Coils & wires to Measure Magnets

Cern Accelerator School on Magnets

Brugge

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L. Walckiers - Cern

Outline

- **Measure $B_y(x)$ with coils**
  - **Flip coils for strength**
  - **Coils displaced along horizontal plane**
  - **Static coils in pulsed fields**
  - **example : system to measure CNAO dipoles**
- **B Train generation in PS reference magnet**
- **Single Stretched Wire [SSW]**
  - **Dipole strength & field direction**
  - **Quadrupole axis**
  - **Quadrupole strength : sag & wire magnetisation**
  - **Vibrating wire for axis search**

Flip coils to measure magnet strength

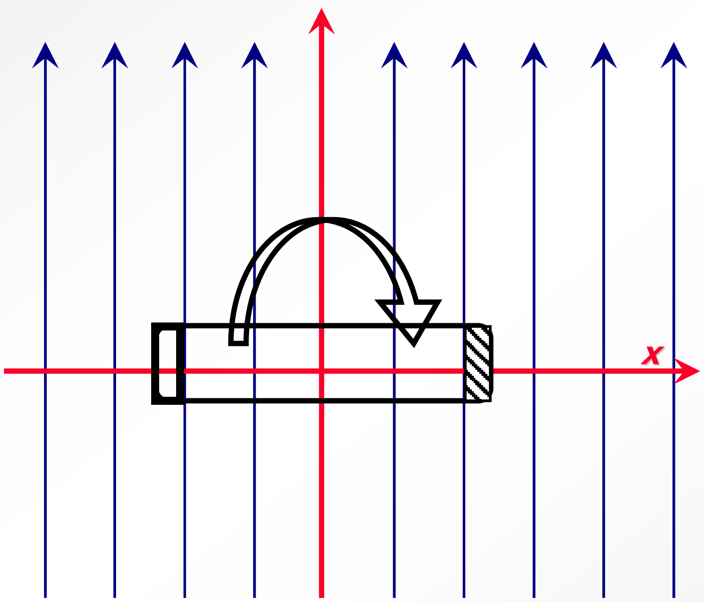
- Advantage : measure the whole particle trajectory in one signal. Particles (most often) see integrated fields
- Most important

  Dipole : ∫Bdl(I) or Transfer Function = ∫Bdl / I [T·m/kA]

  Quadr : ∫Gdl(I) or Transfer Function = ∫Gdl / I [T/kA]

$$\Psi(\pi) - \Psi(0) = 2 \cdot \int_0^L B_y(x) \cdot dl$$

Integrators measure Flux differences



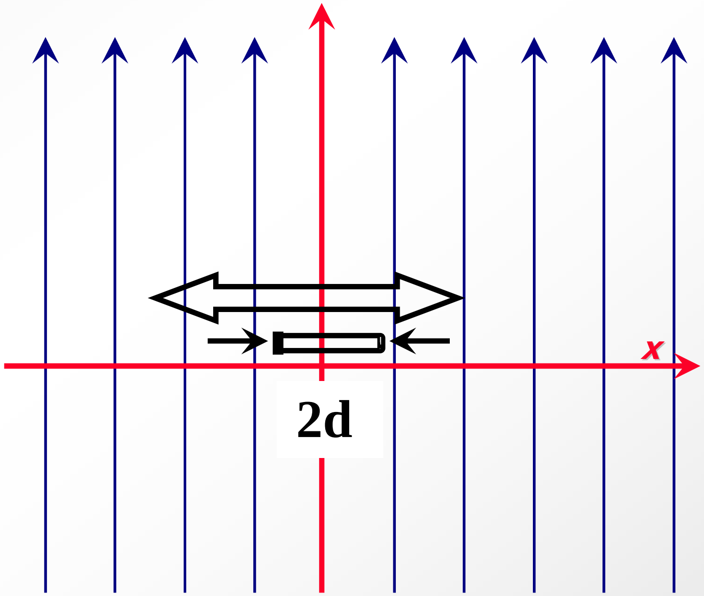
Coil must be longer than the magnet

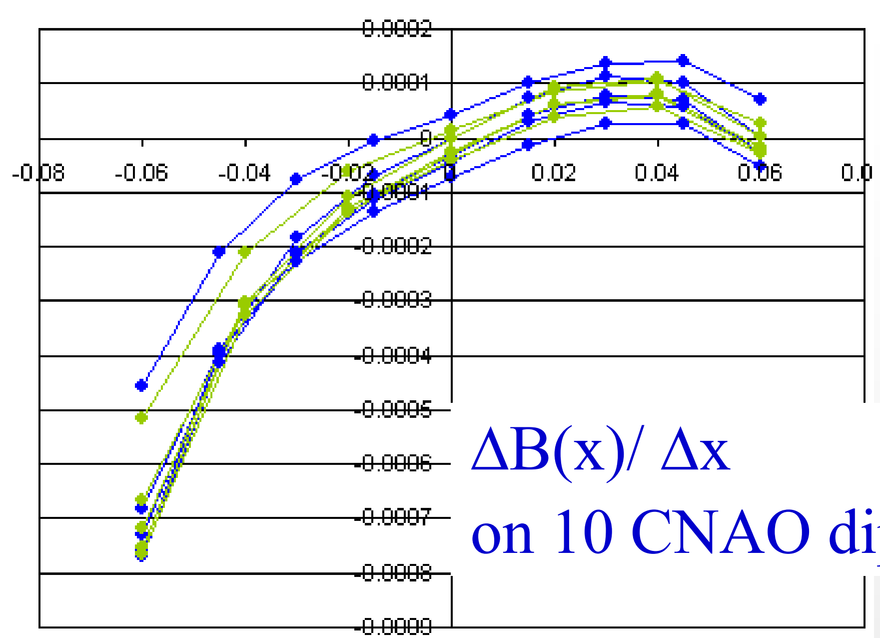
- Rule of thumb : should extend outside by 2.5 * aperture
- perform B(z) scanning with Hall plate
- full 3D calculation

Measure Field Quality by lateral displacement

Coil with
- 1 turn (or very small winding section)
- small width 2d << ΔB(x)/ Δx
- (2D case i.e. per unit length)

$$\frac{\Delta B_y(x)}{\Delta x} = \frac{\Psi(x+\delta) - \Psi(x)}{2d}$$





ΔB(x)/ Δx
on 10 CNAO dipoles

Limitation for this simple coil :
no sensitivity

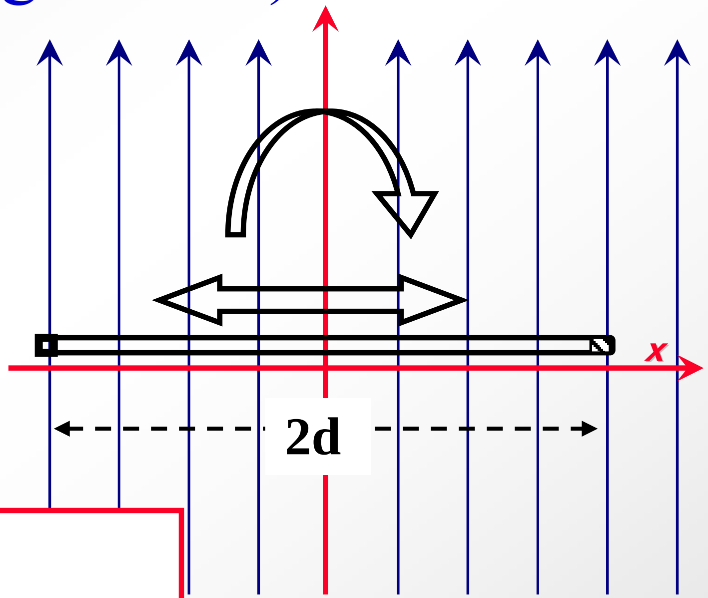
The coil picks-up a large surface

Coil with 1 turn (or very small winding section)

$$B_y(x) = B_1 + B_2 \cdot x + B_3 \cdot x^2 + ...$$

Coil going from $[x - d]$ to $[x + d]$

$$\Psi(x) = B_1 \cdot 2d + B_2 \cdot 2dx + B_3 \cdot (6x^2 d + 2d^3)$$



The sextupole enters for flip of half turn

$$\Psi(\pi, x=0) - \Psi(0, x=0) = 2 \cdot \left(2d \cdot B_1 + 2d^3 \cdot B_3\right)$$

Displacement : harmonics enter with different & varying sensitivity

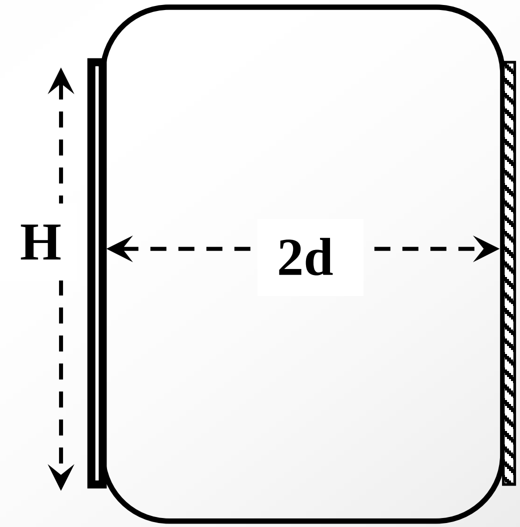
$$\Psi(x+\delta) - \Psi(x) = 2d\delta \cdot B_2 + 6d \cdot (2x\delta + \delta^2) \cdot B_3 + ...$$

What is measured is not B_1 at coil center

Square Coil with more turns

One layer coil with width of coil = height of winding

2d = H



$$B_y(x) = B_1 + B_2 \cdot x + B_3 \cdot x^2 + ...$$

$$\Psi(x) = B_1 \cdot 2d \cdot N_{turns} + 0 \cdot B_2 + 0 \cdot B_3 + ...$$

Unsensitive to perturbations from
both quadrupole and sextupole harmonics
Still sensitive to the average B_1 on the coil.

Why not use the Harmonic method ?

- Dipole magnets are bent : how a bent rotating coil ?

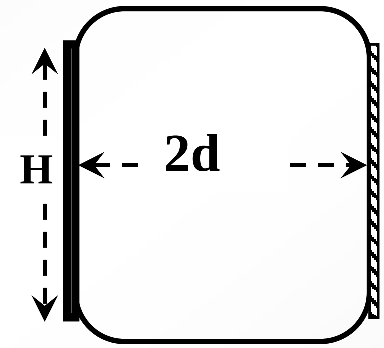
- Dipole for small accelerators have wide apertures compared to gap height

- Harmonic method does not measure (easily) pulsed fields (i.e. when $\Delta B/\Delta t$ cannot be neglected over one coil revolution period)

  The case for most "accelerator magnets" vs. storage ring magnets

Static Coils in Pulsed Fields

$$\Psi(t) = B_1(t) \cdot 2d \cdot N_{turns}$$



$B_1(t)$ depends on

- $K_{tf} \cdot I(t)$
- saturation effect

  measured continously with (recent) integrators

  cf. oversampling in P. Arpaia lecture
- eddy current effects

  measure at different dI/dt
- remanent field (3 ways to compensate)

  have bipolar power supply

  demagnetise first your magnet

  measure at I=0 with Hall plate or flipped coil

CNAO dipoles : curved and pulsed

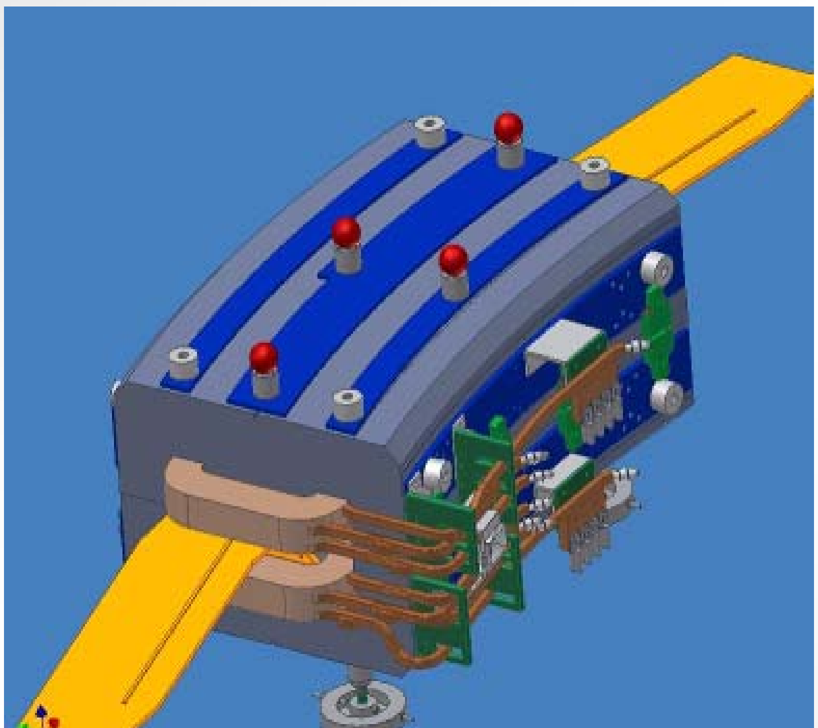
Field Rise time ≈ 2 s

=> no coil movement

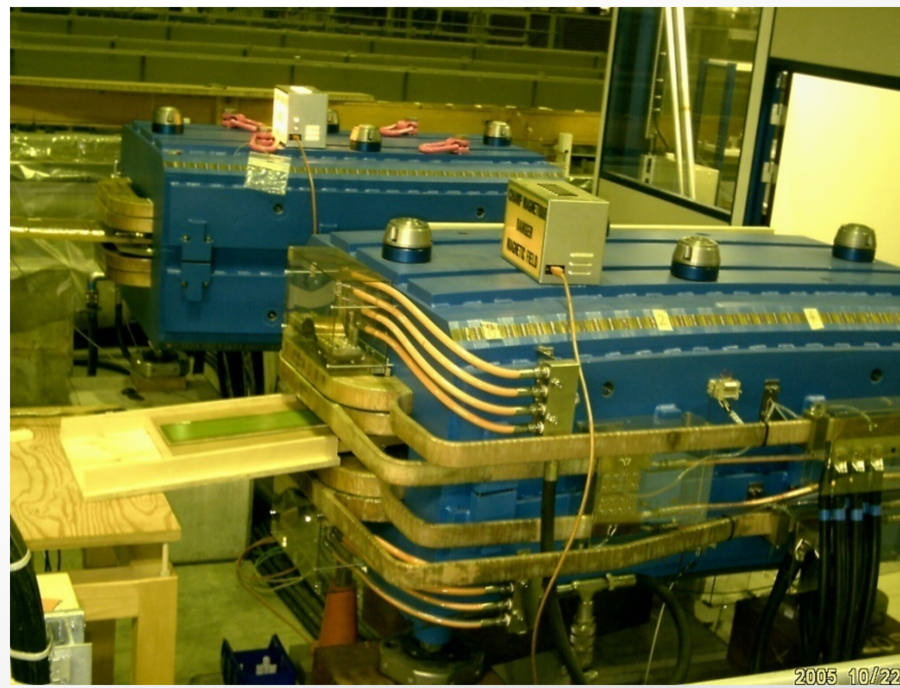
Curved 11-coil fluxmeter

& reference coil for cross calibration

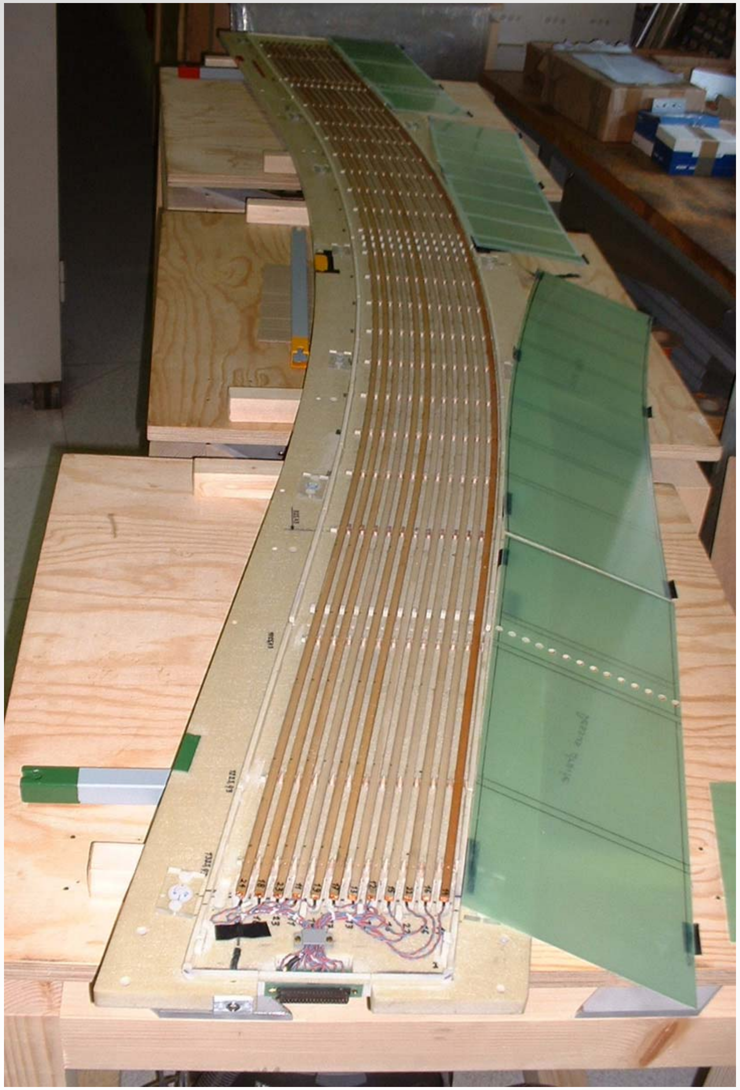
B_{max} = 1.5 T
Gap height = 72 mm
Useful aperture ≈ 130 mm
Bending radius = 4.231 m
Bending angle = 22.5°
Magnetic length ~ 1.67 m

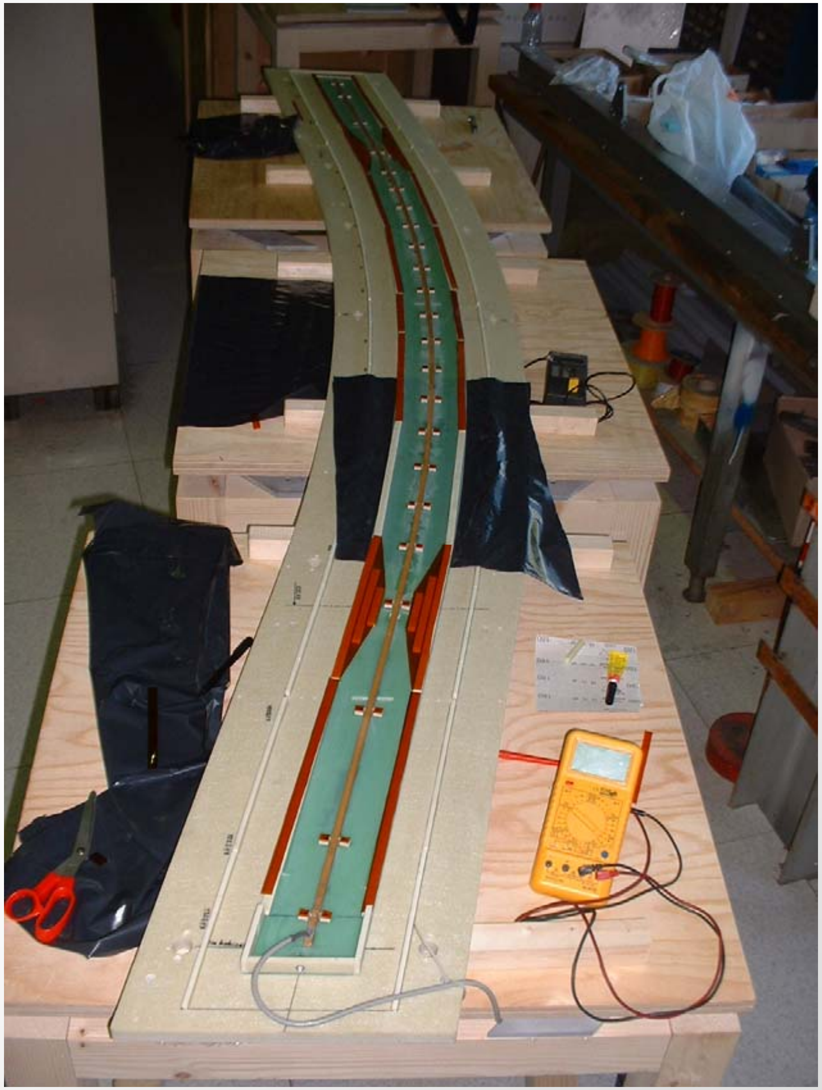


Courtesy of M. Pullia, CNAO



CNAO : 11 coil Fluxmeter

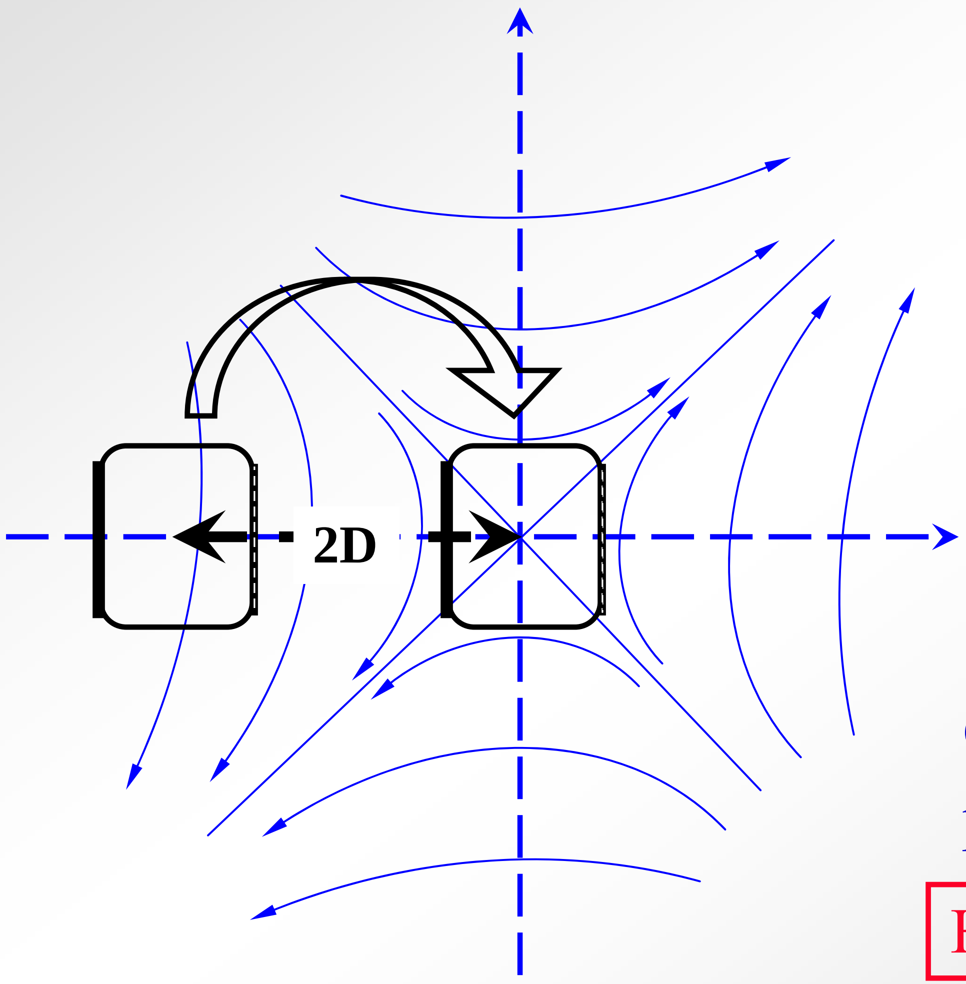




Reference coil to cross calibrate the 11 measuring coils (@ 10^{-4})

Measure quadrupole strength & field quality

For combined function magnets



Each coil unsensitive to local B2 & B3

! but sensitive to B4, B5, ...!

Coils in opposition => unsensitive to dipole

Flip by half turn gives

$B_1(x+D) - B_1(x-D) \approx G(x)$

Can also be done by ¼ turn

Can be applied with pulsed magnets & static coils

Harmonic coils more accurate

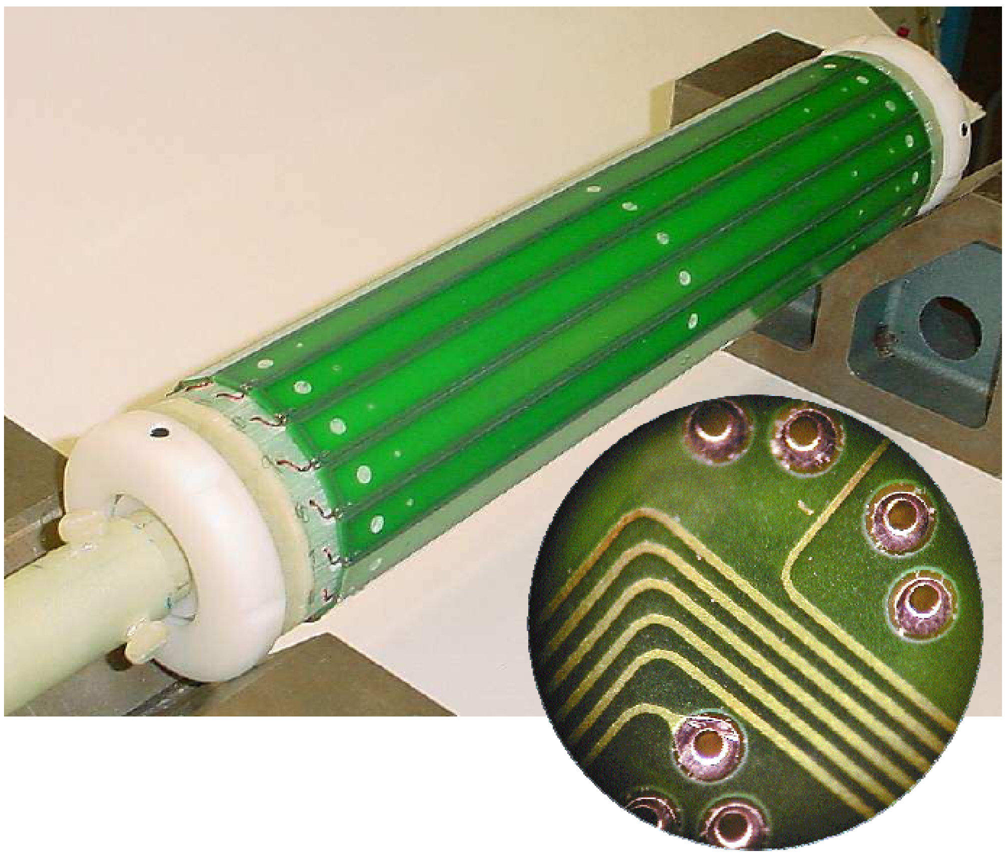
Dedicated static coils for pulsed magnets

Morgan coils (60's) :

coils on cylinder sensitive to harmonic n

[and n·(2m+1)]

BNL Harmonic Coil Array



16 Printed Circuit coils, 10 layers

6 turns/layer

300 mm long

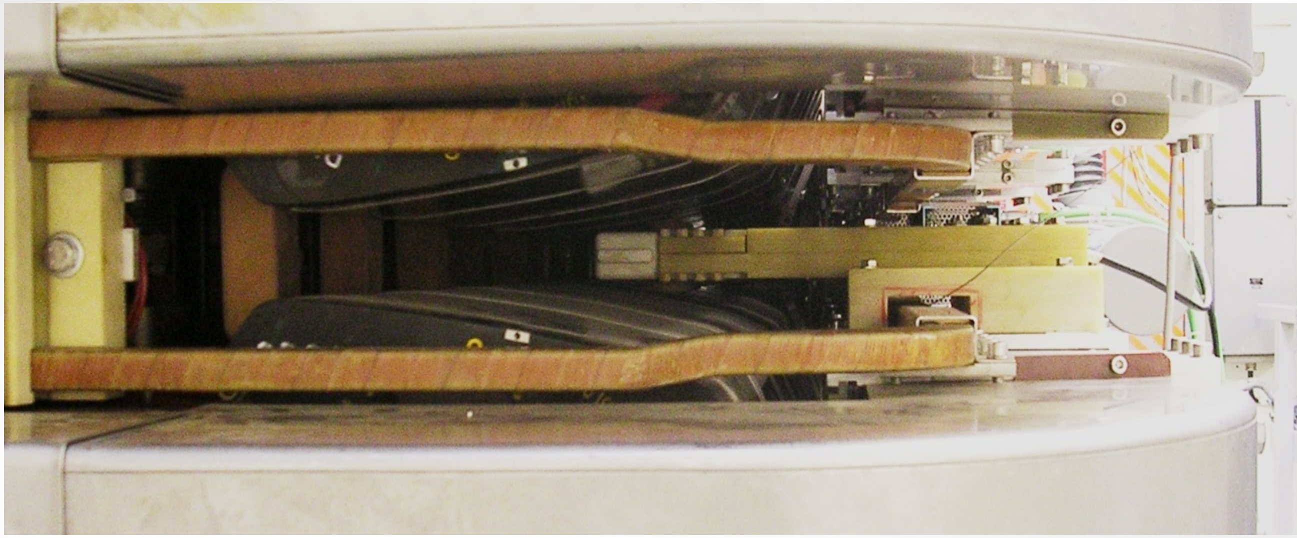
0.1 mm lines with 0.1 mm gaps

Matching coils selected from a production batch

Radius =
35.7 mm (BioMed)
26.8 mm (GSI)

BTrain generation in PS reference magnet

PS main magnets are combined function



Integrator connected to a reference coil sent pulses with constant $\Delta\Psi(t)$ of 0.5 G at closed orbit position

- ➢ Used only for synchronisation of the field

  $\Rightarrow$ calibrated by the beam

- ➢Need a "marker" at B_0 = 49 G (Peaking strip)

(NMR cannot be used because combined function)

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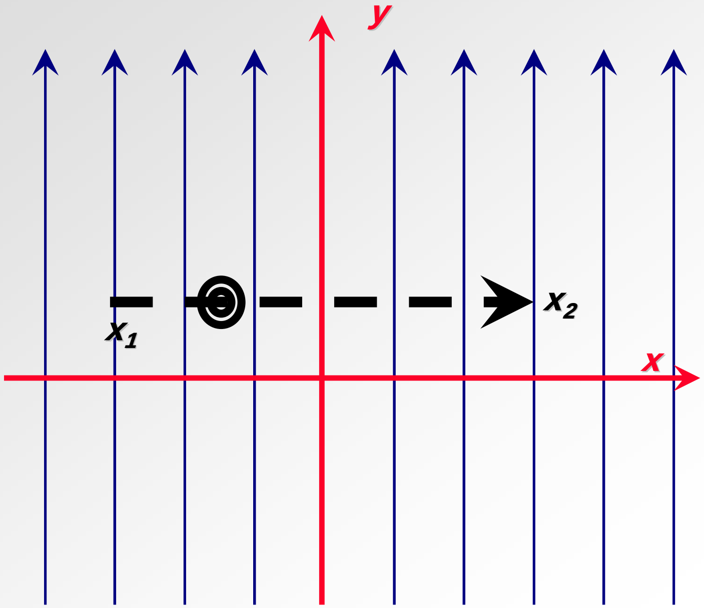
Measure Dipole Strength with a Stretched Wire



Dipole : $B_y = Cst$, $B_x = 0$

Flux seen by wire going from x_1 to x_2

$$\Psi(x_1, x_2) = \int_{x_1}^{x_2} \int_0^L B_y(x, l) \cdot dx \cdot dl = \boxed{d \cdot \int B \cdot dl}$$

with $d = x_2 - x_1$

Directly dipole strength $\int B \cdot dl$

Absolute accuracy given by

- Integrator : 10^{-4} to 10^{-5}
- Distance : $1\mu/10mm = 10^{-4}$

Return wire must not move,

if possible in field free region

χ-check with NMR+Hall

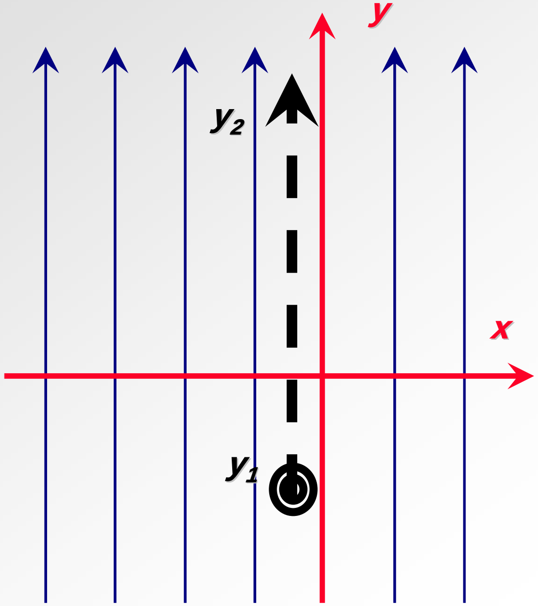
@$5 \cdot 10^{-5}$, SLAC ≈1978

SSW & Dipole Field Direction

Dipole : $B_y = Cst$, $B_x = 0$

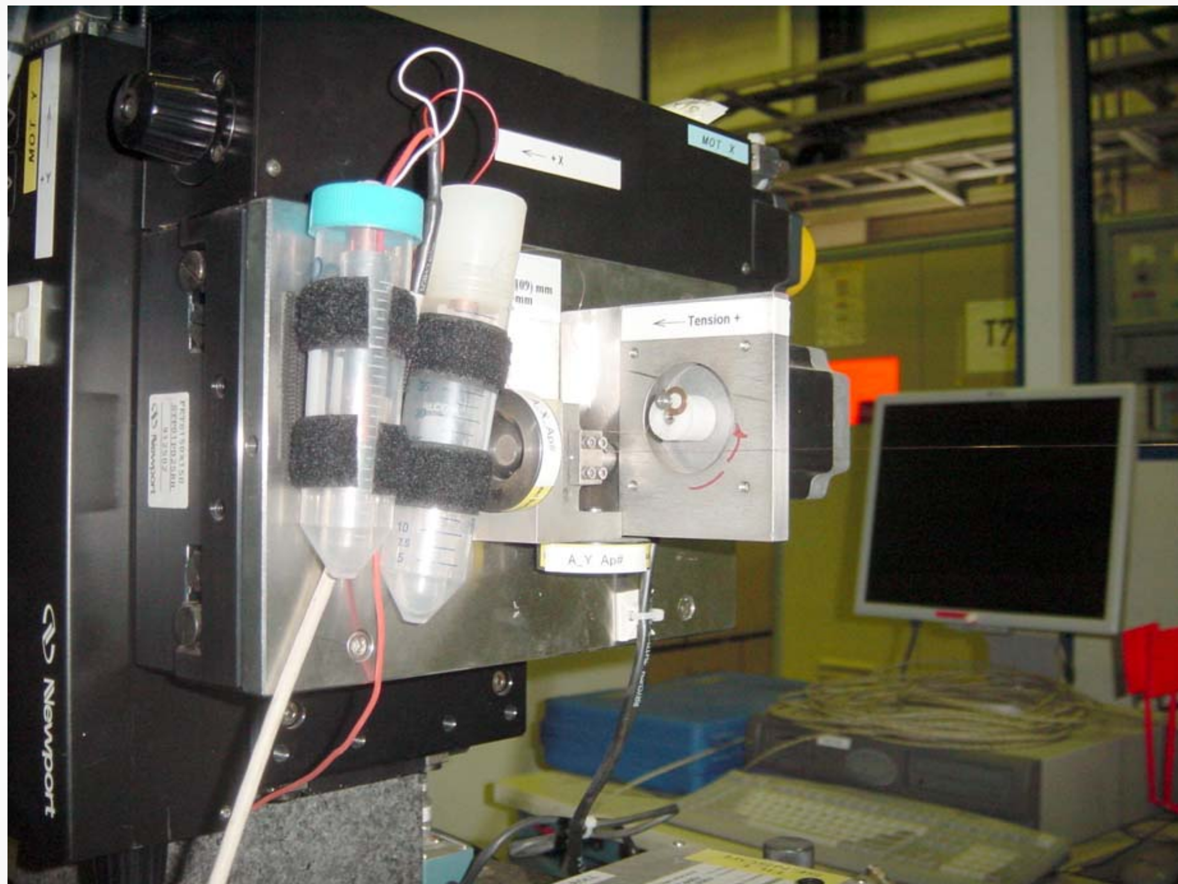
Flux from y_1 to $y_2 = 0$

if Field (& stages) perfectly vertical

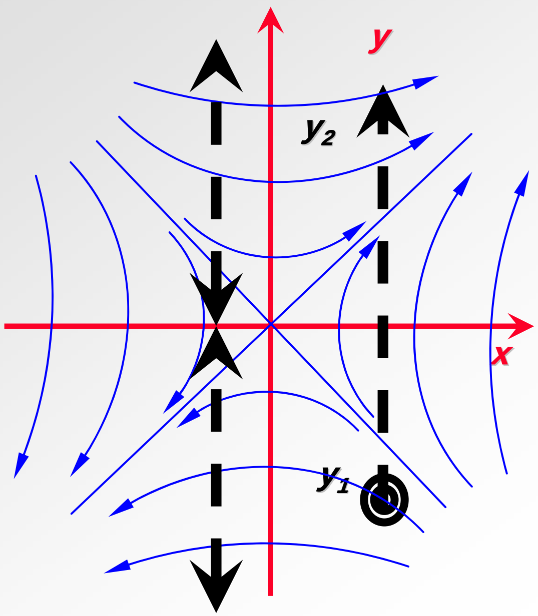


Accuracy ≈0.1 mrad

System developped by FNAL, J. Dimarco



SSW in Quadrupole



Quadrupole : $B_y = G \cdot x$, $B_x = G \cdot y$

Flux from y_1 to y_2

$$\Psi(y_1, y_2) = L_{eff} \int_{y_1}^{y_2} G \cdot y \cdot dy = L_{eff} \cdot \frac{G}{2} \cdot (y_2^2 - y_1^2)$$

Wire deflects due to gravity :

Measure at different tensions & extrapolate to ∞ tension

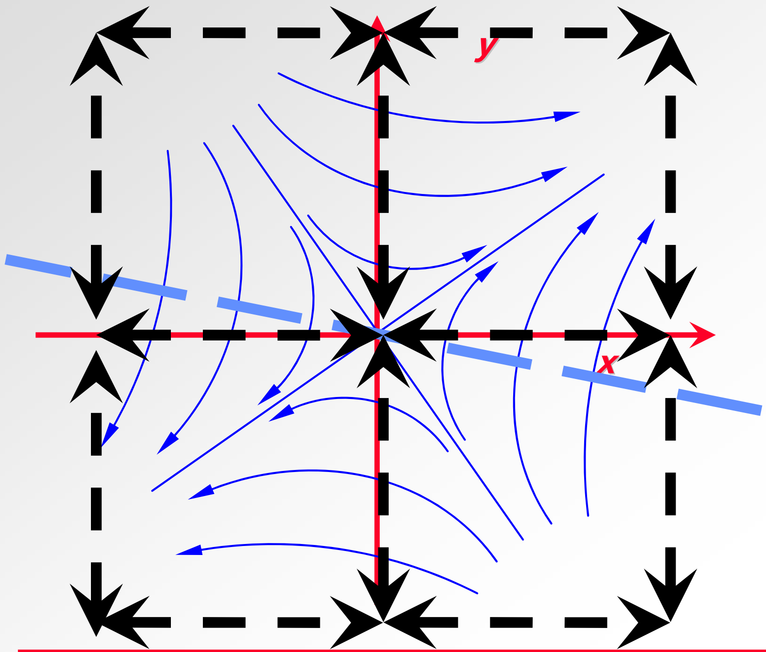
Where is $y_c=0$?

2 intervals meas. , move y_c until

$$\Psi(y_c, y_c + d) = \Psi(y_c, y_c - d)$$

$$(y_c + d)^2 - y_c^2 = (y_c - d)^2 - y_c^2$$

SSW in Quadrupole : align 1st your system



Tilt between Quadrupole and SSW

Find y_c =0 for different x

& Center in 2 directions

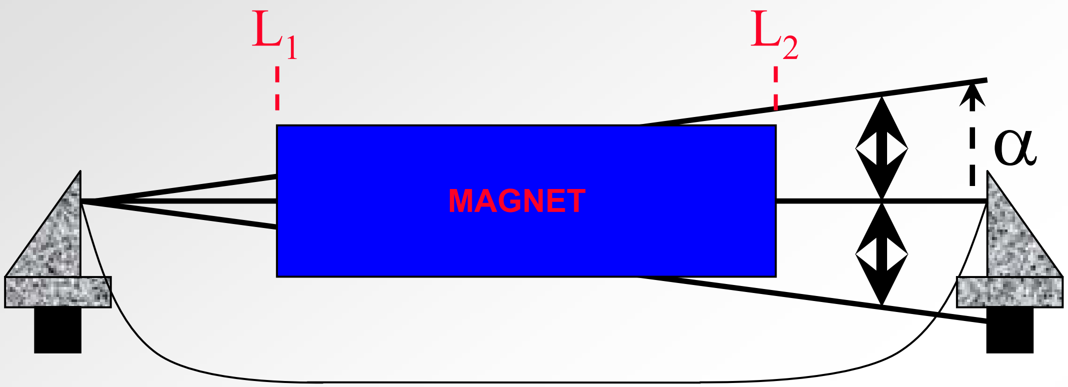
Iterate :

- Measure 8 (12) intervals
- Calculate new reference frame of stages

! stages x & y axis must be parallel !

Stretched Wire non aligned with Quad Axis

Hyp : L_{eff} & Longitudinal position of magnet known



Iterate 2 measurements :

move α_c until

$$\Psi(\alpha_c, \alpha_c + \alpha) = \Psi(\alpha_c, \alpha_c - \alpha)$$

$$\Psi(\alpha_1, \alpha_2) = \int_{\alpha_1}^{\alpha_2} d\alpha \cdot \int_{L_1}^{L_2} G \cdot x(\alpha, l) \cdot dl$$

$$x = l \cdot \alpha$$

$$\Psi(\alpha_1, \alpha_2) = G \cdot \frac{(\alpha_2^2 - \alpha_1^2)}{2} \cdot \frac{(L_2^2 - L_1^2)}{2}$$

Combine

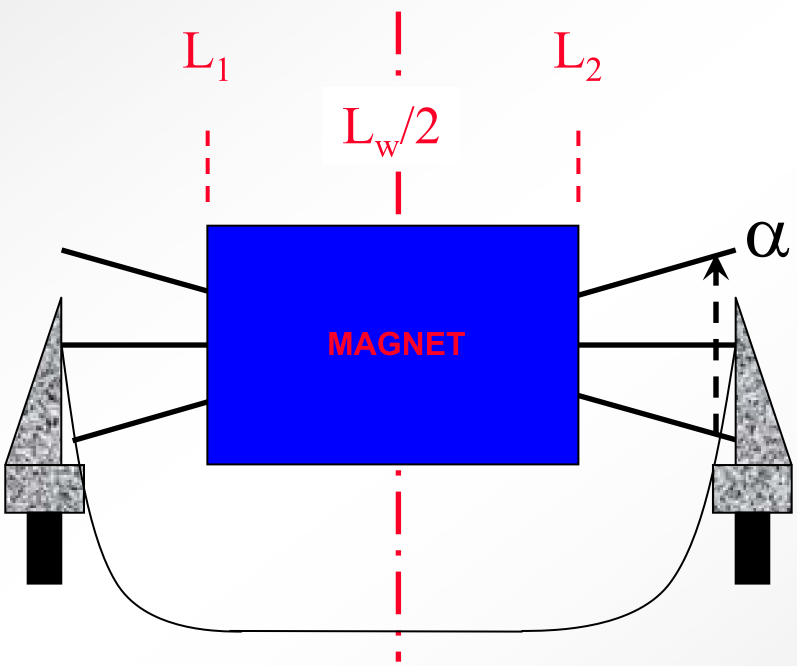
- co-parallel
  (cf. previous slide)
- counter-parallel
  to align axis & wire

Iterate until fully aligned

Find magnet longitudinal location

If Magnet fully centred, and axis // to wire reference position, then we can measure longitudinal position

d = distance from middle of wire length [i.e. $L_w/2$]



$$\Psi(\alpha_1,\alpha_2)=\int_{\alpha_1}^{\alpha_2} d\alpha\cdot\int_{L_1}^{L_2} G\cdot x(\alpha,l)\cdot dl$$

with

$$x=\left(l-\frac{L_w}{2}\right)\cdot\alpha$$

$$L_1=\frac{L_w}{2}-\frac{L_{eff}}{2}+d$$

$$L_2=\frac{L_w}{2}+\frac{L_{eff}}{2}+d$$

$$\Psi(\alpha_1,\alpha_2)=G\cdot(\alpha_2^2-\alpha_1^2)\cdot d\cdot L_w$$

Accuracy for axis and position finding

TABLE I
ERRORS IN AXIS DETERMINATION FOR 11 AND 16 m WIRE LENGTHS

	X-axis (m)		Y-axis (m)	
	11m	16m	11m	16m
Magnet End a	-0.000011	0.000100	0.000119	0.000092
Magnet End b	-0.000059	-0.000111	-0.000156	-0.000142
Center	-0.000033	0.000000	-0.000019	-0.000025

Field Alignment of Quadrupole Magnets for the LHC Interaction Regions

J. DiMarco, H. Glass, M.J. Lamm, P. Schlabach, C. Sylvester, J.C. Tompkins
Fermilab, Batavia, IL, USA

J. Krzywinski
Institute of Physics, Polish Academy of Sciences, Warsaw, Poland.

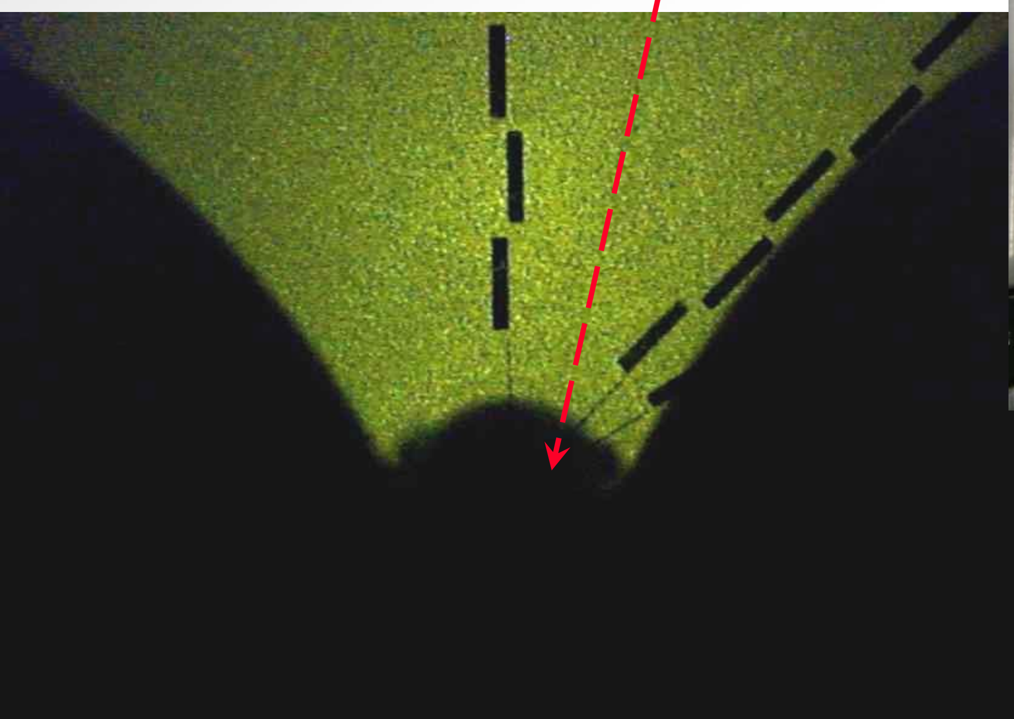
presented at Magnet Technology Conference, Philadelphia, 2007

Longitudinal position within 5 mm

Wire location for axis search

Contour picture of wire 0.1 mm squeezed inside ceramic balls

Accuracy ≈ 0.01 mm



Wire position referred to laser tracker fiducial

Measure the Strength of a quadrupole ∫Gdl

- Needed :

  Dipole : ∫Bdl(I) or Transfer Function = ∫Bdl / I [T·m/kA]

  Quadr : ∫Gdl(I) or Transfer Function = ∫Gdl / I [T/kA]

  Requires current stability & accurate current measurement

- Verify that high order multipoles do not matter.

$$\Psi(x_1, x_2) = \int_{x_1}^{x_2} \int_0^L B_y(x,l) \cdot dx \cdot dl$$

$$B_y(x,l) = B_1 + B_3 \cdot x^3 \text{ in dipole}$$

$$B_y(x,l) = G \cdot x + B_6 \cdot x^5 + (B_4 \cdot x^3) \text{ in quadr.}$$

- Sag of the wire due to gravity and local field gradient

  main issue for ∫Gdl measurement

Measure and compensate wire sag

Sagitta due to gravity

Extrapolate to ∞ tension

$$Sag = \frac{w \cdot g}{8T} L^2$$

$\approx mm$ for

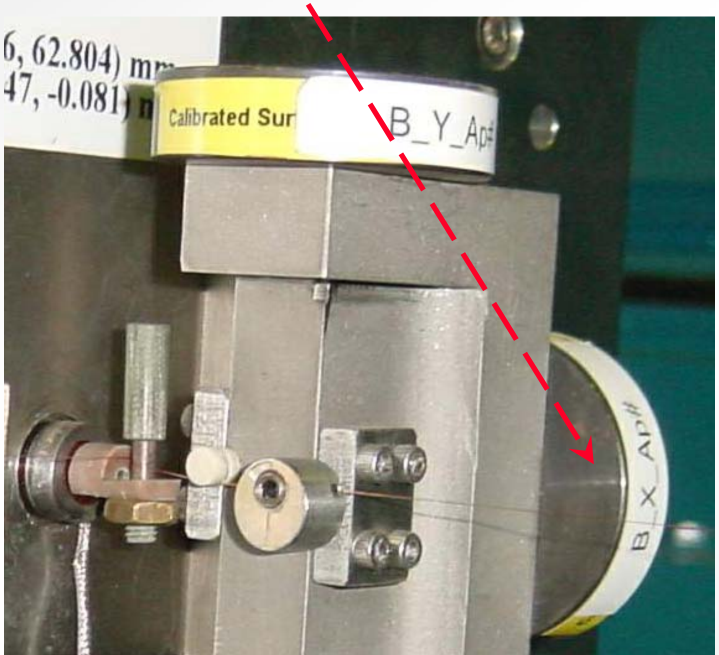
CuBe 0.1 mm wire

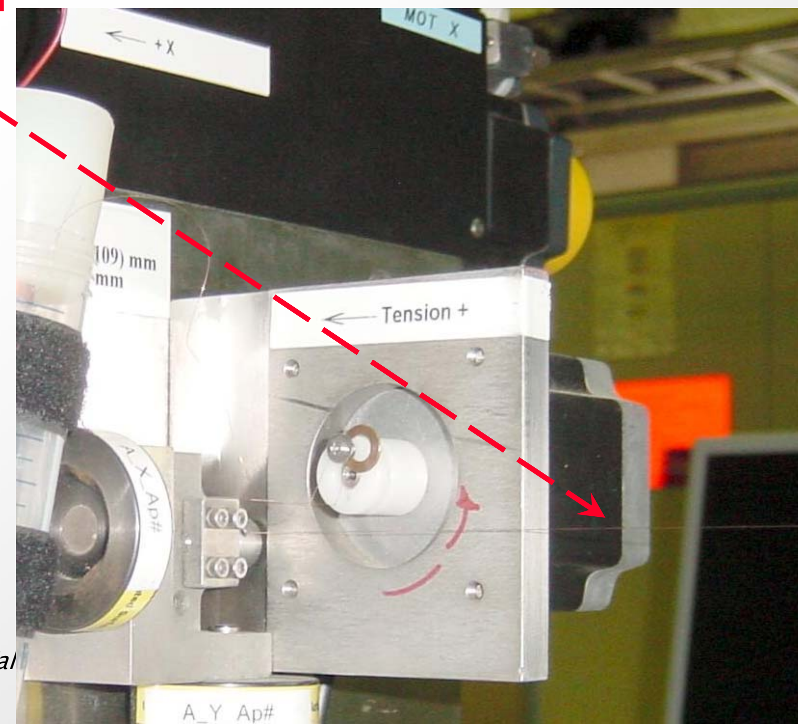
T maximum before break

L = 10 m

Tension gauge to avoid to brake the wire

Actuator to change the tension





Extrapolate wire sag to ∞ tension

Measure the tension

give kick by moving both stages

measure vibration frequency of wire oscillating in field

$$f = \frac{1}{2l_{wire}}\sqrt{\frac{T}{w}}$$

Observations :

➢sag depends on tension

and square of gradient

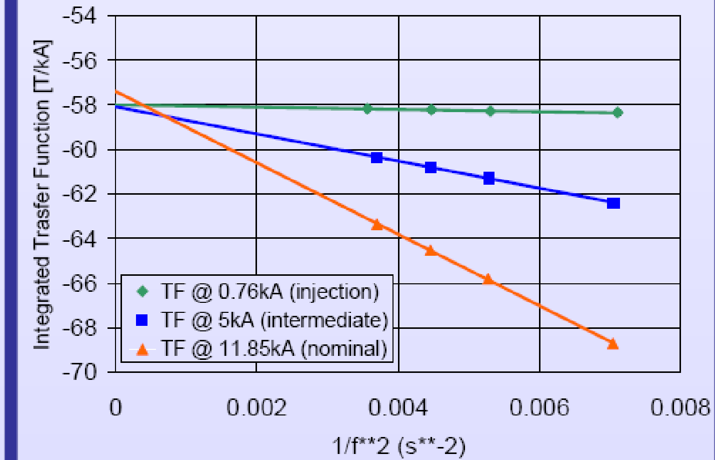
➢value measured by vertical movement is always higher than by horizontal movement

CuBe is para-magnetic

(no norm for the material you purchase.)

Magnetic Property of the Wire

Typical dependence of transfer function versus $1/f^2$



Slope of Gdl for different types of wire:

Wire	0.76kA	5kA	11.85kA	χ
#1	30.4	2000	9480	>0
#2	6.1	500	4977	>0
#3	2.3	50	474	<0
#4	-	-	380	<0

Measure ∫Gdl with Horizontal movement

Magnetic force opens the flux (if CuBe wire is paramagnetic)

With Horizontal displacement

$$F^x{}_{mag} \propto G^2 \times (x_{step})^2$$

The Gdl obtained from a horizontal movement can be calculated from the linear fit of different wire tensions.

With vertical displacement :

$$F^y{}_{mag} \propto G^2 \times (y_{step} + Sag)^2$$

so that dependance with T no more linear

The Gdl obtained from a vertical movement must be calculated with a parabolic fit of different wire tensions.

could be unstable

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Vibrating wire to find Quad axis

- **Equation for the string motion driven by AC current:**

$$w\frac{\partial^2 x}{\partial t^2} = T\frac{\partial^2 x}{\partial z^2} - \gamma\frac{\partial x}{\partial t} + I(t)B(z) \qquad \text{boundary} \quad x(0,t) = x(l,t) = 0$$

$w =$ linear wire density, $T =$ tension, $\gamma =$ damping

$I(t) = I_0 \exp(i\omega t)$ [driving AC current], $B(z) =$ transverse magnetic field

- **Solution - sum of standing waves**

$$x(z,t) = \sum_n x_n \sin\left(\frac{\pi n}{l} z\right)\exp(i\omega t); \text{ where } x_n = \text{standing waves amplitudes}$$

$$x_n = \frac{I_0}{w}\frac{1}{\omega^2 - \omega_n^2 - i\gamma\omega}B_n; \; \omega_n = \frac{\pi n}{l}\sqrt{\frac{T}{w}}$$

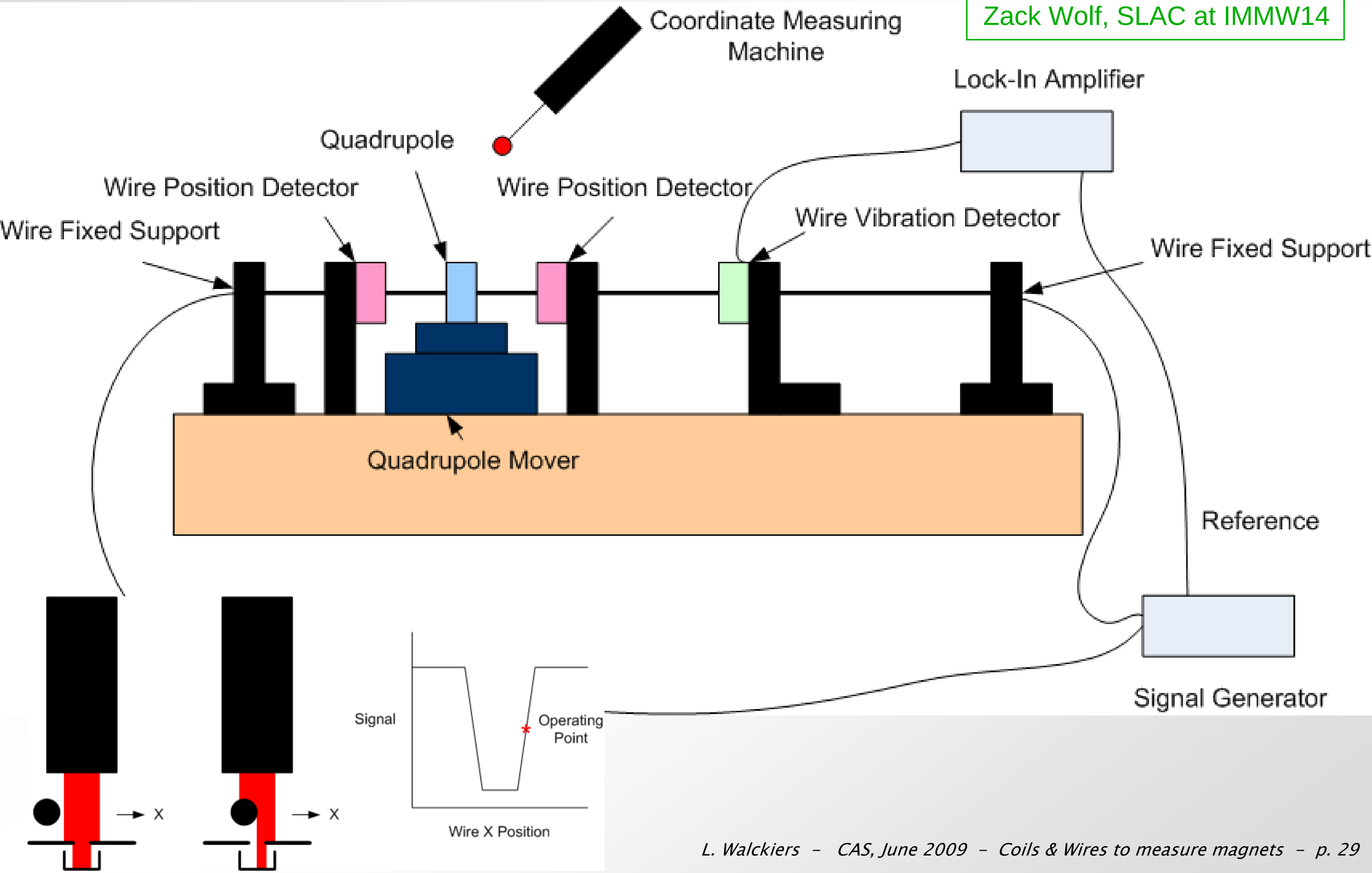
B_n are coefficients of a sinus waves expansion $B(z) = \sum_n B_n \sin\left(\frac{\pi n}{l} z\right)$

- **Measuring x_n one can find B_n and reconstruct $B(z)$!!!**

A. Temnykh, Vibrating wire field-measuring technique, Nuc. Inst., A 399 (1997) 185-194

Vibrating wire system overview

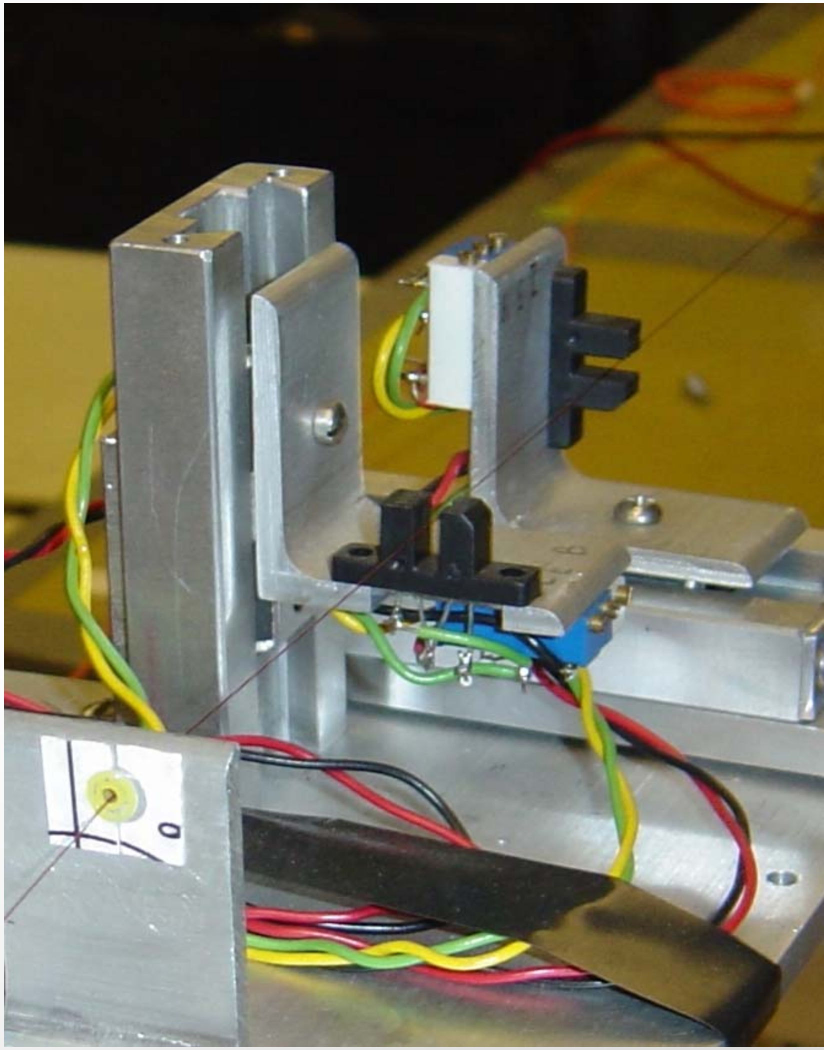
Zack Wolf, SLAC at IMMW14



Measure the wire motion

The wire motion in vertical (horizontal) plane is caused by the Lorentz forces between wire current and horizontal (vertical) magnetic field.

⇒ need to measure wire motion in vertical and horizontal planes.



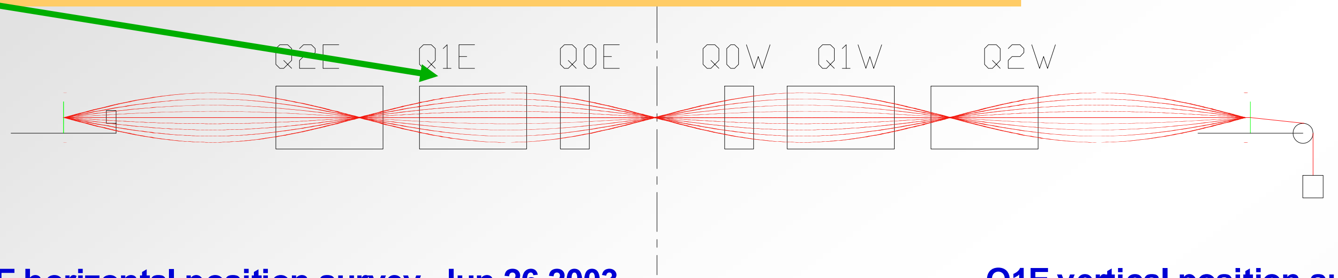
Assembly of optical sensors used shows ~10% coupling between vertical and horizontal wire motion

Need ~1% or less.

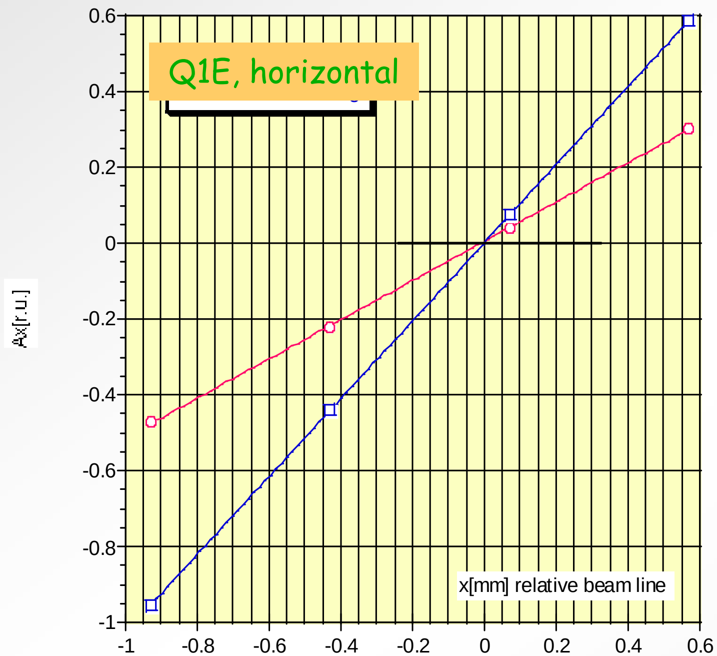
=> Calibration needed

Super-conducting magnets survey

For Q1E survey the 4th order standing wave has been used.

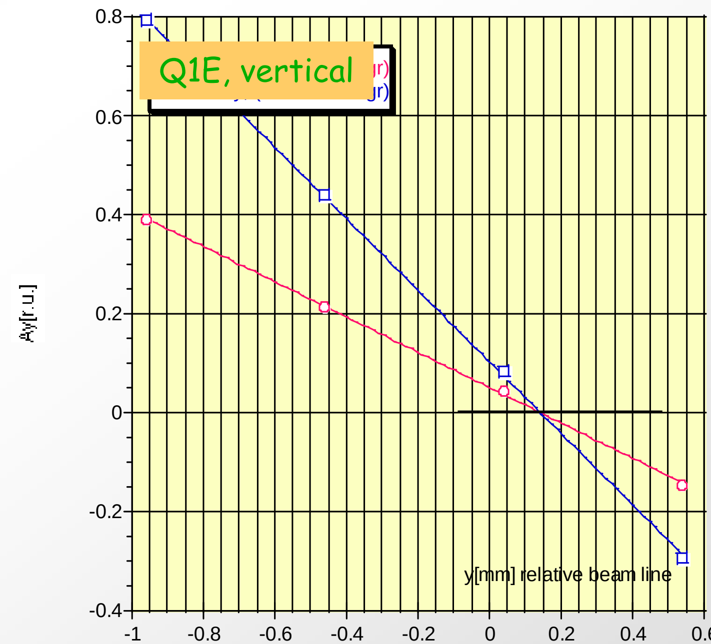


Q1E horizontal position survey, Jun 26 2003



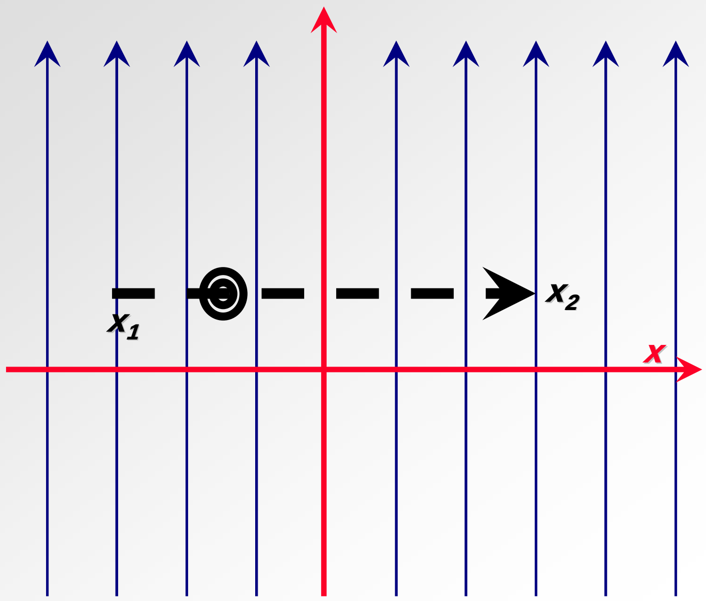
1) I(Q1E) = 231A
x = -0.010 +- 0.004mm
2) I(Q1E) = 466A
x = -0.002 +- 0.001mm

Q1E vertical position survey, Jun 26 2003



1) I(Q1E) = 231A
y = 0.142 +- 0.007mm
2) I(Q1E) = 466A
y = 0.141 +- 0.010mm

SSW to measure undulators & wigglers



- Verify $\int B dl = 0$, i.e. no perturbation for the beam

SSW in displacement is ideal

- Measure amplitude of $B_y(z)$ by pulsed SSW

[ESRF, Grenoble]

Coils wound on frames do not have constant width

- not to use with wigglers
- could also give problems with normal magnets

Coils & Wires : conclusions

Simple coil measure $B_y(x)$ or $G_y(x)$ with

- **static field and flip or displaced coils**
- **pulsed field & static coil**

Single Stretched Wire is the reference for :

- **Dipole & quadrupole strength**
- **Dipole & Quad. axis &field direction**

Vibrating SSW : axis search (small aperture)
magnet strength (limited accuracy)

For full 2D measurements :harmonic coils

$$B_y + i \cdot B_x = \Sigma\, C_n \cdot z^{n-1}$$