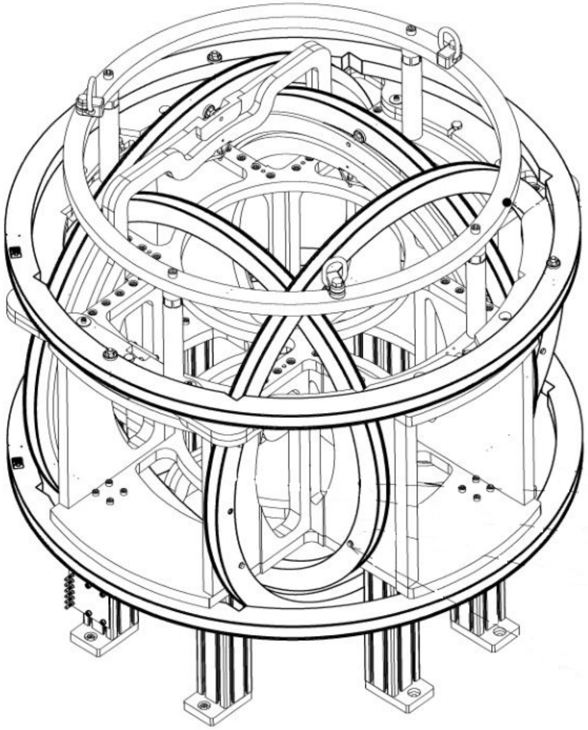
TE-MSC-MM

Magnetic Field Compensation with Helmholtz Coils



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Outline

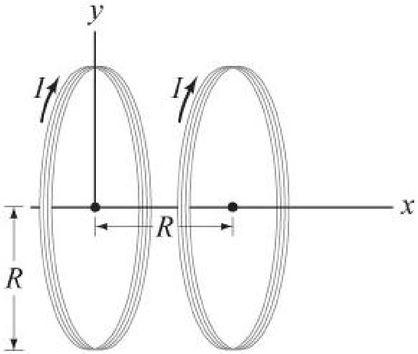
- ✓ What is a Helmholtz Coil?
- ✓ Why do we need a Helmholtz Coil?
- ✓ Specification & Design
- ✓ Construction
- ✓ Geometrical Measurements
- ✓ Magnetic Measurements
- ✓ Powering & Control System
- ✓ What comes next…?

What is a Helmholtz Coil?

Named after the German physicist Hermann von Helmholtz (1821 – 1894)

Def.: (**Merriam-Webster**)
One of two equal parallel coaxial circular coils in series that are separated from each other by a distance equal to the radius of one coil for producing an approximately uniform magnetic field in the space between the coils.

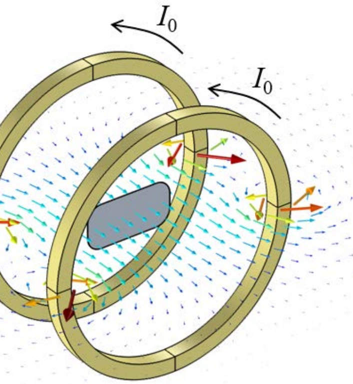
- Two equal circular coils (solenoids)
- Placed symmetrically on the same axis
- Separated by a distance equal to the radius of the coils ($h = R$)
- Both coils powered by identical current in the same direction
- Generate a homogeneous field in the centre between the two coils
- Can be also used in a passive mode as pick-up coils



Field in a Helmholtz coil:

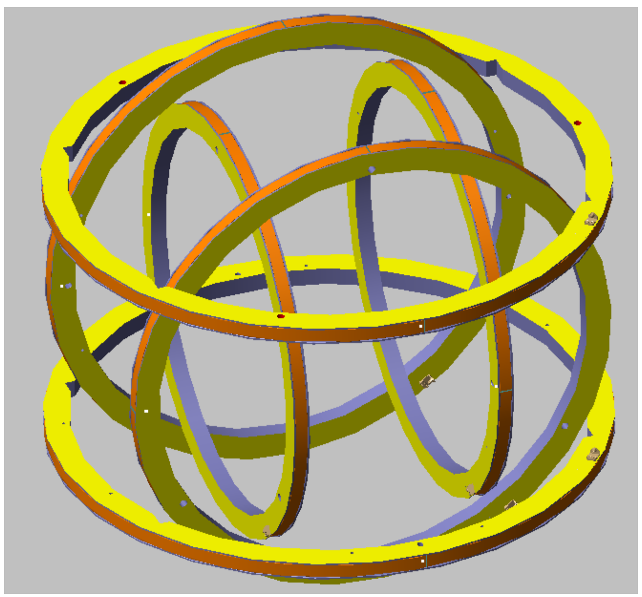
$$B = \left(\frac{4}{5}\right)^{\frac{3}{2}} \mu_0 \frac{NI}{r} \qquad [\mathrm{T}]$$

I = current [A]
N = number of turns
r = coil radius [m]
μ_0 = permeability [$4\pi \times 10^{-7}$ kg·m/(s²·A²)]



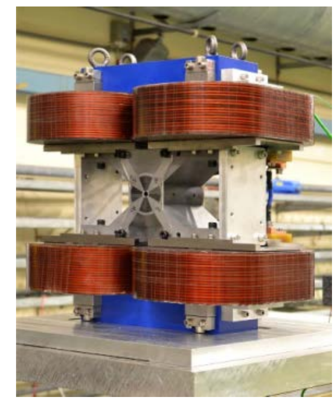
Why do we need a Helmholtz Coil?

Active mode to create a zero-field volume (earth field compensation) or any arbitrary field vector to calibrate magnetic field sensors

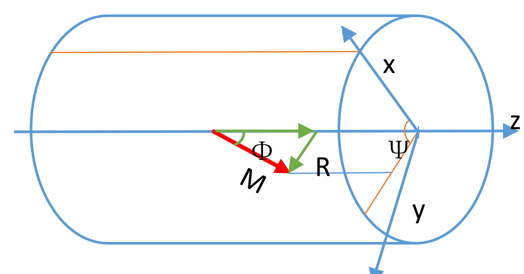


Passive mode to characterize permanent magnets by measuring the magnitude and direction of the magnetic moment

Halbach array in a Linac 4 PMQ



Permanent magnets in the CLIC Q0 Hybrid Quadrupole



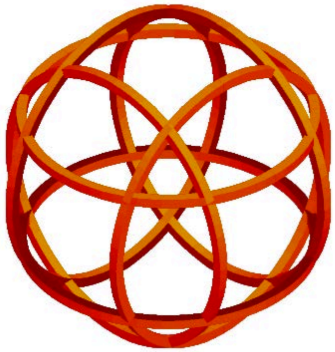
Specification & Design

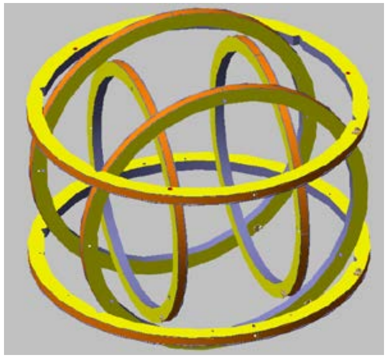
Specification

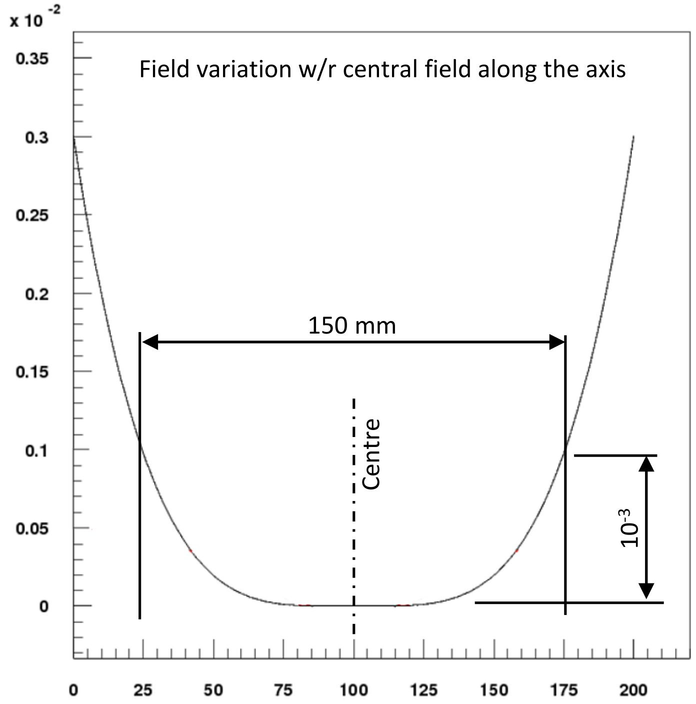
- 3D Arrangement to be operated in active and passive mode
- Good-field region: 150 mm x 150 mm x 150 mm
- Field per axis: 5 – 10 Gauss
- Field homogeneity in GFR: < 10 units (= 10 x 10^{-4})

Design

- Coil radius: r = ~500 mm
- Enamelled copper wire: Ø = 0.5 mm
- Current: I = 0.2 A corresponds to J = ~1 A/mm^2
- Number of turns: N = ~2200
- Max. field: B = 7.9 Gauss

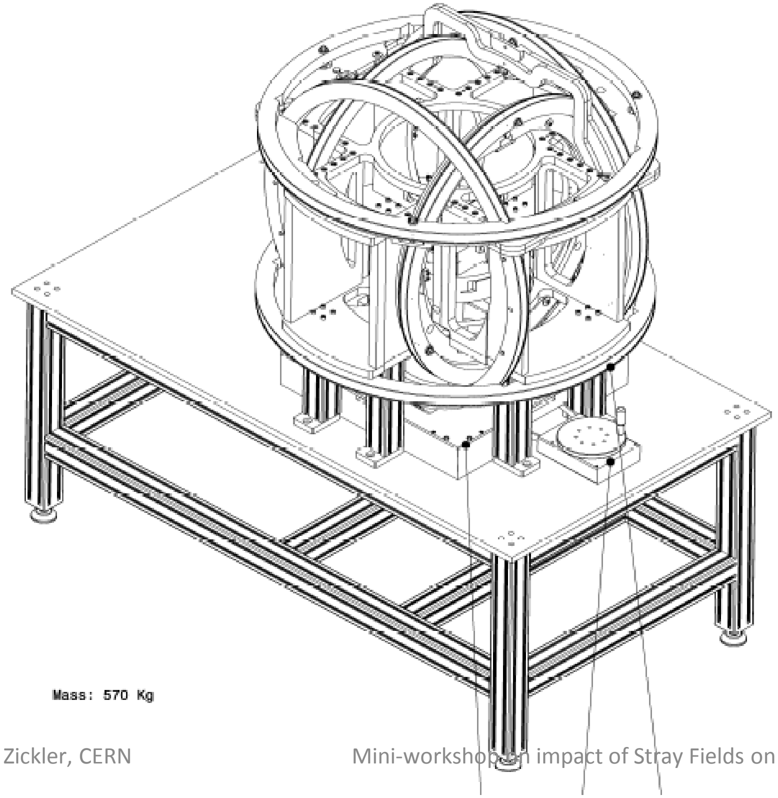


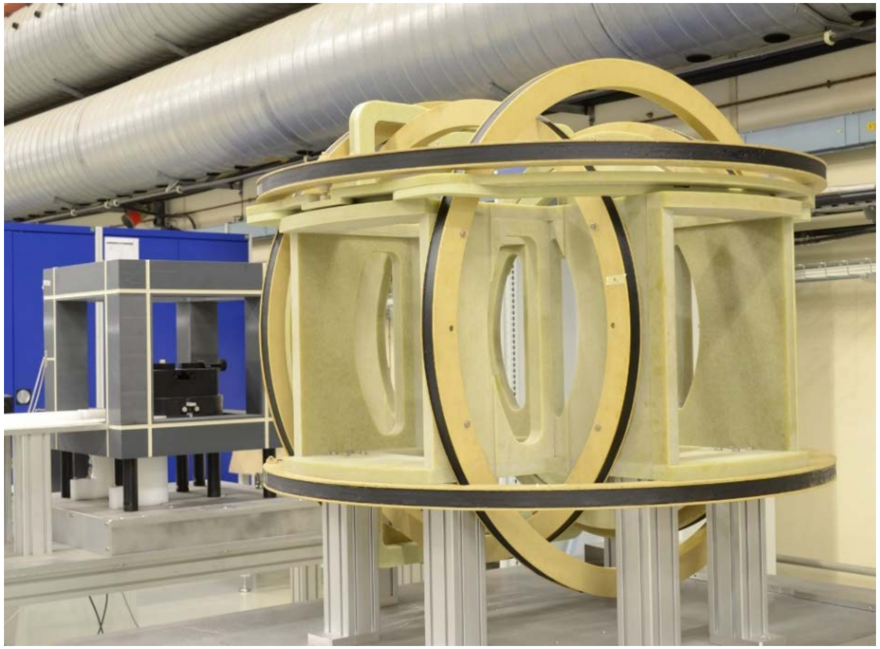




Construction

- Solid support and coil cores from EPGM 203 (G11)
- Machining accuracy < 0.1 mm
- Wide aperture to introduce easily probes and samples
- 1 fixed coil per axis
- 1 adjustable coil per axis to align distance, concentricity and parallelism
- Each coil individually cabled (Helmholtz ↔ Maxwell)





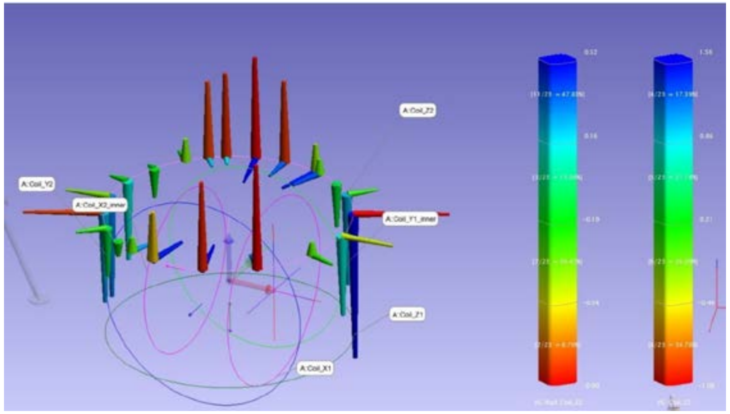
	Radius [mm]	Nb. Turns	Resistance [Ω]	Inductance [H]	Exp. field @ 0.2 A [G]
Coils x	436.5	1955	497	8.3	8.05
Coils y	497.5	2225	645	12.3	8.04
Coils z	563.0	2522	825	17.8	8.05

Geometrical Measurements

Geometrical measurements with Leica AT402 Laser tracker system to identify possible construction and assembly errors

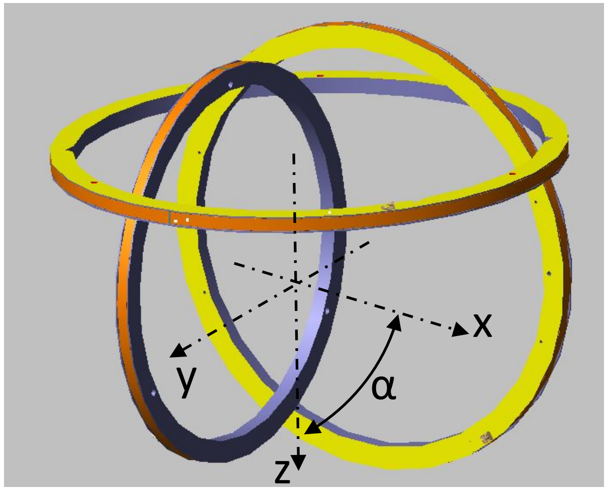
Flatness of the coils:

Coils	min (mm)	max (mm)	abs. (mm)
x_f	-0.40	0.41	0.81
X_a	-0.08	0.12	0.20
Y_f	-0.11	0.17	0.28
Y_a	-0.33	0.38	0.71
z_f	-0.36	0.31	0.67
z_a	-1.50	1.04	2.54



Important irregularity of flatness on the adjustable z-coil

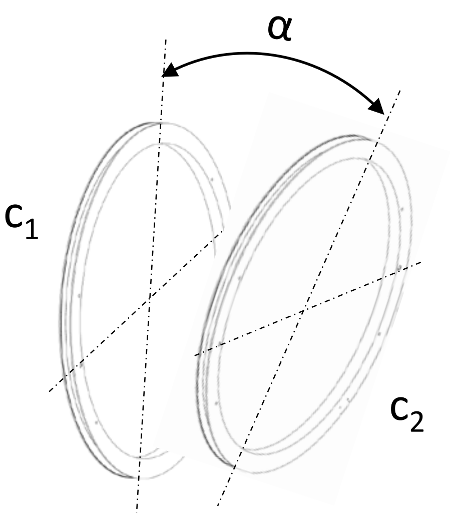
Geometrical Measurements



Perpendicularity between fixed coils:

Coils	A (deg.)	Δα (deg.)	Δα (mrad)
x_f - y_f	89.966	0.034	0.57
x_f - z_f	89.963	0.037	0.65

Perpendicularity: < 0.037°



Parallelism between fixed and adjustable coil:

Coils	α (deg.)	α (mrad)
x_f - x_a	0.0456	0.80
y_f - y_a	0.0953	1.66
z_f - z_a	0.0791	1.38

Tilt angle: < 0.096°

Geometrical Measurements

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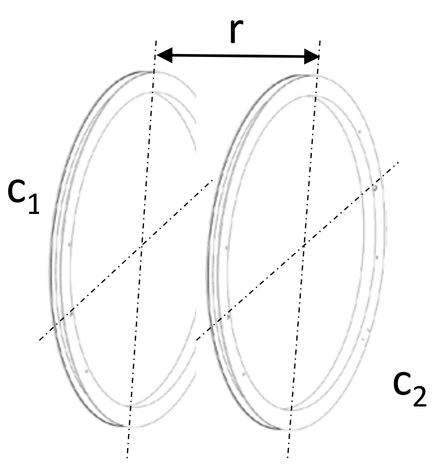
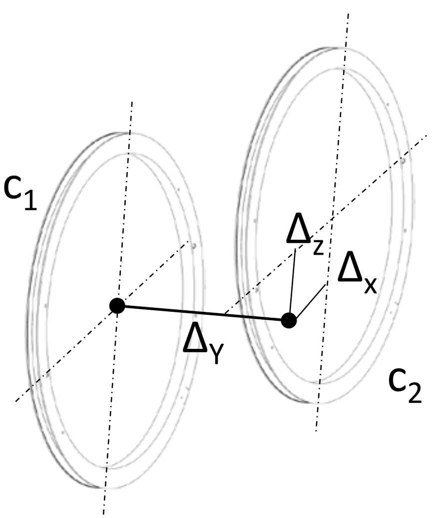


Distance between fixed and adjustable coil:

Coils	r_{theory} (mm)	r_{real} (mm)	Δr (mm)
$x_f - x_a$	436.5	436.29	0.21
$y_f - y_a$	497.5	497.41	0.09
$z_f - z_a$	563.0	563.30	0.30

Helmholtz condition violation: < 0.53%



Concentricity between fixed and adjustable coil:

Coils	X (mm)	Y (mm)	Z (mm)
$x_f - x_a$	---	0.33	0.75
$y_f - y_a$	0.01	---	0.47
$z_f - z_a$	0.31	0.57	---

Axis misalignment: < 0.75 mm

Geometrical Measurements

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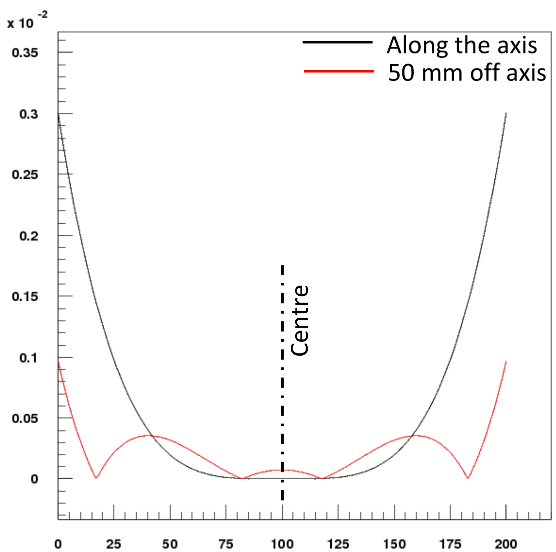
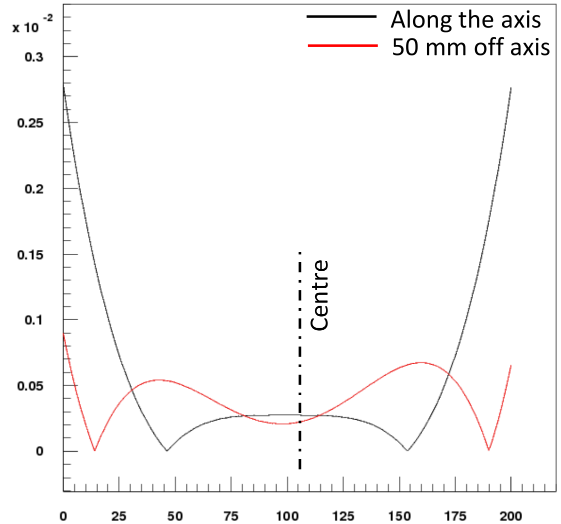
Homogeneous field size and the effect of the geometrical defaults on the good field (Roxie simulation for the smallest coil pair ($x_f - x_a$):



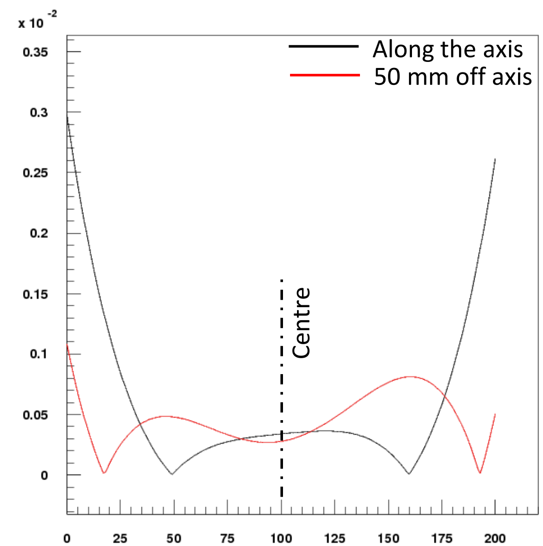
Coils as designed

- Field size: 150 mm
- Field variation: < 10^{-3}



Coils with geometrical defaults

- Field size: 150 mm
- Field variation: < 10^{-3}

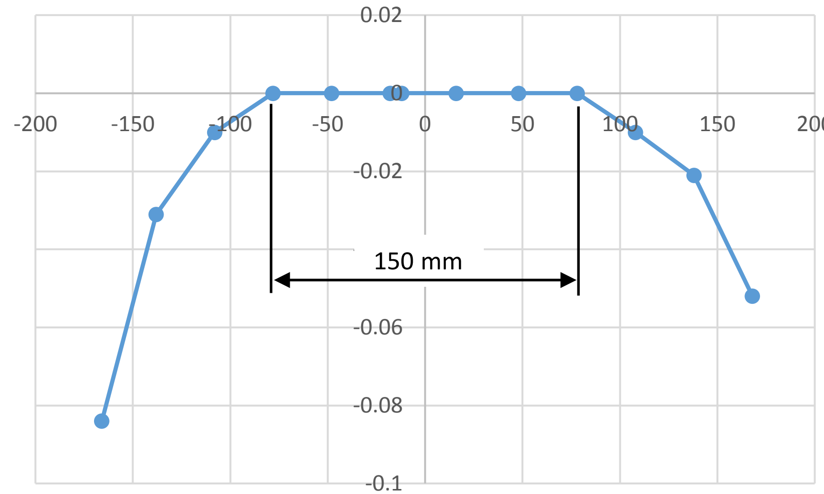


Demonstration:
Simulated angle of 2º between x_f and x_a
Visible effects on the homogeneous field for wider angles [e = f (cos α)]

Effects < 10^{-3} on the homogeneous field.
Min. homogeneous field size (for x_f - x_a): 150 mm (y_f - y_a =190 mm, z_f - z_a = 220 mm).

Magnetic Measurements

Bartington 3D fluxgate Bartington Mag-03MS1000
Range: 0 to 10 G, resolution 0.01 G



Measured field homogeneity for the smallest coils (x) at 200 mA

Central field at 200 mA

Coils	B_{design} (G)	$B_{mes.}$ (G)	ΔB (G)
$x_f - x_a$	8.05	8.30	0.25
$y_f - y_a$	8.04	8.39	0.35
$z_f - z_a$	8.05	8.30	0.25

Reason to be investigated…

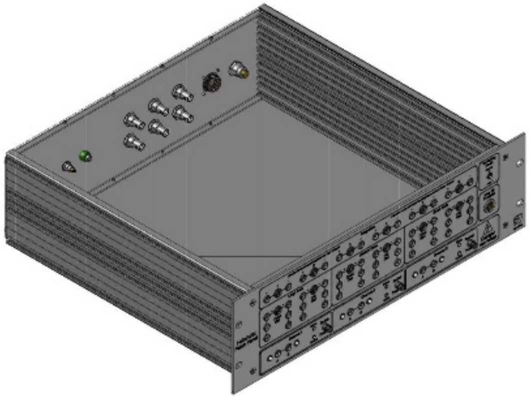
Powering & Control System

Patch Panel to switch between:

- passive mode: characterization of permanent magnets
- active mode: create zero-field or any arbitrary field vector *B*

Technical characteristics of control system:

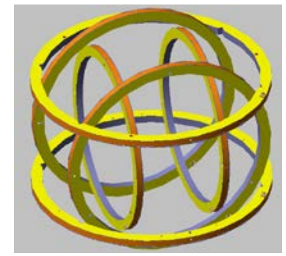
- Automatic earth-field compensation
- Max. zero-field offset: ± 51 nT
- Independently adjustable field components B_x, B_y, B_z between 0-800 µT
- 1 nT resolution
- Pos. and neg. polarity for each axis (switch)
- Automatic compensation for alignment errors between sensor axis and Helmholtz coil axis



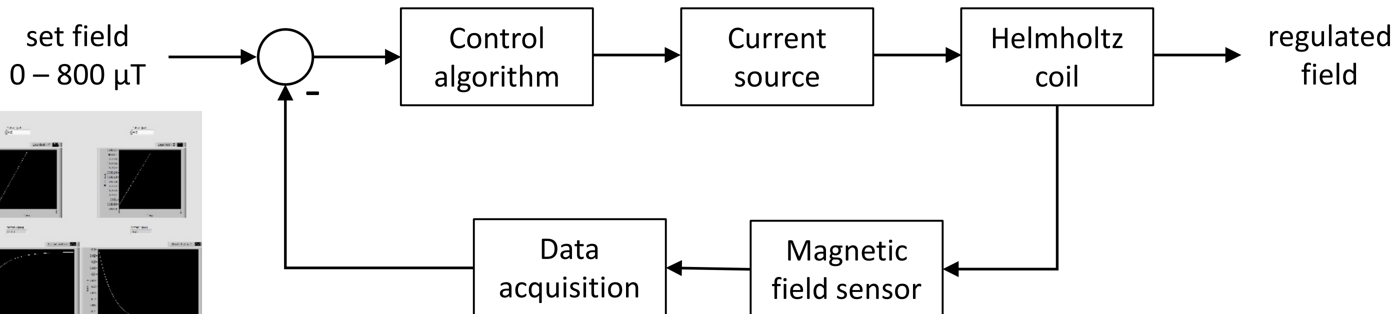
Powering & Control System

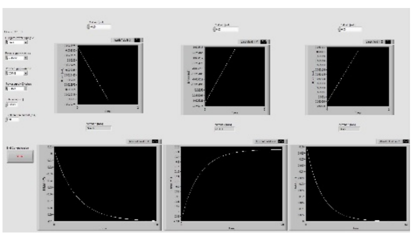
Control system for Helmholtz coils in active mode:

<u>Current source:</u>
FUG MCP 140-6500
0-1000 V, 0-200 mA
Setting range: 0.1% - 100%
with 20 bit resolution



<u>Helmholtz coil:</u>
Diameter: 436 – 563 mm
Windings: 1955 – 2522
Inductance: 8.3 – 17.8 H
Useful volume: r = 75 mm
Field uniformity: < 0.05 dB





<u>Control software in LabVIEW/C++</u>

<u>Data acquisition:</u>
NI PXI 6281
8-ch, 18 Bit, 500 kS/s

<u>Field sensor:</u>
Bartington Mag-03MS1000
3-axis Flux Gate
Measuring range: ±1 mT
Analogue output: 0 to ±10 V
Orthogonality error: 0.05°
Linearity error: < 0.0015%

What comes next…?

- Detailed error and sensitivity analysis
- Measure homogeneous field size and field homogeneity more accurately
- Mechanical readjustment of the coils
- Motorize the rotation unit to automate measurements in passive mode
- New electronics (digital integrators, adjustable gain,… ?)
- Full integration in FFMM
- Study possibility to produce higher field (increase current for short duration)
- Use as Maxwell coil

Thanks for your attention…!

Questions…?

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Geometrical Measurements

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Influence of construction and assembly errors on the field quality