Workshop on Axion
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INFN-Laboratori Nazionali di Frascati.

High Homogeneity Superconducting Magnets

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Outline

High homogeneity magnetic field

- ✓ Definitions
- ✓ Practical solutions
- ✓ Magnetic field profile around superconducting structures

Case study

- ✓ QSAL solenoid: correcting bobbins
- ✓ Design of a solenoid for the QUAX DEMO experiment

Conclusions

Magnetic Field Homogeneity

A uniform magnetic field is important in many different experimental situations :

- In the solenoid center for the national standards in order to calibrate magnetometers;
- In physical experiments such as the measurement of the proton gyromagnetic ratio;
- In nuclear magnetic resonance (NMR) applications

The degree of required uniformity depends on the kind of experiment. It ranges from 100 ppm for J_c measurements, down to 0.1 ppm for high resolution NMR spectroscopy.

The magnetic field inhomogeneity η_i in ppm within a defined region of space, is defined as:

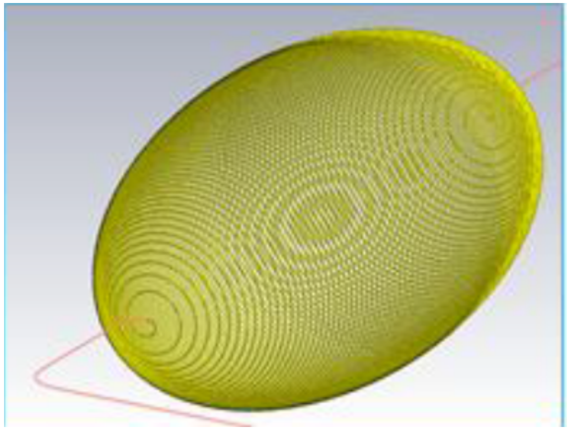
$$\eta_i = \left(\frac{B_{\max} - B_{\min}}{B_{avg}} \right) \cdot 10^6$$

Conversely magnetic field homogeneity η_h is instead defined as:

$$\eta_h = 1 - \left(\frac{B_{\max} - B_{\min}}{B_{avg}} \right)$$

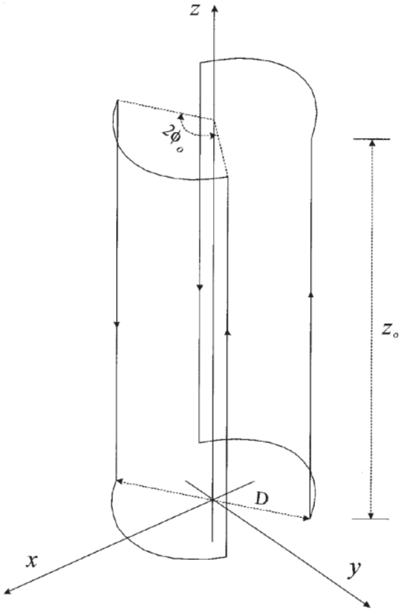
Generation of a Uniform Magnetic Field

Different geometries of source currents can be considered in order to generate a magnetic field with high homogeneity. In this context we shall consider just air core windings, i.e. without iron cores.



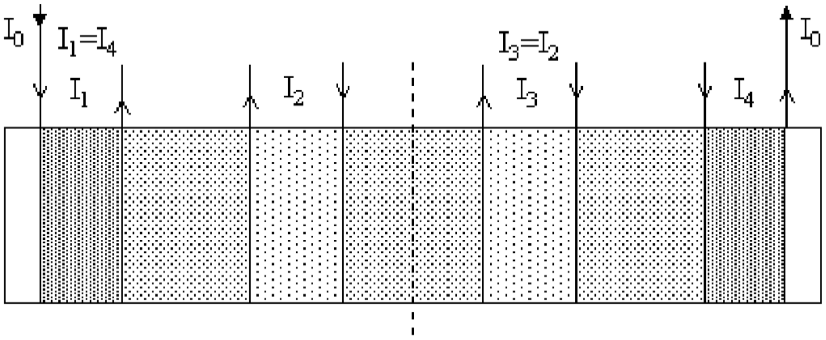
Spheroidal

Yavuz Ozturk, Bekir Aktaş, Journal of Physics: Conference Series 667 (2016) 012009



saddle

F. BONETTO, E. ANOARDO, M. POLELLO, Concepts in Magnetic Resonance Part B (Magnetic Resonance Engineering) DOI 10.1002/cmr.b

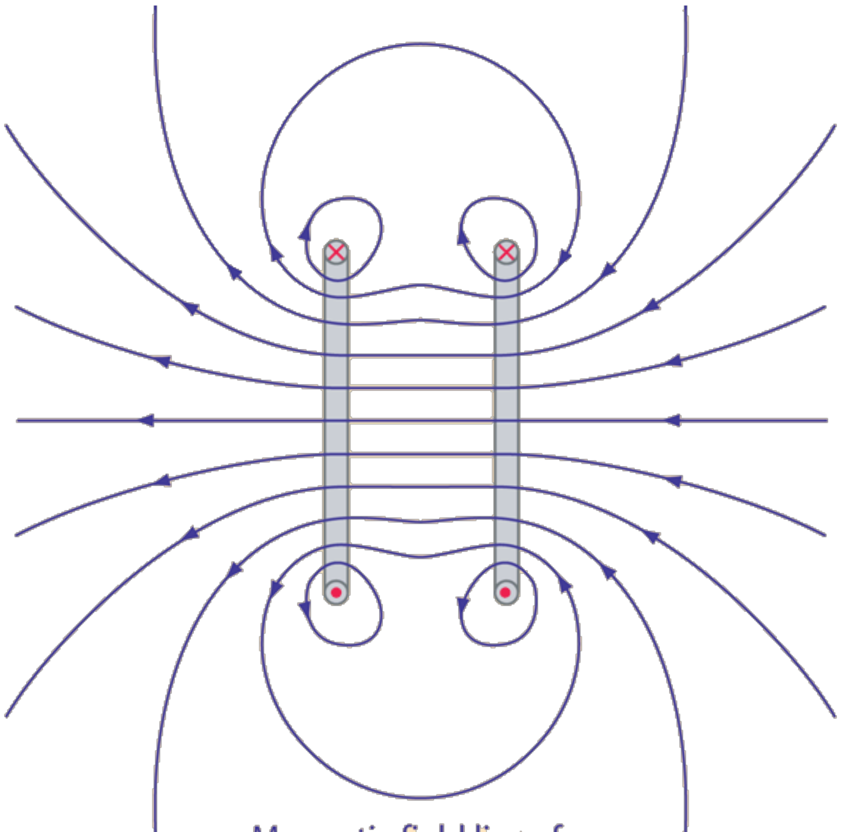


multi-current solenoid

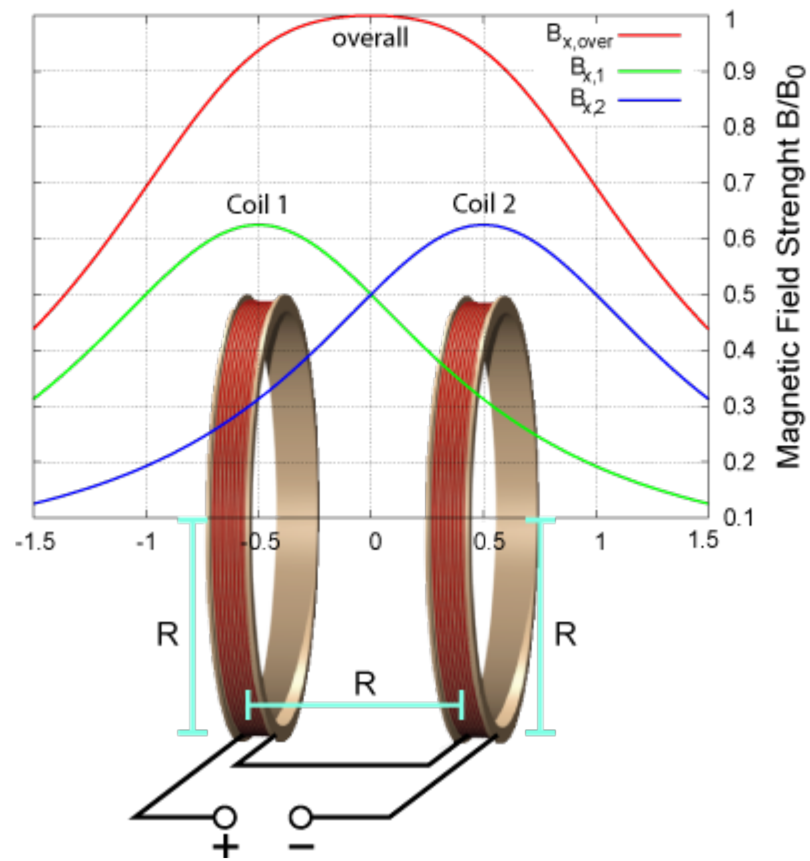
PO GYU PARK, WAN-SEOP KIM, V.N. KHOREV, V.YA. SHIFRIN, MAPAN Journal of Metrology Society of India, vol. 24 (2009) 9-14

Homogeneity of the Helmholtz coils

However the Helmholtz coils **<u>are the most practical and widely used</u>** winding structures for obtaining field uniformity in a relatively small region.



Magnetic field lines for Helmholtz coils.



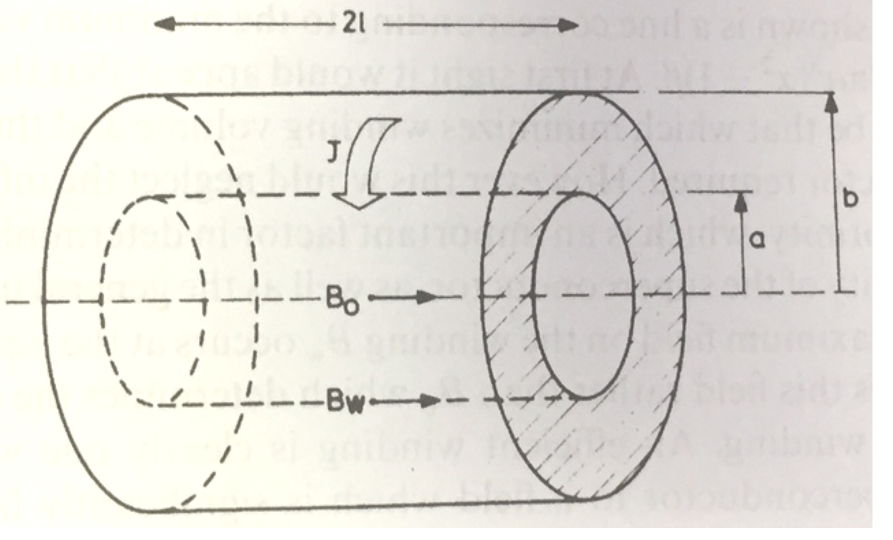
Homogeneity of a Magnetic Field

Helmholtz coils are the most practical and widely used winding structures for obtaining field uniformity in a relatively small region.
For this winding geometry an analytical formula can be used in order to obtain the field distribution on central axis.

$$B(z)=\tfrac{1}{2}J\,a\left\{F(\alpha\,\beta_1)+F(\alpha\,\beta_2)\right\}$$

$$F(\alpha\,\beta)=\mu_0\beta\,\ln\left\{\frac{\alpha+\sqrt{\alpha^2+\beta^2}}{1+\sqrt{1+\beta^2}}\right\}$$

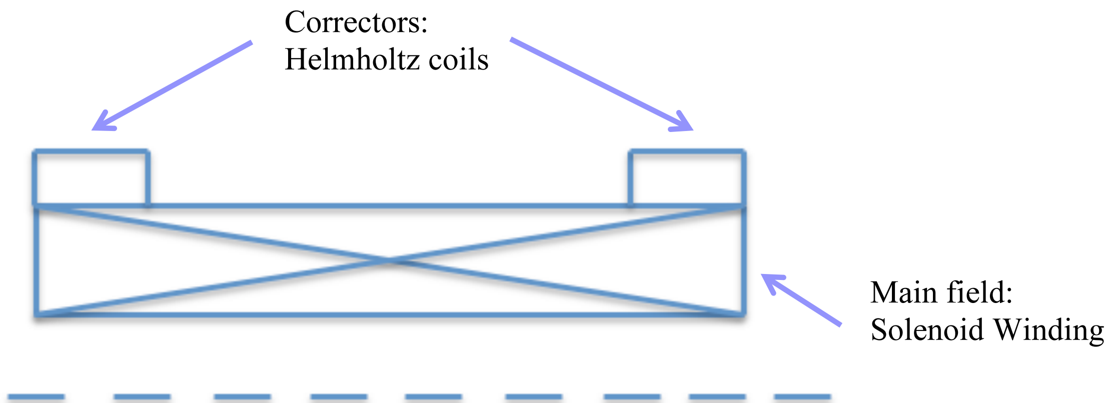
$$\alpha=b/a\qquad \beta_1=(l-z)/a\qquad \beta_2=(l+z)/a$$

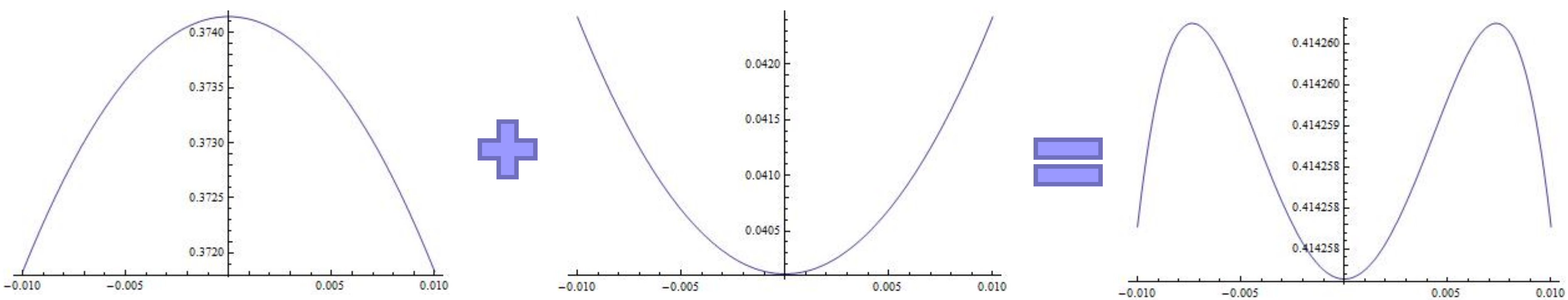


where l is the coil length while a and b are the inner and outer coil radius, respectively

Homogeneity of a Magnetic Field

The simplest strategy to obtain an uniform field is the superimposition of the magnetic field generated by three coils: two of them act as an Helmholtz coil system and one as a main field generator.





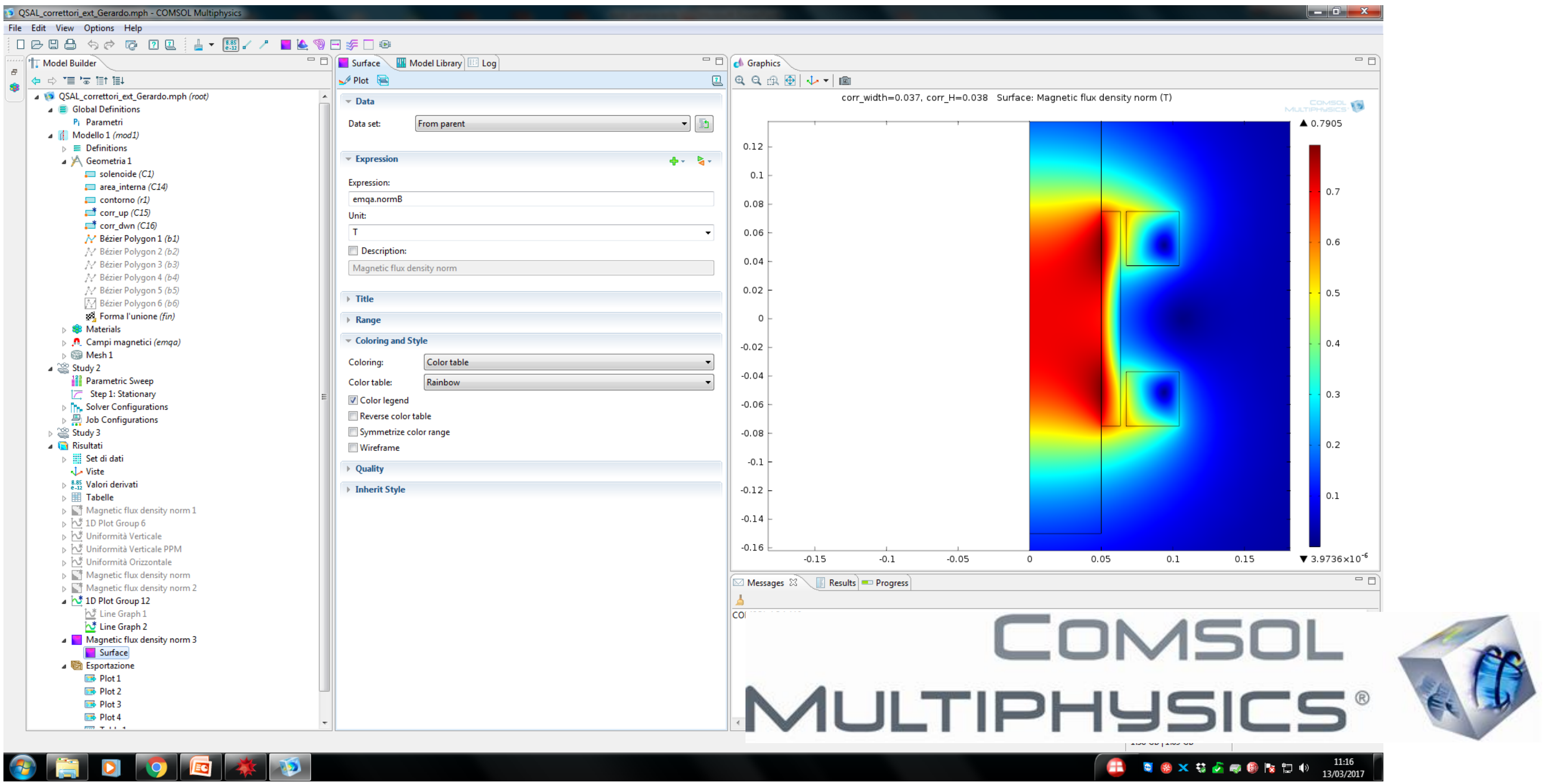
Main field: 6193 ppm

Correction field

Total field: 10 ppm

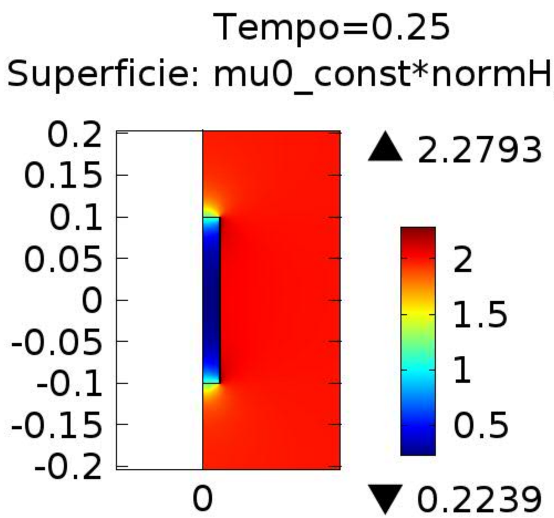
Homogeneity of a Magnetic Field

Simple geometries leads to analytic equations that are easy to manage and corresponding FEM models are simple to simulate with very good results. The main advantage of using FEM simulation is the easiness to deal with non regular geometry, to implement parametric sweeps, and to analyze the field when a superconducting structure is placed inside a magnet.

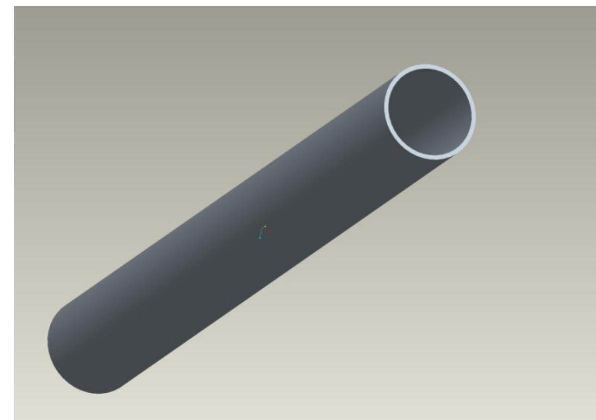


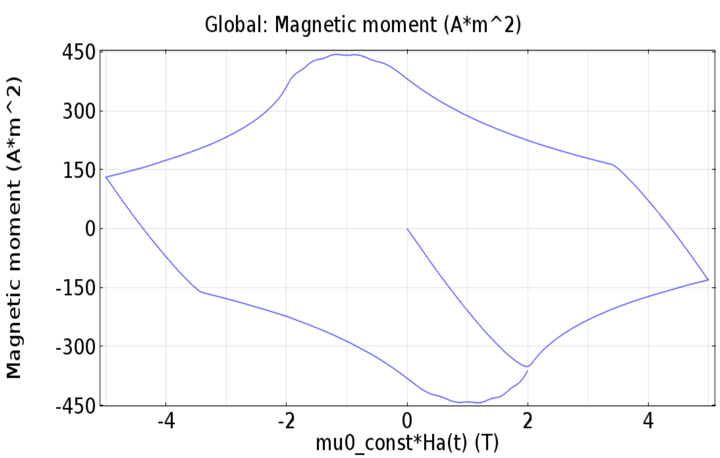
Homogeneity in the presence of superconductors

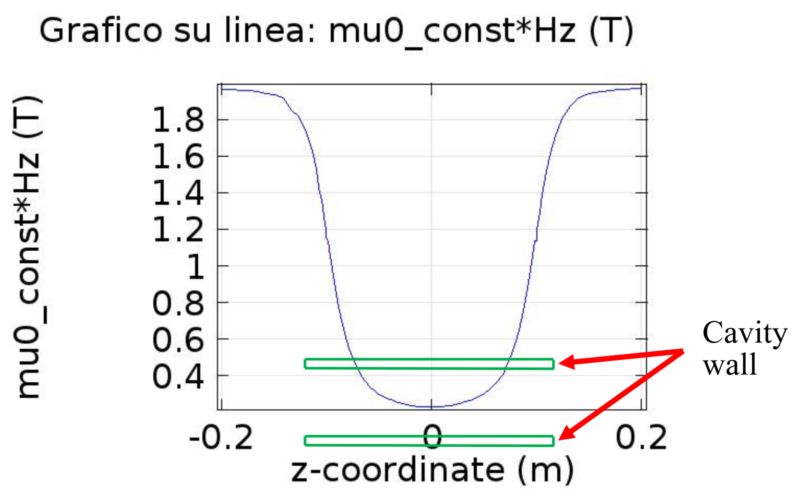
The presence of superconducting structure in a homogeneous axial field, significantly affects the field lines, up to destroy the homogeneity of the field inside the structure.



In a cylindric superconducting cavity, even without ending plugs the field inside is fully shielded: FEM with a uniform field 0->2T and J_{c0}=2 10^9 A/m^2 and a “Bottura style” J_c(B).

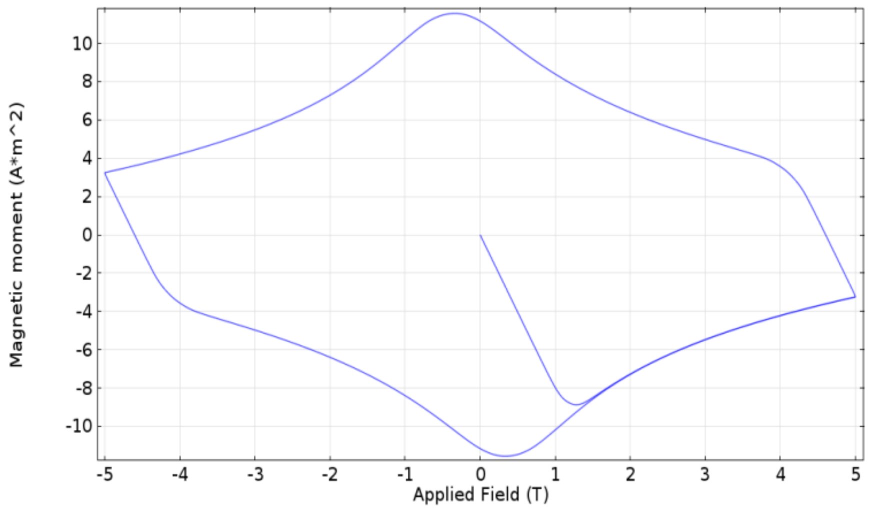


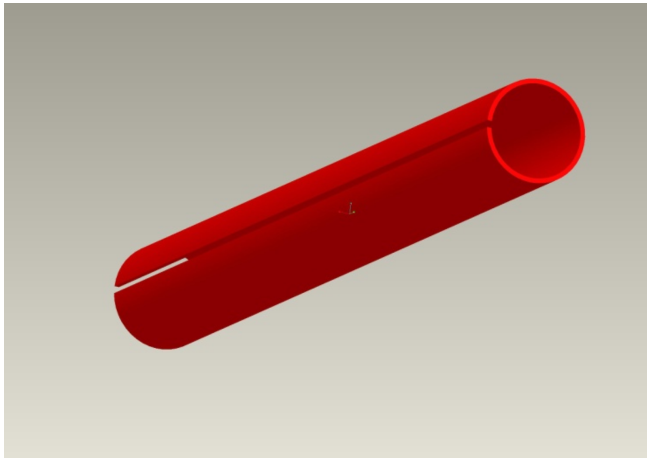




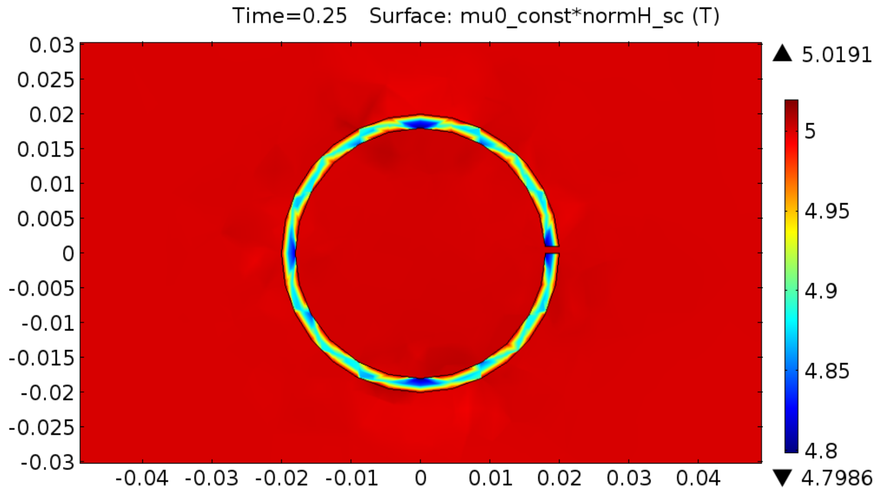
Homogeneity in the presence of superconductors

Considering that the RF cavity modes will excite longitudinal currents only, a possible solution to overcame the magnetic response of the superconducting cavity is to cut a small part of the cavity wall





The field lines fully penetrate the cavity inner volume, and the only shielded part is the volume occupied by the superconductor.



Case study: Magnets for the QUAX Experiment

QUAX (QUaerere AXion) Experiment:

A new proposal for a search of galactic axions using magnetized materials

The experiment requires high homogenity field in order to obtain detectable signals.

In the 2017-2018 we shall take care of the superconducting magnet for the detector. We shall start with a low field approach (0.4 T) generated by an existing superconducting solenoid, which must be corrected in the field profile to attain reasonable inhomogeneity (below 100 ppm).

This preliminary step will be followed by a new demo superconducting magnet which will be designed and manufactured to fulfill the field uniformity requirements at the field strength of 2 T.

More info at http://www.pd.infn.it/QUAX/

The QSAL magnet: characteristics

We investigated some working hypothesis in order to quickly improve the magnetic field uniformity of an existent superconducting coil: the primary winding of a flux transformer used to feed the helicoidal quadrupole of the **SuperB** acceterator (QSAL experiment) developed in Genoa. It is made of a primary winding (a 4000 turns NbTi coil) able to make 3 T with about 100 A

The coil of the primary winding was not designed for the purpose of a good uniformity of the magnetic field because he was designed as pure solenoid with the following radius over length ratio

R/L=0,33
(L=150mm, R=50mm)

However, the room inside the coil is sufficient for the execution of the first tests of the resonant cavity within a magnetic field.

The figure on the left shows the magnet surrounded by soft iron, in order to reduce the stray field.

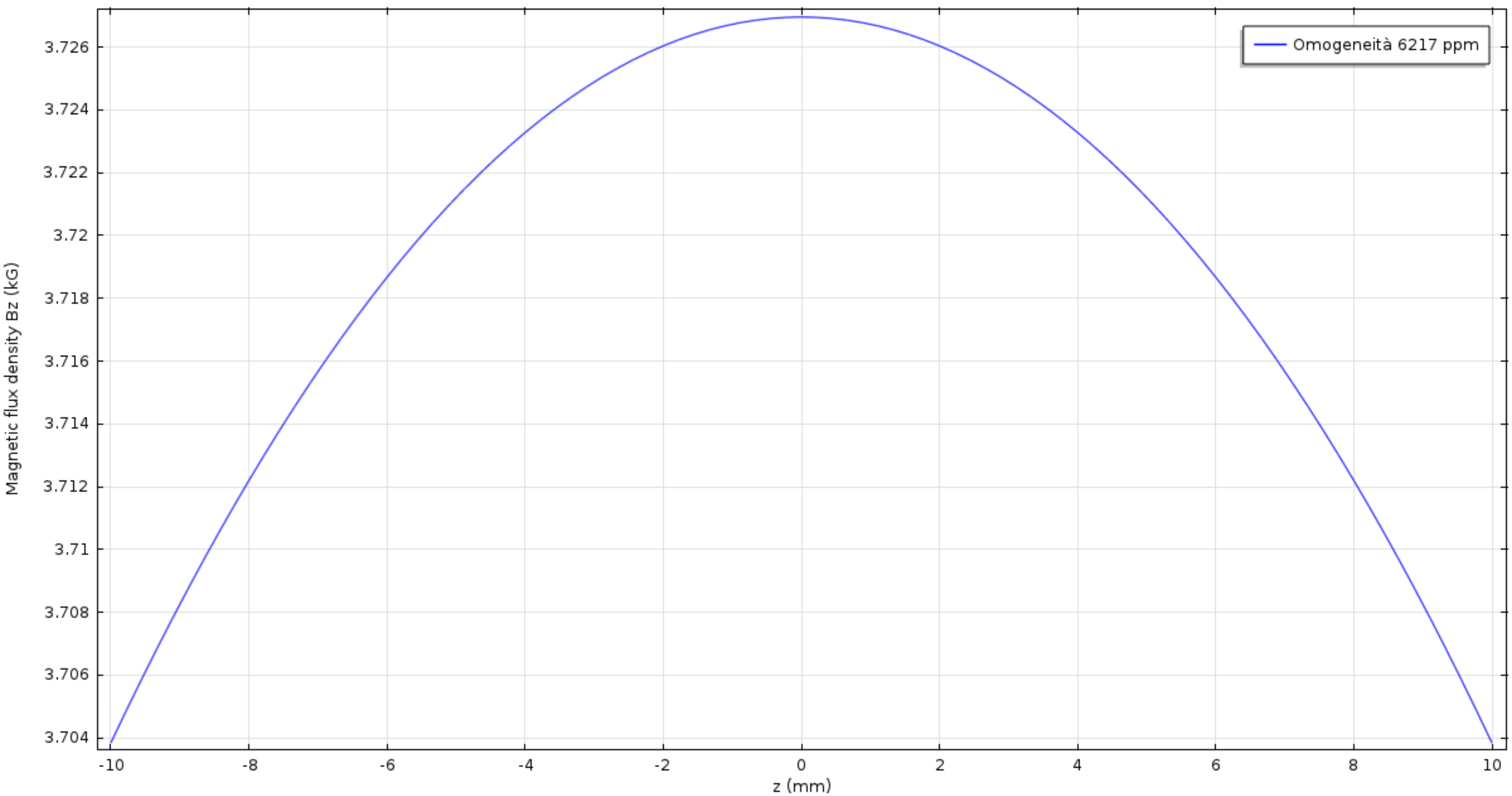
The QSAL magnet: requirements

Requirements and constraints:

1) No grading. All coils should share the same current (only one stable power supply);
2) Homogeneity below 100 ppm within a cylindrical region of 5 mm in radius and 20 mm in length;
3) Low budget;
4) Rapid fabrication (choose wires already existing, with given thicknesses);
5) Keep as much free space as possible inside the coil;
6) Must fit inside the cryostat already in use.

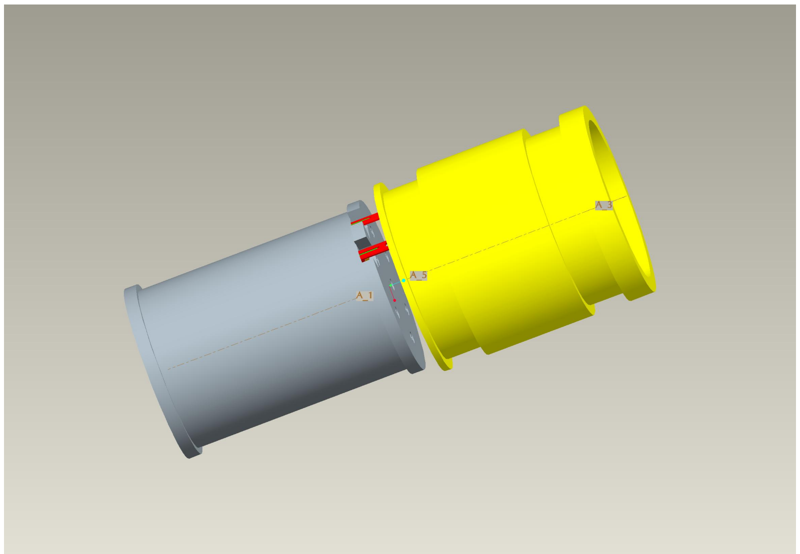
The QSAL magnet: Homogenization

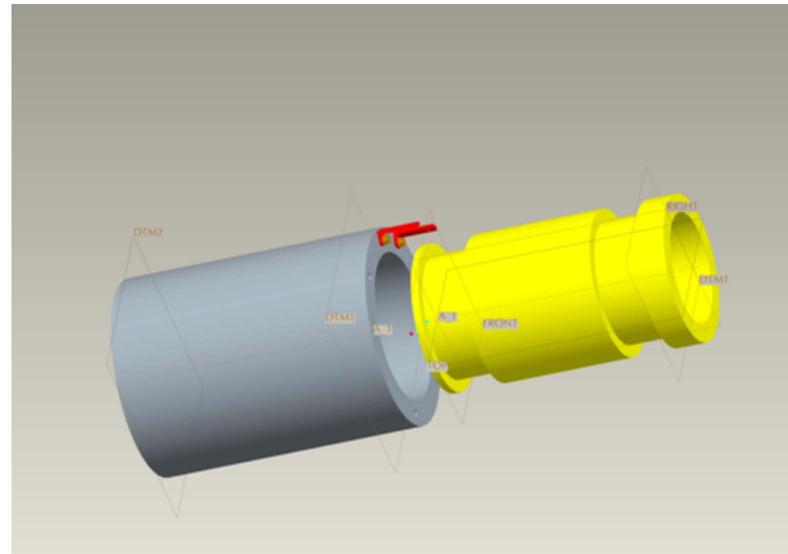
Our goal is the improvement of the magnetic field homogeneity by the addition of two Helmholtz coil that will act as a magnetic field correctors. As a starting point we will evaluate the homogeneity of the magnetic field generated by the main coil alone.



The QSAL magnet: Homogenization

Two possibible strategies could be taken into account:





External Correction

Advantage: More space inside the bore;

Disadvantage: Larger winding corrector volume;

Greater distance from center.

Internal Correction

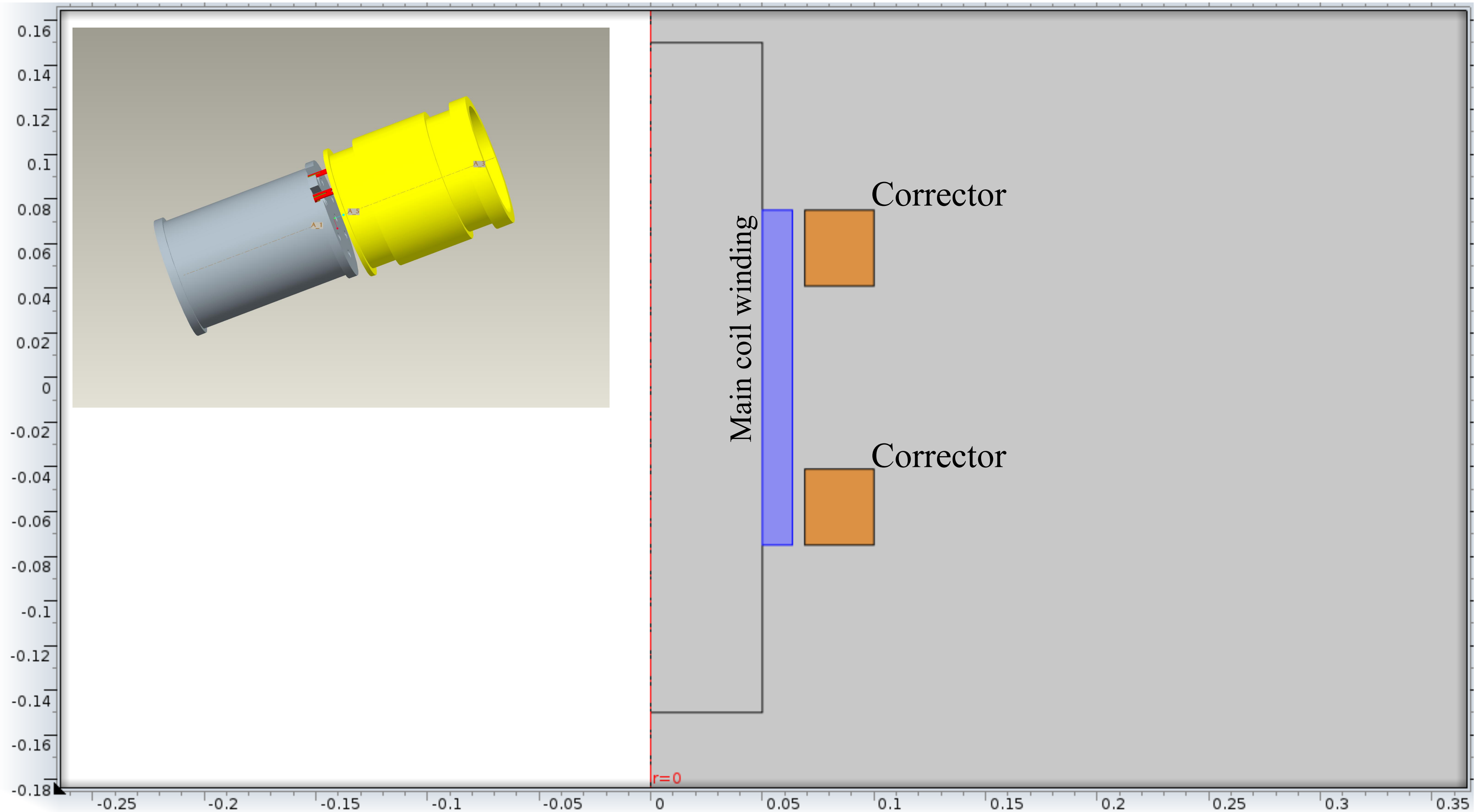
Advantage: Small winding volume;

Correction more effective;

Disadvantage: Less space inside the bore.

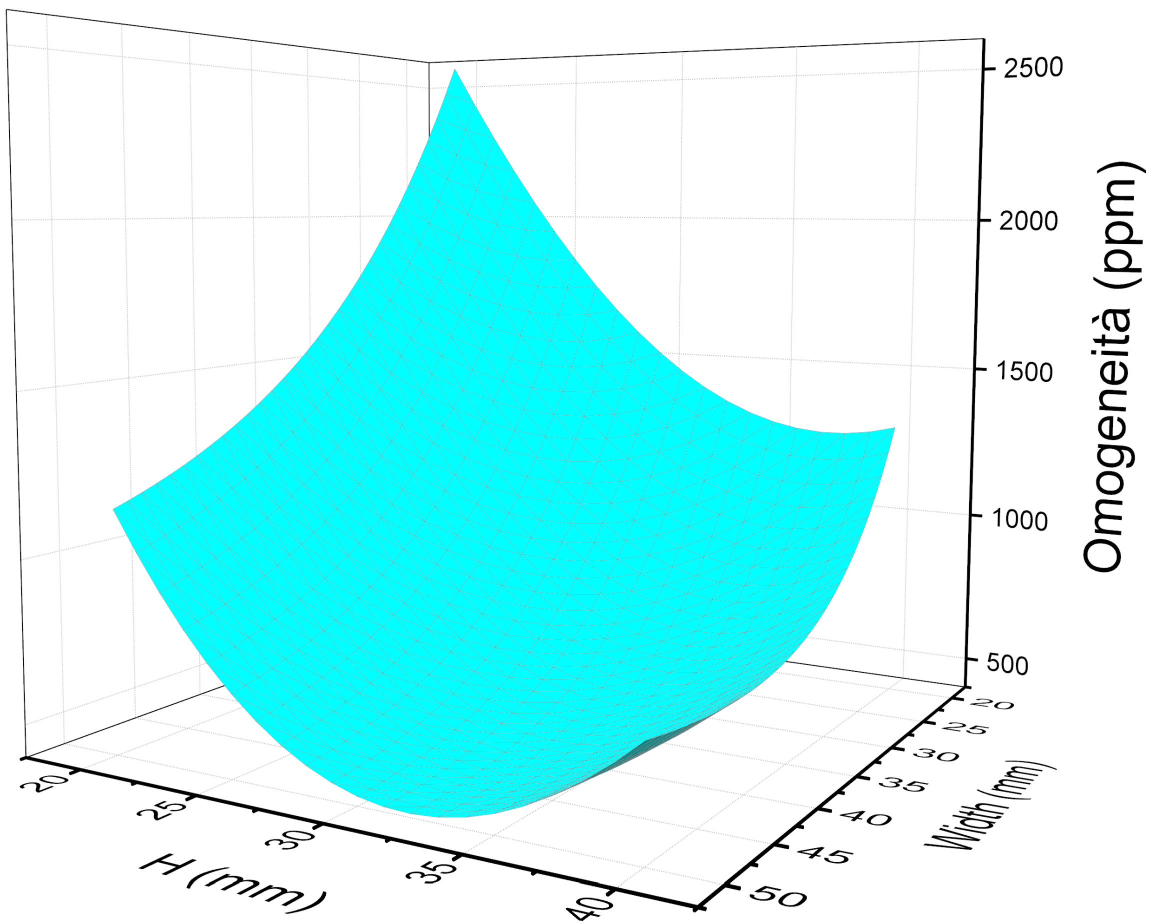
The QSAL magnet: External Correction

Homogeneity improvement with the addition of a couple of **external coils**.
FEM simulation have been performed with Comsol Multiphysics.



The QSAL magnet: External Correction

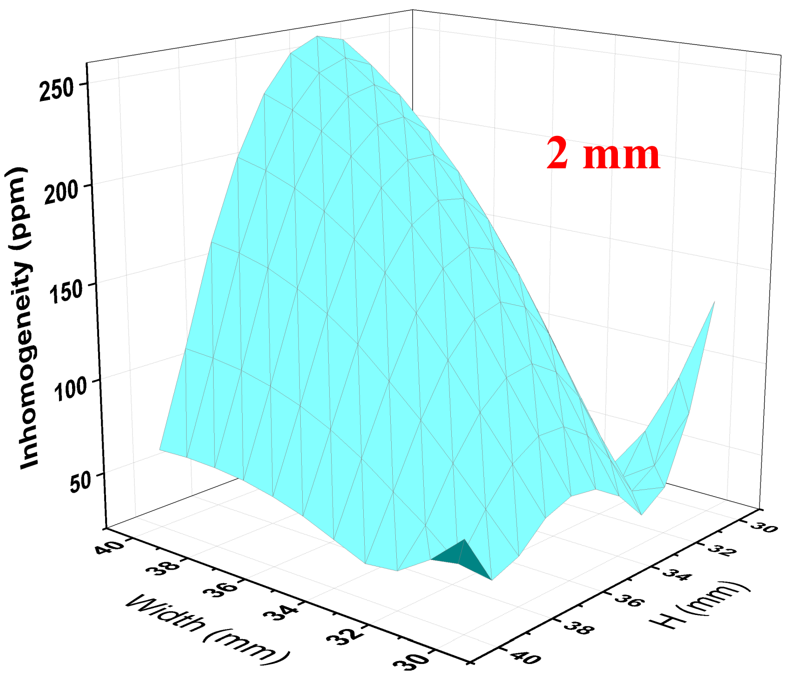
A parametric sweep, over the length (H_{corr}) and the width (W_{corr}) of the correctors coil dimension, found a couple of parameters that minimize the inhomogeneity. The correction coils are placed at 5.5 mm far from the main coil.

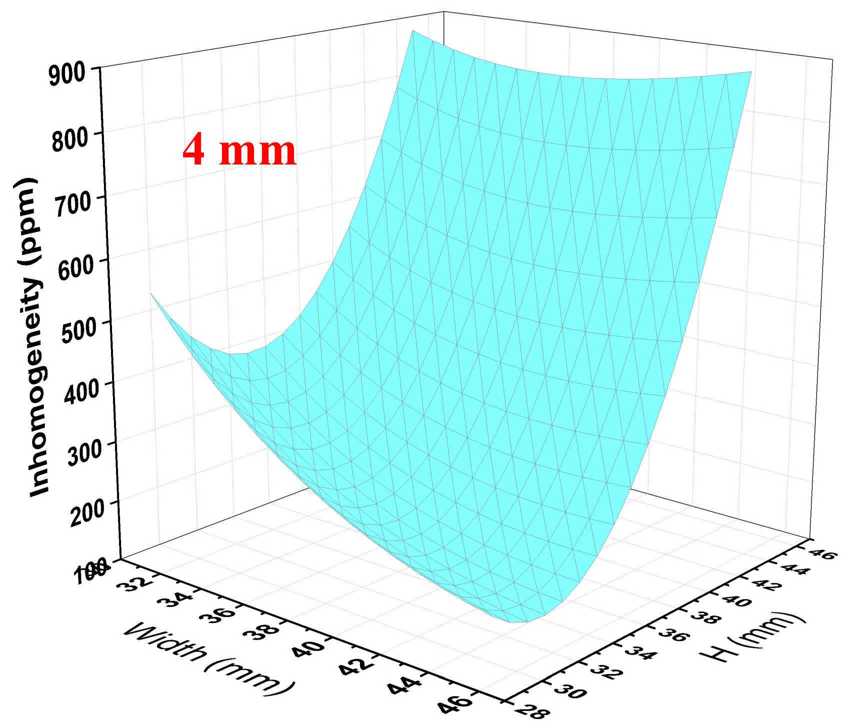


The best inhomogeneity of 411 ppm is obtained with W_{corr}=50 and H_{corr}=32 mm

The QSAL magnet: External Correction

Further parametric sweep, when the correction coils are placed at **2.0 mm** and **4.0 mm** far from the main coil.





The best inhomogeneity of 31 ppm is obtained with W_{corr}=33 and H_{corr}=30 mm

The best inhomogeneity of 132 ppm is obtained with W_{corr}=45 mm e H_{corr}=33 mm

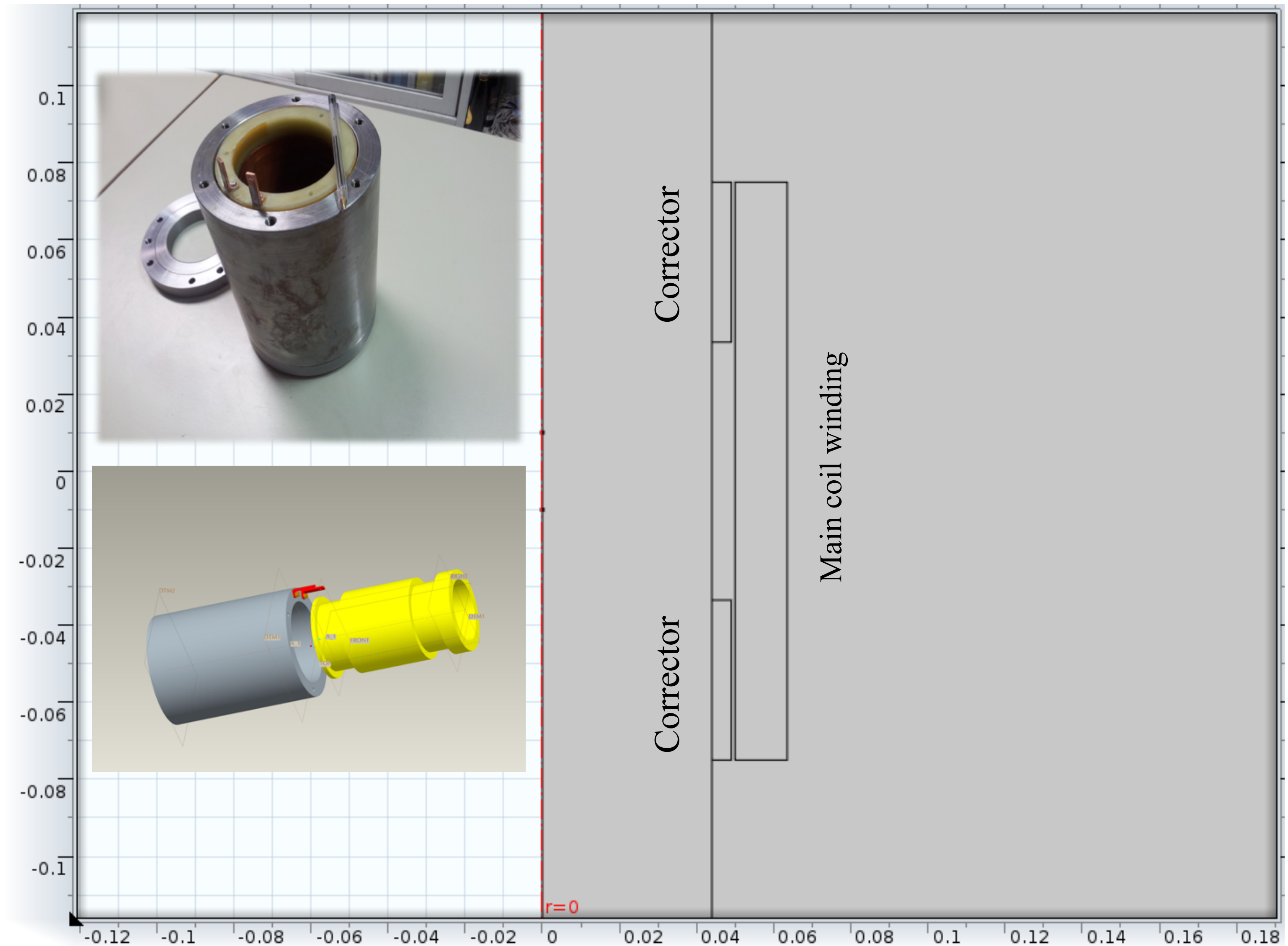
The QSAL magnet: External Correction

External correction leads to the following problem:

1. Minimun internal diameter of the corrector winding is 8 mm larger than the solenoid external diameter, and η_i>100;
2. The optimized correction winding volume is larger than the primary winding volume: practically a new magnet has to be built (cost and manufacturing problems);
3. Mechanical constrains (cryostat diam=250 mm) do not allow to fit this volume (expected magnet diam=248mm).

Taking into account these aspects we decided to adpot the internal correction.

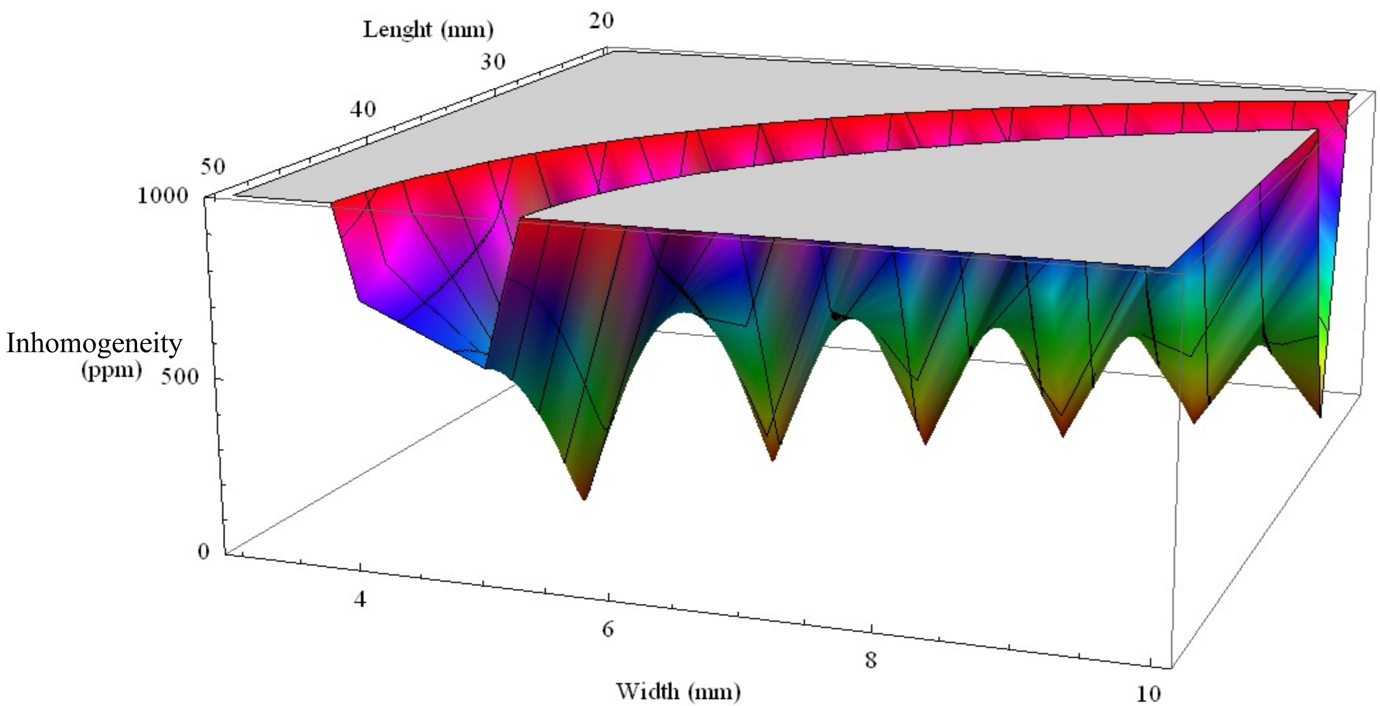
The QSAL magnet: Internal Correction



The QSAL magnet: Internal Correction

Once again we perform a parametric sweep, over the length (H_{corr}) and the width (W_{corr}) of the corrector coil dimensions, found a couple of parameters that minimize the inhomogeneity.

The best inhomogeneity obtainable by tuning the winding geometrical dimensions is achieved with H_{corr}=43 mm and W_{corr}=5 mm. In our numerical simulation we also considered the gap between the solenoid and the correction coil (2 mm on the diameter).



The best homogeneity of 39.5 ppm is obtained with W_{corr}=5 and H_{corr}=43 mm

The QSAL magnet: conclusion

- ✓ Optimization of the corrector coils give minima very tight: small mechanical error can largely affect the inhomogeneity;

- ✓ Correctors are new elements that have to be added to a preexisting magnet: we do not have neither any mechanical reference to align the axes of the two windings nor *z* reference to match the magnetic centers;

- ✓ The usage of the grading appears to be necessary but, without a different power supply the only way to improve the coil homogeneity is to act on the number of turns with the usage of thinner wires. This will requires a verification of the availability of thinner wires.

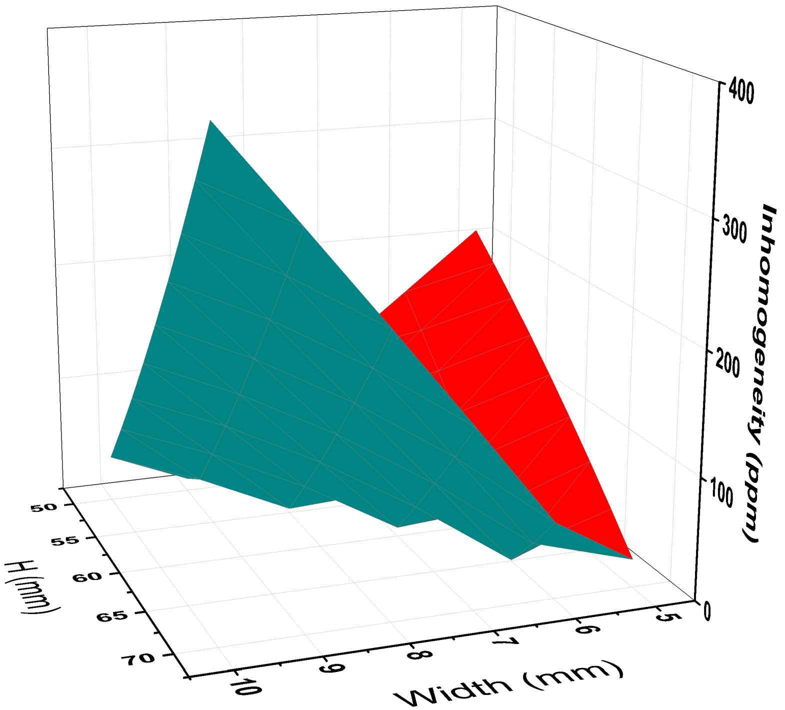
The Demo magnet: features

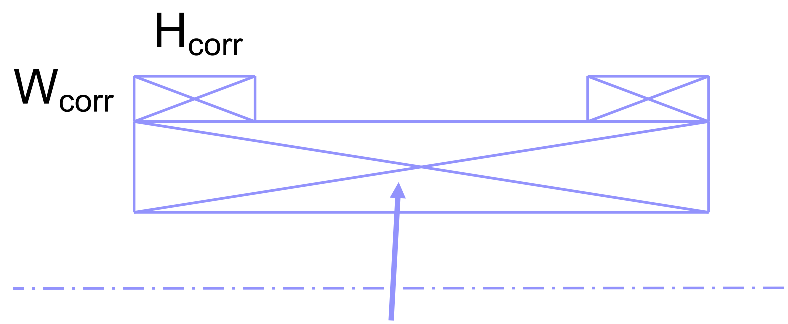
We investigated the feasibility of a new 2T superconducting solenoid for performing higher accuracy experiment, having the following requirements and constraints:

1. No grading. All coils should share the same current (only one stable power supply);
2. homogeneity below 50 ppm within a cylindrical region of 5 mm in radius and 20 mm in length;
3. low budget (25 k€);
4. rapid fabrication (choose wires already existing, with given thicknesses);
5. keep as much free space as possible inside the coil;
6. the maximum magnetic field is required at the coil center;
7. must fit inside the cryostat already in use: *i.e.* as pure solenoid it can have the following radius over length ratio

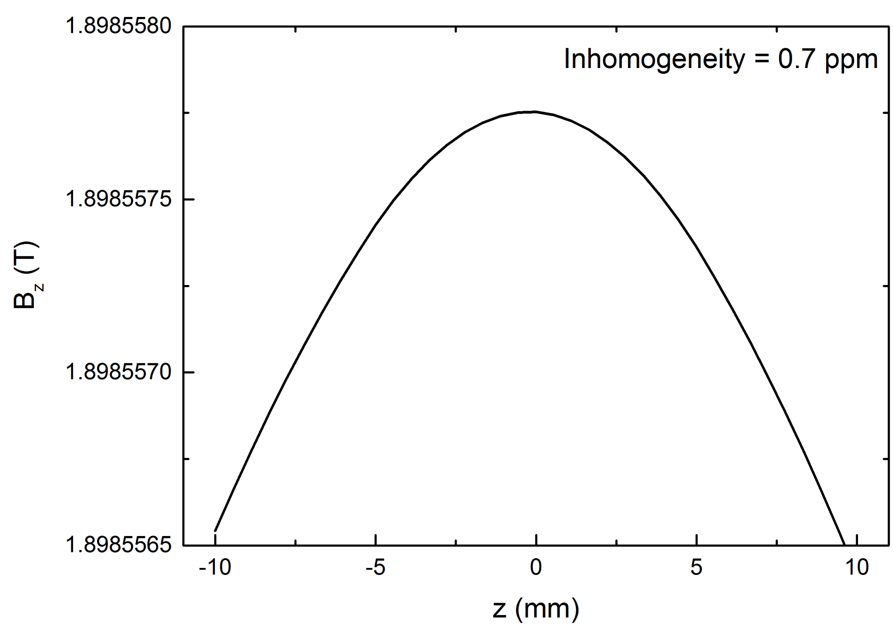
R/L=0,187 - (L=400mm, R=75mm)

The Demo magnet: features





100 A - 400 turns-14 layers



Parametric sweep gives 0.7 ppm minimum for H_{corr}=65mm W_{corr}=6mm

Conclusion

✓ High homogeneity magnetic field (～1-10 ppm) can be achieved in superconducting solenoid with simple correction bobbins;

✓ Actually special care must be taken when other superconducting structures (like a s/c cavity) have to be interposed in between the field source and the material to be magnetized ;

✓ The case study reported will provide enough performance to investigate the s/c cavity performance in the presence of a background magnetic field.

A new method to achieve the best Homogenization profile

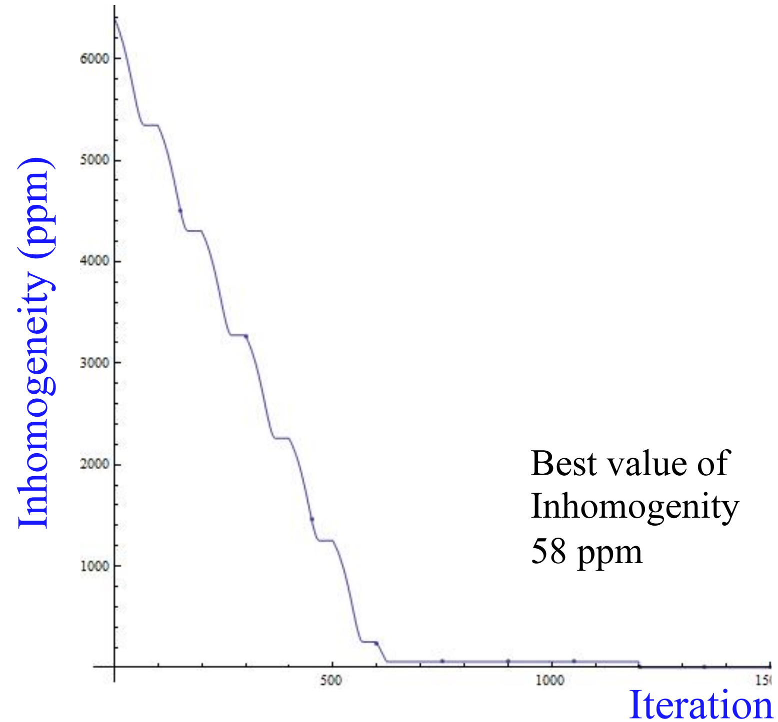
We developed a numerical code to explore different profile of the correction solenoids.

Each pixel represents a single wire.

- ✓ If pixel value is 1 (black) in the wire flows a current I_{bias};
- ✓ If pixel value is 0 (white) no-current flows.

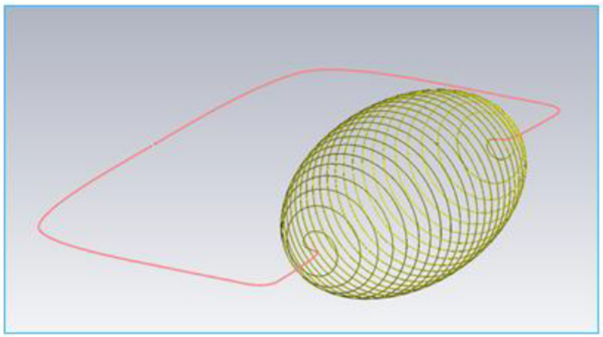
Each black pixel contribute to the field along magnet axis with a term:

$$\mathbf{B}_0(z) = \hat{n}\frac{\mu_0 I R^2}{2(z^2 + R^2)^{3/2}}$$

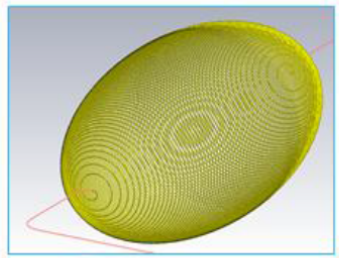


The algorithm explore different pixel configurations. At each iteration the inhomogeneity is calculated and configuration is changed in order to achieve the lowest inhomogeneity value.

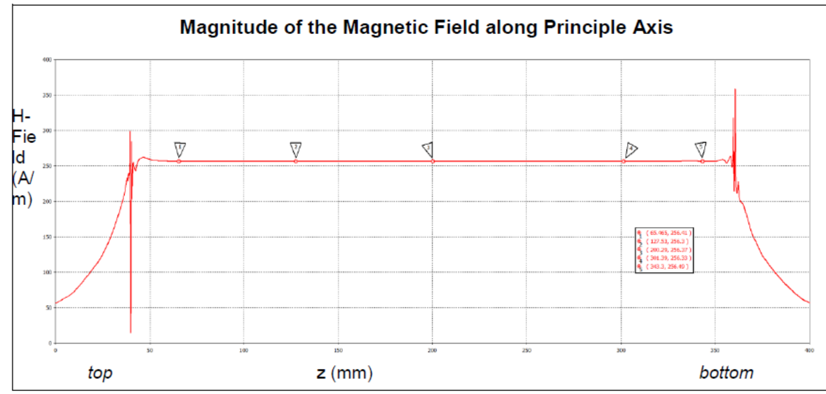
Generation of a Uniform Magnetic Field



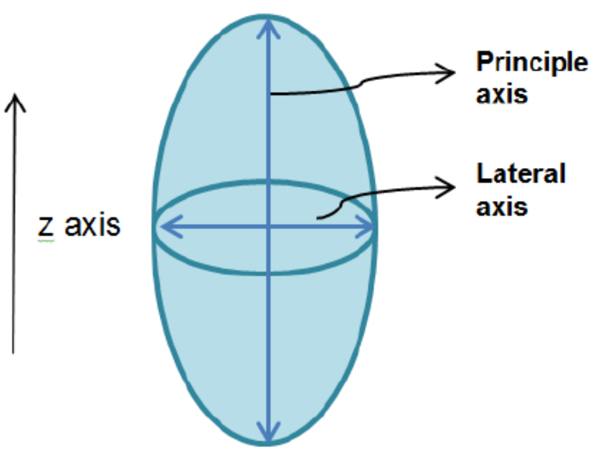
Spheroidal Helical Coil w/ 25 windings of copper wire having 0.9 mm diameter.

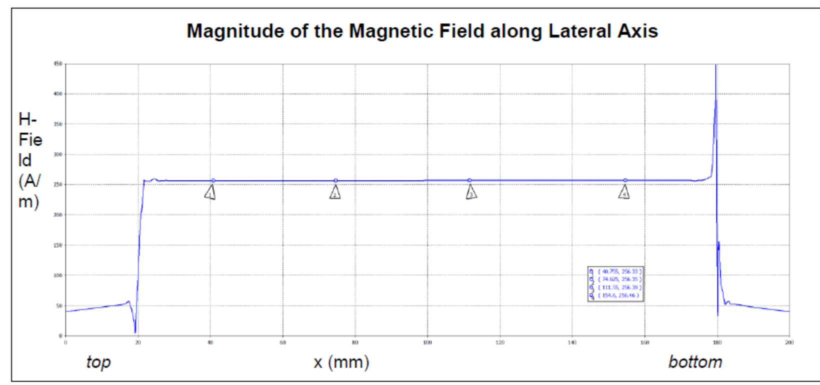


Spheroidal Helical Coil w/ 100 windings of copper wire having 0.9 mm diameter.



Spheroidal winding

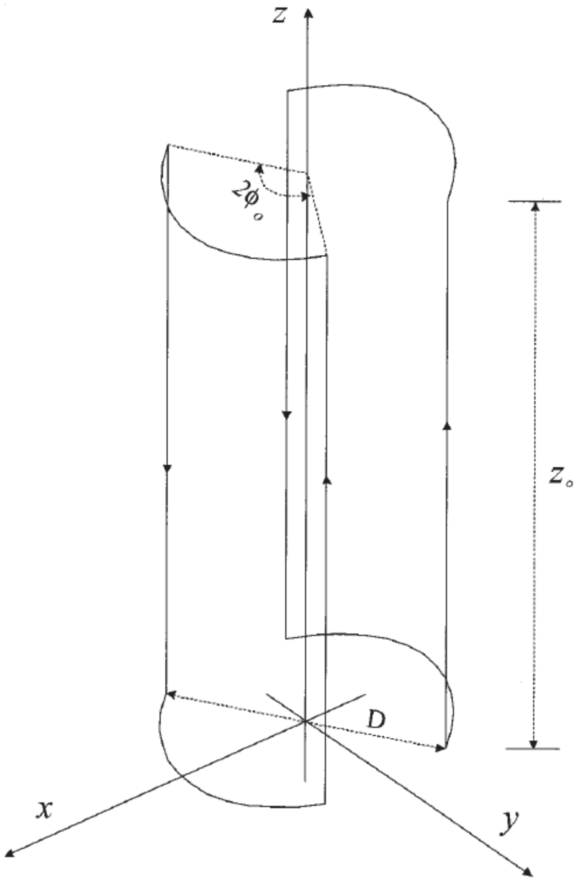




Field Uniformity: 0.15% (1500 ppm)

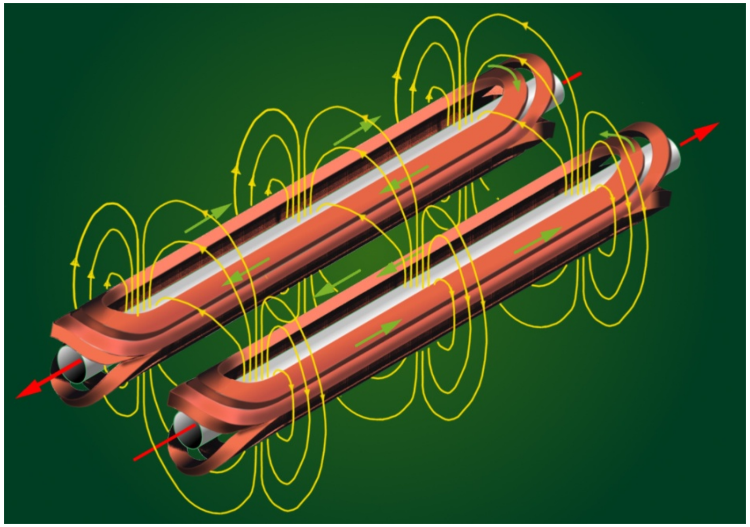
Yavuz Ozturk, Bekir Aktaş, Journal of Physics: Conference Series 667 (2016) 012009

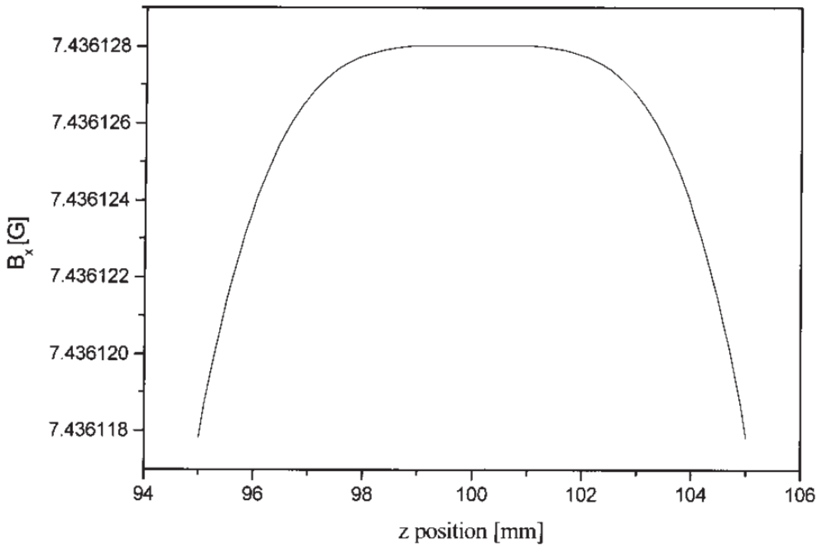
Generation of a Uniform Magnetic Field



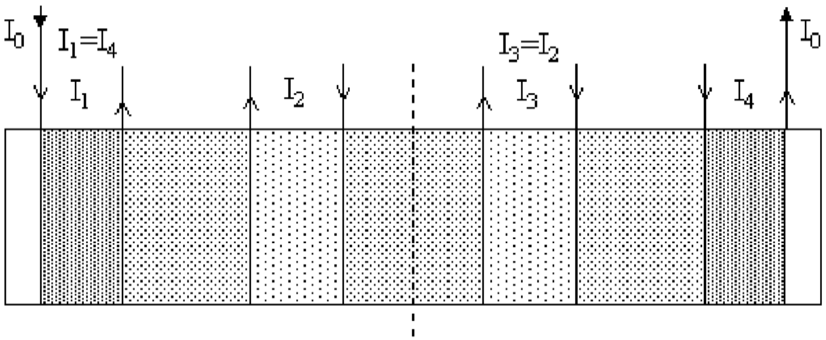
Saddle Coil Windings

F. BONETTO, E. ANOARDO, M. POLELLO, Concepts in Magnetic Resonance Part B (Magnetic Resonance Engineering) DOI 10.1002/cmr.b

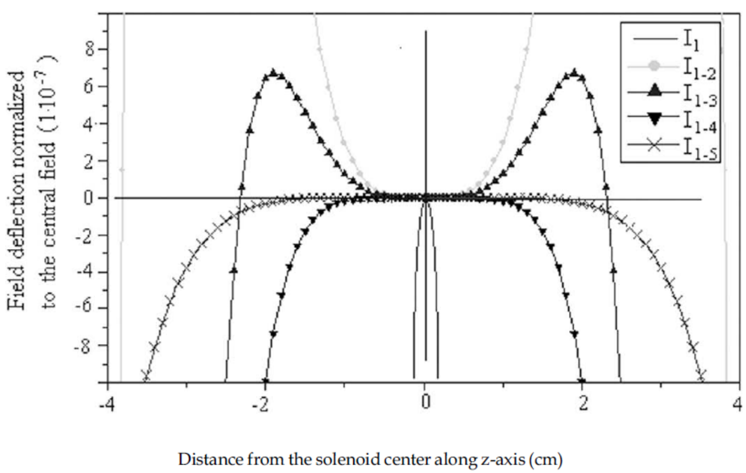




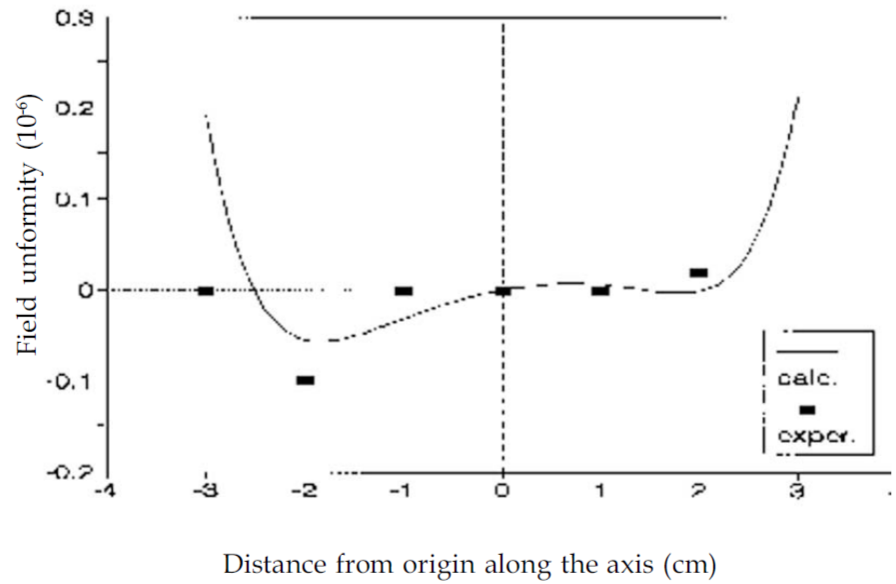
Generation of a Uniform Magnetic Field



Multi-current solenoid



Po Gyu Park, Wan-Seop Kim, V.N. Khorev and V.Ya. Shifrin



The measured and calculated field uniformity near the center of the 5-current solenoid

PO GYU PARK, WAN-SEOP KIM, V.N. KHOREV, V.YA. SHIFRIN, MAPAN Journal of Metrology Society of India, vol. 24 (2009) 9-14