A multi-purpose 3D-Helmholtz-Coil for high accuracy measurements and calibration

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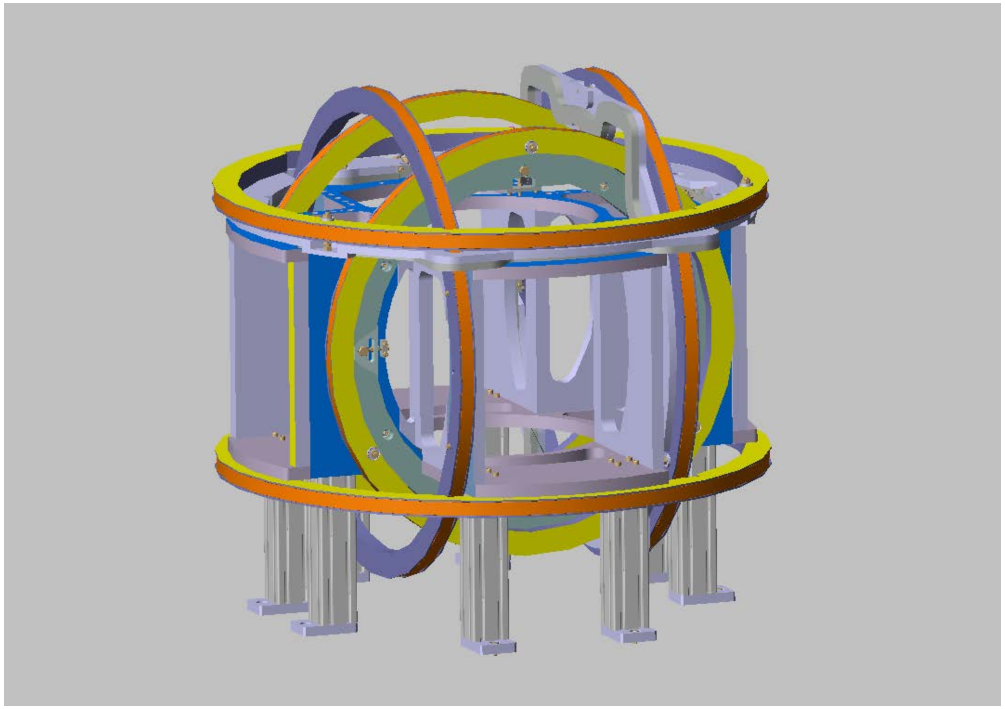

IMMW20
International Magnetic Measurement Workshop
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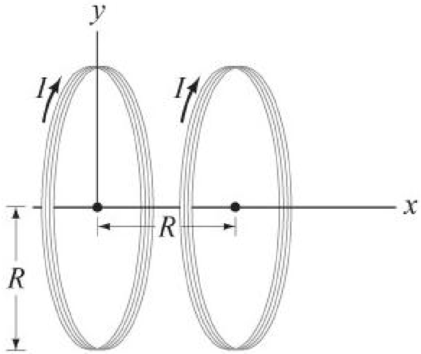
CERN Technology Department

TE-MSC-MM

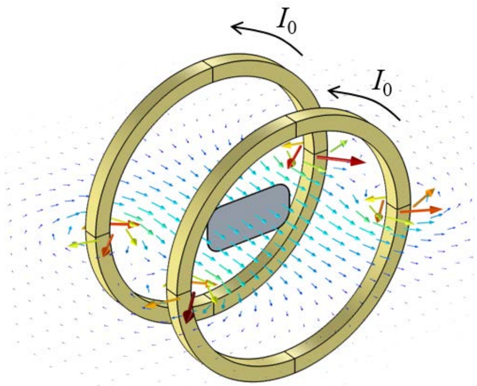
What is a Helmholtz coil?

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
- Generates a homogeneous field in the centre between the two coils
- Works also as a 3 dimensional construction
- Can be used in a passive mode as pick-up coils



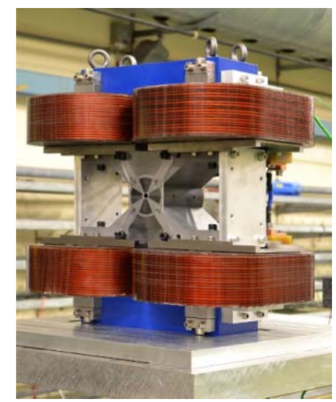
Why an accurate 3D Helmholtz coil for CERN ?

- Increasing need for qualification of permanent magnets for accelerator projects (i.e. Linac 4, n-tof, Clic)
- Dimensions from ~10 mm up to 80 mm edge length
- Various calibration issues (see talk Thomas Zickler on 05-06-2017):
  * Hall sensors (3D)
  * Earth field compensation
- Off-the-shelf coils: Accuracy >> 1%, extremely low field and/or small homogeneous field size

Halbach array in a Linac 4 PMQ

SM_2CO_{17} Permanent magnet with edge length of 80 mm

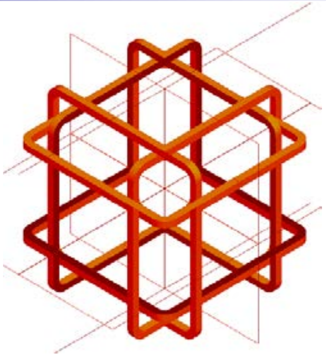
168 of those magnets assembled to a 2.6 t dipole for the n-Tof EAR2 experiment



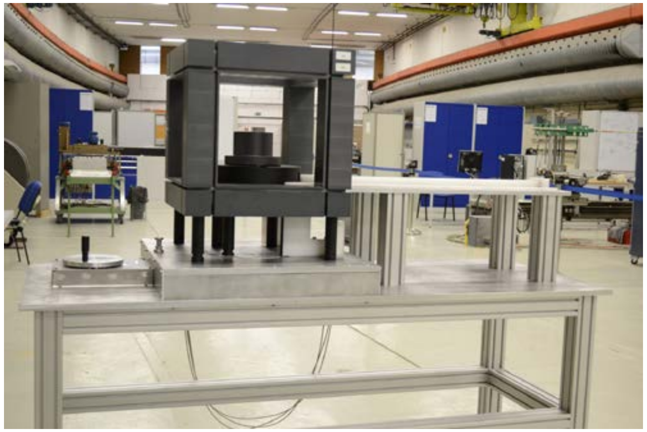
Permanent magnets in the CLIC Q0 Hybrid Quadrupole

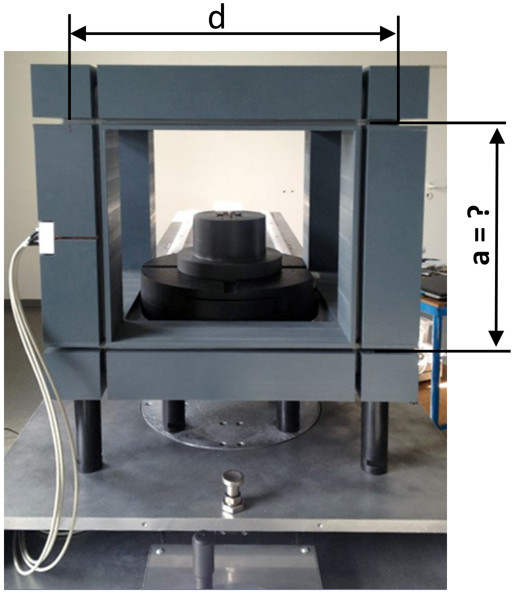
Customized design from industry:

- Limited resources for in-house development
- We buy a customized design from an industrial supplier
- Proposal of a square-shaped design
- Simply up scaled from an existing, small 'standard' design



Ideal design for square-shaped Helmholtz Coil
a = 0.5445 d





Square-shaped Helmholtz Coil from industry

Problem:
For round coils: **a = 0.5 d**
For square shaped coils: **a = 0.5445 d !**
(6th order polynomial…)

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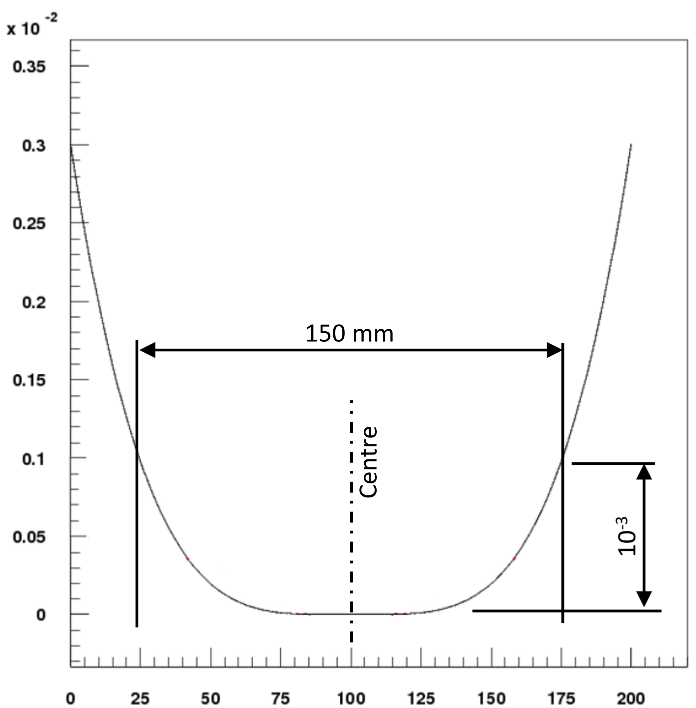
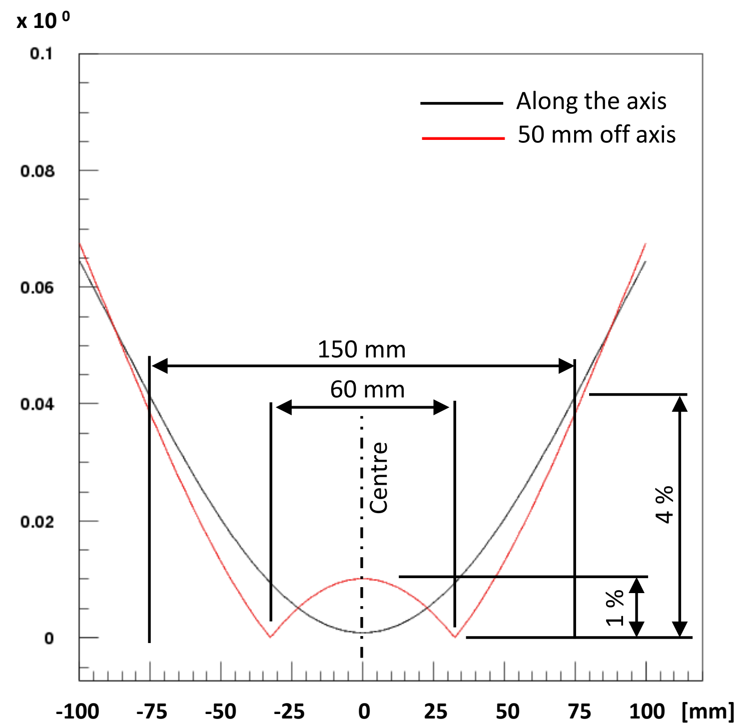
Customized design from industry:

→ Consequence for the good field:



Field variation w/r central field along the axis
for **a = 0.5 d** with round coils



Field variation w/r central field along the axis
for **a = 0.5 d** with square-shaped coils

We strongly depend on a high reproducibility of the probe position in the coils.

Specification of our own design:

"Wish-list"	Specification frame
3D construction	
Largest possible homogeneous field size to reduce dependence on accurate mechanical support.	~ 150 mm
Highest possible homogeneous field (~ 10x earth field) to optimize the resolution for calibration issues.	5 – 10 Gauss
Field homogeneity of the good field	~ 10 units
Operation both in passive and active mode.	Adequate power supply
Non conductive supports to avoid Eddy-currents in case of dynamic operation.	EPGM 203 (G11), PEEK
Same field strength for all three axes in using one power supply	Needs to compensate with coil size and number of turns

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Design parameters:

Coil design to optimize homogeneous field size and field strength or:
How to choose "reasonable" parameters to get our "wish gift"?

Field strength 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 [$4\pi \times 10^{-7}$ N/A^2]

Our approximation:

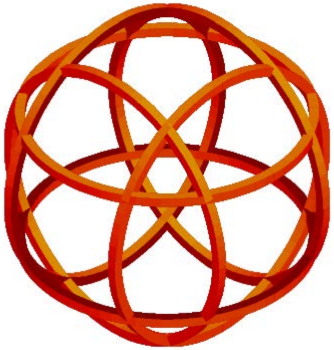
- Coil Ø: ~1000 mm, r = ~500 (to get ~150 mm homogeneous field size)
- Conductor diameter: 0.5 mm (enamelled copper wire)
- Current: I =0.2 A (corresponds to ~1 A/mm^2, quite conservative)
- Number of turns: N ~ 2200

B ~ 7.9 G - this is what we want

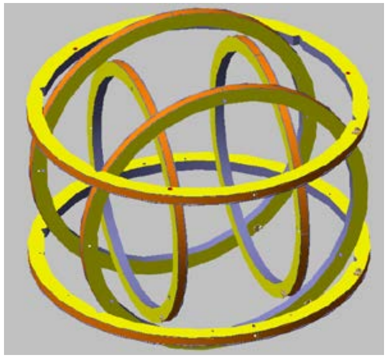
Design and construction:

Optimize the coil design for a 3D construction (3 coil pairs) :
Remember: Same field for the three directions with on power supply.

Ideally 3 identical coil pairs with identical distance $\Longrightarrow$ in practice not feasible!



Virtual…
(all coils the same size)



…Reality
(3 different coil diameters)

Final coil parameters with 3 different coil pairs:

	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**

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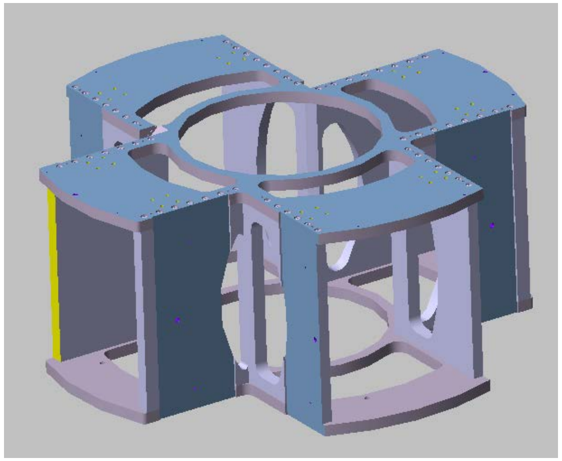
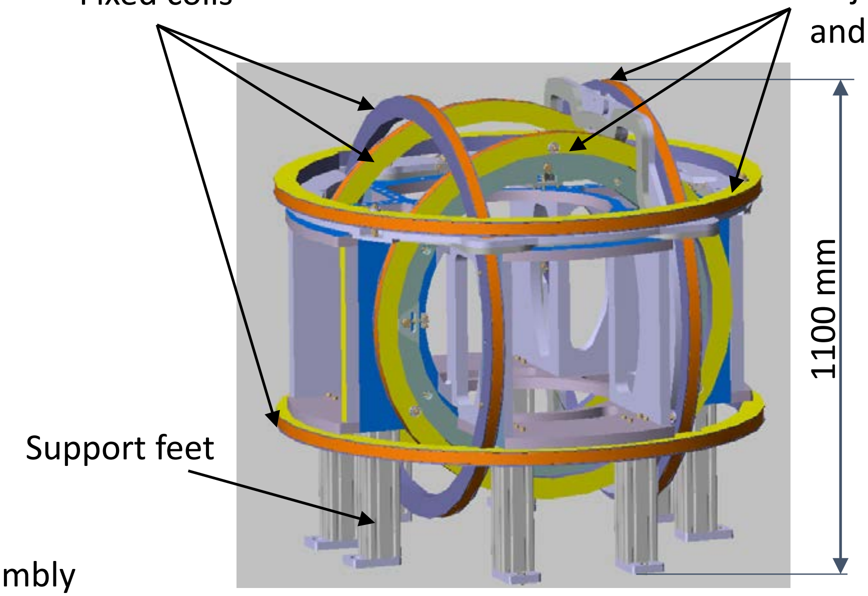
Design and construction:

The construction:

- Solid support and coil cores from EPGM 203 (G11), accuracy 0.1 mm.
- Wide apertures to introduce easily even bigger probes.
- 1 fixed coil for each axis (orthogonality relying on the accuracy of the support).
- 1 adjustable coil for each axis to align distance, coil axes and planarity.
- Accurate layer winding of the coils to ensure good field quality
- Each coil individually cabled (possible configuration as Maxwell-Coil, gradients, etc.)





Helmholtz coil central support and assembly

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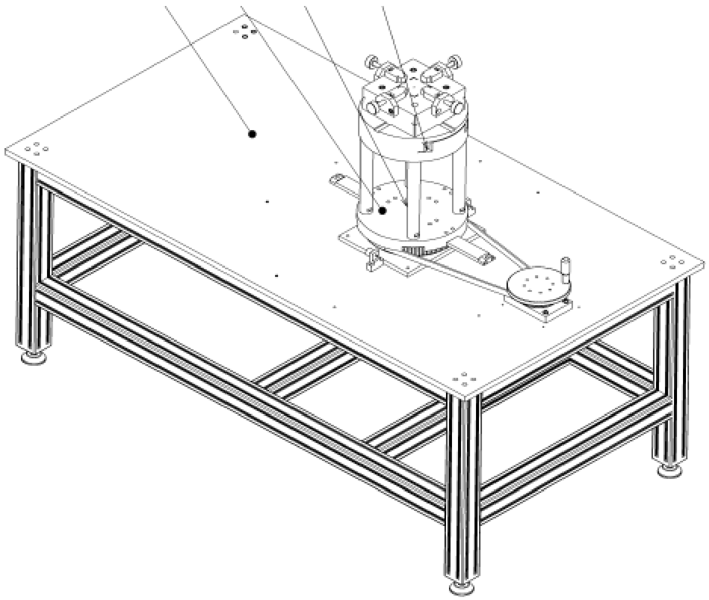
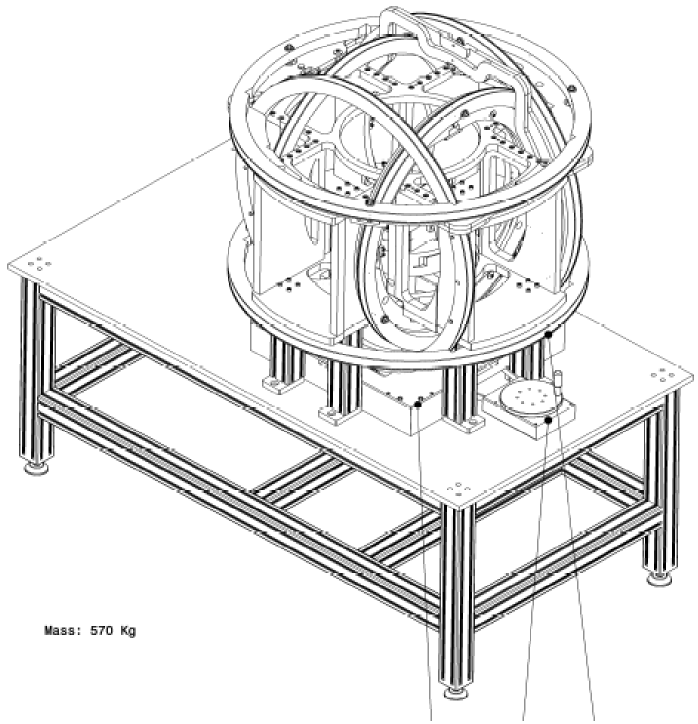
Design and construction:

The complete picture:



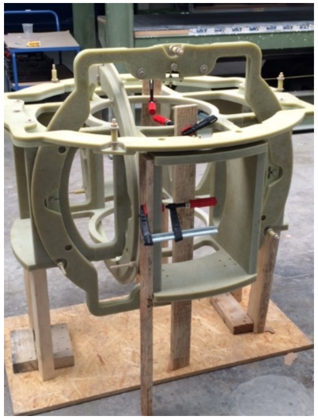
Support table with hand driven rotation device
(recovered from industry project)



Helmholtz coil on its support table

Assembly:

Some pictures from the production in industry…




Assembly of the central support

Coil cores before winding

Hand winding facility

Accurate layer winding

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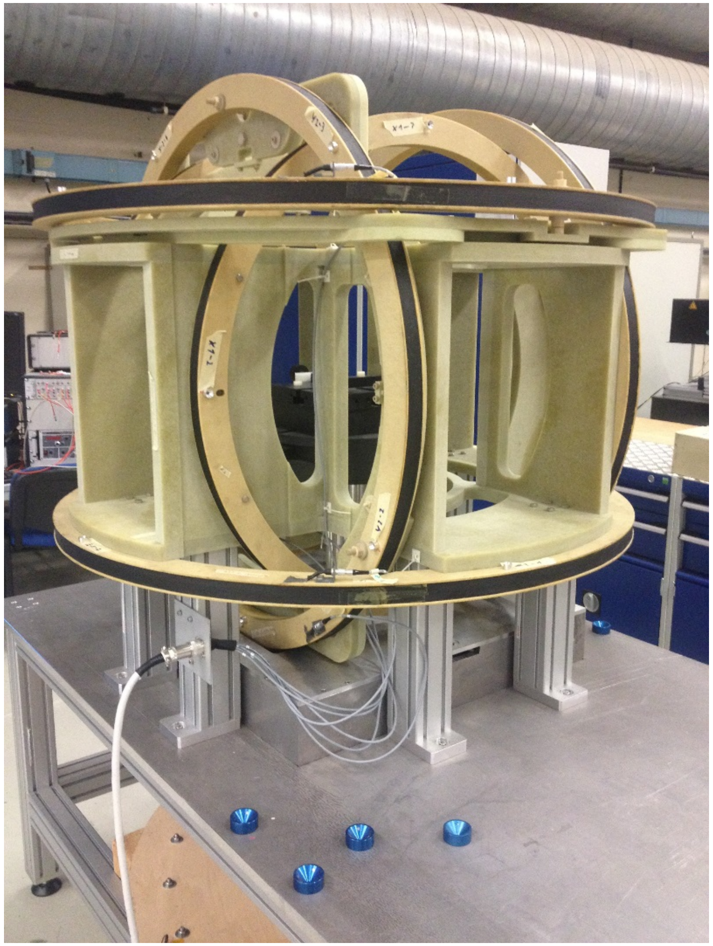
Assembly:

…and the assembly at CERN:

Mounting of the lowest coil and the support feet

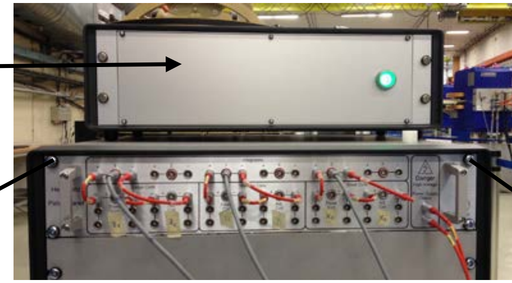


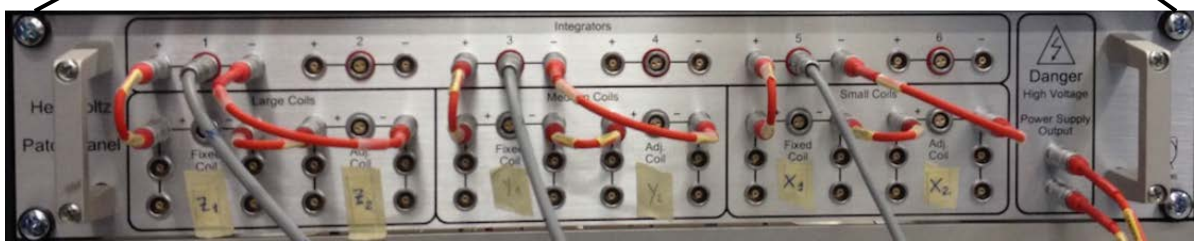
Helmholtz coil completely assembled

Assembly:

The measurement system:

3 analog integrators
(low drift: < 1 µVs/min)
(recovered from industry project)





Switchboard allowing interconnecting and powering individually all 6 coils

DC power supply:
FUG MCP 140-6500
0-1000 V, 0-200 mA
Setting range: 0.1% - 100%
with 20 bit resolution

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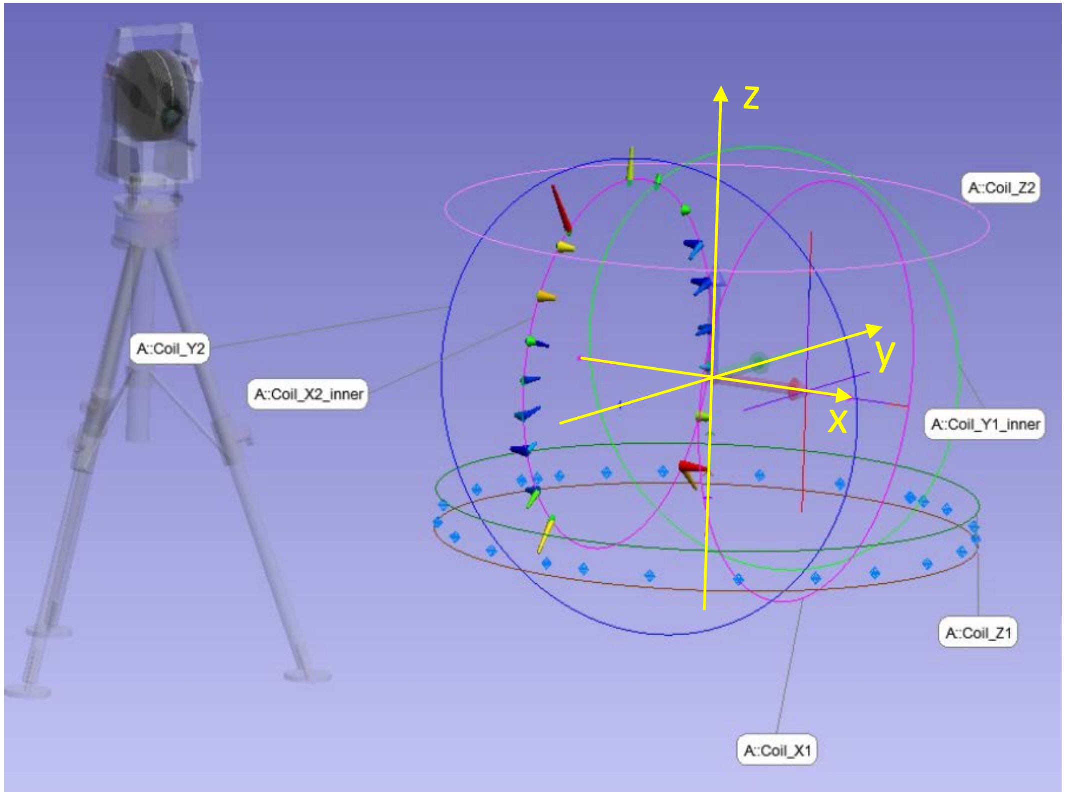
Commissioning and measurements:

Geometrical check:



Laser tracker measurements of the geometry after the first assembly:

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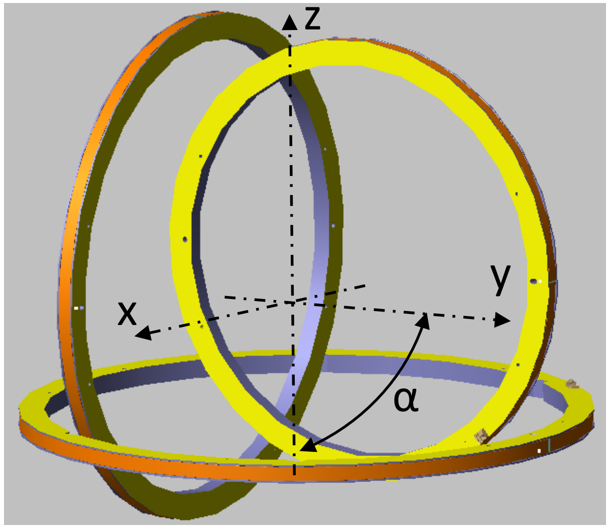
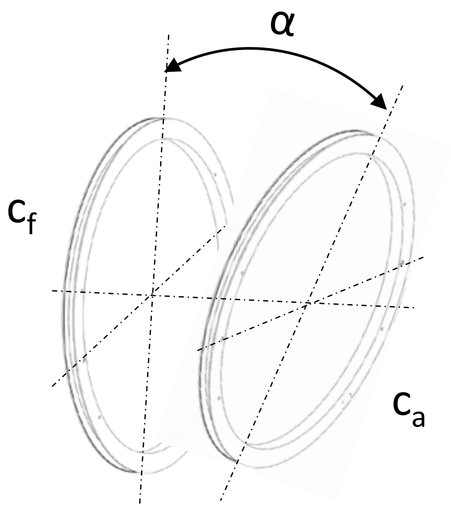
Commissioning and measurements:



Orthogonality of the 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



Angle between fixed and adjustable coils:

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

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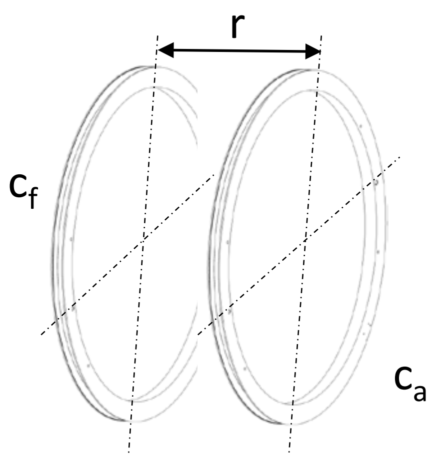
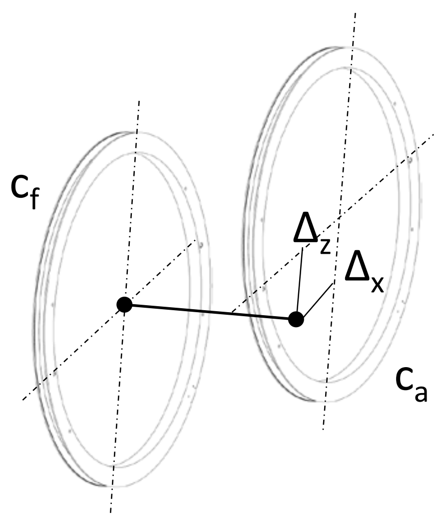
Commissioning and measurements:



Distance between fixed and adjustable coils:

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



Concentricity between fixed and adjustable coils:

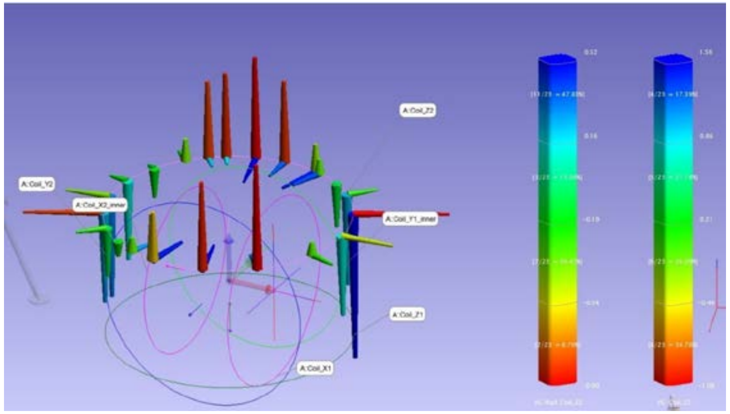
Coils	X (mm)	Y (mm)	Z (mm)
x_f - x_a	---	0.33	0.75
y_f - y_a	0.01	---	0.47
z_f - z_a	0.31	0.57	---

Commissioning and measurements:

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

Must be looked up more closely and be redressed.



Important irregularity of flatness on the adjustable z-coil.

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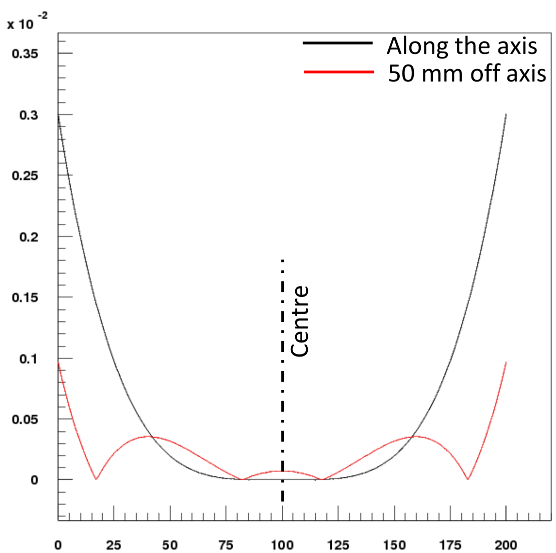
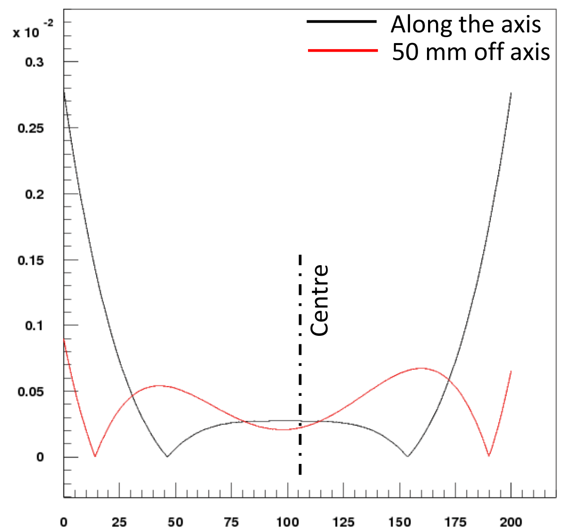
Commissioning and measurements:

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



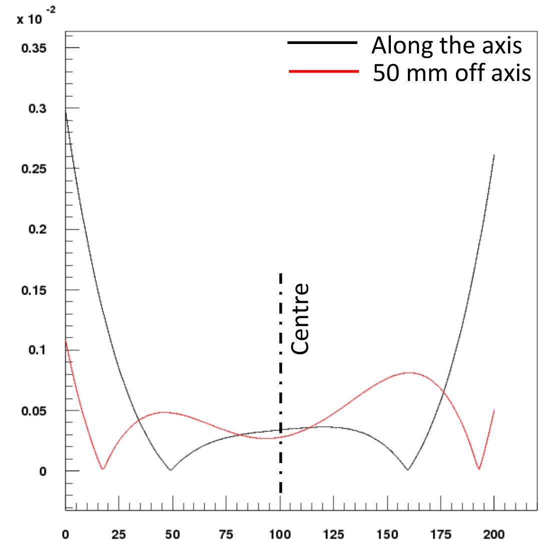
Coils as designed

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



Coils with geometrical defaults

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



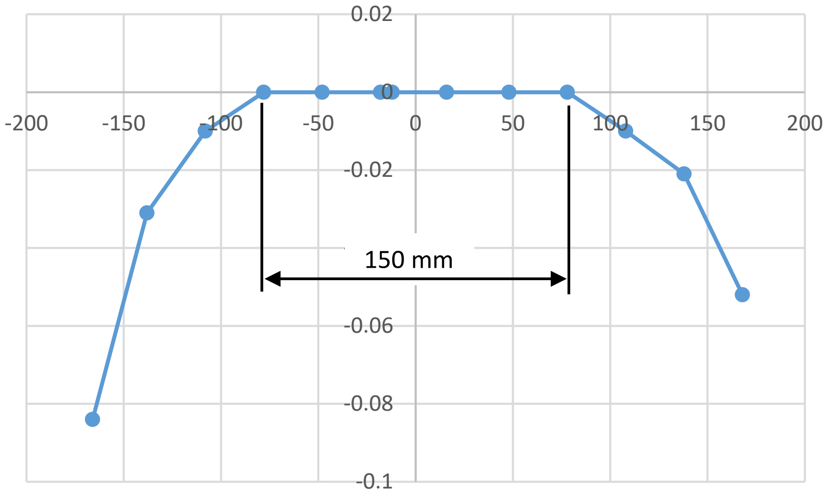
Demonstration:
Simulated angle of 2° between x_f and x_a
Visible effects on the homogeneous field for wider angles [e = f (cos α)]

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).

Commissioning and measurements:

First measurements of field strength and homogeneity :

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



Measured homogenious field size for the smallest coils (x) @ 200 mA

Field in the centre (@ 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

Most probably due to:
- Earth field
- Fluxgate accuracy

Work still ahead:

- Measure homogeneous field size and field homogeneity more accurately
- Adjust geometry (if necessary)
- Motorize the rotation to reduce measurement time (integrator drift)
- New electronics (digital integrators, adjustable gain,… ?)
- Achieve higher field (increase current for short duration)
- Use as Maxwell coil
- Etc…
- And, of course, measure magnets and calibrate instruments !

Thank you for listening! → Any questions?