Toward an internal polarizing magnet

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in collaboration with

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POLARIZED TARGET BONN

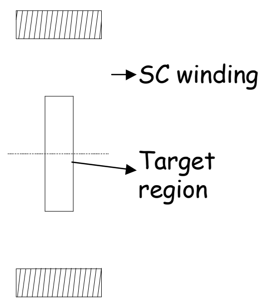
2nd Meeting "Polarized Nucleon Targets for Europe"
Miltenberg, 2-4 June 2005

Requirements:

High field (~2.5 T)
+
High homogeneity ($\Delta B/B \sim 10^{-4}$) in the target region

Constraints on:

- Magnet thickness (particle absorption)
- Number of Bias Leads (heat load)
- Mechanical feasibility



Well, that's challenging!

What's on the market? 1.

DESIGN the SC-magnet through FE software (Opera, Femlab, FEMM…)

LIMITS:
- Assume homogeneity of the SC
- Accuracy / limits in mesh refinement
- Optimization algorithms not implemented

What's on the market? 2.

OPTIMIZATION of the HOMOGENEITY through:

- Try and error

Requires an a priori assumption on shape and position of shim coils

- Series expansion

- Genetic Algorithms

Series expansion

(Mongomery 1969)

$$B_z(z,0) = B_0\left\{1 + E_2\left(\frac{z}{a}\right)^2 + E_4\left(\frac{z}{a}\right)^4 + E_6\left(\frac{z}{a}\right)^6 + \ldots\right\},$$

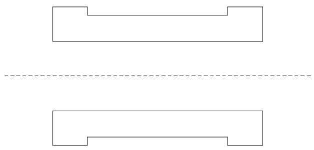
$$B_r(0,r) = B_0\{$$

Alternatively:
Spherical harmonic expansion

$$E_{2n} = \frac{1}{B_0}\cdot\frac{1}{(2n)!}\cdot\left.\frac{d^{2n}B_z(z,0)}{dz^{2n}}\right|_{z=0}$$

i.e. $E_2 = 0 \Rightarrow$ Helmholtz configuration

$E_6 = 0 \Rightarrow$ "Notched" coils



What's on the market? 2.

OPTIMIZATION of the HOMOGENEITY through:

- Try and error

Requires an a priori assumption on shape and position of shim coils

- Series expansion

The optimization is limited to ~20% of the bore radius

- Genetic Algorithms

Genetic Algorithms

From the Wikipedia:

A genetic algorithm (GA) is a heuristic used to find approximate solutions to difficult-to-solve problems through application of the principles of evolutionary biology to computer science. Genetic algorithms use biologically-derived techniques such as **inheritance**, **mutation**, **natural selection**, and **recombination** (or crossover).

- GA can easily locate good solution, even for difficult search spaces

Basilosaurus

$28 \cdot 10^6$ yrs

Dolphin

Global optima?

What's on the market? 2.

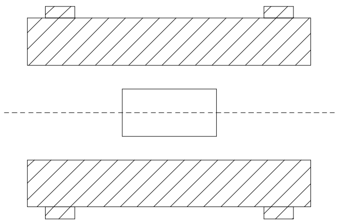
OPTIMIZATION of the HOMOGENEITY through:

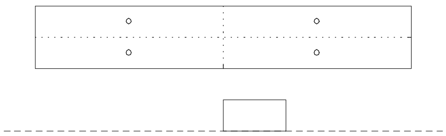
- Try and error — Requires an a priori assumption on shape and position of shim coils.
- Series expansion — The optimization is limited to ~20% of the internal volume.
- Genetic Algorithms — No proof of convergence. Costly in terms of time and computing power.

The PT-Bonn experience: the "feld.c" code

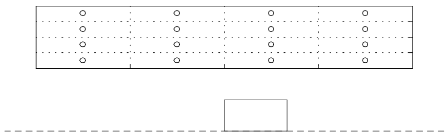
History:
Jan. 1982 - FELDN.FOR (version for minuit)
Oct. 1991 – MAGFELD.for
Jan. 1994 – feld.c (R. Gehring)

Jan. 2005 – feld1.c (R. Gehring, FZ Karlsruhe)





Starting point



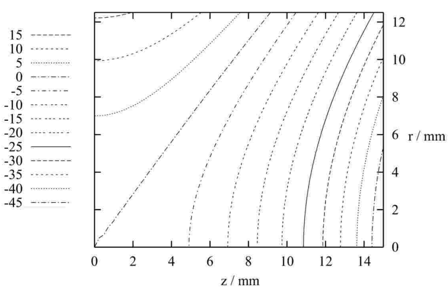
Step 1

…and iterate

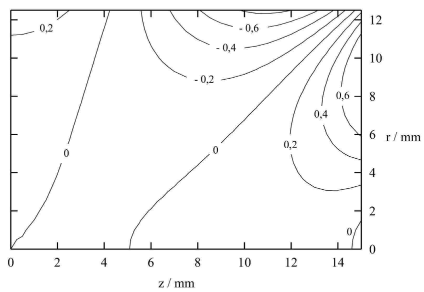
The "feld.c" code - results

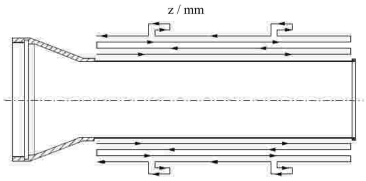
Homogeneity contour lines for a 150 mm long solenoid (units of 10^{-4})

Uncorrected solenoid



With 38 correction windings





C. Rohlof, PhD thesis, Bonn 2003

The "feld.c" code - limits

- **Assumption of homogeneity of the SC**
  - not correct even with small wire diameter
  - the field homogeneity is overestimated
- **Convergence after 32x32 or even 64x64 divisions**
  - in the radial direction simulates a SC uniformity that is far from the actual discretization
  - the computing power is the same that would be required for a calculation on the actual coils
- **"Stability" of the solution**
  - the homogeneity depends on micrometric positioning of the correction coils
- **Requires a try and error (manual) approach and has a poor flexibility**

→ A new code performing integration on the actual coils

Some advantages…

Allows one to study the effect on the field homogeneity of:

- Limited accuracy in the winding
- Irregularities (random variations in the coil number in a layer)
- SC wire diameter

Allows the implementation of optimization algorithms

… and a new idea

Biot-Savart integral $$\vec{B} = \frac{\mu_0 I}{4\pi} \int_{r_1}^{r_2} \frac{\vec{r} \wedge d\vec{r}}{r^3}$$

Shaping the support for the winding makes possible a

Fine Tuning of the field intensity in the target region

Calculating the Biot-Savart integral on a circular coil

$$B_r = \frac{\mu_0 I}{2\pi} \frac{z}{r} \frac{1}{\left[(a+r)^2 + z^2\right]^{1/2}} \left\{ -K(k) + \frac{a^2 + r^2 + z^2}{(a-r)^2 + z^2} E(k) \right\}$$

$$B_z = \frac{\mu_0 I}{2\pi} \frac{1}{\left[(a+r)^2 + z^2\right]^{1/2}} \left\{ K(k) + \frac{a^2 - r^2 - z^2}{(a-r)^2 + z^2} E(k) \right\}$$

$$K(k) = \int_0^{\pi/2} \frac{d\theta}{\left(1 - k^2 \sin^2\theta\right)^{1/2}}$$

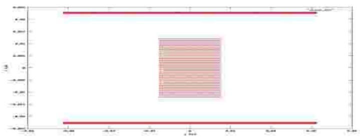
$$E(k) = \int_0^{\pi/2} \left(1 - k^2 \sin^2\theta\right)^{1/2} d\theta$$

$$k^2 = \frac{4ar}{\left\{(a+r)^2 + z^2\right\}}$$

To calculate:
750 points on the grid x
2000 coils x
2 elliptical integrals =
$3 \cdot 10^6$ integrals

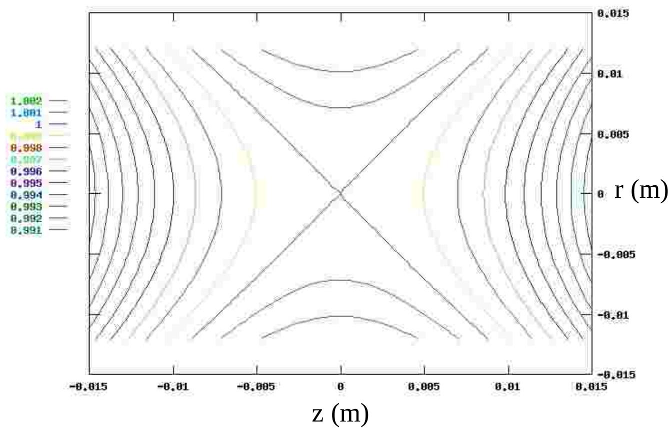
Takes ~ 1 min.

The new code is still in the debugging phase…

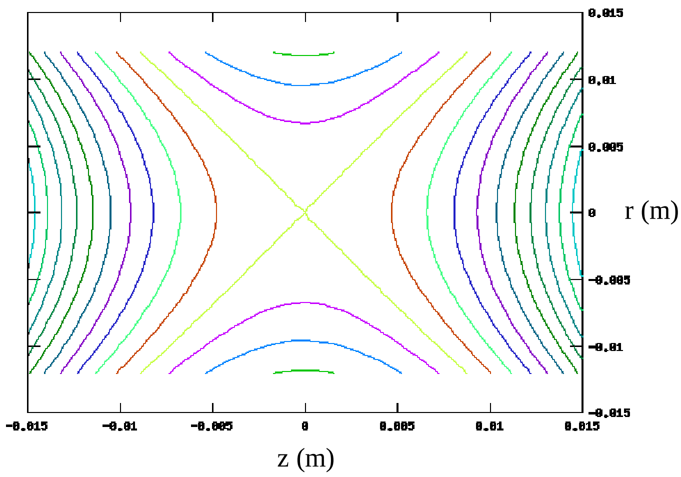


Setup

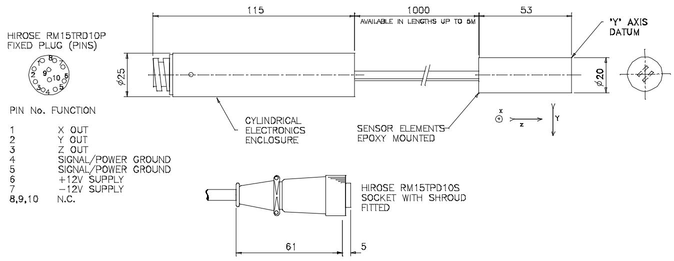
Field intensity relative to central field



Effect of the curvature of the winding support on the field homogeneity



The homogeneity of the prototypes will have to be tested…



Bartington Instruments | Mag-03 Three-axis Magnetic Field Sensors

Fluxgate magnetometers
+
computer controlled positioning system (…)