

3T MRI magnet system design calculations

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This is an example of the type of calculations needed at the design stage on superconducting magnets for MRI and NMR.

This note presents some analysis results for an MRI magnet system described in published literature.

Full listings of magnet coil dimensions are rarely quoted publicly because designs are usually the property of commercial manufacturers and are thus confidential.

Reference

[1] Liebel, H. 2011. High-Field Superconducting Magnets. Chapter in: Hennig, J. & Speck, O. *High-Field MR Imaging*. Springer-Verlag. (ISBN 978-3-540-85090-8)

Purpose

Design features of this system are described below.

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Introduction: a six-coil, unshielded 3T MRI magnet system

This interesting example is given by Liebel in Hennig & Speck (2011) [1], where the following operating parameters are presented:

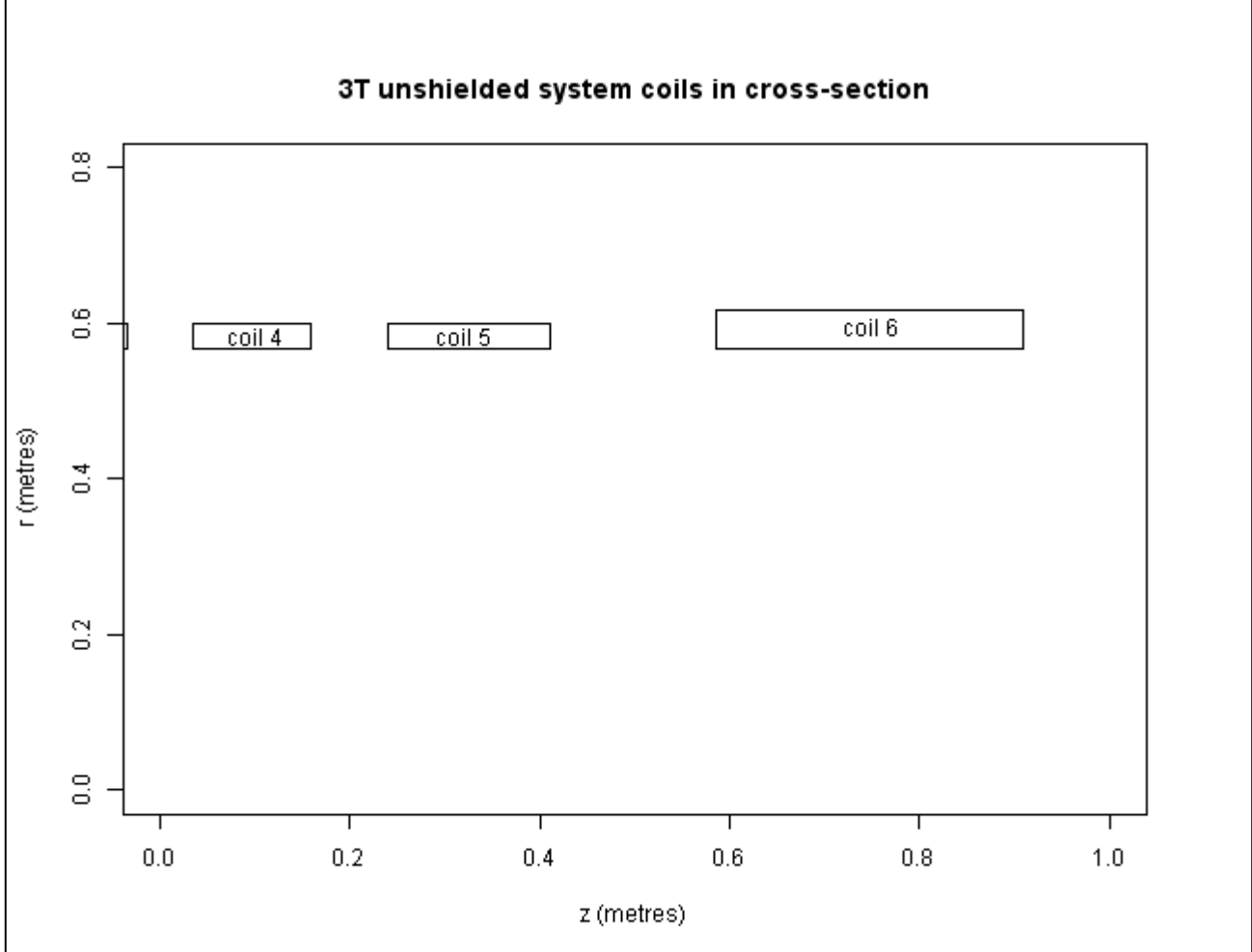
- coil dimensions for each coil
- numbers of turns on each coil
- central field
- field uniformity (<10ppm on 45cm DSV)

Coils layout for the 3T MRI magnet system

From the table of coil dimensions, the coils can be sketched in cross-section as shown. This is an unshielded magnet so the coils all have similar mean radius.

Distances are shown in **metres**.

Figure 1 Coils layout for 3T MRI system



Zonal harmonics table for the 3T MRI magnet system

Tables of zonal harmonics for the coils are shown in Table 1 and Table 2.

The coilset is symmetrical about the centreline so the tables show just half of the coils, on the right hand side of the origin. The field component harmonics are evaluated on a radius of 22.5cm, corresponding to the 45 cm DSV spec volume.

Units: **tesla per amp**.

Table 1 Lower order zonal coefficients

coil	A[0,0]	A[2,0]	A[4,0]	A[6,0]	A[8,0]	A[10,0]
4	2.007E-03	-3.719E-04	4.905E-05	-4.589E-06	1.365E-07	6.383E-08
5	1.942E-03	4.575E-05	-4.898E-05	6.133E-06	-1.153E-07	-7.040E-08
6	1.931E-03	3.260E-04	-7.160E-08	-1.543E-06	-2.102E-08	6.431E-09
total	5.880E-03	-1.742E-07	-1.410E-09	1.365E-09	2.459E-10	-1.332E-10
ppm	1000000.00	-29.63	-0.24	0.23	0.04	-0.02

Table 2 Higher order zonal coefficients

coil	A[12,0]	A[14,0]	A[16,0]	A[18,0]	A[20,0]
4	-2.009E-08	4.044E-09	-6.678E-10	9.677E-11	-1.268E-11
5	1.158E-08	-7.704E-10	-3.237E-11	1.483E-11	-1.967E-12
6	1.265E-10	-2.777E-11	-6.055E-13	1.271E-13	2.848E-15
total	-8.386E-09	3.246E-09	-7.008E-10	1.117E-10	-1.464E-11
ppm	-1.43	0.55	-0.12	0.02	0.00

The zonals table indicates that the operating current for a central field of 3 tesla is 255.12 amps. This may differ slightly from the operating current used in practice for technical reasons relating to the spectrometer radiofrequency settings.

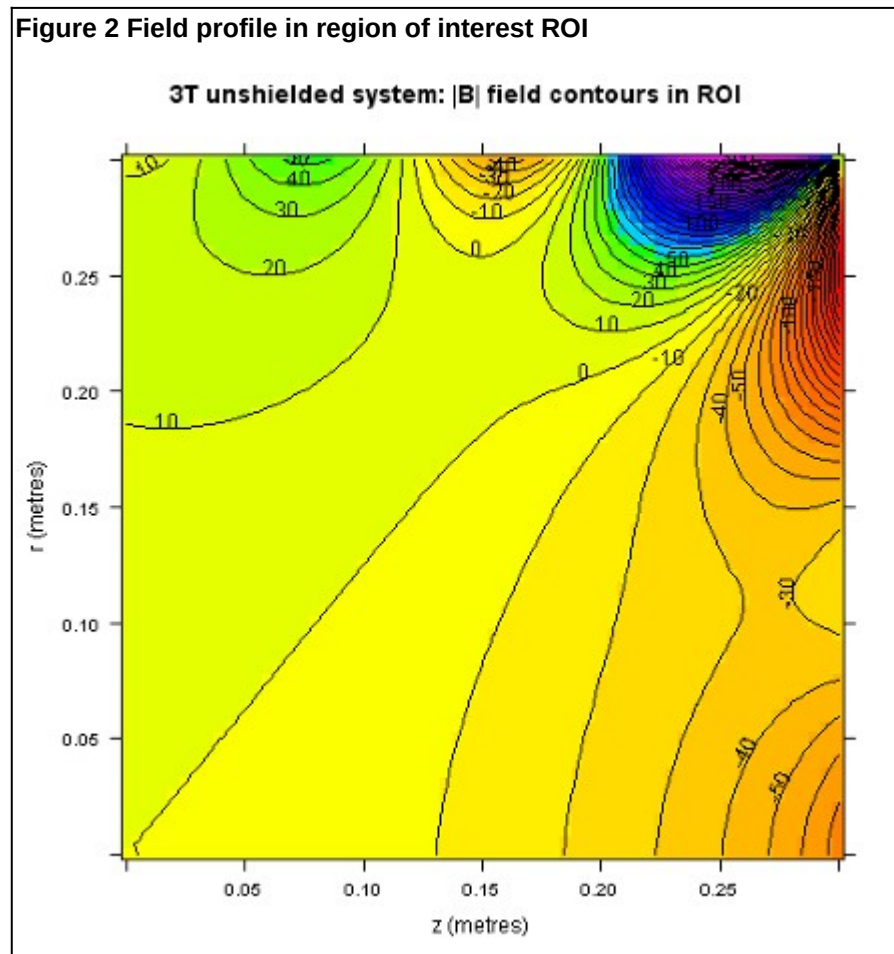
The table also shows that the design is balanced to tenth order, as reported. The first effectively non-zero harmonic is twelfth. A significant amount of residual second order is present, but this would presumably be dealt with by the shimming process during system installation.

Field in the region of interest (ROI), 3T MRI magnet system

A contour plot of the field in the imaging region or region of interest (**ROI**) for the 3T MRI magnet system is shown. This is sometimes termed the magnetic field profile of the magnet.

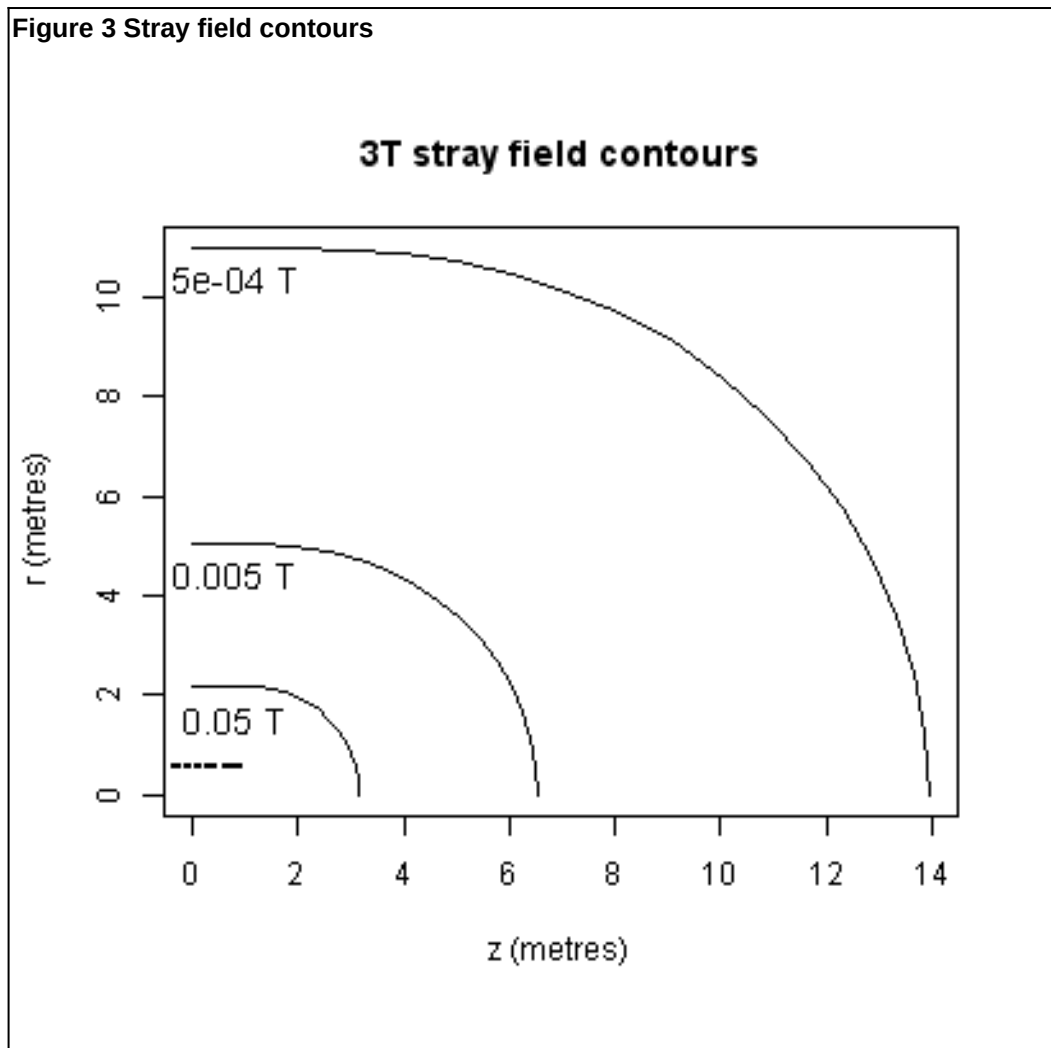
Reddish tones indicate negative ridges whereas blue indicates positive ridges. The effects of the small residual 2nd order field component can be seen near to the origin but the general shape of the high-uniformity ROI is still evident.

Going from theta = zero to theta = 90 degrees on a constant radius, the magnetic field profile shows a series of alternating highs and lows. This is characteristic of MRI magnet systems (and magnets constructed from short solenoids in general).



Stray field contours

Stray field contours are shown in the next plot. The 5 gauss contour extends further than in a typical active-shielded magnet (units for the plot are tesla: 5 G is equal to $5 \cdot 10^{-4}$ T).



Inductance matrix for the 3T system

The inductance matrix for the magnet, calculated using Garrett's elliptic integral solver, is shown in Table 3.

Units: **henries**.

Total inductance is **325.78 henries**.

Table 3 Inductance matrix for the 3T system

	[,1]	[,2]	[,3]	[,4]	[,5]	[,6]
[1,]	8.388E+01	9.434E+00	3.718E+00	2.385E+00	2.073E+00	2.788E+00
[2,]	9.434E+00	1.407E+01	4.380E+00	2.368E+00	1.820E+00	2.073E+00
[3,]	3.718E+00	4.380E+00	8.059E+00	3.562E+00	2.368E+00	2.385E+00
[4,]	2.385E+00	2.368E+00	3.562E+00	8.059E+00	4.380E+00	3.718E+00
[5,]	2.073E+00	1.820E+00	2.368E+00	4.380E+00	1.407E+01	9.434E+00
[6,]	2.788E+00	2.073E+00	2.385E+00	3.718E+00	9.434E+00	8.388E+01

Coil forces matrix for the 3T system

Next is the matrix of coil forces for the magnet (Table 4). Some of the forces are very large. The net force between either of the end coils (1 or 6) and the rest of the magnet is 3.26 meganewtons, or 332 tonnes force.

Units: **newtons**.

Table 4 Coil forces matrix for the 3T system

	[,1]	[,2]	[,3]	[,4]	[,5]	[,6]
[1,]	5.001E-10	-1.782E+06	-5.866E+05	-3.377E+05	-2.623E+05	-2.913E+05
[2,]	1.782E+06	-7.475E-12	-1.058E+06	-4.361E+05	-2.862E+05	-2.623E+05
[3,]	5.866E+05	1.058E+06	4.029E-11	-9.185E+05	-4.361E+05	-3.377E+05
[4,]	3.377E+05	4.361E+05	9.185E+05	4.029E-11	-1.058E+06	-5.866E+05
[5,]	2.623E+05	2.862E+05	4.361E+05	1.058E+06	-7.475E-12	-1.782E+06
[6,]	2.913E+05	2.623E+05	3.377E+05	5.866E+05	1.782E+06	5.001E-10
sum	3.260E+06	2.600E+05	4.815E+04	-4.815E+04	-2.600E+05	-3.260E+06