A thin, superconducting magnet for the Polarized Target

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EU-HP3 WP17: DNP Mag

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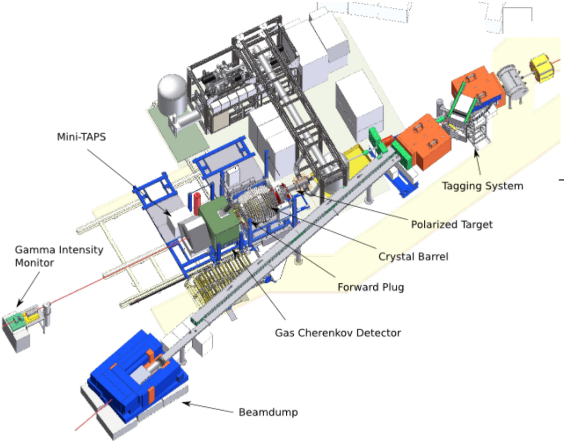
Motivation - Crystal-Barrel-Experiment

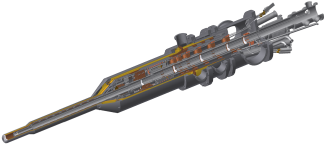
Crystal-Barrel-Experiment at ELSA



Polarisation for a spin 1/2-Ensemble:

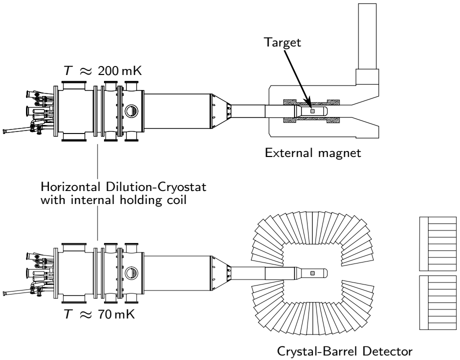
$$P = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

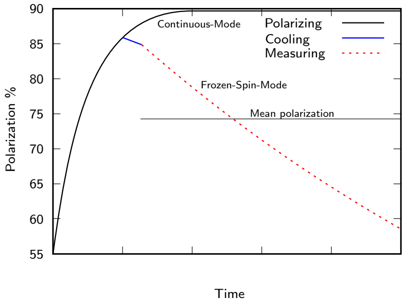
Dilution refrigerator



- Observation of excitation spectra of baryons with double-polarisation observables
- Cryogenic temperatures, high magnetic field, microwaves are needed for Dynamic Nucleon Polarisation (DNP)
- Polarized Target Bonn: Frozen-Spin-Technique

Motivation - 4π-Continuous-Mode Target





- Frozen-Spin-Target: External magnet (2.5 T), internal holding coil (0.6 T)
- Advantage: Large angular acceptance, 4π-Detector,
- Disadvantage: Continuous loss of polarization during data taking, interruption of the experiment, complex handling, low particle flow (4 nA)

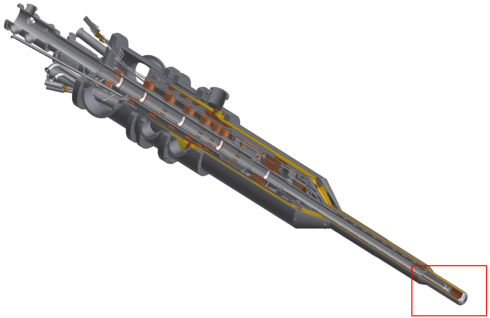
4π-Continuous-Mode Target

Combines the advantages of the high Polarisation and the large angular acceptance
Key element: Internal magnet with the same magnetic properties as the external magnet

Internal polarisation magnet - Basic parameters

Basic parameters are given by:

Cryostat	$\rightarrow$	Position of the target, length, limited number of current leads
Experiment	$\rightarrow$	Magnet thickness
Polarization	$\rightarrow$	Magnetic field



- Cylindrical profile, $\varnothing \sim 4.5\,\mathrm{cm}$
- Length $\sim 15\,\mathrm{cm}$
- As thin as possible
  $\rightarrow$ Overall thinkness $< 2\,\mathrm{mm}$
  $\rightarrow$ Maximize (tech.) current density
- Internal magnet with $B_0 = 2.5\,\mathrm{T}$
- For polarizing deuterons:
  Inhomogeneity within the target volume:

$$\boxed{\frac{\Delta B}{B_0} \ll 10^{-4}}$$

- $V_{\mathrm{hom}}/V_{\mathrm{Overall}} = 1/40$

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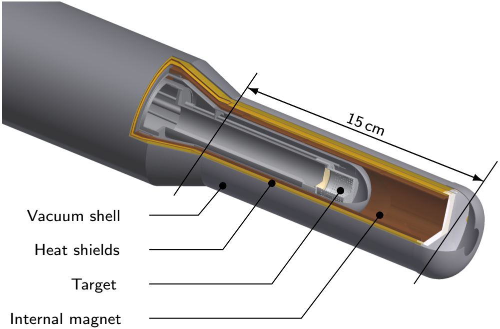

- Cylindrical profile, Ø $\sim$ 4.5 cm
- Length $\sim$ 15 cm
- As thin as possible
  $\rightarrow$ Overall thinkness < 2 mm
  $\rightarrow$ Maximize (tech.) current density
- Internal magnet with $B_0 = 2.5$ T
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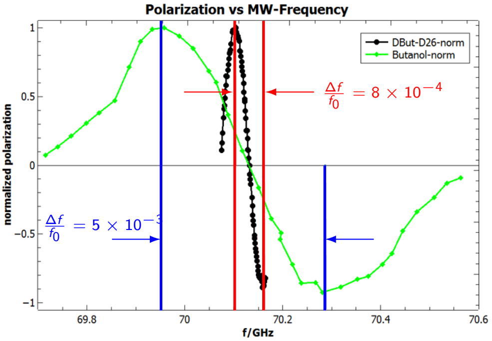

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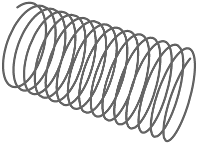
Internal polarisation magnet - Principle of field correction

Solenoid (with given geometry)



- Solenoidal field inhomogeneity is not sufficient for the polarizing mechanism
- Two additional, very thin coils can correct the inhomogeneity to a sufficient value
- No additional current leads are needed
- **Precise wire guiding with notches within the carrier (Inverse Notched Coil)**

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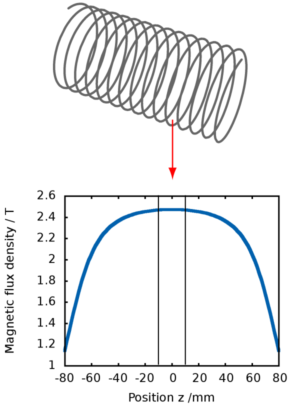

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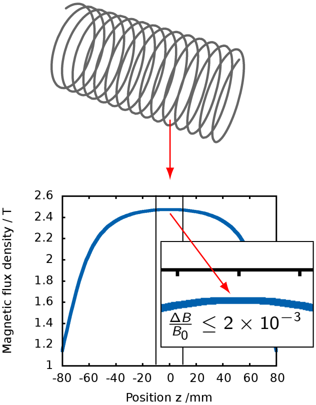

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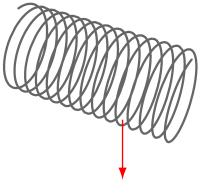
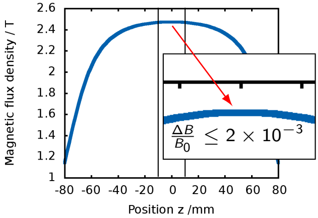
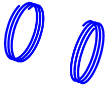
Additional correction coils







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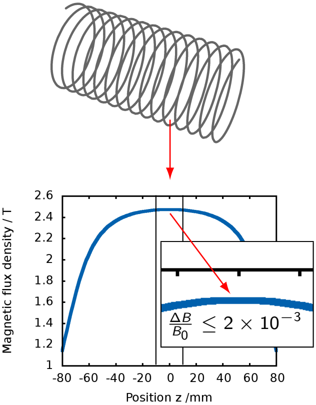

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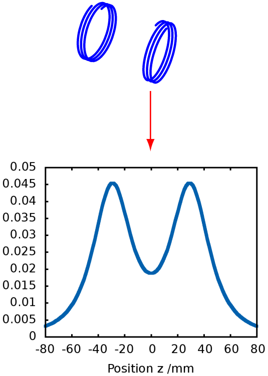

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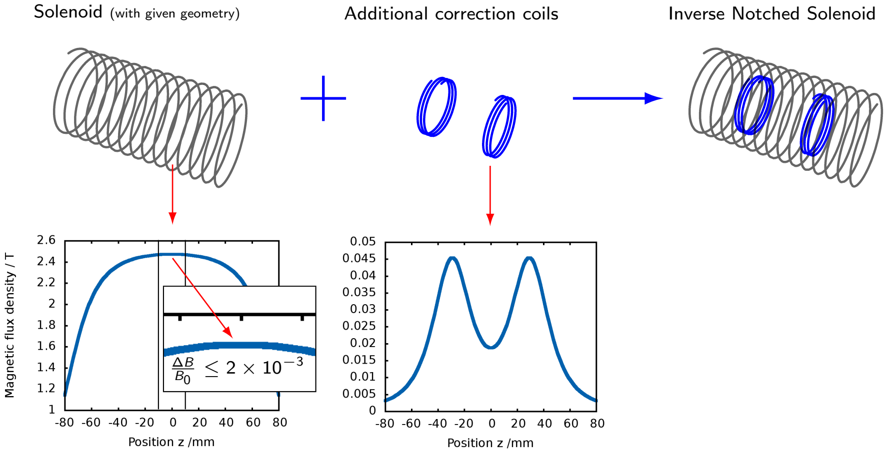

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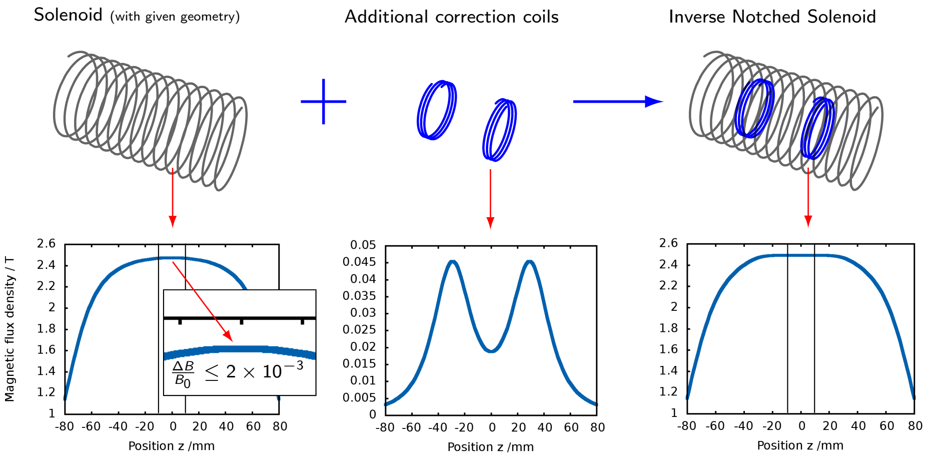

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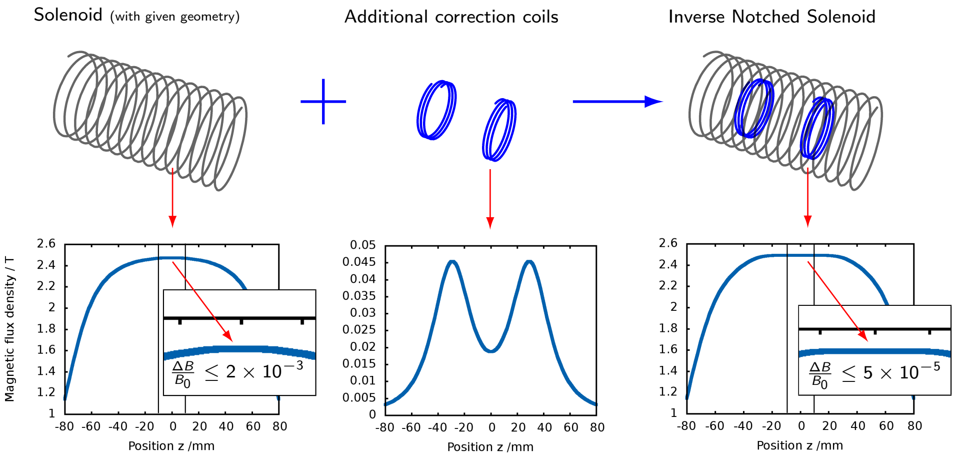

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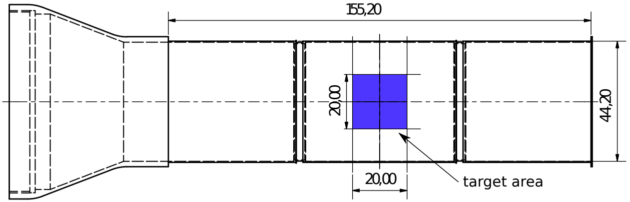


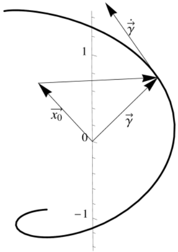
Biot-Savart-Law:

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

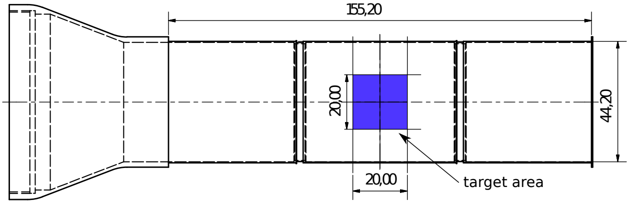
Loop parametrization:

$$\vec{\gamma} = (r\cos(t), r\sin(t), n \cdot d)$$

r: radius of each loop
$n \cdot d$: loop position
d: effective distance between 2 wires
(in practice: $d \neq \varnothing_{\mathrm{wire}}$)



Internal polarisation magnet - Field calculation



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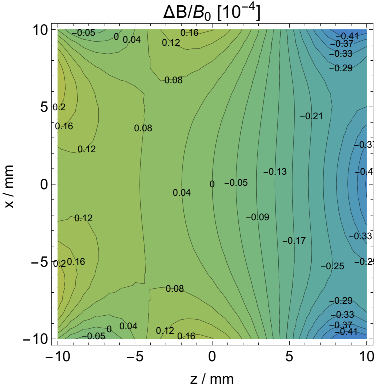
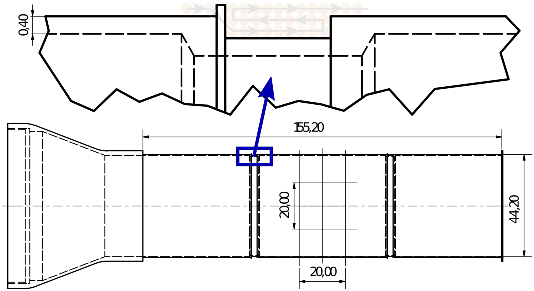
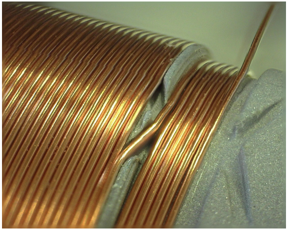
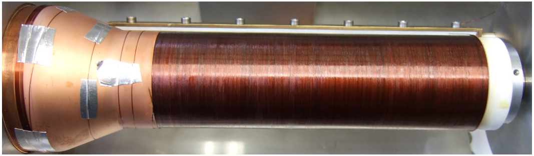


Internal polarisation magnet - Production







- Carrier thickness + wire < 2 mm
- Orthocyclic winding pattern $\rightarrow$ highest filling factor
- NbTi, $\varnothing = 0.254\,\mathrm{mm}$ ($j_{el} = 2185\,\mathrm{A\,mm^{-2}}$)
- 6×590 windings @90 A @ 1 K + 2×9 windings for each notch
- $|\Delta B/B_0| \leq 5 \times 10^{-5}$
- Inductance $L = 160\,\mathrm{mH}$
- Stored energy $E = 650\,\mathrm{J}$
- Building process by wet wiring
- Wires are fixed by cryogenic epoxy

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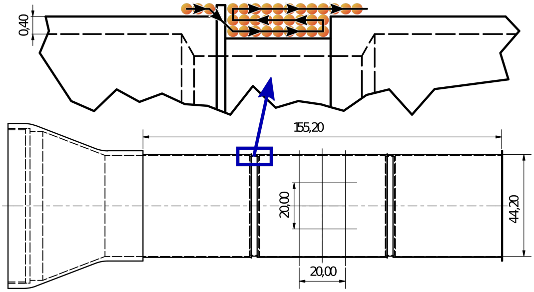

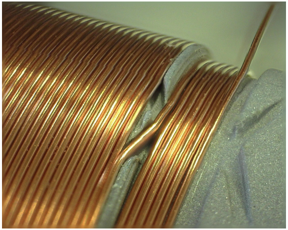

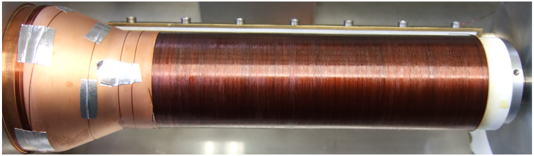

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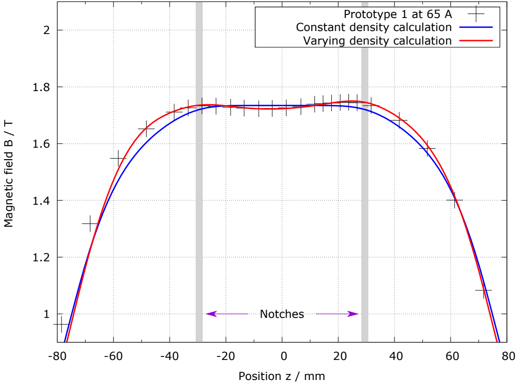
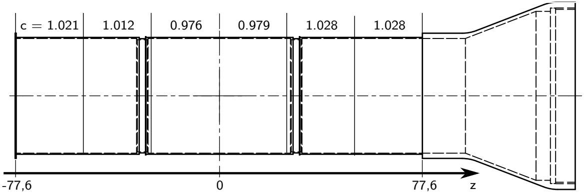
Protype 1: Field Measurement



Prototype 1

- Asymmetric structure with two local maxima
- $\frac{\Delta B}{B_0} > 10^{-3}$, no DNP
- Reason: local varying current density caused by wiring process (Varying density calculation, surface analysis)
- **Solenoidal winding diminishes the homogeneity**
  $\rightarrow$ Conclusion: Better Wiring skills are necessary



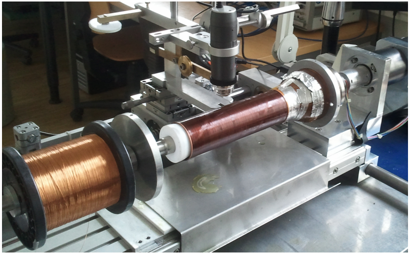
$$d' = \frac{1}{c} \cdot d$$

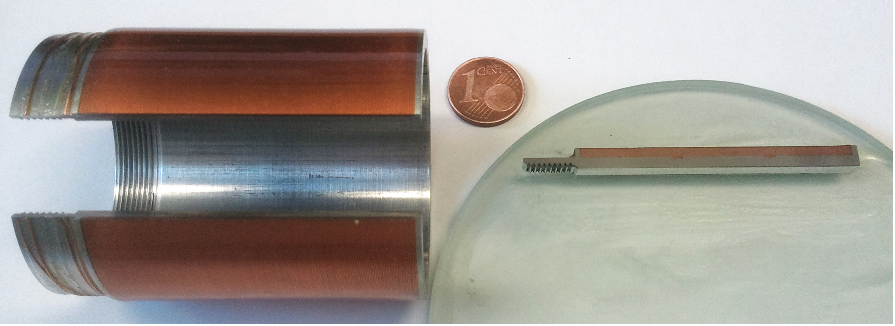
$$|1 - c| > 2\,\%$$

$d \approx 0.274\,\text{mm}$: effective distance

First tests with new wiring apparatus

- Modification of the wiring apparatus for better wire guiding
- Wet wiring test with an aluminium carrier, length $l = 50\,\mathrm{mm}$, Copper wire $\varnothing 0.254\,\mathrm{mm}$
- Cross-sectional view: nearly perfect orthocyclic winding pattern
- Fluctuation of the effective distance could be reduced to $< 1\,\%$
- A much better performance can be noticed in comparison to early wiring tests





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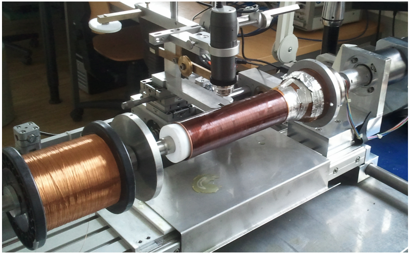

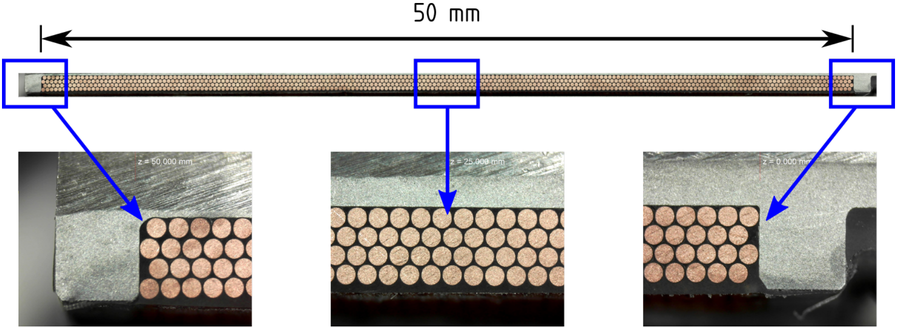

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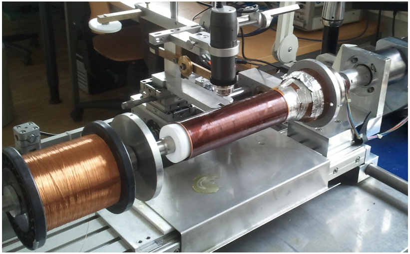
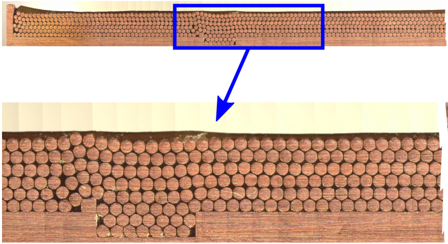
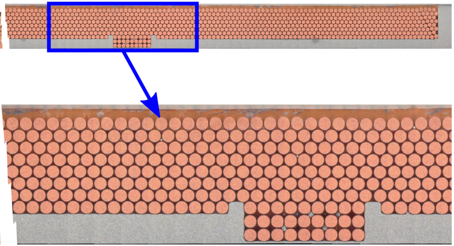


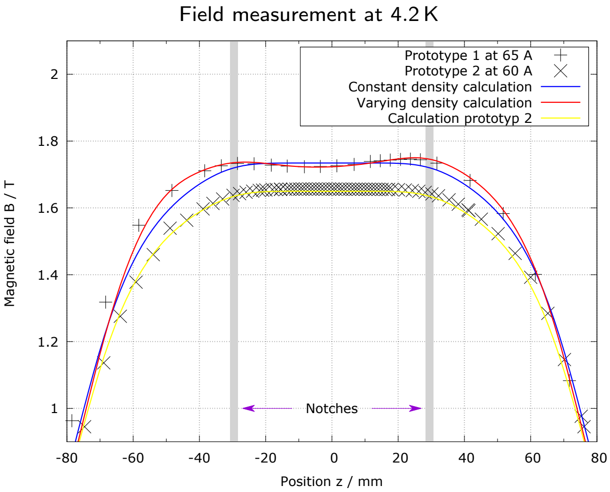


Cross-sectional view of a very early wiring test



Cross-sectional view of the latest wiring test

Prototype 2: Field measurement and other results

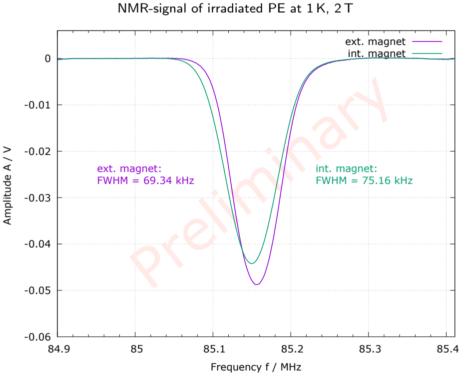


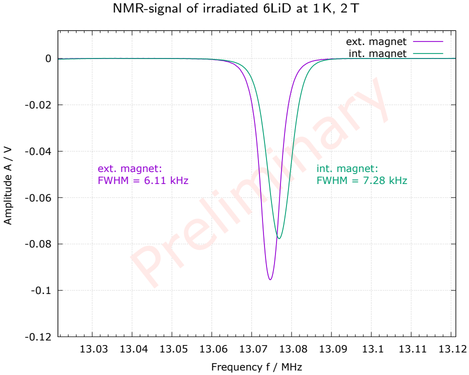
- Flat plateau in the central area
- $\frac{\Delta B}{B_0} < 10^{-3}$, sufficient for DNP

} Polarization experiment with Proton/Deuteron target

Result of magnet tests in 4He-Refrigerator

A proton and a deuteron target could be dynamically polarized with an internal magnet





Homogeneity criteria suffient for

- Protons (easy)
- 6LiD (challenging)

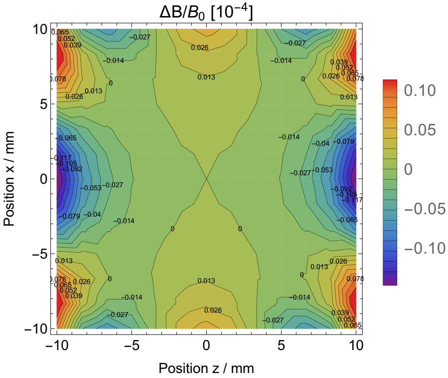
- Inversed Notched Coil works for DNP

Summary

- Motivation for development: **4π-Continuous-Mode-Target**
- Geometry and basic condition $\rightarrow$ **Inverse Notched Coil**
- Homogeneity $\rightarrow$ **Get every wire into its calculated position**
- **First time a proton/Deuteron-DNP-signal was measured when using an internal polarisation magnet**

Outlook

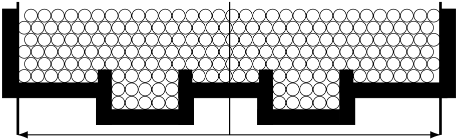
- Mounting within the new dilution refrigerator
- Construction of the final version



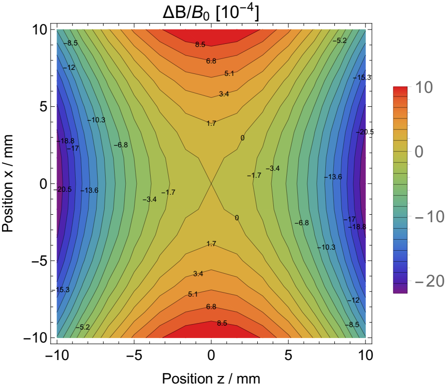
d_{eff}	0.265	mm
length	176.225	mm
radius	23.3	mm
Correcton width	9	d_{eff}
Correction position	105 to 116	d_{eff}
Current	70	A
Center field B_0	2.574	T
Homogeneity $\lvert\Delta B/B_0\rvert$	1.5×10^{-5}	

Additional Information - Symmetric vs. Asymmetric - Field maps

Asymmetric case

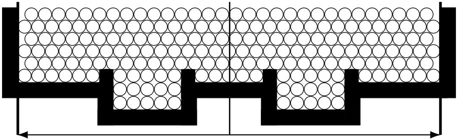


length $= 31 d_{eff} + d_{eff}/2$



Field created by a solenoid with asymmetric winding pattern

Symmetric case



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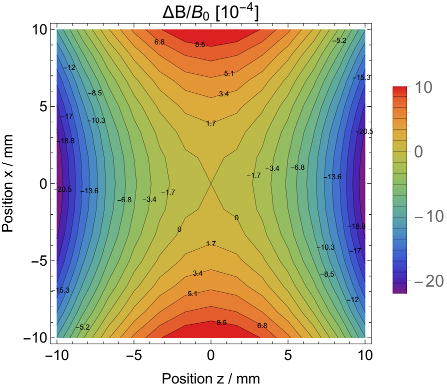

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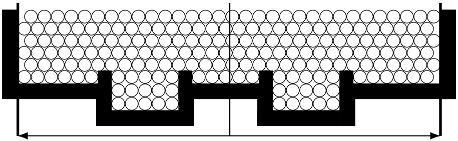
Asymmetric case



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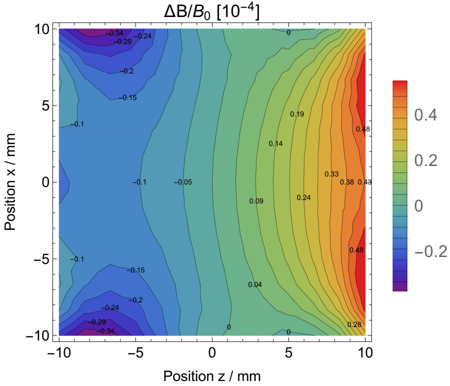
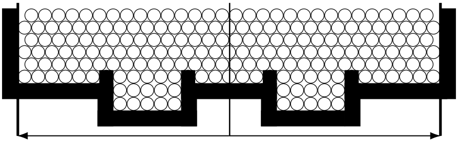
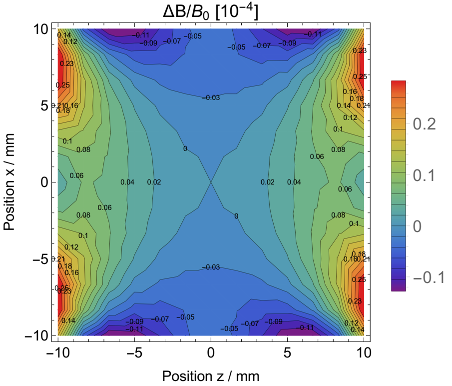


Effect of the correction coils to the asymmetric winding pattern

Symmetric case

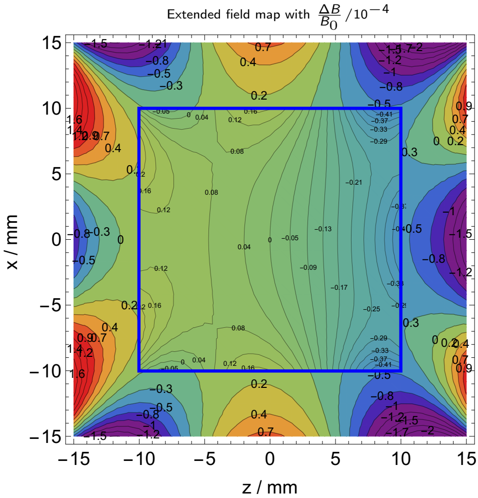


length $= 31 d_{eff}$



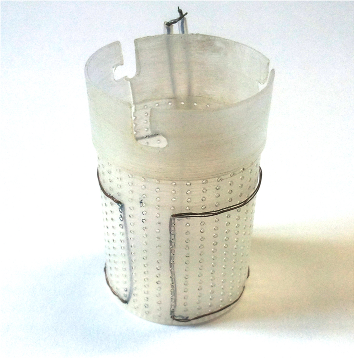
Effect of the correction coils to the symmetric winding pattern

Additional Information - Extended field map



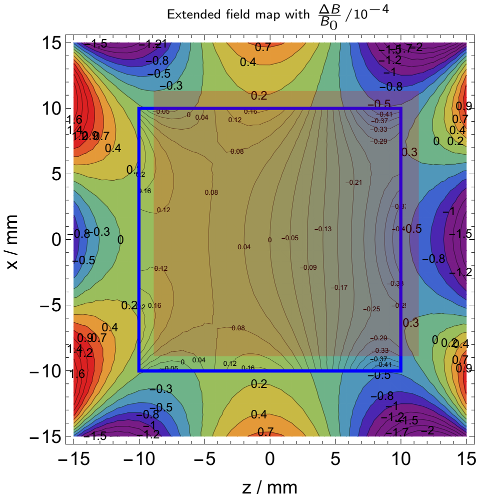
- Target misalignment in x- and z-direction makes parts of the target lay in much more inhomogeneous regions

Target container with NMR-saddle coil



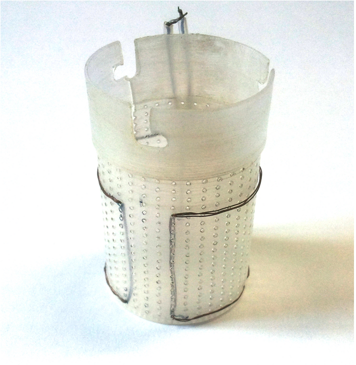
- Absorbed r.f. power: $P = 2\boldsymbol{H}_1^2 \chi'' \omega$
- NMR geometry and position give weight to certain regions
- Outer inhomogeneous regions are more weighted with a saddle coil

Additional Information - Extended field map



- Target misalignment in x- and z-direction makes parts of the target lay in much more inhomogeneous regions

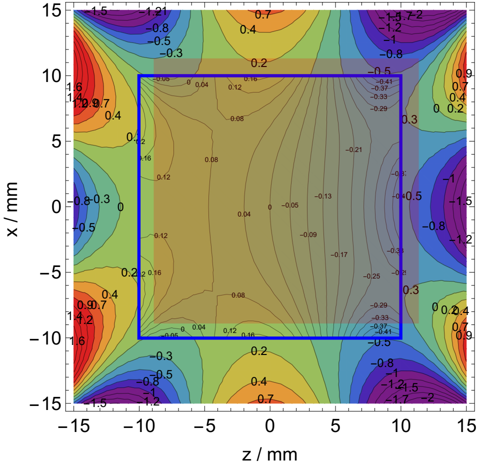
Target container with NMR-saddle coil



- Absorbed r.f. power: $P = 2\boldsymbol{H_1^2}\chi''\omega$
- NMR geometry and position give weight to certain regions
- Outer inhomogeneous regions are more weighted with a saddle coil

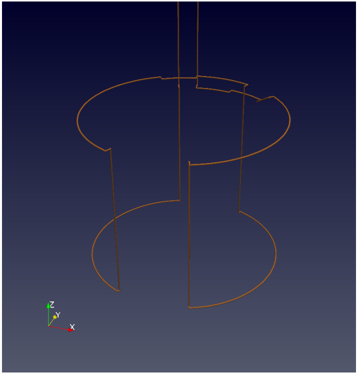
Additional Information - Extended field map

Extended field map with $\frac{\Delta B}{B_0}/10^{-4}$



- Target misalignment in x- and z-direction makes parts of the target lay in much more inhomogeneous regions

CAD-Model of the NMR-saddle coil



- Absorbed r.f. power: $P = 2\boldsymbol{H_1^2}\chi''\omega$
- NMR geometry and position give weight to certain regions
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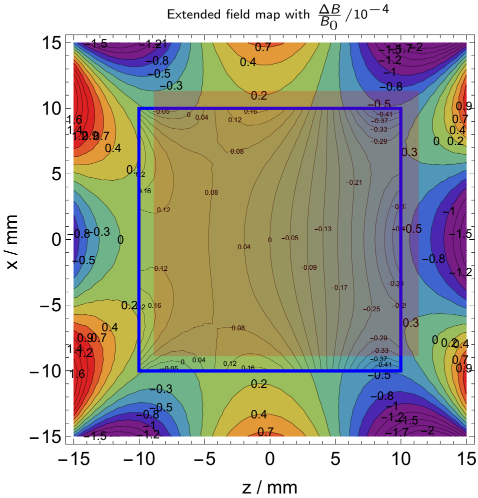
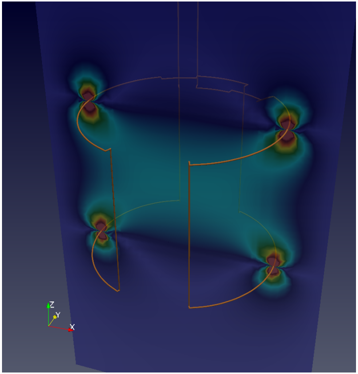
Additional Information - Extended field map



- Target misalignment in x- and z-direction makes parts of the target lay in much more inhomogeneous regions

CAD-Model of the NMR-saddle coil with xz-plane



- Absorbed r.f. power: $P = 2\boldsymbol{H}_1^2\chi''\omega$
- NMR geometry and position give weight to certain regions
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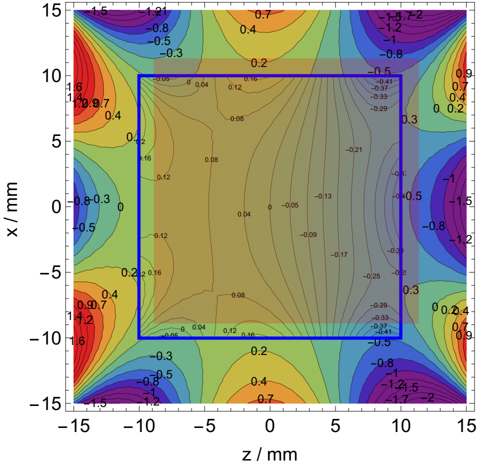
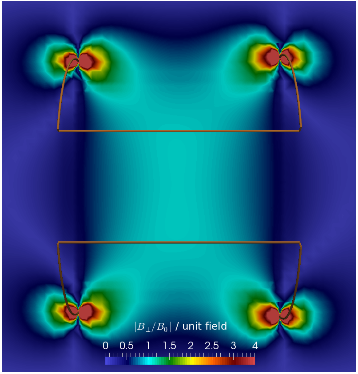
Additional Information - Extended field map

Extended field map with $\frac{\Delta B}{B_0}/10^{-4}$



- Target misalignment in x- and z-direction makes parts of the target lay in much more inhomogeneous regions

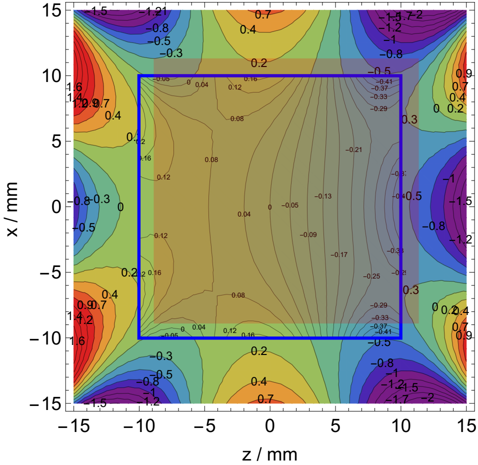
FEM-Simulation of normalized field $B_1 \perp B_z$ of the NMR-saddle coil in xz-plane



- Absorbed r.f. power: $P = 2\boldsymbol{H}_1^2 \chi'' \omega$
- NMR geometry and position give weight to certain regions
- Outer inhomogeneous regions are more weighted with a saddle coil

Additional Information - Extended field map

Extended field map with $\frac{\Delta B}{B_0}/10^{-4}$



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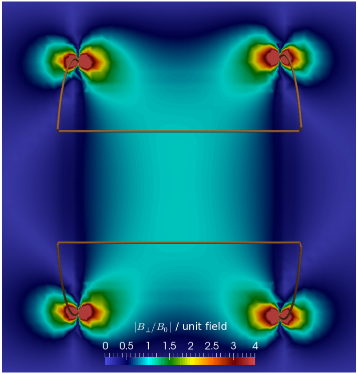

- Absorbed r.f. power: $P = 2\boldsymbol{H}_1^2\chi''\omega$
- NMR geometry and position give weight to certain regions
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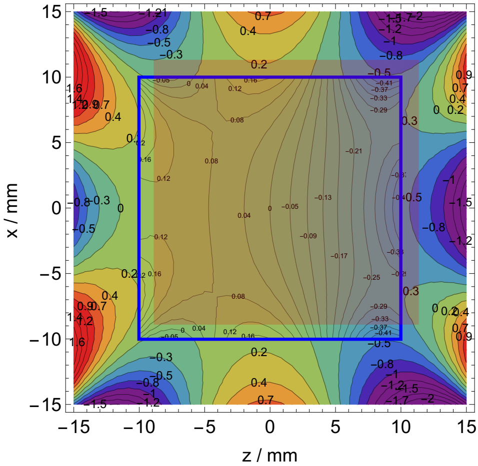
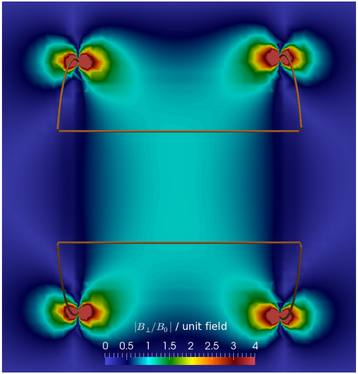
Additional Information - Extended field map

Extended field map with $\frac{\Delta B}{B_0}/10^{-4}$



- Target misalignment in x- and z-direction makes parts of the target lay in much more inhomogeneous regions

FEM-Simulation of normalized field $B_1 \perp B_z$ of the NMR-saddle coil in xz-plane



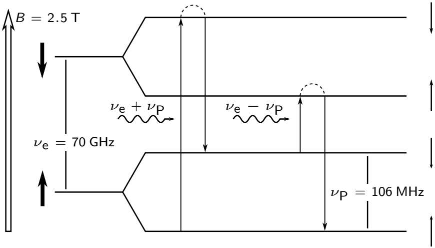
- Absorbed r.f. power: $P = 2\boldsymbol{H}_{\boldsymbol{1}}^{\boldsymbol{2}}\chi''\omega$
- NMR geometry and position give weight to certain regions
- Outer inhomogeneous regions are more weighted with a saddle coil

Additional Information - DNP

Condition for (internal) polarisation magnets:

Homogeneity: $$\frac{\Delta B}{B_0} \ll 10^{-4}$$

Dynamic Nucleon Polarisation: Solid-State-Effect



Zeeman: $E_{M,m} = g_e \mu_B M B - g_p \mu_p m B$

Condition: $\Delta\nu_e \ll \nu_P$

Relation: $\dfrac{\Delta\nu_e}{\nu_e} = \dfrac{\Delta B}{B_0}$

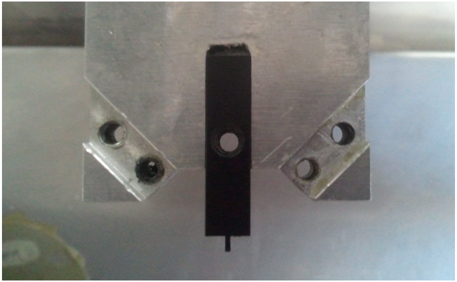
$\rightarrow \quad \dfrac{\Delta B}{B_0} \ll \dfrac{\nu_P}{\nu_e}$

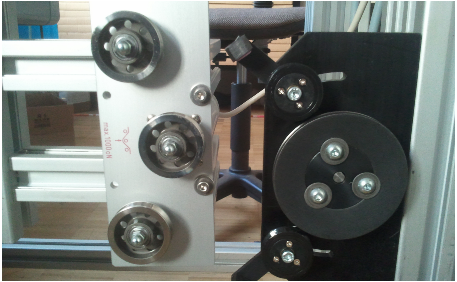
Protons: $$\frac{\Delta B}{B_0} \ll \frac{106\,\text{MHz}}{70\,\text{GHz}} \approx 1.5 \times 10^{-3}$$

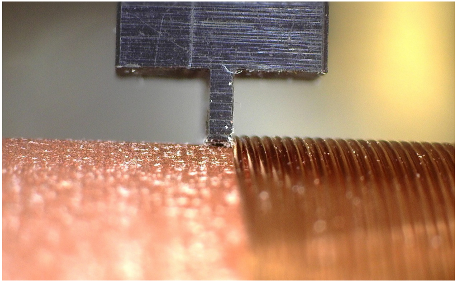
Deuterons: $$\frac{\Delta B}{B_0} \ll \frac{16\,\text{MHz}}{70\,\text{GHz}} \approx \boxed{2.3 \times 10^{-4}}$$

Additional Information - Main modification of the wiring apparatus

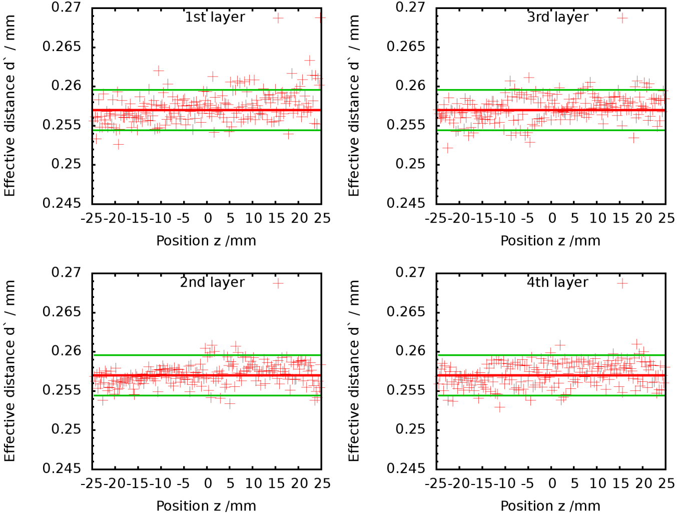
- Hysteresis-brake and sensor for constant wire tension
- Mechanical wire-guiding with a fingertip (Width ca. 0.5 mm)
- PID-loop controlled feeding for constant pressing force





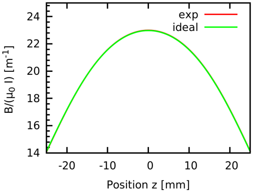


Additional Information



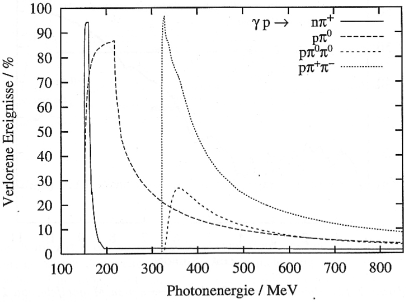
$\bar{d}$	0.257 mm	
Δd	0.003 mm	1.32 %
σ_1	0.002 mm	0.80 %
σ_2	0.001 mm	0.53 %
σ_3	0.002 mm	0.62 %
σ_4	0.002 mm	0.59 %

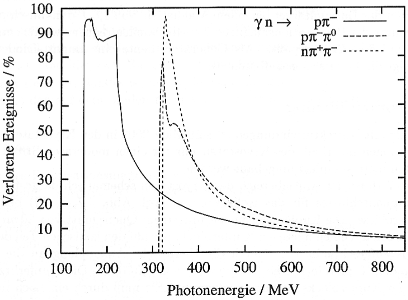
- fluctuation of $d' < 1\,\%$
- local fluctuation of d' looks more randomly



Additional Information

Detection threshold of the internal holding coil[1] (Thickness ≈ 0.7 mm) for certain reactions

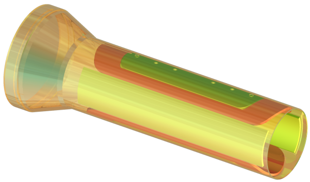




[1] C. Rohlof, *Entwicklung polarisierter Targets zur Messung der Gerasimov-Drell-Hearn-Summenregel an ELSA*, PHD-Thesis, Bonn 2003

Additional Information

Holding coil with transverse magnetic field



- Saddle coils within the copper carrier
- Alternative: Counter cross wiring