Stretched-wire systems for the magnetic measurement of small-aperture magnets

Domenico Caiazza ESR 2.1

3rd Supervisory
Board Meeting
22/09/2016

ESR2.1, WP2 / Magnetic measurements

- Contract start date: *1st February 2014*
- PACMAN subject: *Magnetic measurements by stretched wires*
- PhD in *Information Technologies for Engineering*
- PhD Institution: *University of Sannio*
- Secondments: *Sigmaphi, Metrolab, National Instruments*

CERN Supervisor	Prof. Stephan RUSSENSCHUCK
Academic supervisor	Prof. Pasquale ARPAIA
Industry supervisors	Marie-julie LERAY, Philip KELLER, Jacques TINEMBART, Joe WOODFORD, Botond BARABAS

OUTLINE

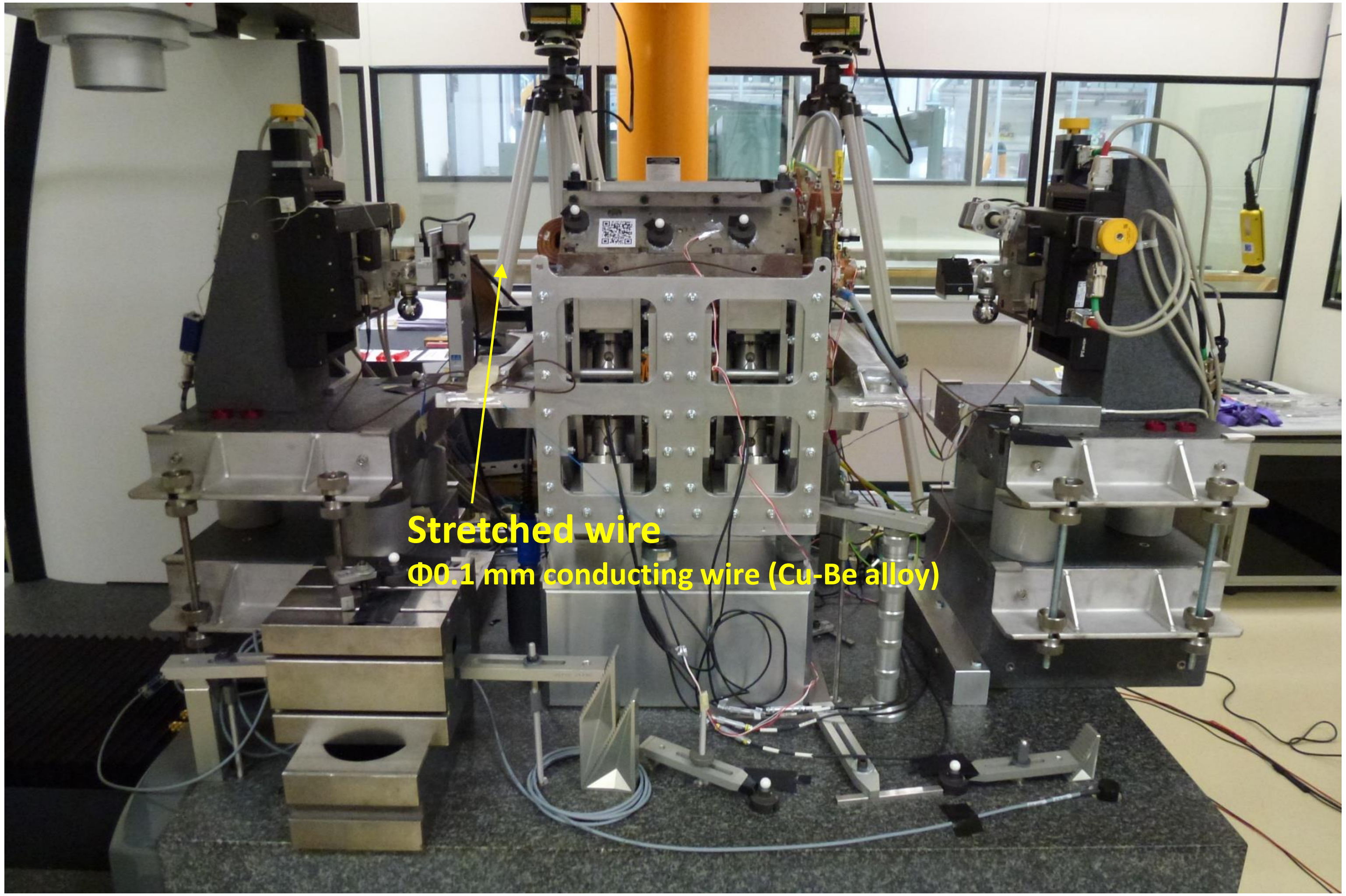
- State of the art
    - Stretched-wire systems for magnetic measurements
    - Stretched-wire and vibrating wire methods
- Achievements
    - Comparing stretched and vibrating wire
    - Performance optimization for the vibrating wire
    - Measurements of the CLIC Main Beam Quadrupole
    - Secondment in National Instruments

Wire-based transducers

A measurement system for:

- field strength and direction
- field quality
- field profiles
- magnetic axis

Compliant with different magnet types and geometries



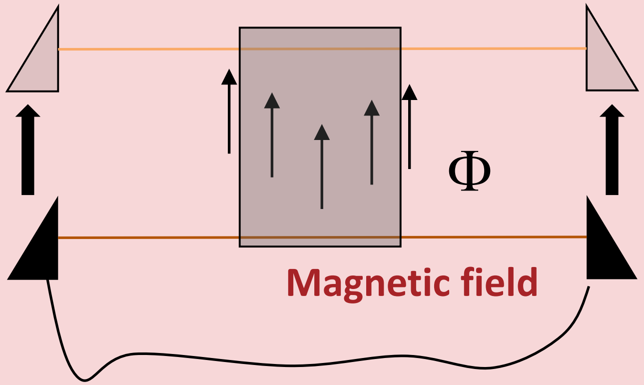
Stretched wire

Φ0.1 mm conducting wire (Cu-Be alloy)

State of the art / Wire methods

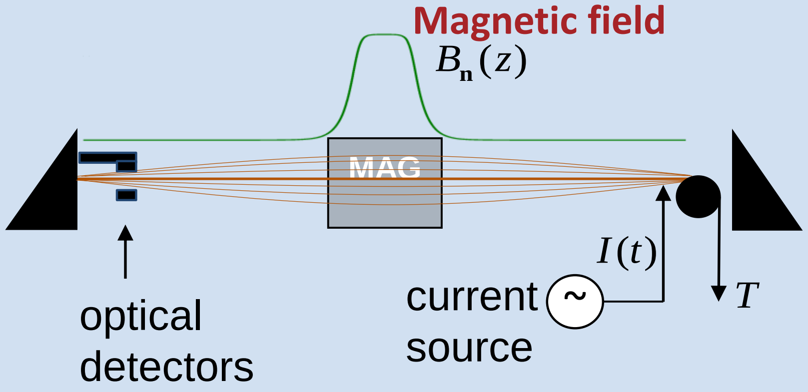
Stretched wire

Faraday's law



Oscillating/vibrating wire

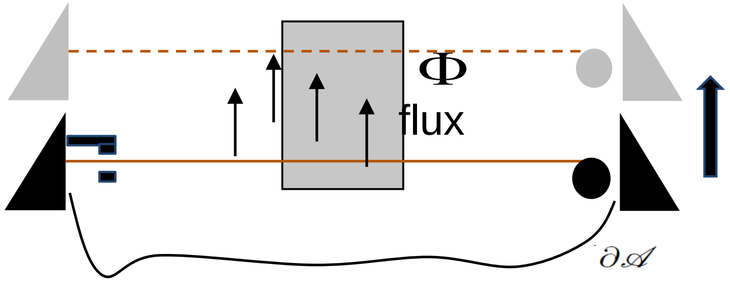
Lorentz force



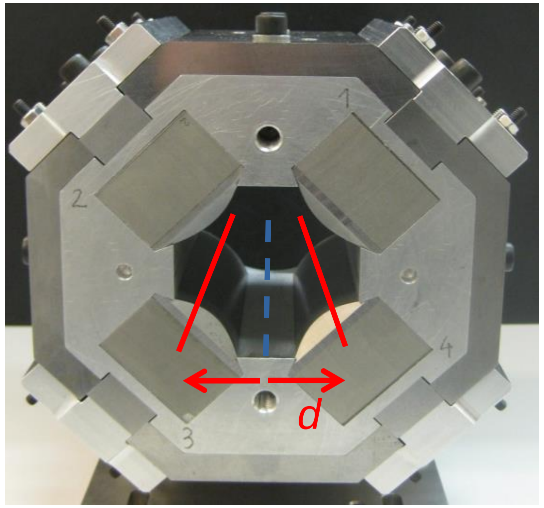
State of the art / Stretched wire method

Measurements for LHC magnets

- ✓integrated field strength (10^{-5} uncertainty)
- ✓field direction
- ✓magnetic axis (50-100 µm)



The wire is translating



Magnetic center coordinates

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

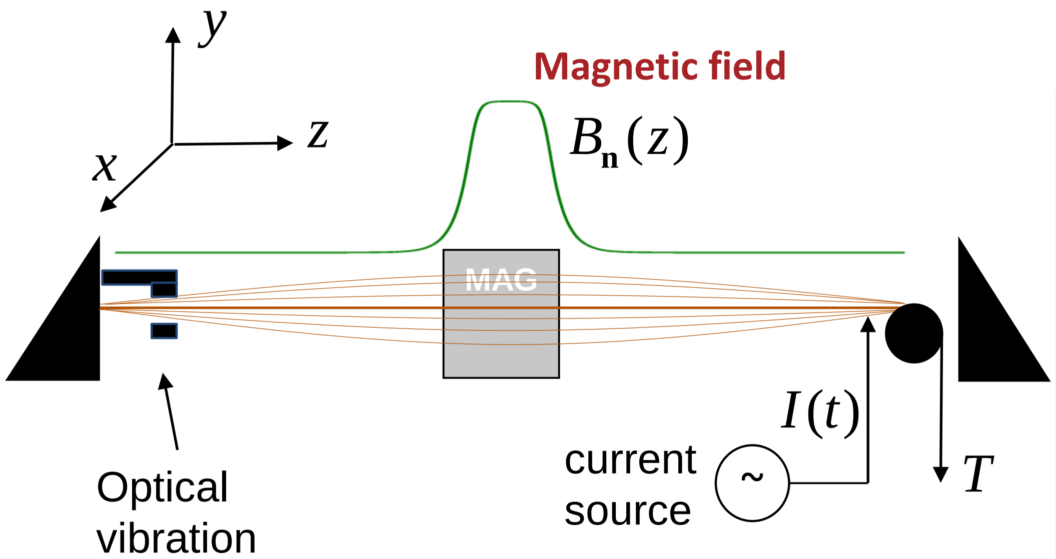
$$y_c = y_0 - \frac{d}{2}\frac{\Phi(y_0, y_0+d) - \Phi(y_0, y_0-d)}{\Phi(y_0, y_0+d) + \Phi(y_0, y_0-d)}$$

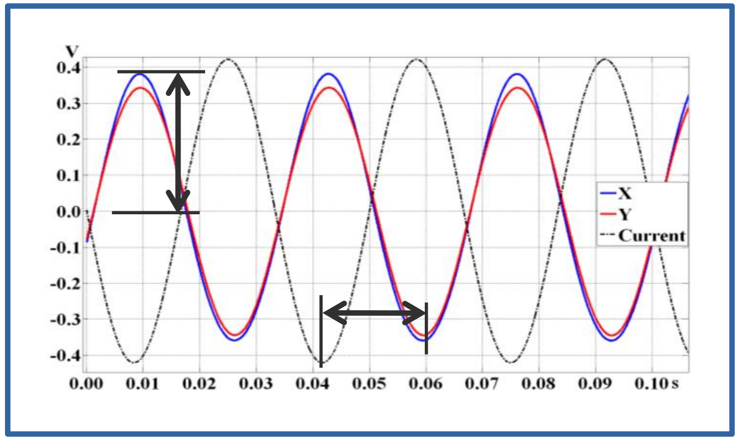
J. Di Marco et al., “Field alignment of quadrupole magnets for the LHC interaction Regions”. *IEEE Transactions on Applied Superconductivity*, 2000.

State of the art / Vibrating/oscillating wire method

Used in particular for alignment and magnetic field quality (multipoles)

high sensitivity also for low field and small apertures





Wire in magnetic field

⇩

Feeding the wire by alternating current (Lorentz force)

⇩

Measure wire vibrations (X and Y components)

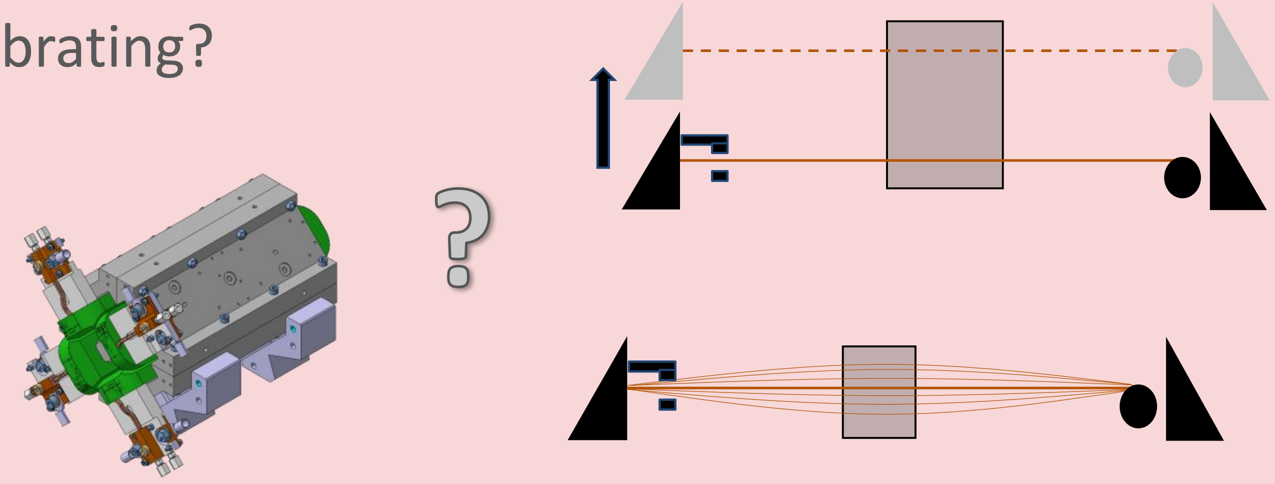
⇩

Relate vibrations to magnetic field

- **A. Temnykh**. “Vibrating wire field-measuring technique”. *Nuclear Instruments and Methods in Physics Research,* **1997**.
- **P. Arpaia, M. Buzio, J. G. Perez, C. Petrone, S. Russenschuck, L. Walckiers**. “Measuring field multipoles in accelerator magnets with small-aperture by an oscillating moved on a circular trajectory”. *JINST – Journal of Instrumentation,* **2012**.

Achievements\ comparative study for the alignment

Stretched or vibrating?



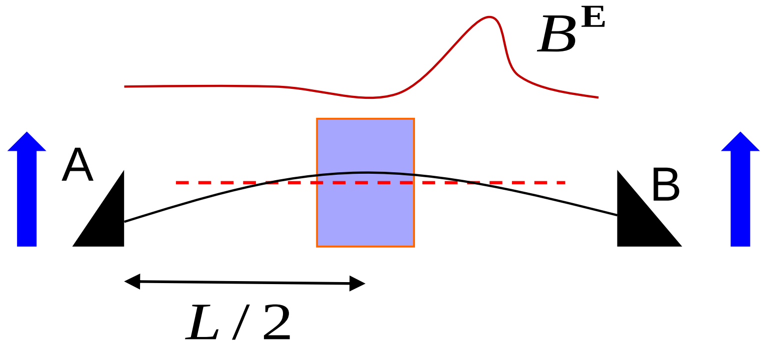
- ✓ The two methods agree within the measurement precision
  - After suitable correction of background fields
  - and multipole field errors
- ✓ Vibrating wire preferred if
  - Multipole field errors are unknown
  - Low strength and small wire travel range (linked flux < 120 µWb)

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**.

Achievements\
Background field influence

Correction of inhomogeneous background fields

- Earth magnetic field
- Fringe field from equipment



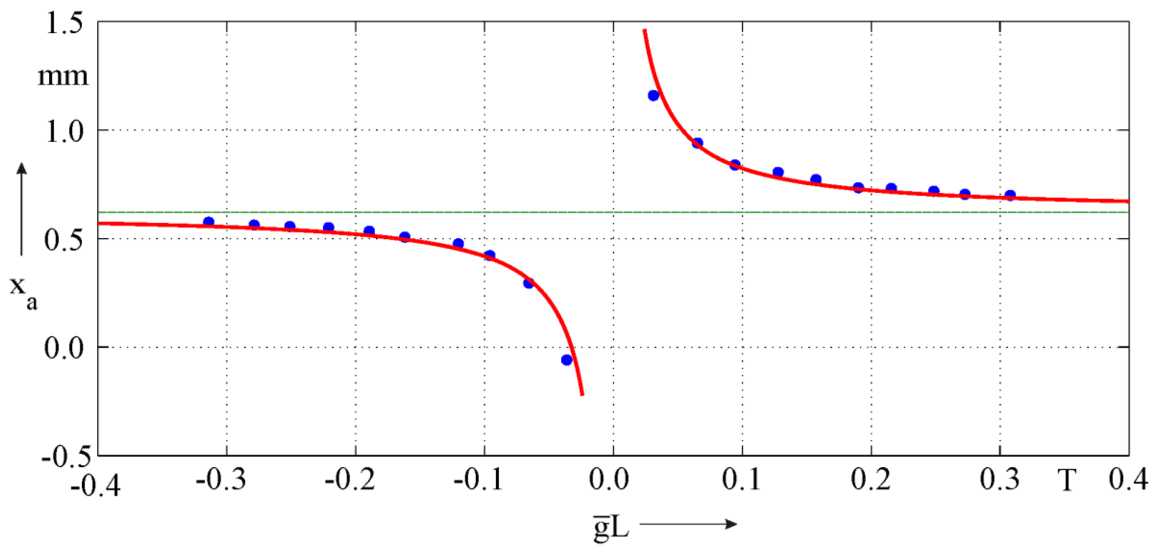
Fit to the model

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

Apparent center

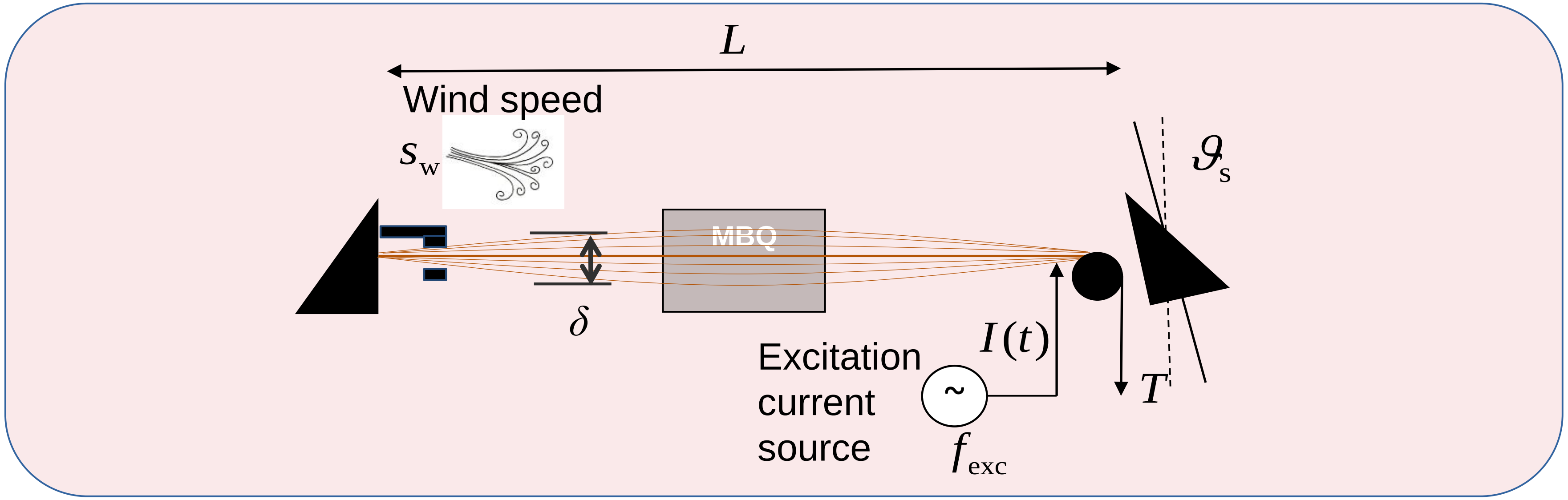
Actual center

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\ optimization for the vibrating wire



Outcomes:

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

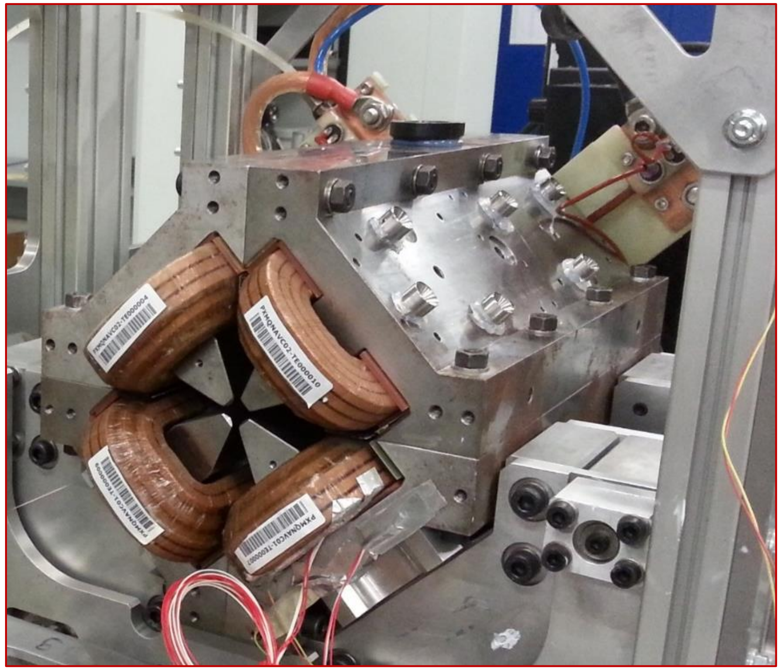
Repeatability σ_c	x	y	m.u.
1-m wire length	±2.6	±4.6	µm
4-m wire length	±0.9	±1.1	µm

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



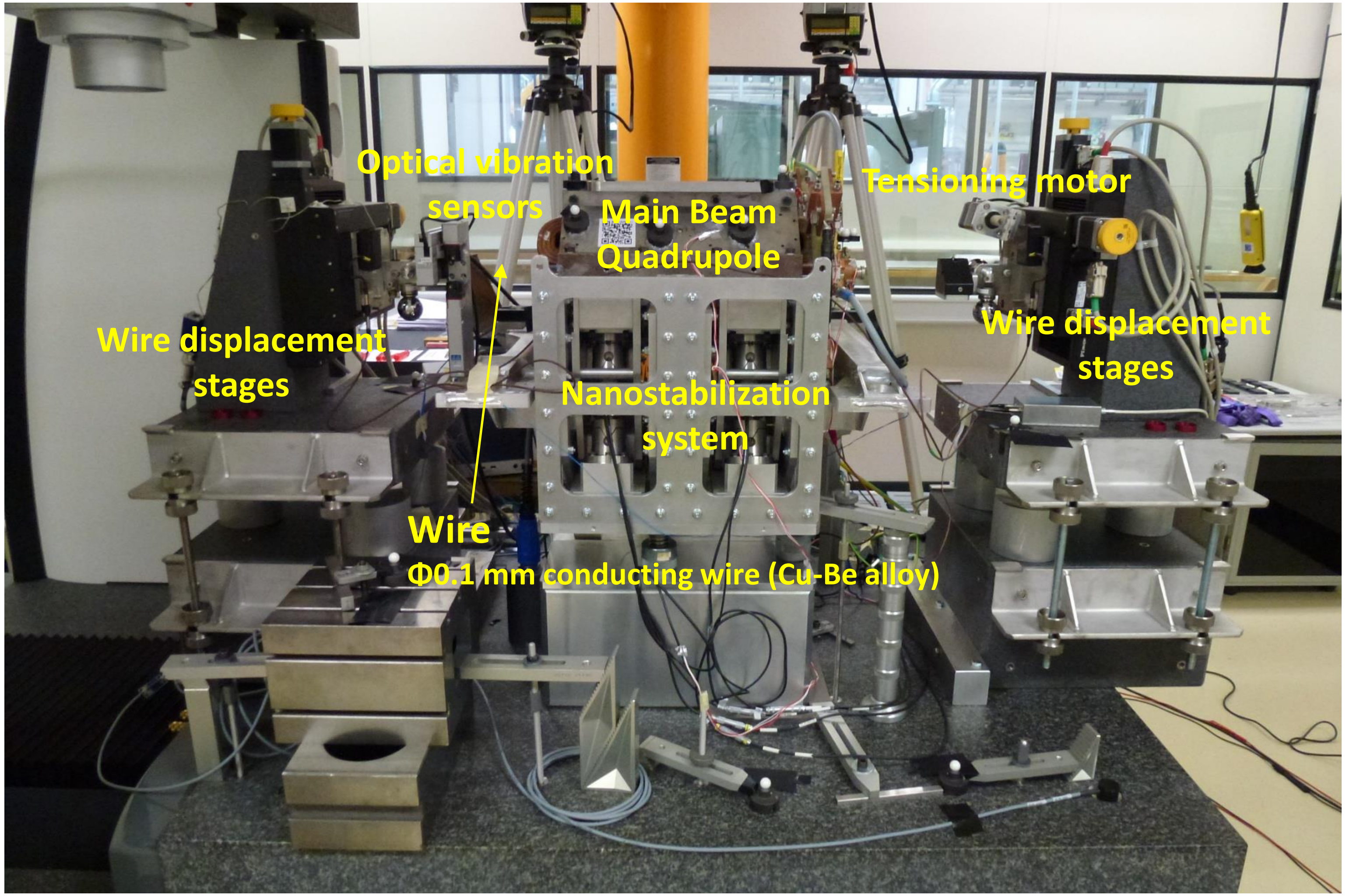
Measurements taken at different magnet currents and referred to the axis at nominal gradient

Magnet current	x_c	y_c	ϕ_c	θ_c
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

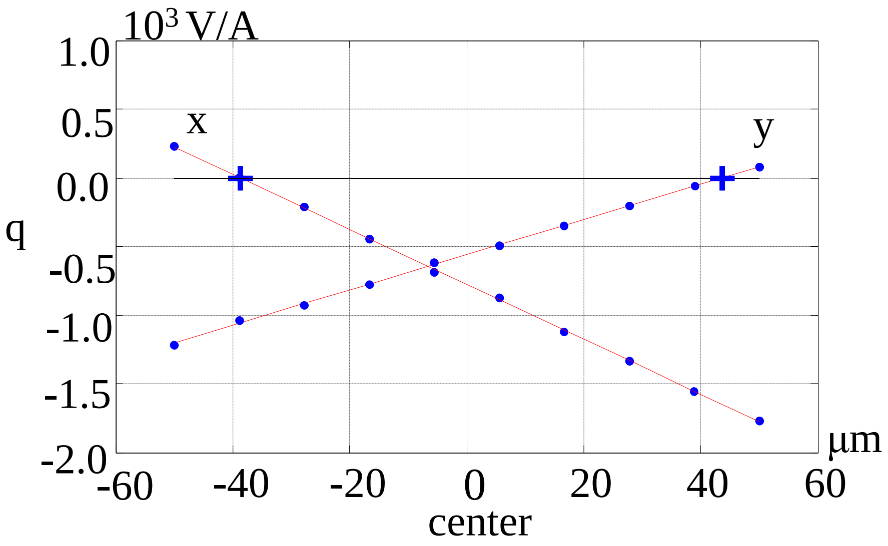
Repeatability

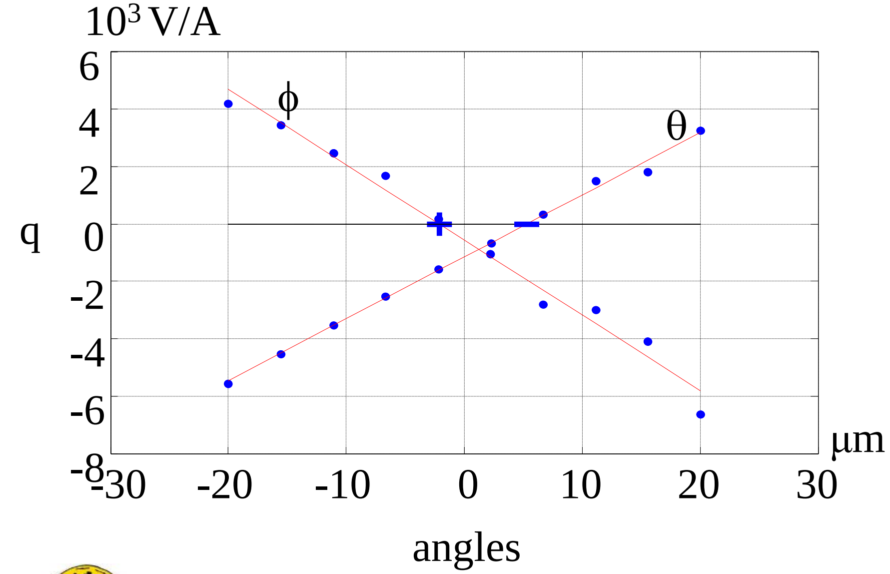
- Within ±0.2 µm for the centers
- Within ±0.9 µrad for the angles (worst cases)
- Also at 4 A

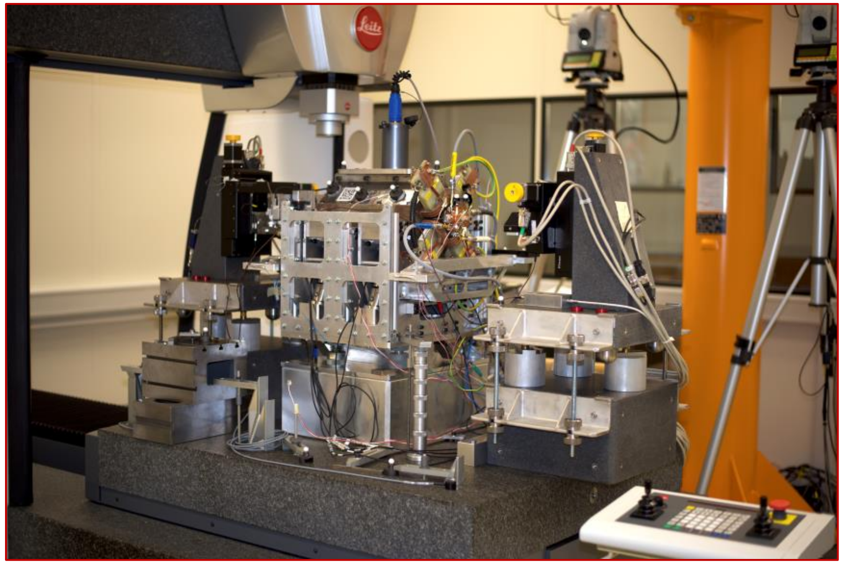
PACMAN Wire system



Measurement on the CMM







1-σ standard deviation on 10 repetitions

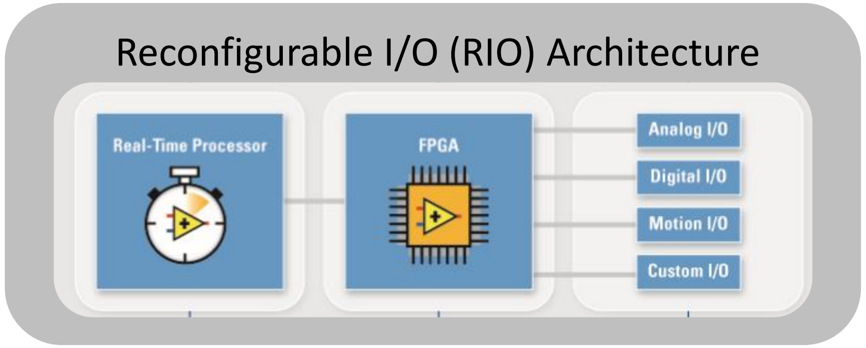
x_c	y_c	ϕ_c	θ_c
µm	µm	µrad	µm
0.058	**0.077**	**1.940**	**0.413**

Wire sag: 9 µm

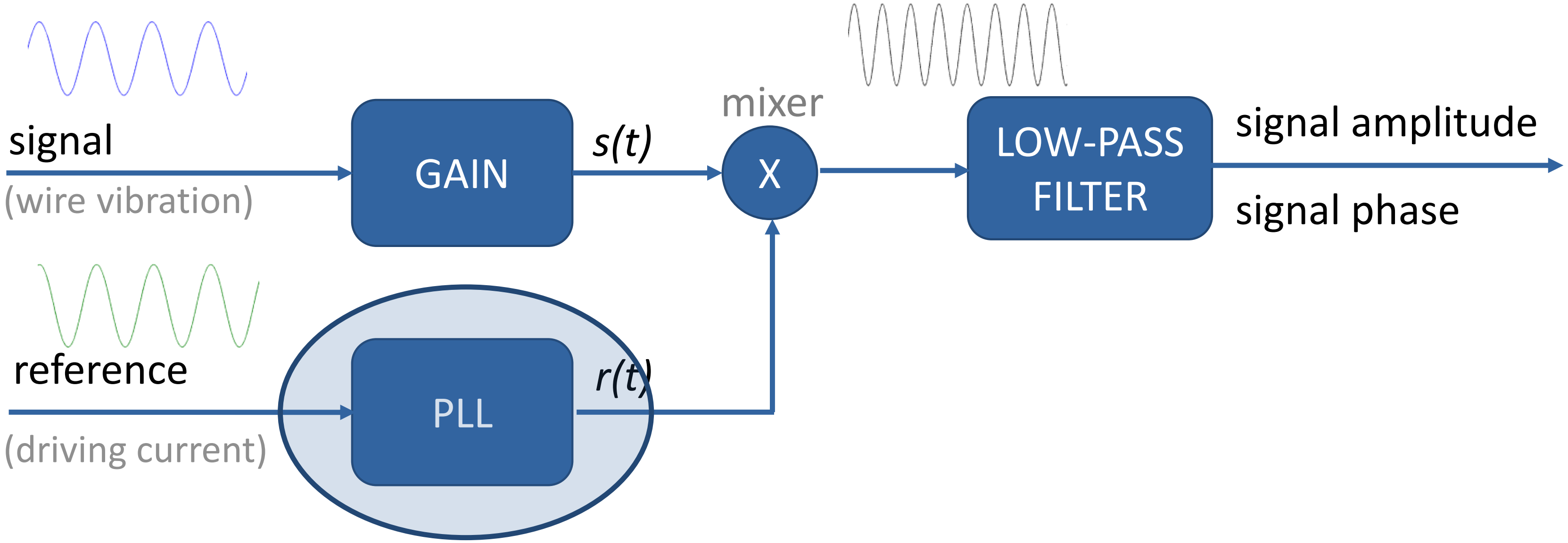
Secondment in National Instruments

- Implementation of lock-in amplifier for the vibrating wire by LabView FPGA

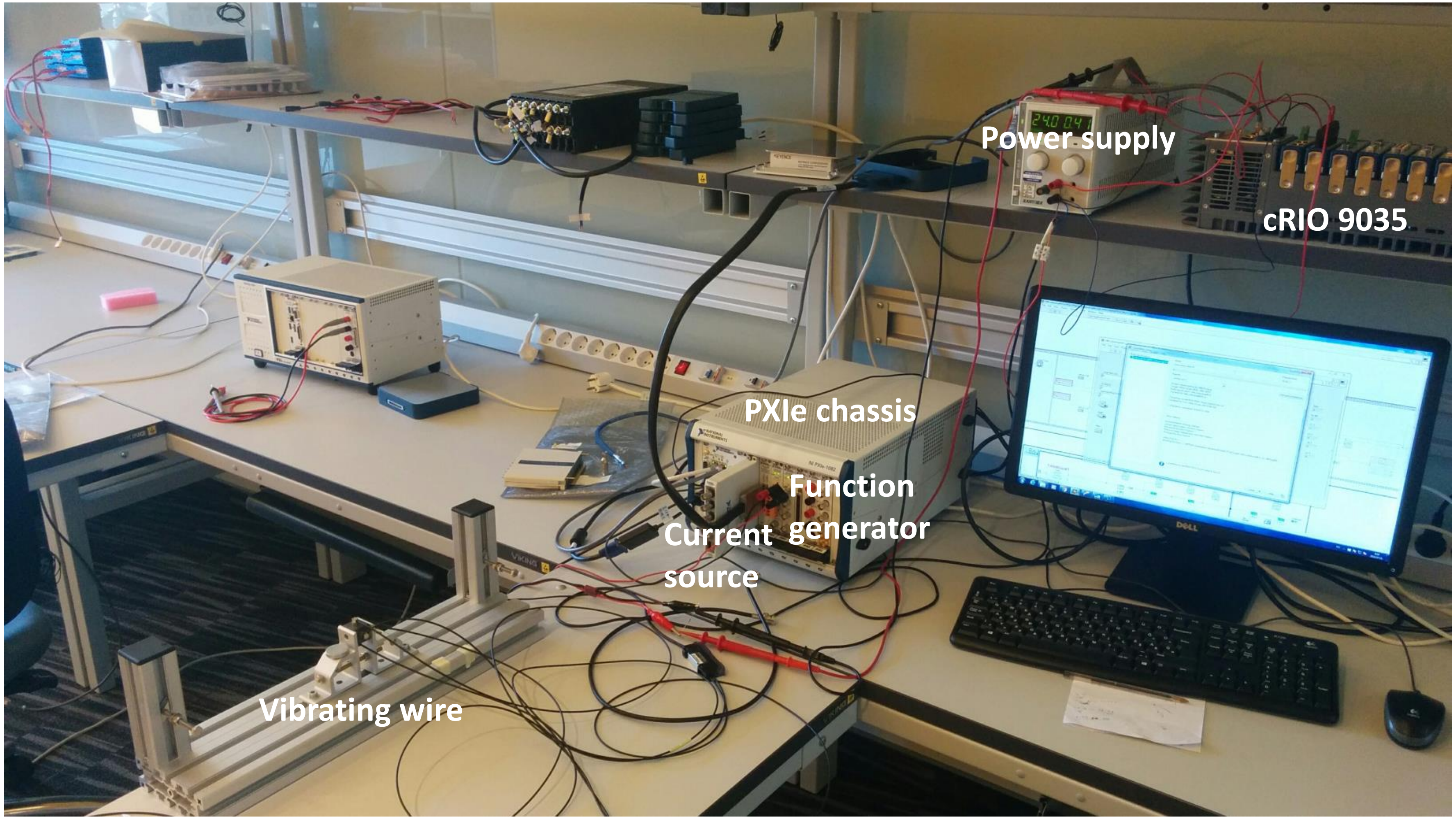
NI Compact RIO 9035



Reconfigurable I/O (RIO) Architecture

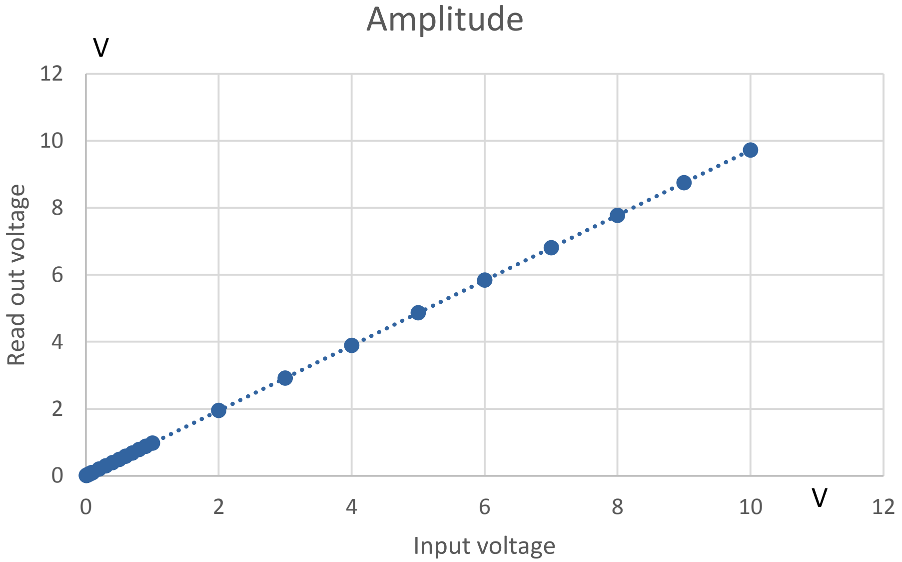


Secondment in National Instruments



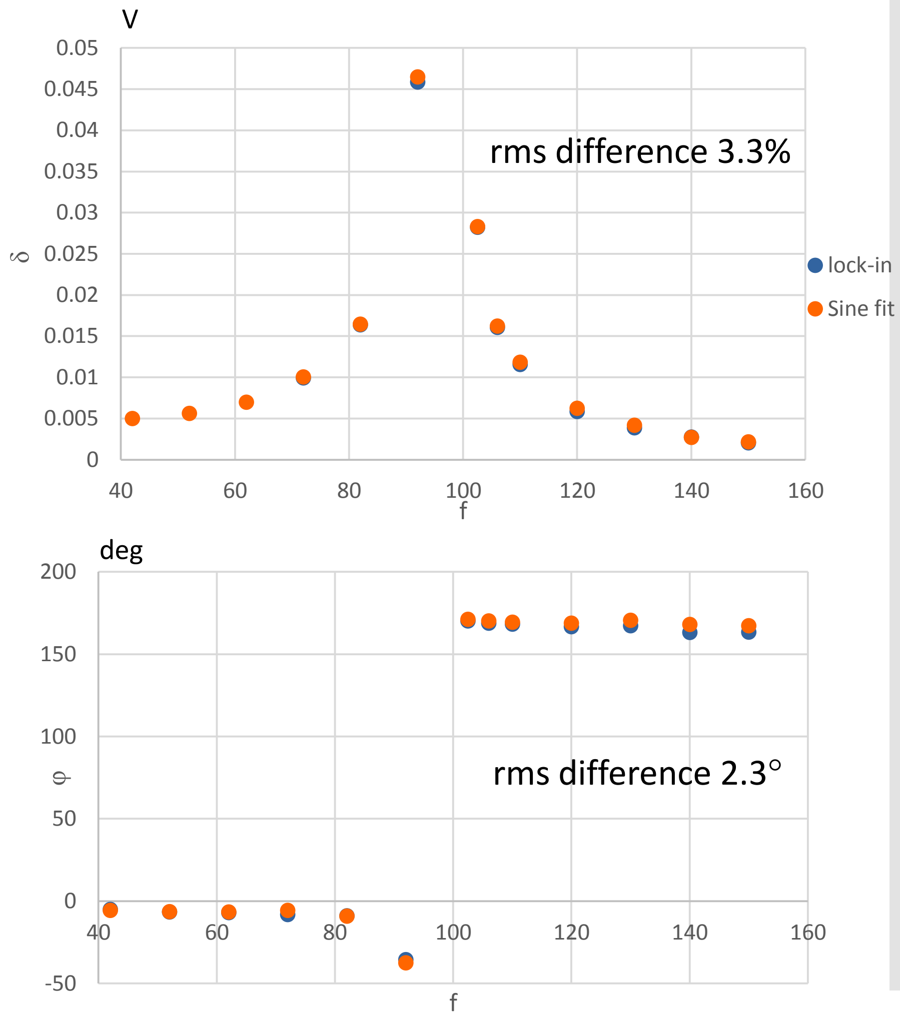
Secondment in National Instruments

- Calibration against function generator
  - Reference sine wave frequency 100 Hz



Slope	**Offset**	**Residual rms**
0.972 V/V	$-3.07 \cdot 10^{-5}$ V	$5.3 \cdot 10^{-3}$ V

Vibrating-wire resonance curve



Conclusions

- System assembled and validated
- Methodology validated and improved (inhomogeneous background fields, performance optimization)

- Further steps
  - Evaluation of reproducibility
  - Assessment of final uncertainty

- Further themes
  - Field harmonics by stretched and vibrating wire: comparative study
  - Investigation on the physics of the vibrating wire (non viscous damping, string stiffness, nonlinearities …)

Thank you for your attention

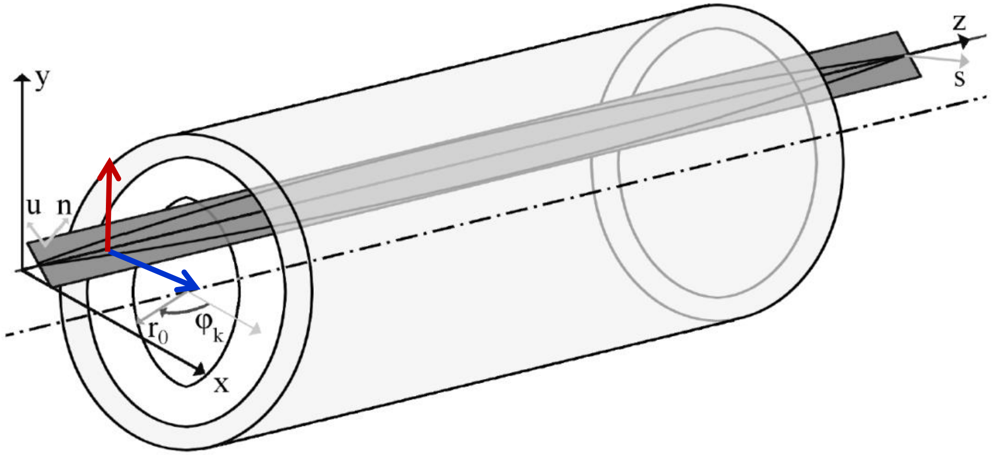
3rd Supervisory
Board Meeting
22/09/2016

SPARES

Project /

Background

Vibrating-wire method



Wire in magnetic field

Feeding the wire by alternating current (Lorentz Force)

$$F = Q\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right)$$

Measure wire motion amplitude X and Y components

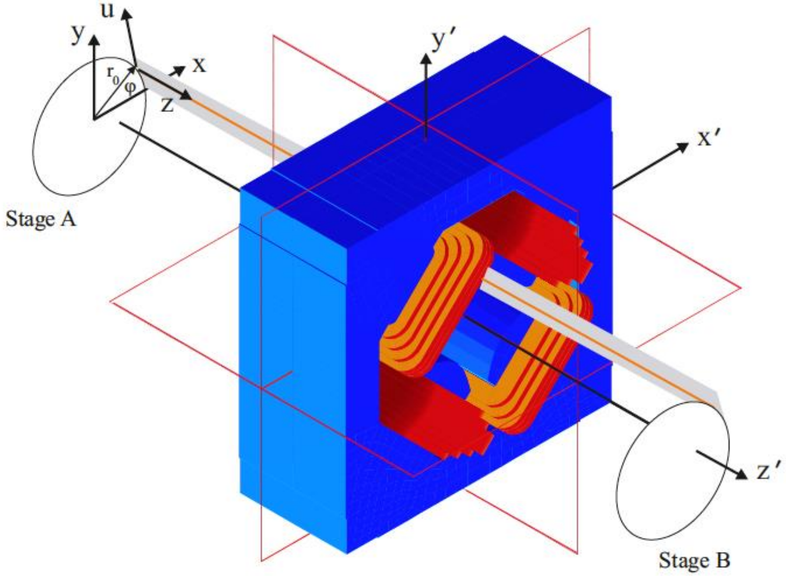
Relate motion to magnetic field properties

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

Project / Background

Assumptions and mathematical model

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



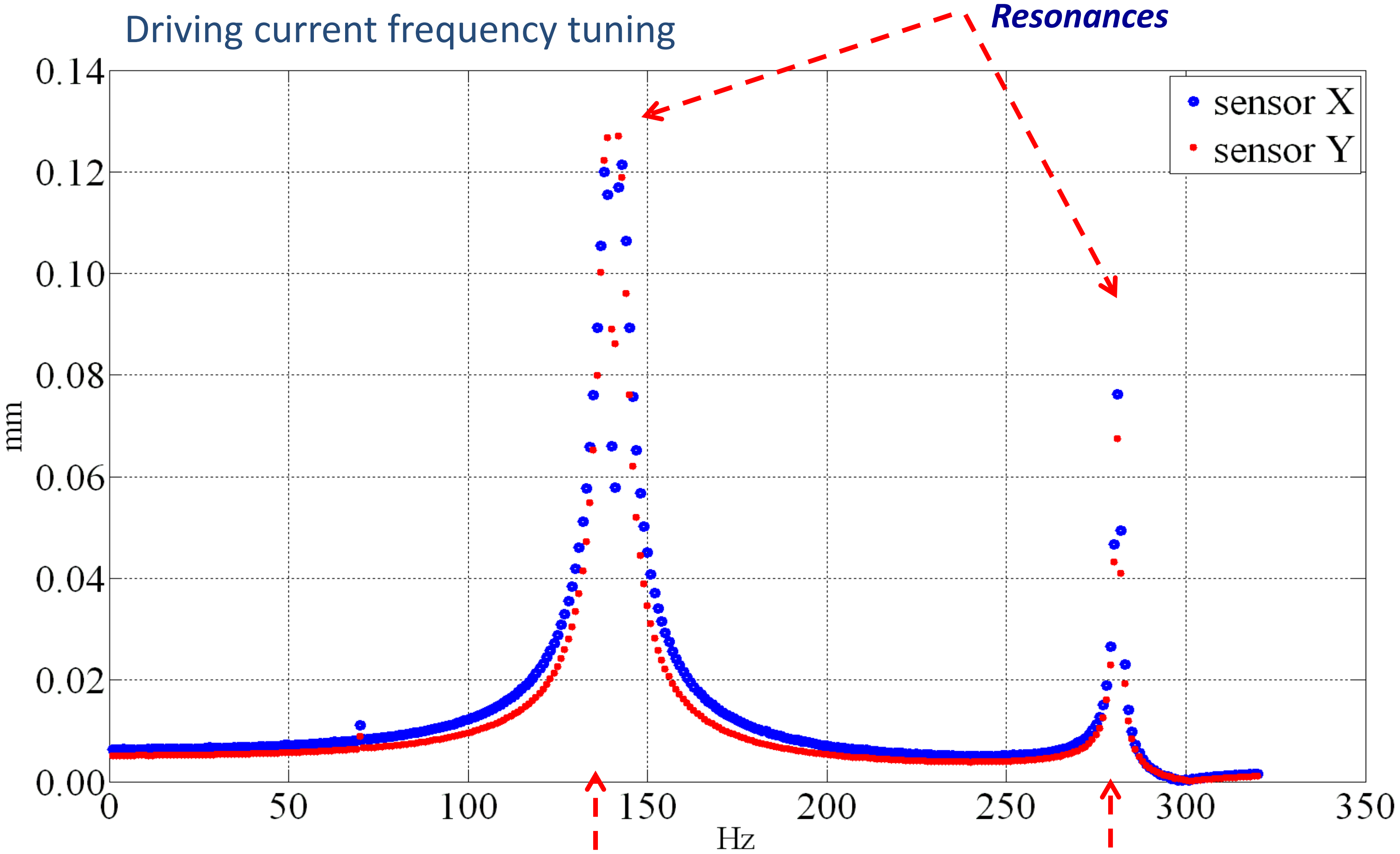
$$u(z,t)=\frac{2I_0}{L}\sum_m \frac{\int_0^L B_{\mathrm{n}}(z)\sin\left(\frac{m\pi}{L}z\right)\mathrm{d}z}{\sqrt{\left[T\left(\frac{m\pi}{L}\right)^2-\rho\omega^2\right]^2+(\alpha\omega)^2}}\sin\left(\frac{m\pi}{L}z\right)\sin(\omega t-\varphi_m)$$

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

Measurement system design

Project /

Background

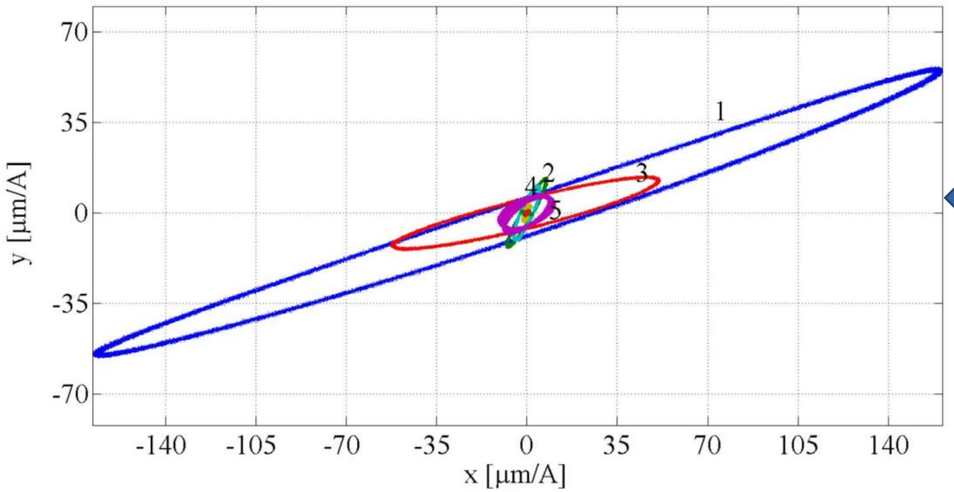


Working frequencies for max sensitivity

Project /

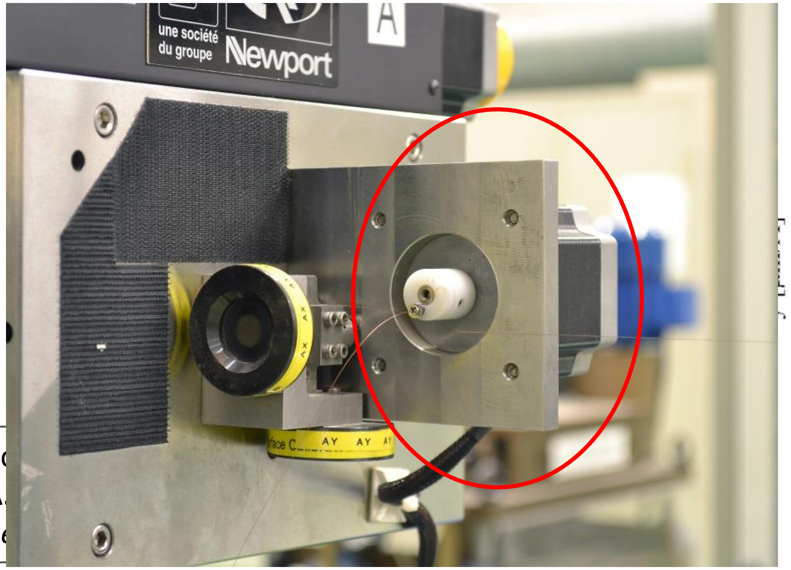
Experimental characterization

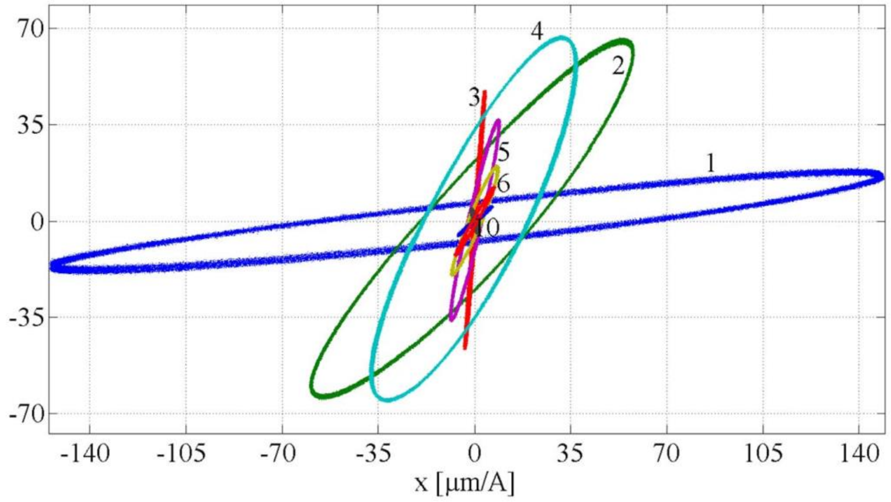
Background field & elliptic motion



- No magnet on the measurement station
- Background fields
  - 2% alteration of first harmonic

Prec
J. A.
Ame



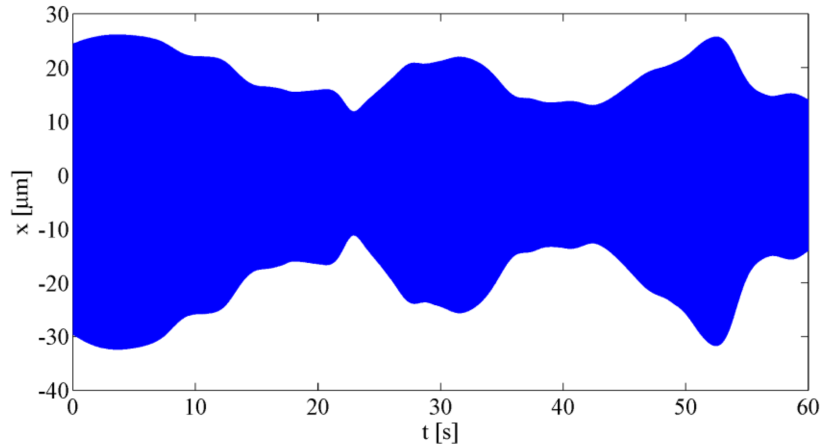


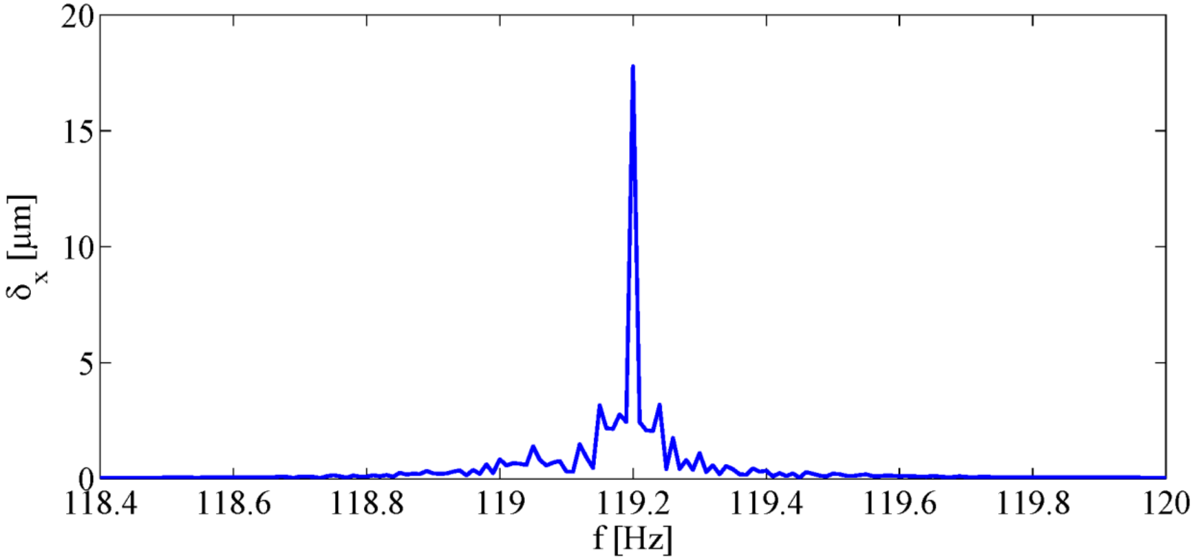
Resonance instability

Project /

Experimental characterization

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





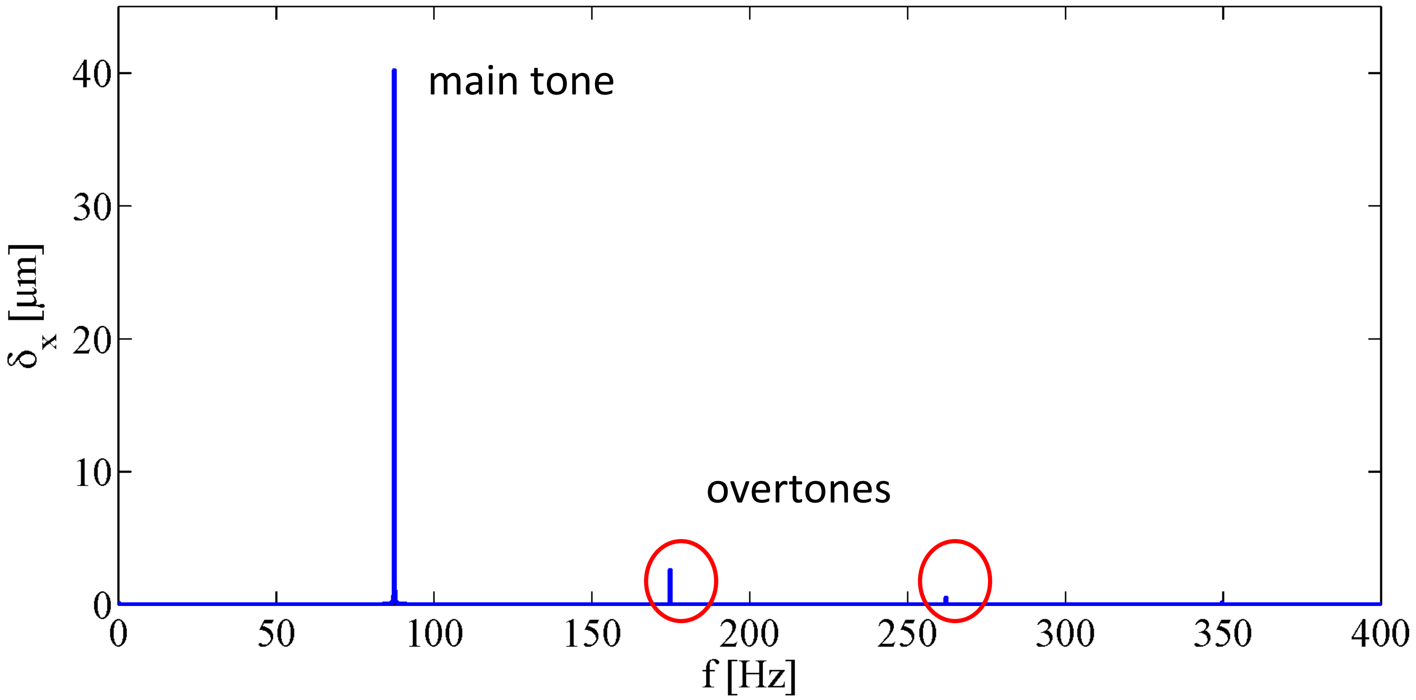
Possible reasons

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

Nonlinearity and overtones

Project /

Experimental characterizatior



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

➡ Nonlinearity!

Optical sensors for measuring wire vibration

Project /

Results

Phototransistors
- ✓ cheap
- ✓ very sensitive

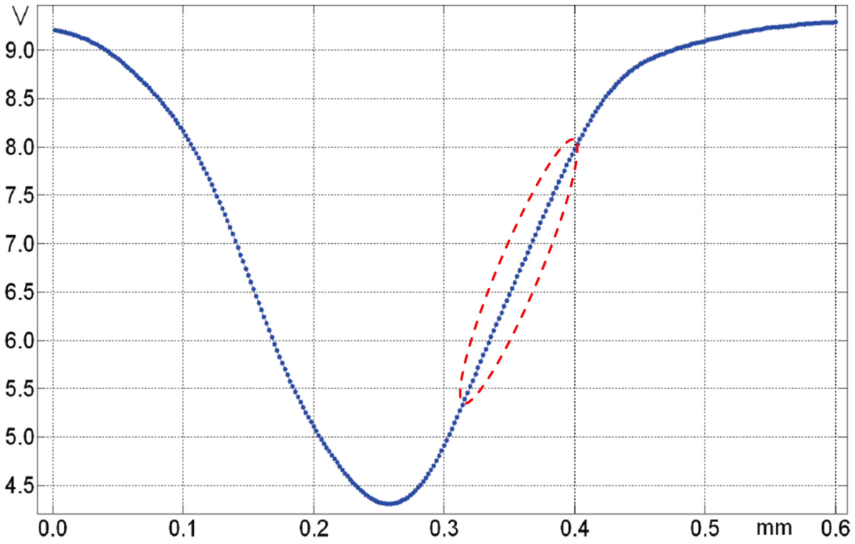
Fiber optics
- ✓ immune to magnetic field

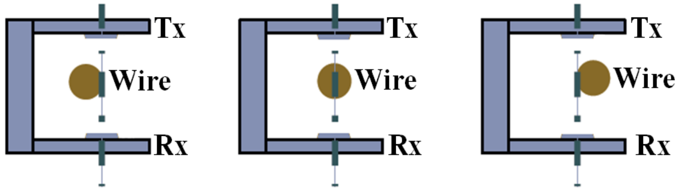
Need piezo-stages to hold the working point

CMOS sensors
- ✓ linear
- ✓ wide range

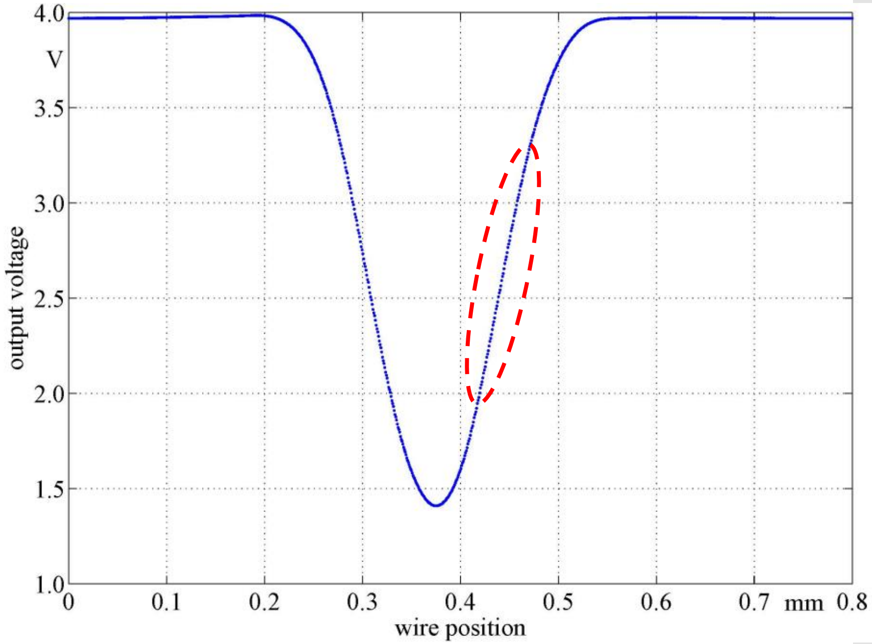
Characterization

Phototransistors





Fiber optics units



Range:	~50 µm
Sensitivity:	28.4 V/mm

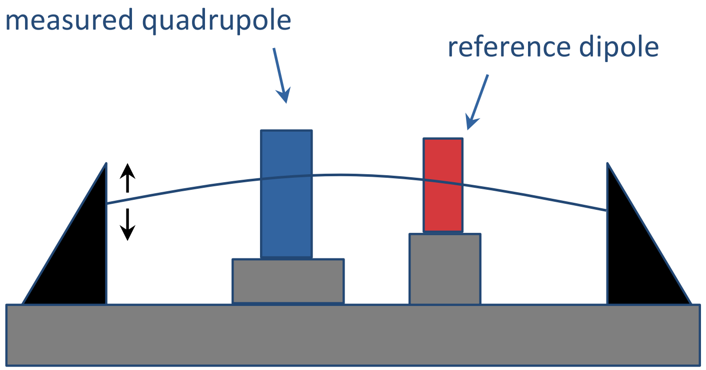
Range:	~40 µm
Sensitivity:	26.1 V/mm

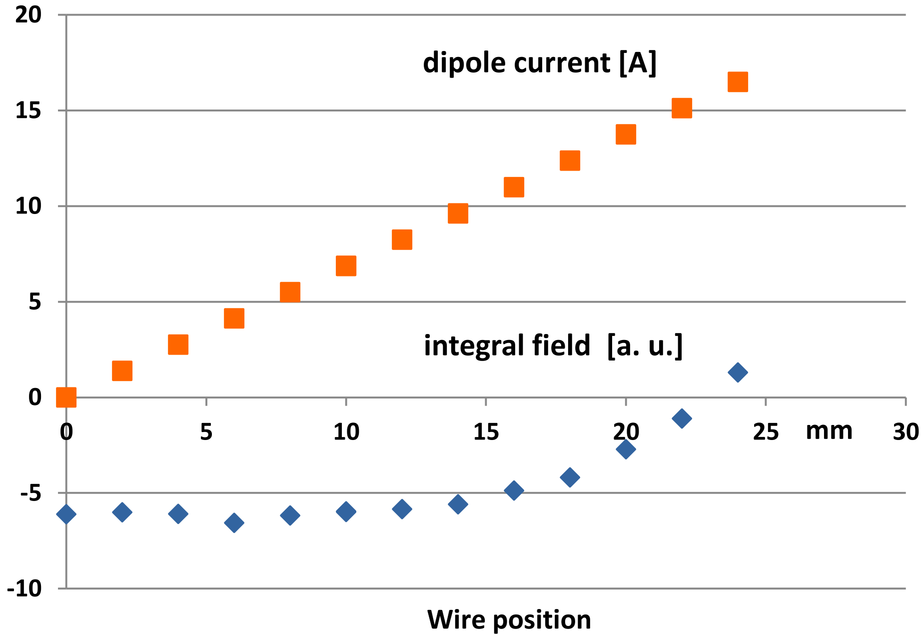
Project /

Results

Opposition method for the vibrating wire

In collaboration with A. B. Temnykh, Cornell University



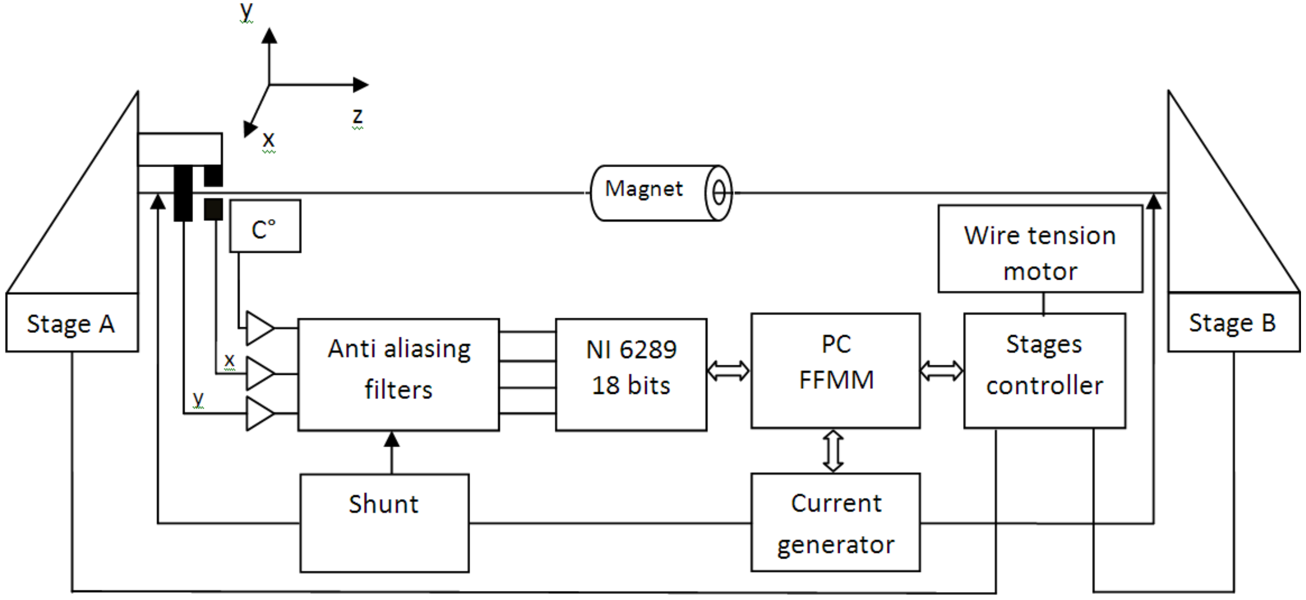


Opposition method

- ➢ use a reference dipole to compensate wire vibrations

Repeatability of dipole current measurement within $1\cdot10^{-4}$

- Applications: magnet quality and strength
- Drawback: transfer function of the reference dipole not linear and must be known accurately
- Possible solutions: air-coils



- ***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

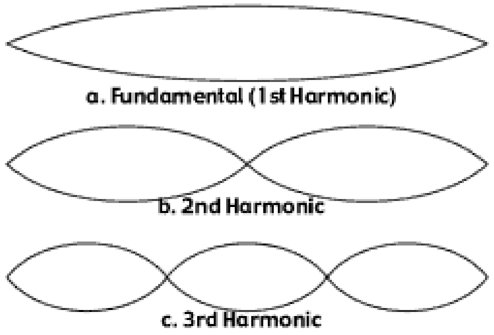
- Measure the frequency response
  - Vibration amplitude and phase
- Fit with the mathematical model
  - Longitudinal field coefficients

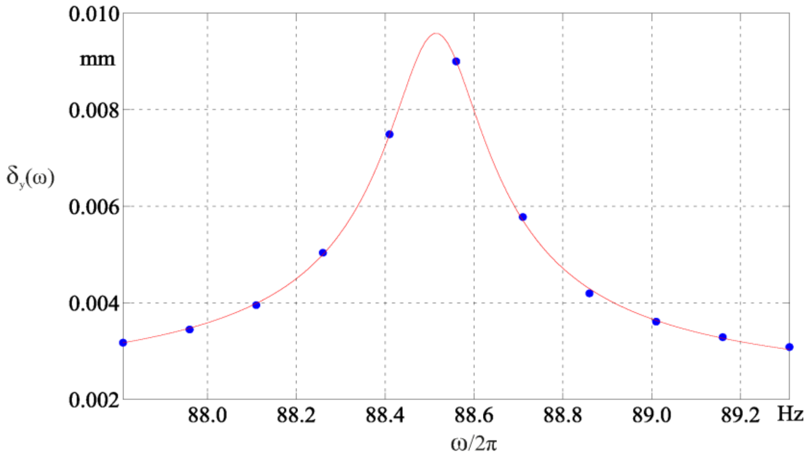
$$\boxed{\mathcal{C}_m := \frac{2}{L}\int_0^L B_\mathrm{n}(z)\sin\left(\frac{m\pi}{L}z\right)\mathrm{d}z}$$

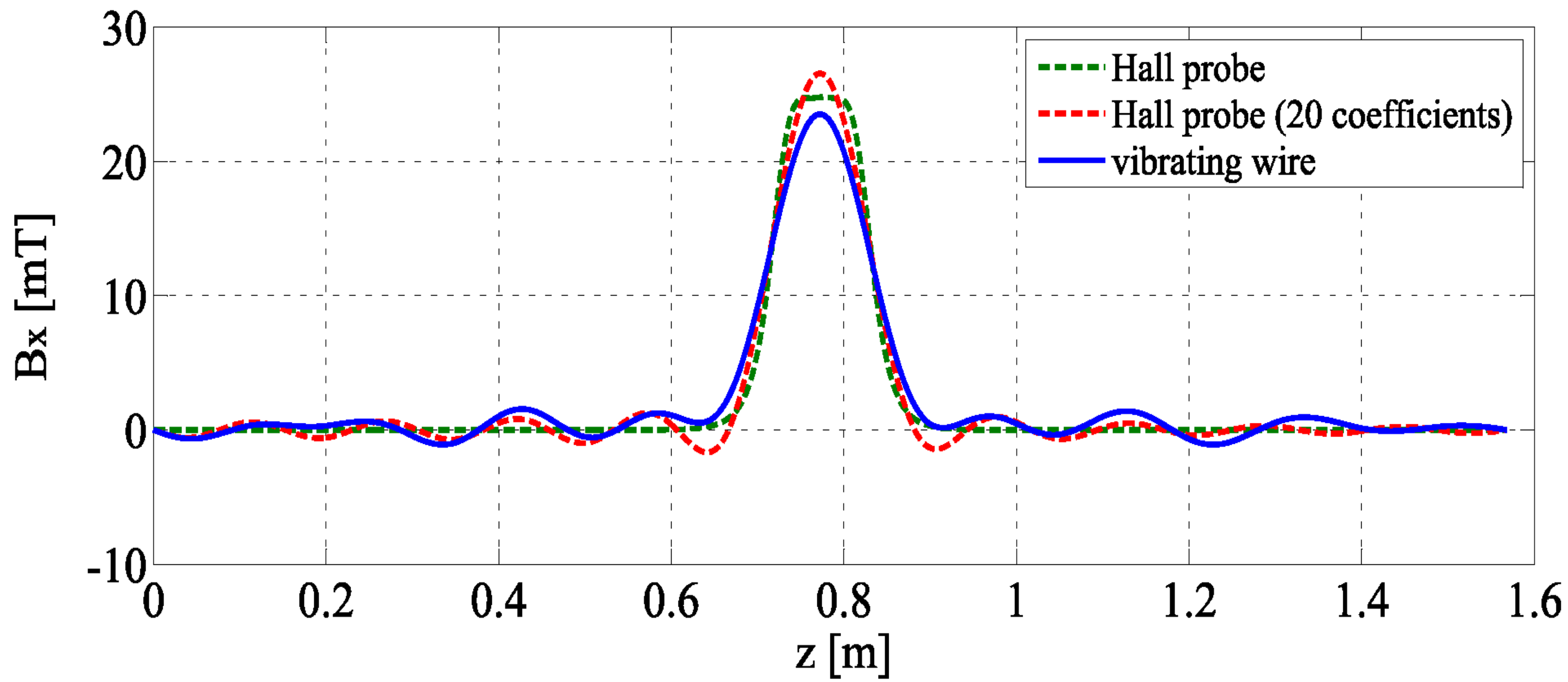
- Calculate the longitudinal field profile (by inverse Fourier transform)

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

Natural vibration modes







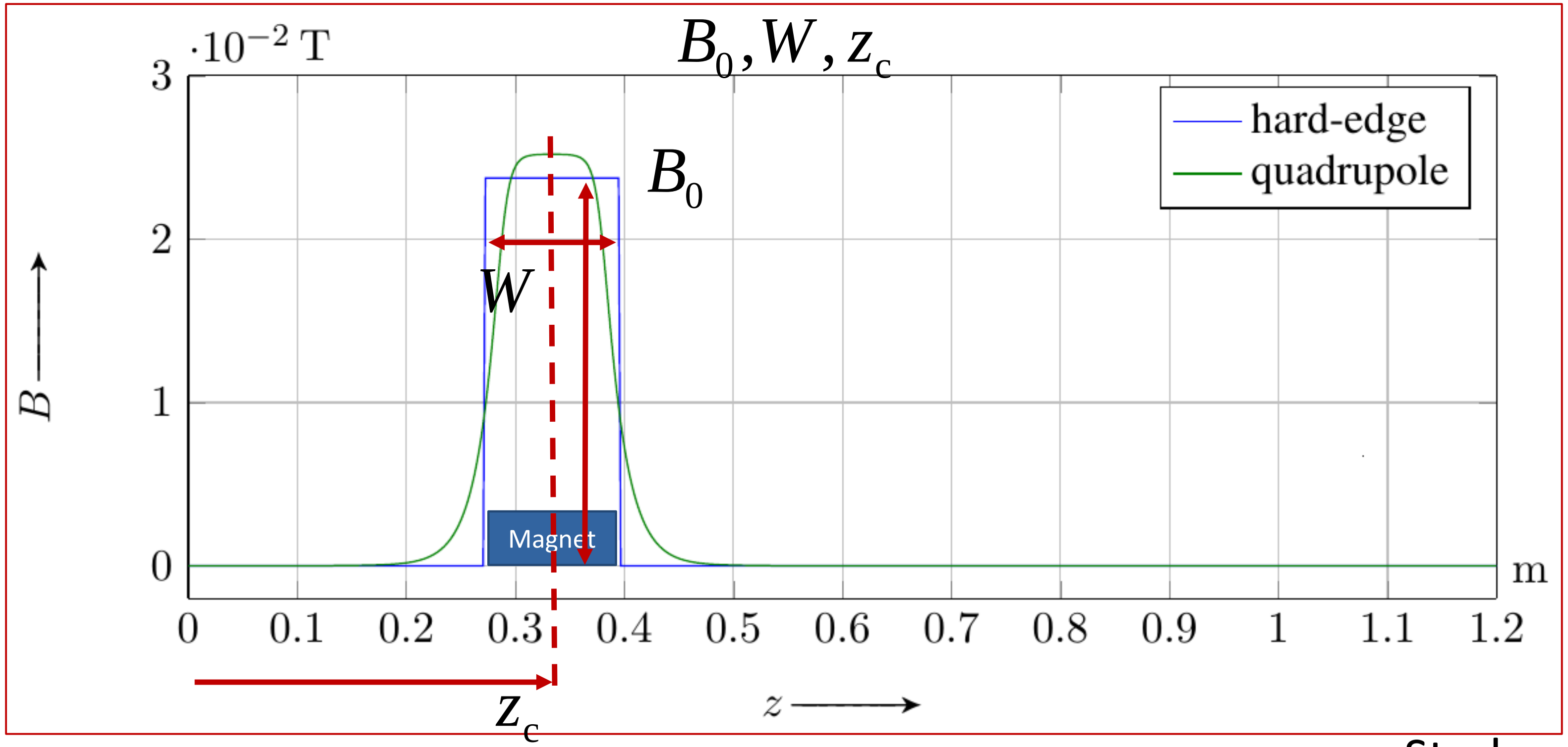
- Reconstruction error 3% of the field peak
- Repeatability 2%
  - RMS difference

- Bandwidth limitation
- Uncertainty sources

Applications

- Determination of the hard-edge equivalent
- Measuring few vibration harmonics

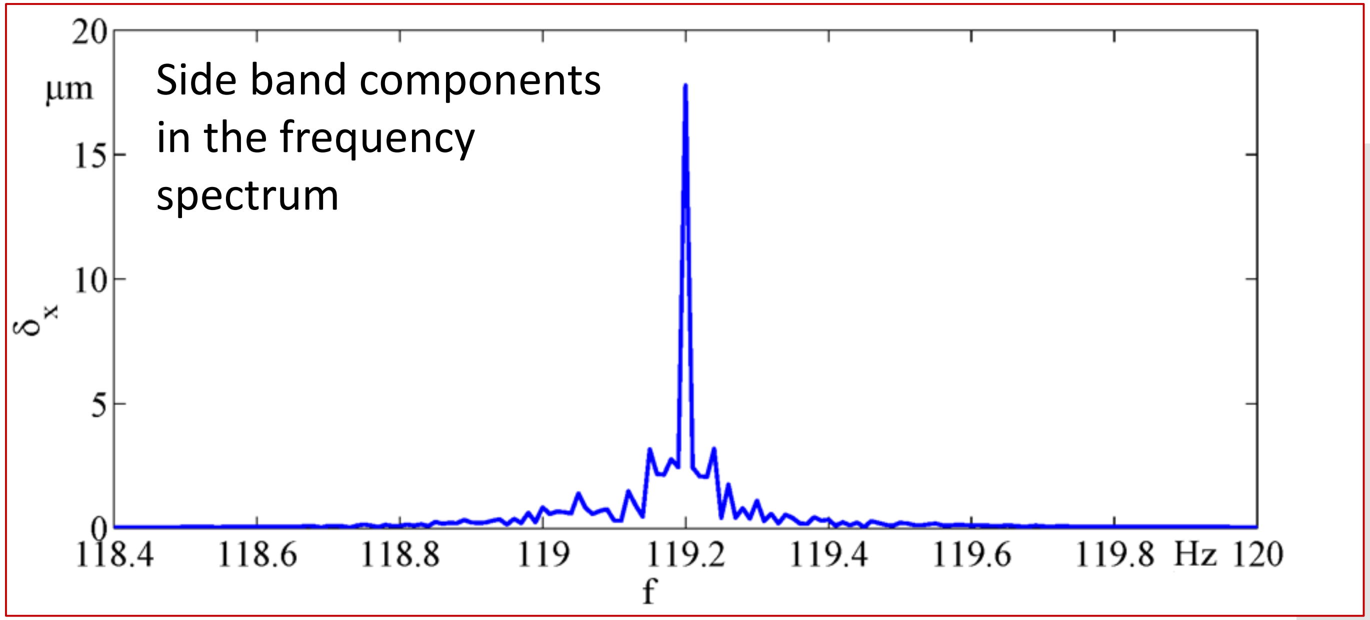
- For the detection of the longitudinal displacement of the magnet z_c

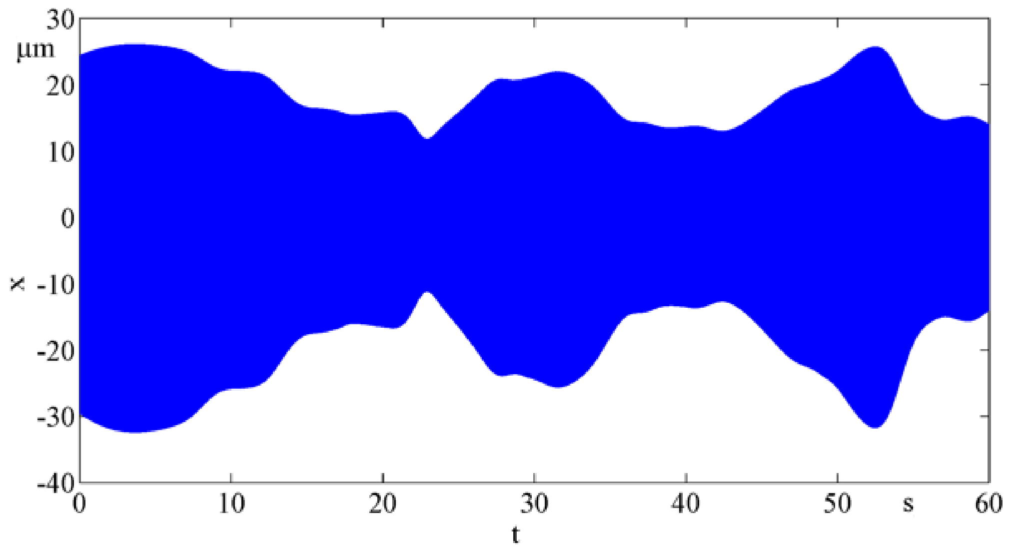


… Study ongoing …

Steady state modulation

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

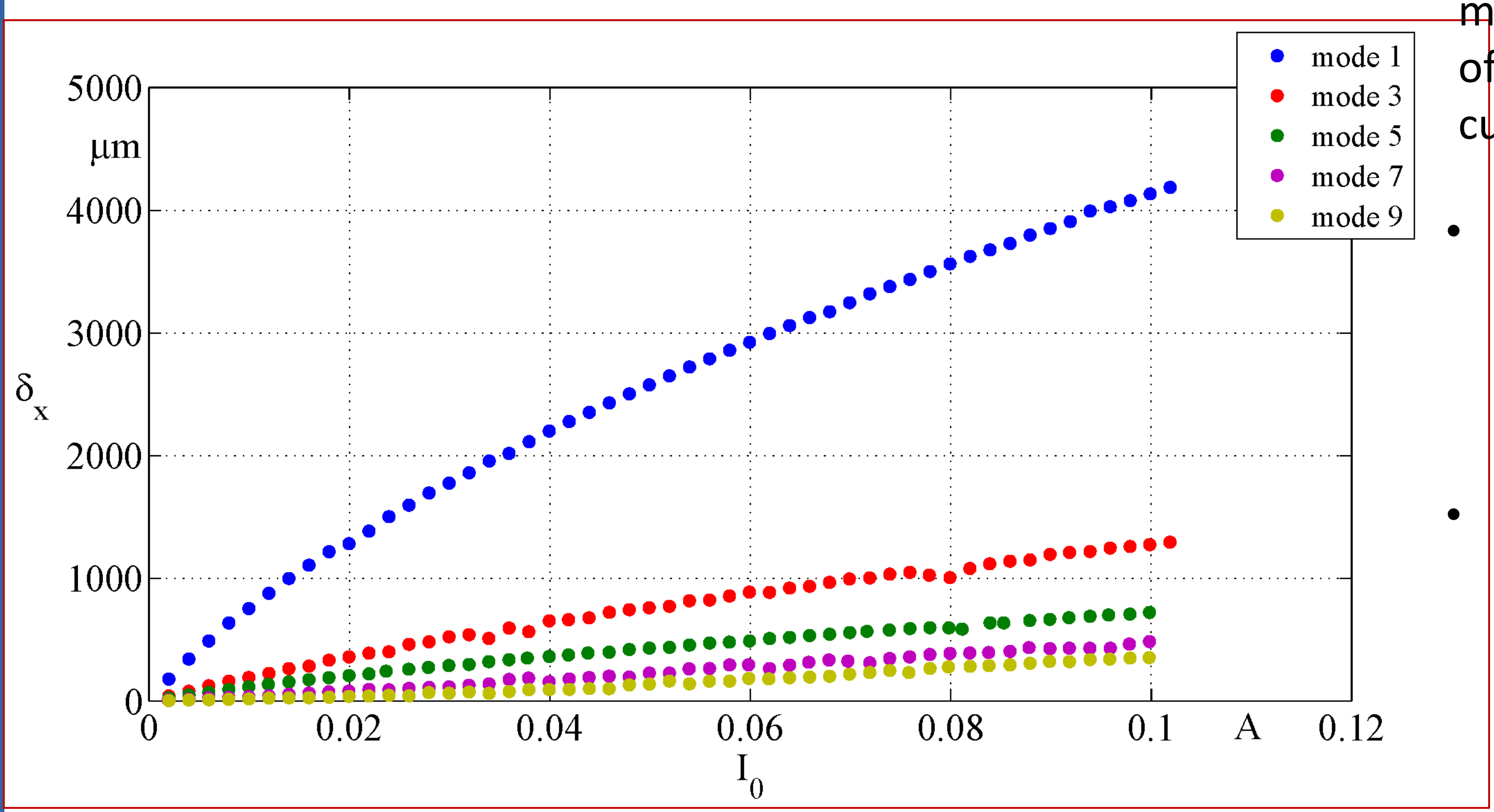




- Possible reasons
  - Non constant length and/or tension
  - Non ideal clamping (friction on the supports)
  - Excluded: coupling with ground vibrations

- Linearity with driving current lost for large vibration amplitudes

Linearity loss (1/2)

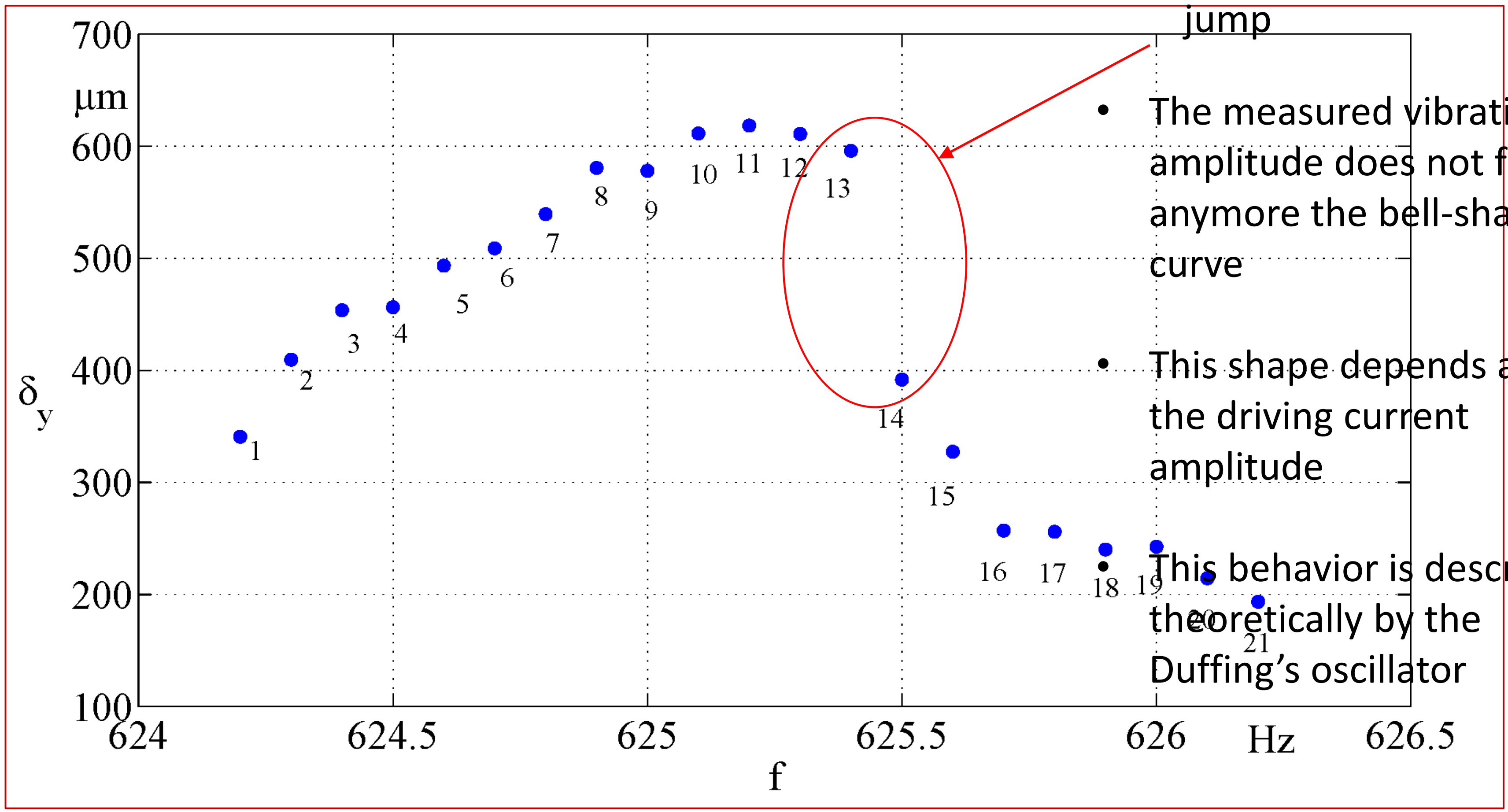


Measured vibration amplitudes at different vibration modes as a function of the driving current

- The deviation from linearity is more pronounced with increasing tension
- Beating more evident in the higher modes

Linearity loss (2/2)

Measurement at high frequencies – 5th vibration mode



jump

- The measured vibration amplitude does not follow anymore the bell-shaped curve
- This shape depends also on the driving current amplitude
- This behavior is described theoretically by the Duffing's oscillator