Development of a Superconducting Cryostat-Internal Polarizing Magnet for Polarized Targets

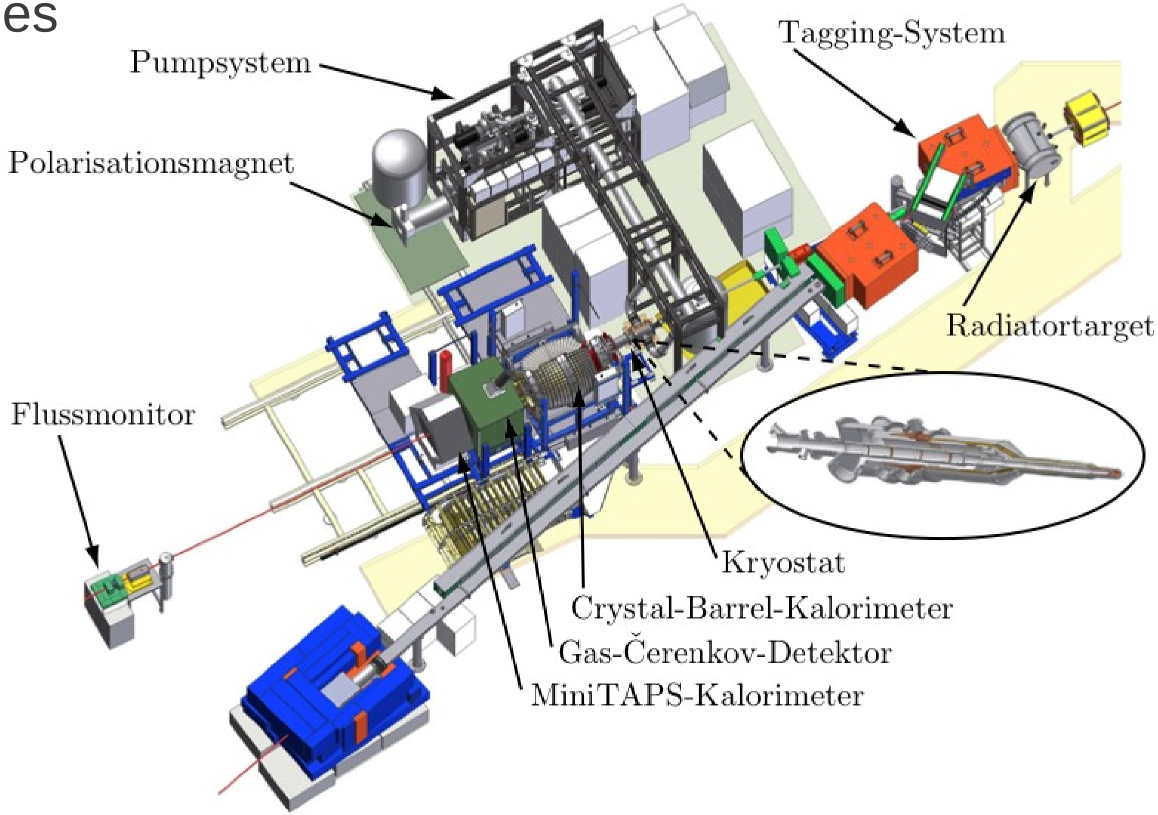
- Overview
    - The Crystal-Barrel Experiment at ELSA (Electron Stretcher and Accelerator) in Bonn
    - Elements of a Polarized Target
    - Advantages of an internal polarizing magnet
    - Homogeneity requirement
    - Development so far

Development of a Superconducting Cryostat-Internal Polarizing Magnet for Polarized Targets

- Simulation
  - Mathematical model
  - Parametrization
- Results
  - Solenoid without correction
  - Corrected solenoid/ Technical difficulties
  - Strayfield
  - Quench
- Further steps and prospect

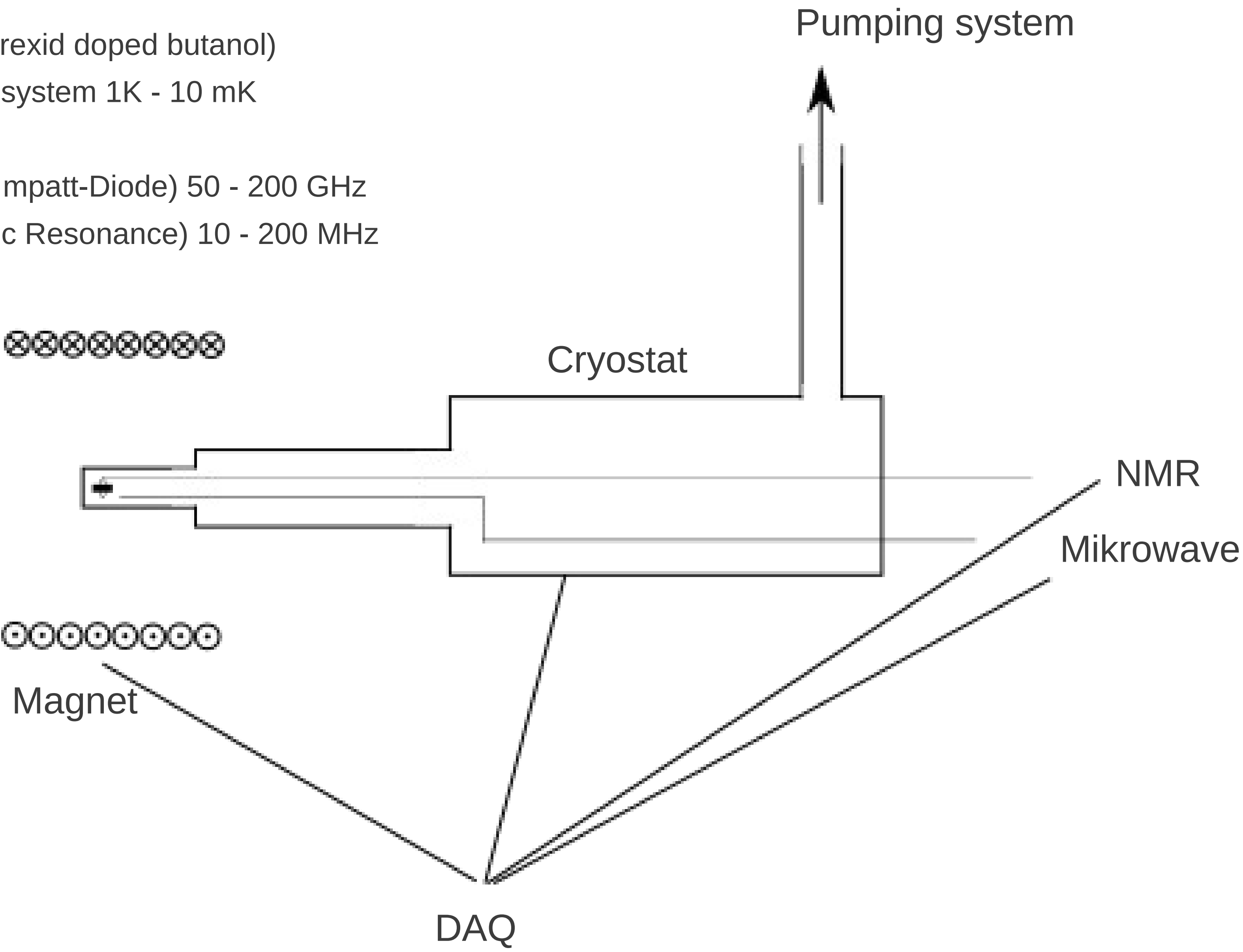
The Crystal-Barrel Experiment at ELSA

- Dubble polarization experiment
- Investigation of the nucleon structure by determination of relevant polarization observables as complete as possible
- Frozen-Spin-Technology



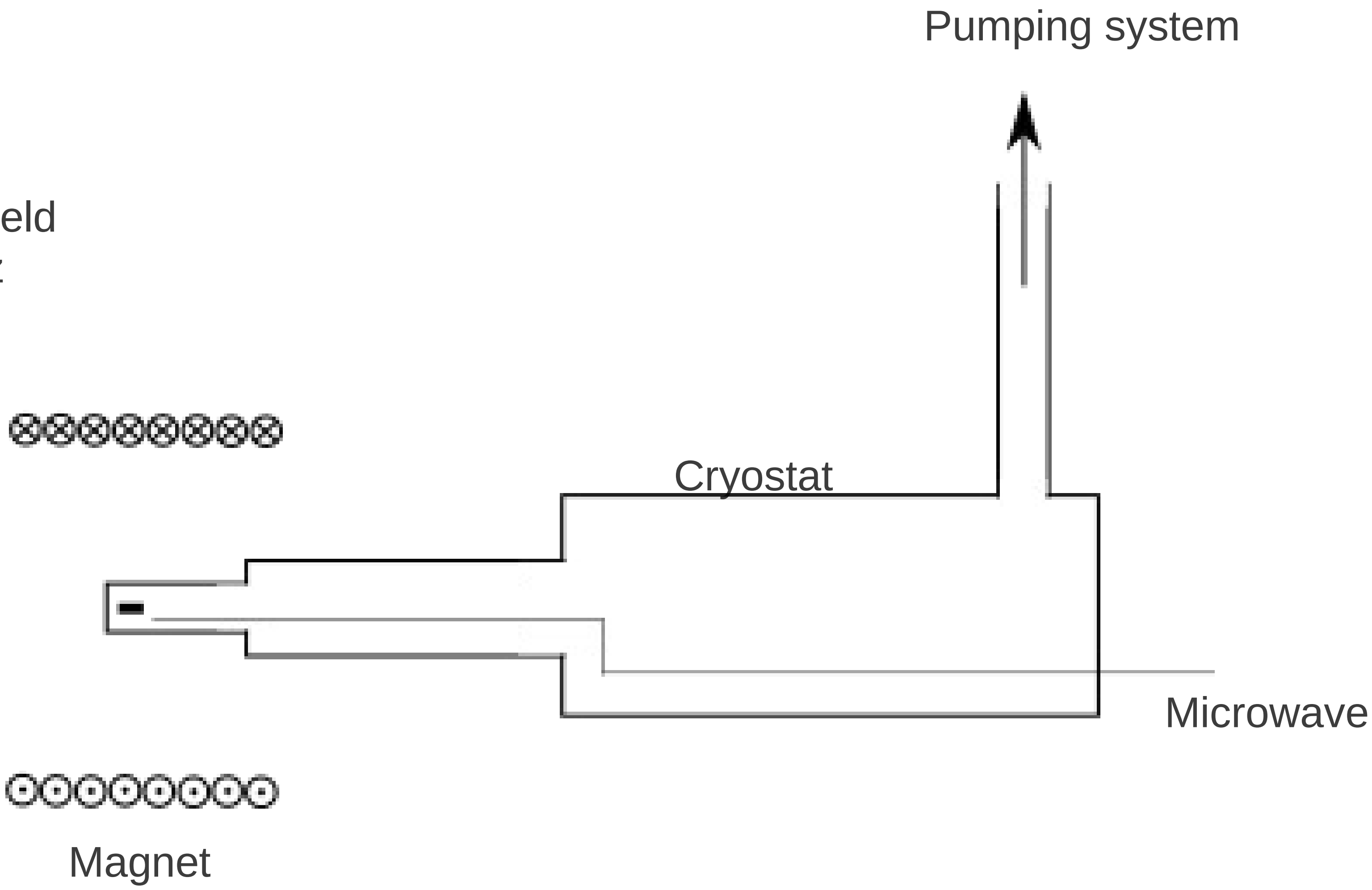
Elements of the Polarized Target

- Targetmaterial (Porphyrexid doped butanol)
- Cryostat with pumping system 1K - 10 mK
- Magnet 1 - 7 T
- Mikrowave generator (Impatt-Diode) 50 - 200 GHz
- NMR (Nuclear Magnetic Resonance) 10 - 200 MHz
- DAQ



Frozen-Spin-Concept

250 mK DNP
at 2.5 T polarizing field
70 GHz ± 106 MHz

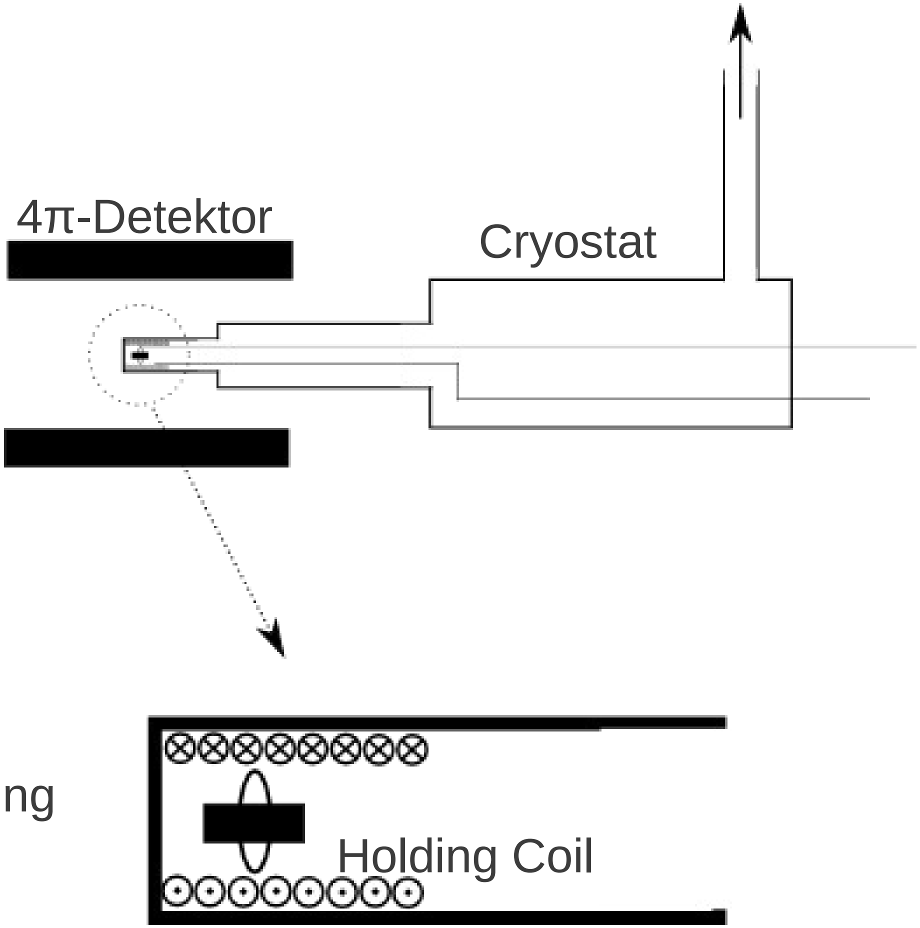


Frozen-Spin-Concept

60 mK Frozen-Spin-Mode
at 0.6 T holding field

Process developed in Bonn
Allows operation of a 4π-Detektor

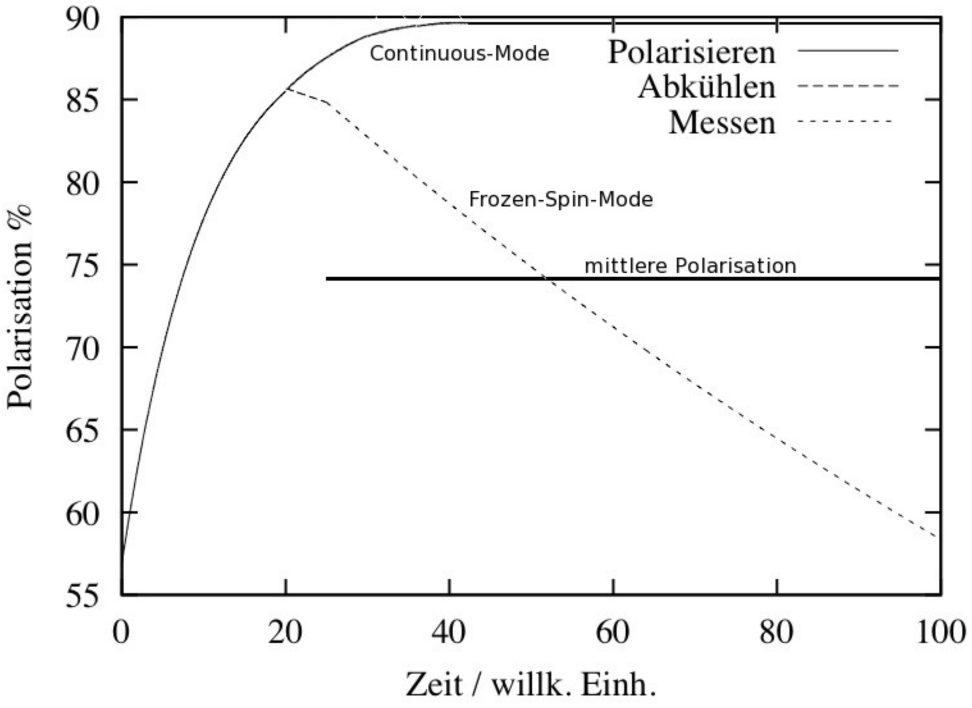
Halt of the experiment for polarization
Relaxation of the polarization during data taking



Advantages of an Internal Polarizing Magnet

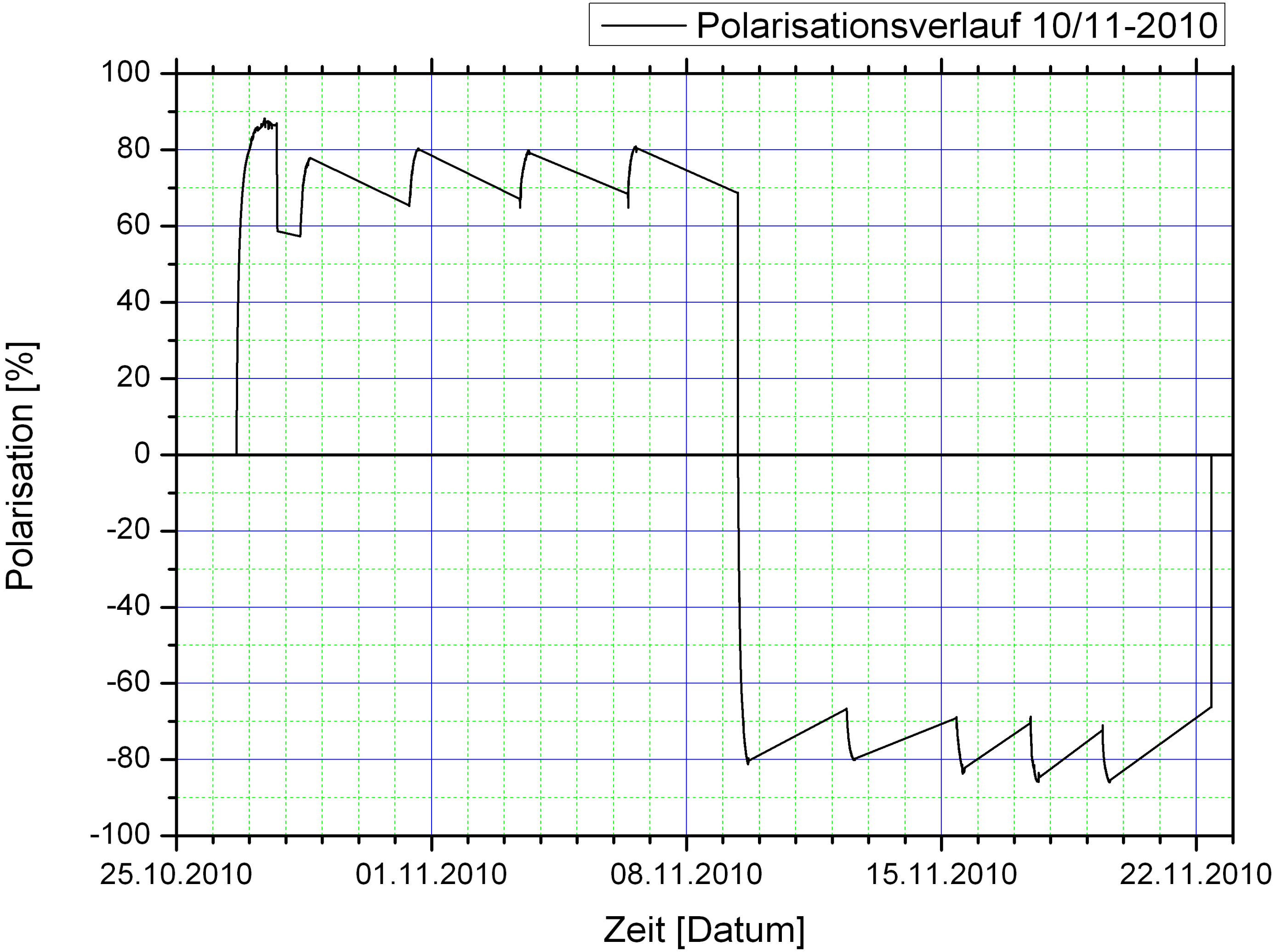
- Continuous 90% polarization and simultaneous operation of a 4π-Detektor instead of 75% mean polarization in Frozen-Spin-Mode
- No halt of the experiment for polarization
- Measurement of polarization any time

$$\Delta A \propto \frac{1}{P\sqrt{T}}$$

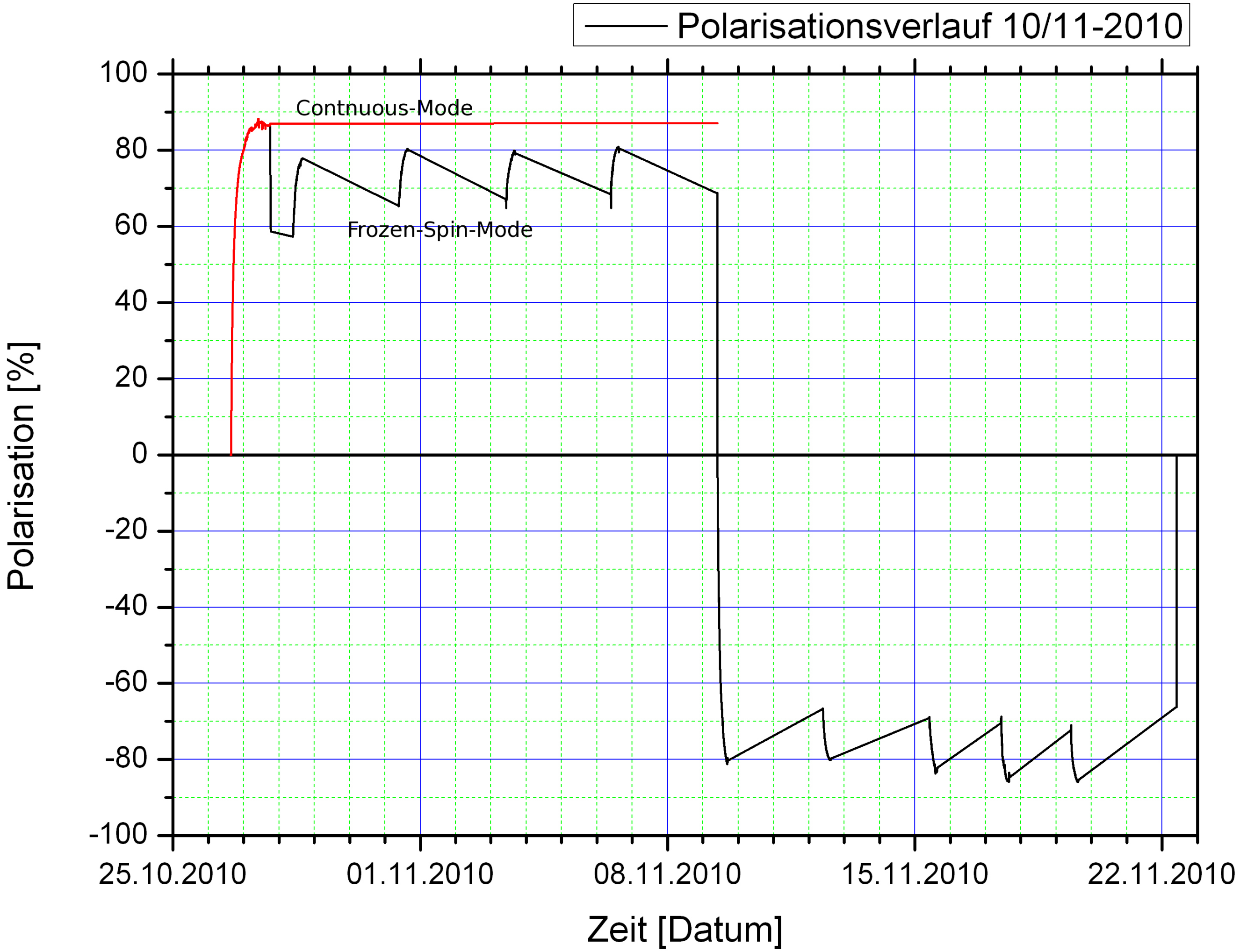


→ Upgrade of the internal holding coil by an internal polarizing magnet

Polarization Cycle

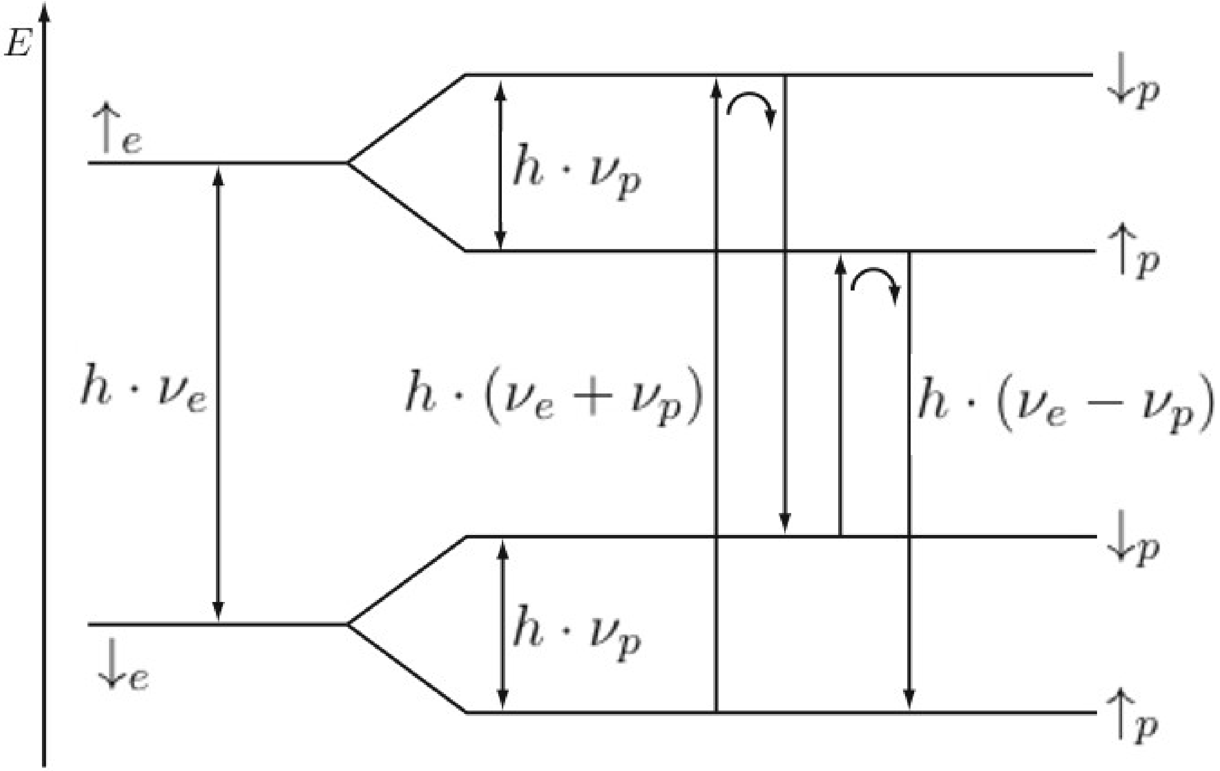


Polarization Cycle



Constraints on the Inhomogeneity of the Magnetic Field

$\nu_e = 70 \text{ GHz}$ $\nu_p = 106 \text{ MHz}$ B=2.5 T



Polarization:

$$P_{1/2} = \frac{N_+ - N_-}{N_+ + N_-}$$

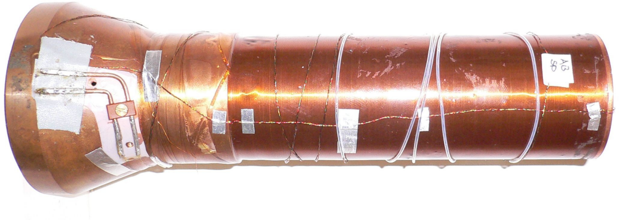
$$\Delta\nu_e \ll \nu_p$$

$$h\nu = \gamma B$$

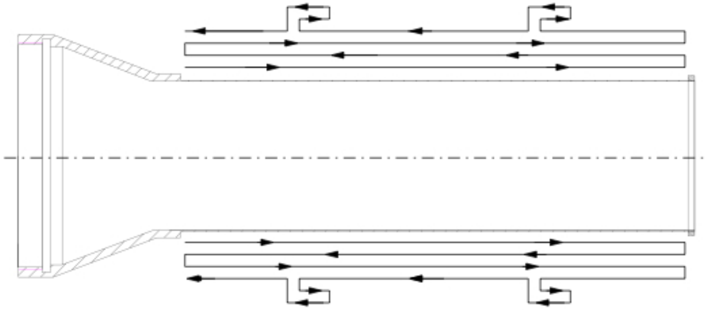
$$\frac{\Delta B}{B_0} = \frac{\Delta\nu_e}{\nu_e} \ll \frac{106\text{MHz}}{70\text{GHz}} \approx 10^{-3} \longrightarrow 10^{-4}$$

Development So Far in Bonn

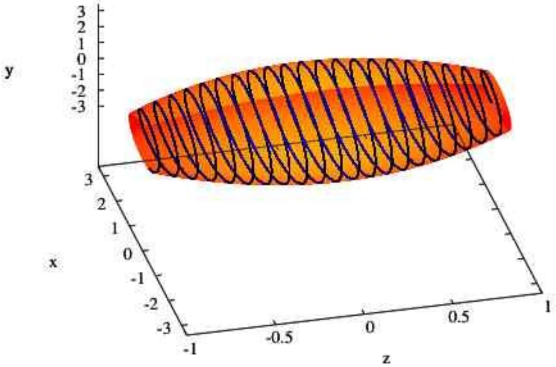
- Rainer Gehring: Development of an internal holding coil, Diplomarbeit 1993



- Christian Rohlof: Development of an internal polarizing magnet with an extremely high field and less inhomogeneity (Notched Coil), Dissertation 2003

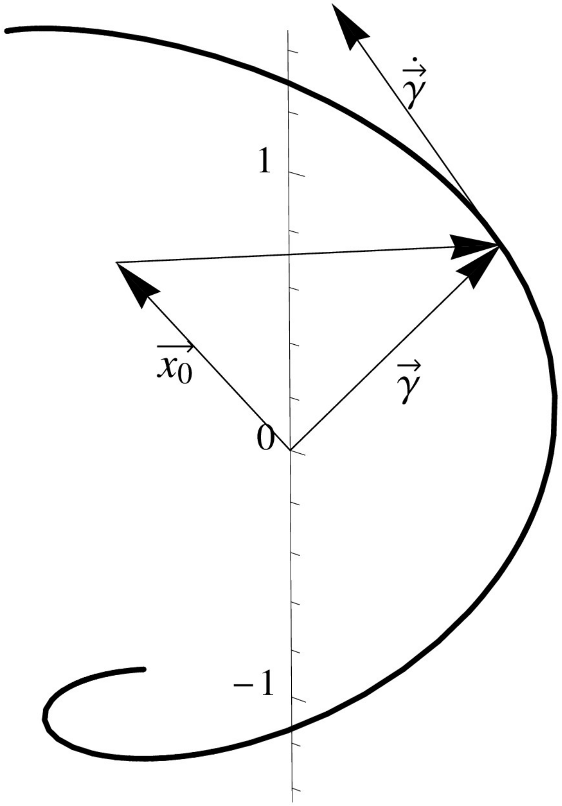


- Fadi Zarife: further possibilities of correction, Diplomarbeit 2008



Biot-Savart-Law

$$\overrightarrow{B}(\overrightarrow{x_0}) = \frac{\mu_0}{4\pi} I \int \frac{(\vec{\gamma}(t) - \overrightarrow{x_0}) \times \frac{\dot{\vec{\gamma}}(t)}{|\dot{\vec{\gamma}}(t)|}}{|(\vec{\gamma}(t) - \overrightarrow{x_0})|^3} dl$$

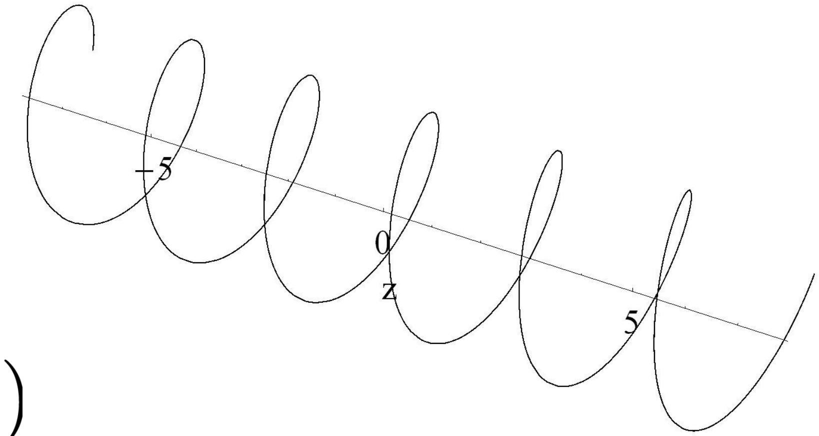


with

$$dl = \sqrt{\dot{\overrightarrow{\gamma}}(t)\dot{\overrightarrow{\gamma}}(t)}dt$$

$$\vec{\gamma}(t) = (x(t), y(t), z(t))$$

Parametrisation of a Solenoid



$$\overrightarrow{\gamma}(t) = (f\cos t, f\sin t, \frac{r}{2\pi}t)$$

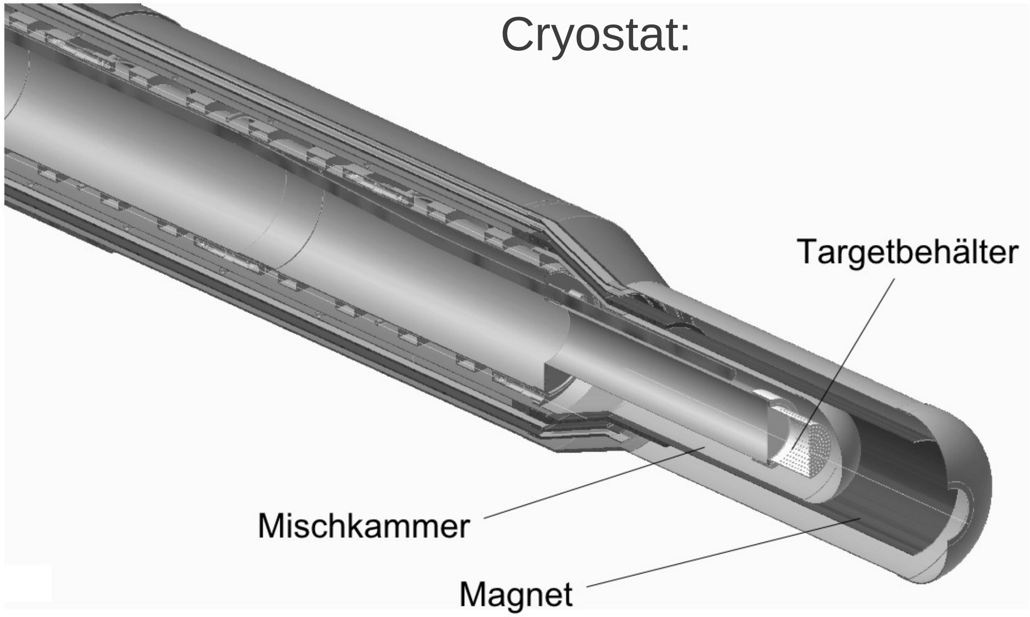
$$-\text{number of windings}\ \pi < t < \text{number of windings}\ \pi$$

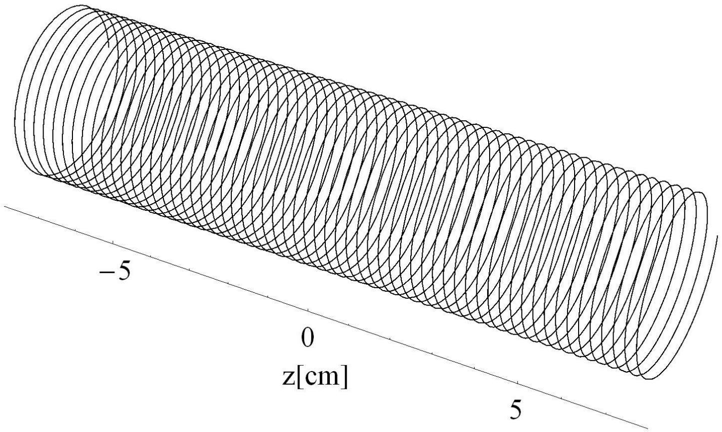
$$\text{radius of the coil}\ : f$$

$$\text{space (diameter) of the wire}\ : r$$

Display of the Inhomogeneity in the Target Region

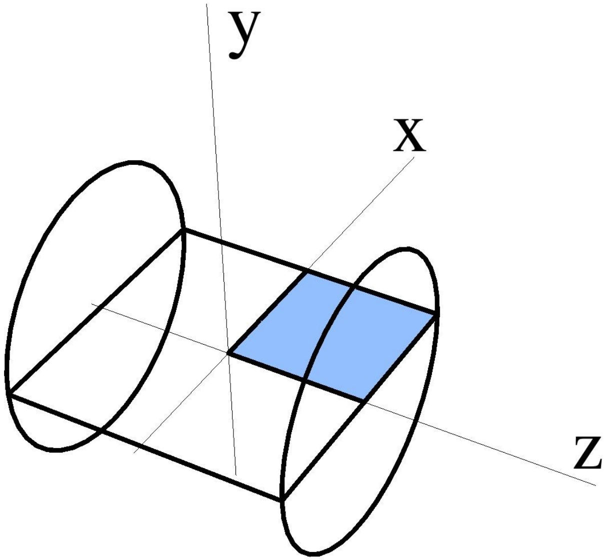
Cryostat:





$$\frac{B(\vec{x})-B_0}{B_0}$$

Target volume:



Rotational symmetry along the z-Axes

Mirror symmetry along the x-Axes

Solenoid Without Correction

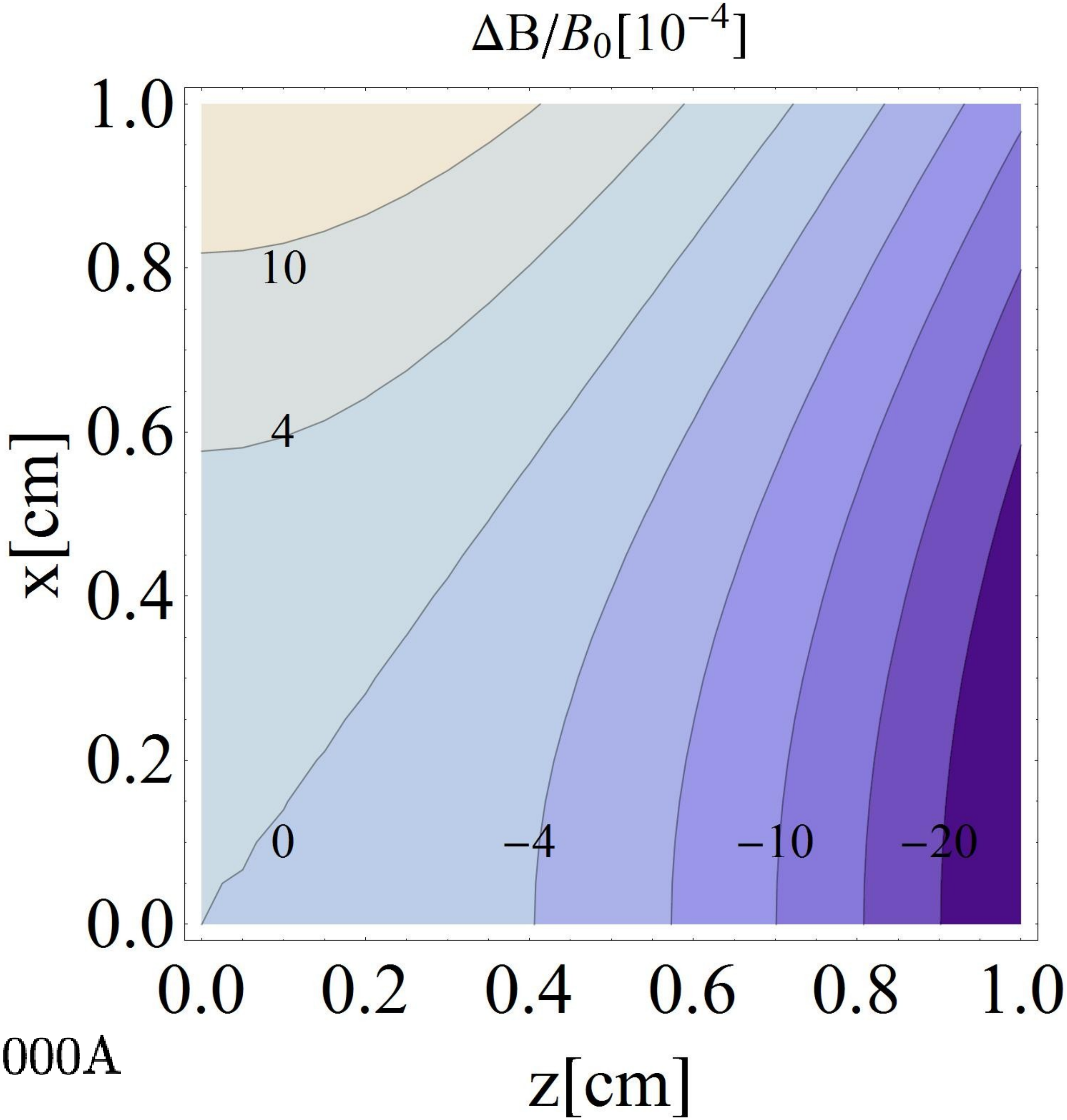
Length of the coil: l = 150 mm
Diameter of the coil support: 44.6 mm

Diameter of the wire: 0.254 mm
Number of windings: N = 3540
Number of layers: 6
Overall thickness of the magnet: 2.4 mm

Inductivity: 160 mH
Stored energy: 650 J

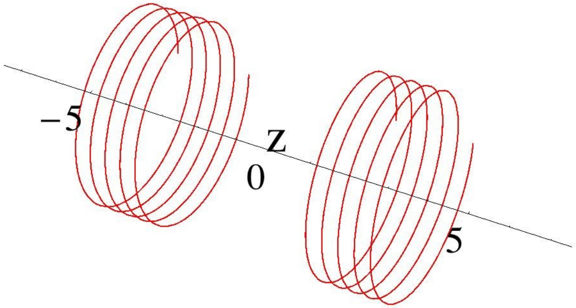
Current: I = 90 A

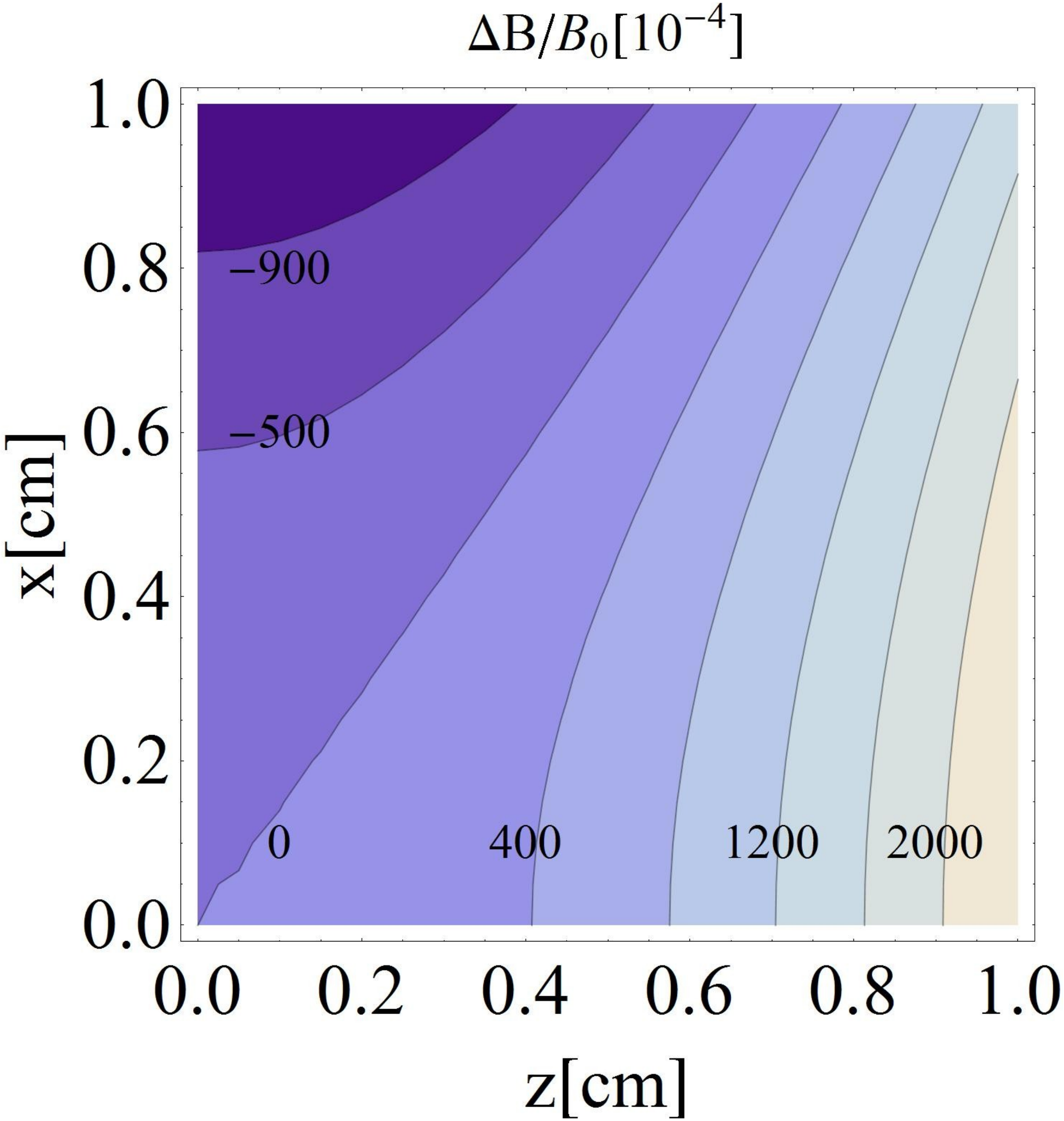
Magnetic flux density in the centre: $B_o = 2.5$ T



$$IN = \frac{Bl}{\mu_0} = \frac{2{,}5\mathrm{T}\ 0{,}15\mathrm{m}}{4\pi 10^{-7}\frac{\mathrm{Vs}}{\mathrm{Am}}} \approx 298000\mathrm{A}$$

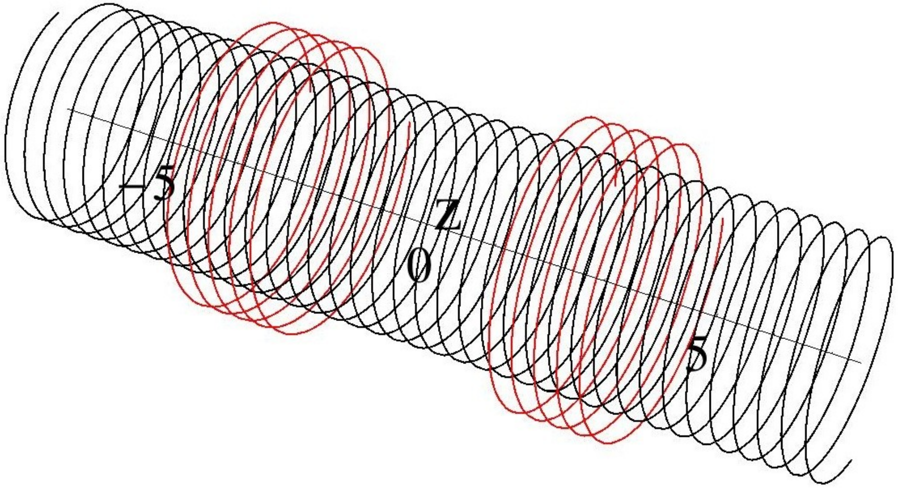
Correction Windings (Helmholtzlike Configuration)



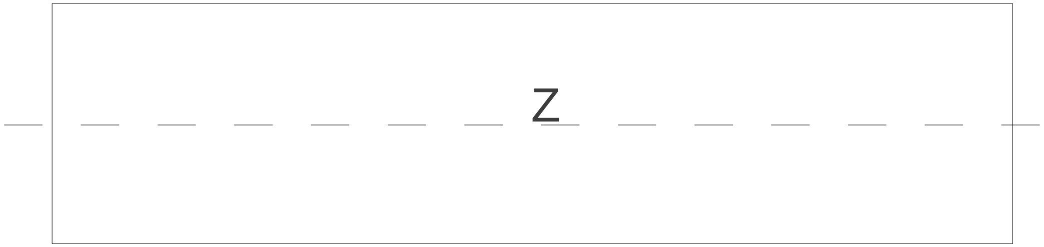


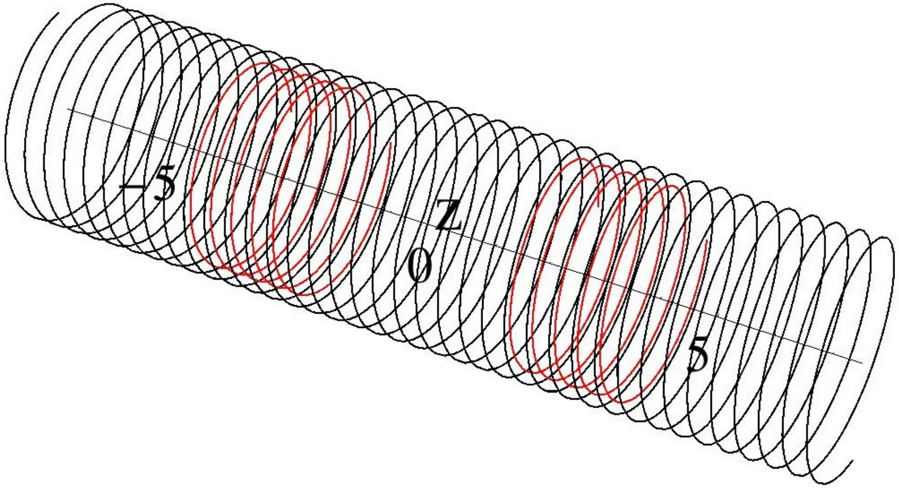
Results

Concept of the Inverse Notched Coil (Correction Coil in Helmholtzlike Configuration)

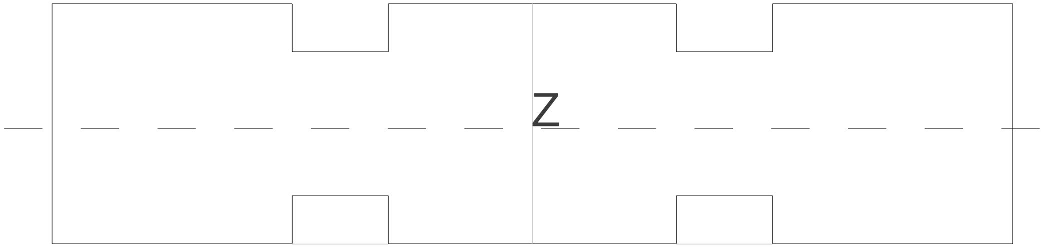


Coil support Notched Coil



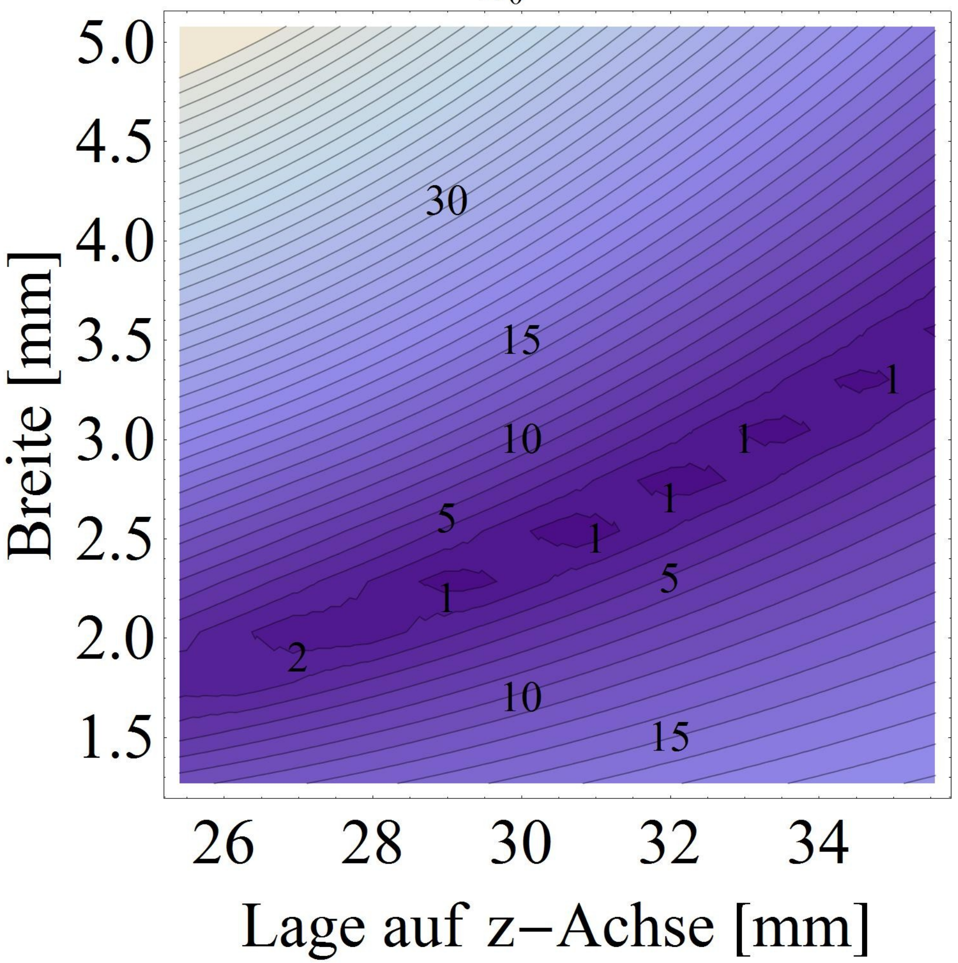


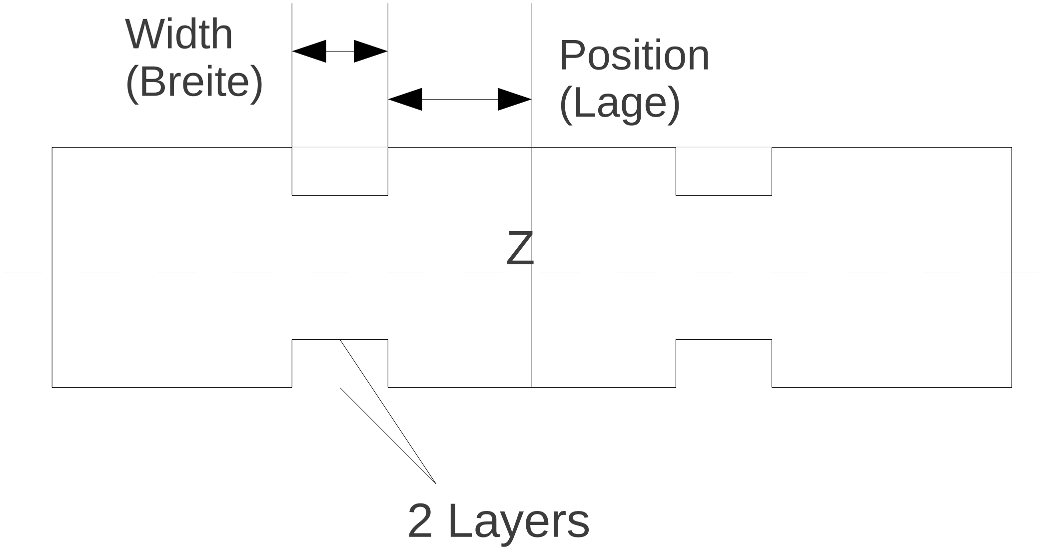
Coil support with indentations



Parameter Surface of the Correction Coil Location

$(\frac{B_{\mathrm{max}} - B_{\mathrm{min}}}{B_0})[10^{-4}]$



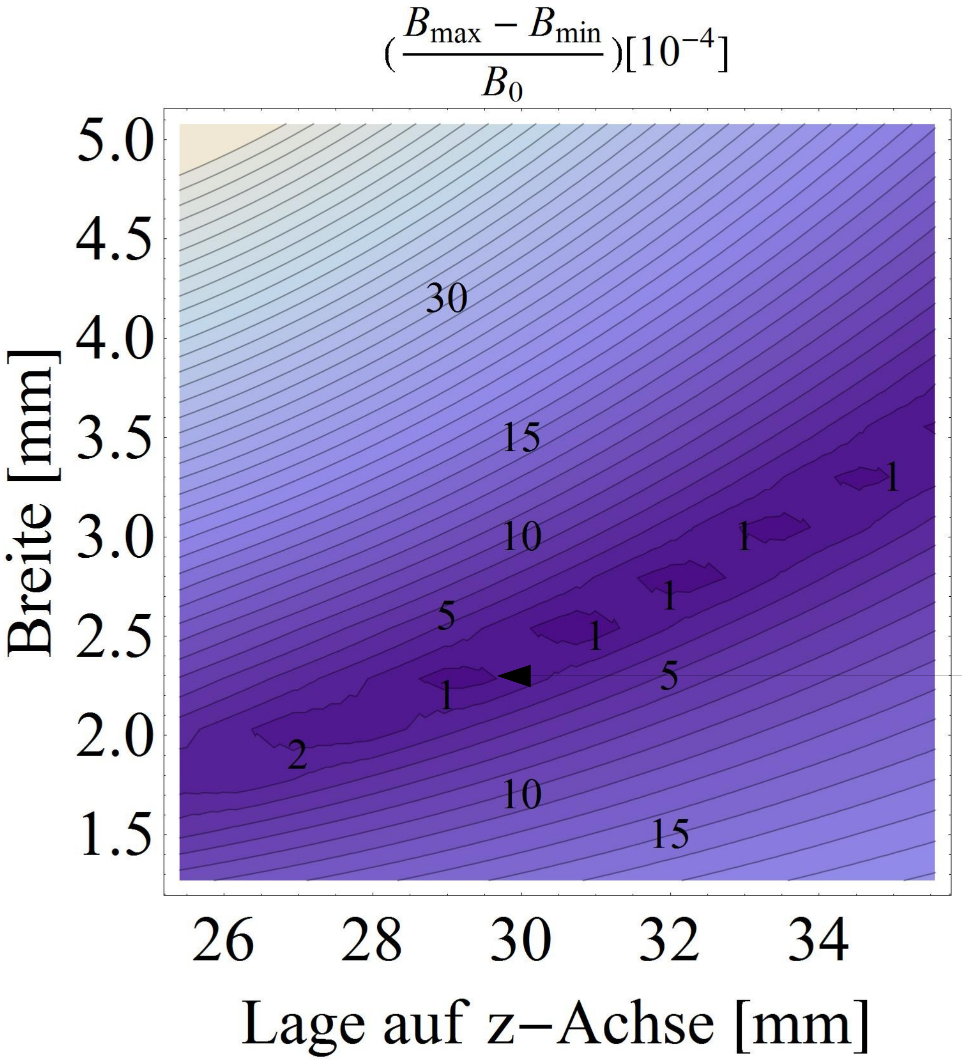

Width (Breite)

Position (Lage)

Z

2 Layers

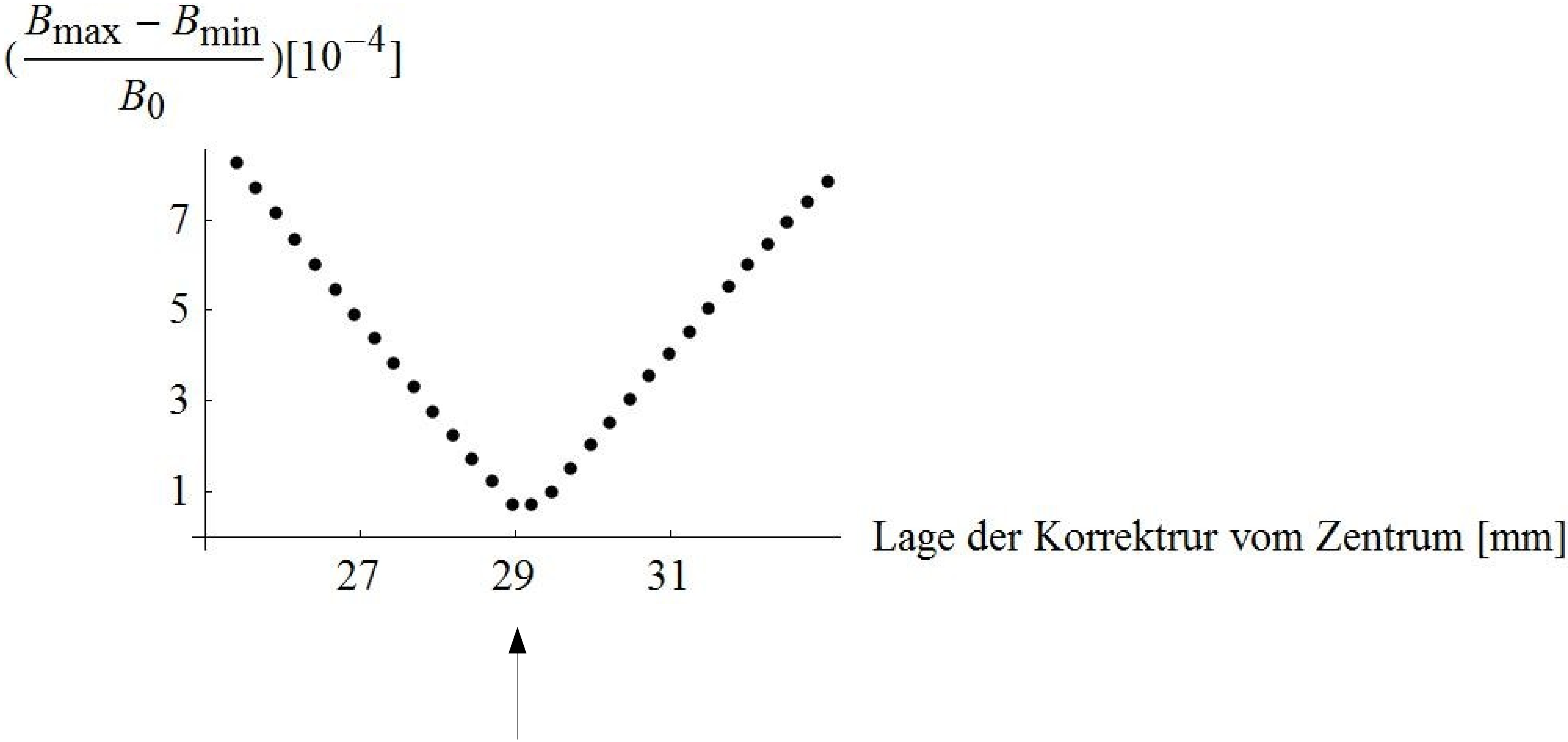
Parameter Surface of the Correction Coil Location



Fix Width 2.3mm

As less windings as possible to reduce winding errors

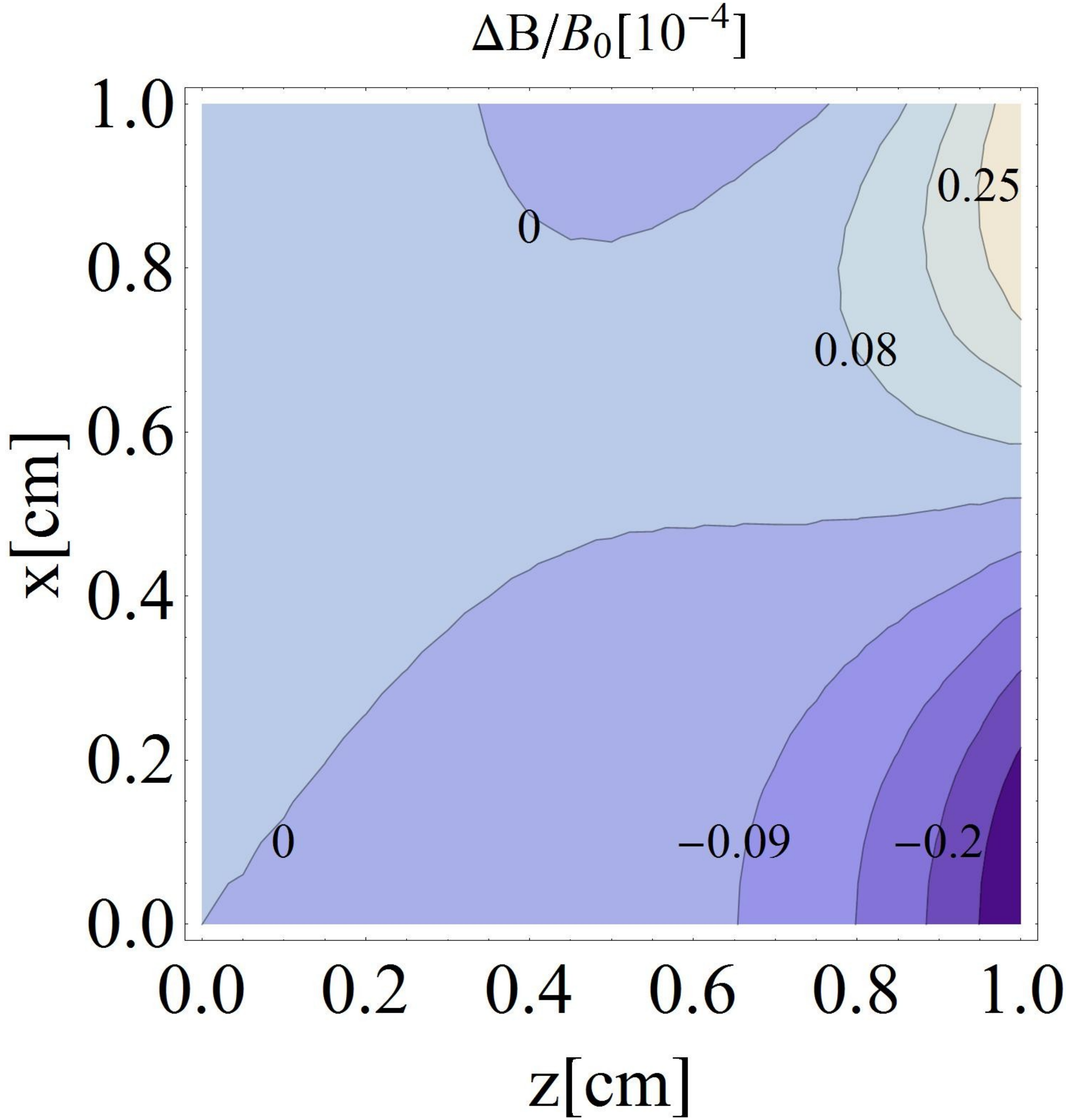
Fixed Width to 2.3 mm



Minimum at 29mm

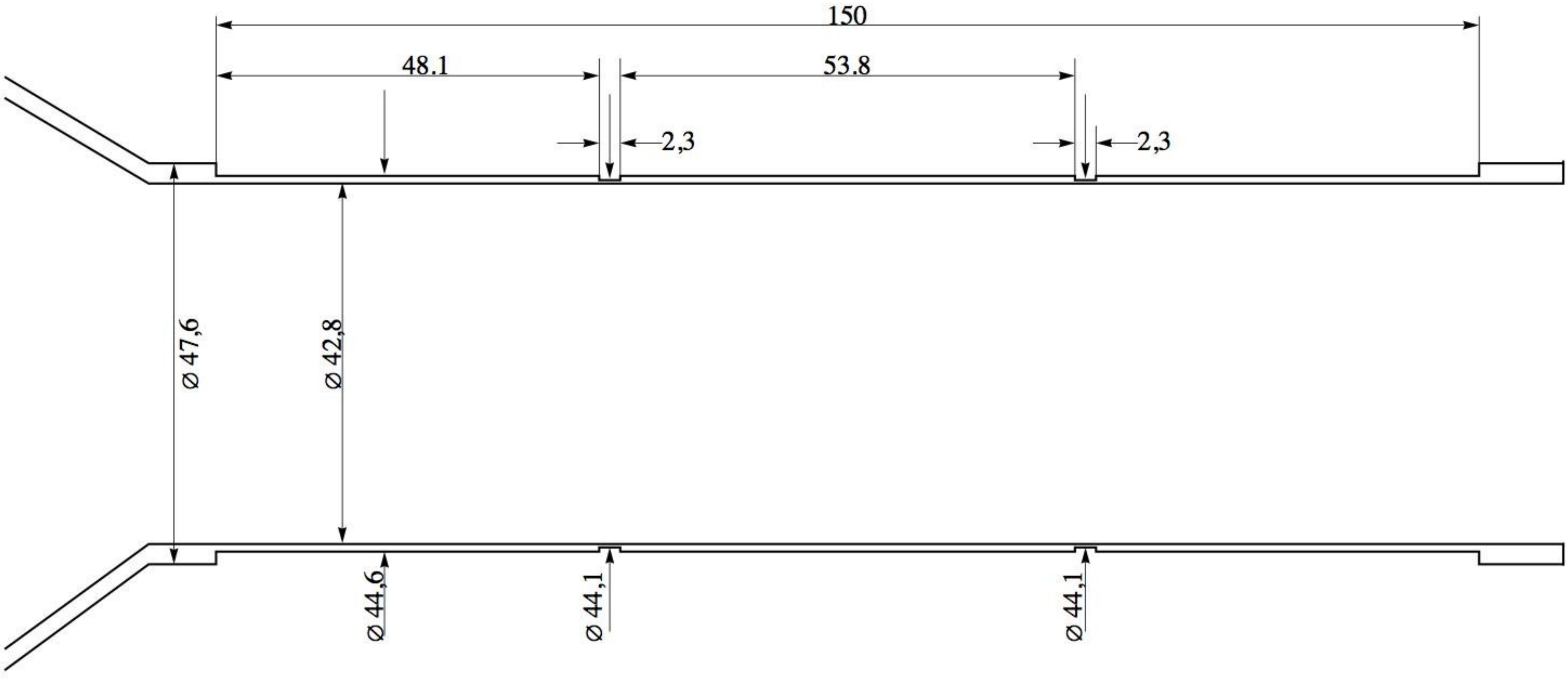
Corrected Coil

(Inverse Notched Coil)



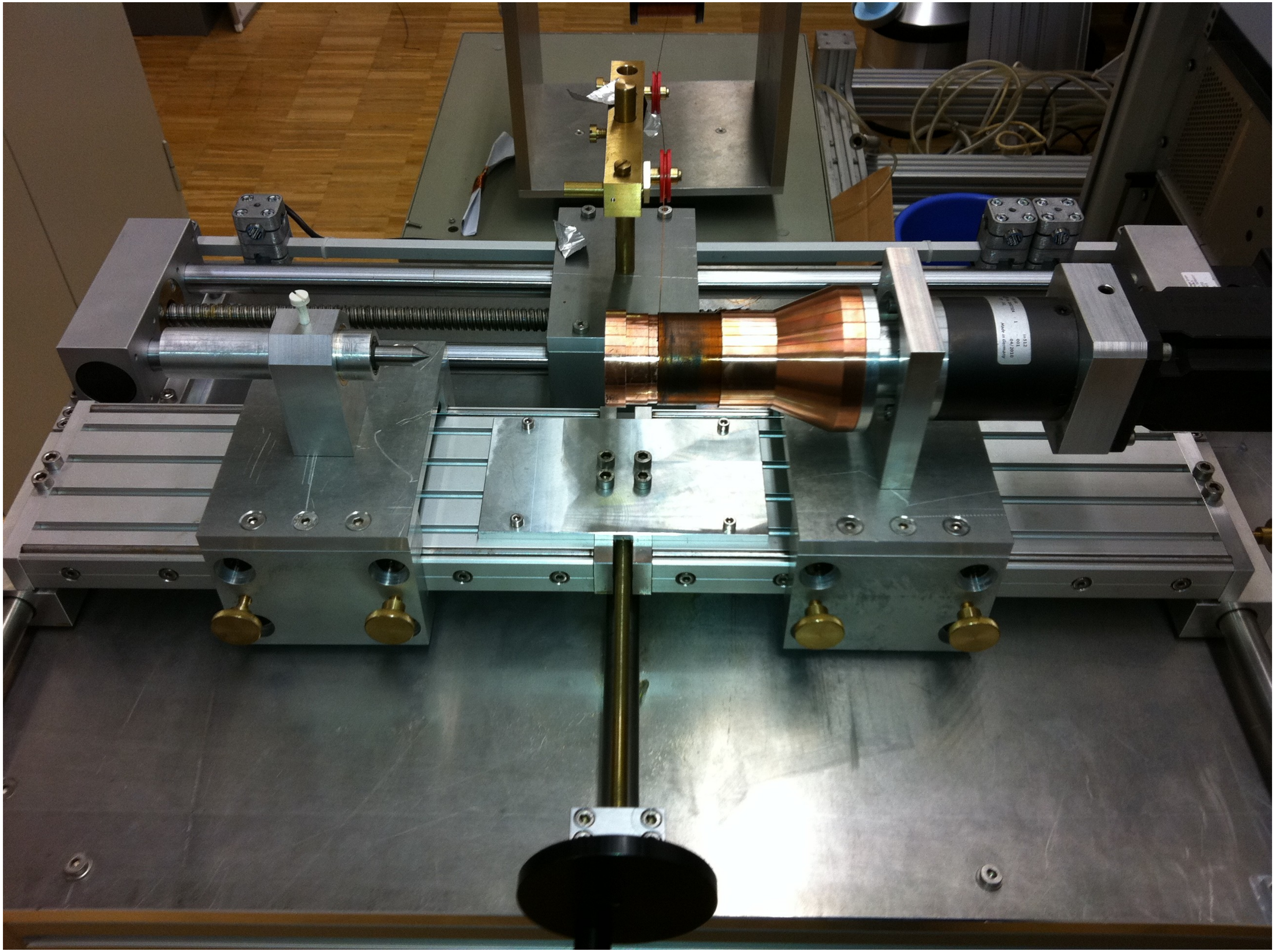
Superposition of solenoid and correction coil pair width 2.3 mm and distance 53,8 mm 2 layers

Design of the Support (OF Copper) (Inverse Notched Coil)

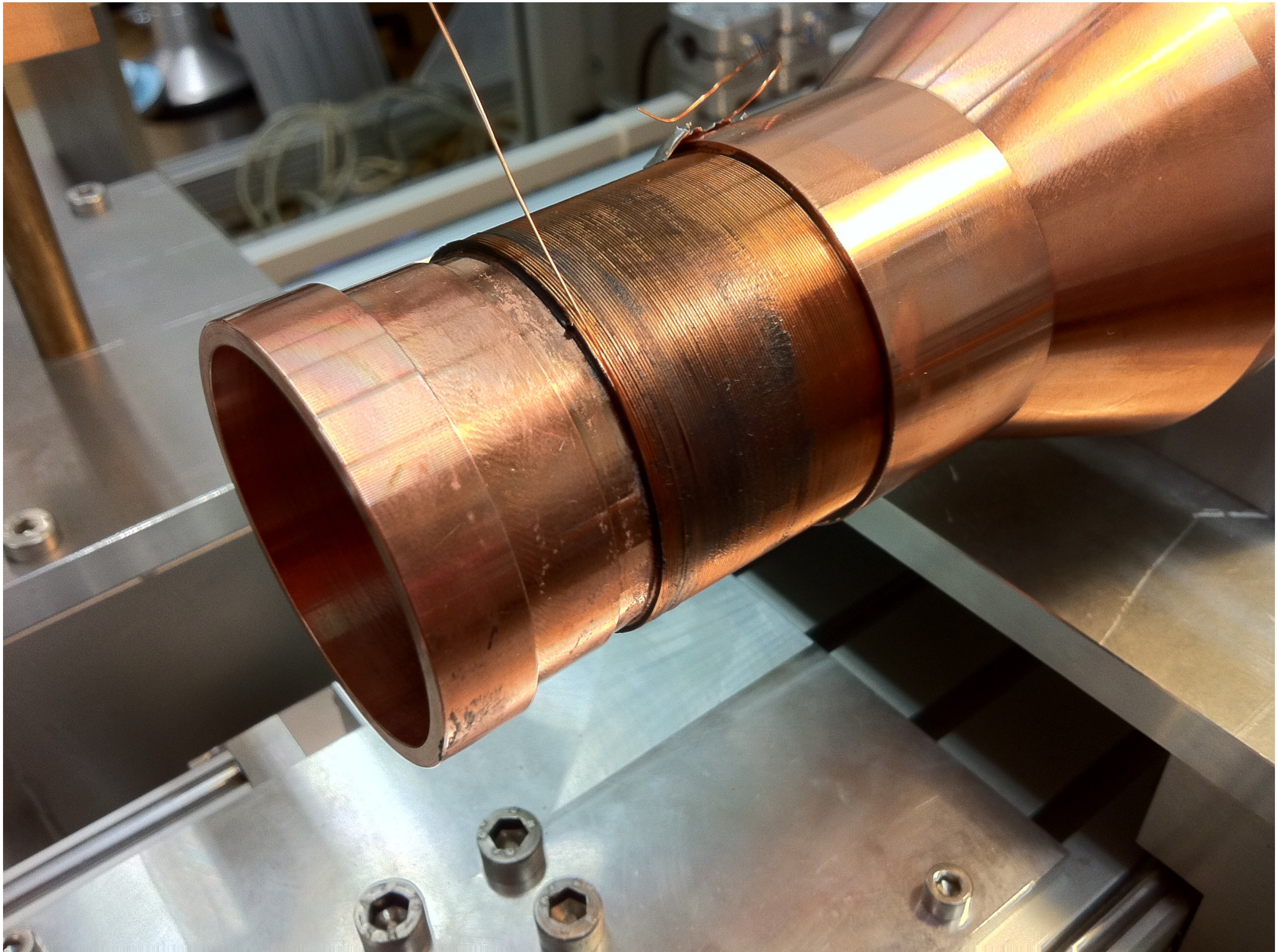


Angaben in mm (±0.05 mm)

Test of the Production Process

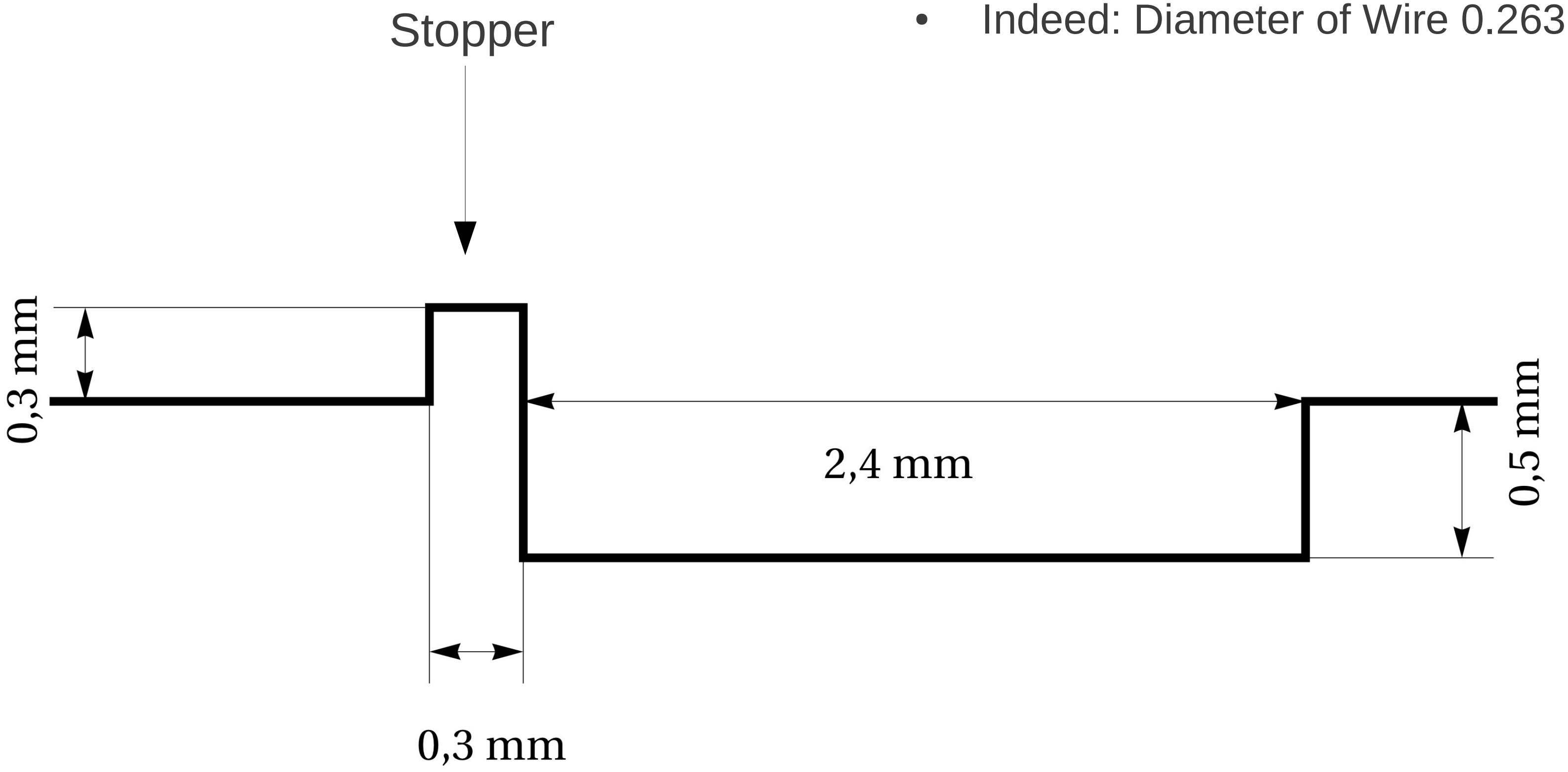


Test of the Production Process

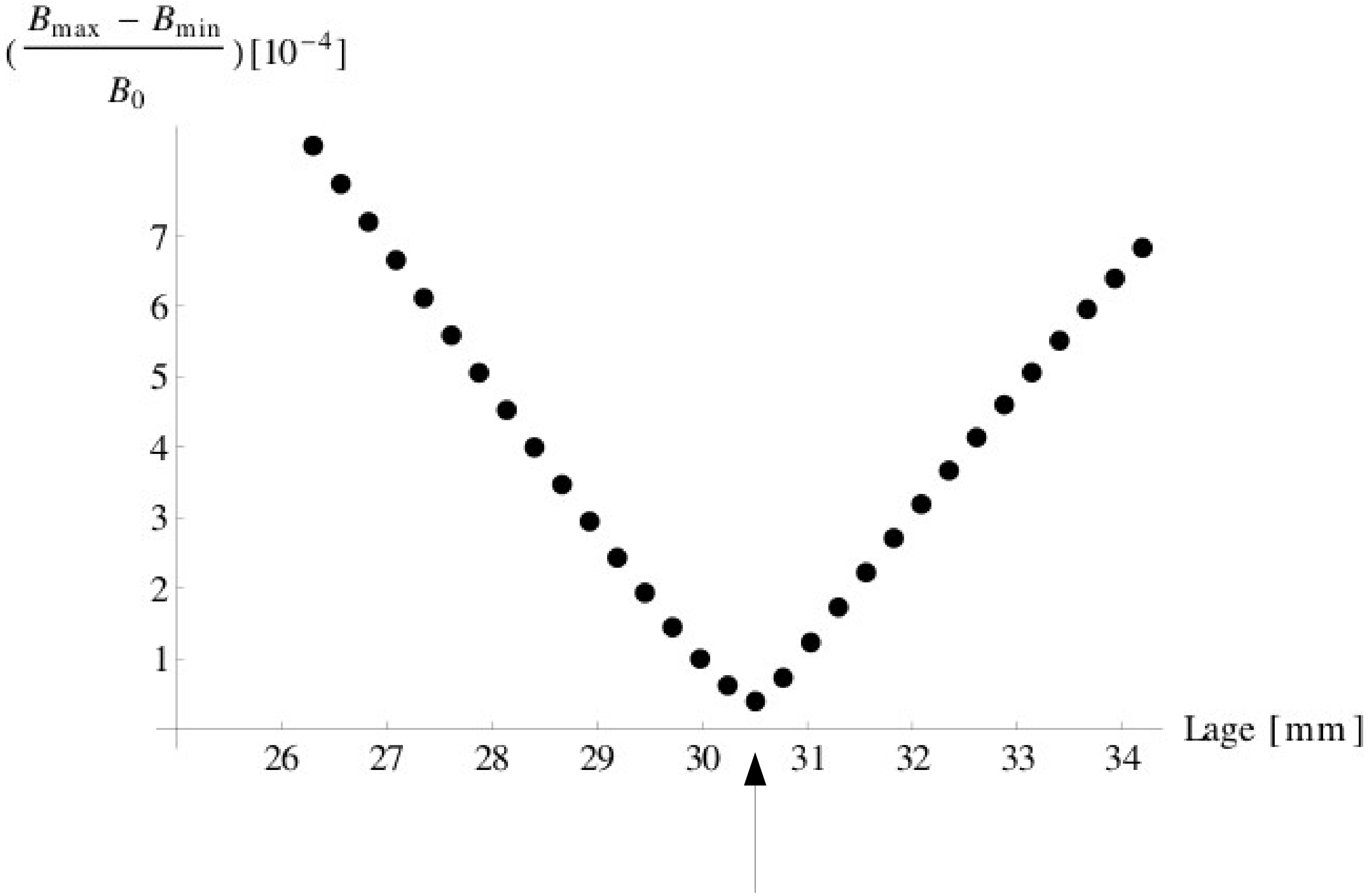


Solution: Windings Stopper

- Stopper reduces windings at the correction position (1 winding less on each side)
- Indeed: Diameter of Wire 0.263 mm

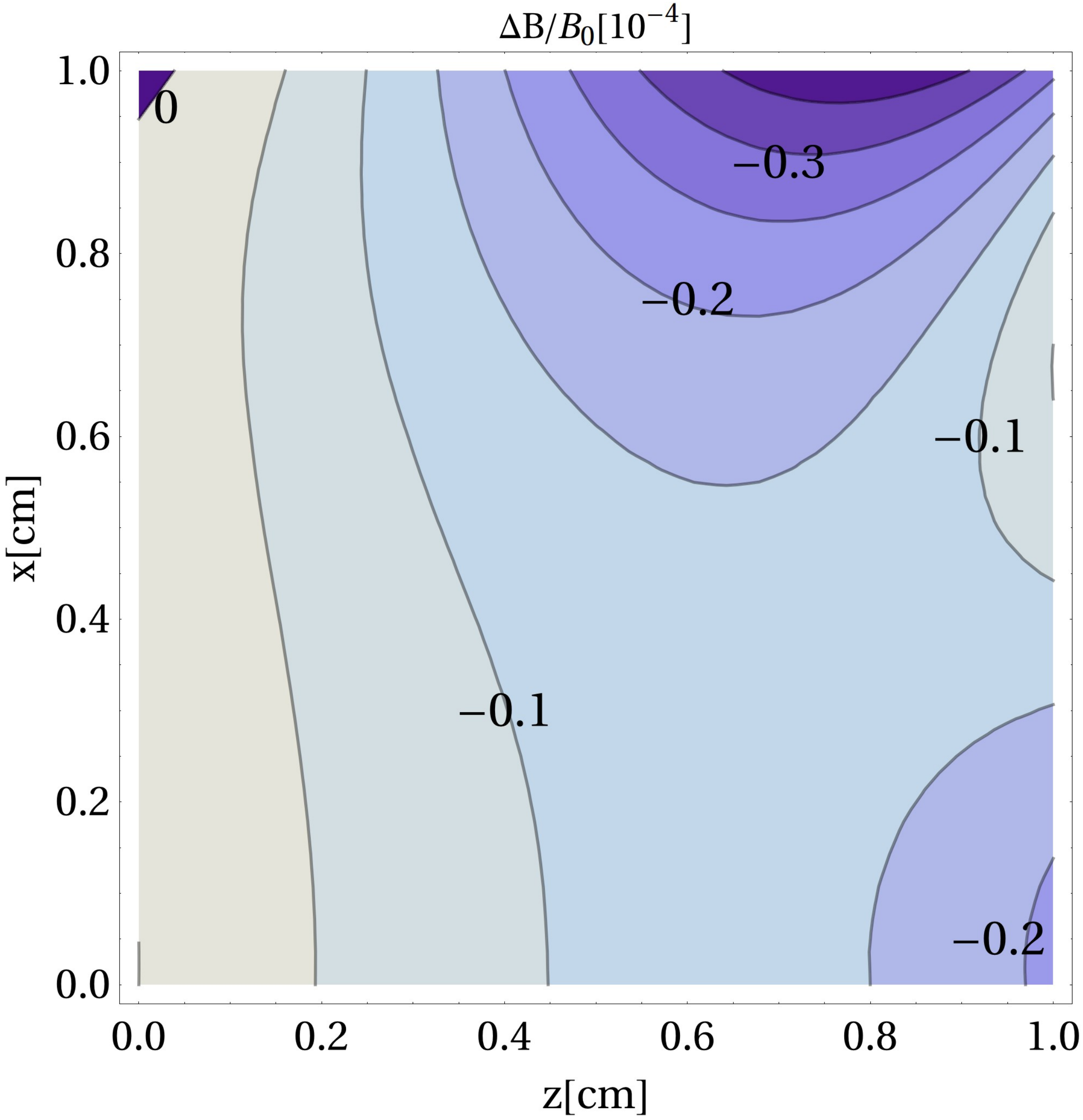


Optimum with new arrangement

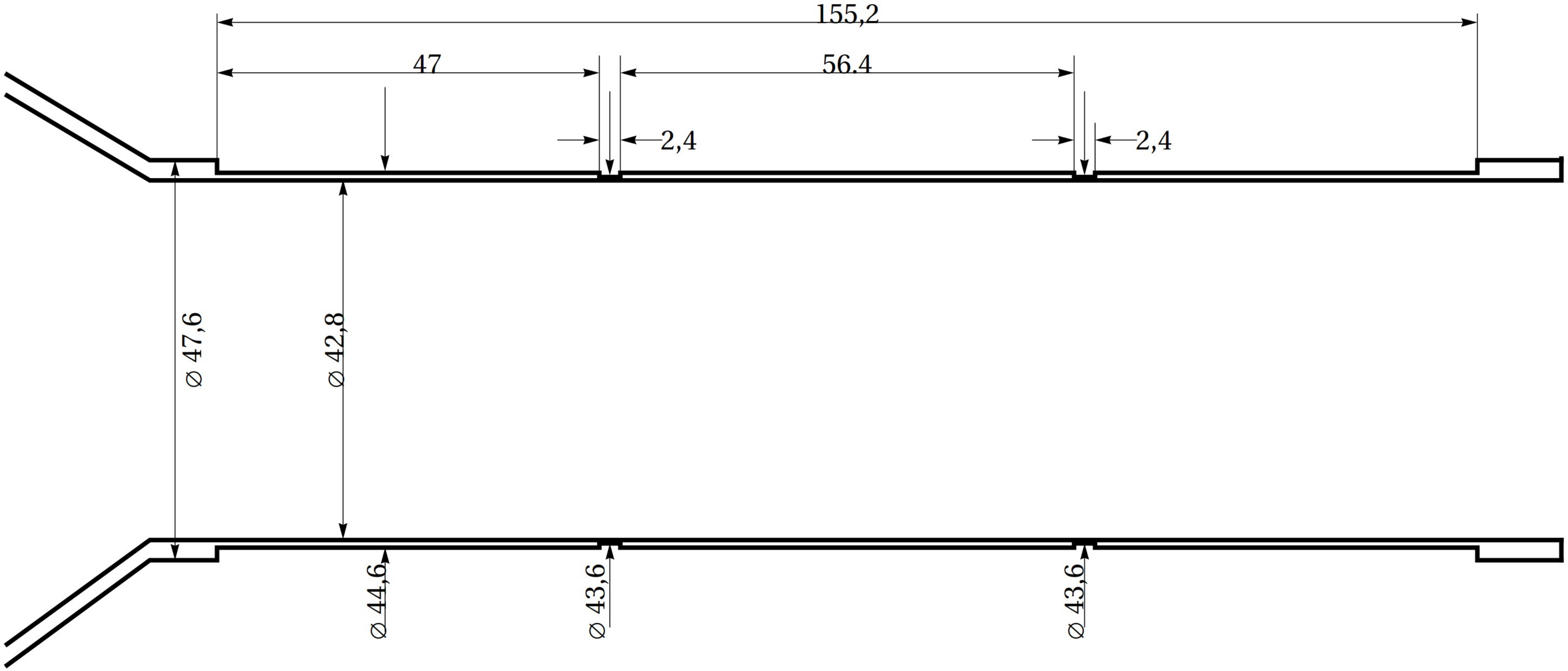


Minimum at 30.5 mm

Corrected Coil

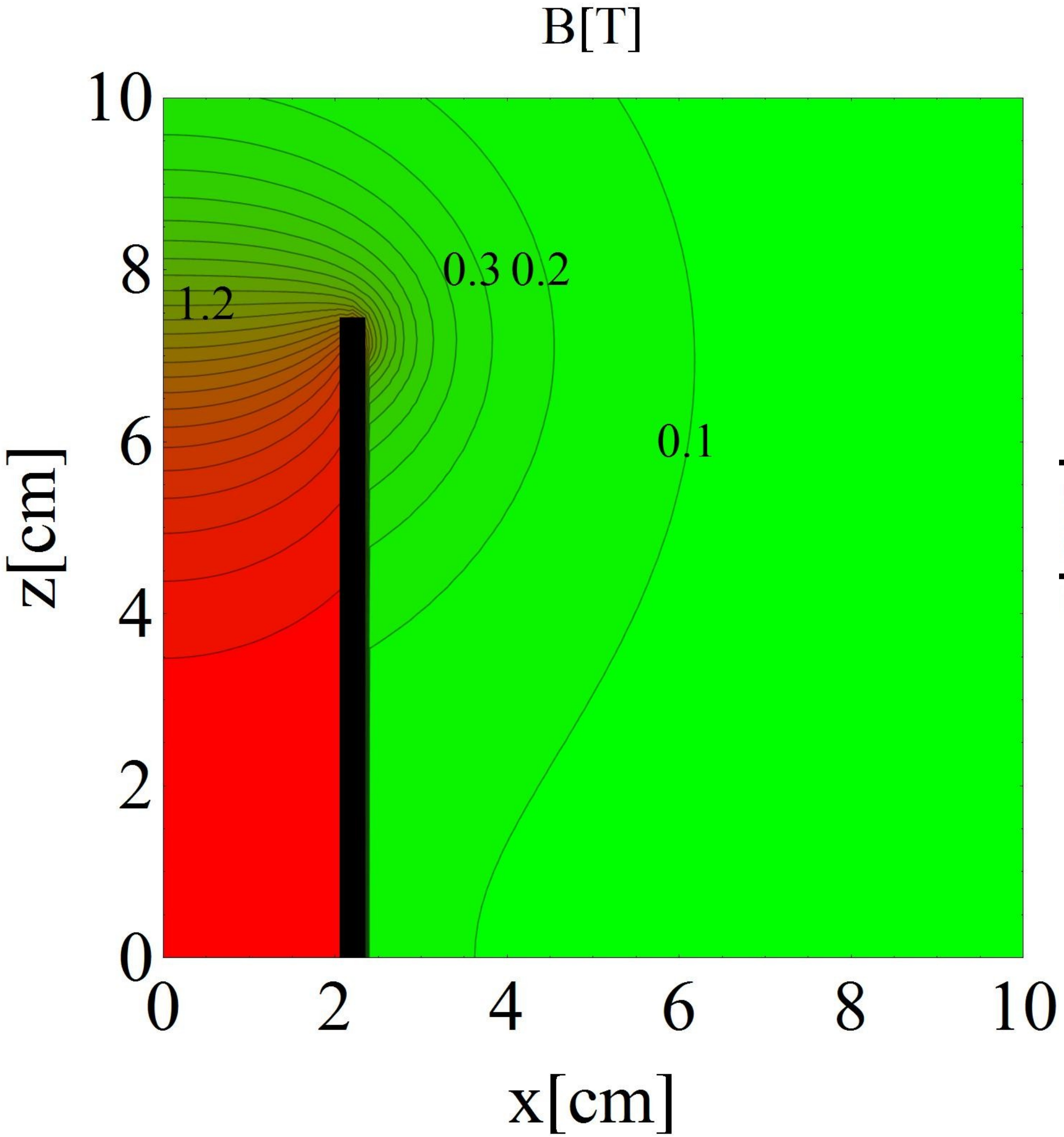


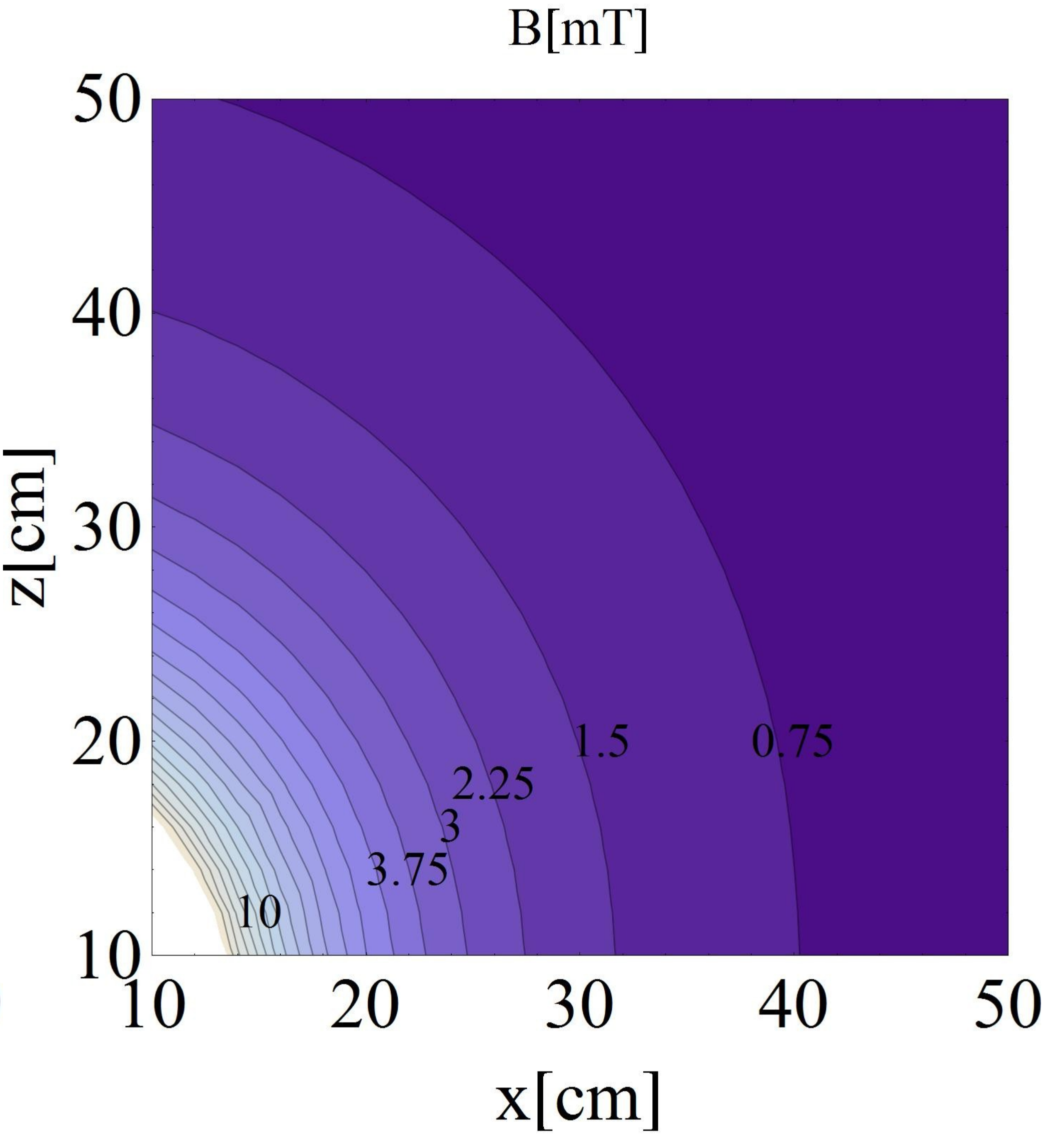
Redesign of the Support (OF Copper) (Inverse Notched Coil)



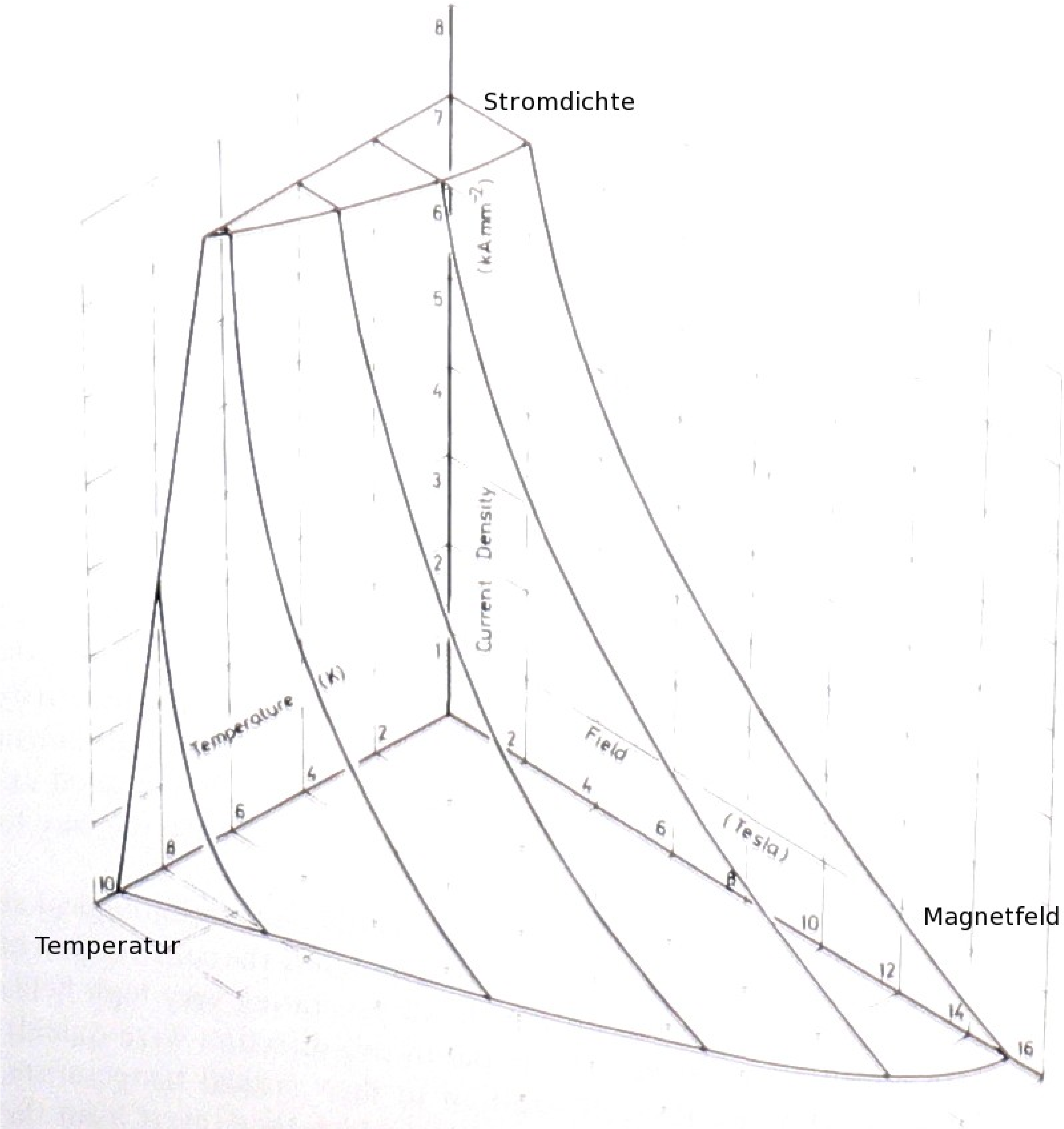
Angaben in mm (±0.05 mm)

Strayfield

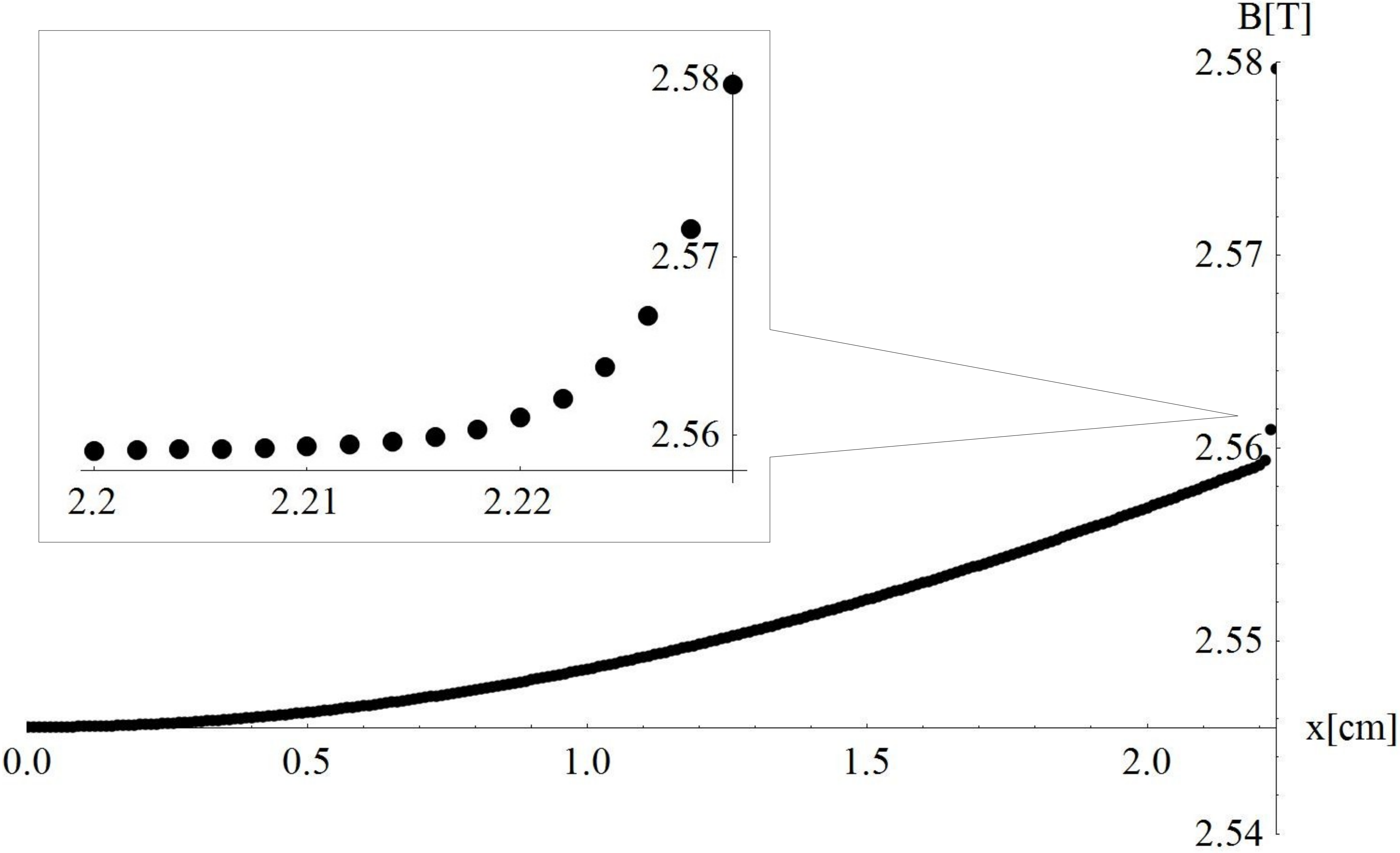

B[T]
1.2
0.3
0.2
0.1
z[cm]
10
8
6
4
2
0
x[cm]
0
2
4
6
8
10


B[mT]
1.5
0.75
2.25
3
3.75
10
z[cm]
50
40
30
20
10
x[cm]
10
20
30
40
50

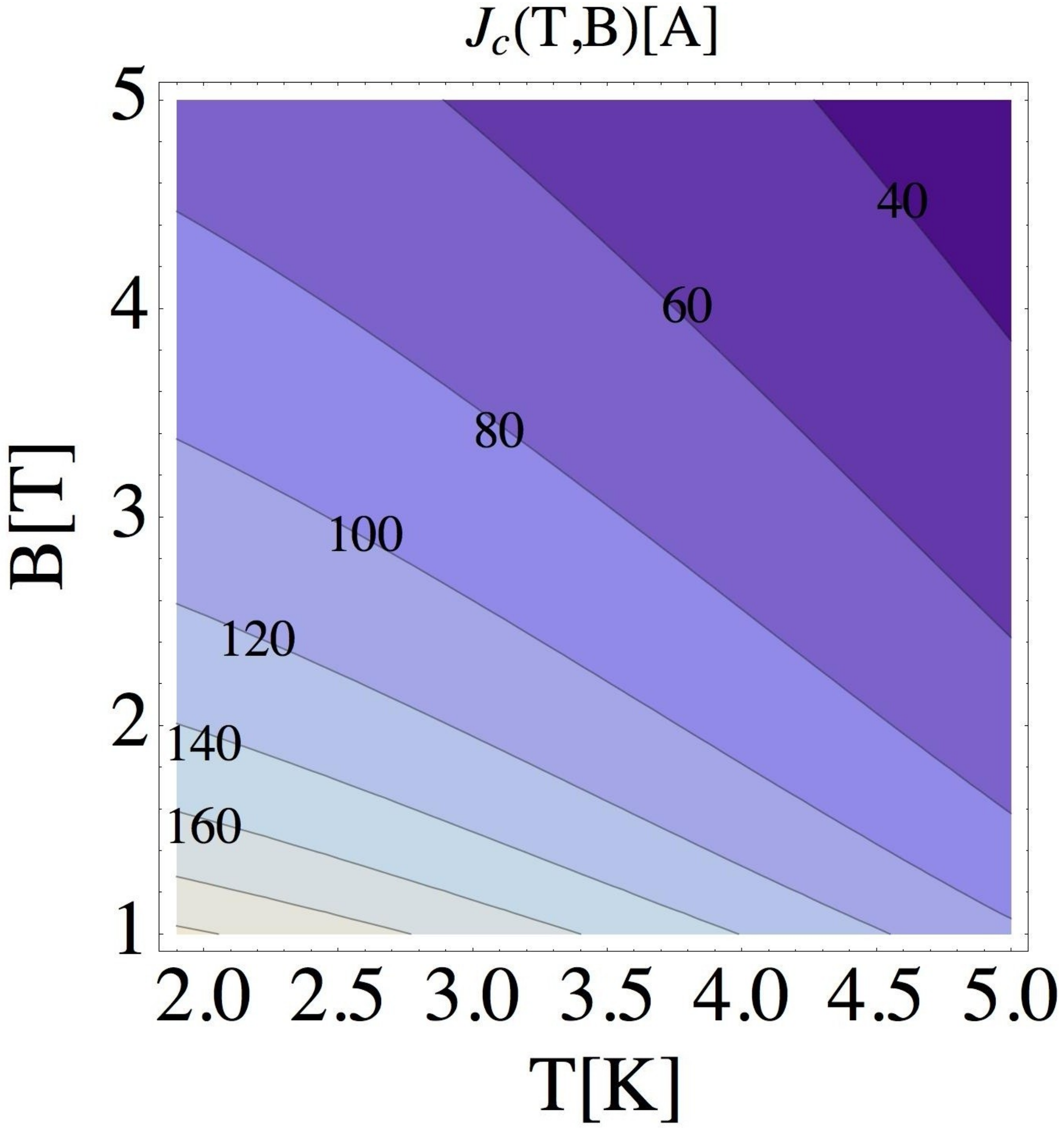
Critical Surface J(T,B)



Maximum Flux Density at the Conductor



Critical Surface Fit



L.Bottura, “A Practical Fit for the Critical Surface of NbTi”

- Status Quo
  - Test winding with copper wire on a part of the coils support
- Further Steps
  - Winding on a whole support structure with copper wire
  - Measurement of the coil at room temperature
  - Winding of the coil with superconductor
  - Installation in the new cryostat
  - Polarization
  - Measurement of the polarization via NMR

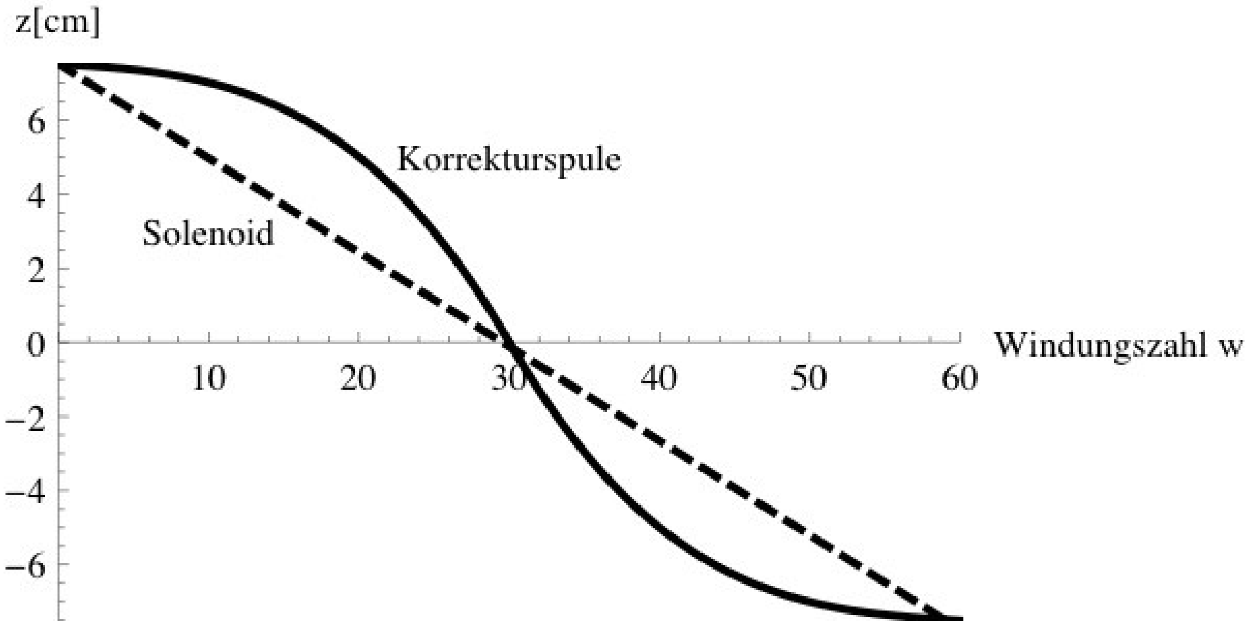
Conclusion of the Inverse Notched Coil Concept

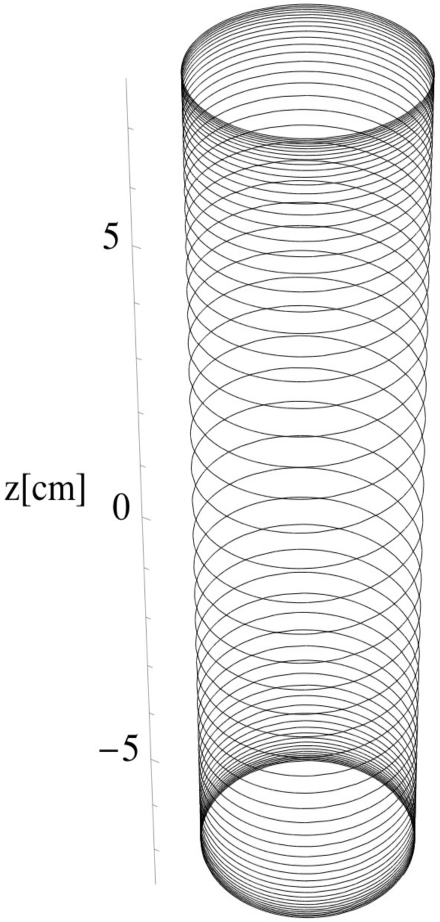
- Internal polarization magnet with flux density 2.5 T
- Inhomogeneity under 10^{-4}
- Recalculation with stopper and thicker wire
- Small strayfield does not disturb the detector components
- Stability of operation (No quenching)

Alternative Correction Coil

Differential Winding Density

Example with
60 windings





Parametrisation of Correction Coil

One half of the coil

$$\overrightarrow{\gamma}(t) = (f\cos(t), f\sin(-t), L - (\underbrace{\frac{r}{\pi}t}_{\text{minimal slope}} + kt^3))$$

$$-\text{number of windings}\ \pi < t < \text{number of windings}\ \pi$$

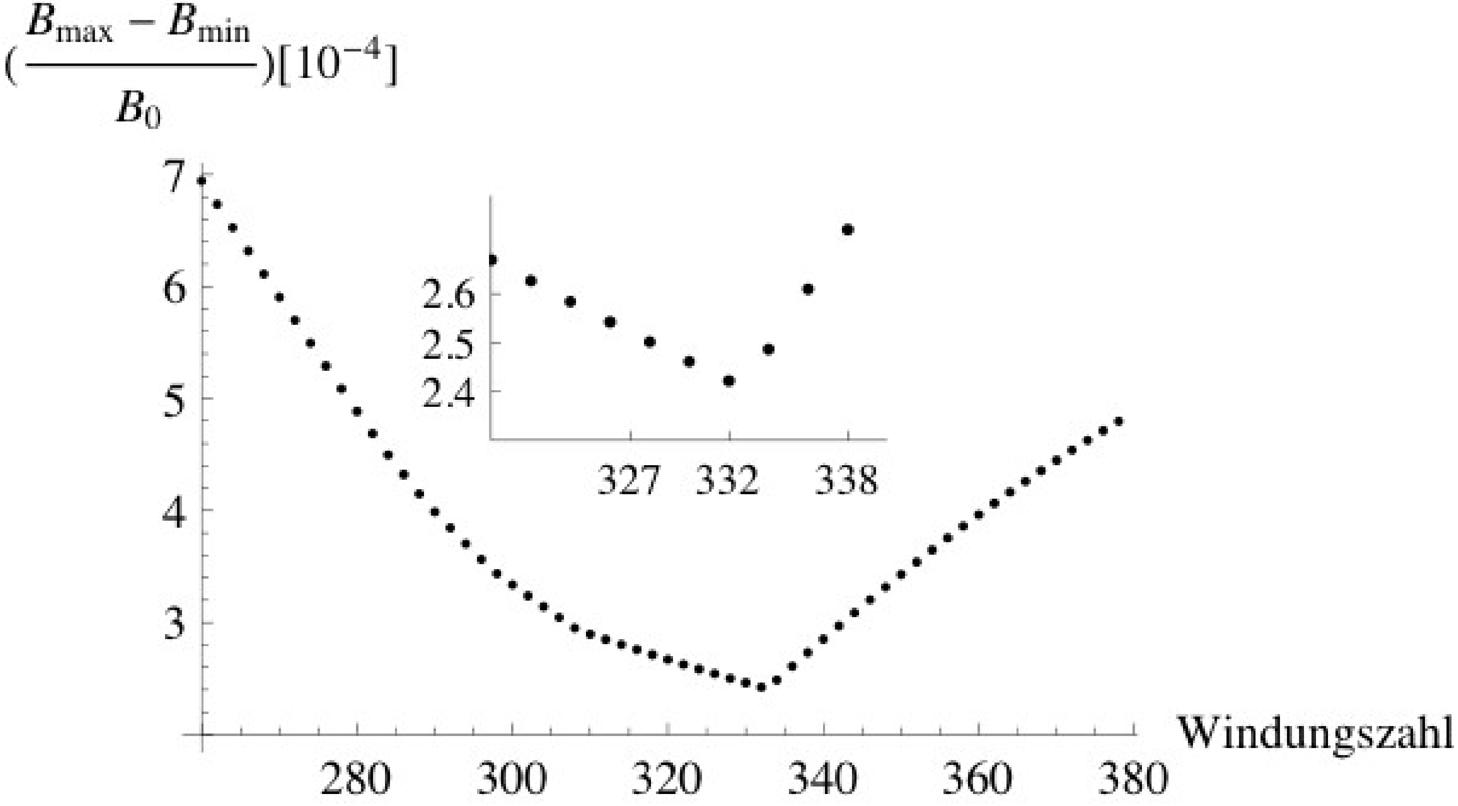
$$k(w) = \frac{L - 2rw}{8\pi^3 w^3}$$

Number of windings : w

Total length of coil : $2L$

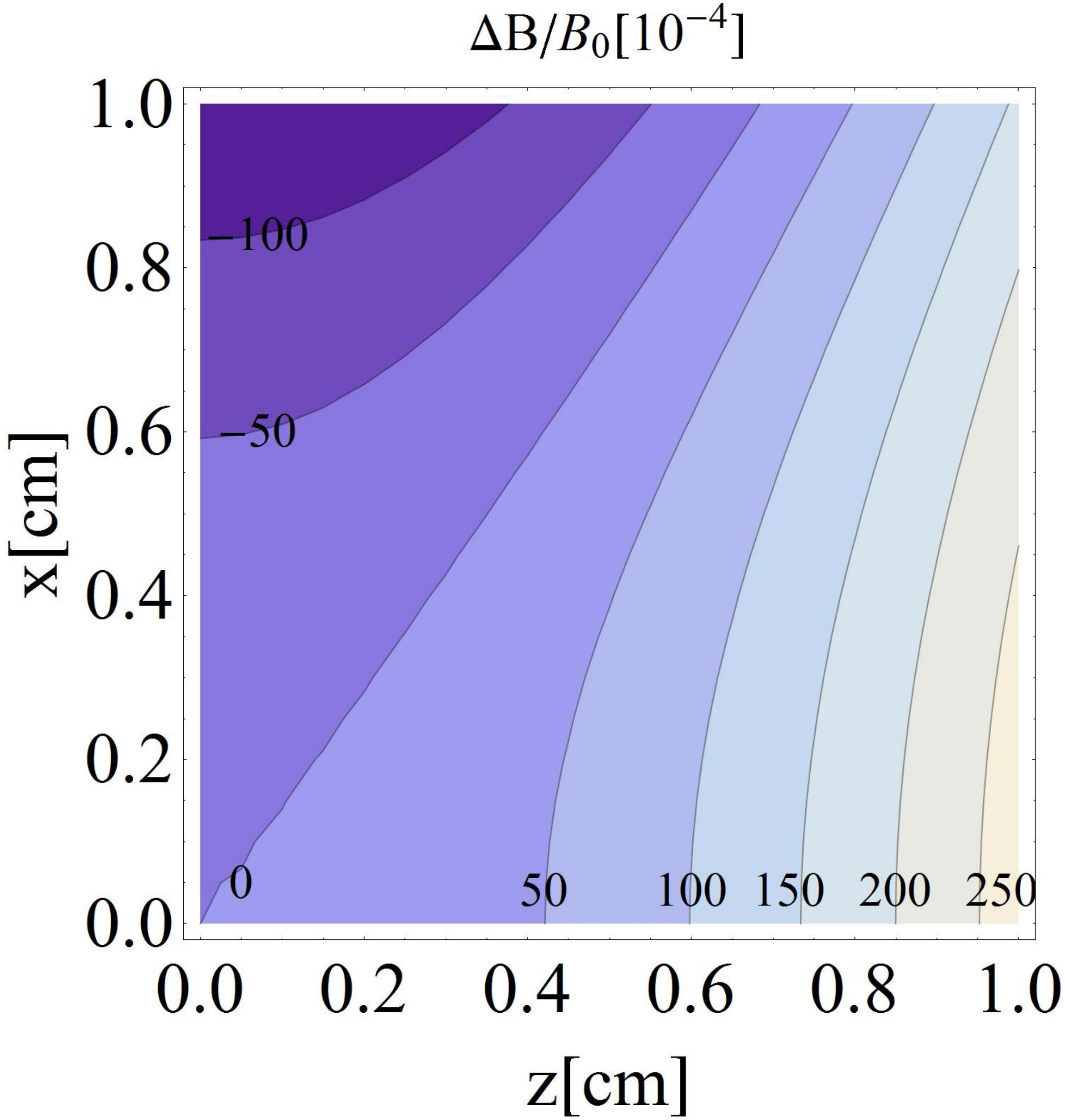
$$dl = \sqrt{\dot{\overrightarrow{x}}(t)\dot{\overrightarrow{x}}(t)}dt = \sqrt{f^2 + \frac{(r + 3\pi k t^2)^2}{\pi^2}}dt$$

Parameter-Sweep

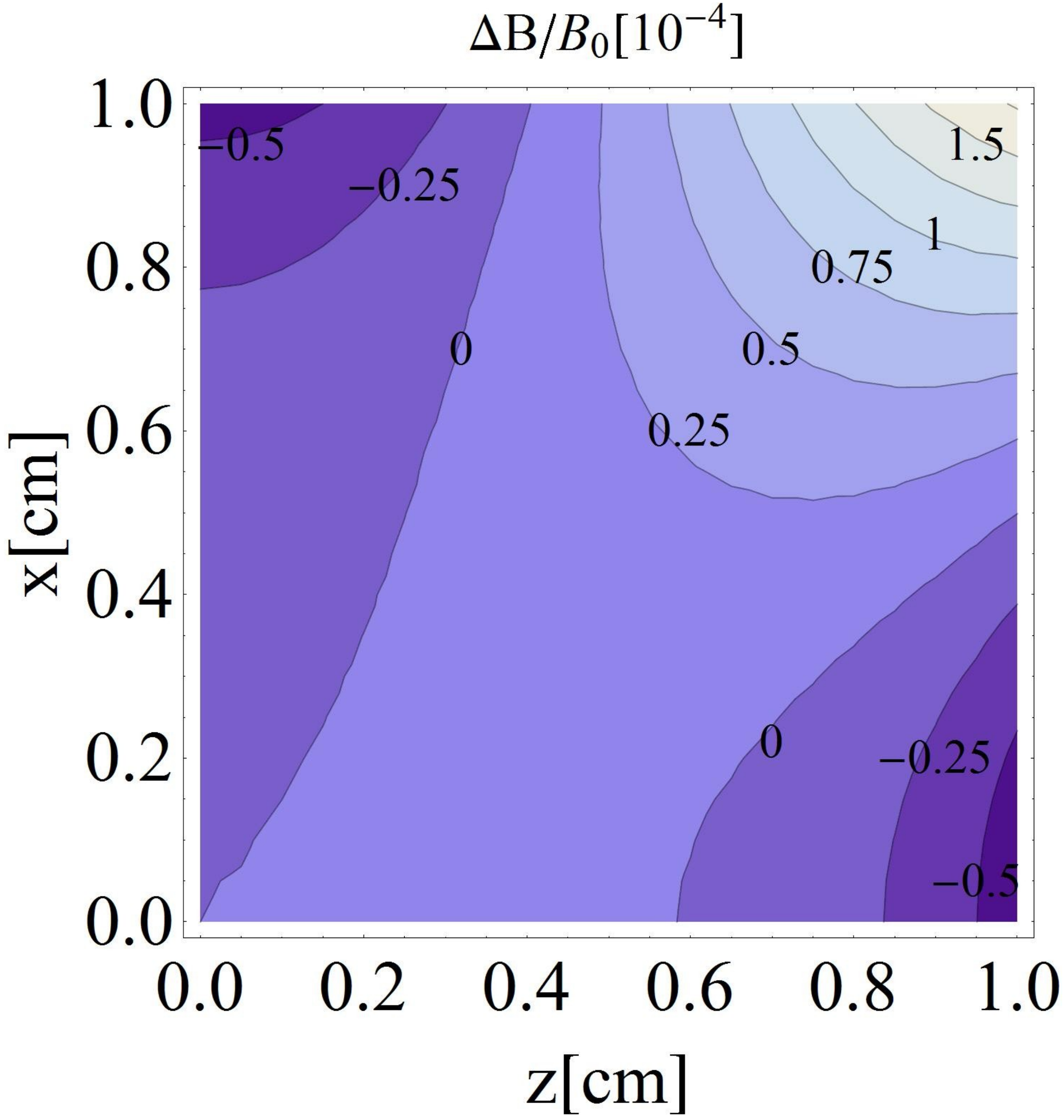


Minimum at (332;2)

Inhomogeneity of the Correction Coil



Corrected, 5-Layer-Solenoid with 332 Correction Windings



Conclusion

- Numerical simulation of an internal polarizing magnet with high field and low inhomogeneity for continuous polarization
- Two different solutions regarding the problem of inhomogeneity of a solenoid
- Comparison of the two models