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NSE: **Magnetic Field Simulation and Optimization**

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Outline

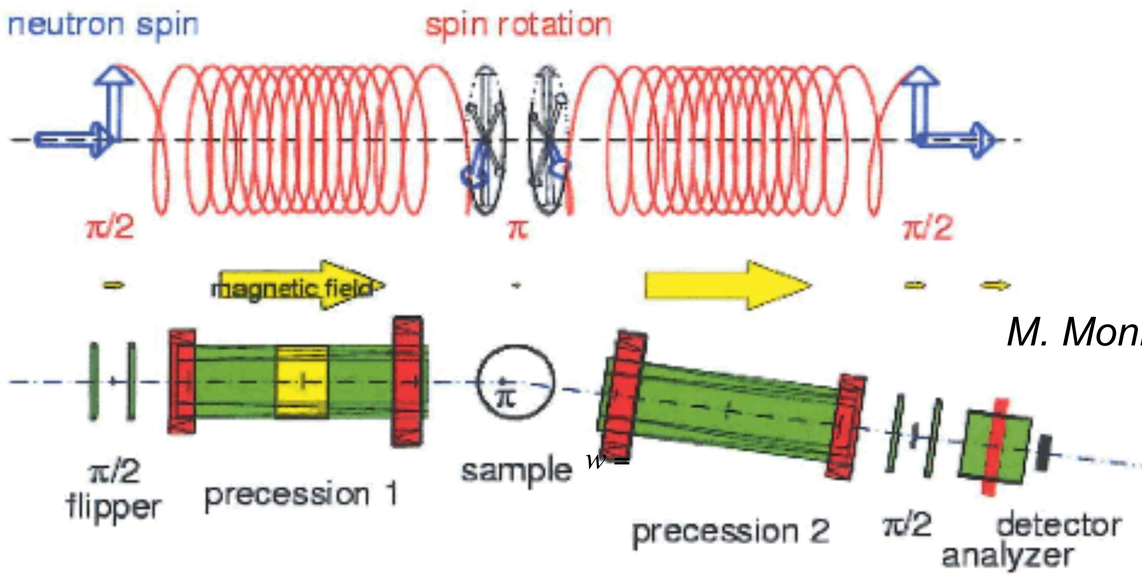
1. Problem: Asymmetries and inhomogeneities

2. Strategy: Optimum magnetic field-shape

   ↳ B-shape with higher field homogeneity

3. Magnetic coil optimization for standard NSE

Neutron Spin Echo Spectrometer



M. Monkenbusch

polarized beam

$$\phi_1 = \frac{2\omega_z^{(1)} L_1}{v_1} \qquad \phi_2 = -\frac{2\omega_z^{(2)} L_2}{v_2}$$

$$\phi = \phi_1 + \phi_2 = 2\omega_z L \left[\frac{1}{v_1} - \frac{1}{v_2} \right]$$

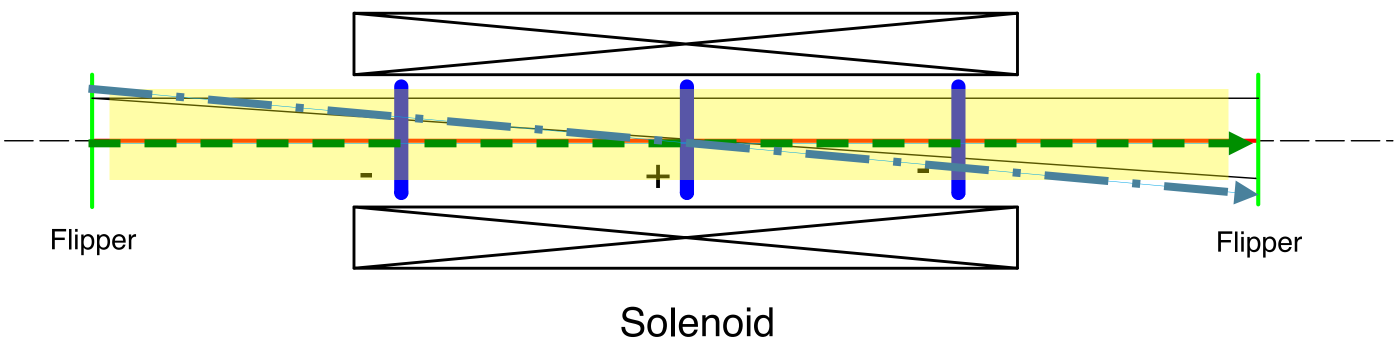
Quasi-elastic scattering → $\phi = \delta v \left[\frac{d\phi}{dv_2} \right]_{v_2 = v_1} = \frac{2\omega_z L}{v_1^2} \delta v$ $\quad (\omega_z = \gamma B)$

If elastic scattering and the two arms are exactly symmetric → $\phi = 0$

Problem: Asymmetries in NSE

Φ≠0
if the symmetry in the two arms is broken!

(e.g. no corrections on)



- Different trajectories in the two arms ➔ different phase accumulation

  ➔ Different time spent in each arm

  ➔ Different magnetic field experienced, (*magnetic field inhomogeneities)*

Resolution in NSE

$$P_{echo} \sim R * S(q,t)/S(q)$$

Resolution → 1   for $\phi_{ideal} \to 0$

The last resolution is achieved by reduction of magnetic field inhomogeneities **through correction coils,** but…

STRATEGY ➡ **Reduce the inhomogeneities by designing the magnetic field as homogeneous as possible**

The magnetic field integral functional

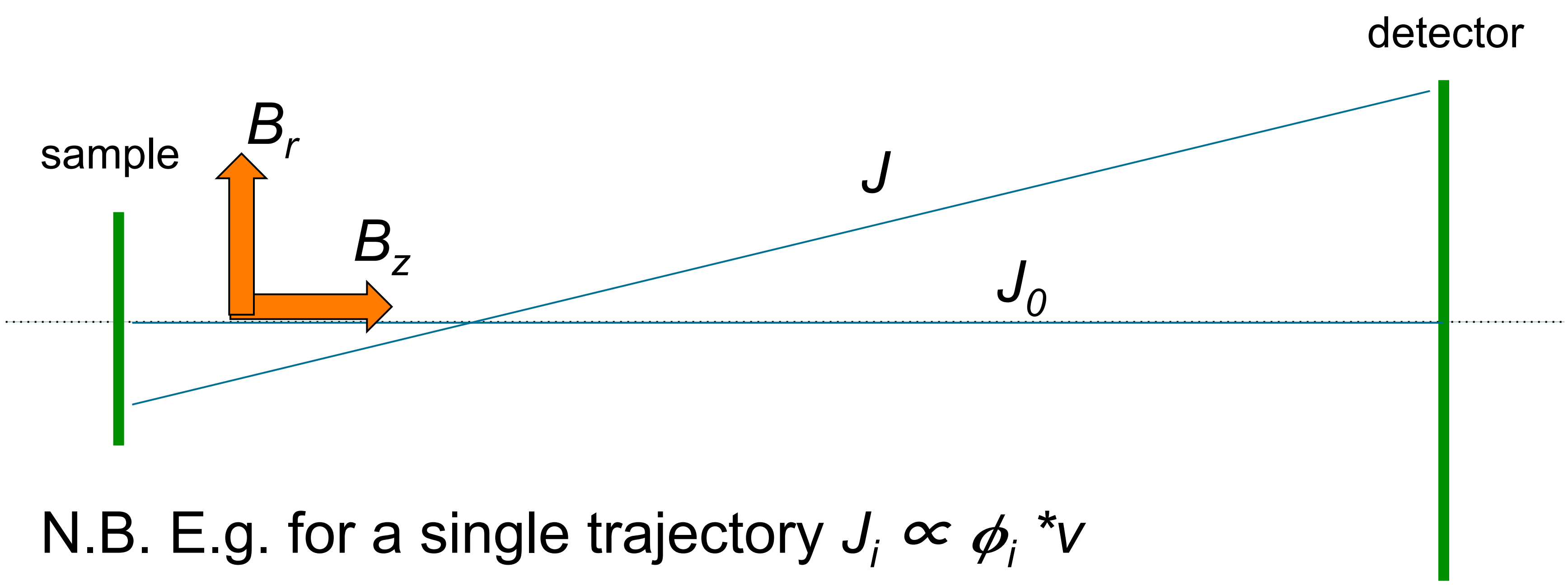
$$J = \int^{L} |\vec{B}| \mathrm{d}l.$$

Field integral inhomogeneity

$$\Delta J = J - J_0.$$

Divergent trajectory (J)

Trajectory along axis (J_0)

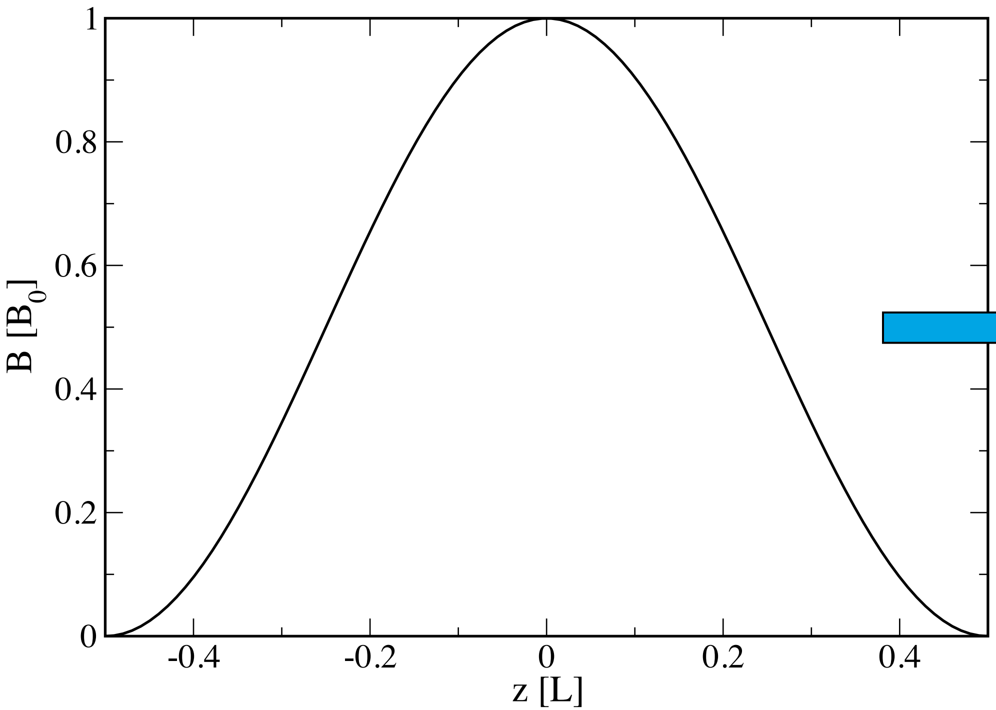


N.B. E.g. for a single trajectory $J_i \propto \phi_i * v$

Zeyen & Rem and the idea of FIELD SHAPING

$$B_z(z) = B_0 \cos^2\left(\frac{\pi \; z}{L}\right)$$

axial magnetic field along a distance L → **iNSE @ Tokai**



This shape minimizes the difference of field Integral

$$\Delta J = J - J_0$$

for some configurations

Zeyen & Rem (1996)

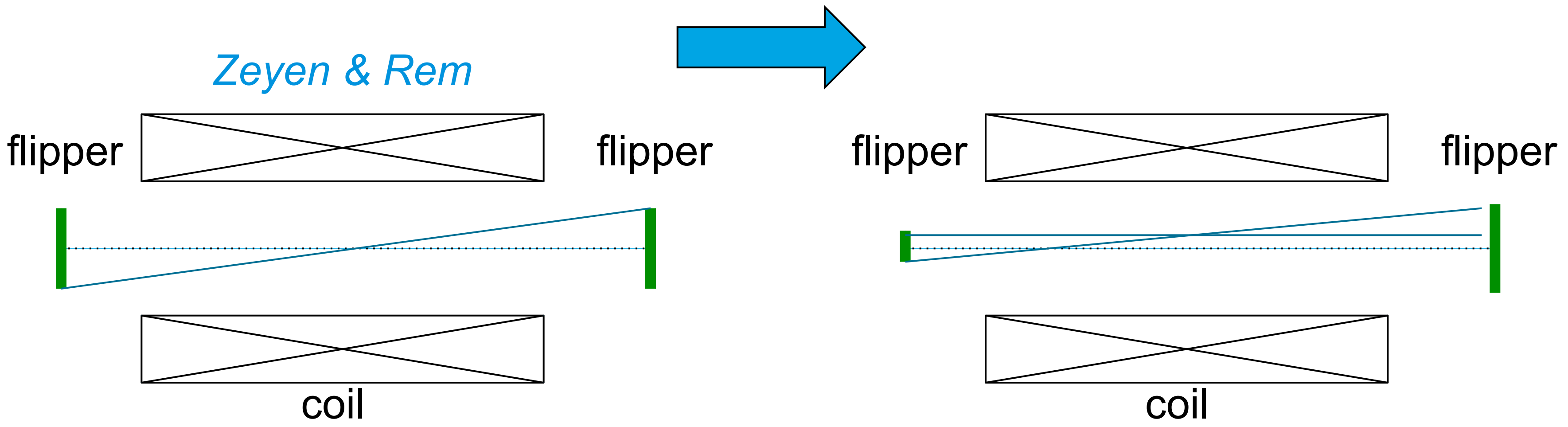
The design strategy of the new coils for J-NSE

1 – A new semi-analytical derivation of the optimal magnetic field shape that minimizes the field integral inhomogeneity and a derivation of the lower bound for the inhomogeneity.

2 – A numerical optimization of the coil geometry of standard NSE.

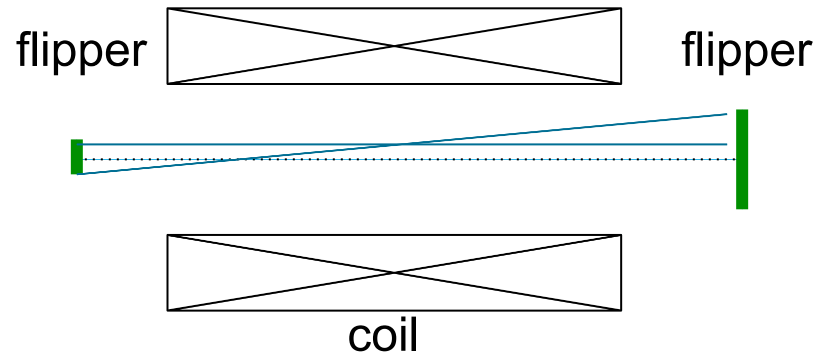
Our approach

1 – We consider also asymmetric beam configurations



What is new in our approach?

1 – We consider also asymmetric beam configurations



2 – We average over all possible neutron trajectories before minimizing

3 – We minimize all the terms in the leading order of the magnetic field integral inhomogeneity

The magnetic field integral functional

For $B_r(z,r) \ll B_z(z,r)$ ⇒ Taylor expansion of B components

$$B_z(z,r) = B_z(z,0) - \frac{1}{4}r^2\partial_z^2 B_z(z,0) + O(r^4)$$

$$B_r(z,r) = -\frac{1}{2}r\partial_z B_z(z,0) + O(r^3).$$

(Btygin and Toptygin)

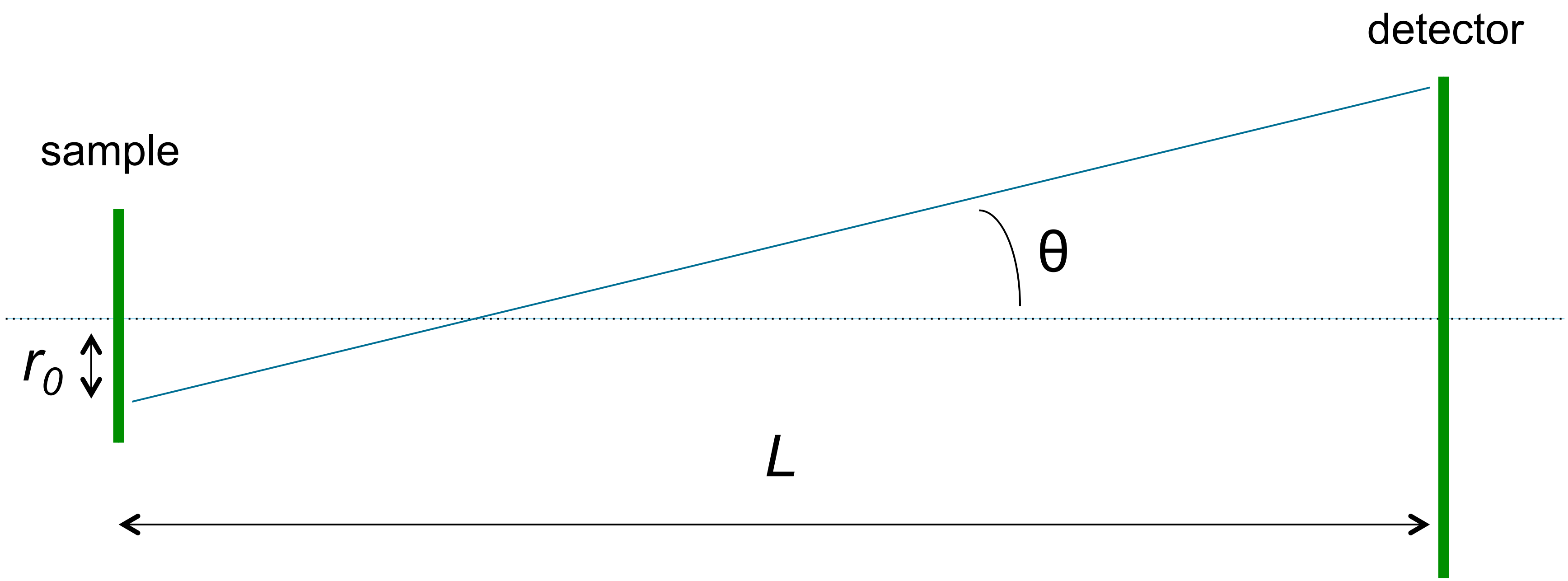
To be minimized

$$\langle \Delta J[B(z)] \rangle \simeq \langle \tan^2\theta \rangle \; G + \langle r_0^2 \rangle \; H + \langle 2r_0 \tan\theta \rangle \; U$$

The magnetic field integral functional

$$\langle \Delta J[B(z)] \rangle \simeq \langle \tan^2\theta \rangle \; G + \langle r_0^2 \rangle \; H + \langle 2 r_0 \tan\theta \rangle \; U$$

Divergence and axial-offset of each neutron path



The magnetic field integral functional

$$\langle \Delta J[B(z)] \rangle \simeq \langle \tan^2 \theta \rangle \, G + \langle r_0^2 \rangle \, H + \langle 2 r_0 \tan \theta \rangle \, U$$

- Averages over all paths

- They can be calculated exactly for given dimensions of the sample and of the detector they are numbers

The magnetic field integral functional

$$\langle \Delta J[B(z)] \rangle \simeq \langle \tan^2 \theta \rangle \, G + \langle r_0^2 \rangle \, H + \langle 2 r_0 \tan \theta \rangle \, U$$

Integral functions of $B_z(z)$

$$U := \int_{-L/2}^{L/2} \mathrm{d}z \left[\frac{1}{8} \frac{(\partial_z B_z(z))^2}{B_z(z)} - \frac{1}{4} \partial_z^2 B_z(z) \right] z$$

$$H := \int_{-L/2}^{L/2} \mathrm{d}z \left[\frac{1}{8} \frac{(\partial_z B_z(z))^2}{B_z(z)} - \frac{1}{4} \partial_z^2 B_z(z) \right],$$

$$G := \frac{1}{2} \int_{-L/2}^{L/2} \mathrm{d}z \; B_z(z) + \int_{-L/2}^{L/2} \mathrm{d}z \; z^2 \left[\frac{1}{8} \frac{(\partial_z B_z(z))^2}{B_z(z)} - \frac{1}{4} \partial_z^2 B_z(z) \right]$$

A parametrization for B:

$$B_z(z) = B_0\ y(z)^2$$ with $$y(z) = \sum_{i=1}^{N} a_i \sin\left[i\frac{\pi}{L}\frac{z}{}\right]$$

it satisfies boundary cond. ➔ $B_z = \partial_z B_z = 0$ @ $z = 0$, L

The problem of minimizing ΔJ at constant J_0...

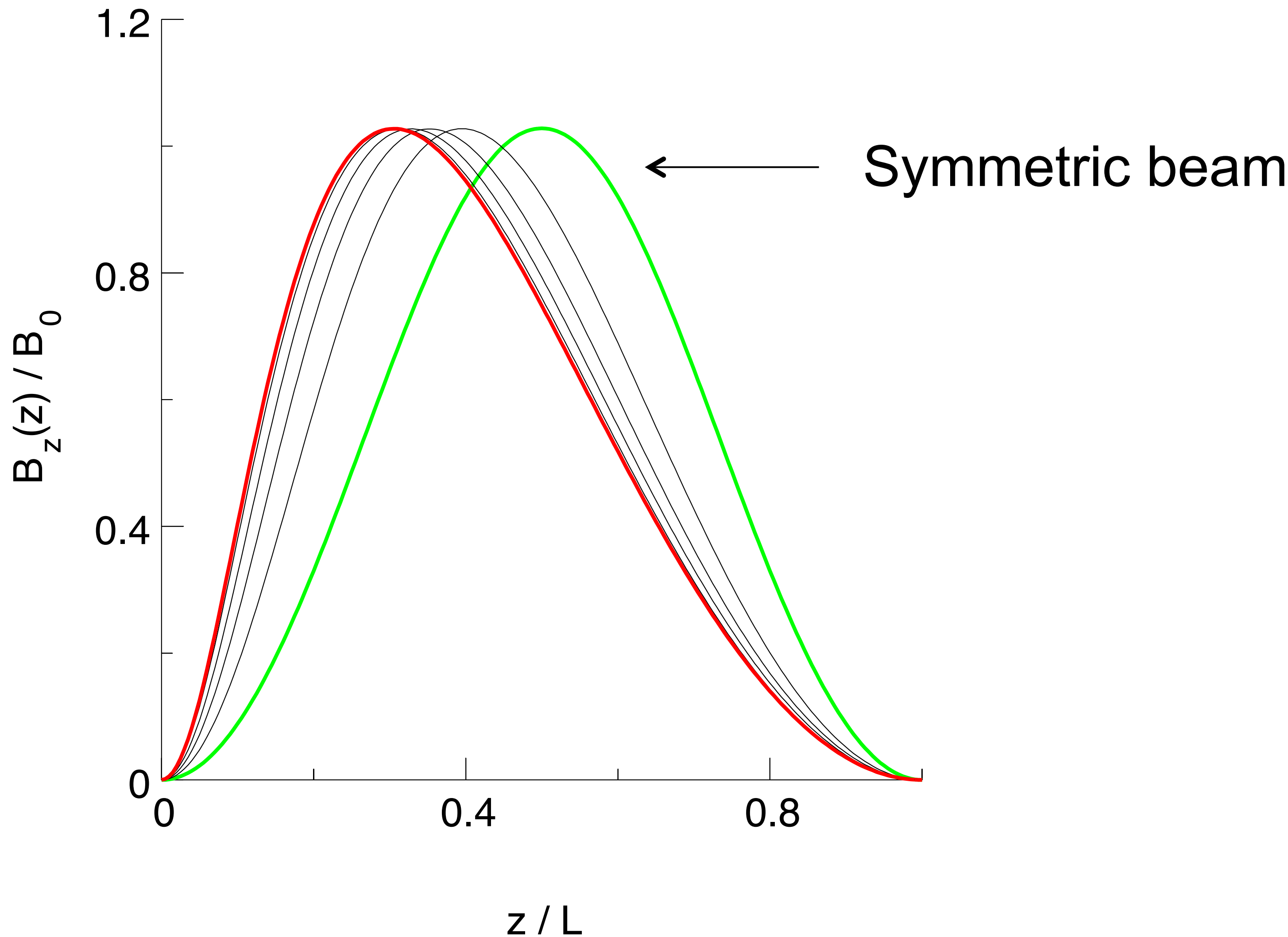
$$\langle \Delta J \rangle - \lambda J_0 = L \sum_{i,j}^{N} \left[C_{i,j} - \lambda \frac{1}{2} B_0\, \delta_{i,j} \right] a_i a_j$$

...translates into the diagonalization of a matrix!

The coefficients $C_{ij} = B_0 C_{ij}(\theta, r_0)$ are known.

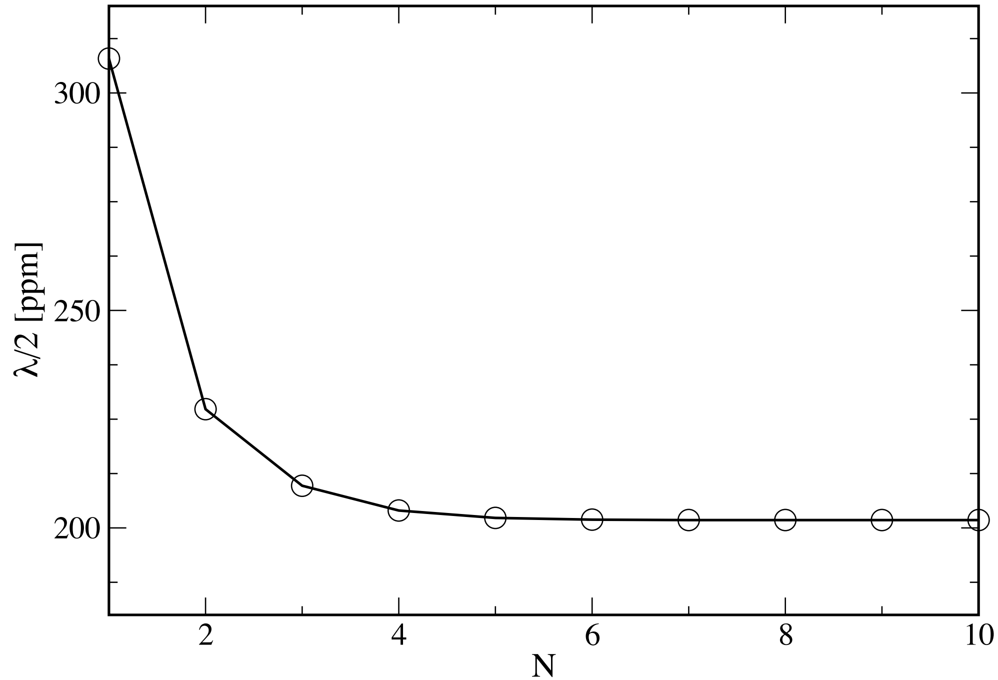
Pasini and Monkenbusch, MST 2015

The optimum shape tends to be asymmetric!



Pasini and Monkenbusch,
Measurement Science and Technology 26 (2015) 035501

A lower bound for the inhomogeneity

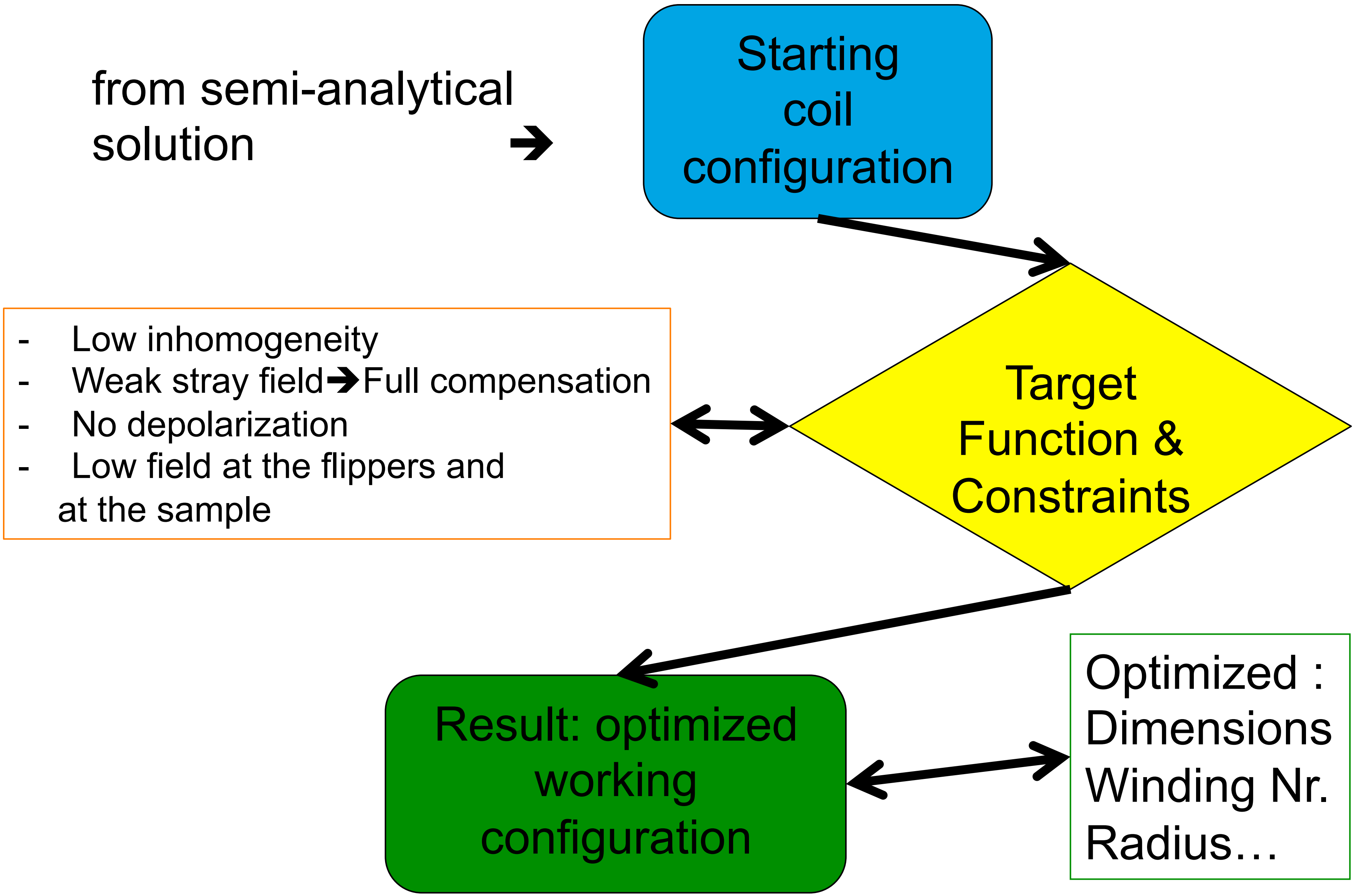


$$\langle \Delta J \rangle_{RMS} = \sqrt{\langle \Delta J^2 \rangle - \langle \Delta J \rangle^2}$$

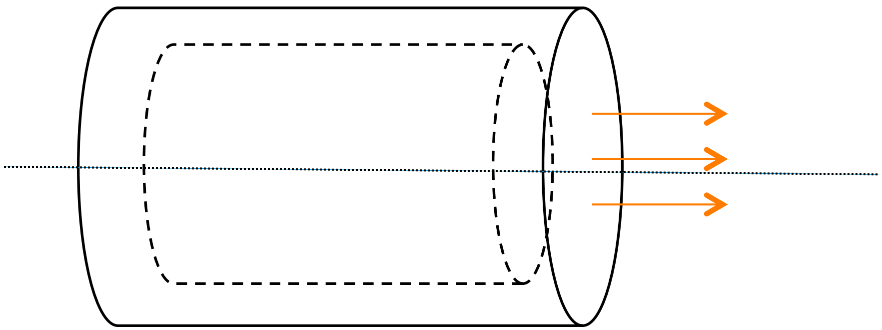
$$\langle \Delta J \rangle_{RMS} / J_0 \simeq 215 \text{ ppm}$$

For L=4m, r_0=2cm and $r_{\pi/2}$= 10cm

Modified operational program for the optimization of the coil geometry



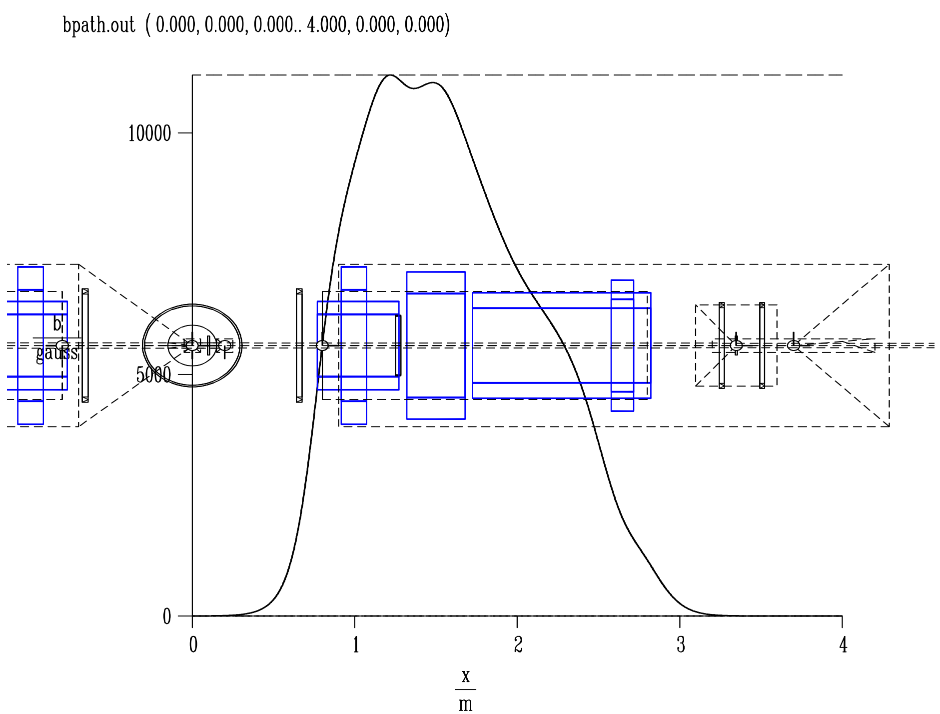
Full compensated coils



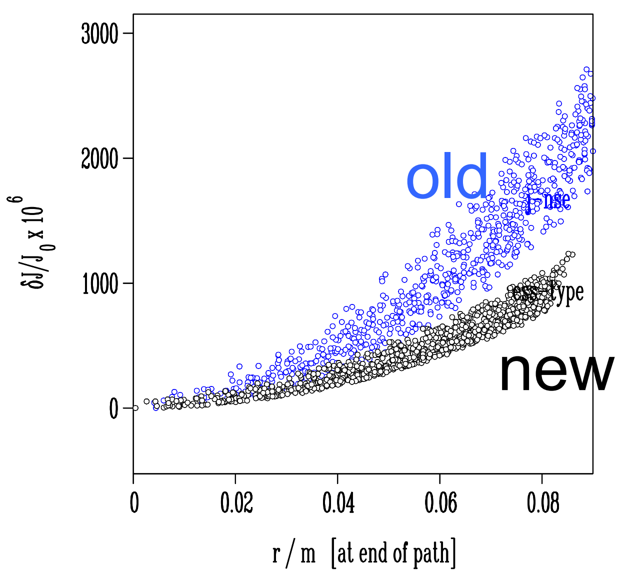
weaker stray fields

possible with superconducting coils

New optimized field shape for J-NSE by superconducting compensated coil set (5 x 2)



intrinsic field integral deviations



The need for Correction coils

Requirements for a functioning NSE → ~1ppm homogeneity

$$P_{echo} \sim R * S(q,t)/S(q)$$

$$Resolution = e^{\frac{-(\langle \Delta J^2 \rangle \lambda^2 m_n (2\pi\gamma)^2)}{2\, h^2}} > e^{-1}$$

$$\rightarrow \lambda\sqrt{\langle \Delta J^2 \rangle} \leq 2 \times 10^{-15}\mathrm{T}m^2$$

$$\rightarrow \sqrt{\langle \Delta J^2 \rangle} \leq 2 \times 10^{-6}\mathrm{Tm\ for\ \lambda \leq 1nm}$$

↓

Correction coils still needed

Fresnel correction coils

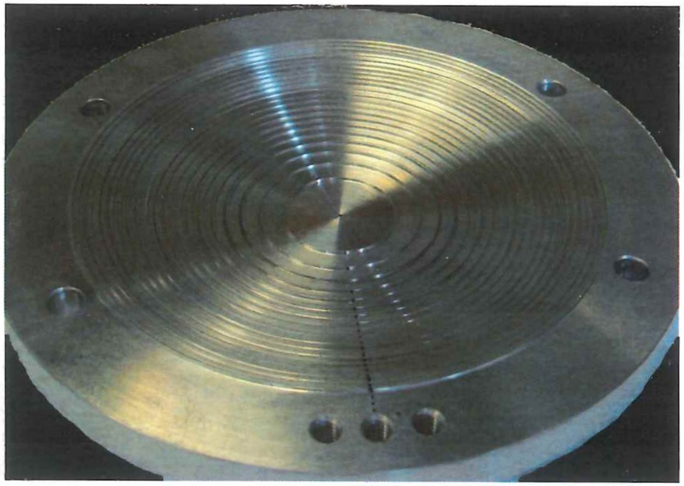
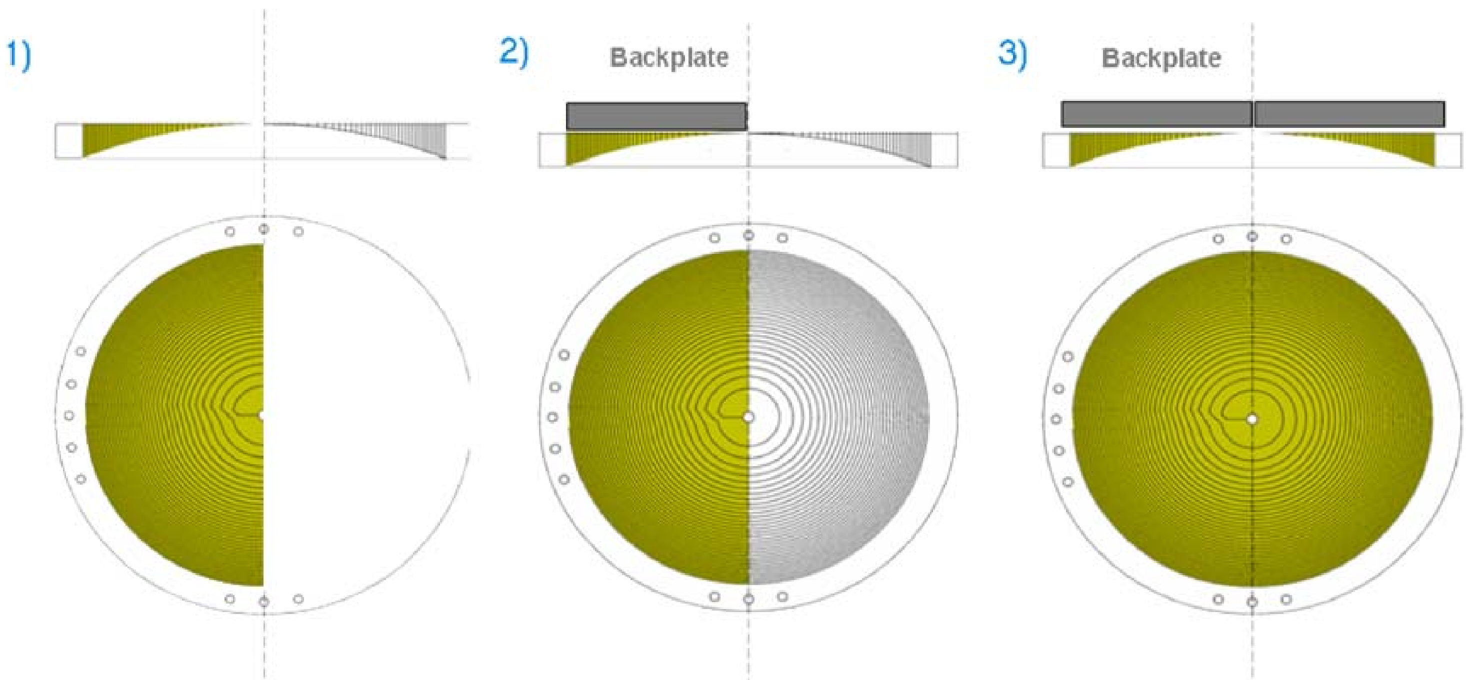
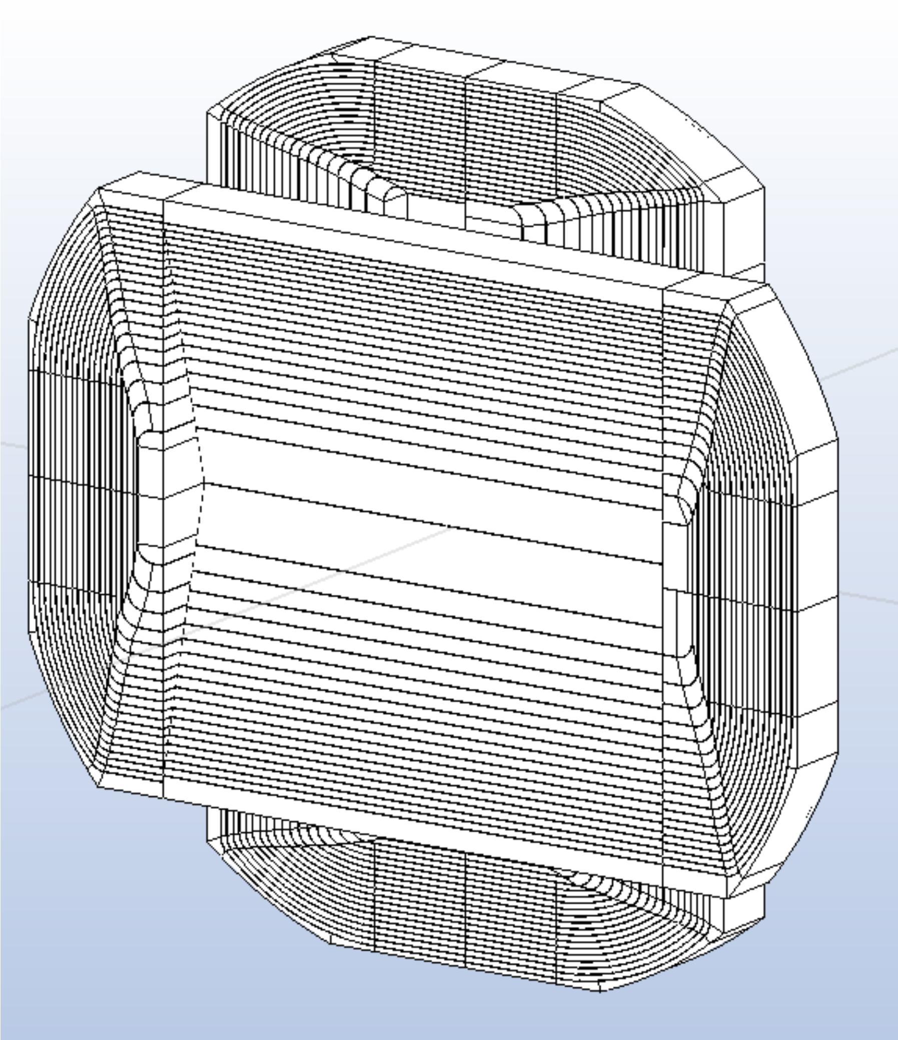


Fig. 24. Cutting scheme with oblique cuts, first mechanical test for a small (100mm diameter) correction coil.

M. Ohl et al. / Physica B 356 (2005) 234–238



Pythagoras correction coils



Thank You