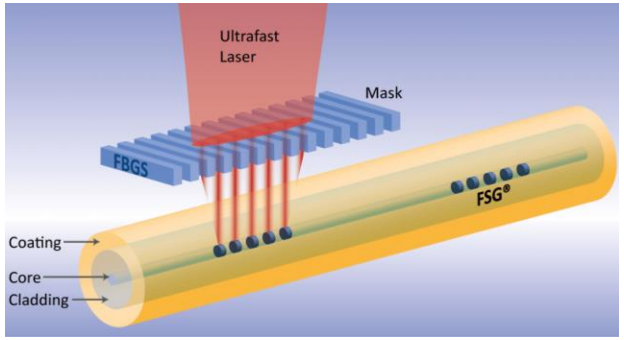
RBS:

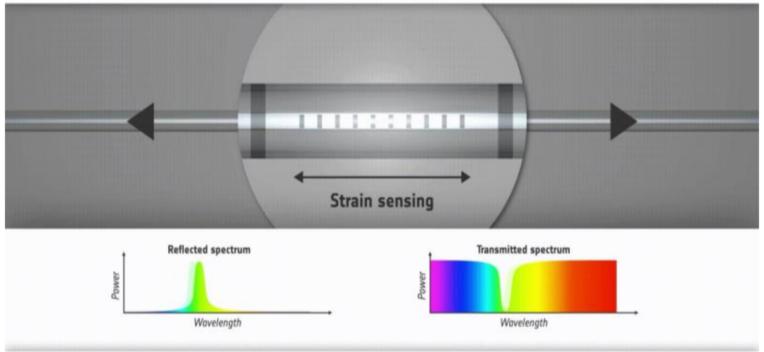
- Single optical fiber for distributed measurement points with Sub mm spatial resolution
- Challenging bonding process for cryogenic temperatures
- <u>Not sensitive to magnetic field</u>
- ~ 0 heat dissipation on measurement point

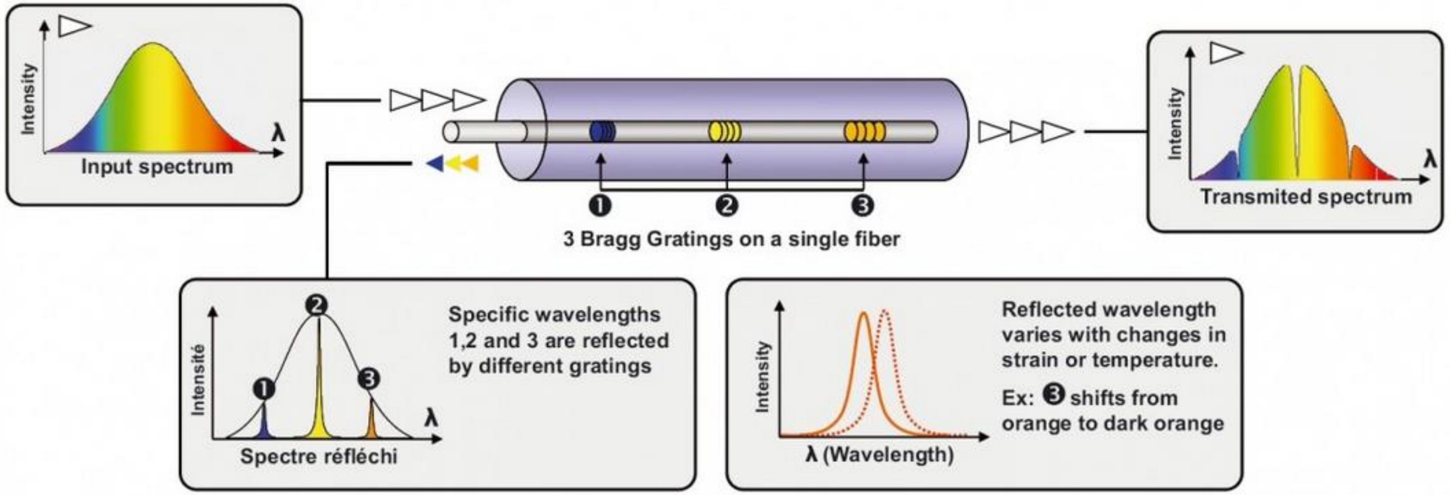
Remark: Optical fibres remain flexible at cryogenic temperature

Bragg Fibre Grating

Hands-on session







$$\Delta\lambda_B = \lambda_B[(1 - p_e)\varepsilon + (\alpha + \xi)\Delta T]$$

Strain Temperature

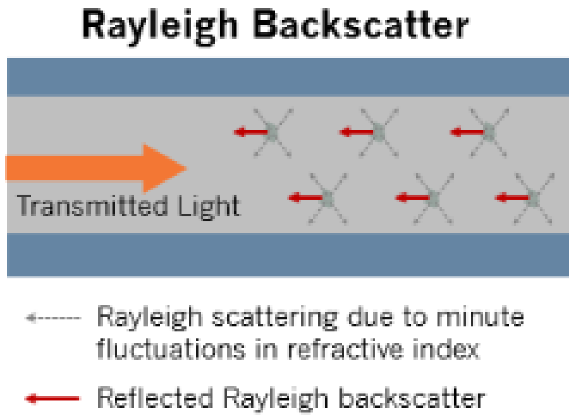
p_e = photo sensitivity of fibre
ε_{ax} = axial strain
α_s = Thermal expansion coefficient of fibre
ζ_s = Thermo-optic coefficient of fibre

- Up to 40 sensors /fibre (depends on FBG interrogator)
- Static and dynamic measurements up to 2 kHz
- Validated in liquid Helium* and in SC magnets

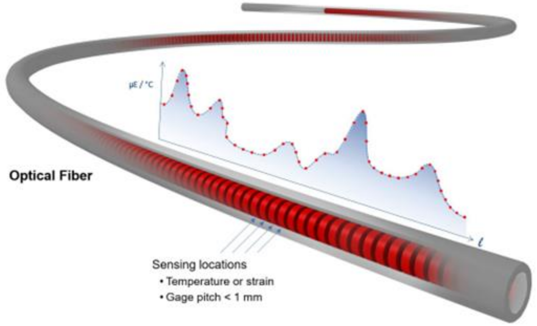
Use similar techniques as for strain gauges (bridge configurations) for temperature compensation.

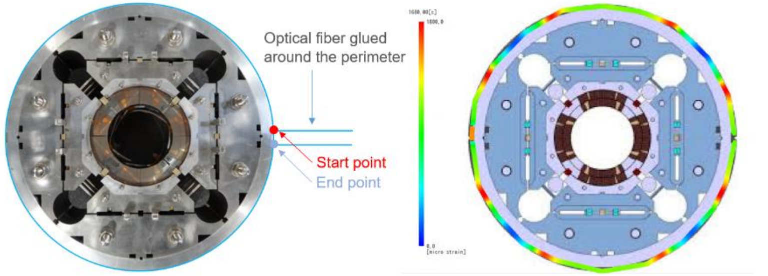
*Reference: M. Guinchard et al., Mechanical Strain measurements based on Fiber Bragg Grating down to Cryogenic Temperature- Precision and Trueness determination, 26th Int. Conf. On Optical Fiber sensors

Rayleigh backscattering RBS sensors



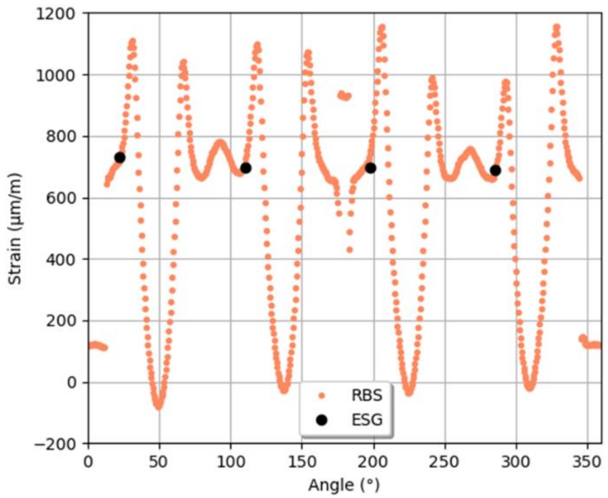
Rayleigh backscattering is caused by the random fluctuations (smaller than the light wavelength) in the index profile along the optical fibre

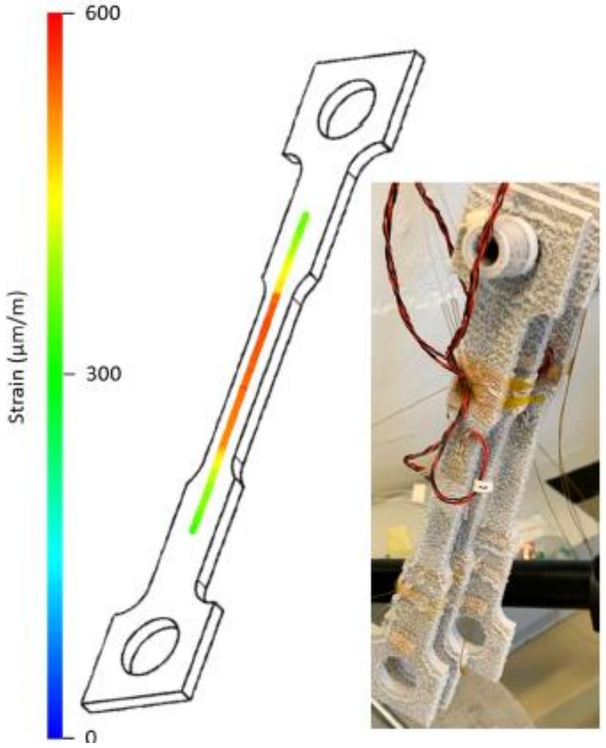




Measurements with RBS during loading phases of

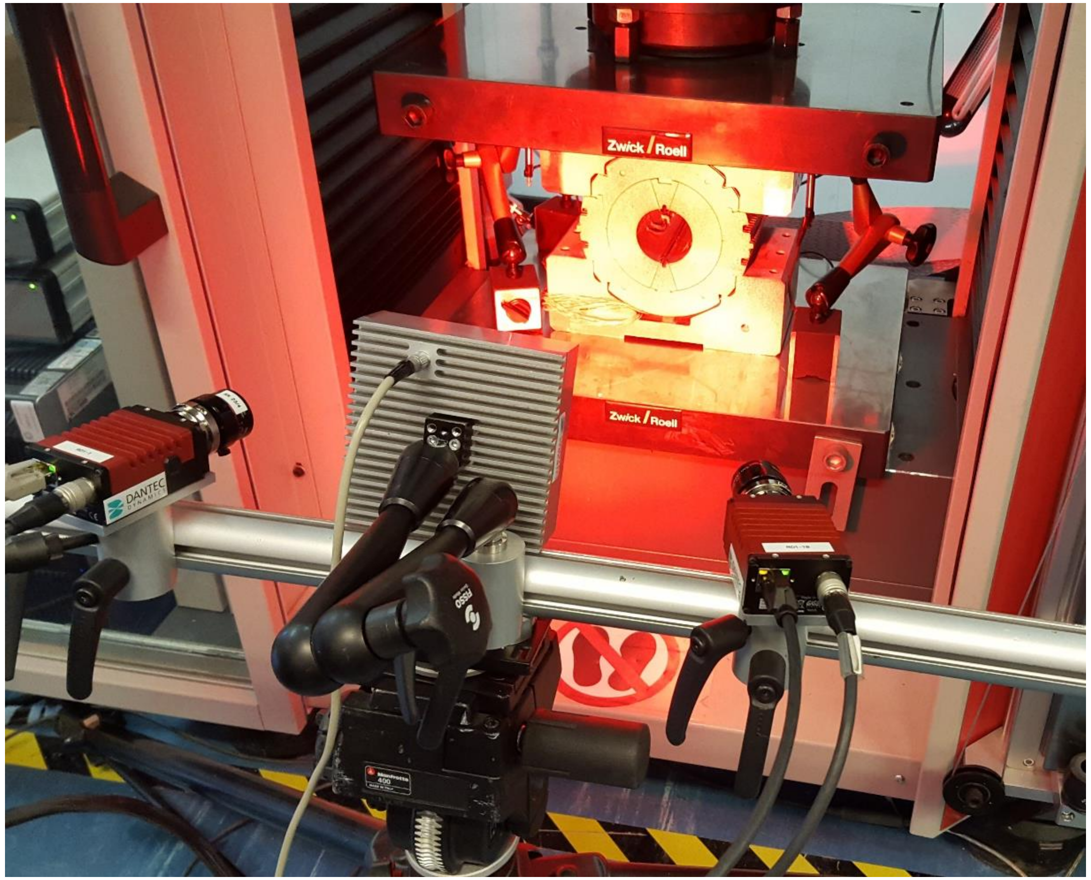
- Sub mm spatial resolution (depends on interrogator) for distributed measurements
- Static and dynamic measurements up to 250 Hz (depends on interrogator)
- Tested in liquid Helium*, technique under development at CERN



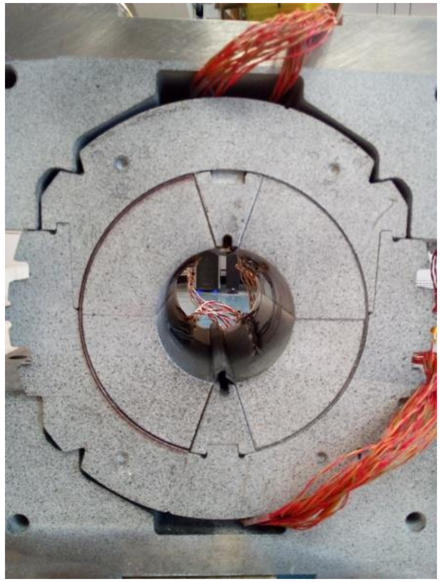


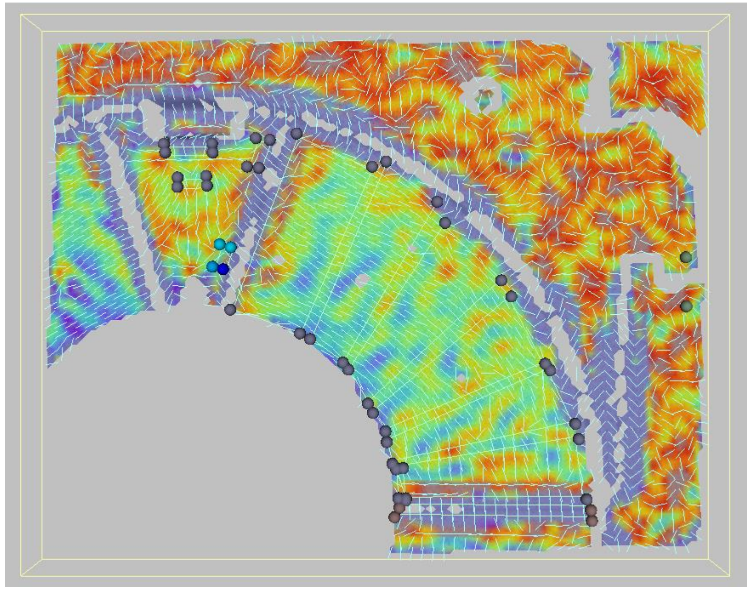
*Reference: K. Kandemir et al., Distributed optical strain sensing measurements down to cryogenic temperatures, Applied Optics, Vol 62, #16, June 2023

Digital Image Correlation



Digital image correlation is an optical method that employs tracking and image registration techniques for accurate 2D and 3D strain measurements.

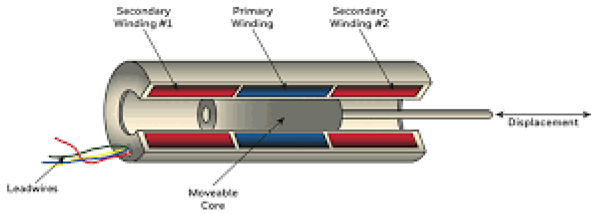




Other measurables

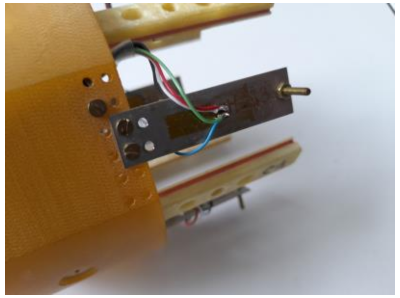
Displacement

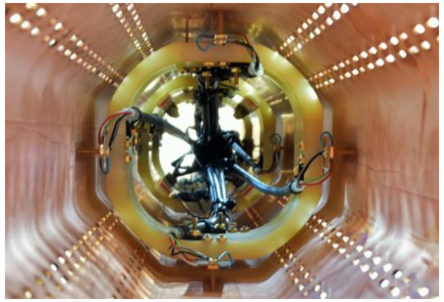
- LVDT



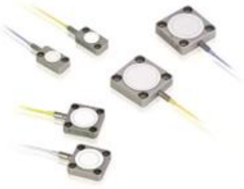
- Conductive plastic potentiometer
  (tip: mount it as voltage divider, 5 wires)

- Strain gauge based





- Capacitive

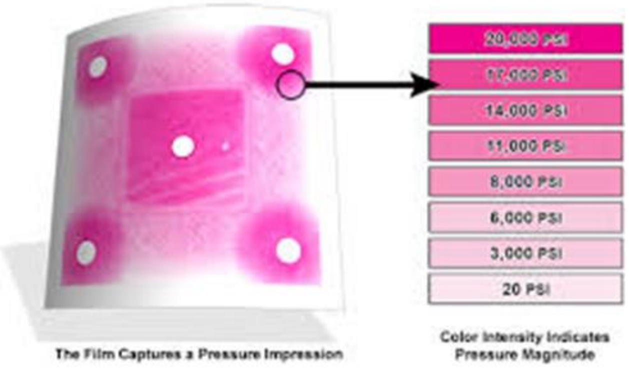


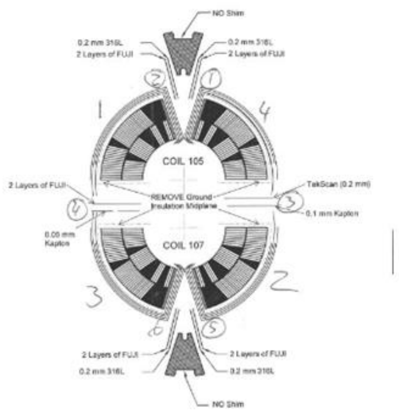
- <u>LASER</u>
- Optical rulers, Moiré gratings,….

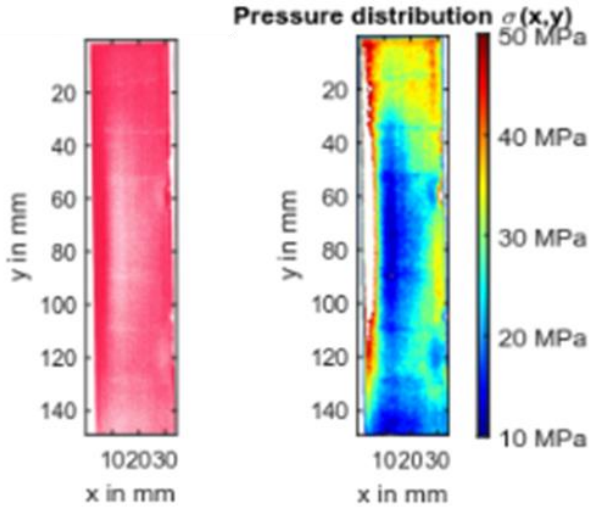
"Challenge" Hands-on session:
"Invent" a displacement gauge during one of the subjects

Contact pressure

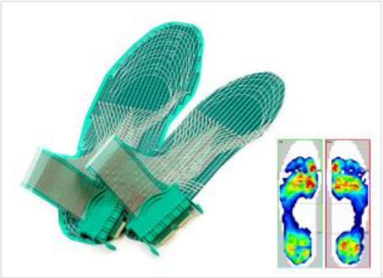
- Fuji paper

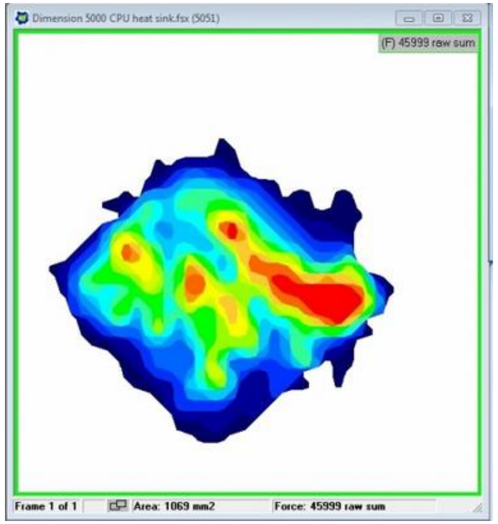


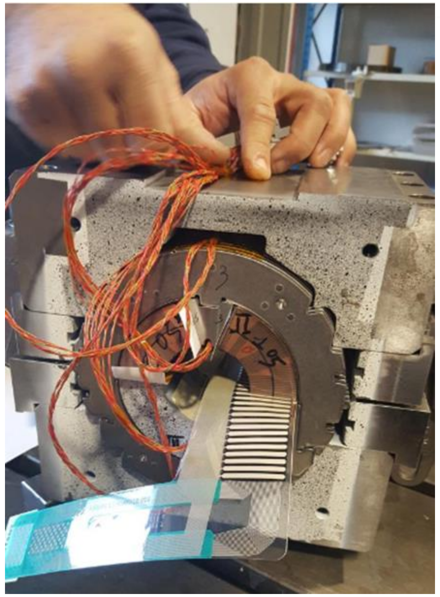




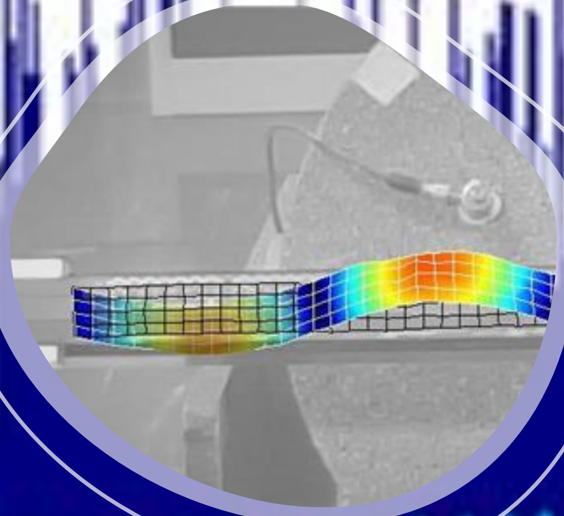
- Pressure mapping sensors







Dynamic measurements



Dynamic measurements

- Dynamic signals
  - Deterministic
    - Periodic
    - Transient
  - Random
    - Stationary
    - Non-Stationary

Periodic
- Modal analysis with shaker
- Rotating machines

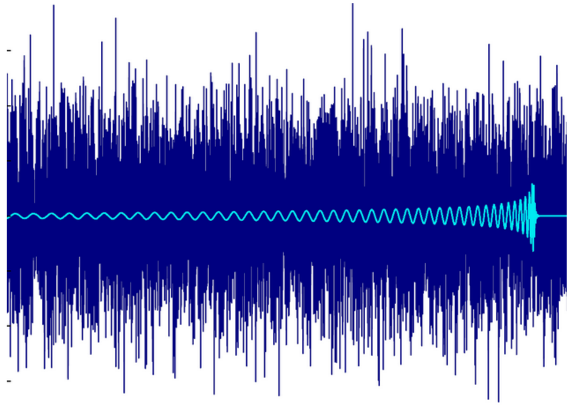
Transient
- Modal analysis with hammer
- Accelerating rotating machines

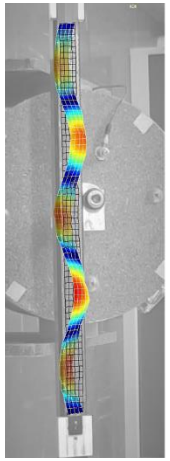
Stationary
- Ground motion measurements*
- Water cooling, air cooling

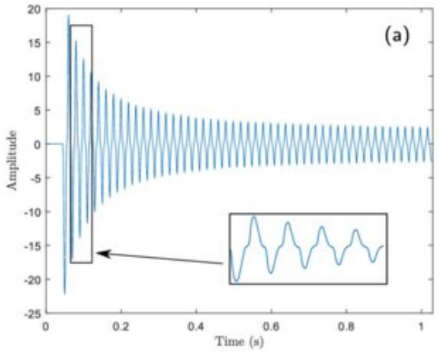
Non-Stationary
- Transient Ground motion measurements
- changing water cooling

« Dynamic » measurements?

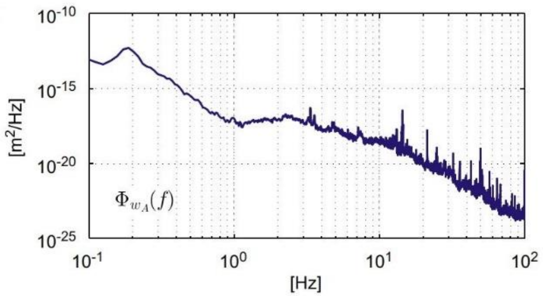
- Time resolution, sampling speed
- Frequency contents of signal
- Signal analysis
- Cables, filters,……
- Dynamic range
- Noise curve



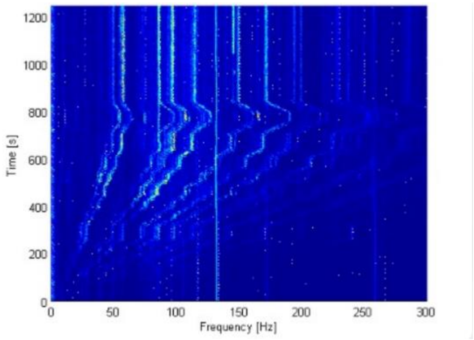




FFT



PSD



Spectrogram or water fall plot

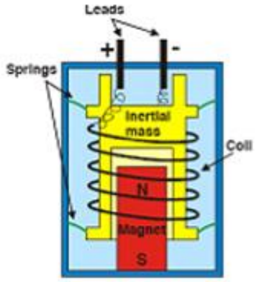
Sensors

- Any sensor that can be measured with sufficient bandwidth (strain gauges, fibres)
- In particular for vibration measurements:

Accelerometer

- Measures acceleration (F=m*a)
- Piezo, capacitive; voltage driven
- Mass on spring, Measures before F_{res}
- Coaxial cables
- Higher frequencies

Geophone, seismometer

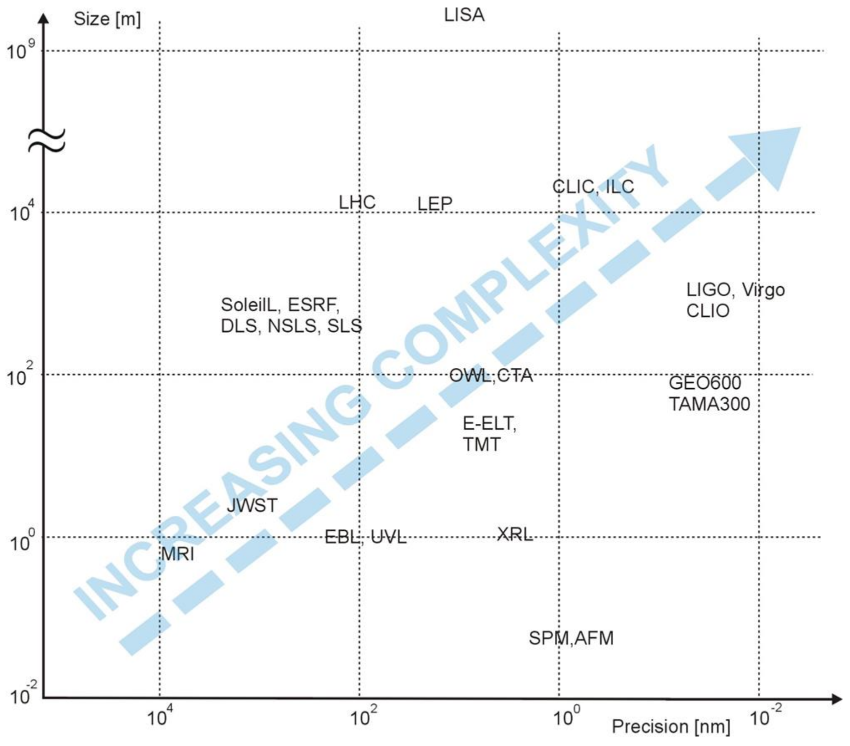


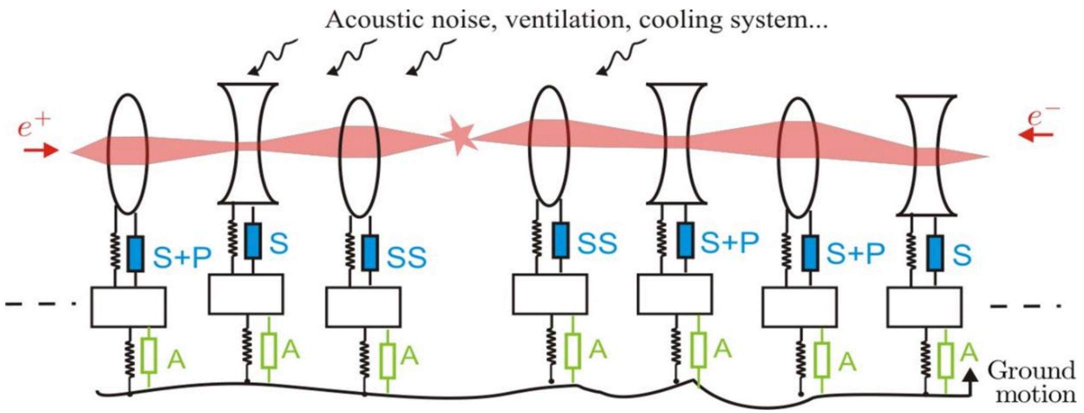
- Measures velocity change
- Magnet and coil; current driven
- Mass on spring, Measures after F_{res}
- Twisted wires in shielded cables
- Lower frequencies

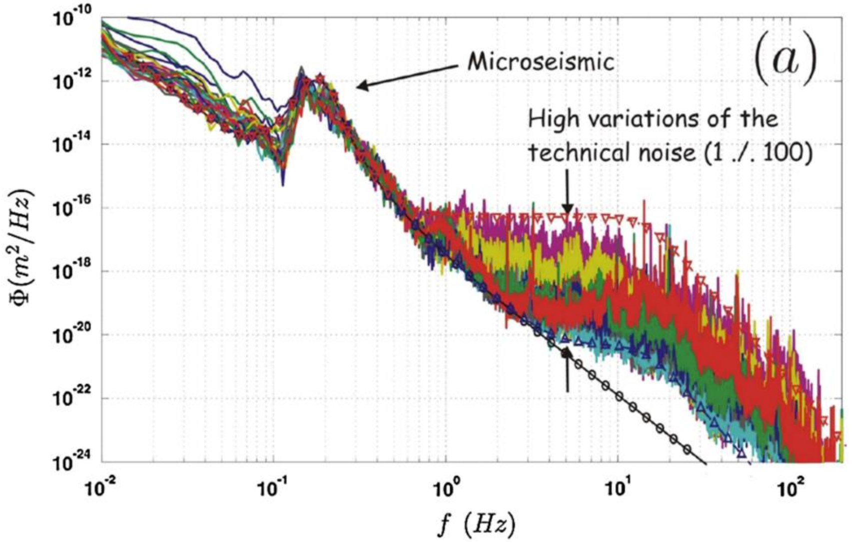
Displacement

- Measures position/displacement
- LASER of different types, capacitive, inductive, LVDT, strain gauges,…….
- Contact, non-contact
- Characteristics depends on technique used

Ground motion measurements for accelerators ?

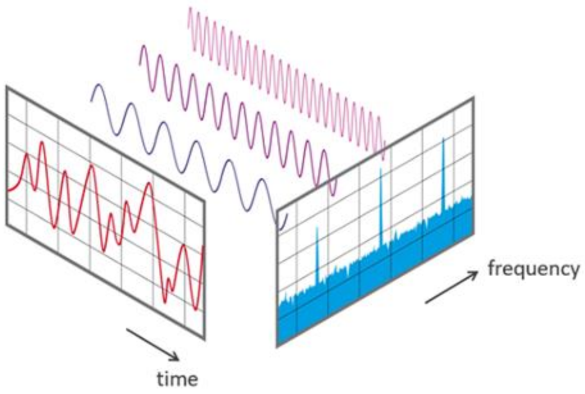






References: C. Collette et al., Seismic response of linear accelerators, Physical review special topics, accelerators and beams 13, 2010; M. Guinchard et al., The effect of ground motion on the LHC and HL-LHC beam orbit, NIMA, Section A volume 1055, 2023, 168495

Signal analysis in frequency domain

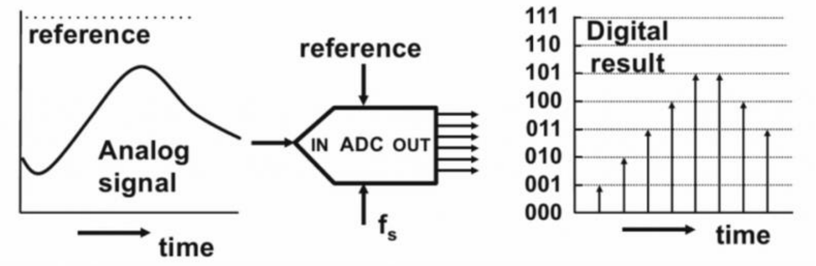


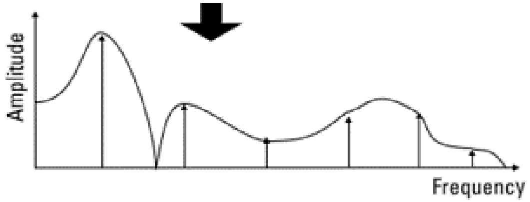
Fourier transformation (of functions)

$$F(\omega) = \int_{-\infty}^{\infty} f(t) e^{j\omega t} \partial t$$

$M e^{j\omega t}$= Acos (ωt) + jBsin(ωt)

Sampling of signal at $\mathbf{f_s}$





Discrete Fourier Transformation DFT

$$X[k] = \sum_{n=0}^{N-1} x_n \, e^{-j\frac{2\pi}{N}kn}$$

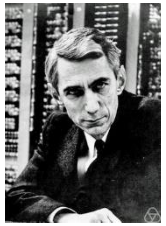
$$\begin{pmatrix} X_0 \\ X_1 \\ \vdots \\ X_{N-2} \\ X_{N-1} \end{pmatrix} = \begin{pmatrix} 1 & 1 & \cdots & 1 \\ 1 & \omega_N & \cdots & \omega_N^{N-1} \\ 1 & \omega_N^2 & \cdots & \omega_N^{2(N-1)} \\ \vdots & \vdots & \ddots & \vdots \\ 1 & \omega_N^{N-1} & \cdots & \omega_N^{(N-1)^2} \end{pmatrix} \begin{pmatrix} x_0 \\ x_1 \\ \vdots \\ x_{N-2} \\ x_{N-1} \end{pmatrix}$$

$$\omega_N = e^{-j2\pi/N}$$

Fast Fourier Transform FFT is the efficient way to calculate DFT digitally fast

Examples for different cases in the hands-on session!

Nyquist/Shannon and aliasing

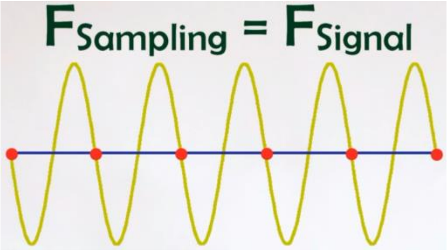
Nyquist Theorem:

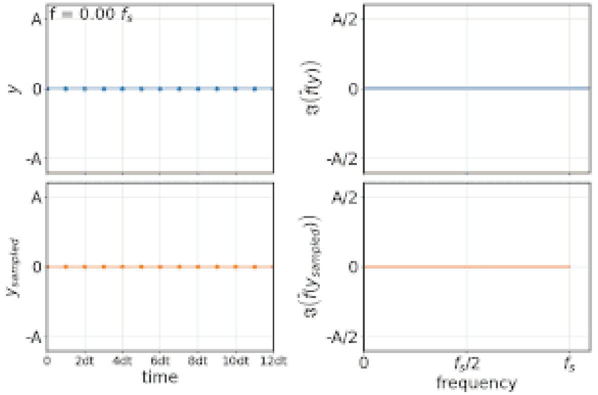
"If a function x (t) contains no frequencies higher than B Hertz, then it can be completely determined from its ordinates at a sequence of points spaced less than 1 / (2 B) seconds apart."

Or: f_s must be at least double the highest frequency component of the signal.

Bandwidth FFT $f_n = \frac{f_s}{2}$ Nyquist/(Shannon)

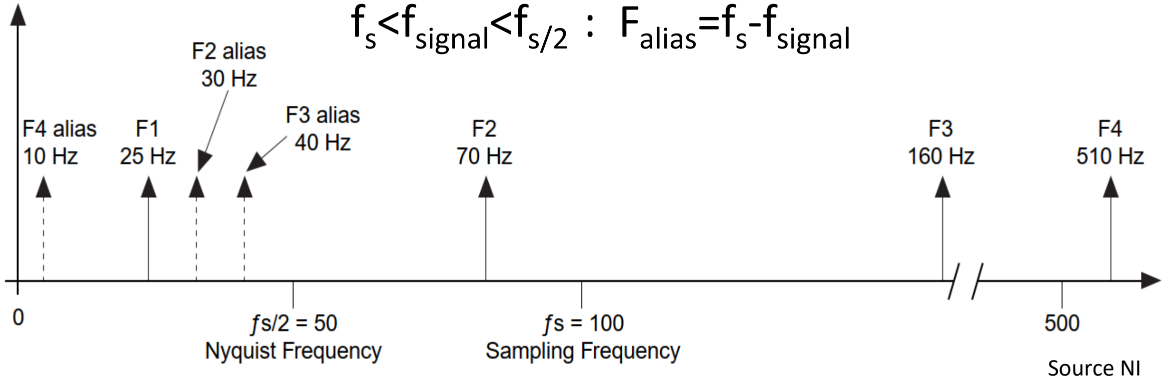
hands-on session





Signal component with frequency higher than fn will appear as an **alias frequency inside the f_n bandwidth**

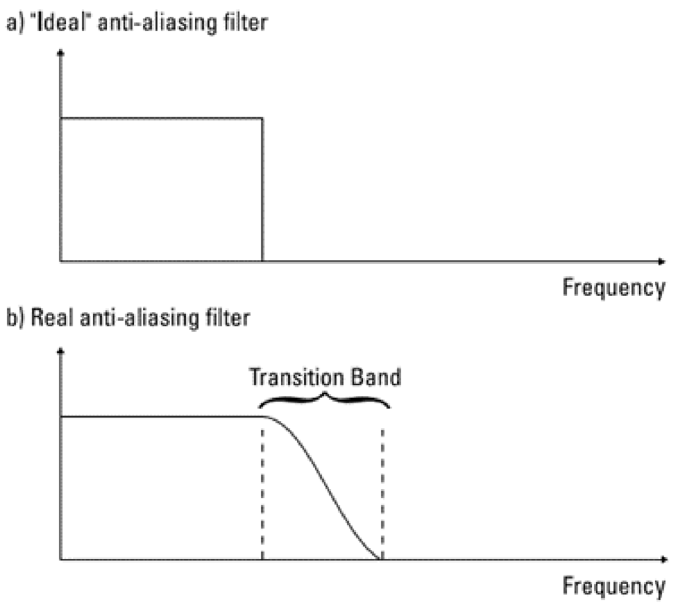
$f_s < f_{signal} < f_{s/2}$: $F_{alias} = f_s - f_{signal}$

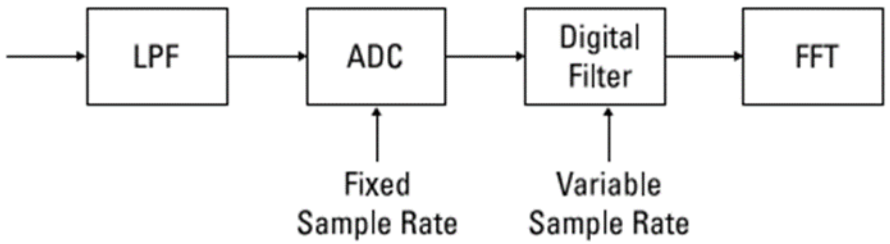


Source NI

- Highest frequency component can also be noise
- **Anti-alias filter (analogue filter) to be used**
- DAQ card versus DSP Signal analyser
- **Test: change fs and see if any of the peaks moves**

Anti-alias filter and Down sampling

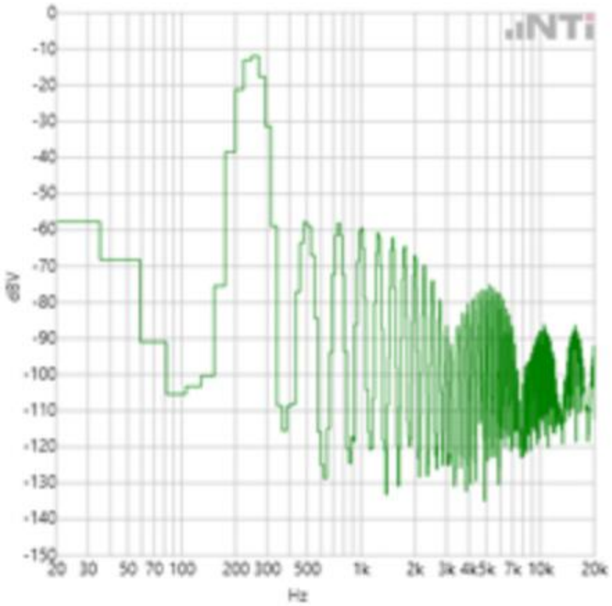


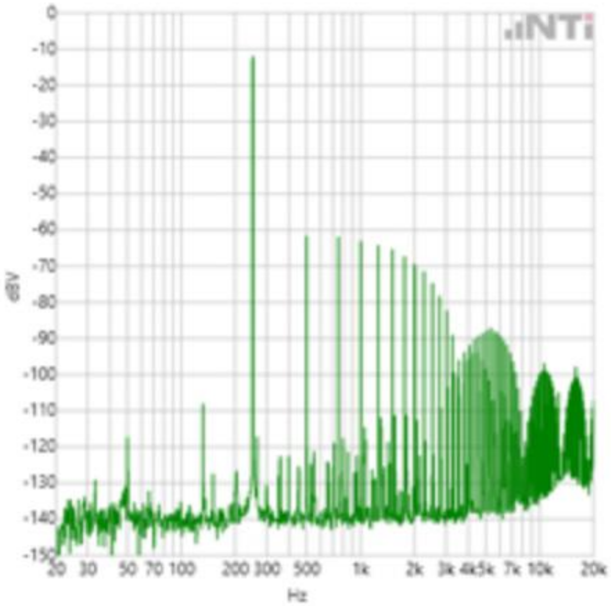


Frequency resolution df: trade off and limitations

$d_f \sim \frac{f_s}{BL}$

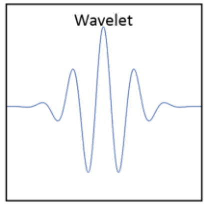
BL or BS (Block Length or Block Size) are the number of samples going into FFT analysis





$$\begin{pmatrix} X_0 \\ X_1 \\ \vdots \\ X_{N-2} \\ X_{N-1} \end{pmatrix} = \begin{pmatrix} 1 & 1 & \cdots & 1 \\ 1 & \omega_N & \cdots & \omega_N^{N-1} \\ 1 & \omega_N^2 & \cdots & \omega_N^{2(N-1)} \\ \vdots & \vdots & \ddots & \vdots \\ 1 & \omega_N^{N-1} & \cdots & \omega_N^{(N-1)^2} \end{pmatrix} \begin{pmatrix} x_0 \\ x_1 \\ \vdots \\ x_{N-2} \\ x_{N-1} \end{pmatrix}$$

For short transient events frequency resolution is a problem with FFT, in that case look at Wavelets
https://community.sw.siemens.com/s/article/wavelets-time-frequency-analysis

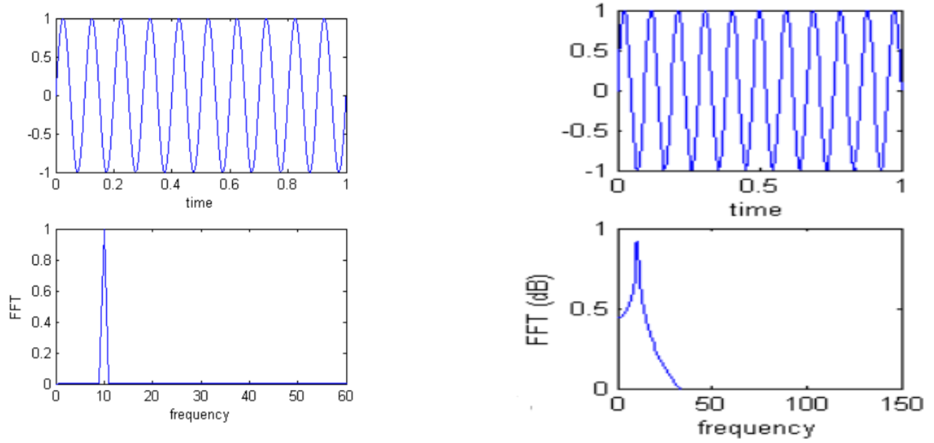


Spectral leakage

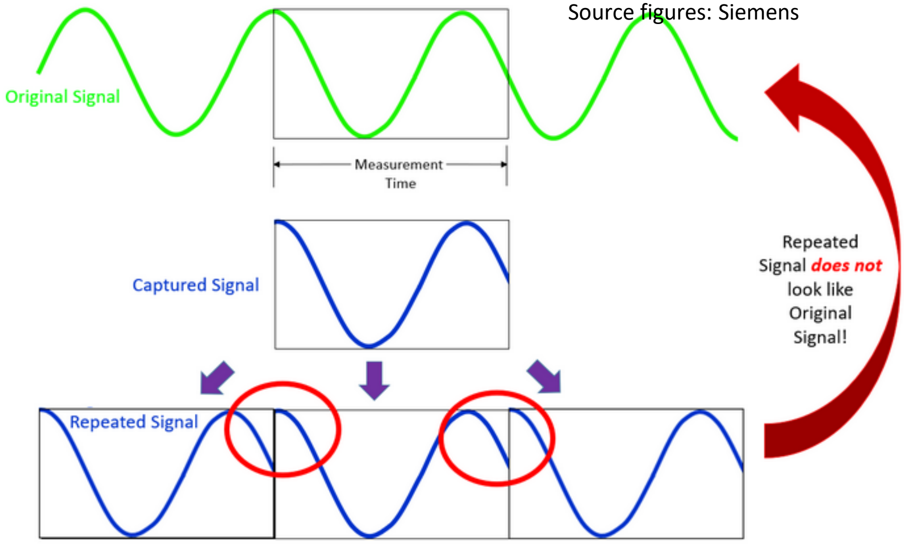
Spectral leakage changes: amplitude, shape spectrum, frequency, integrated rms, damping coefficient,…

FFT is only suitable for periodic signals

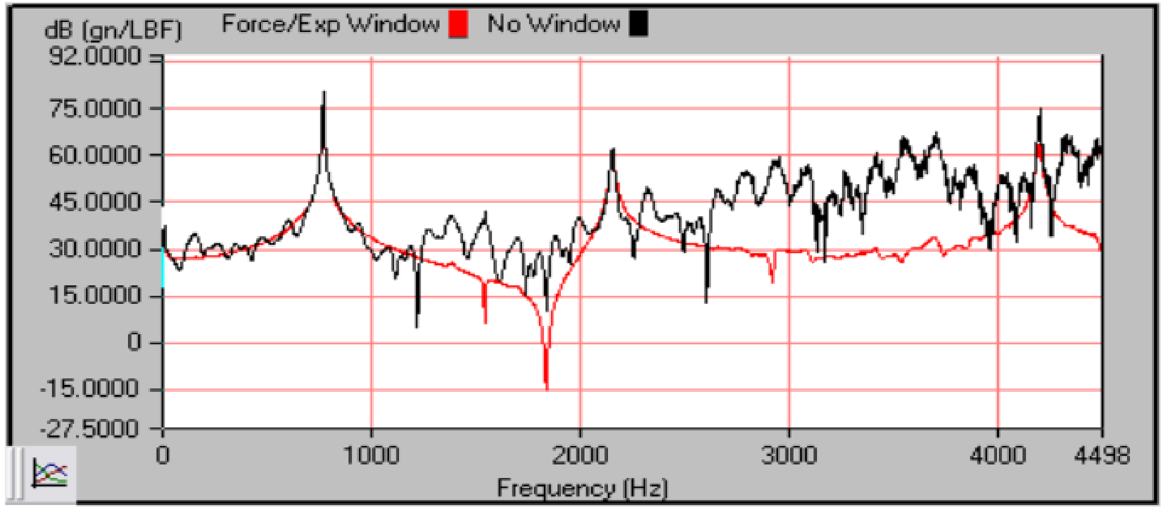
- The FFT input block <u>must contain an integer number of periods</u>

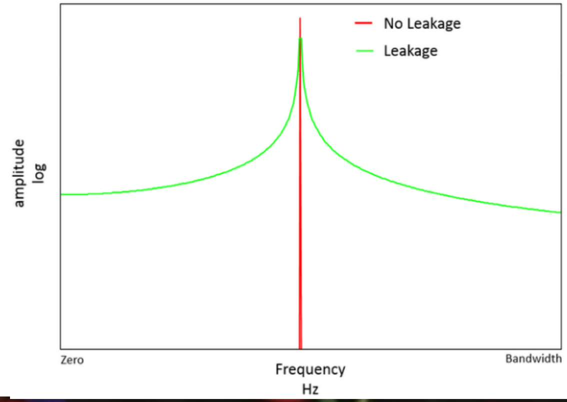


Source figures: Siemens

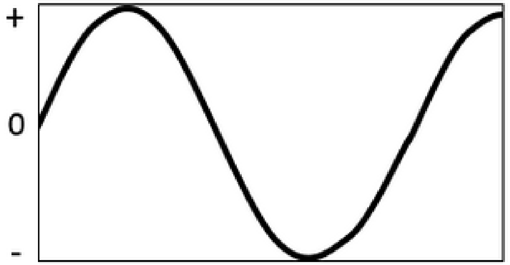


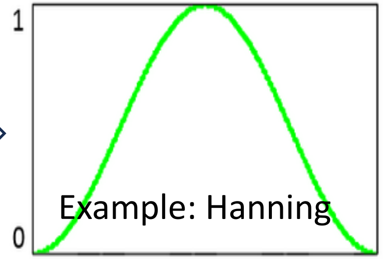
Example leakage with more frequency components:

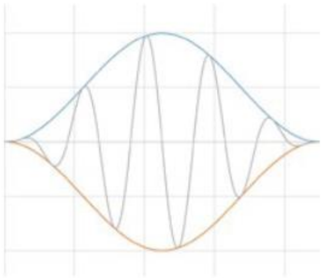




Windowing to improve spectral leakage



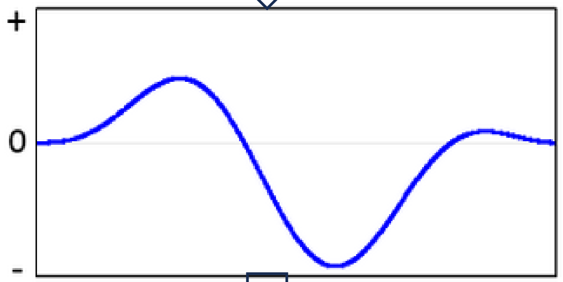




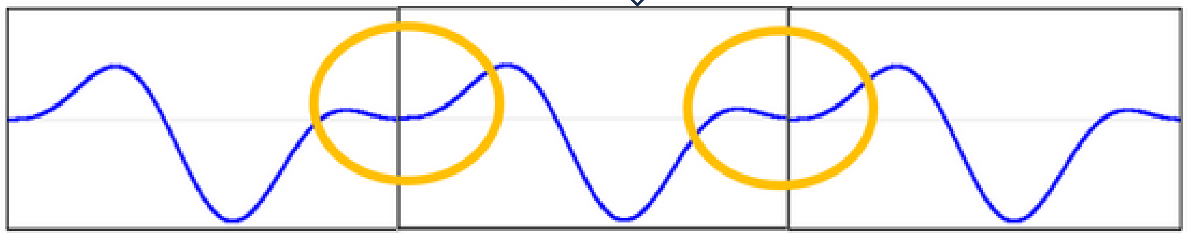
- Leakage area limited
- Amplitude not exact but…

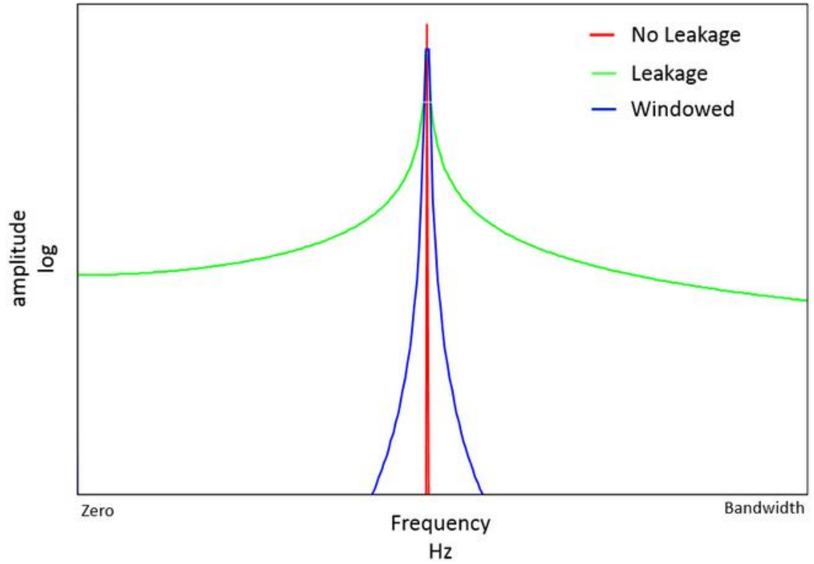
- Distinguishing multiple frequencies
- Makes possible some calculations , e.g. integrated RMS

- Window correction factors are applied (check if done, amplitude or energy)

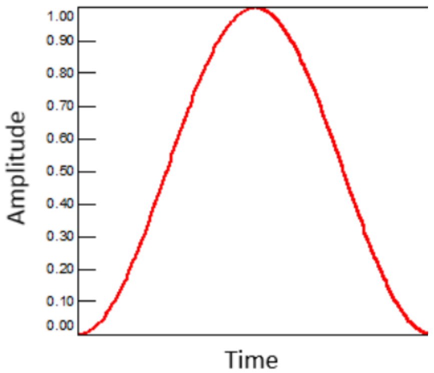


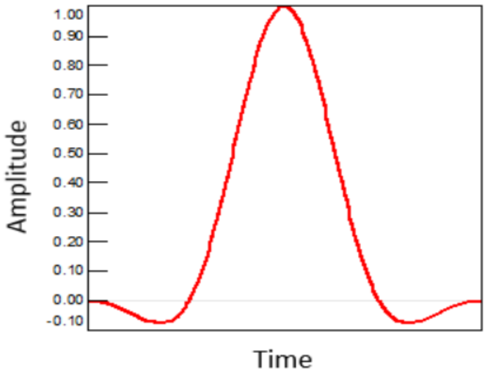
- Not exact signal
- But no more impulses

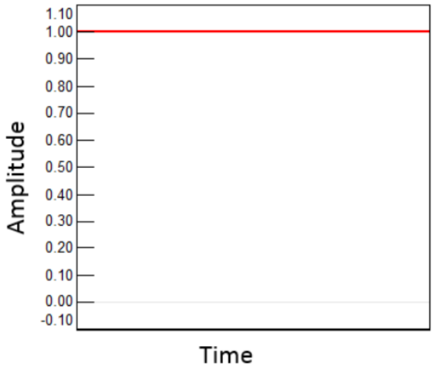


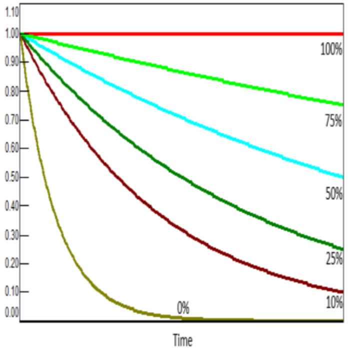


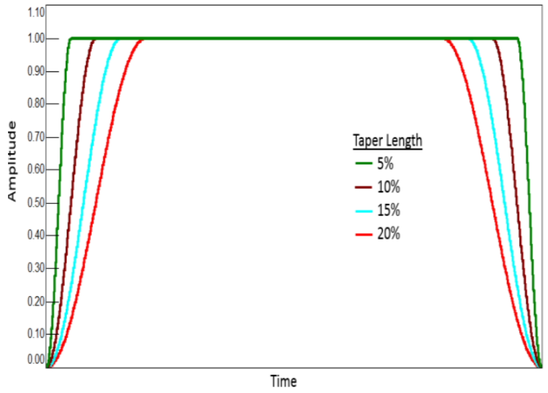
Selecting the best window

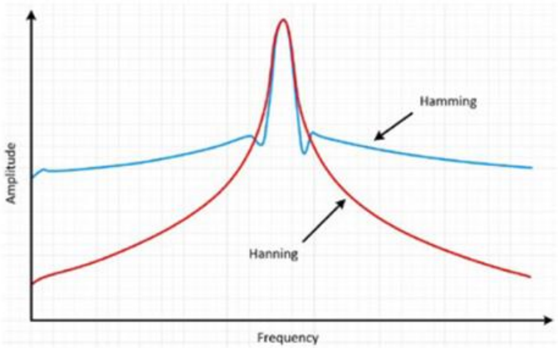


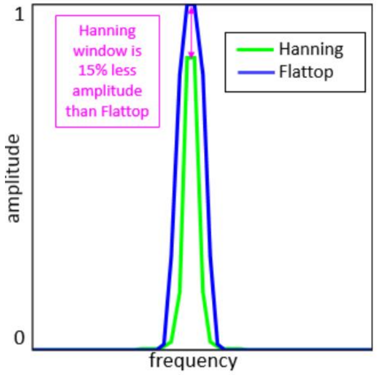


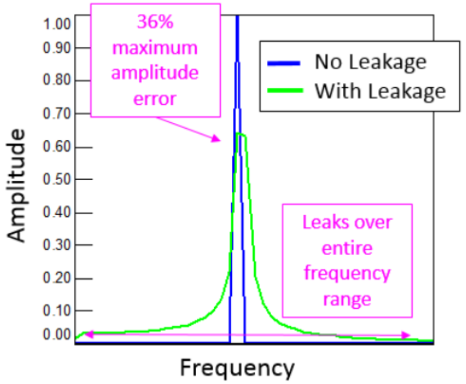


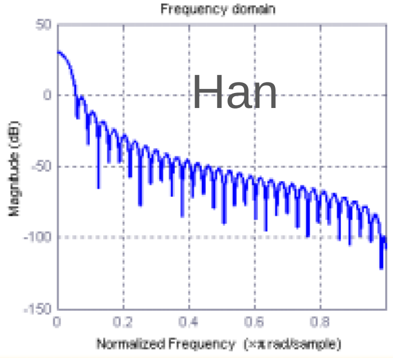


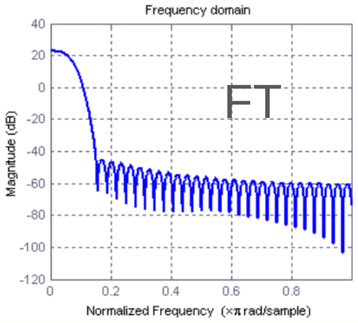










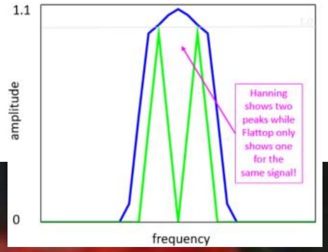


Hanning

Good compromise in most cases
Other: Hamming, Blackman Harris, Kaiser Bessel

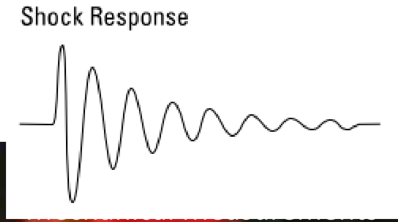
Flat top

Amplitude more accurate
Not adapted when frequencies are near



Uniform (no window)

Only valid for signals zero at start and end (periodic):
Impact, sweep, chirp, ….



Exponential

When not sure about zero at end

Tukey

When not sure about zero at start and end
For some transients

Selecting the best window

Sine wave or combination of sine waves	Hann
Sine wave (amplitude accuracy is important)	Flat Top
Narrowband random signal (vibration data)	Hann
Broadband random (white noise)	Uniform
Closely spaced sine waves	Uniform, Hamming
Excitation signals (hammer blow)	Force
Response signals	Exponential
Unknown content	Hann
Sine wave or combination of sine waves	Hann
Sine wave (amplitude accuracy is important)	Flat Top
Narrowband random signal (vibration data)	Hann
Broadband random (white noise)	Uniform
Two tones with frequencies close but amplitudes very different	Kaiser-Bessel
Two tones with frequencies close and almost equal amplitudes	Uniform
Accurate single tone amplitude measurements	Flat Top

Signal Type	Window	Frequency Resolution	Spectral Leakage	Amplitude Accuracy
Sinusoid (when amplitude accuracy is important)	Flat Top	Poor	Good	Best
Random	Hanning	Good	Good	Fair
Transient and Synchronous Sampling	Uniform	Best	Poor	Poor

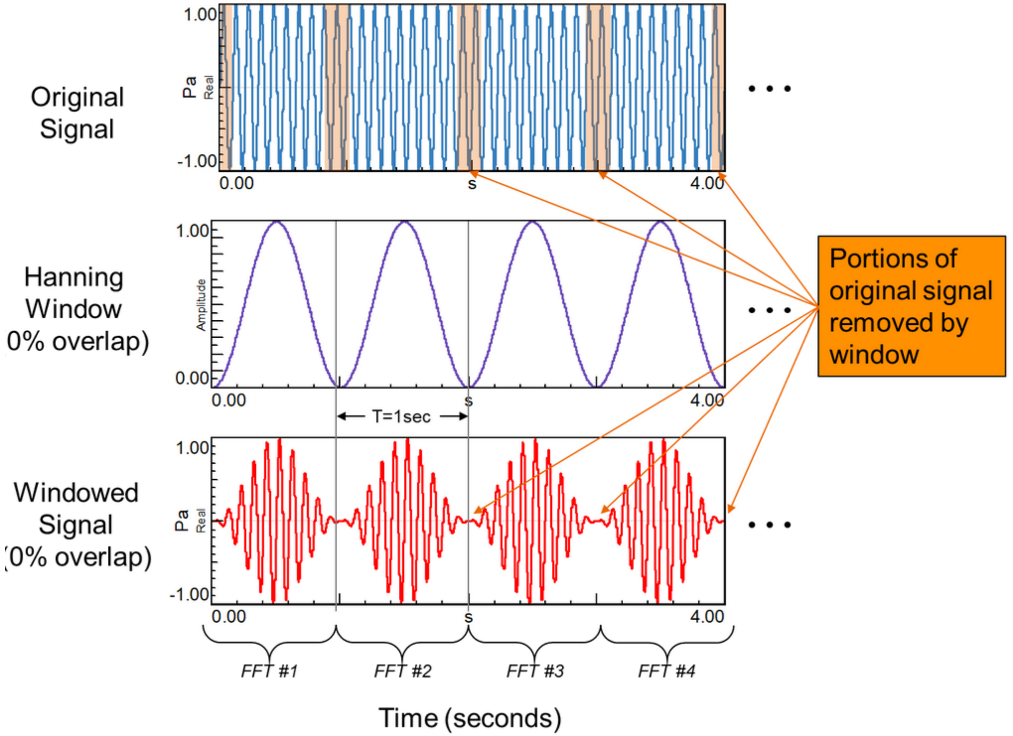
To determine the best window function to use for the application, estimate the frequency content of the signal and/or compare the performance of the different window functions.

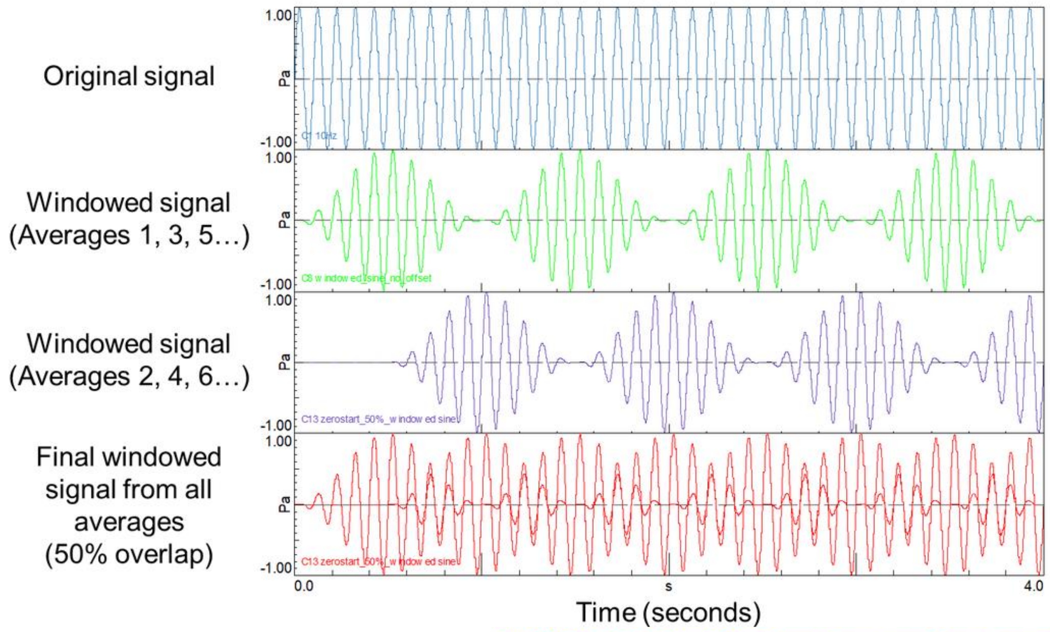
Application	Recommended Window	
General data analysis, most common (when frequency peaks are not guaranteed to be well-separated from each other)	Hanning	Good tradeoff between frequency and amplitude accuracy, reduced spectral leakage
Performing Calibration or other single tone amplitude measurements (when frequency peaks are likely to be distinct and well-separated from each other)	Flat Top	Excellent accuracy for amplitude
When signal spectrum is rather flat or broadband in frequency (broadband random, such as white noise)	Uniform	
Two tones with frequencies not well-separated and almost equal amplitudes	Uniform	

More info available in documentation Matlab, Labview etc

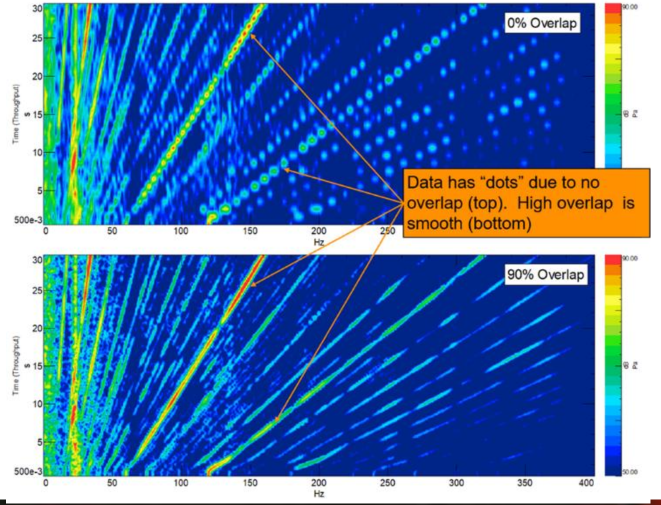
In case of doubt: test it

Overlap and Averaging

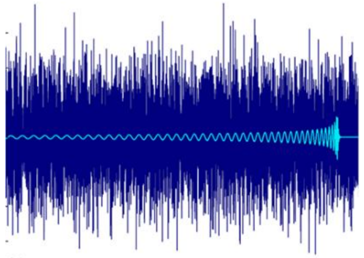




Figures source Siemens



- Window correction factors for perfectly stationary, deterministic signals
- Problem for Transient or random signals (stationary and non-stationary)



Summary

- Short introduction to the field

But hopefully:

- Overview of different techniques (not complete)
- Idea of what can be done with mechanical measurements in challenging environments
- Hinted some pitfalls: Think twice, verify, calibrate and only then measure it!
- Foresee mechanical measurements early in your design
- A collection of references to build your own library of references
- Beginning of a nice network

We hope you enjoyed the lecture

Tune in for the hands-on session!

Thank you for your attention