Vibrating-wire measurements for the alignment of small-aperture magnets

2nd PACMAN Workshop
13-15/06/2016

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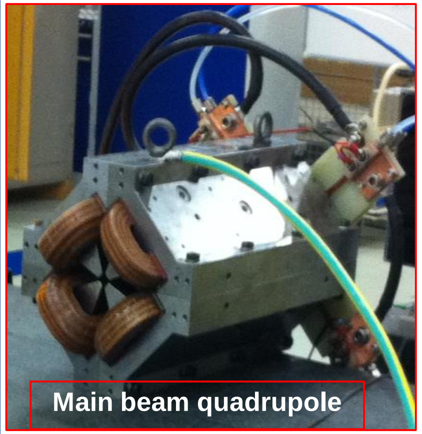
OUTLINE

- Stretched-wire systems for magnetic measurements
- Stretched-wire and vibrating-wire methods
- Achievements
  - Comparing stretched and vibrating wire
  - Performance optimization for the vibrating wire
  - Preliminary measurements on the CLIC Main Beam Quadrupole
- The PACMAN stretched-wire system

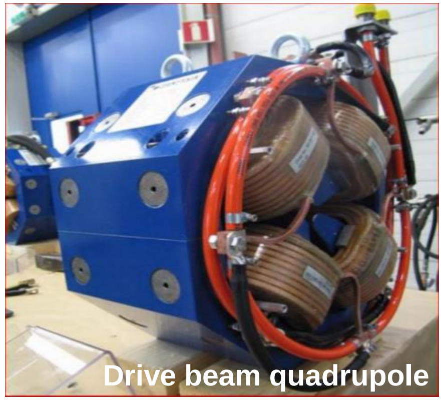
44,020 magnets for CLIC

Two-beam technology: drive and main beams


Main beam quadrupole

Quadrupole magnets to focus the beams

- ✓ 40 000 units in the drive beam
- ✓ 4020 units in the main beam


Drive beam quadrupole

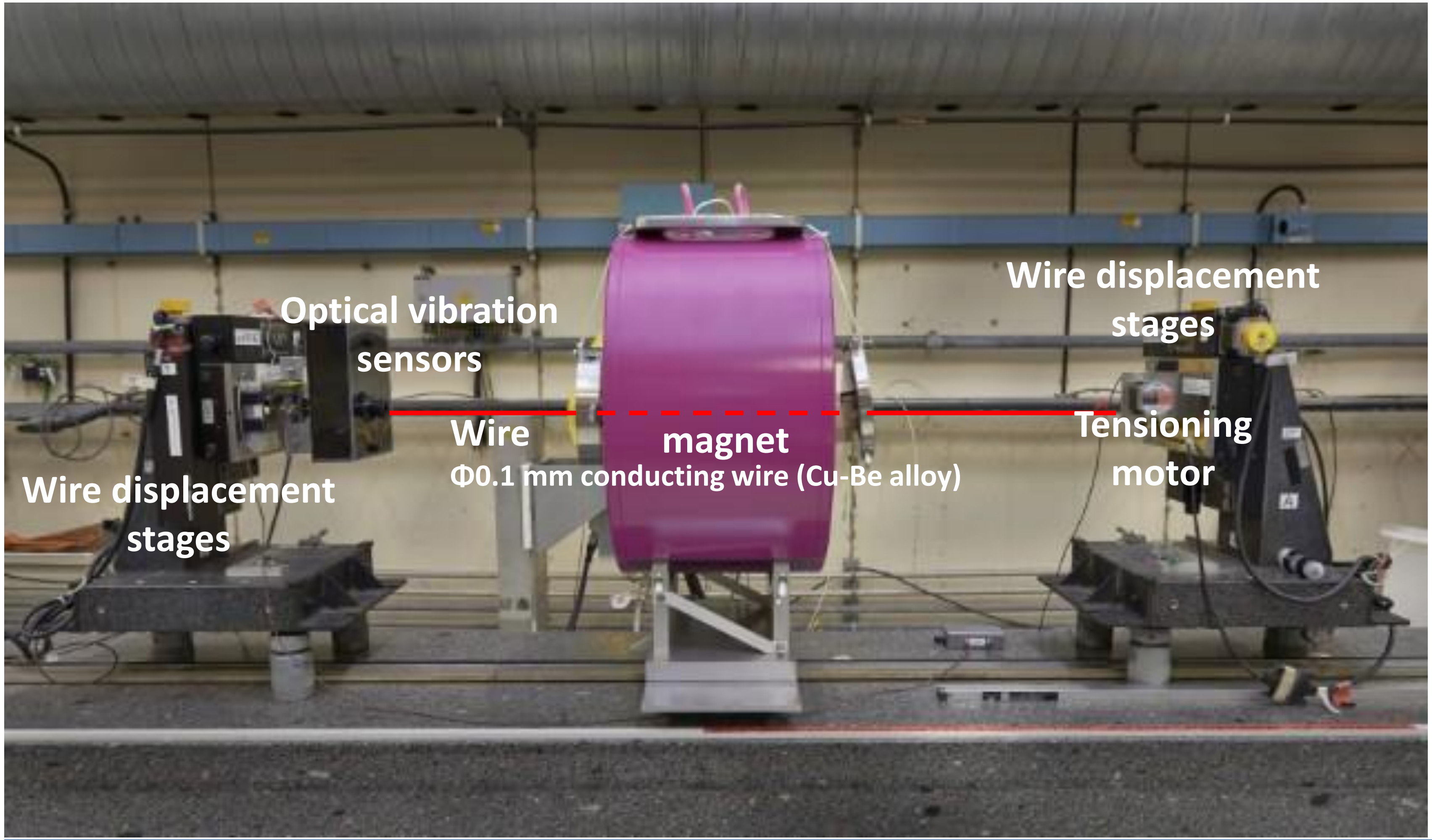
V. AA., "A Multi-TeV linear collider based on CLIC technology: CLIC Conceptual Design Report". CERN-2012-007. 2012.

Wire-based transducers

A measurement system for:

- field strength and direction
- field quality
- field profiles
- <u>magnetic axis</u>

Compliant with different magnet types and geometries

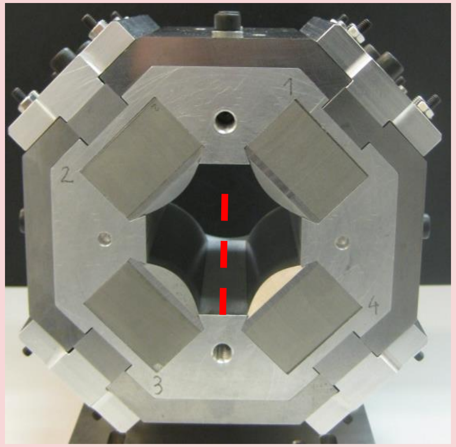


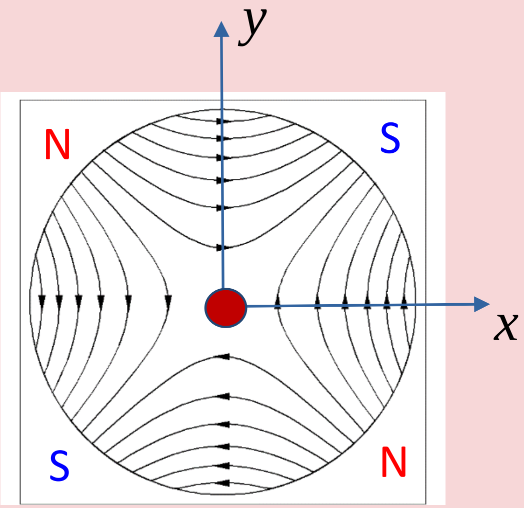
P. Arpaia, C. Petrone, S. Russenschuck, L. Walkiers. "Vibrating-wire measurement method for centering and alignment of solenoids". *JINST – Journal of Instrumentation*, **2013**.

Magnetic axis localization

Magnetic axis:

- Locus of points where the magnetic flux density is zero
- Reference for the magnet alignment
- The wire materializes the magnetic axis





$$B_x = G y$$
$$B_y = G x$$

Quadrupole section

Stretched wire method

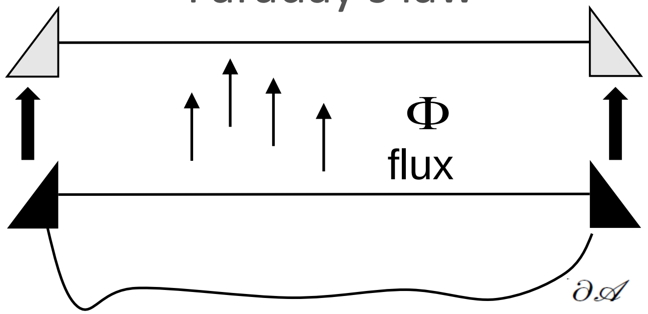
Main measurement system for LHC magnets

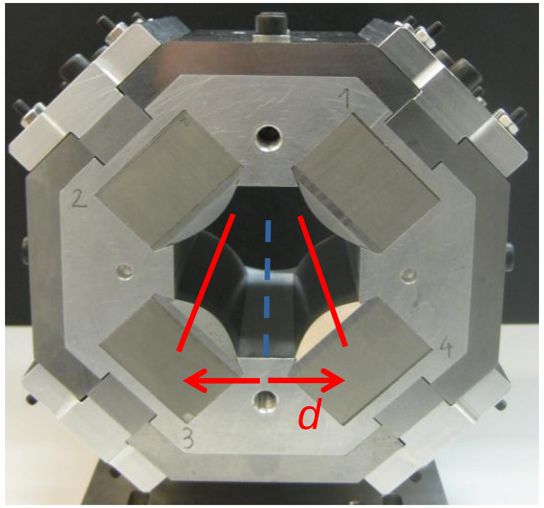
✓integrated field strength

✓field direction

✓magnetic axis

Faraday's law





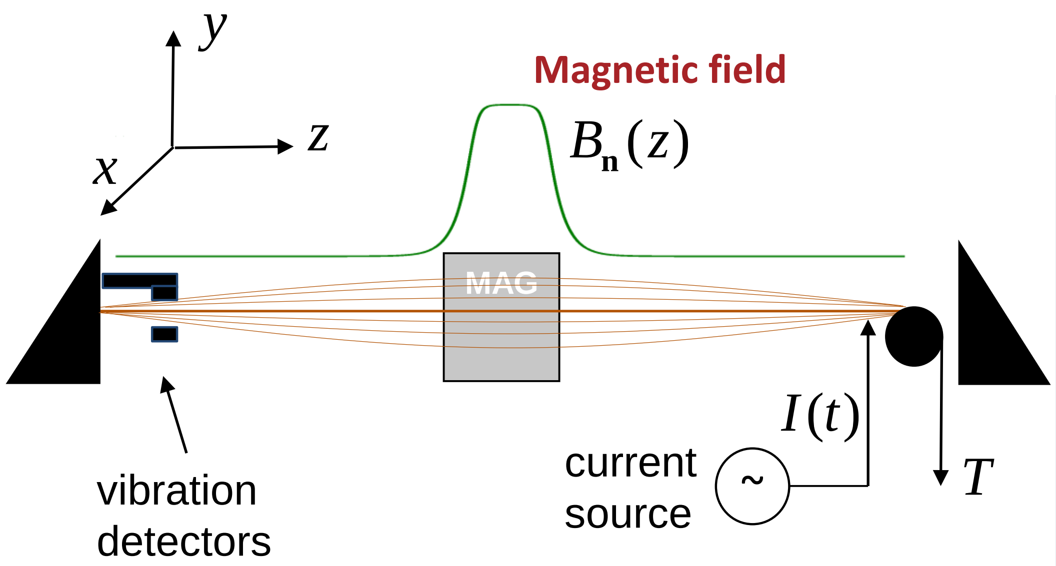
Magnetic center coordinates

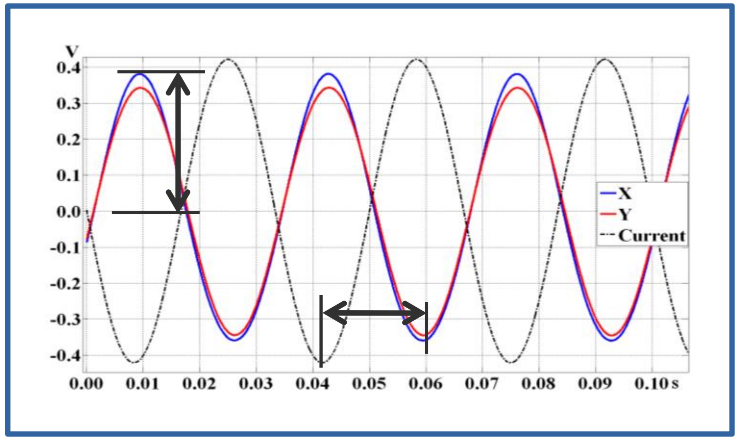
$$x_c = x_0 - \frac{d}{2}\frac{\Phi(x_0, x_0 + d) - \Phi(x_0, x_0 - d)}{\Phi(x_0, x_0 + d) + \Phi(x_0, x_0 - d)}$$

$$y_c = y_0 - \frac{d}{2}\frac{\Phi(y_0, y_0 + d) - \Phi(y_0, y_0 - d)}{\Phi(y_0, y_0 + d) + \Phi(y_0, y_0 - d)}$$

J. Di Marco et al., "Field alignment of quadrupole magnets for the LHC interaction Regions". *IEEE Transactions on Applied Superconductivity*, 2000.

Vibrating wire method





Wire in magnetic field

⇩

Feeding the wire by alternating current (Lorentz force)

⇩

Measure wire vibrations (X and Y components)

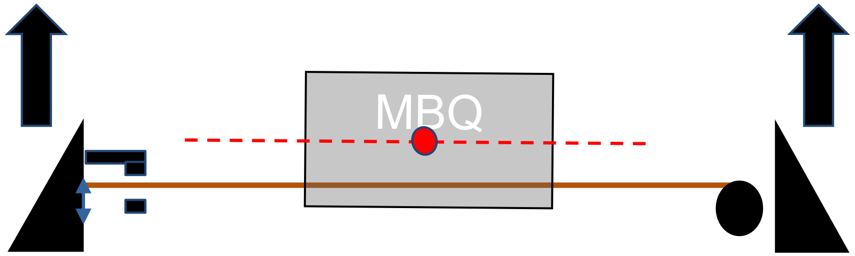
⇩

Relate vibrations to magnetic field

A. Temnykh. "Vibrating wire field-measuring technique". *Nuclear Instruments and Methods in Physics Research*, **1997**.

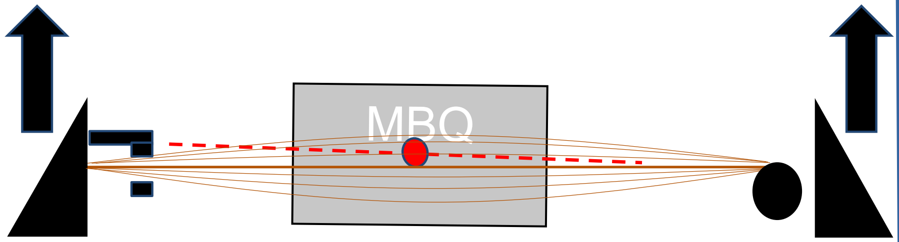
Locating the axis

Magnet center



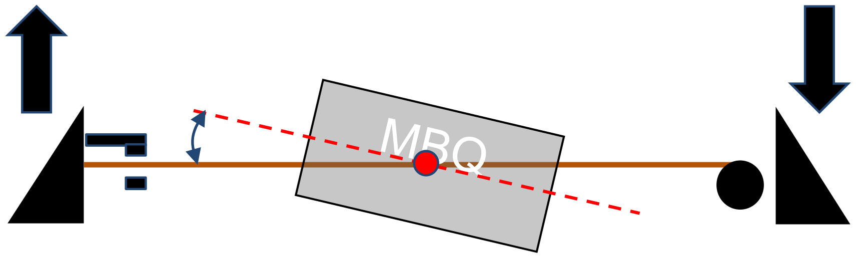
The first wire eigenmode is excited when off-centered

$$f_1 = \frac{1}{2L}\sqrt{\frac{T}{\rho}}$$



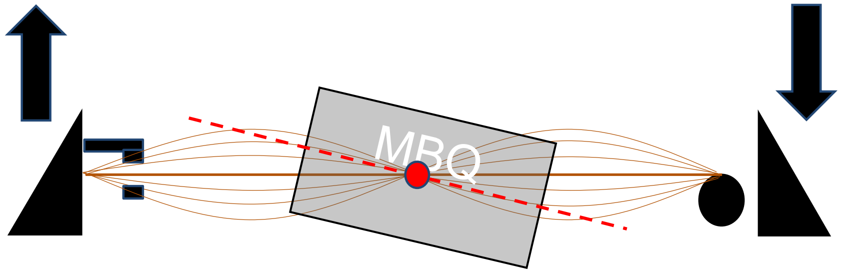
L: wire length
T: tension
ρ: linear mass density

Magnet angles



The second wire eigenmode is excited when misaligned in angle

$$f_2 = \frac{2}{2L}\sqrt{\frac{T}{\rho}}$$



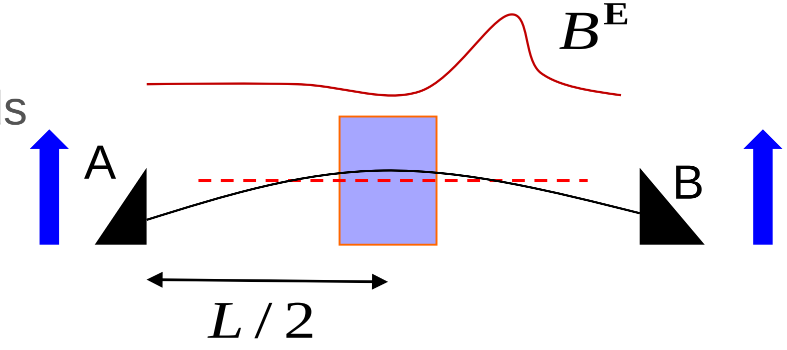
Typical values

f_1 = 120 Hz - f_2 = 240 Hz

Background field influence

Correction of non-homogeneous background fields

- Earth magnetic field
- Fringe field from equipment



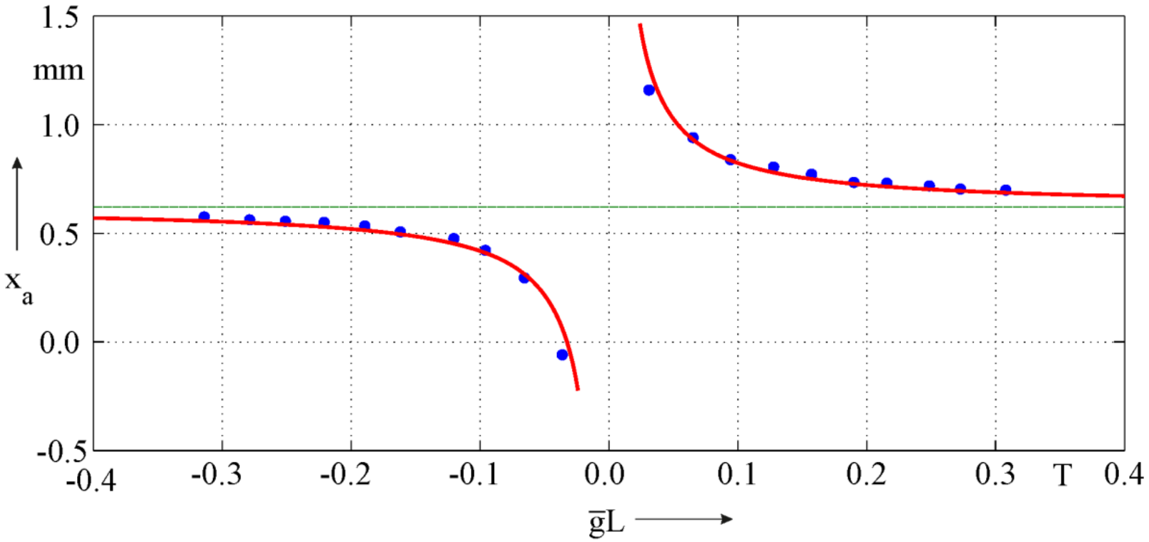
Fit to the model

$$x_a = x_c - \frac{d_E}{k_g g L}$$

Apparent center

Actual center

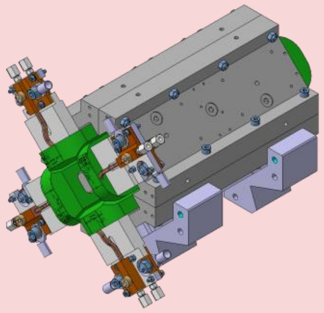
Magnetic center as a function of the magnet strength

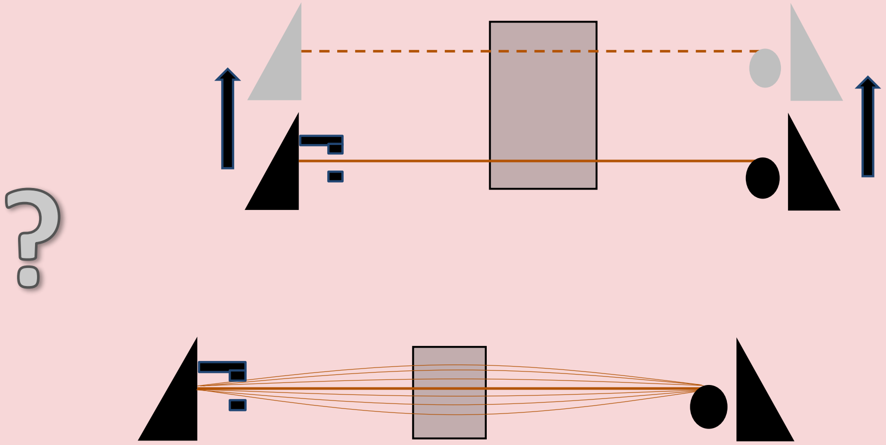


P. Arpaia, D Caiazza, C. Petrone, S. Russenschuck. "Performance of the stretched- and vibrating-wire techniques and correction of background fields in locating quadrupole magnetic axes". *IMEKO World Congress,* Prague, **2015**.

Achievements: comparing stretched- and vibrating-wire methods

Stretched or vibrating?





✓The two methods agree within the measurement precision

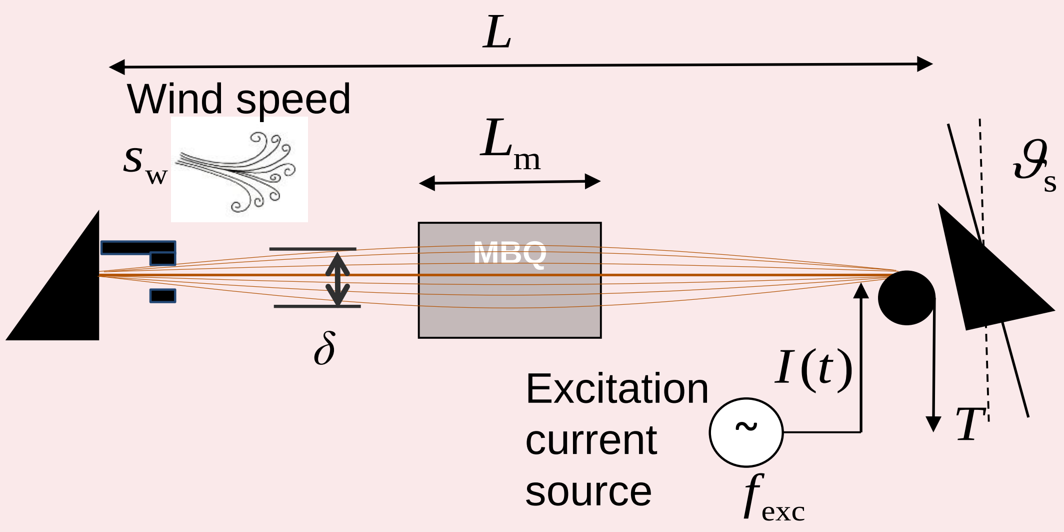
- After corrections for background fields
- and multipole field errors

✓Vibrating wire preferred if

- Multipole field errors are unknown
- Low strength and small wire displacement (linked flux < 120 µWb)

P. Arpaia, D Caiazza, C. Petrone, S. Russenschuck. "Performance of the stretched- and vibrating-wire techniques and correction of background fields in locating quadrupole magnetic axes". *IMEKO World Congress,* Prague, **2015**.

Performance optimization for the vibrating wire



Outcomes:

- ✓ Excitation frequency lower than resonance for more stability
- ✓ Long wire and high tension for improving repeatability

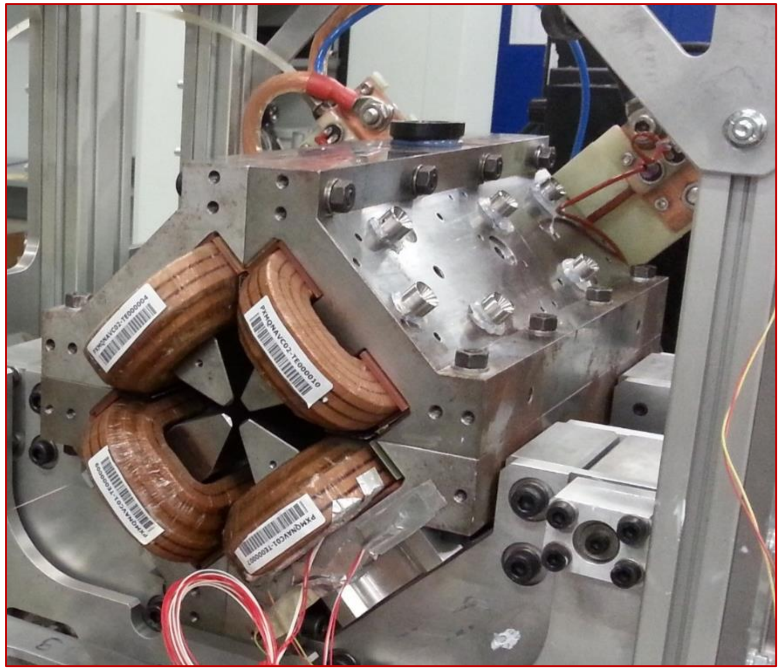
Repeatability σ_c	x	y	m.u.
1-m wire length	±2.6	±4.6	µm
4-m wire length	±0.9	±1.1	µm

P. Arpaia, D Caiazza, C. Petrone, S. Russenschuck. "Uncertainty analysis of a vibrating-wire system for magnetic axes localization". *ICST - International conference on sensing technology,* Auckland, **2015**.

Preliminary tests on the Main Beam Quadrupole

Alignment by vibrating wire method

CLIC main beam quadrupole



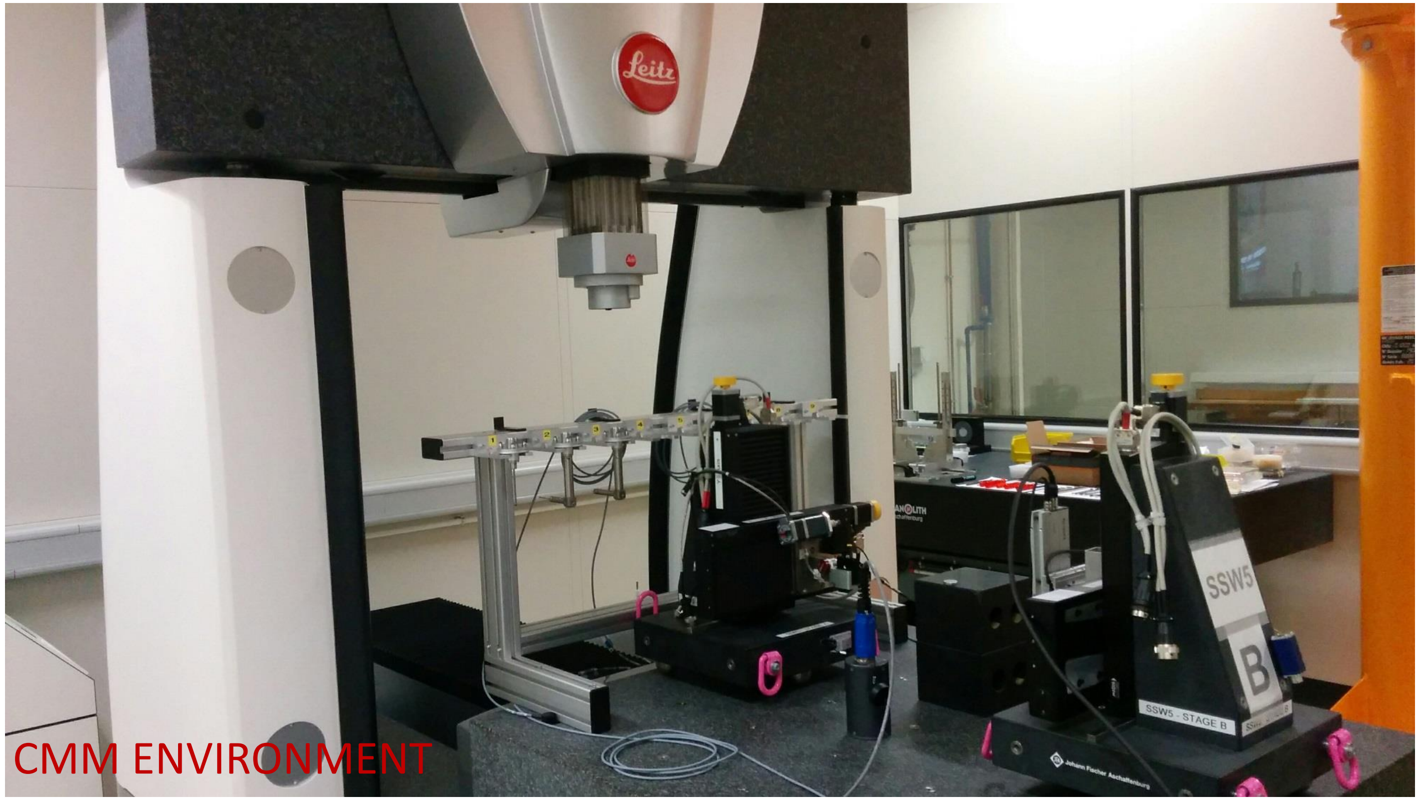
Measurements taken at different magnet currents and referred to the axis at nominal gradient

Magnet current				
126	0	0	0	0
65	3.8	-0.9	0.9	4.6
4	2.9	3.1	-2.3	-5.1
A	µm	µm	µrad	µrad

Repeatability

- Within ±0.2 µm for the centers
- Within ±0.9 µrad for the angles (worst cases)
- Also at 4 A

Compatibility tests



CMM ENVIRONMENT

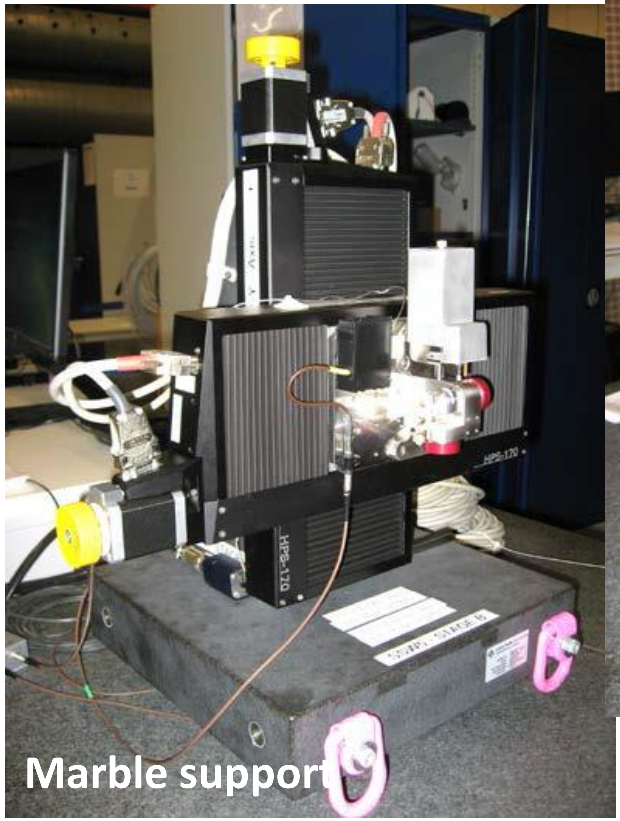
No factor impacting the operation of the wire system

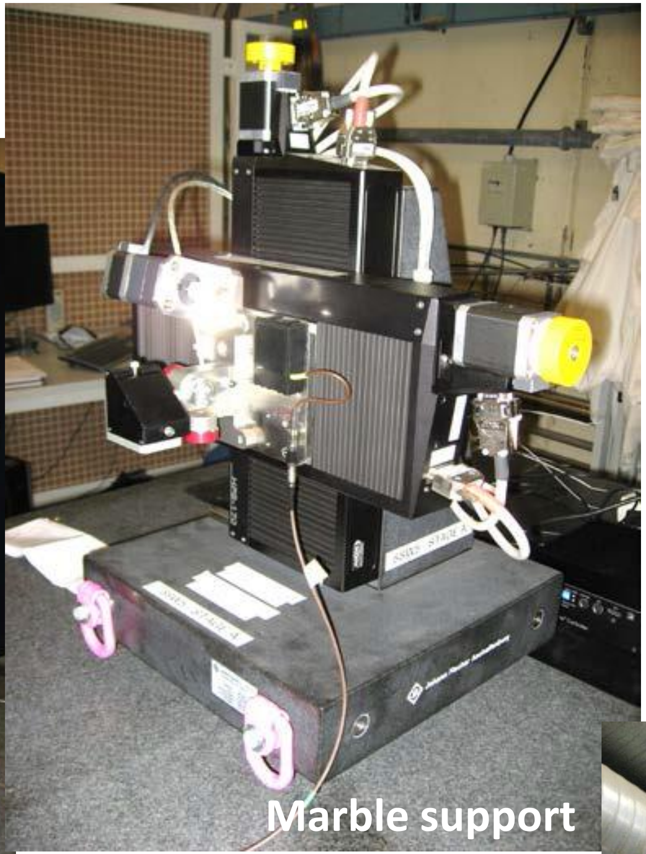
- ✓ The wire is stable when moving the CMM table
- ✓ The wire is stable when moving the CMM arm
- ✓ There is no influence of the cooling system

Thanks to Didier Glaude for operating the CMM

PACMAN Wire system

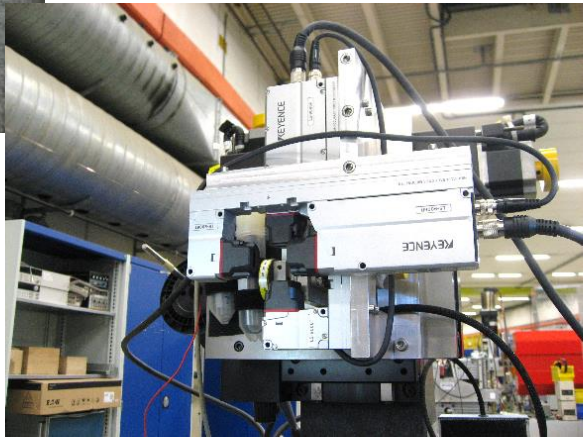
Based on an existing wire system





Components received and being validated

Keyence LS9000 CCD optical micrometres in x-y mount based in CCD technology



6 mm sensitive range

Conclusions

- Vibrating-wire method for alignment of the Main Beam Quadrupole
  - ✓Low powering (4 A) feasibility
  - ✓Correction of the background field
  - ✓Compatibility with the CMM environment
- The PACMAN stretched-wire system
  - ✓Linear displacement stages received and being validated
  - ✓Hardware and software being prepared

Thank you for your attention

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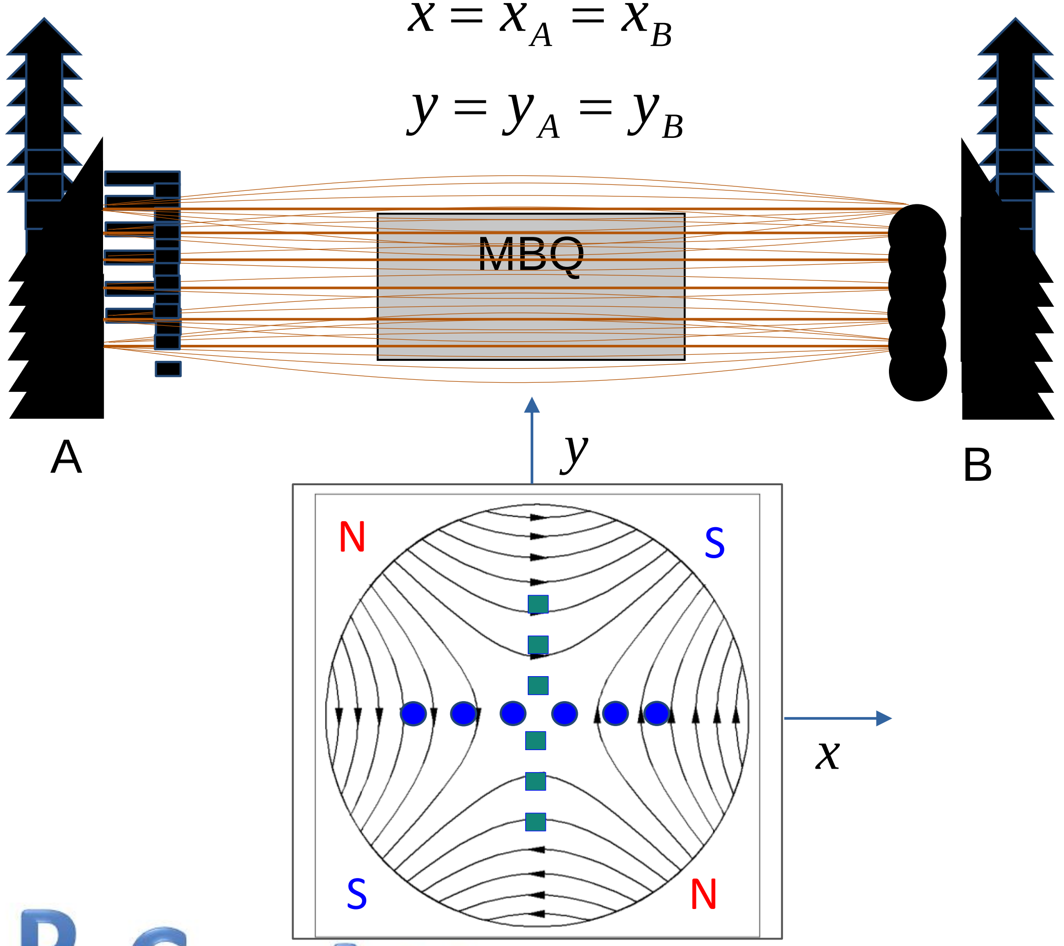
SPARES

Measurement procedure

- 1. Step-wise co-directional scan

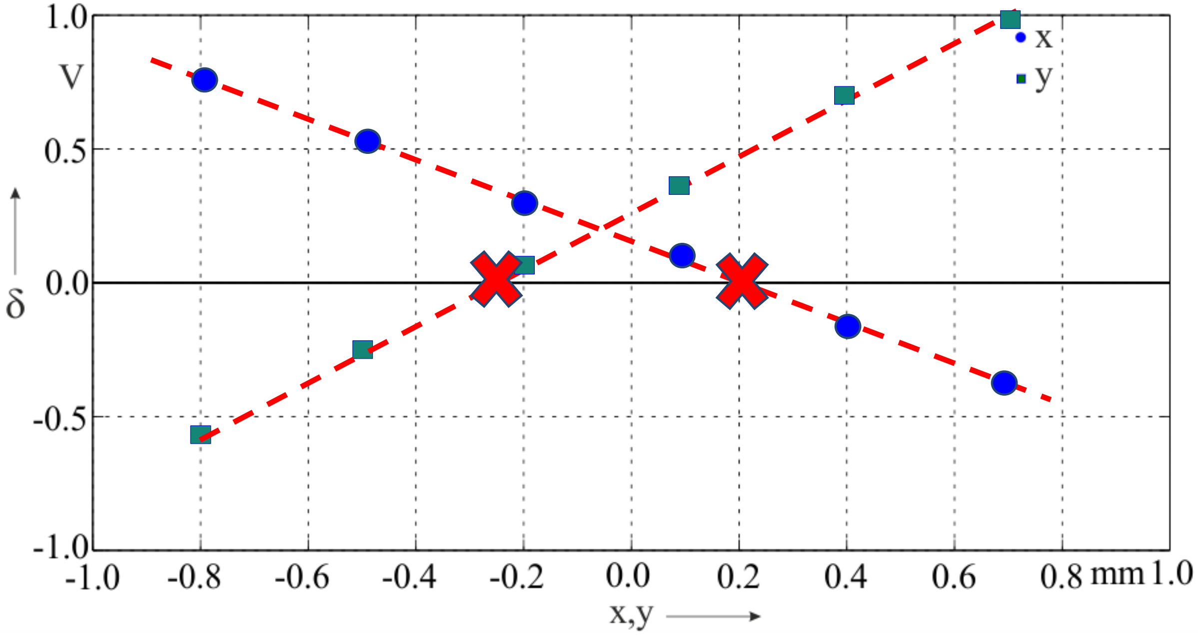
$$x = x_A = x_B$$

$$y = y_A = y_B$$



Vibration amplitude

- With phase change



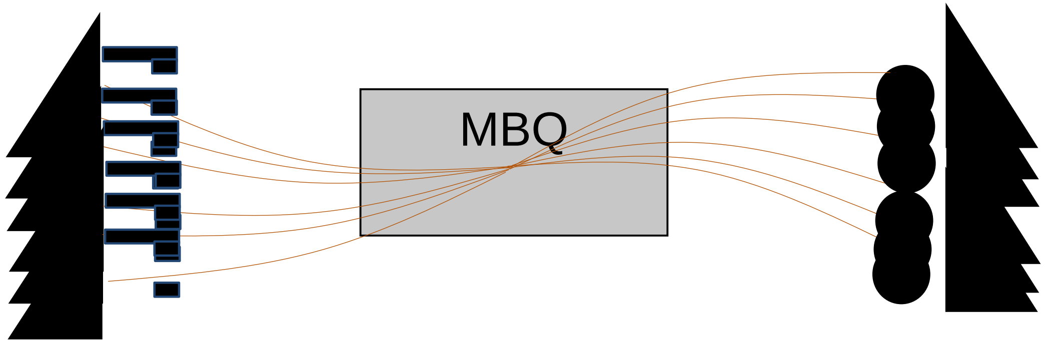
Output: (x_c, y_c)

Measurement procedure

- 2. Step-wise counter-directional scan

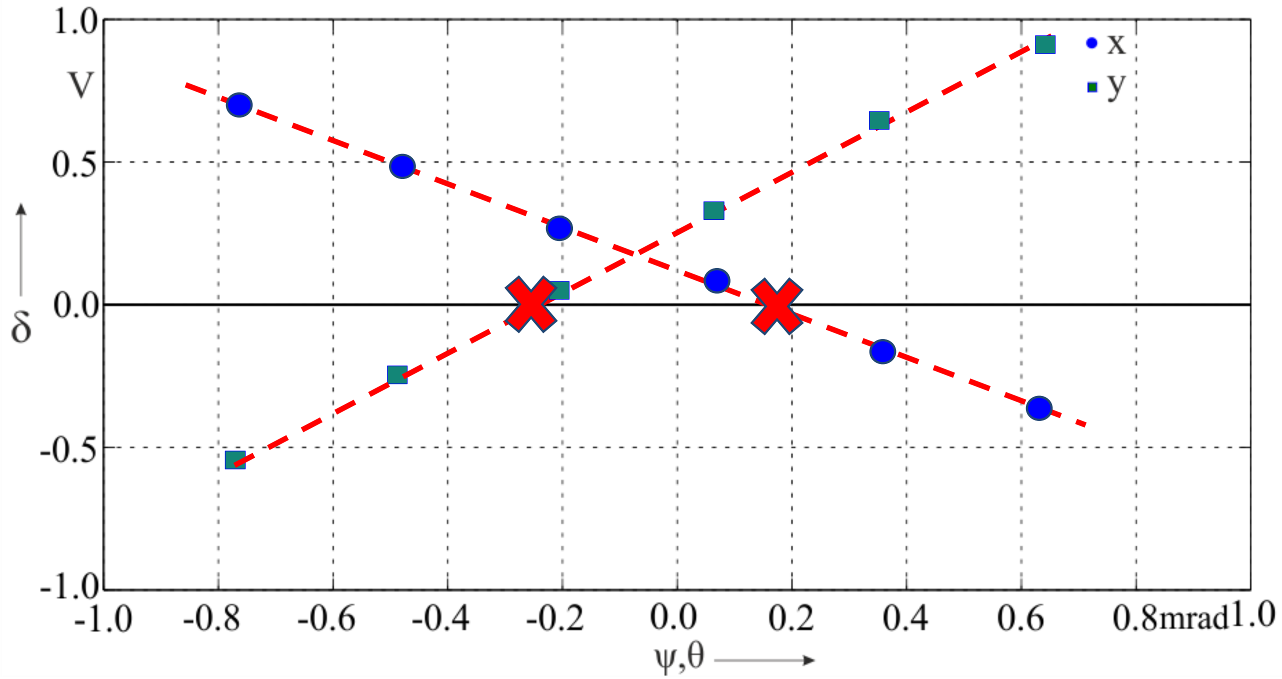
$$x = x_A = -x_B$$

$$y = y_A = -y_B$$



Vibration amplitude

- with phase change



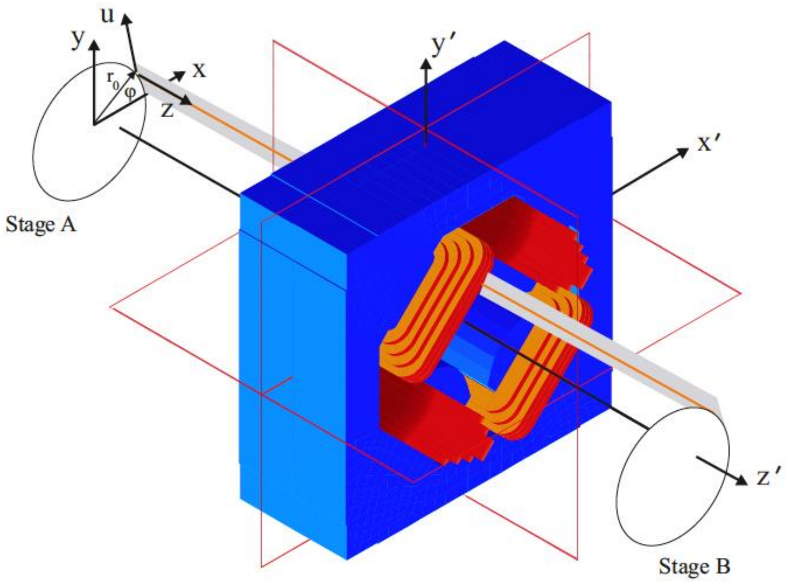
Output: (ψ_c, θ_c)

Project /

Background

Assumptions and mathematical model

- Linearity
- Plane motion
- Uniform and constant tension
- Small deflections
- Constant length
- Uniform mass distribution



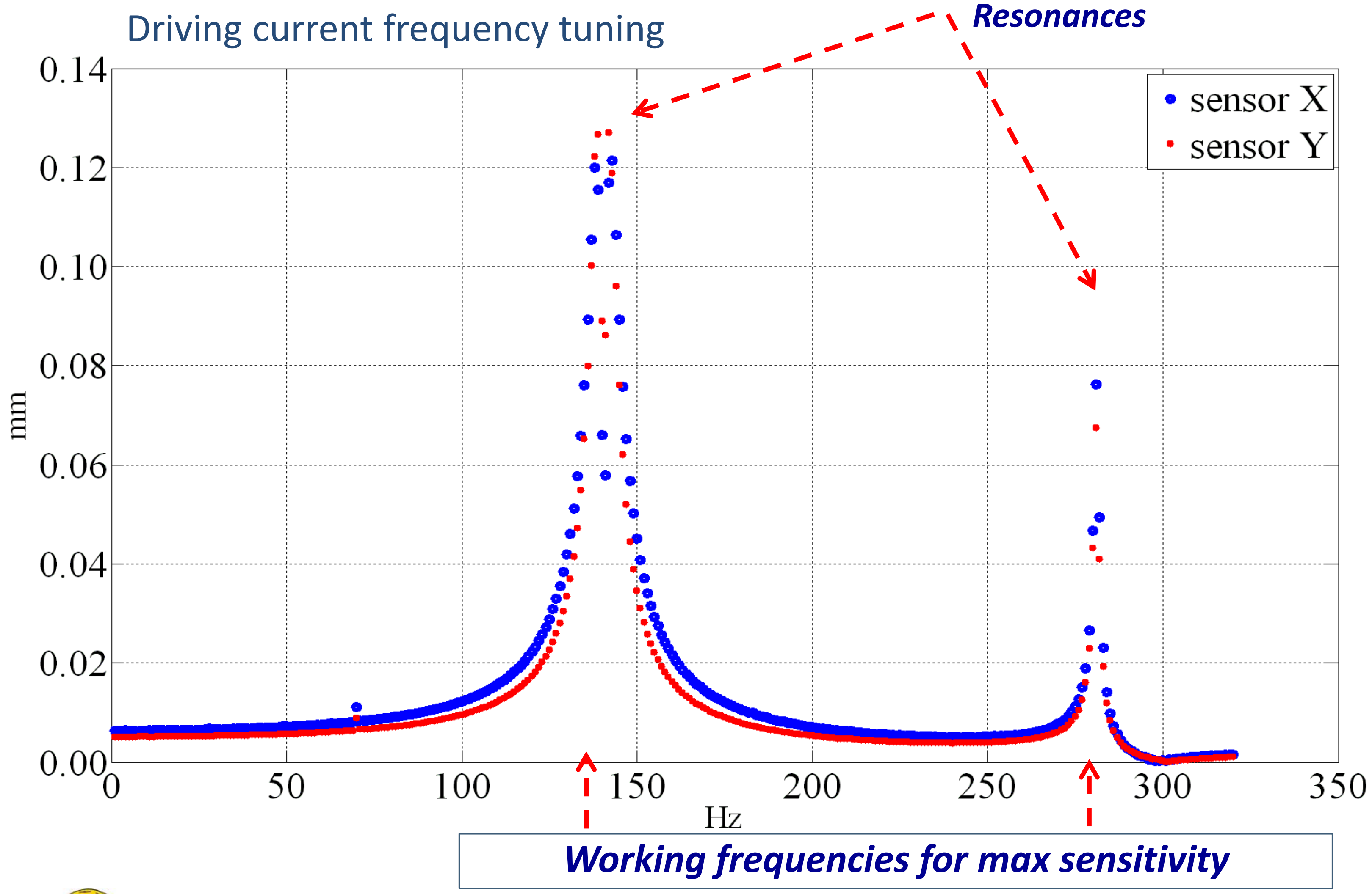
$$u(z,t)=\frac{2I_0}{L}\sum_m \frac{\int_0^L B_n(z)\sin\left(\frac{m\pi}{L}z\right)\mathrm{d}z}{\sqrt{\left[T\left(\frac{m\pi}{L}\right)^2-\rho\omega^2\right]^2+(\alpha\omega)^2}}\sin\left(\frac{m\pi}{L}z\right)\sin(\omega t-\varphi_m)$$

$$\varphi_m=\arctan\left(\frac{\alpha\omega}{-\rho\omega^2+T\left(\frac{m\pi}{L}\right)^2}\right)$$

Measurement system design

Project /

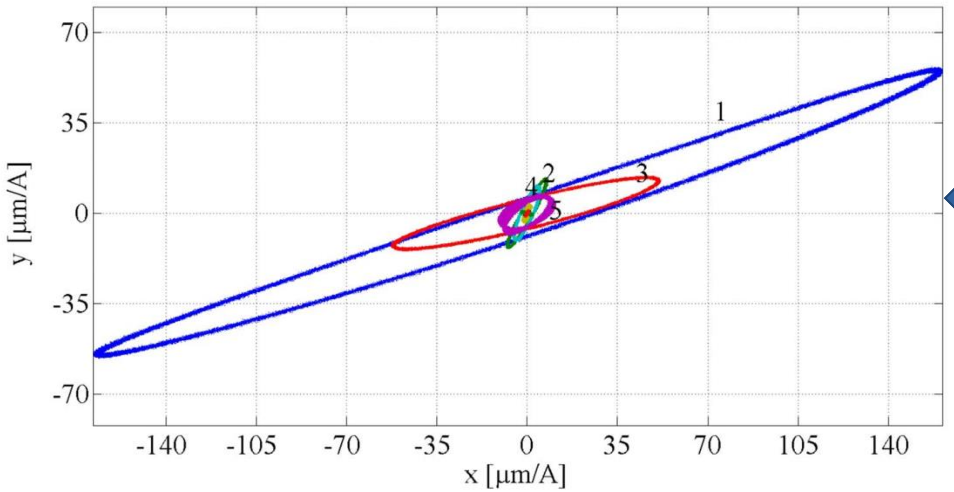
Background



Background field & elliptic motion

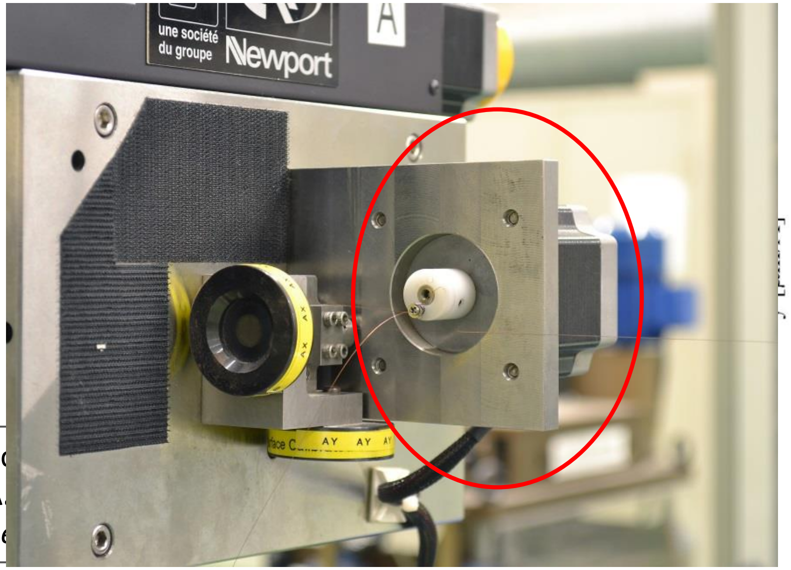
Project /

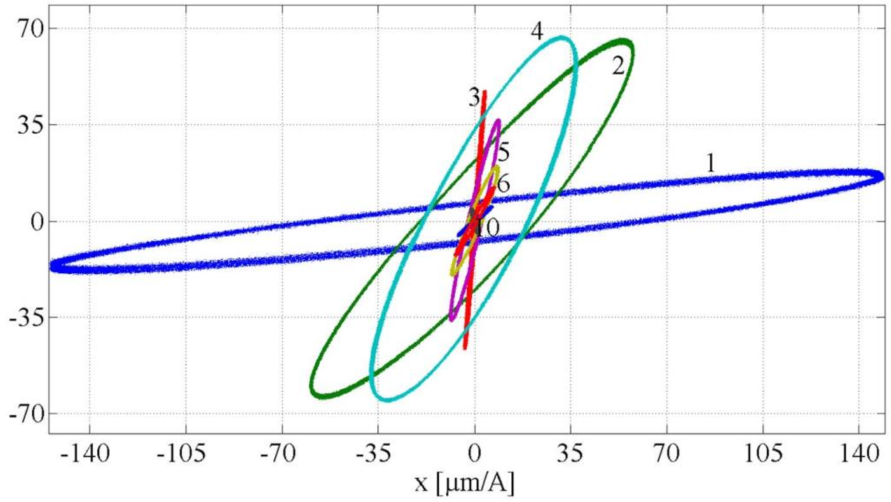
Experimental characterization



- No magnet on the measurement station

- Background fields
  - 2% alteration of first harmonic





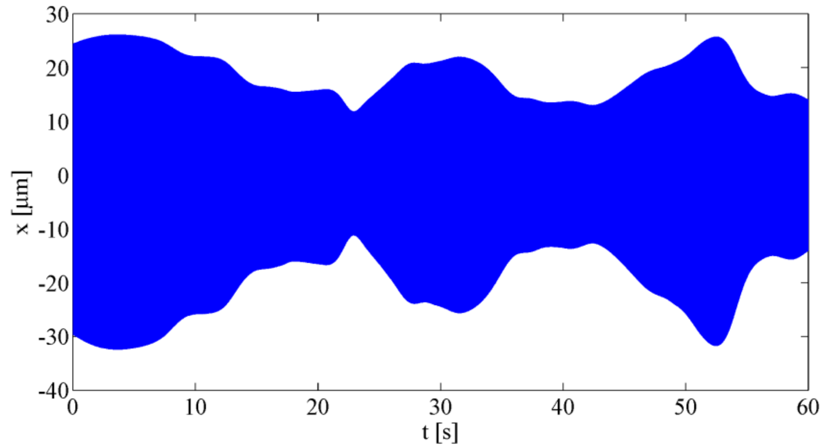
Prec
J. A.
Ame

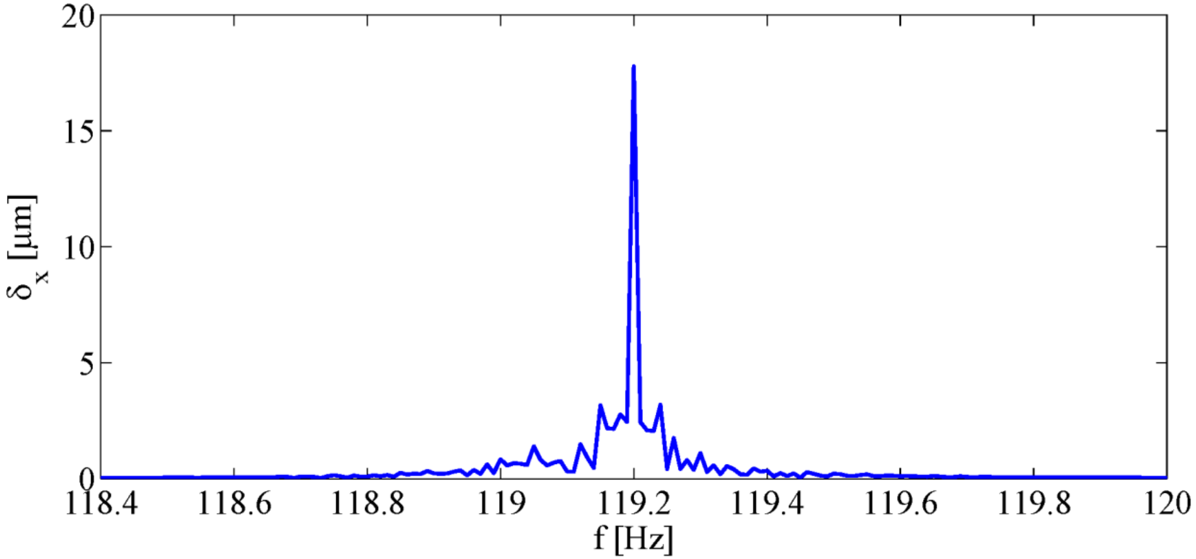
Project /

Experimental characterization

Resonance instability

- Around resonance
  - Non-constant oscillation amplitude!!!
  - Effect depending on the excitation frequency: minimal in resonance condition (5%)





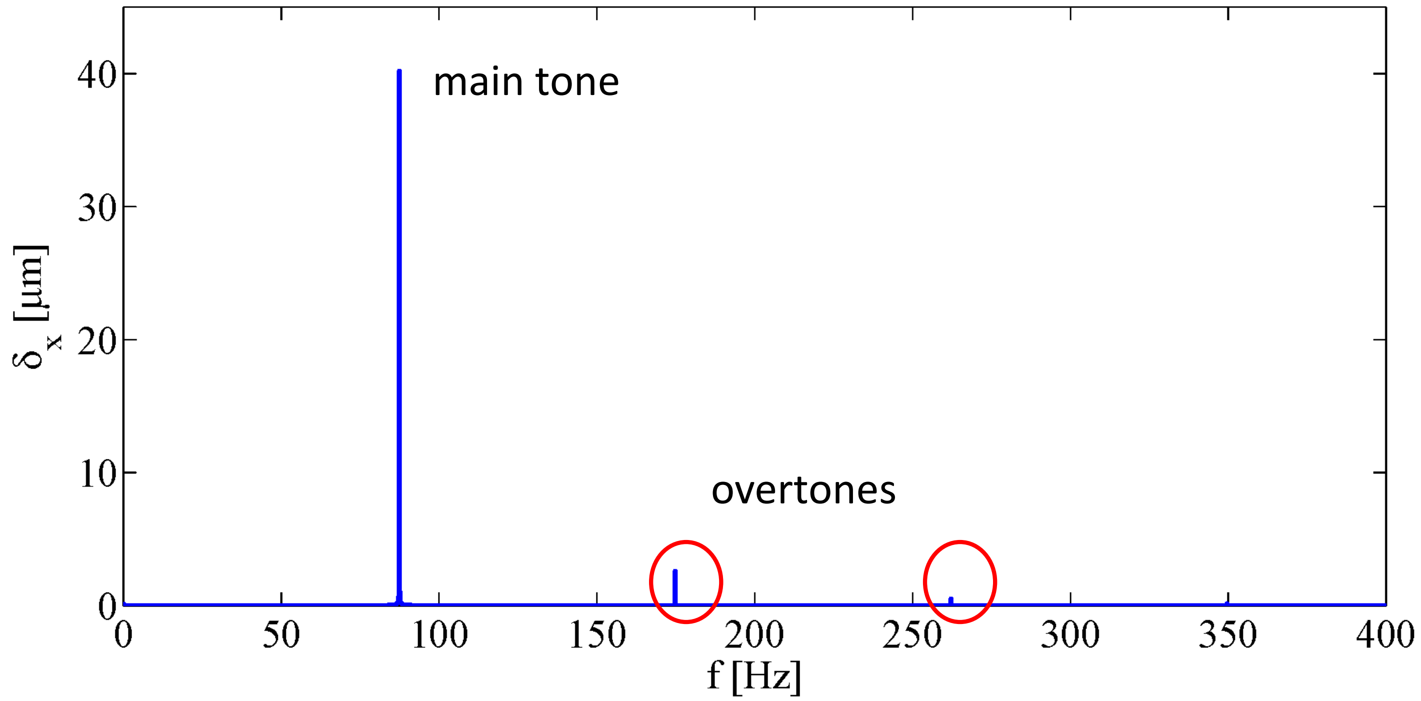
Possible reasons

- Non constant length and/or tension
- Non ideal clamping (friction on the supports)
- Excluded: coupling with ground vibrations

Nonlinearity and overtones

Project /

Experimental characterization

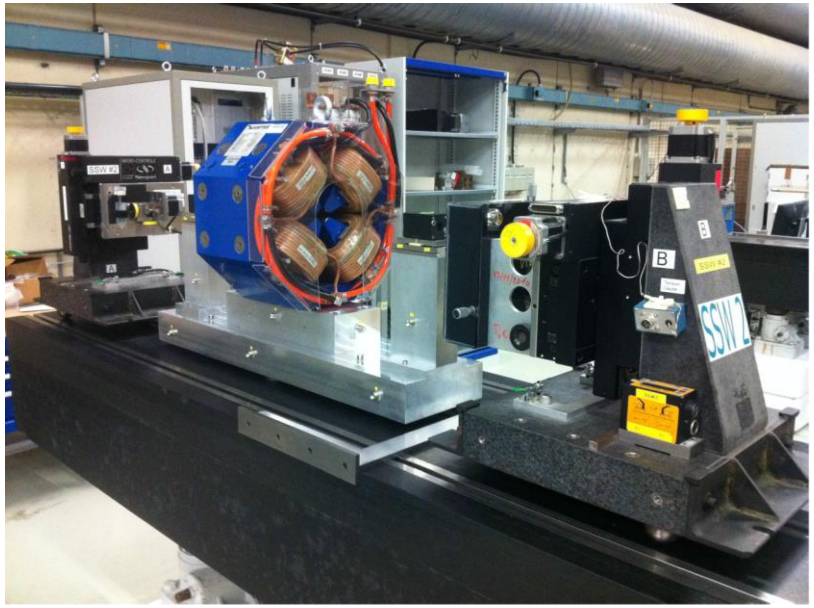


- Overtone amplitude from 2% to 7% of the main tone
  - Depending on system configuration
- Overtones not contained in the current excitation signal

➡ Nonlinearity!

Axis localization of a CLIC Drive Beam quadrupole

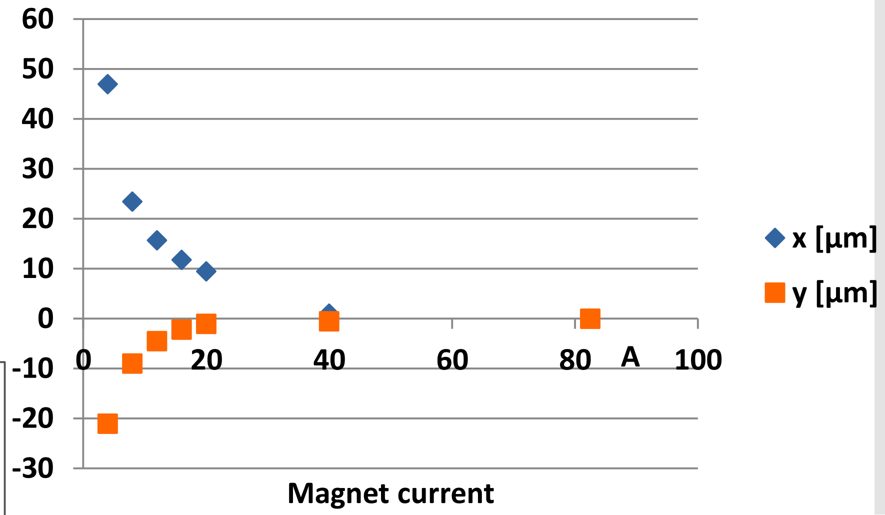
Project / Results



CLIC DBQ (12 T integrated gradient) on the fiducialization bench with vibrating wire system

- ✓ Magnetic axis measurement + fiducial markers localization
  - In collaboration with EN-MEF-SU (Large Scale Metrology Section)
- ✓ Both center and tilt were measured by the vibrating wire
- ✓ Axis determination with ±3 µm horizontal and ±4 µm vertical precision

Magnetic center as a function of the magnet current



M. Duquenne et al., "Determination of the magnetic axis of a CLIC drive beam quadrupole with respect to external alignment targets using a combination of wps, cmm and laser tracker measurements". Proceedings of **IPAC2014**, Dresden, 2014.

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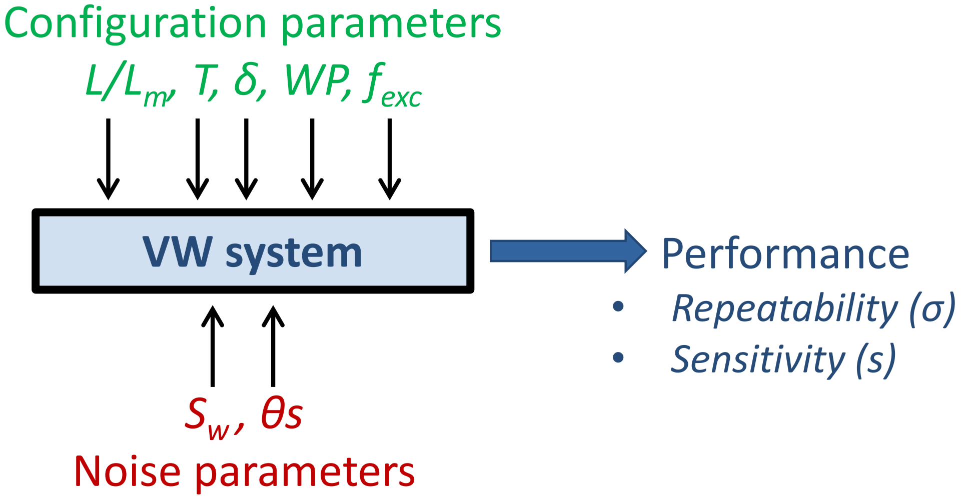
SIGMAPHI

METROlab

CLIC CERN

Project / Results

Uncertainty analysis



- Choice of parameters and range
- Definition of performance characteristic
- Planning of experiments
- Analysis

Design of experiments (Taguchi)

Experiment#	L/L_m	T [g]	δ [V]	WP [V]	s_w [m/s]	Δf_{exc} [Hz]	ϑ_s
1	5.3	600	0.1	5.7	0.3	0	0
2	5.3	900	0.7	6.1	0.15	-0.5	-5
3	5.3	1100	1.5	6.5	0.7	-1	-10
4	10.14	600	0.1	6.1	0.15	-1	-10
5	10.14	900	0.7	6.5	0.7	0	0
6	10.14	1100	1.5	5.7	0.3	-0.5	-5
7	20.4	600	0.7	5.7	0.7	-0.5	-10
8	20.4	900	1.5	6.1	0.3	-1	0
…	…	…	…	…	…	…	…

A linear model to relate the performance to the parameters

$$q_i = \mu_i + \sum_{k=1}^{p} \delta_{ik} v_k + \varepsilon$$

performance mean

parameter effect

model uncertainty

Optical sensors for measuring wire vibration

Phototransistors
- ✓ cheap
- ✓ very sensitive

Fiber optics
- ✓ immune to magnetic field

CMOS sensors
- ✓ linear
- ✓ wide range

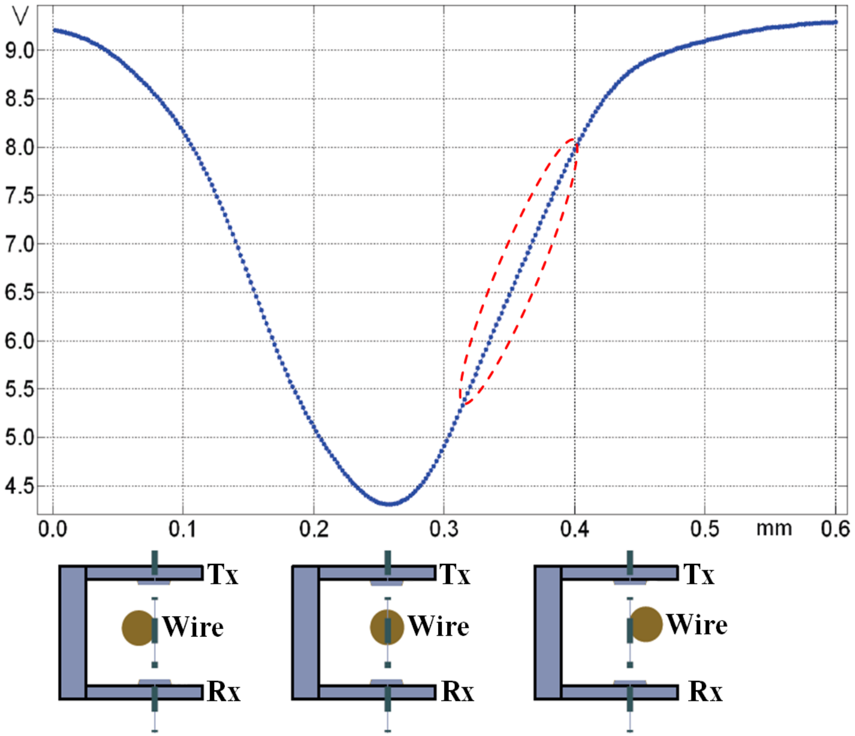
Need piezo-stages to hold the working point

Project /

Results

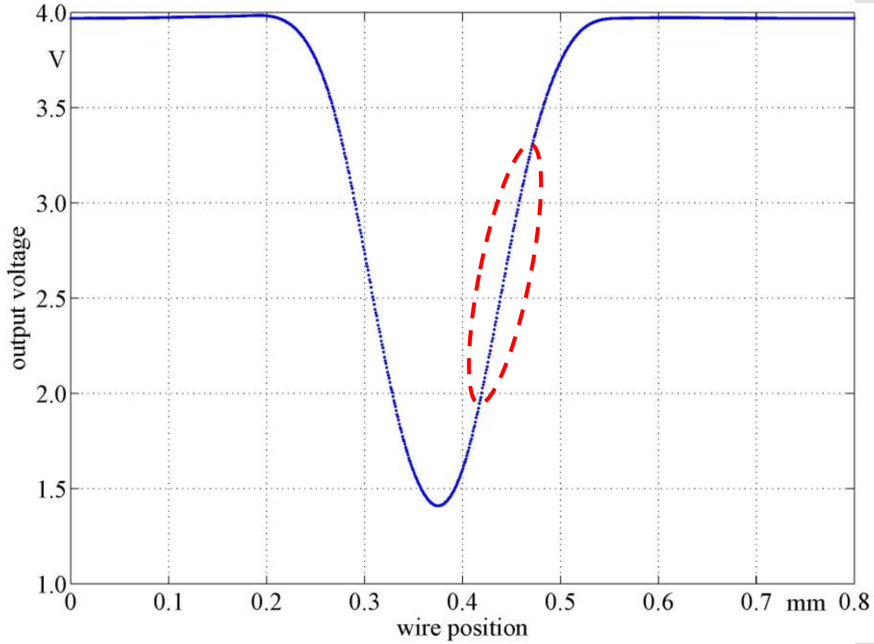
Characterization

Phototransistors



Range: ~50 µm
Sensitivity: 28.4 V/mm

Fiber optics units



Range: ~40 µm
Sensitivity: 26.1 V/mm

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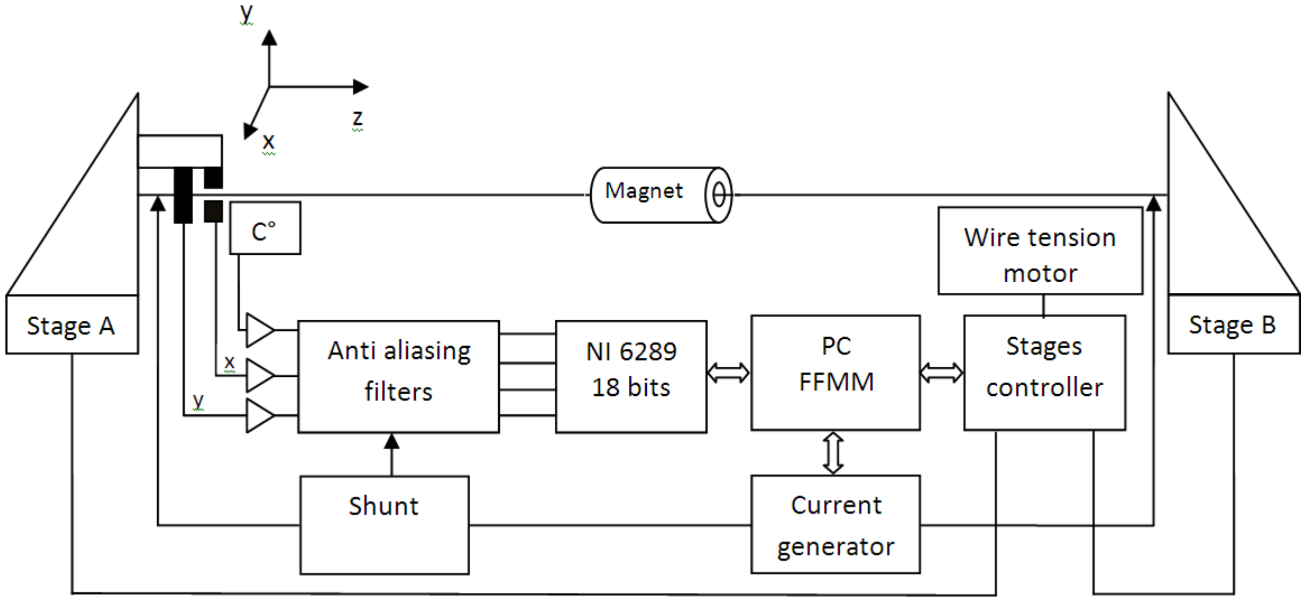


- ***Sensors**: phototransistor Sharp GP1S094HCZ0F*
- ***Current generator**: Keithley 6351*
- ***Common marble** support for magnets and stages*

P. Arpaia, M. Buzio, J. G. Perez, C. Petrone, S. Russenschuck, L. Walckiers.
“Measuring field multipoles in accelerator magnets with small-apertures by an oscillating wire moved on a circular trajectory”, *JINST - Journal of Instrumentation, 2012*

Measurement method

- Measure the frequency response
  - Vibration amplitude and phase

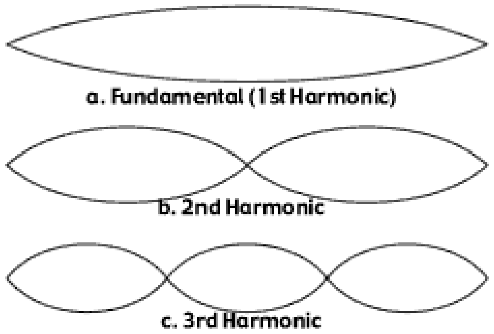
- Fit with the mathematical model
  - Longitudinal field coefficients

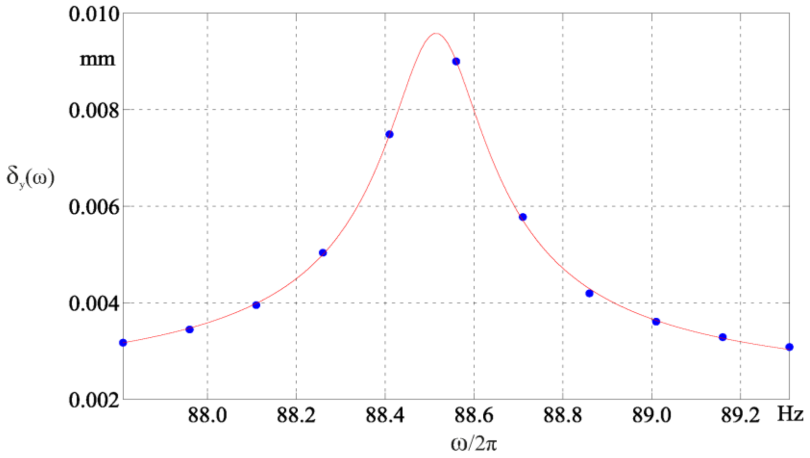
$$\mathcal{C}_m := \frac{2}{L}\int_0^L B_{\mathrm{n}}(z)\sin\left(\frac{m\pi}{L}z\right)\mathrm{d}z$$

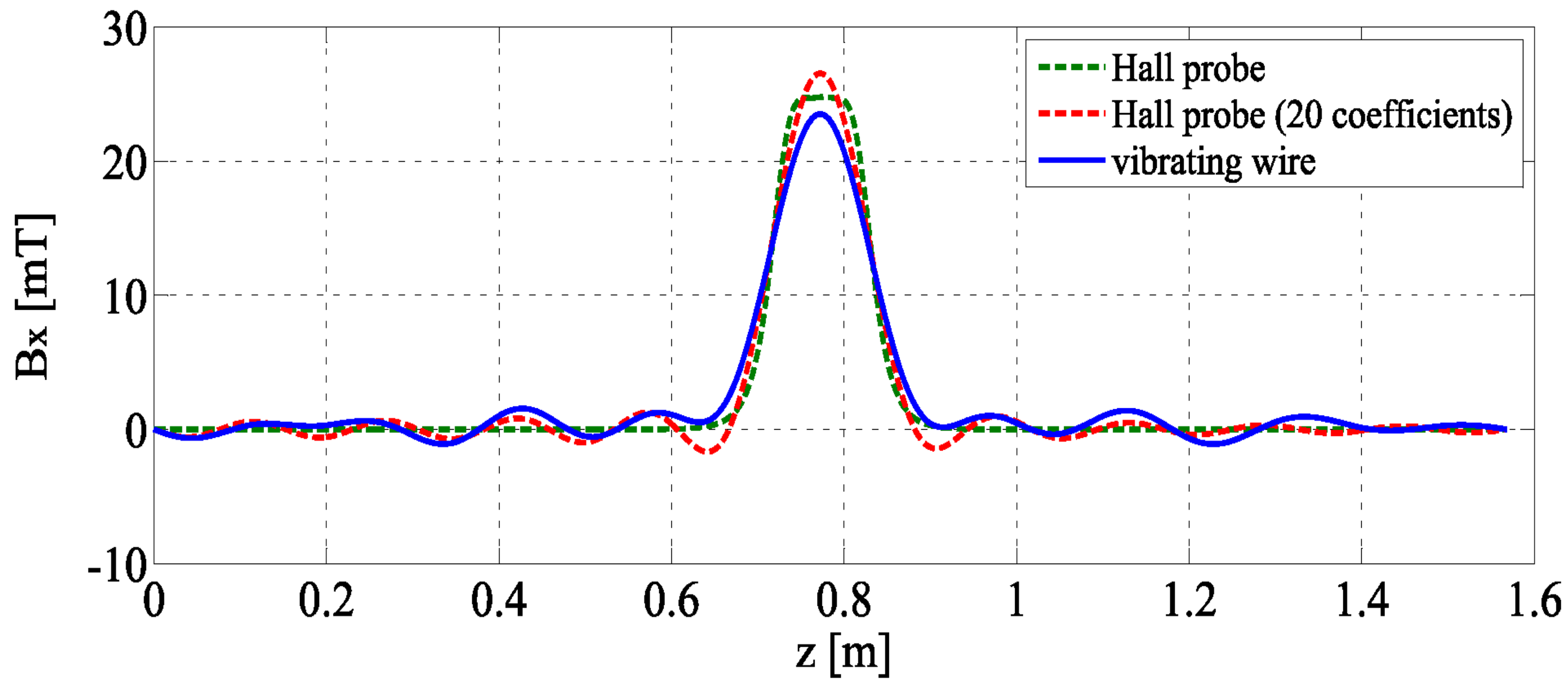
- Calculate the longitudinal field profile (by inverse Fourier transform)

$$B_{\mathrm{n}}(z) = \sum_m \mathcal{C}_m \sin\left(\frac{m\pi}{L}z\right)$$

Natural vibration modes







- Reconstruction error 3% of the field peak
- Repeatability 2%
  - RMS difference

- Bandwidth limitation
- Uncertainty sources