Characterization of out-of-vacuum undulators and wiggler using a Hall probe system.
Some remarks.

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IMMW17

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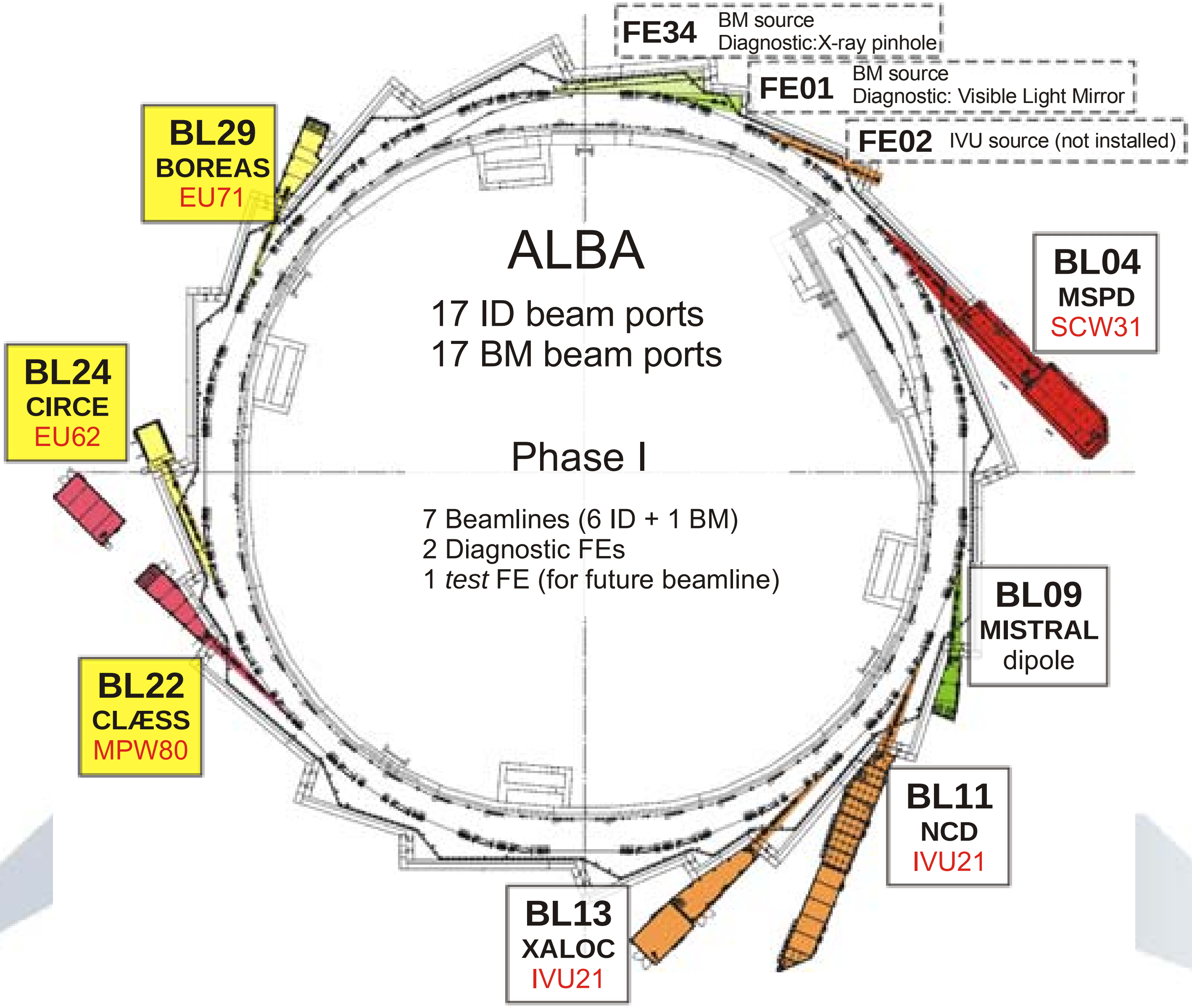
Outline

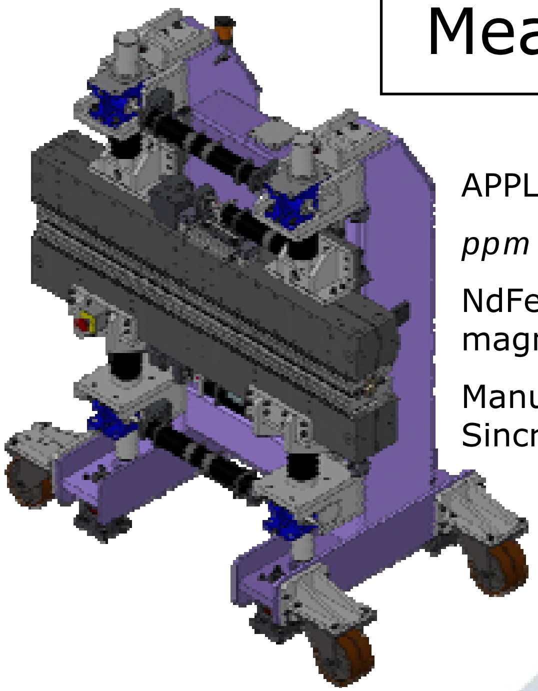
- Introduction
  - Measured Insertion Devices
  - Magnetic Measurements system
  - Alignment procedure
- Obtained results
  - MPW80
  - EU71
  - EU62
  - Field Integrals agreement
- Conclusions

Introduction



Introduction

Measured IDs

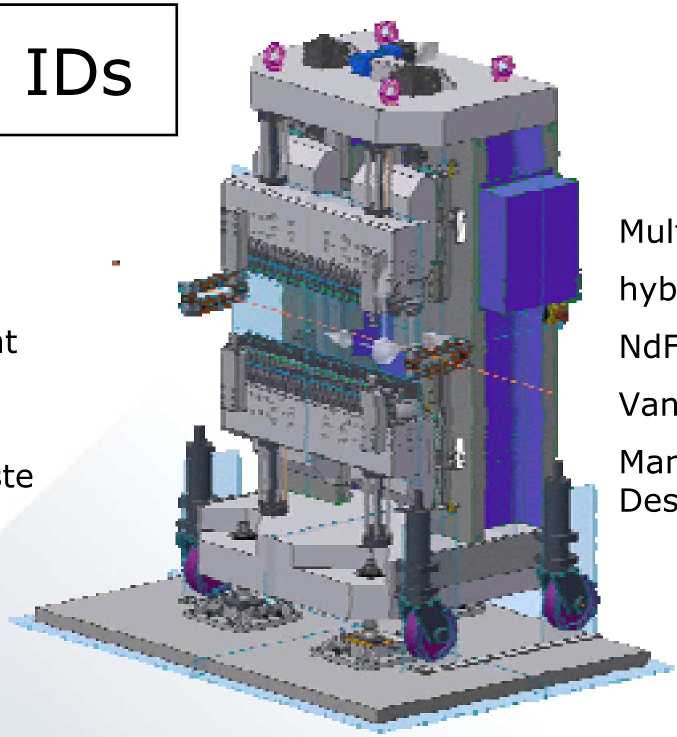


APPLE-II devices

ppm technology

NdFeB permanent magnets

Manufacturer: Sincrotrone Trieste



Multipole Wiggler

hybrid technology

NdFeB permanent magnets

Vanadium permendur poles

Manufacturer: Advanced Design Consulting (ADC)

EU62	EU71
λ_0=62.36mm	λ_0=71.36mm
57 poles (~1.8m)	47 poles (~1.7m)
gap_{min}=15.5mm	gap_{min}=15.5mm
B_y^{max}(H-mode)=0.86T	B_y^{max}(H-mode)=0.93T
B_x^{max}(V-mode)=0.61T	B_x^{max}(V-mode)=0.7T
$B_{x,y}$(C-mode)=0.5T	$B_{x,y}$(C-mode)=0.57T

MPW80

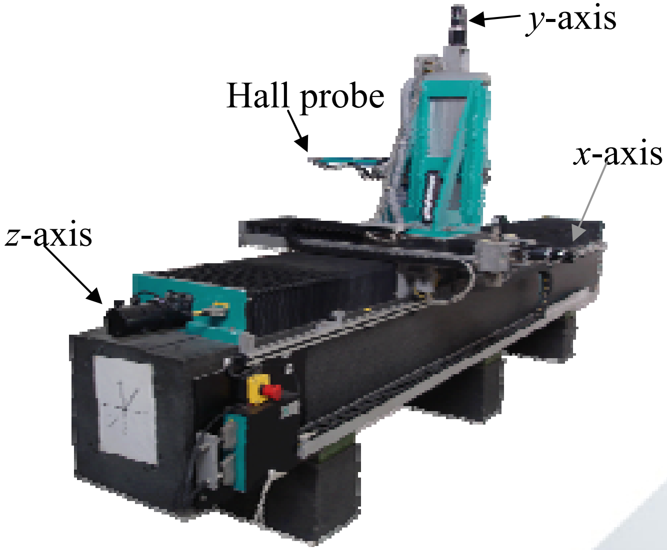
λ_0=80.00mm

27 poles (~1m)

gap_{min}=12.5mm

B_y^{max}=1.74T

ALBA-CELLS magnetic measurements lab



Hall probe bench (local field determination)

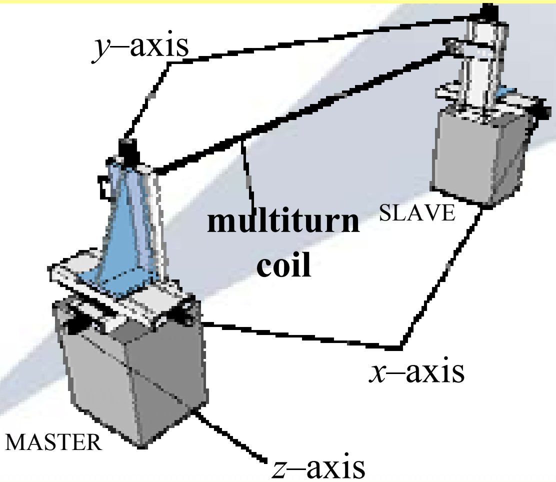
3-axes Hall probe

Scanning volume $(\Delta x\times\Delta y\times\Delta z)$=500×250×3000 mm^3

Characteristics of on-the-fly measurement mode:

Maximum velocity	v_z= 16 mm/sec
Minimum step size	δz= 20 µm
Min. "dead time" between acquisitions	$\delta\tau$=6 msec
Max. number points/scan	30000
Field Absolute accuracy	~0.5 Gauss
Field Integrals accuracy	not better than 10^{-5}T·m=10 G·cm

J. Campmany, J. Marcos, V. Massana, and Z. Martí, *"Construction & Commissioning of a 3D Hall probe bench for Insertion Devices measurements at ALBA Synchrotron Light Source"*, **IMMW15**, Fermilab, August 2007



Flipping coil bench (field integrals determination)

Field Integrals Absolute accuracy (IDs) ~ 10^{-6} T·m=1 G·cm

3-axes Hall probe

F.W. Bell Hall sensors

Model GH-700

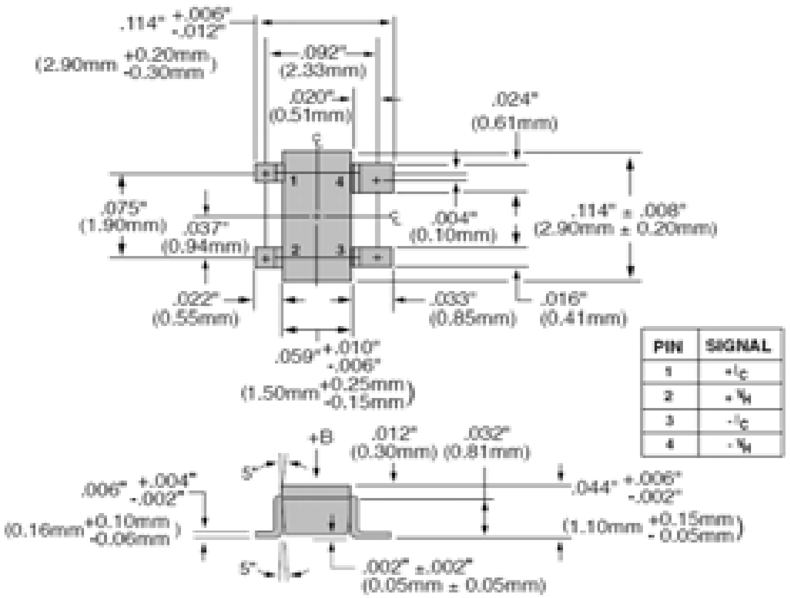
Gallium Arsenide

Nominal current: I_{nom} =5 mA

Magnetic Sensitivity ~ 1 V/Tesla

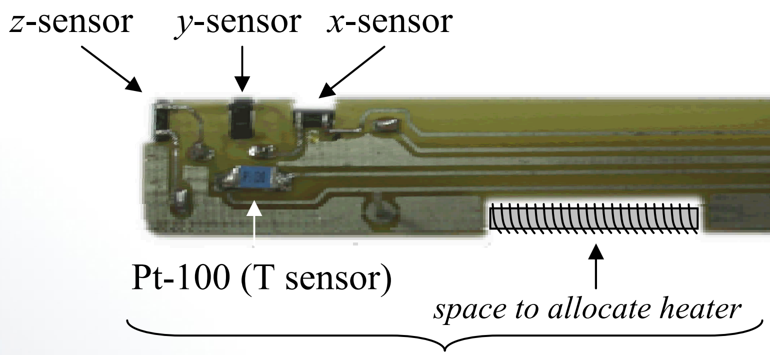
Max. linearity error (±1 Tesla): ±2%

Temperature coefficient: -0.07%/ºC



PIN	SIGNAL
1	$+I_C$
2	$+V_H$
3	$-I_C$
4	$-V_H$

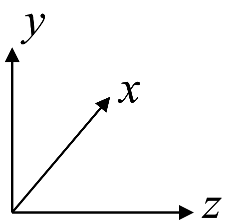
Detail of Hall probe circuit board:

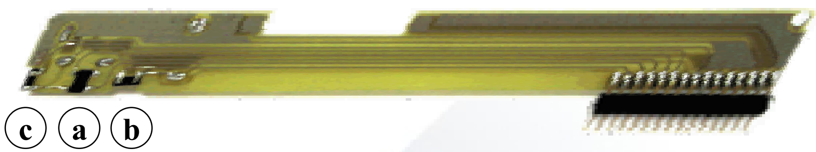


the temperature sensor and the manganine heater, in combination with a PID controller (*Eurotherm 3508*) allow to control the temperature of the probe within ±0.05ºC

Relative position between Hall sensors

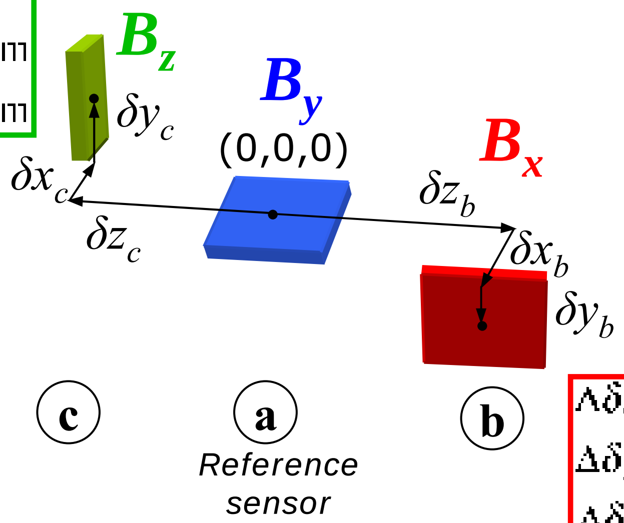
Refinement of the relative positioning between the sensitive areas of the three sensors using Maxwell equations





$$\begin{cases} \vec{\nabla} \cdot \vec{B}(\vec{r}) = 0 \\ \vec{\nabla} \times \vec{B}(\vec{r}) = 0 \end{cases}$$

$$\boxed{\begin{aligned} \Delta\delta x_c &= (-0.28 \pm 0.05)\,\mathrm{mm} \\ \Delta\delta y_c &= (+0.02 \pm 0.05)\,\mathrm{mm} \\ \Delta\delta z_c &= (+0.05 \pm 0.05)\,\mathrm{mm} \end{aligned}}$$



Ideal values by design:

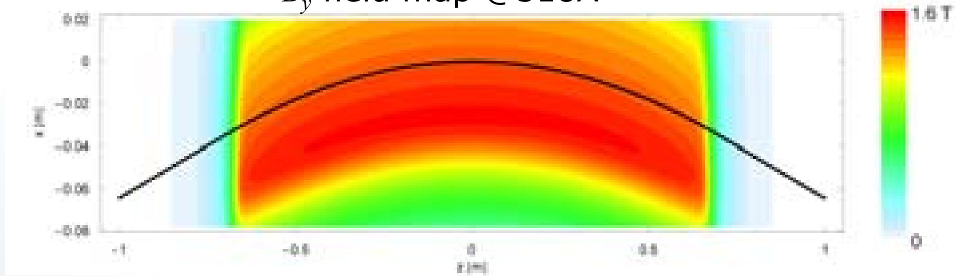
$$\begin{cases} \delta z_b = -\delta z_c = 5.5\,\mathrm{mm} \\ \delta x_b, \delta x_c = 0 \\ \delta y_b, \delta y_c = 0 \end{cases}$$

$$\boxed{\begin{aligned} \Delta\delta x_b &= (-0.08 \pm 0.1)\,\mathrm{mm} \\ \Delta\delta y_b &= (0.43 \pm 0.1)\,\mathrm{mm} \\ \Delta\delta z_b &= (0.04 \pm 0.05)\,\mathrm{mm} \end{aligned}}$$

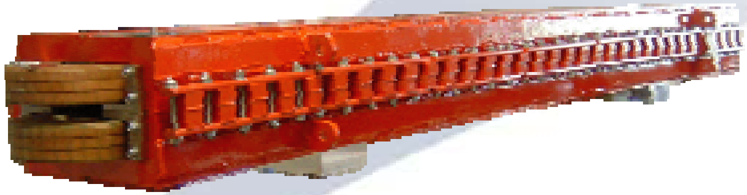
Previous usage of Hall probe bench

a) Complete characterization of all (32) Bending Magnets of ALBA Storage Ring

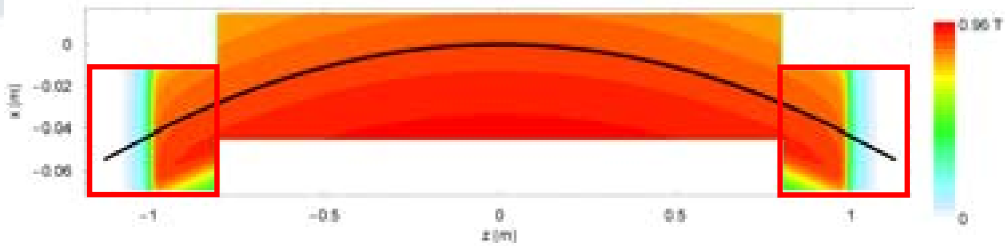
B_y field map @518A



b) Analysis of Booster Bending Magnets (fringe field properties, excitation curves…)



B_y field map @670A



J. Campmany, J. Marcos, D. Einfeld, M. Pont and V. Massana, *"Characterization of magnets for the ALBA booster synchrotron"*, **IMMW16**, Bad Zurzach, October 2009

J. Campmany, J. Marcos, D. Einfeld, M. Pont and V. Massana, "Characterization of ALBA Storage ring bending magnets using a high precision Hall probe bench", **IMMW16**, Bad Zurzach, October 2009

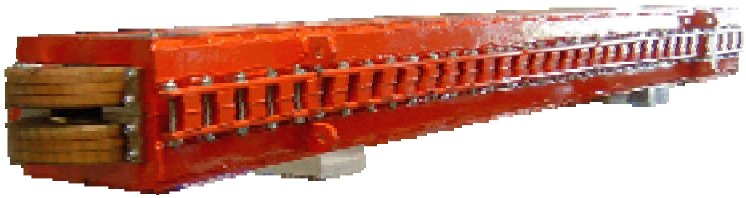
Bending Magnets *vs* Insertion Devices

Only $B_y \neq 0$ and $B_x \sim B_z \sim 0$

Magnetic fields up to 1.7 Tesla

Magnetic field gradients up to 25 Tesla/m

Large field integrals: up to 2 Tesla·m

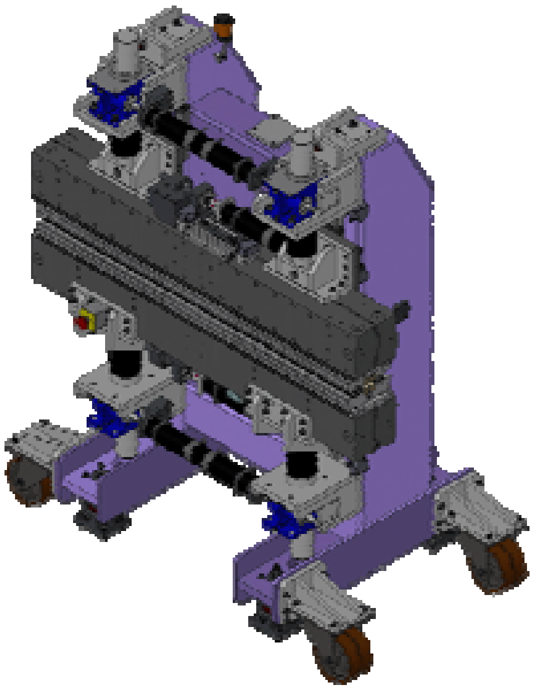


$B_x \neq 0$; $B_y \neq 0$; $B_z \neq 0$ simultaneously

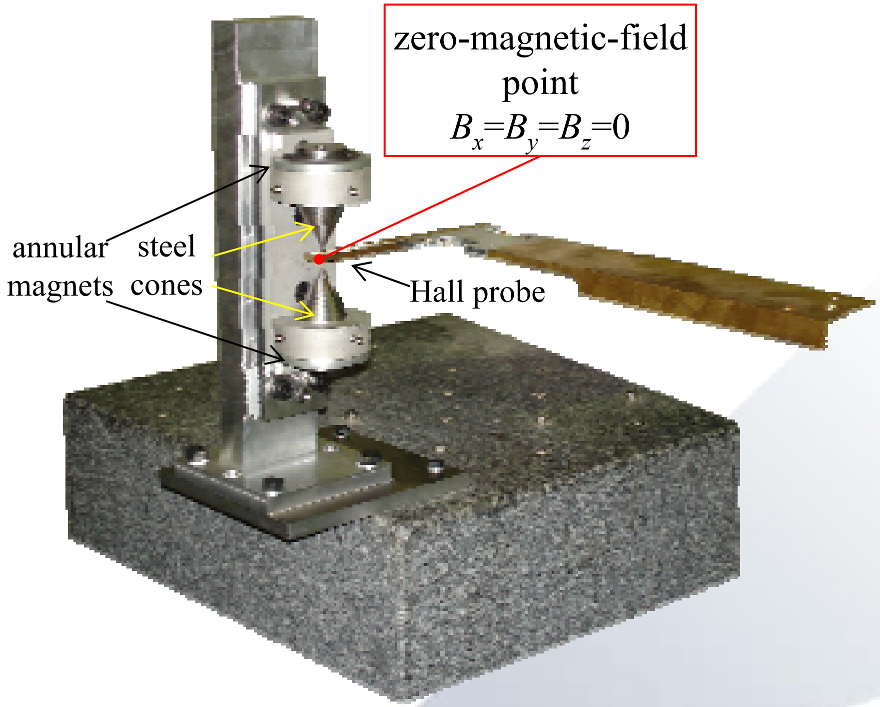
Magnetic fields up to 1.7 Tesla

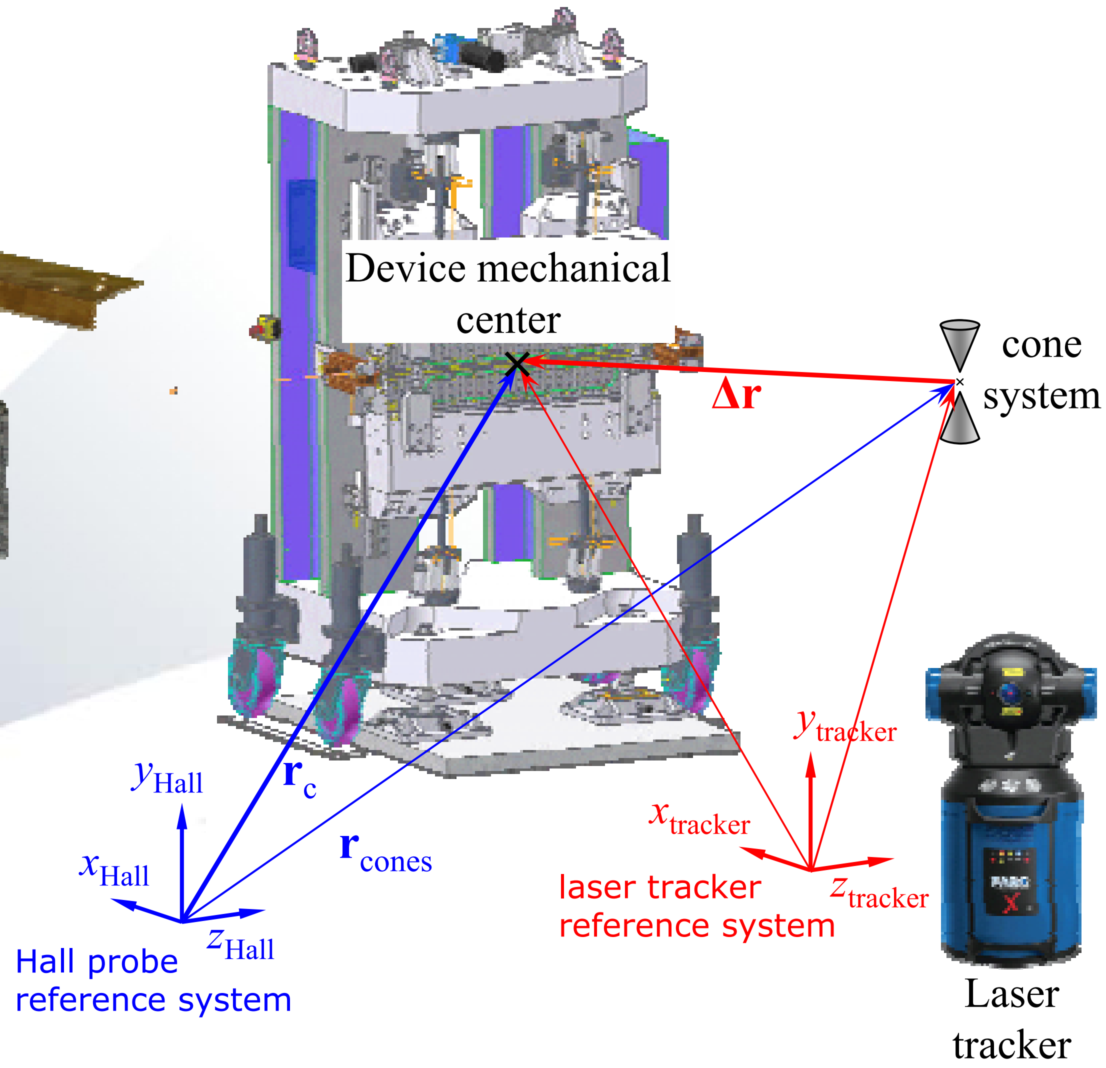
Magnetic field gradients up to **100 Tesla/m**

Very small field integrals: **~10^{-4} Tesla·m**



Alignment considerations





Alignment procedure precisions:

Positioning: ≲100μm

Angles: ≲200μrad

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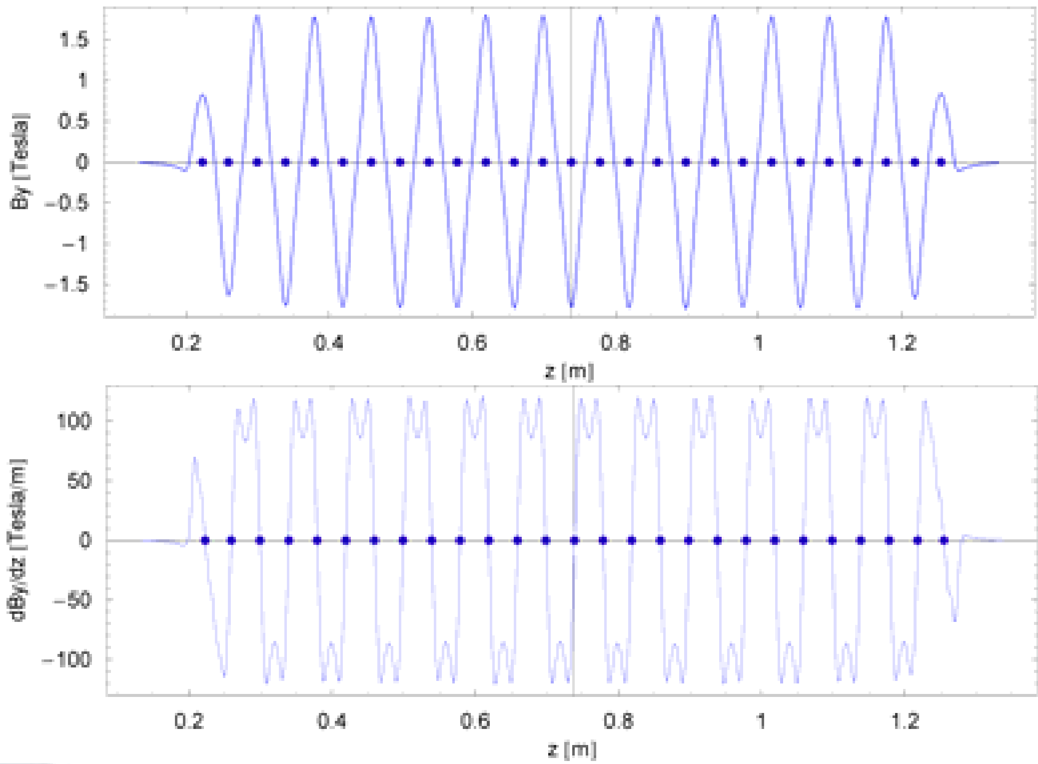
(a) MPW80: magnetic mid-plane

1st step: determination of pole positions by means of longitudinal scan of B_y along nominal (mechanical) axis

measurement @ gap$_{min}$=12.5mm



Condition to identify pole positions $\frac{dB_y}{dz} = 0$

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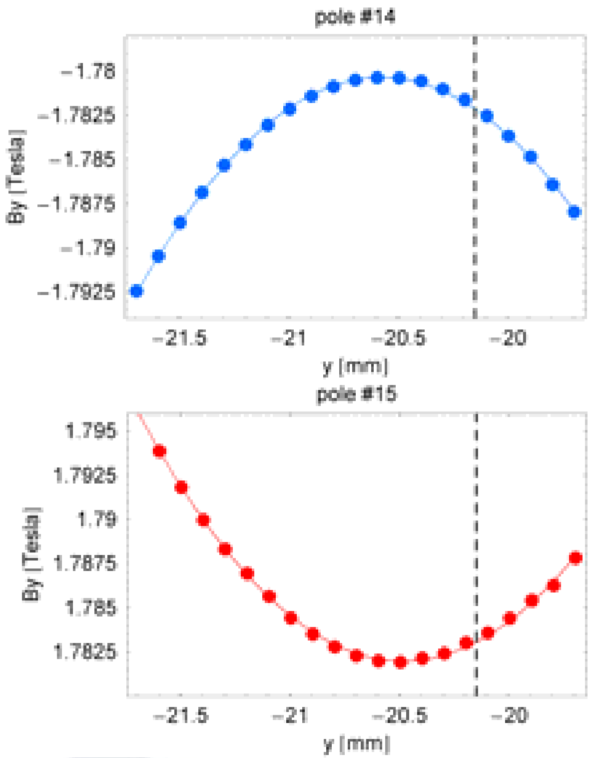
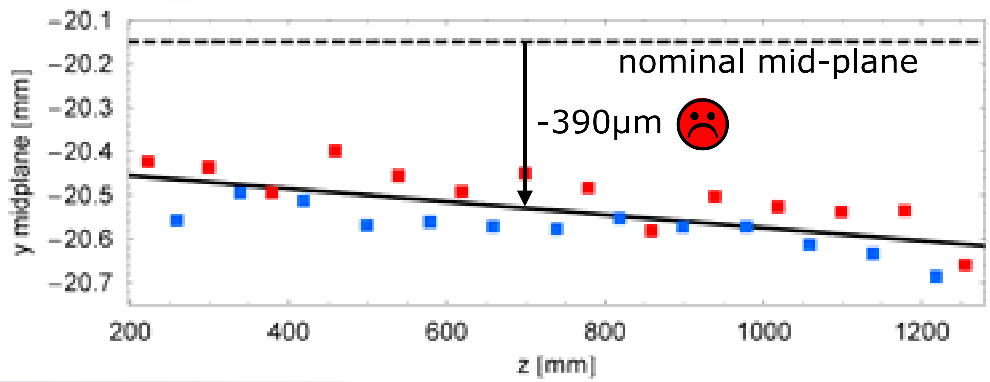
2[nd] step: vertical scan (±1mm) of B_y at the position of the poles and determination of maximum/minimum by means of parabolic fit



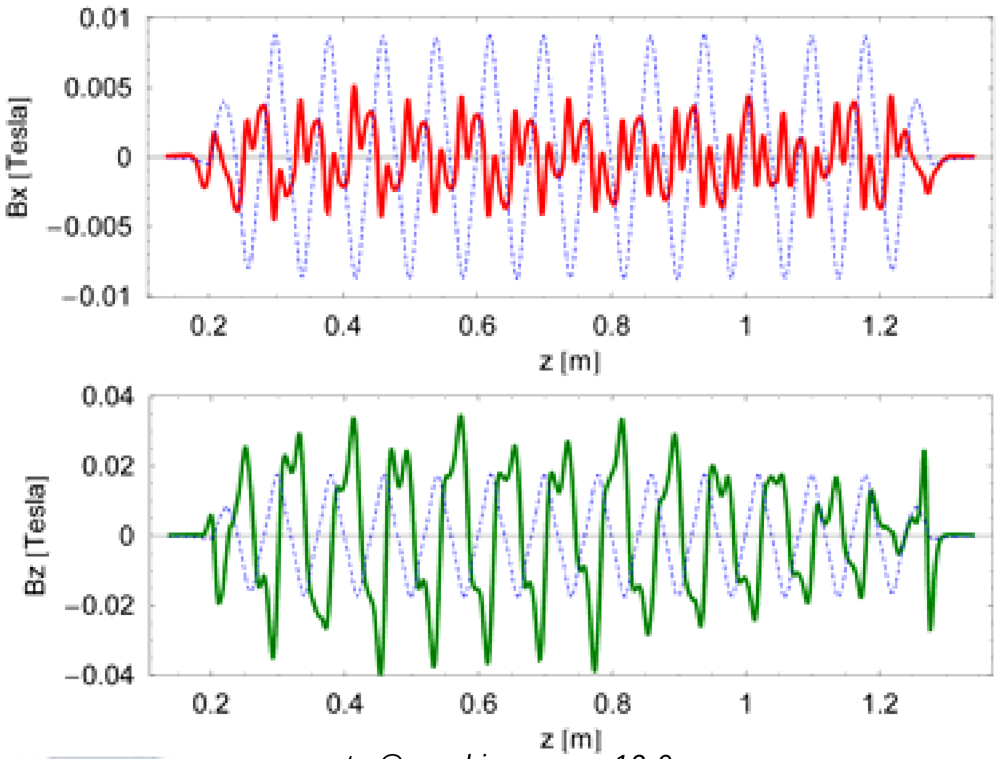


measurements @ gap_{min}=12.5mm

W80 magnetic mid-plane (B_y – gap$_{min}$ = 12.5 mm – taper = 0)	
Vertical position (y_m)	(-20.535 ± 0.050) mm
Tilt angle (pitch)	$(-150 \pm 30)\,\mu$rad

(b) MPW80: analysis of minor components

Minor components measured along magnetic mid-plane



measurements @ working gap$_1$=12.9mm

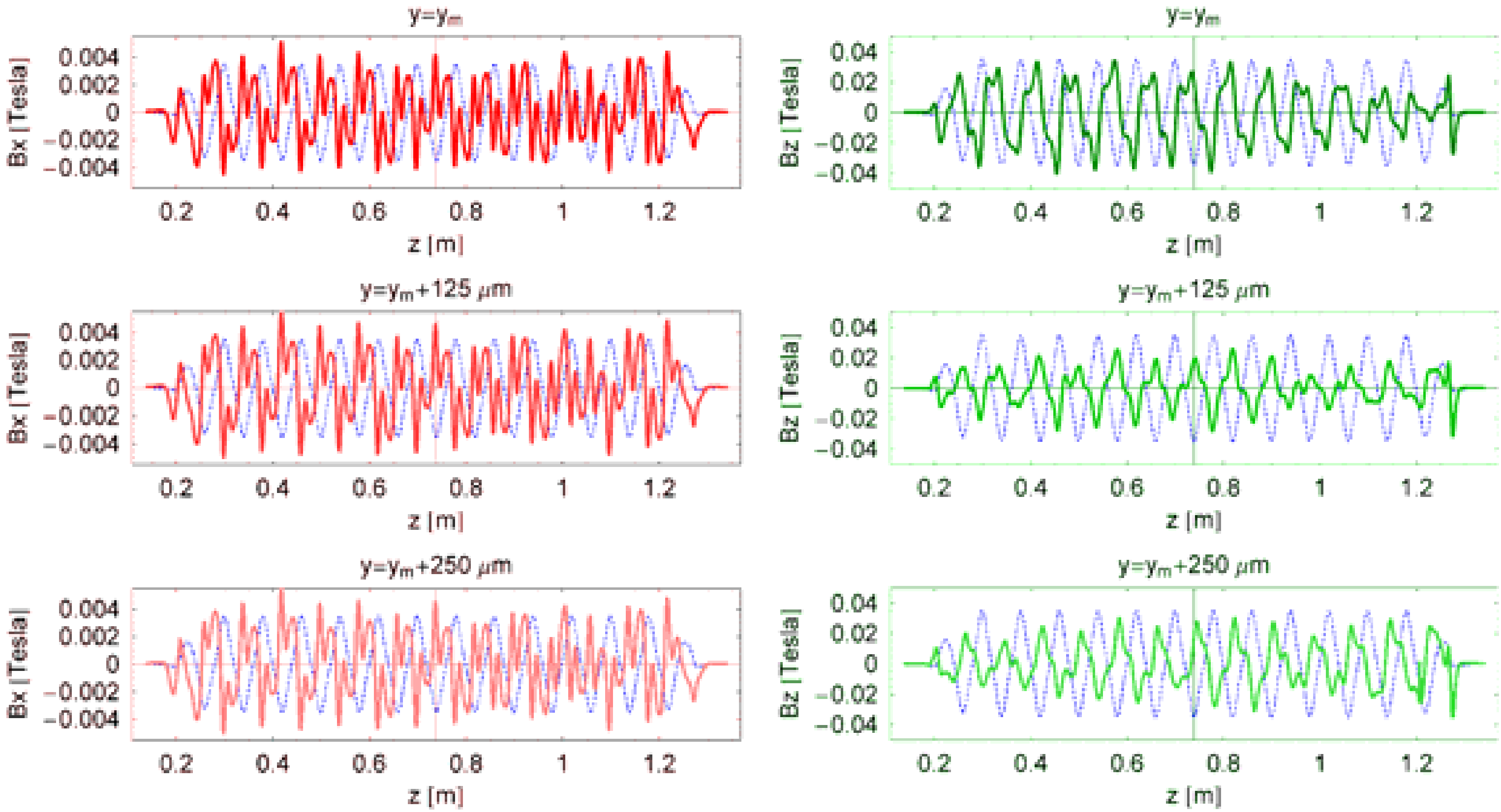
B_x 0.003 Tesla amplitude

B_z 0.03Tesla amplitude

(b) MPW80: analysis of minor components

Dependence with vertical position (y) of minor components

Horizontal component B_x — Longitudinal component B_z

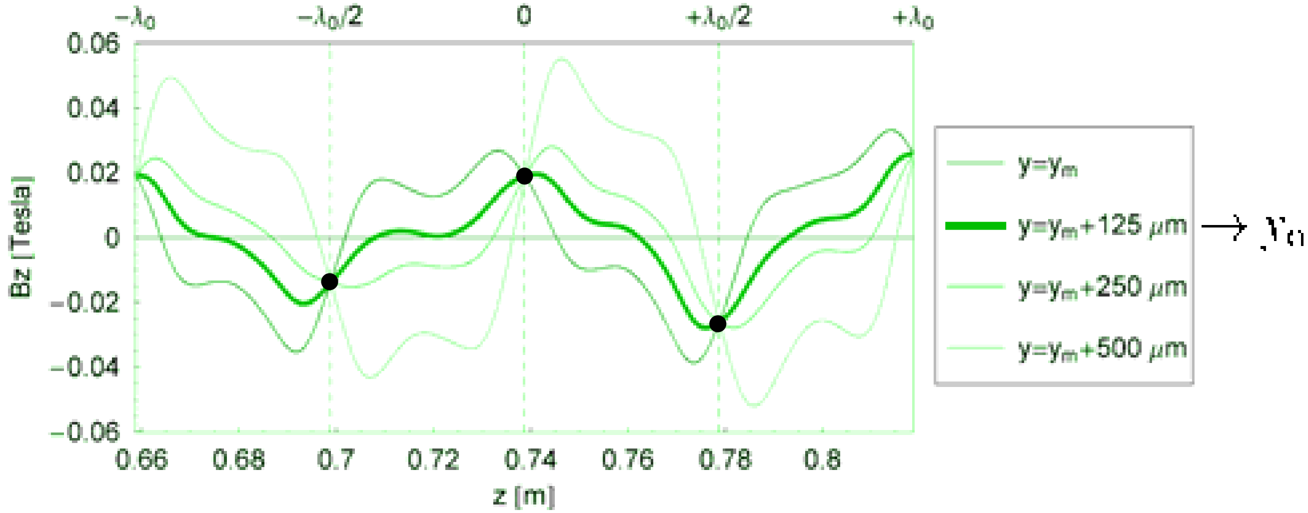


B_z ~ in phase with B_y

no change of B_x with y — B_z changes with y

(b) MPW80: analysis of minor components

Characteristics of B_z: components in quadrature and in phase



$$B_z(z,y) \approx \boxed{B_z^{quad}(z,y)} + \boxed{B_z^{phase}(z)} = \boxed{\sum_{n=1} B_{z,n}^{quad}(y)\sin\left[\frac{2\pi n(z-z_0)}{\lambda_0}\right]} + \boxed{\sum_{n=1} B_{z,n}^{phase}\cos\left[\frac{2\pi n(z-z_0)}{\lambda_0}\right]}$$

usual contribution in quadrature with respect to B_y

unexpected contribution in phase with respect to B_y

Antisymmetric wrt y

y independent

Properties of quadrature contribution

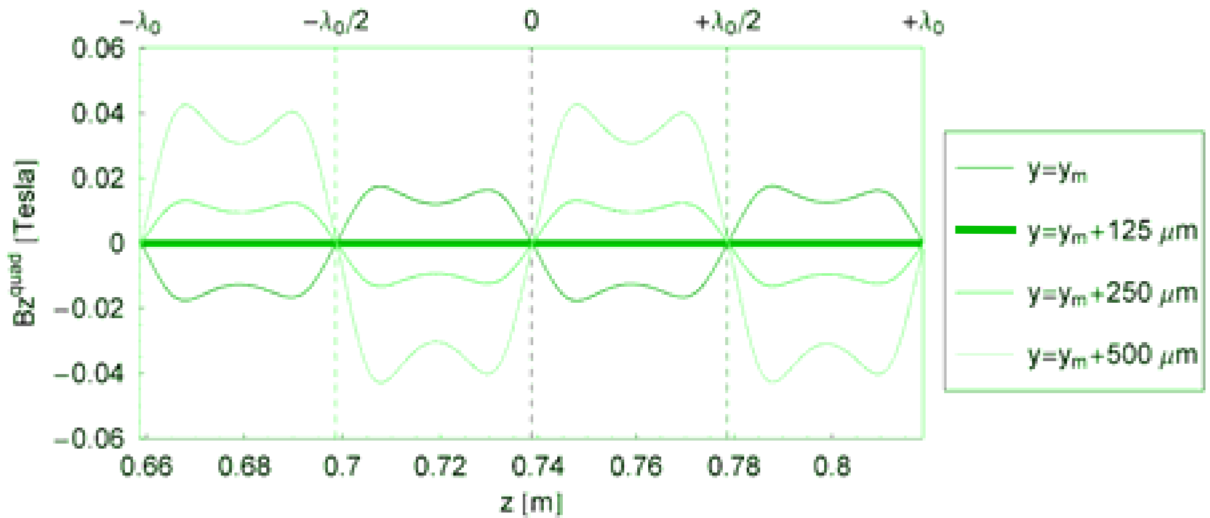
$$B_{z,n}^{quad}(y_0+y) = -B_{z,n}^{quad}(y_0-y)$$
$$B_{z,n}^{quad}(y_0) = 0$$

$$\boxed{B_z(z,y_0) = B_z^{phase}(z)}$$

(b) MPW80: analysis of minor components

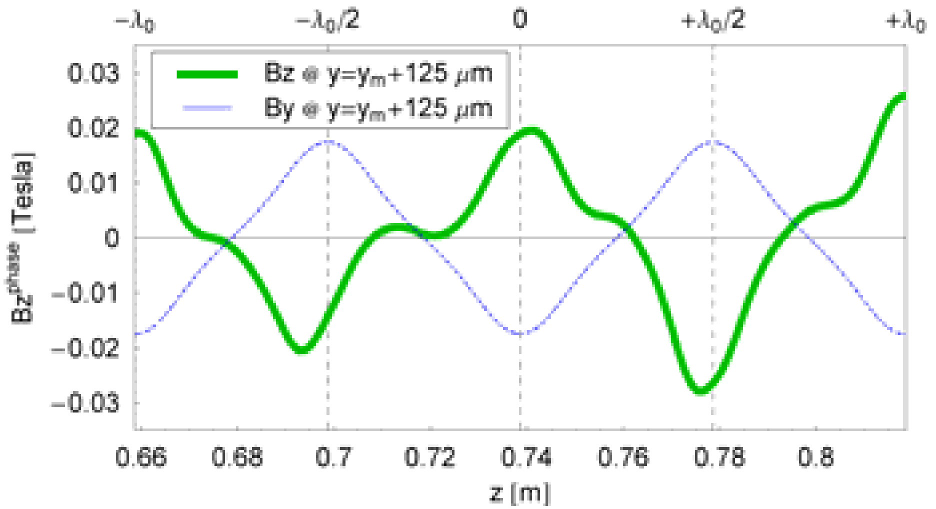
Characteristics of B_z: component in quadrature

$$B_z(z,y) - B_z^{\text{phase}}(z) = B_z(z,y) - B_z(z,y_0) = B_z^{\text{quad}}(z,y) \approx y\,\frac{\partial B_y}{\partial z}$$



(b) MPW80: analysis of minor components

Characteristics of B_z: component in phase



Which is the origin of the component in phase?

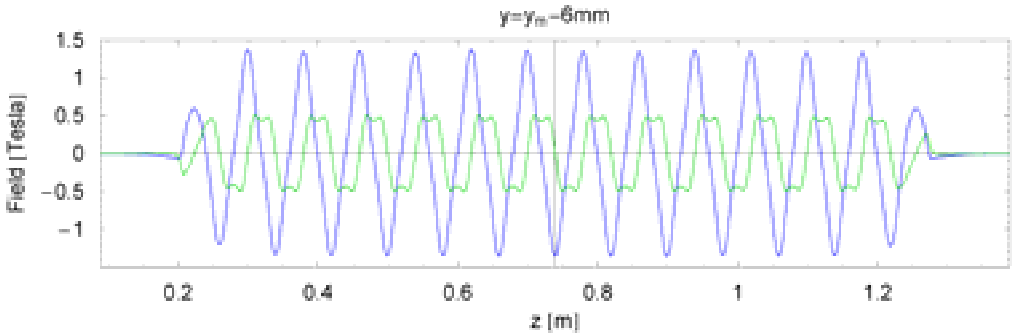
- Misalignment of Hall probe?
- Upper and Lower magnetic arrays not properly aligned along z?

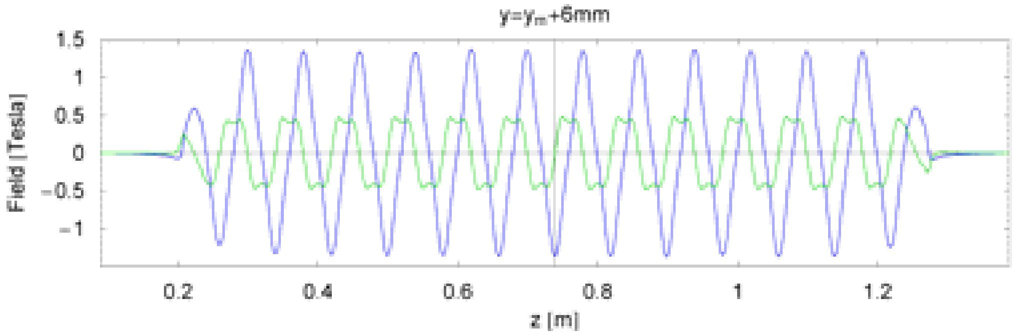
(b) MPW80: analysis of minor components

Characteristics of B_z: component in phase

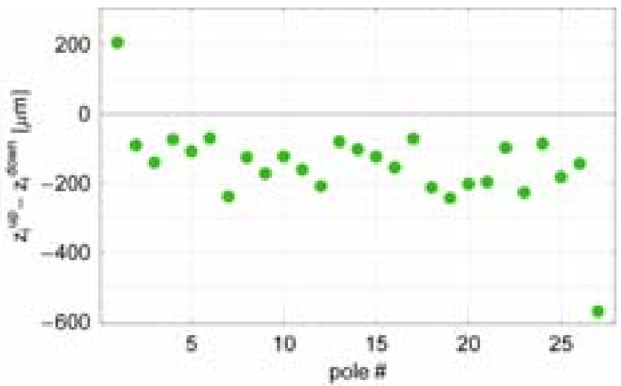
Upper and Lower magnetic arrays not properly aligned along z?

$\rightarrow$Determination of pole positions away from mid-plane





measurements @ gap=20mm

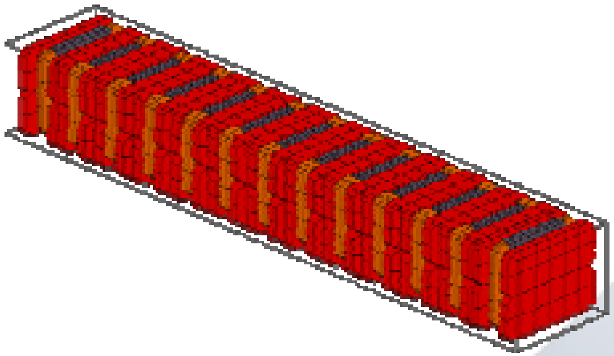


$$z^{up} - z^{down} = (-150 \pm 50)\,\mu m$$

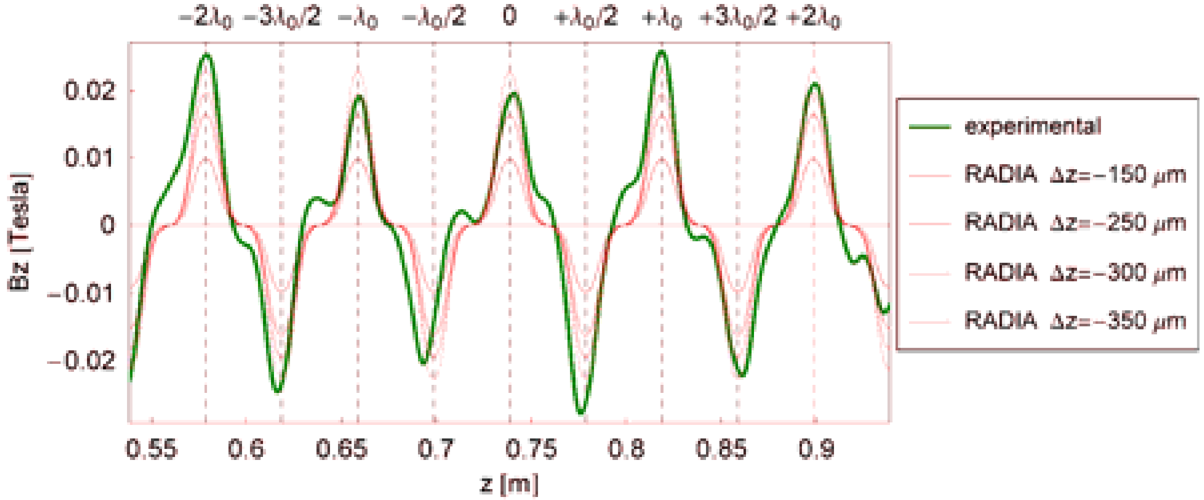
Differences between poles positions on two planes separated vertically Δy=12mm for a gap=20mm

(b) MPW80: analysis of minor components

RADIA model with Δz displacement between upper and lower jaws



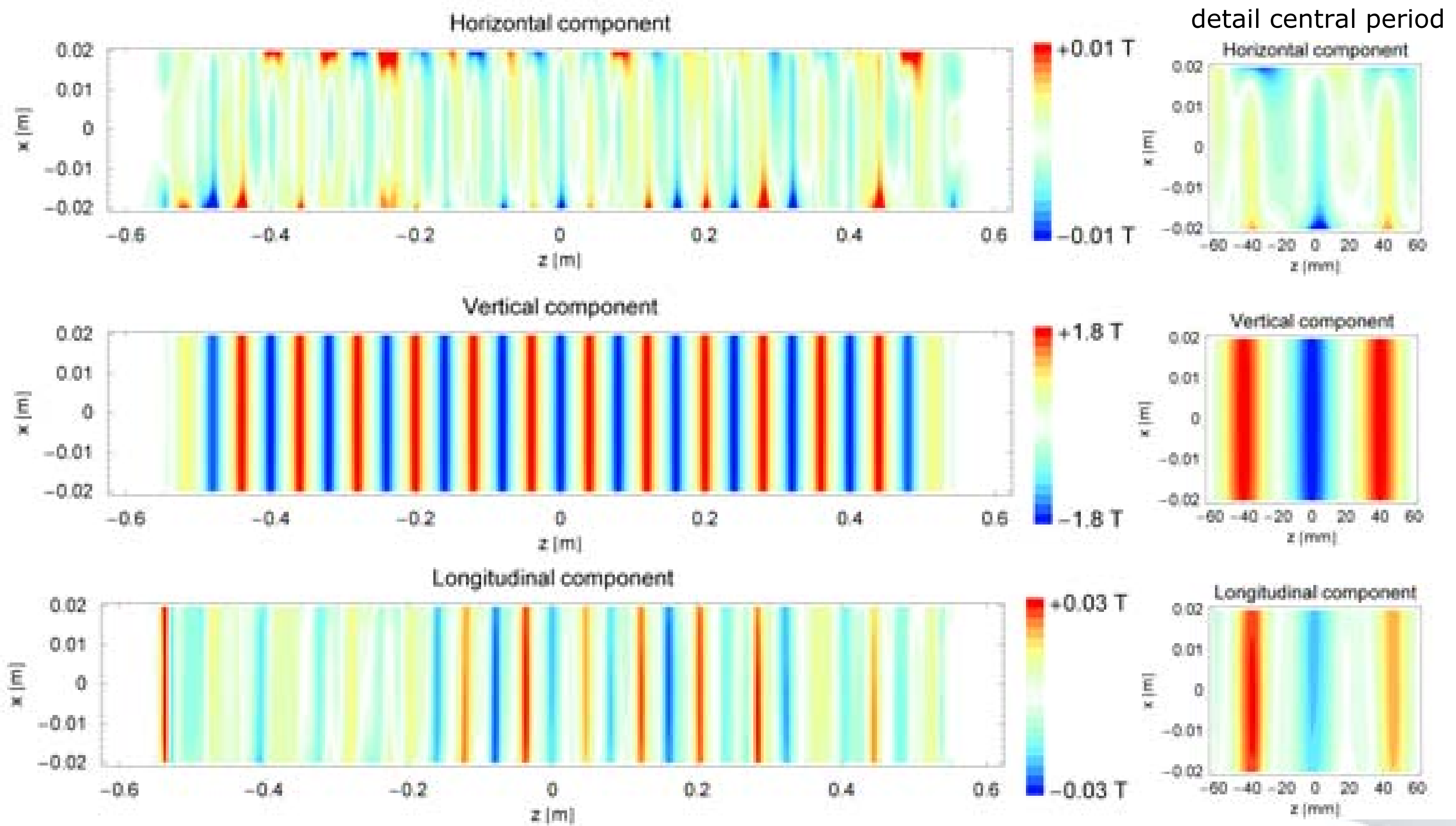
Measurements and simulations @ gap$_1$=12.9mm



Result according to RADIA simulations:	Δz~(-300±50)µm
Result according to z^{up}-z^{down} measurements correcting by a factor gap/Δy:	Δz~(-250±80)µm

(c) MPW80: magnetic axis determination

1st step: field map within magnetic mid-plane

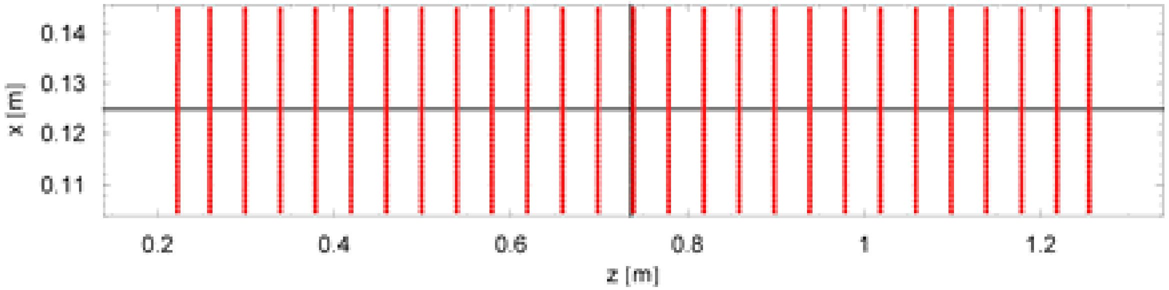


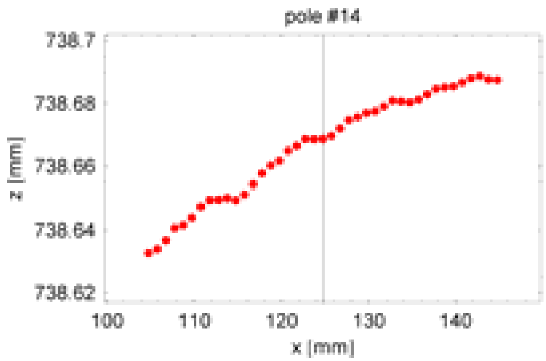
measurement @ gap_1=12.5mm & taper =0

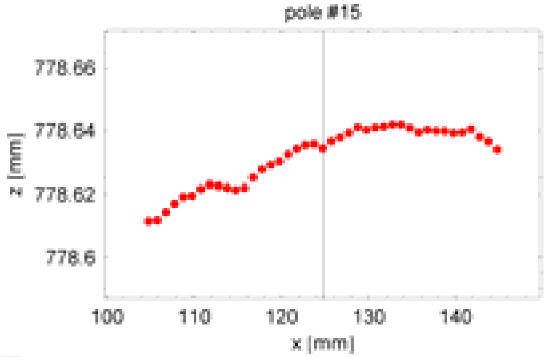
(c) MPW80: magnetic axis determination

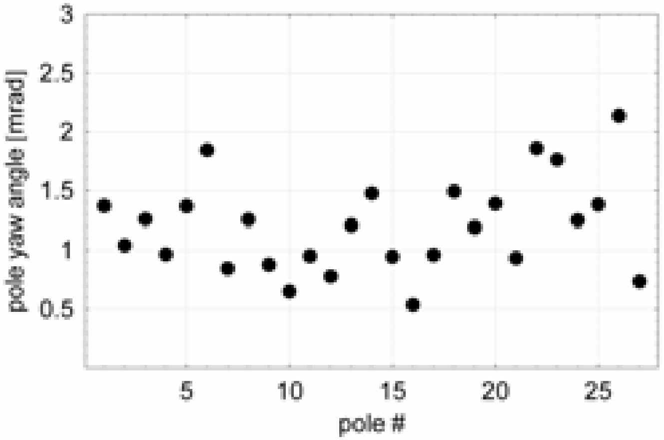
2nd step: determination of z-positions where $B_y(z,x)$ is max/min for x=ctant

$$\left.\frac{\partial B_y(z,x)}{\partial z}\right|_{z=z_i} = 0 \quad \text{for } i = 1 \ldots n_{poles}$$







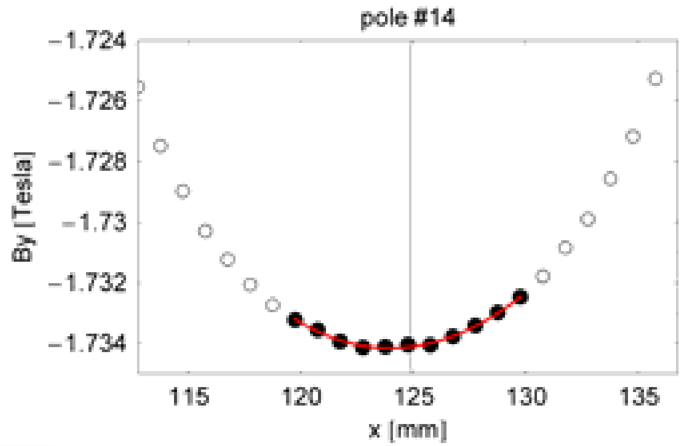


Yaw angle = (-1.2 ± 0.4) mrad

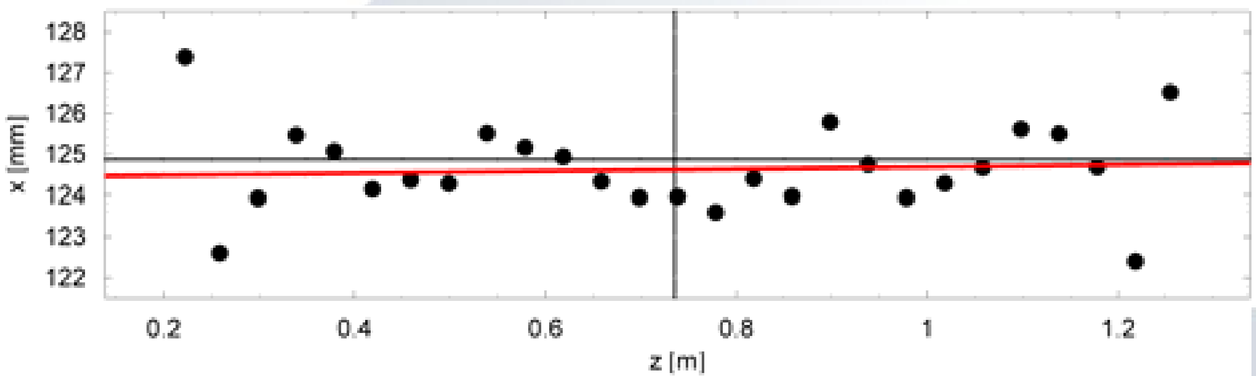
(c) MPW80: magnetic axis determination

3rd step: determination of the max/min of the magnetic field along the pole profile $z_i(x)$

$$\left.\frac{\mathrm{d}B_y\left[z_i(x),x\right]}{\mathrm{d}x}\right|_{(x_m)_i} = 0 \quad \text{for } i = 1 \ldots n_{\text{poles}}$$



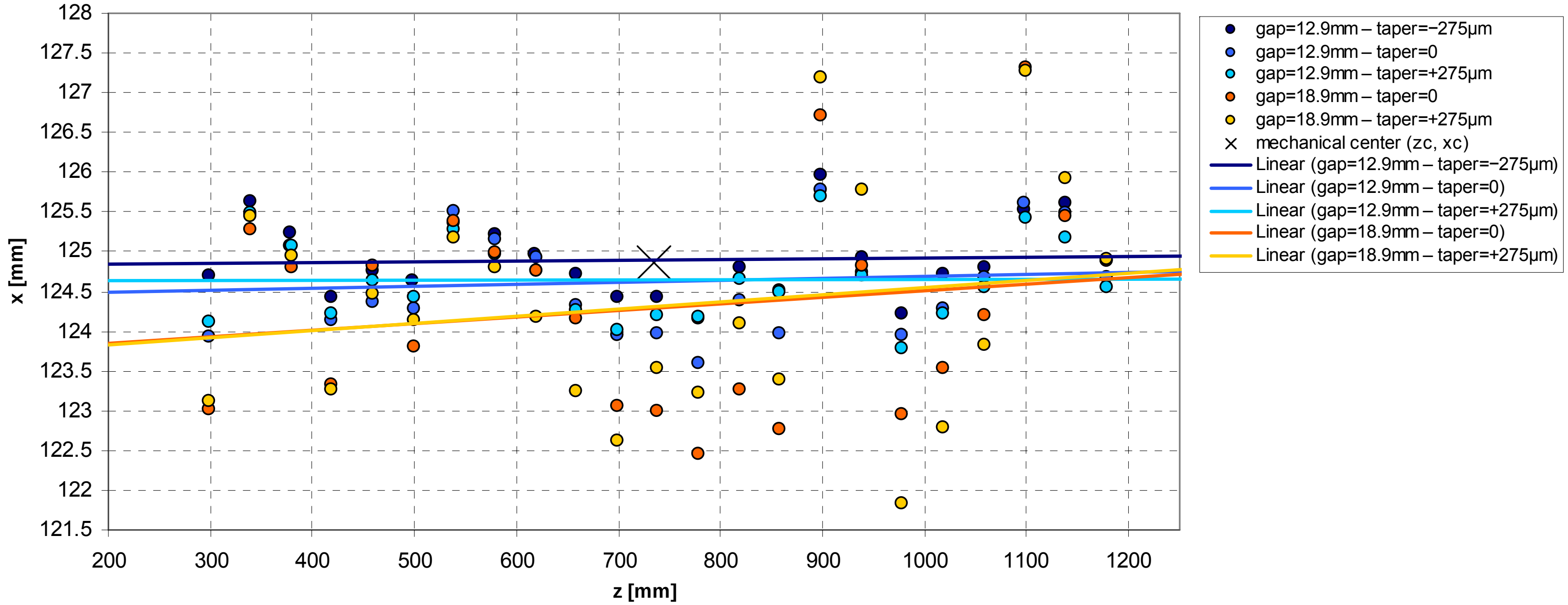
pole positions @ gap$_1$=12.5mm & taper =0



MPW80 magnetic axis (gap$_1$ = 12.9mm – taper = 0)	
Horizontal position (x_m)	(+124.620 ± 0.100) mm
Yaw angle	(+260 ± 500) μrad 😐

(c) MPW80: magnetic axis determination

4th step: repeat the process for different working configurations



MPW80 magnetic axis			
gap [mm]	taper [μm]	axis horizontal position $x_m(z_c)$ [mm]	axis yaw angle [μrad]
12.9	−275	$(+124.900 \pm 0.100)$	$(+95 \pm 400)$
12.9	0	$(+124.620 \pm 0.100)$	$(+260 \pm 500)$
12.9	+275	$(+124.650 \pm 0.100)$	$(+28 \pm 400)$
18.9	0	$(+124.290 \pm 0.300)$	$(+820 \pm 1000)$
18.9	+275	$(+124.310 \pm 0.300)$	$(+900 \pm 1000)$
Average		$(+124.550 \pm 0.090)$	$(+420 \pm 300)$

Results

(d) MPW80: magnetic center

MPW80 center							
Mechanical center [mm]		Magnetic center [mm]			Difference [μm]		
x_c	(124.867 ± 0.100)	x_o	(average all poles)	**(124.550±0.900)**	Δx	(-320 ± 900)	😐
		$(x_m)_{14}$	(central pole)	(123.820±0.600)		(-1050 ± 600)	
y_c	(-20.149 ± 0.100)	y_m	(B_y max/min)	(−20.535±0.050)	Δy	(-390 ± 100)	😐
		y_o	(B_z null)	**(−20.410±0.050)**		(-260 ± 100)	
z_c	(735.492 ± 0.100)	z_o	(average all poles)	**(738.750±0.250)**	Δz	$(+3300 \pm 250)$	☹
		$(z_m)_{14}$	(central pole)	(738.680±0.040)		$(+3200 \pm 100)$	

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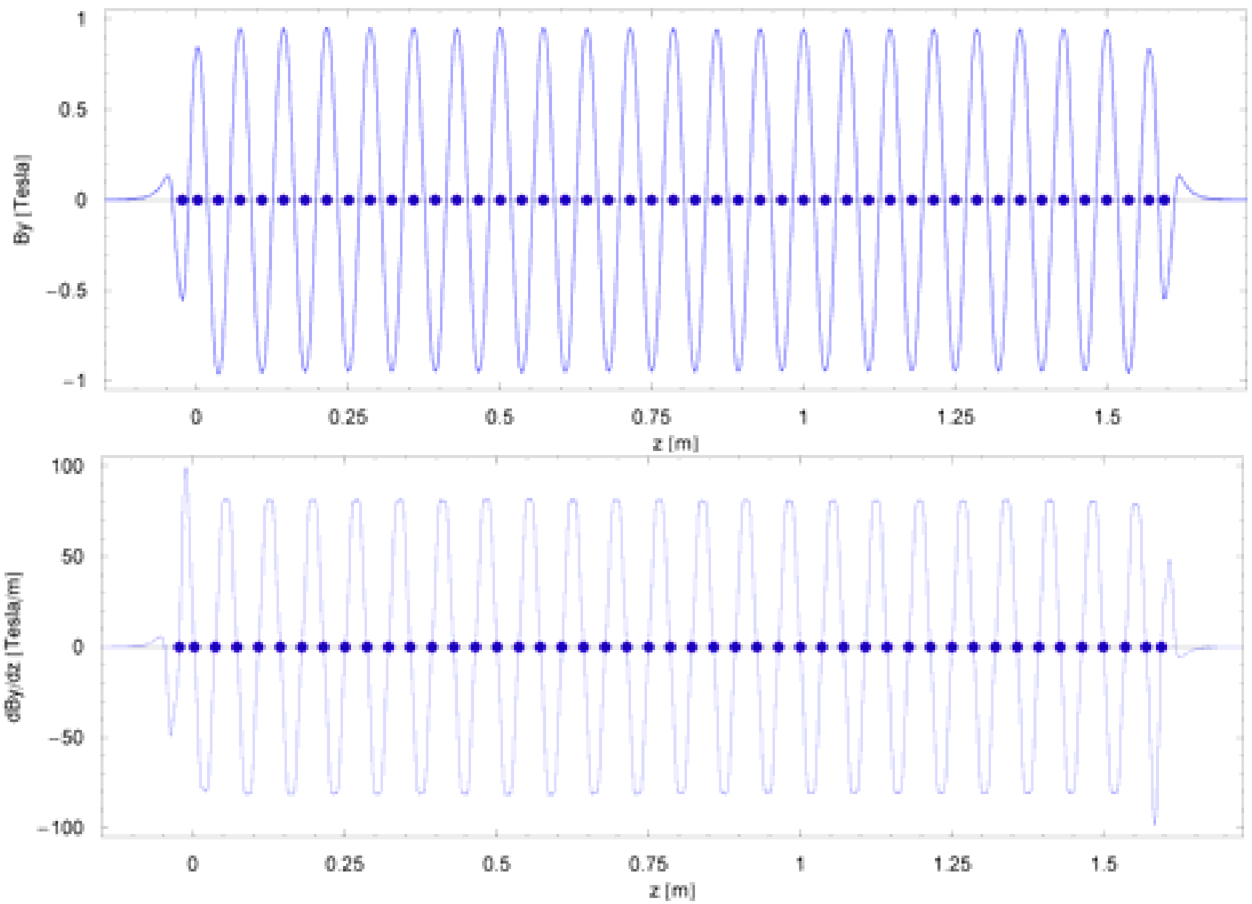
(a) EU71: magnetic mid-plane

1st step: determination of pole positions by means of longitudinal scan of B_y along nominal (mechanical) axis

measurement @ gap_{min}=15.5mm & phase=0



Condition to identify pole positions $\frac{dB_y}{dz} = 0$

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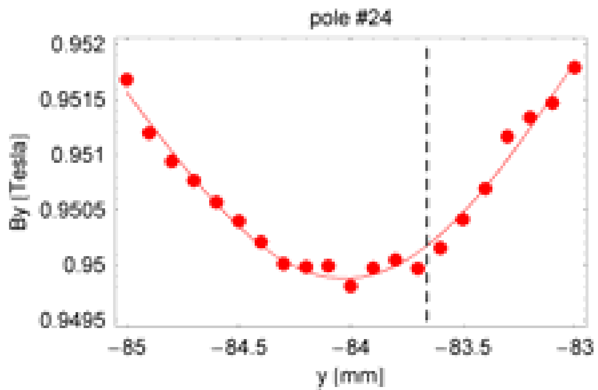
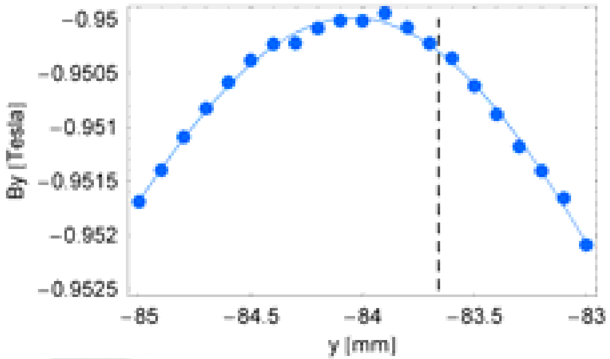
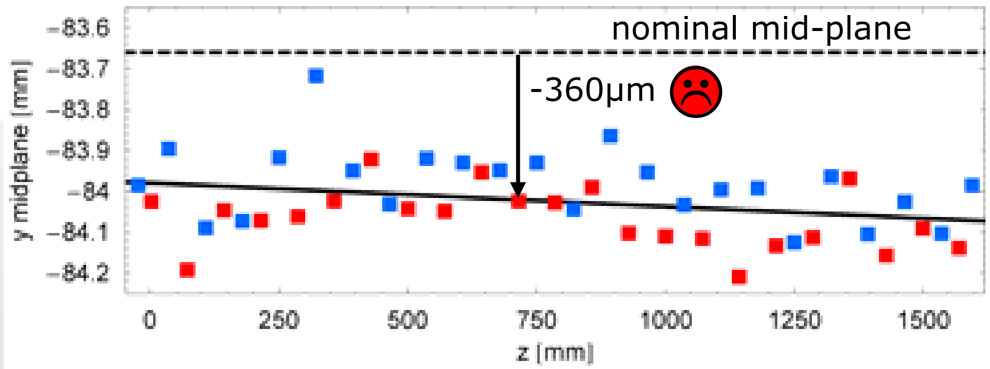




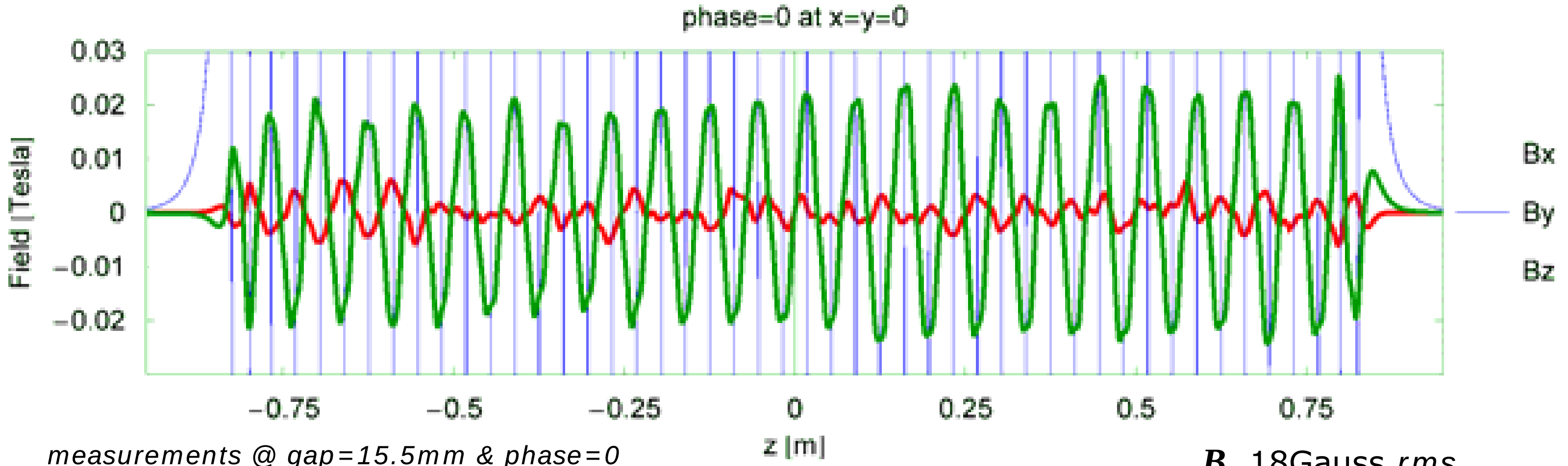
measurements @ gap_{min}=15.5mm



EU71 magnetic mid-plane (B_y – gap = 15.5 mm – phase = 0)	
Vertical position (y_m)	(-84.024 ± 0.010) mm
Tilt angle (pitch)	$(-58 \pm 25)\,\mu$rad

(b) EU71: analysis of minor components

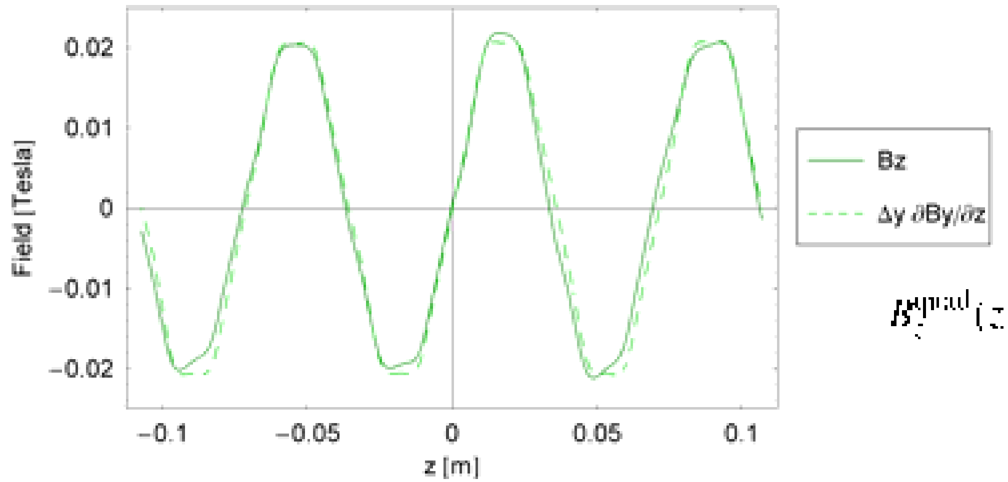
Minor components along magnetic mid-plane



measurements @ gap=15.5mm & phase=0

B_x 18Gauss *rms*

B_z 0.02Tesla amplitude

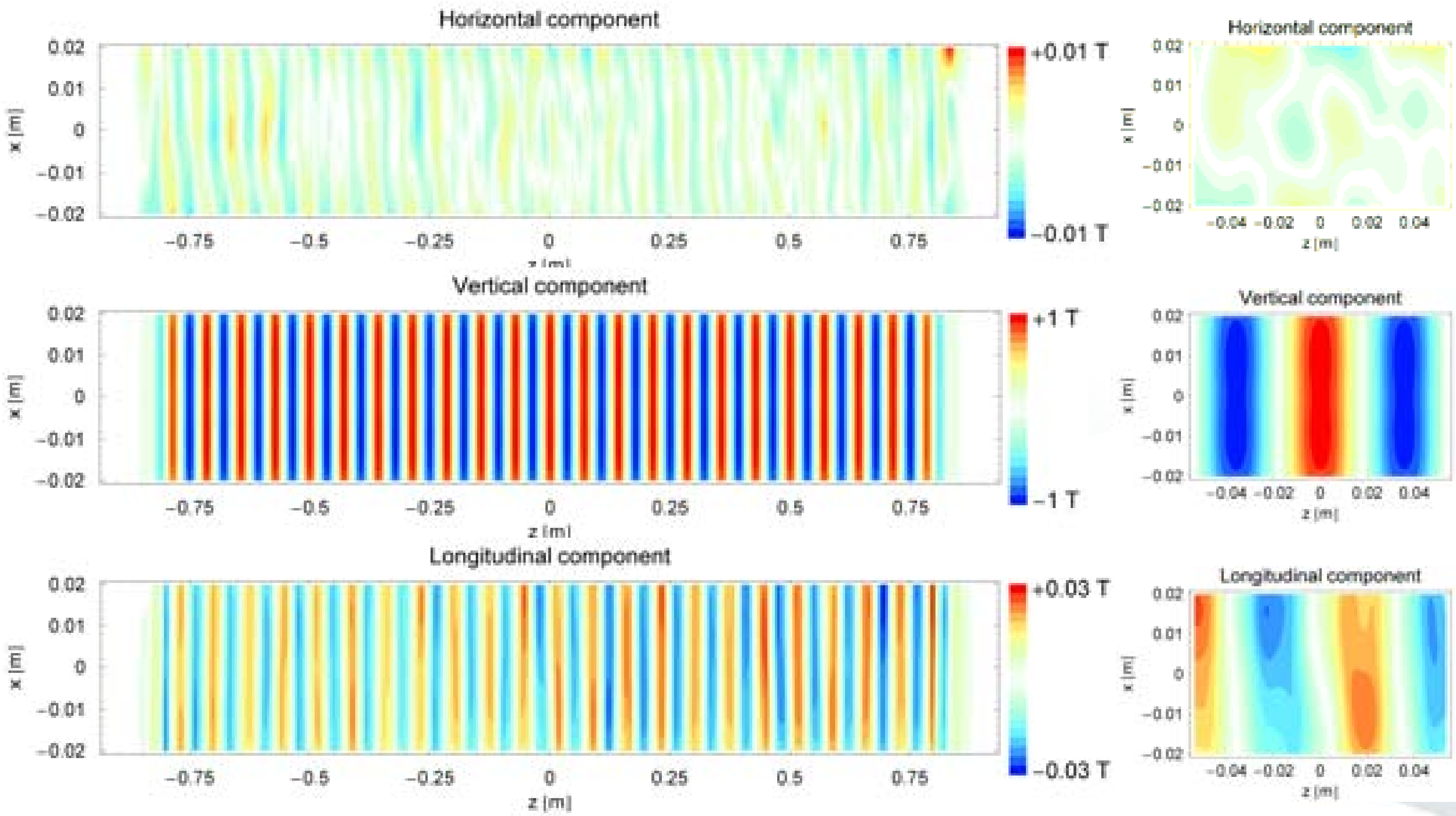


$$B_z^{appar}(z,y) \approx \Delta y \frac{\partial B_y}{\partial z} \Rightarrow \boxed{\Delta y = (-255 \pm 25)\,\mu m}$$

(c) EU71: magnetic axis determination

1st step: field map within magnetic mid-plane

detail central period

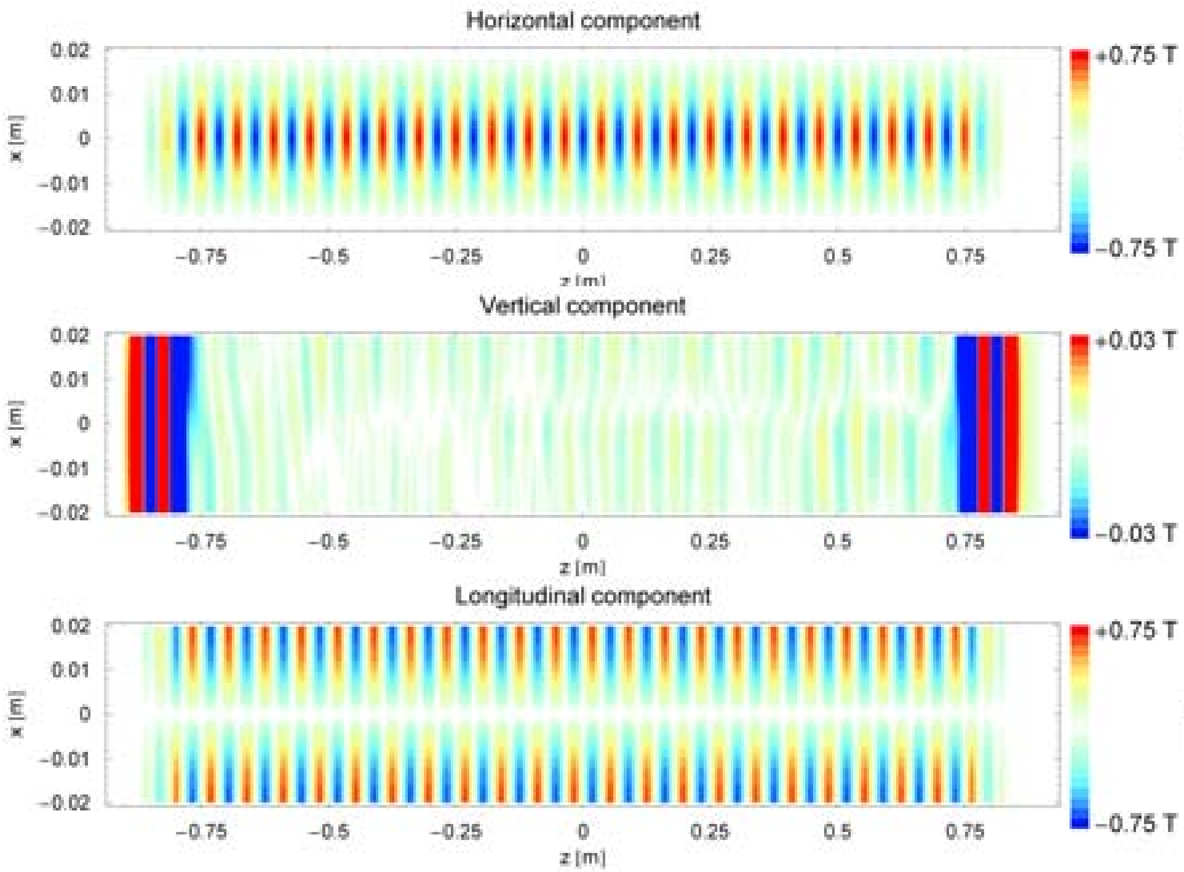


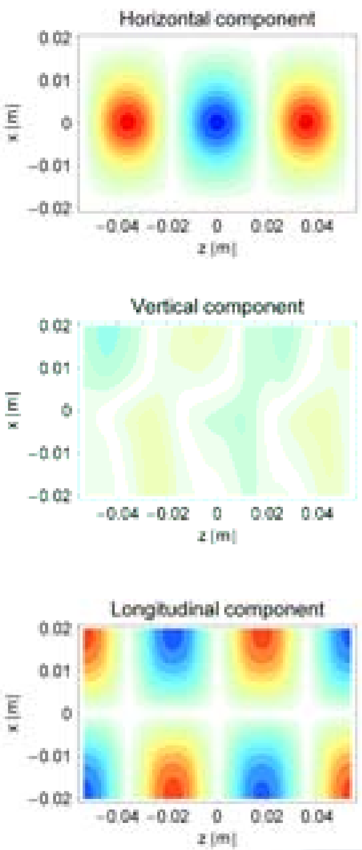
measurement @ gap=15.5mm & phase =0

(c) EU71: magnetic axis determination

1st step: field map within magnetic mid-plane

detail central period



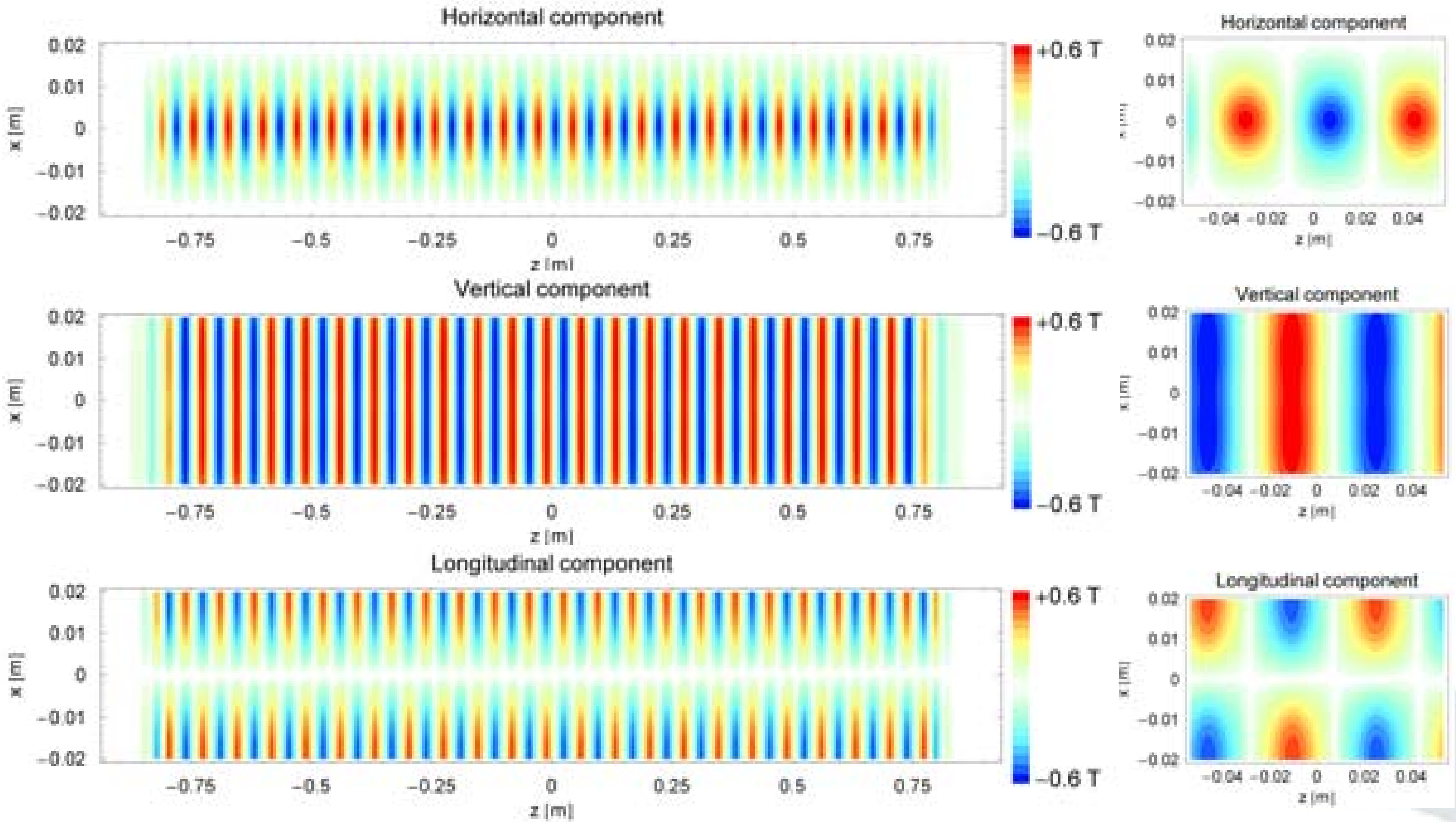


measurement @ gap=15.5mm & phase =180°

(c) EU71: magnetic axis determination

1st step: field map within magnetic mid-plane

detail central period



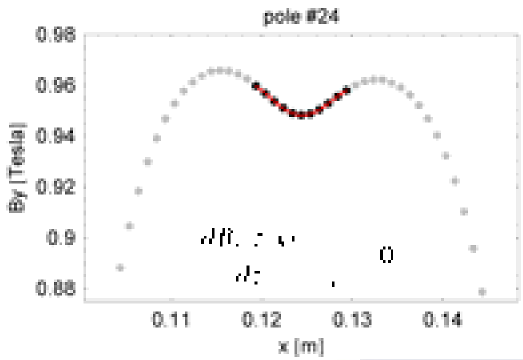
measurement @ gap=15.5mm & phase =107º (circular)

(c) EU71: magnetic axis determination

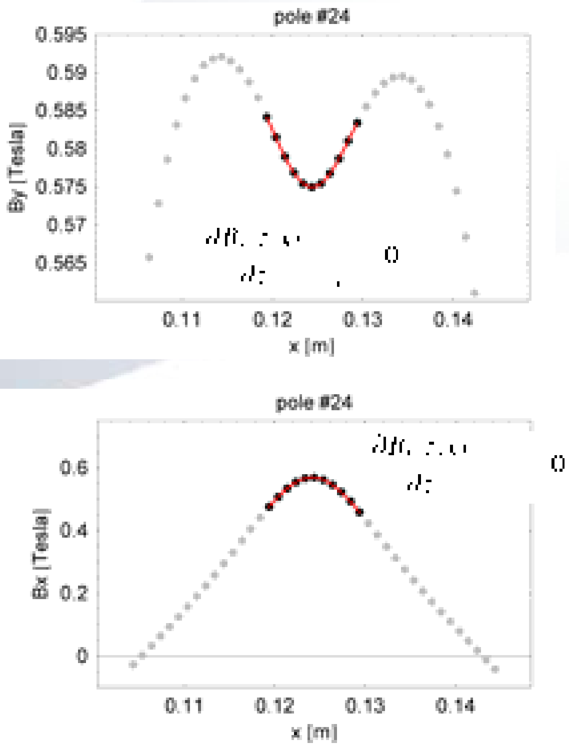
2nd step: determination of z-positions where $B_y(z,x)$ and/or $B_x(z,x)$ is max/min for x=ctant

3rd step: determination of the max/min of the magnetic field along the pole profile $z_i(x)$

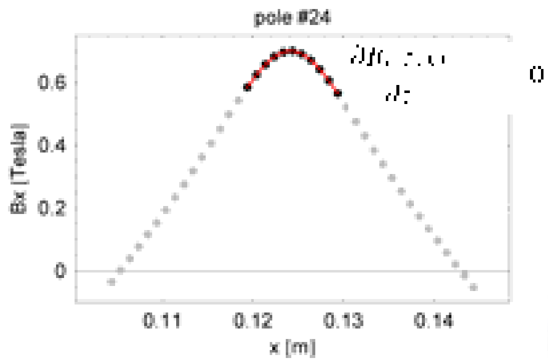
H-mode (phase 0)



C-mode (phase 107º)

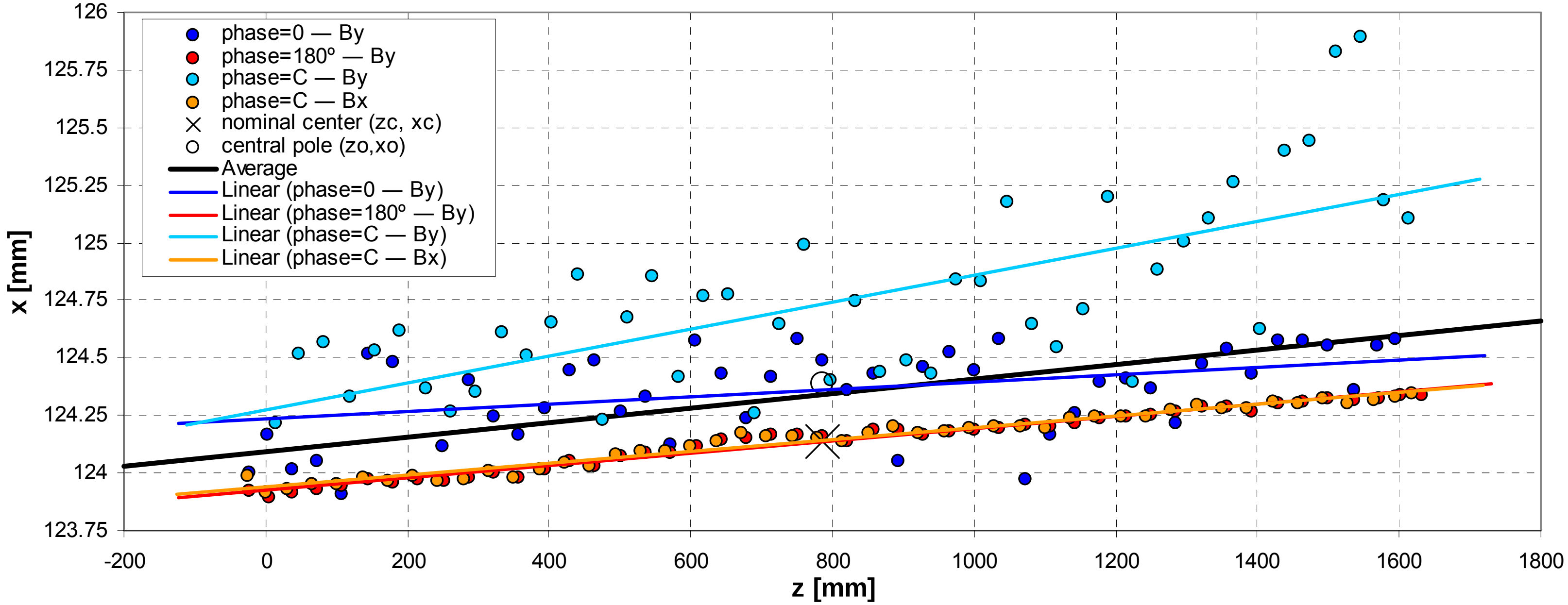


V-mode (phase 180º)



(c) EU71: magnetic axis determination

4^{th} step: repeat the process for different working configurations



EU71 magnetic axis		
configuration	axis horizontal position $x_m(z_c)$ [mm]	axis yaw angle [μrad]
phase 0 – B_y component	$(+124.360 \pm 0.030)$	$(+160 \pm 60)$
phase C – B_y component	$(+124.734 \pm 0.040)$	$(+590 \pm 90)$
phase C – B_x component	$(+124.138 \pm 0.005)$	$(+290 \pm 6)$
phase 180° – B_x component	$(+124.133 \pm 0.005)$	$(+267 \pm 6)$
Average	$(+124.339 \pm 0.040)$	$(+320 \pm 50)$ 😐

(d) EU71: magnetic center

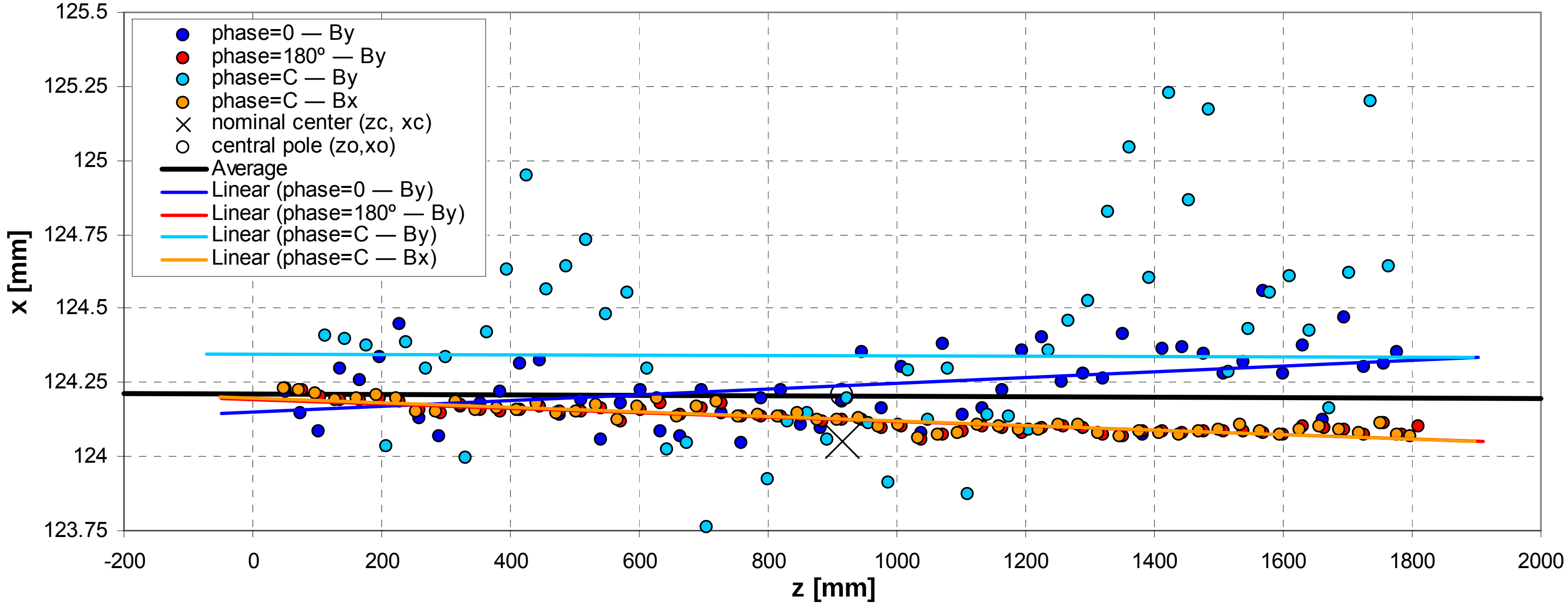
EU71 center						
Mechanical center [mm]		Magnetic center [mm]			Difference [μm]	
x_c	(124.136 ± 0.100)	$(x_{mH})_{24}$	(central pole phase 0)	(124.486 ± 0.050)	Δx 😐	$(+350 \pm 100)$
		$(x_{mV})_{24}$	(central pole phase 180°)	(124.159 ± 0.050)		$(+25 \pm 100)$
y_c	(-83.660 ± 0.100)	y_m	(B_y max/min)	(-84.024 ± 0.010)	Δy 😐	(-360 ± 100)
		y_o	(B_z null)	(-83.769 ± 0.050)		(-110 ± 100)
z_c	(785.605 ± 0.100)	$(z_{mH})_{24}$	(central pole phase 0)	(786.009 ± 0.030)	Δz 😐	$(+400 \pm 100)$
		$(z_{mV})_{24}$	(central pole phase 180°)	(786.220 ± 0.030)		$(+600 \pm 100)$

Outline

- Introduction
  - Measured Insertion Devices
  - Magnetic Measurements system
  - Alignment procedure
- Obtained results
  - MPW80
  - EU71
  - EU62
  - Field Integrals agreement
- Conclusions

(c) EU62: magnetic axis determination

4th step: repeat the process for different working configurations



EU62 magnetic axis		
configuration	axis horizontal position $x_m(z_c)$ [mm]	axis yaw angle [μrad]
phase 0 – B_y component	$(+124.239 \pm 0.015)$	$(+94 \pm 30)$
phase C – B_y component	$(+124.330 \pm 0.070)$	$(+35 \pm 100)$
phase C – B_x component	$(+124.128 \pm 0.003)$	(-75 ± 6)
phase 180º – B_x component	$(+124.126 \pm 0.003)$	(-74 ± 5)
Average	$(+124.200 \pm 0.040)$	(-7 ± 30)

(d) EU62: magnetic center

EU62 center					
Mechanical center [mm]		Magnetic center [mm]			Difference [μm]
x_c	(124.050 ± 0.100)	$(x_{mH})_{29}$	(central pole phase 0)	(124.180 ± 0.050)	Δx $(+130 \pm 100)$
		$(x_{mV})_{29}$	(central pole phase 180°)	(124.120 ± 0.050)	$(+70 \pm 100)$
y_c	(-86.277 ± 0.100)	y_m	(B_y max/min)	(-86.240 ± 0.060)	Δy $(+40 \pm 100)$
		y_o	(B_z null)	(-86.000 ± 0.050)	$(+280 \pm 100)$
z_c	(914.131 ± 0.100)	$(z_{mH})_{29}$	(central pole phase 0)	(914.530 ± 0.030)	Δz $(+400 \pm 100)$
		$(z_{mV})_{29}$	(central pole phase 180°)	(914.710 ± 0.030)	$(+580 \pm 100)$

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Field integrals agreement

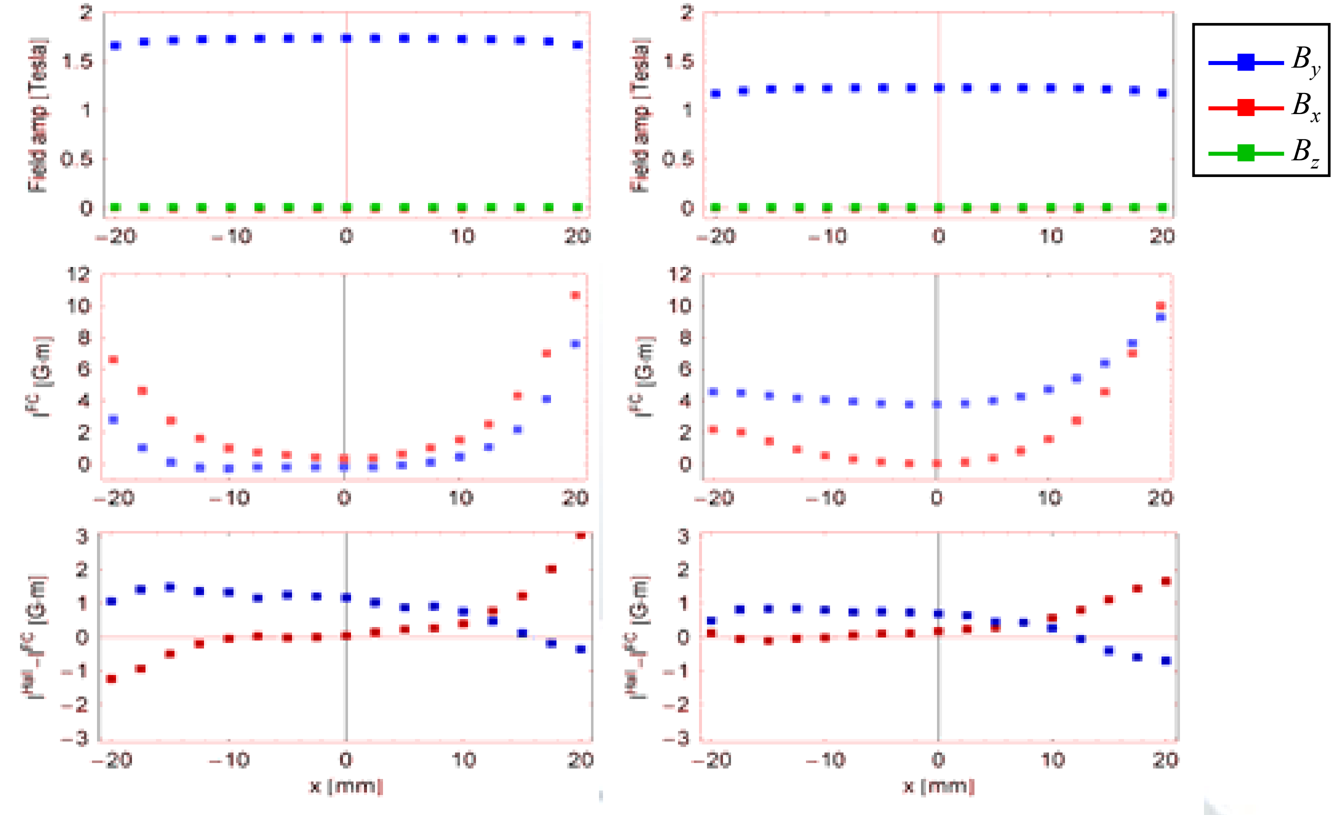
MPW80

gap=12.9mm gap=18.9mm

Magnetic field amplitude along z

Field Integrals measured using Flipping Coil (FC)

Difference between Field Integrals determined using Hall probe and FC



Discrepancies up to 3 G·m

Field integrals agreement

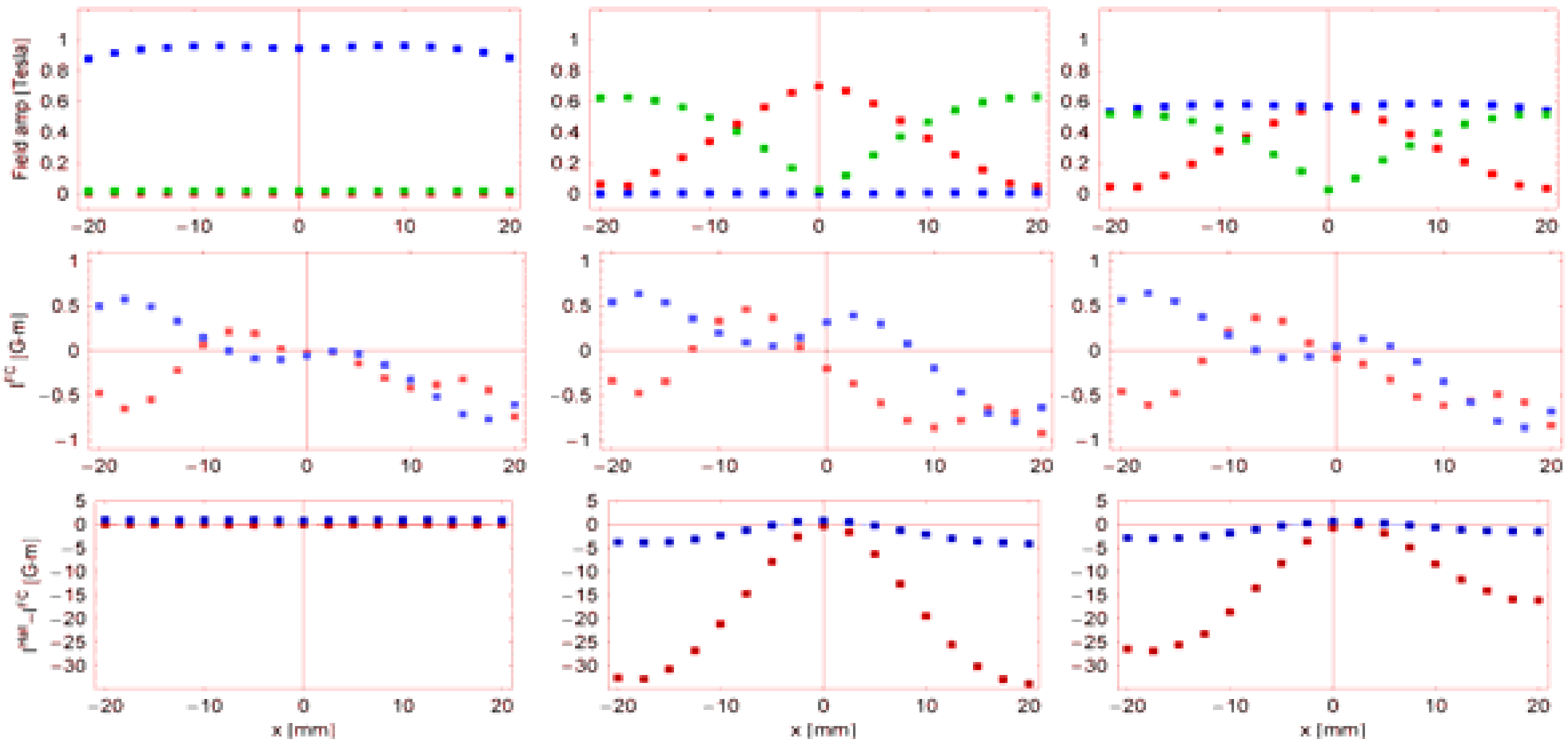
EU71

phase 0 phase 107º phase 180º

Magnetic field amplitude along z

Field Integrals measured using Flipping Coil (FC)

Difference between Field Integrals determined using Hall probe and FC



Discrepancies up to 30 G·m!

We introduce in Hall probe measurements a correction term proportional to $(B_z)^2$ in order to reproduce FC Field Integral measurements

Conclusions

- Magnetically determined magnetic center of IDs in agreement with mechanical data provided by manufacturers typically within $\lesssim$0.5mm
- Tilt angle of magnetic mid-plane always <150μrad
- Yaw angle of magnetic axis <500μrad. Some ambiguity depending on the method used to determine it.
- Magnetic measurements have revealed some minor manufacturing imperfections (yaw misalignment of magnetic poles, misalignment along longitudinal direction of upper and lower magnetic arrays…).
- Systematic discrepancy of ~200-300μm between the vertical location of the plane where B_y is max/min and the plane where B_z=0 $\rightarrow$ relative positions between Hall sensors to be revisited?
- A term proportional to $(B_Z)^2$ has been introduced into B_x and B_y Hall probe data in order to match Flipping Coil Field Integral measurements.

Thanks for your attention