1st PACMAN Workshop

Measuring the magnetic axis of quadrupoles by a stretched wire

Domenico Caiazza

4.2.2015

Outline

- My role in PACMAN
- Magnetic measurements and measurement problem
- Classical stretched-wire method
- Vibrating-wire method
- Preliminary results and comparison
- Criticalities about the vibrating wire system
- Conclusions

European Commission

PACMAN

CERN

WP1 Metrology & Alignment
H. Mainaud Durand

WP2 Magnetic Measurements
S. Russenschuck

WP3 Precision mech. & stabilization
M. Modena

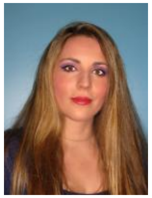
WP4 Beam Instrumentation
M. Wendt


Claude


Solomon


Vasileios


Domenico


Giordana


Iordan


Peter


David


Silvia


Natalia

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

Università degli Studi del Sannio

SIGMAPHI
MAGNETS AND BEAM TRANSPORT

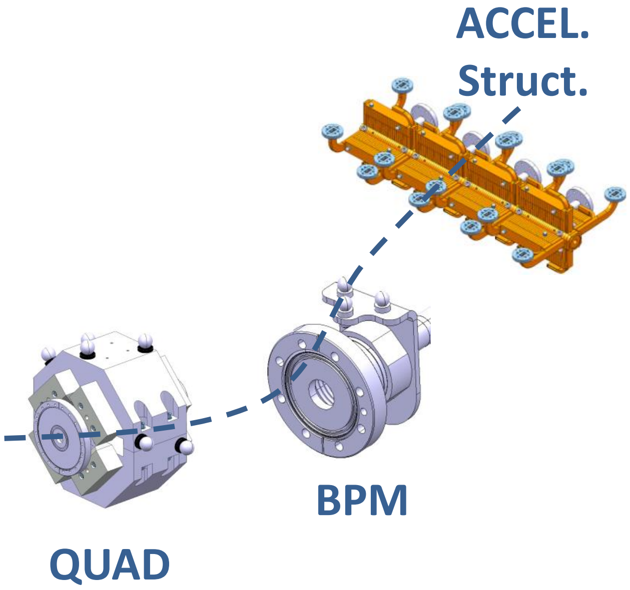
METROLAB
Magnetic precision has a name

CLIC - Compact Linear Collider

A two beams, 50 km, e+/e- collider

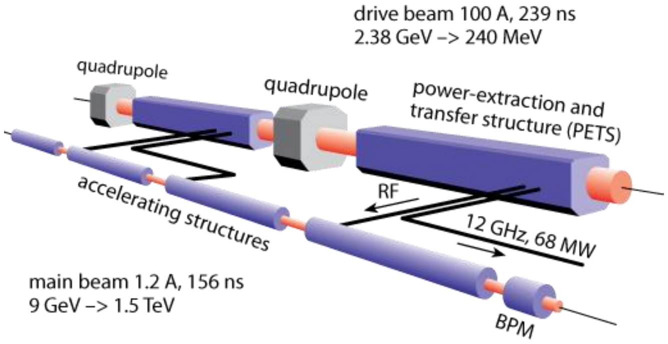
Metrological challenges imposed by CLIC

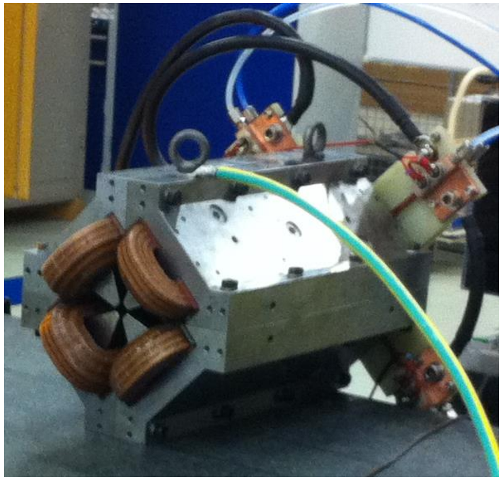
- Small beam size and impact section
  - submicron range
- High-precision in focusing the beam
  - 500 nm horizontal and 5 nm vertical normalized beam emittance
- Tight specifications on components' alignment
  - 14-17 μm error budget over 200 m

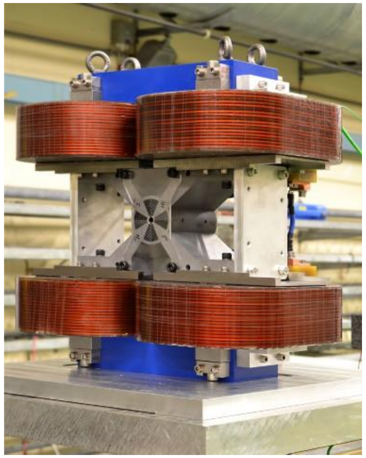


Magnetic measurements

4000 quadrupoles in the main linac



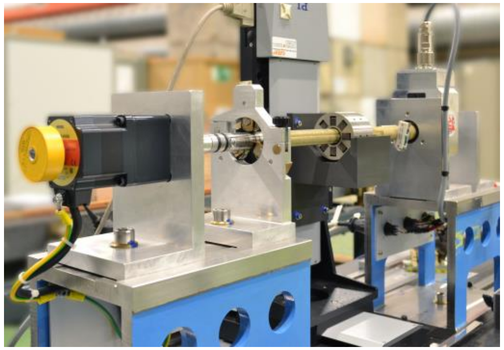

Main beam quad


Final focus quad

Magnetic measurements for PACMAN

Magnetic Measurements Section


Stretched wires

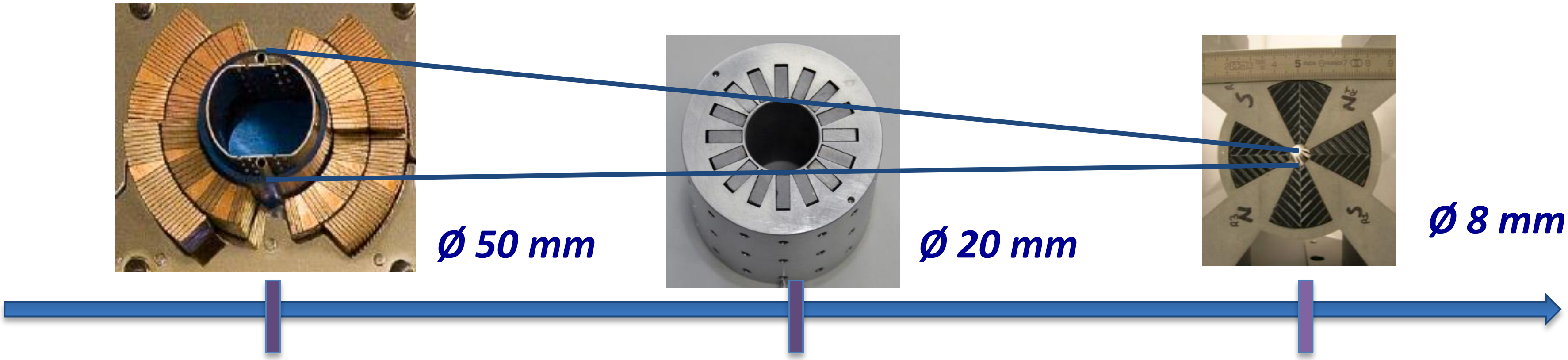

Rotating coils

Measurement problem

Existing large accelerators (Large Hadron Collider)

Upgrade of LHC (Linear Accelerator 4)

Future accelerators (Compact Linear Collider)



Ø 50 mm

Ø 20 mm

Ø 8 mm

2008

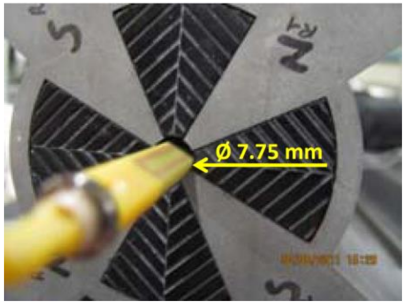
2.5 x

2015

2.5 x

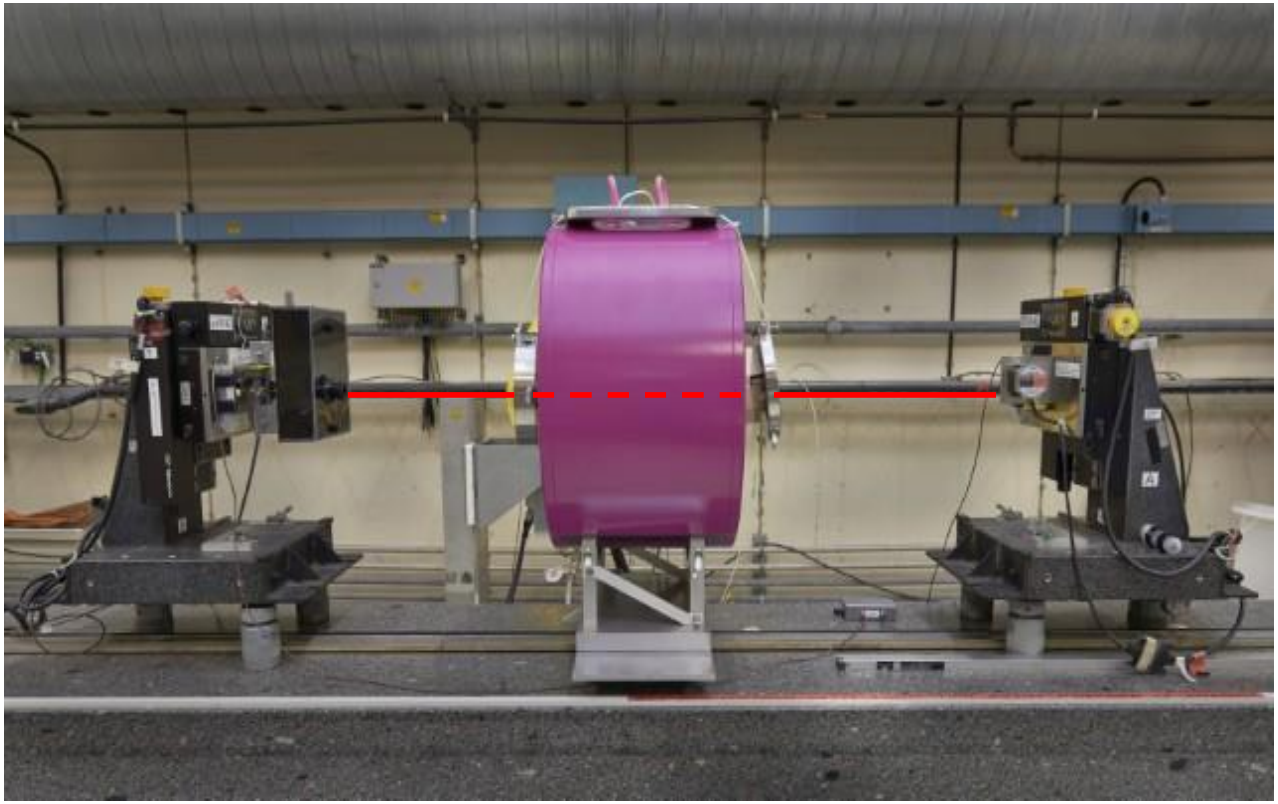
2020

- Limited access for Hall probe
- The smaller the radius coils, the higher the uncertainty



Wire-based transducers

A single stretched wire

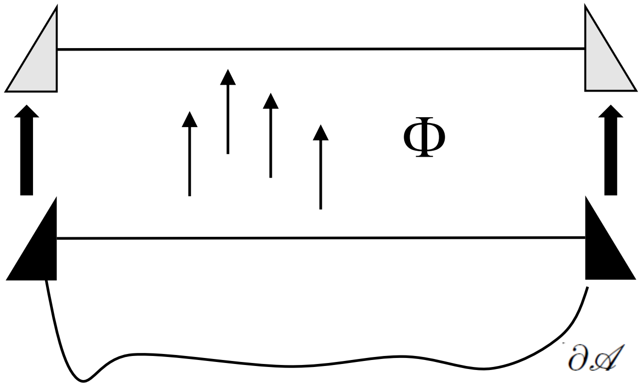


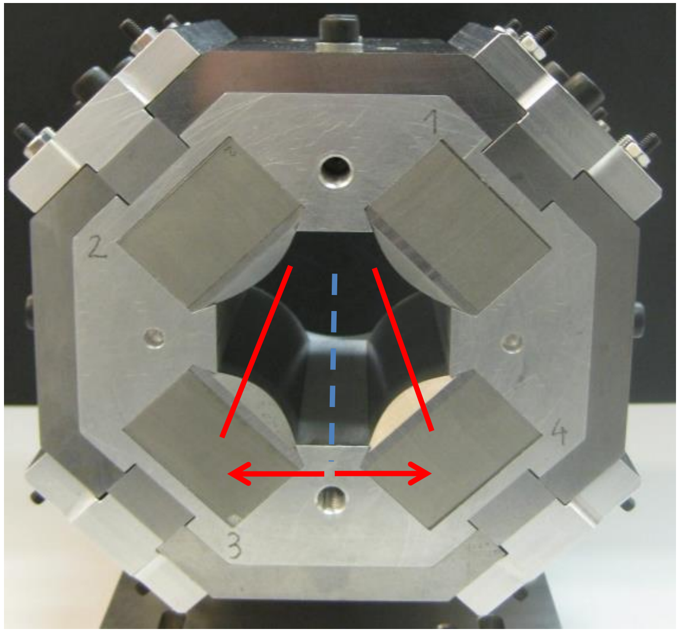
Magnetic measurements
- ✓ field strength and direction
- ✓ field harmonics
- ✓ magnetic axis
- ✓ longitudinal field profile

Solution 1: Stretched-wire method

- <u>Metrological reference</u> for integrated field strength, direction and magnetic axis of LHC magnets
- Magnetic flux measurement

$$\int_{\partial\mathscr{A}} \mathbf{E}\cdot \mathrm{d}\mathbf{r} = -\frac{\mathrm{d}}{\mathrm{d}t}\int_{\mathscr{A}} \mathbf{B}\cdot \mathrm{d}\mathbf{a}$$





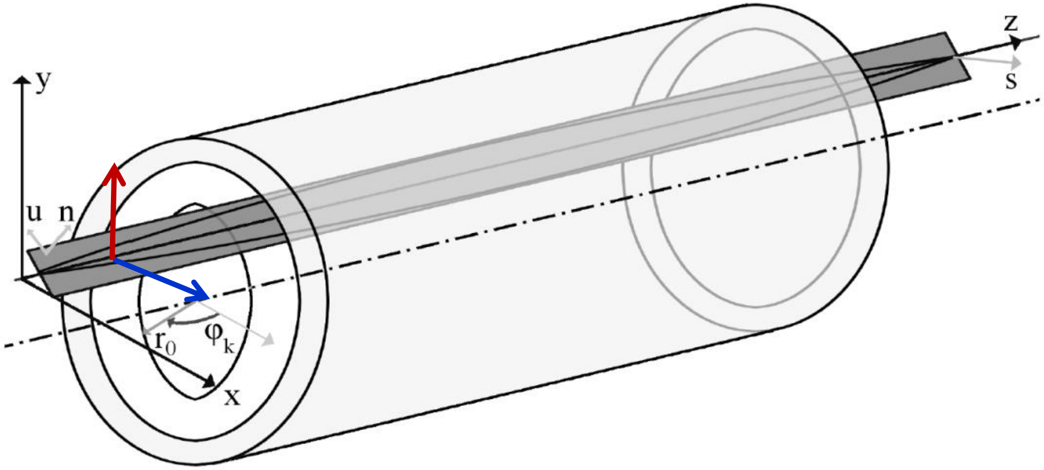
$$x_0 = -\frac{R}{2}\,\frac{\Phi_x(+R) - \Phi_x(-R)}{\Phi_x(+R) + \Phi_x(-R)}$$

$$y_0 = -\frac{R}{2}\,\frac{\Phi_y(+R) - \Phi_y(-R)}{\Phi_y(+R) + \Phi_y(-R)}$$

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

Solution 2: Vibrating-wire method

Plucked string



Wire in magnetic field

Feeding the wire by alternating current (Lorentz Force)

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

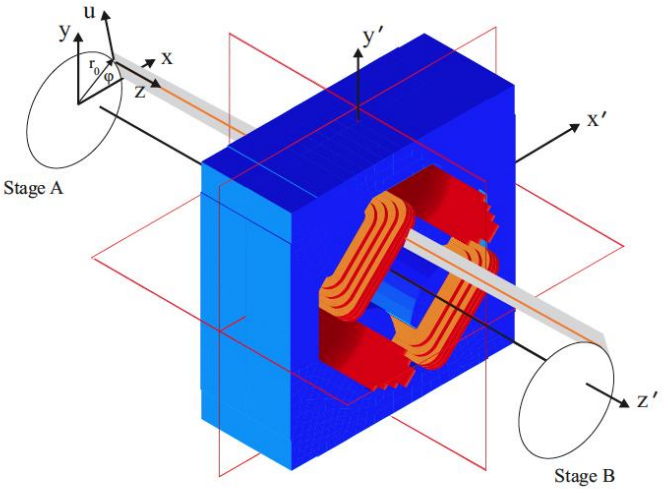
Measure wire motion amplitude X and Y components

Relate motion to magnetic field properties

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

Mathematical model

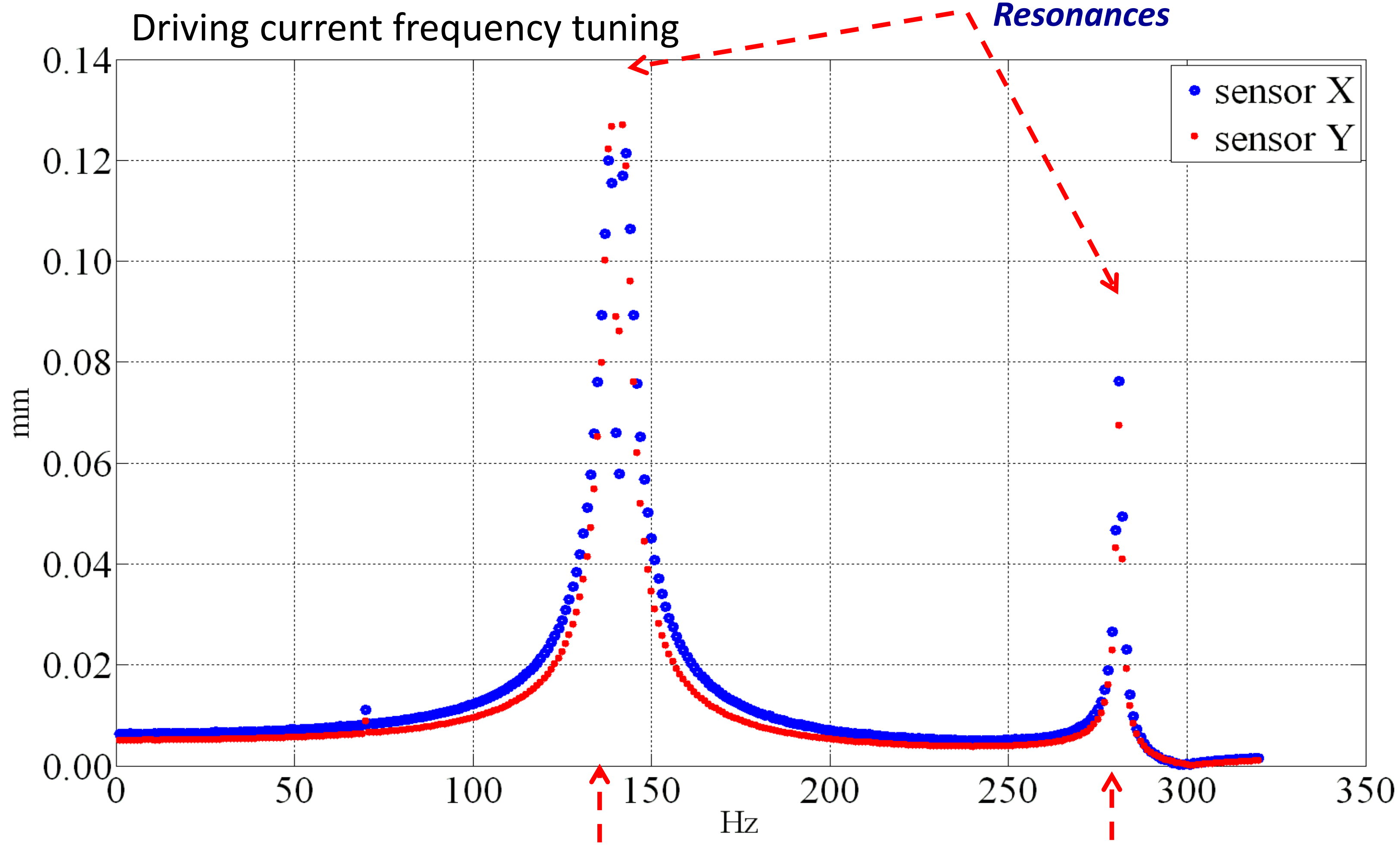
- Linearity
- Plane motion
- Uniform and constant tension
- Small deflections
- Constant length
- Uniform mass distribution



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

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

Measurement system design



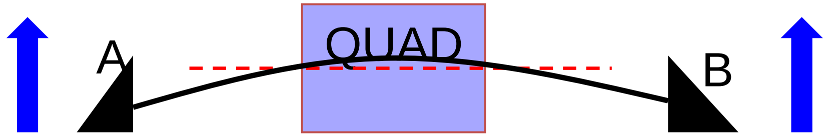
Driving current frequency tuning

Resonances

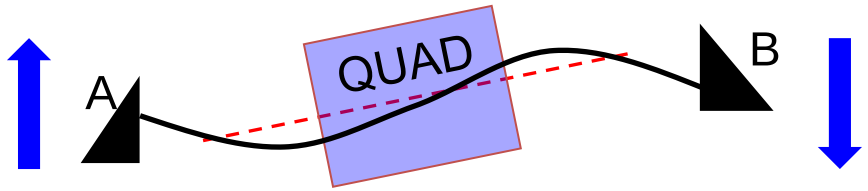
Working frequencies for max sensitivity

Vibrating-wire axis measurement

1) Center finding (horizontal and vertical)
   - ➢ First resonance
   - ➢ Co-directional scanning



2) Tilt finding (pitch and yaw)
   - ➢ Second resonance
   - ➢ Counter-directional scanning



A zero-finding problem

$$\mathbf{X}:\left(d_x(\mathbf{X}),d_y(\mathbf{X})\right)=0$$

$$\mathbf{X}:=\left(x_A,y_A,x_B,x_B\right)$$

Vibration amplitude

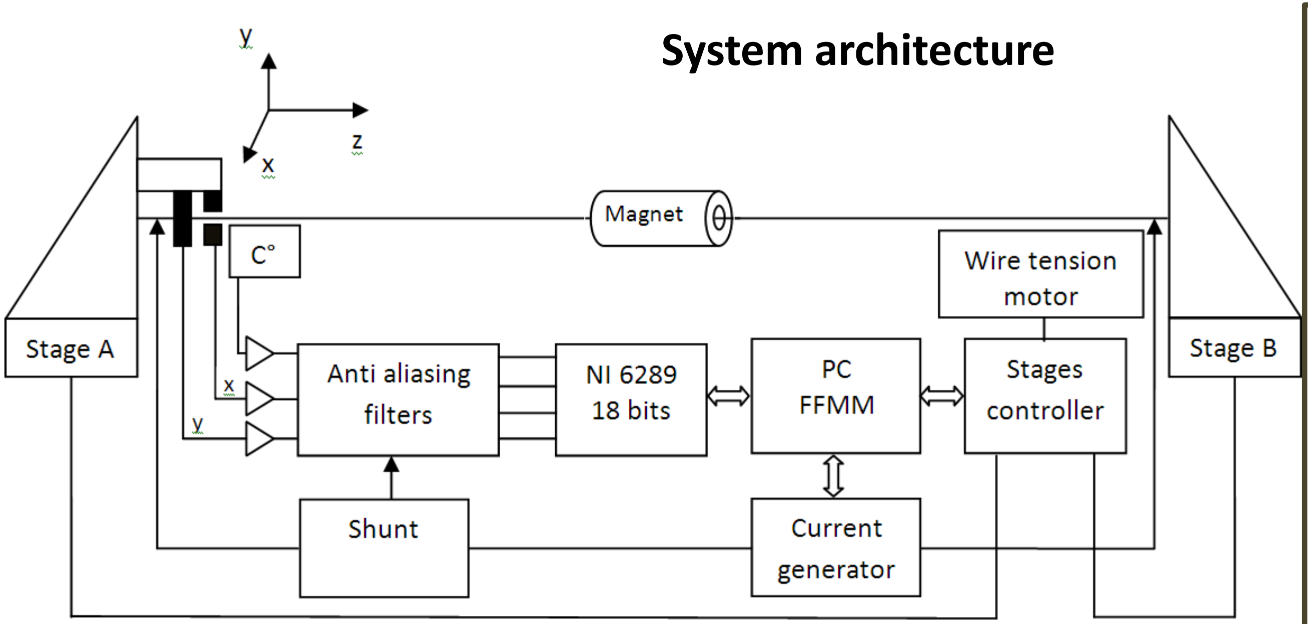
$$d_x(\mathbf{X})=\delta_x(\mathbf{X})\,\mathrm{sign}\left(\sigma_x(\mathbf{X})-\frac{\pi}{2}\right)$$

$$d_y(\mathbf{X})=\delta_y(\mathbf{X})\,\mathrm{sign}\left(\sigma_y(\mathbf{X})-\frac{\pi}{2}\right)$$

- ○ **P. Arpaia, C. Petrone, S. Russenschuck, L. Walckiers,** “Vibrating-wire measurement method for centering and alignment of solenoids”, *IOP Journal of Instrumentation,* Vol. 8, Nov., **2013.**
- ○ **Z. Wolf**. “A Vibrating Wire System For Quadrupole Fiducialization ”, Tech. rep. LCLS-TN-05-1. SLAC National Accelerator Laboratory, Menlo Park, California, USA**, 2005.**

Experimental setup

System architecture

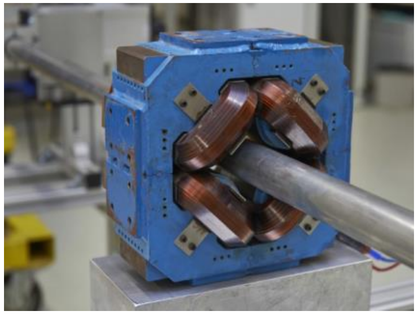


- ***Sensors:*** *phototransistor Sharp™ GP1S094HCZ0F*
- ***Current generator:*** *Keithley® 6351*
- ***Common marble*** *support for magnets and stages*

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", IOP *JINST - Journal of Instrumentation,* **2012.**

- Configuration

Wire alloy	-	Cu-Be
Wire mass density	ρ	$1.1 \cdot 10^{-4}$ Kg·m^{-1}
Wire length	L	1870 mm



Reference magnet

LHC-LI-QS

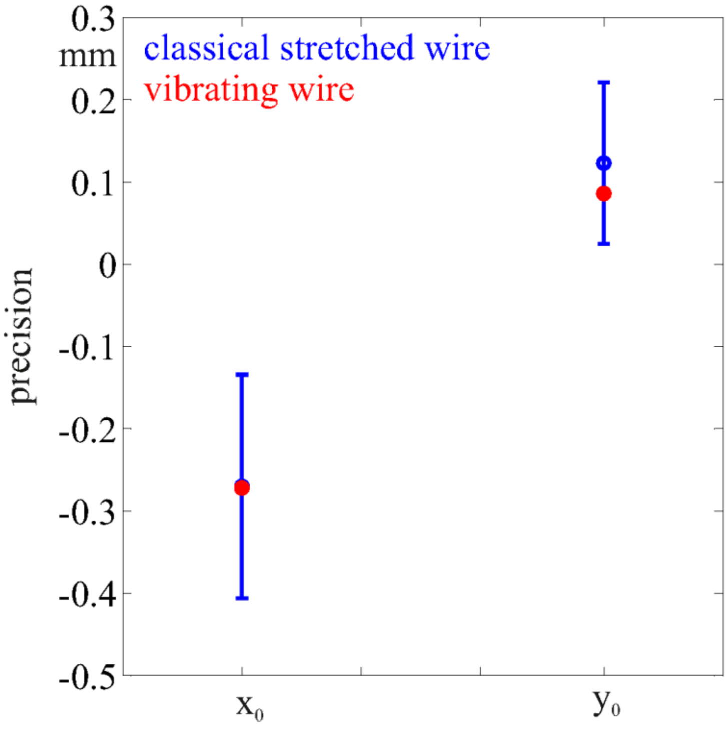
Comparison stretched-vibrating: Preliminary results

Method 1: classical stretched wire center

x_0 [mm]	σ_x [mm]	y_0 [mm]	σ_y [mm]
-0.270	0.136	0.123	0.098

Method 2: vibrating wire center

x_0 [mm]	σ_x [mm]	y_0 [mm]	σ_y [mm]
-0.272	0.003	0.086	0.004

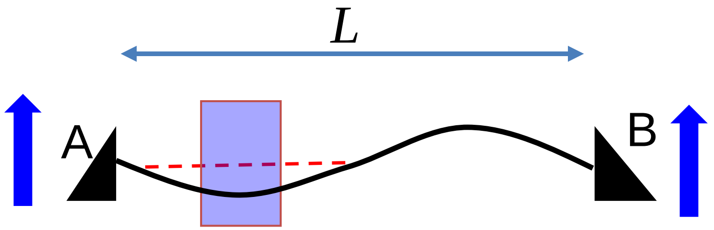


- Precision
  - Compatibility
  - 30 times better for the vibrating wire (3-4 μm)
- Sensitivity
  - Vibrating wire is suitable at low integral gradient (< 0.2 T)
- Background fields
  - Stretched wire not sensitive
  - Compensation needed for vibrating wire

Background field compensation (1/2)

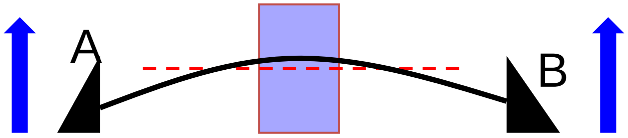
- Solution 1: displace the quadrupole at *L*/4

$$\frac{2}{L}\int_0^L B_E \sin\left(\frac{2\pi}{L}z\right)\mathrm{dz} = 0$$



Z. Wolf. “A Vibrating Wire System For Quadrupole Fiducialization ”, Tech. rep. LCLS-TN-05-1. SLAC National Accelerator Laboratory, Menlo Park, California, USA, **2005**

- Solution 2: measure at different gradients



δ_Q : oscillation from quad field

δ_E : oscillation from external dipole

$$\delta(x) = \delta_Q(x) + \delta_E$$
$$= k(I_0)\cdot G(x - x_0) + \delta_E$$

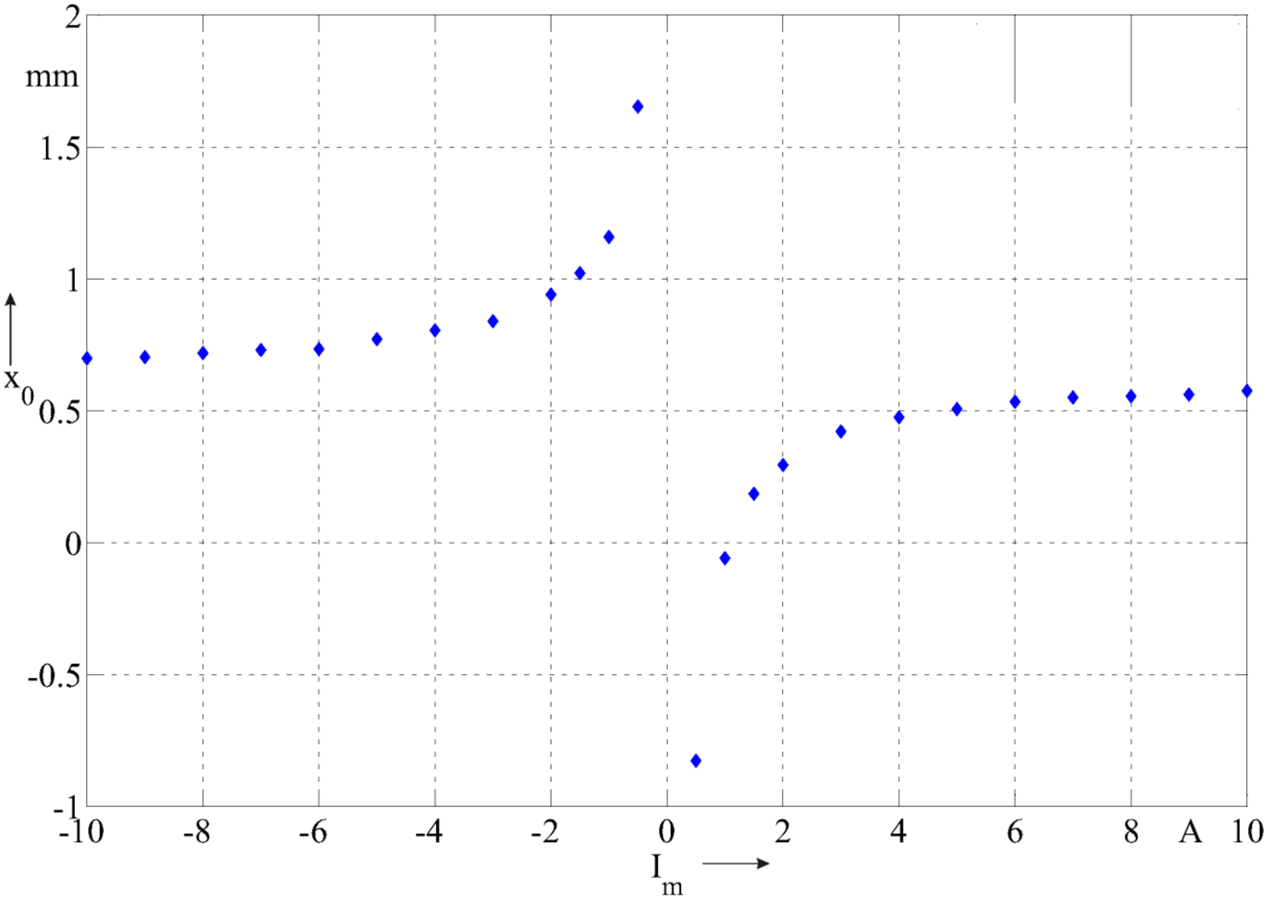
$\Rightarrow$

$$x_0^{'} : \delta(x_0^{'}) = 0$$
$$x_0^{'} = x_0 - \frac{\delta_E}{k \cdot G}$$

Works if there is not a constant dipole in the magnet (not depending on I_m)

Background field compensation (2/2)

Magnetic center as a function of the magnet gradient



Hyperbolic model

$$x'_0 = \boxed{x_0} - \frac{\boxed{\delta_0}}{k \cdot I_m}$$

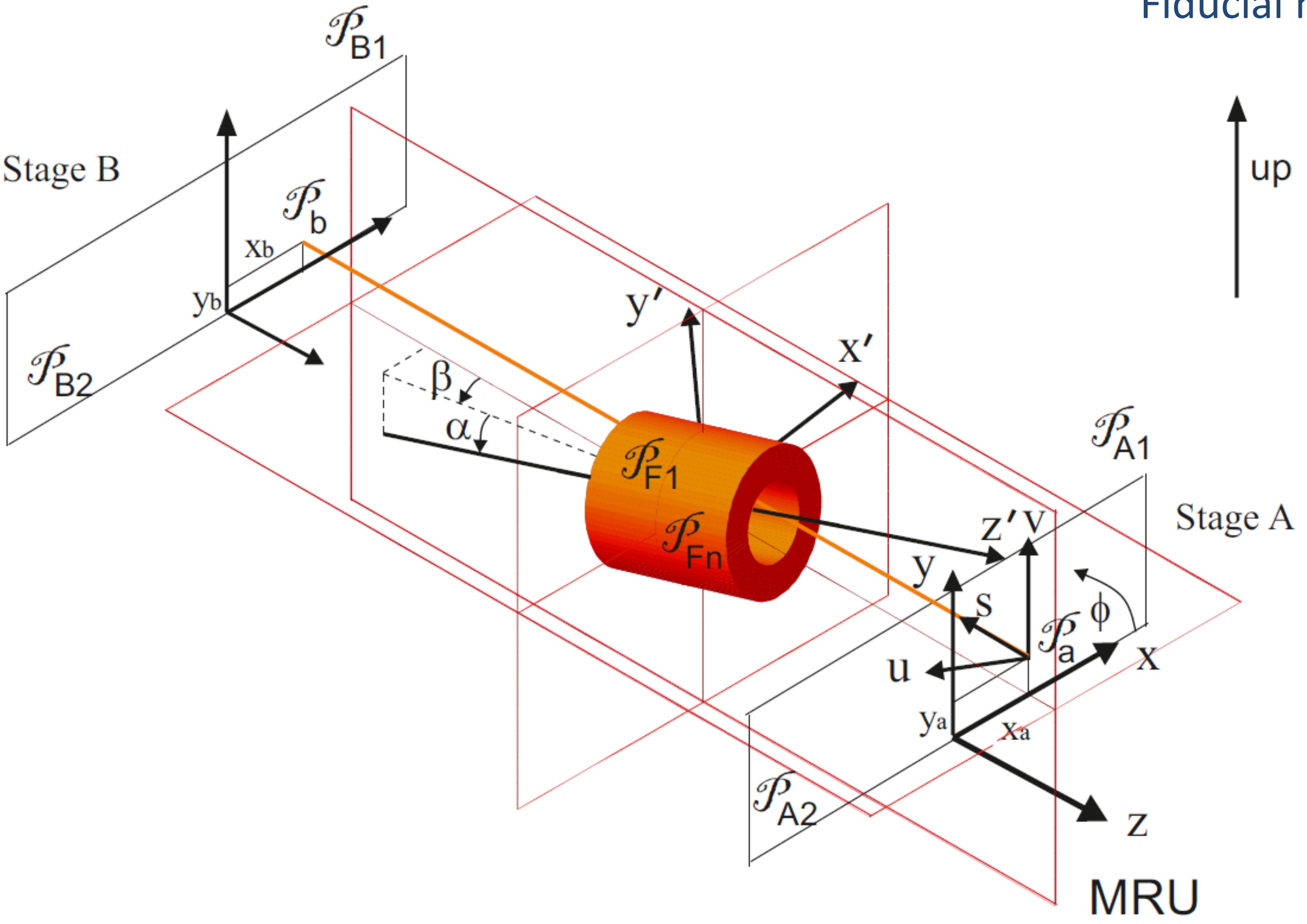
Actual center

Background field effect

- ✓ Fit to the hyperbolic model

Reference frame

Fiducial marker localization

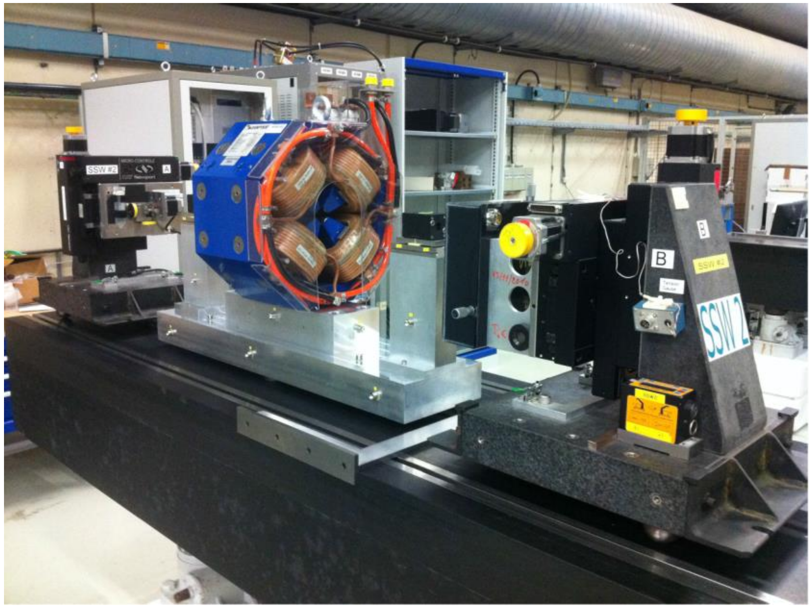


$$d(\mathcal{P}_a, \mathcal{P}_b)?$$

$$d(\mathcal{P}_{A1}, \mathcal{P}_{A2})?$$

$$d(\mathcal{P}_a, \mathcal{P}_{Fn})?$$

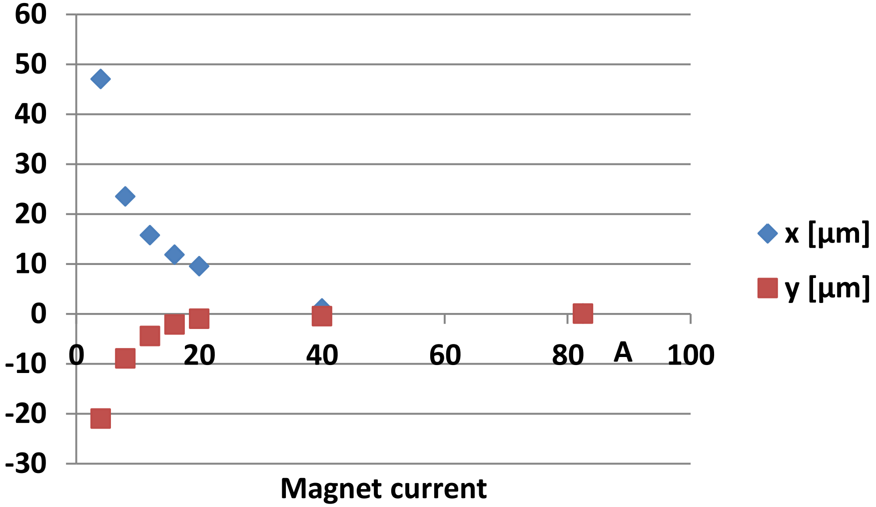
DBQ axis measurement



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

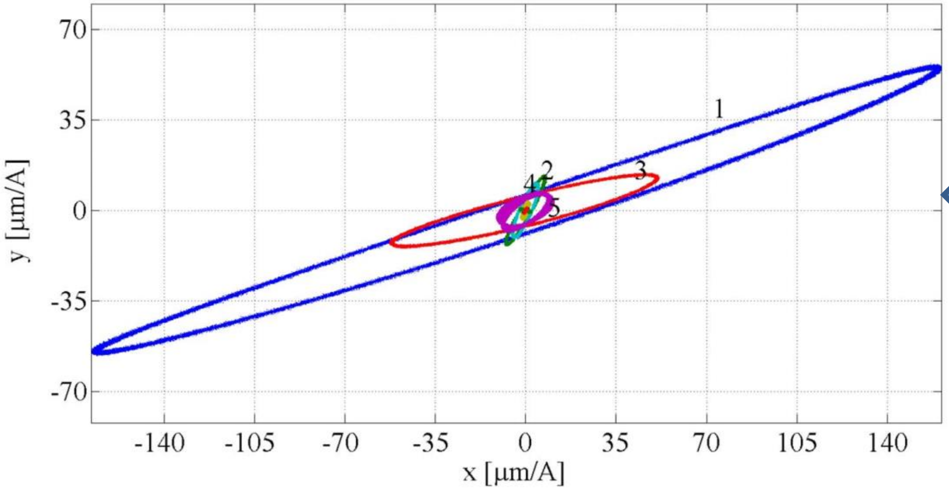
- ✓ Magnetic axis measurement + fiducial markers localization
  - In collaboration with EN-MEF-SU (Large Scale Metrology Section)
- ✓ Both center and tilt were measured by the vibrating wire
- ✓ Axis determination with ±3 µm horizontal and ±4 µm vertical precision

Magnetic center as a function of the magnet current

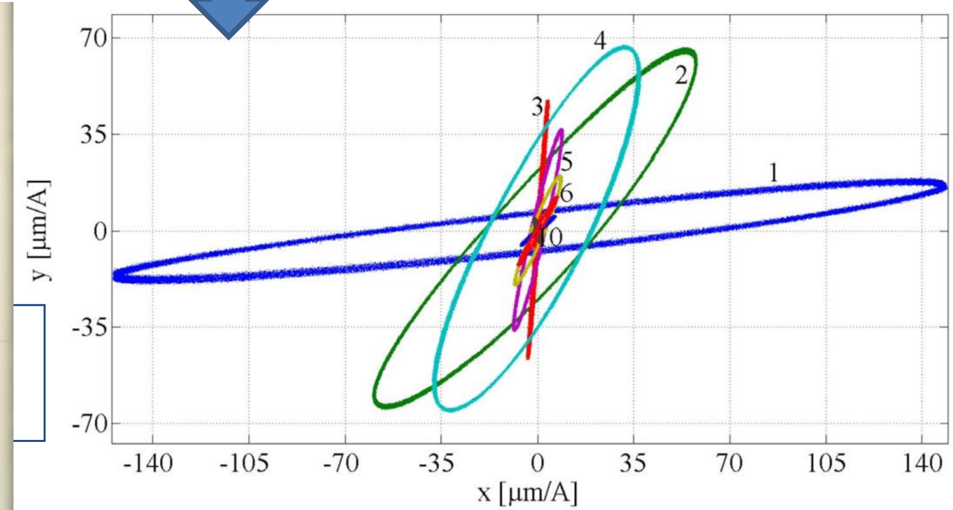


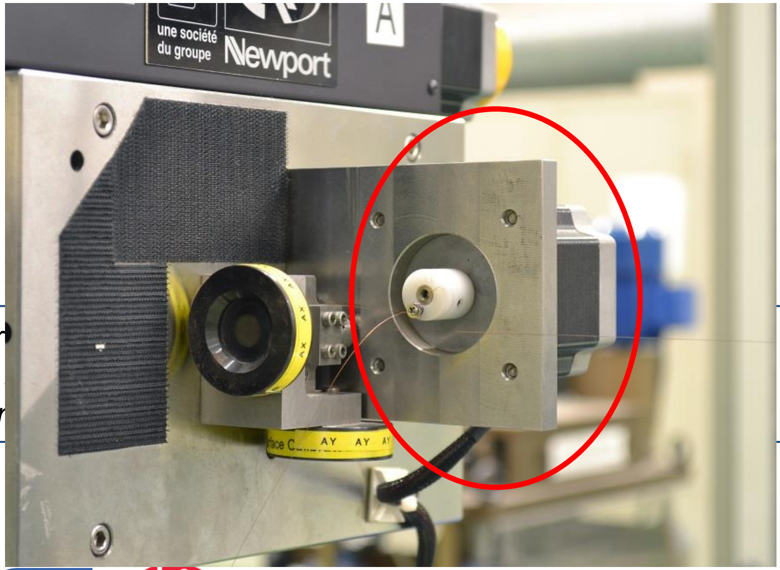
M. Duquenne et al., “Determination of the magnetic axis of a CLIC drive beam quadrupole with respect to external alignment targets using a combination of wps, cmm and laser tracker measurements”. Proceedings of I**PAC2014**, Dresden, 2014.

Background fields & Plane motion



- No magnet on the measurement station
- Background fields
  - 2% alteration of first harmonic
- Fringe field from equipment (tensioning system)
  - High-order modes amplified





Pr
J.
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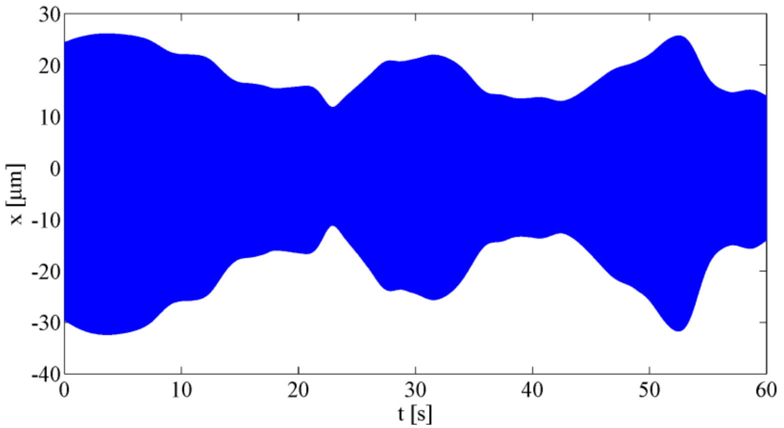
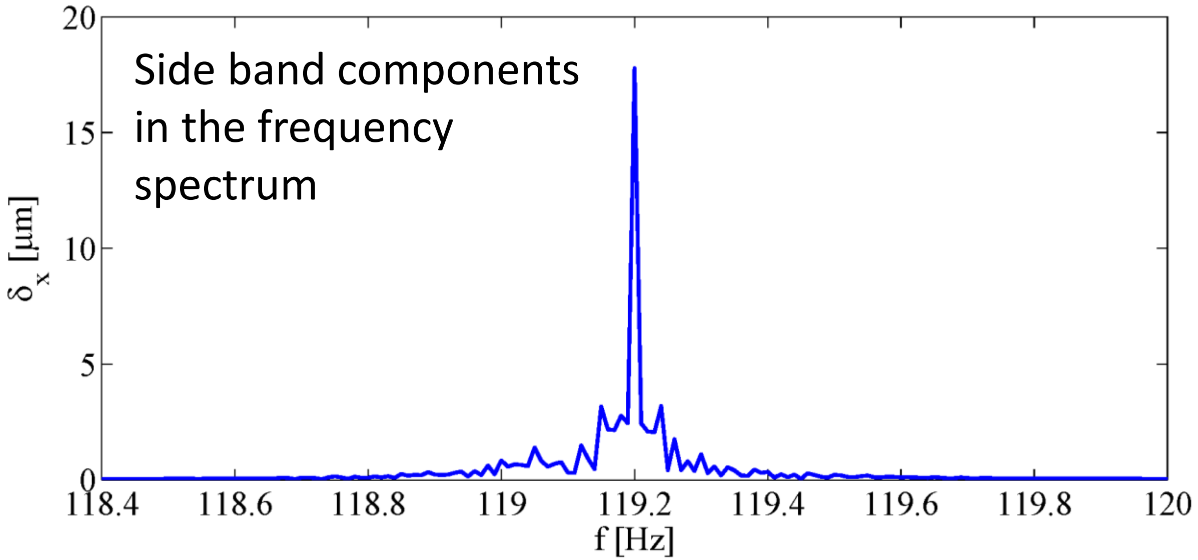
Steady-state modulation

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





Side band components in the frequency spectrum

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

Conclusions

- Two methods for magnetic axis measurement

- Preliminary test on a reference quadrupole
  - Comparison of precision and sensitivity
  - Influence of background field

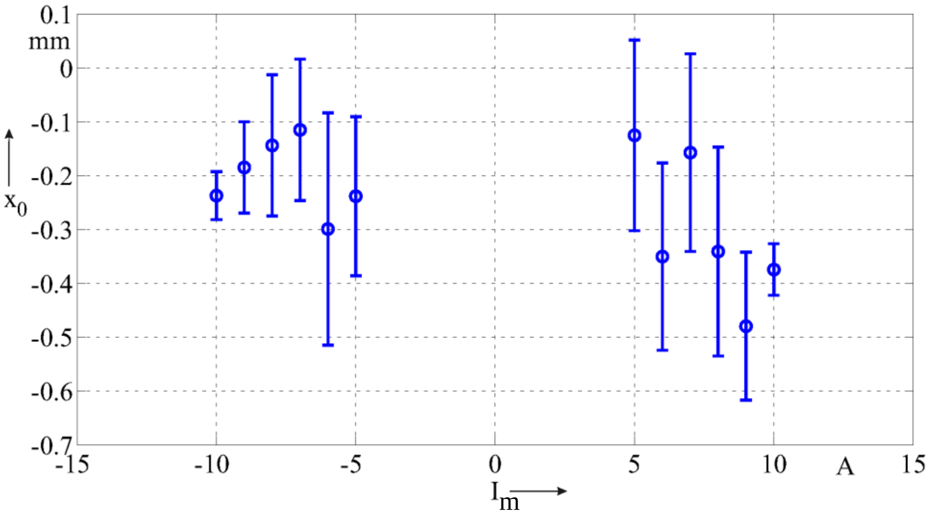
- **Outlook**
  - Uncertainty analysis of the vibrating-wire system
  - Design and commissioning of the PACMAN system
  - Measurement on the CLIC MBQ magnet
  - Comparison with PCB rotating coil

Thank you for your attention

Measuring the magnetic axis of quadrupoles by a stretched wire

SPARES

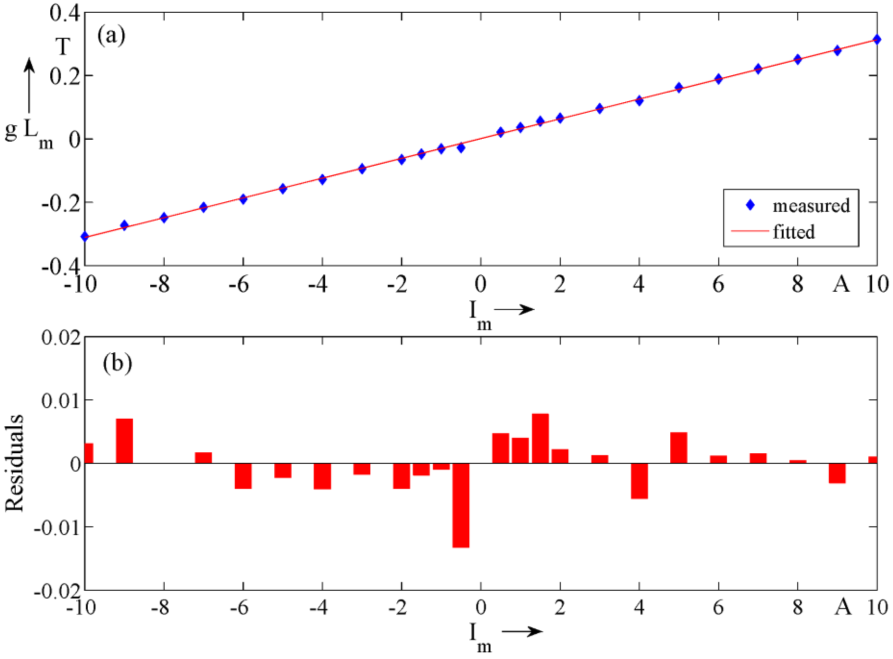
Method 1: preliminary results



Horizontal offset with respect to the magnetic center

±300 µm uncertainty for low-gradient (< 0.2 T/m·m)

Measured gradient as a function of magnet current



Average horizontal and vertical center offset

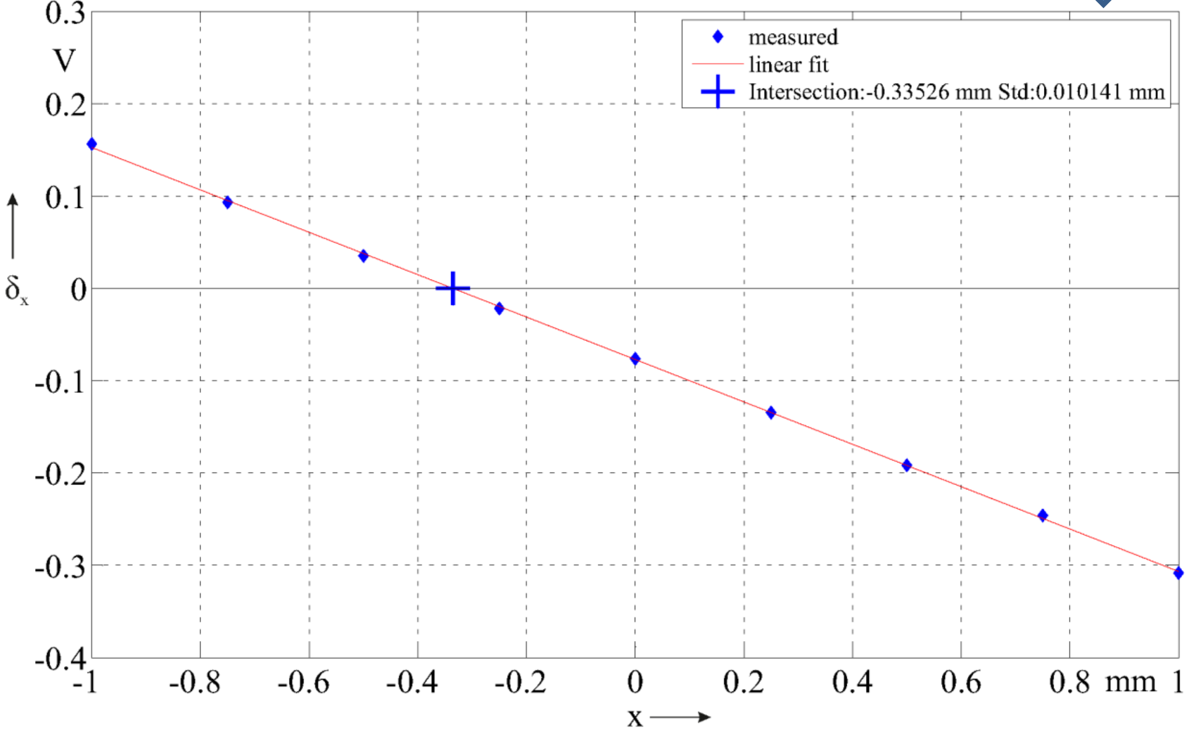
x_0 [mm]	St. Dev. [mm]	y_0 [mm]	St. Dev. [mm]
-0.270	0.136	0.123	0.098

Method 2: preliminary results

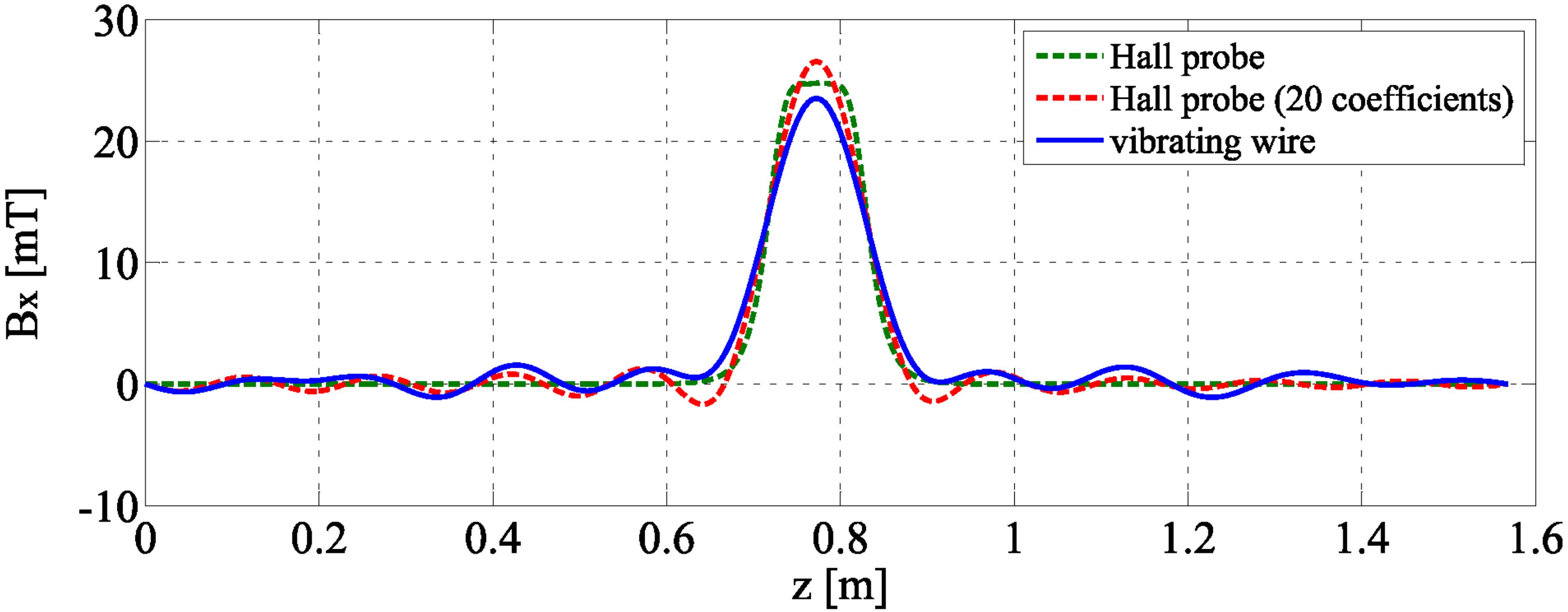
Average horizontal and vertical center offset

x_0 [mm]	St. Dev. [mm]	y_0 [mm]	St. Dev. [µm]
-0.272	0.003	0.086	0.004

Linear regression of wire oscillation amplitude

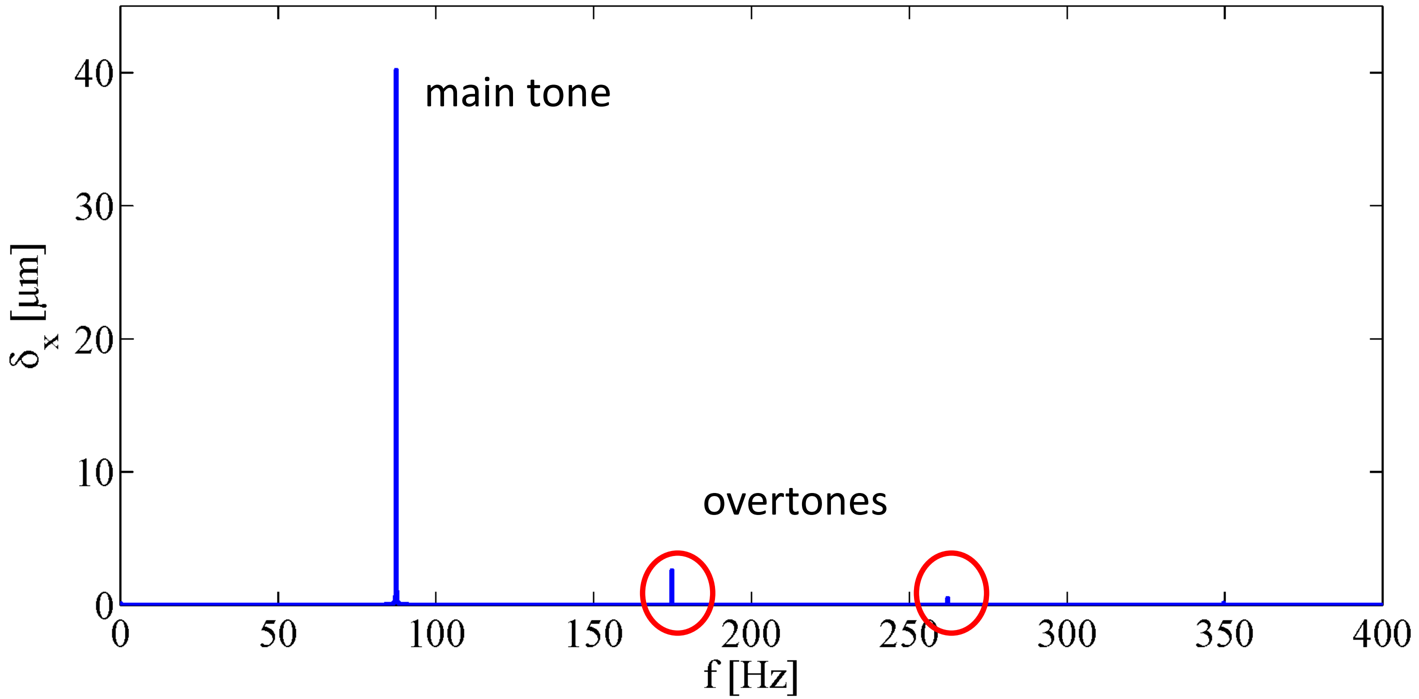


Results



- Reconstruction error 3% of the field peak
- Repeatability 2%
    - RMS difference
- Bandwidth limitation
- Uncertainty sources

Overtones



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

→ Nonlinearity!

Optical sensor characterization

- Sharp® phototransistors (currently employed)
  - Linear domain 40 µm
  - Low price
  - High sensitivity

- Keyence ® CCD sensors
  - Wide linear domain (6 mm)
  - Worse SNR

- Total Harmonic Distortion
  - No harmonic distortion by Sharp®

Overtones are not artifacts from nonlinear sensor response