Development of strong magnetic field gradient coils for q-space Nuclear Magnetic Resonance (NMR) imaging

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Abstract

1

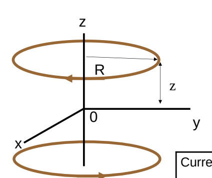
A magnetic field gradient coil is used in Nuclear Magnetic Resonance (NMR) to tag the spatial position of nuclear spins in a sample in both k-space and q-space imaging schemes. In this poster presentation we report on our analysis for generating a gradient field of 500,000 G/cm over a sample volume of 1 mm^3. Previously reported gradient fields with these methods range from 1000 G/cm to 50,000 G/cm. The gradient fields will be used to investigate the structure of a broad range of materials in addition to quantum dynamics in homogenous solids in our laboratory at York College.

Applications of magnetic field gradients

2

- q-space imaging: Measures the average probability of molecular displacement of molecules in a porous structure. Limits of resolution are dictated by how well one can reproduce the gradient pulse areas and gradient strength.
- k-space imaging: Measures spin density versus spatial position. Limits of resolution are dictated by the strength of the gradient and molecular diffusion.

Gradient generated by single Maxwell pair



$$G = \frac{3z\mu I}{\left(1+\left(\frac{z}{R}\right)^2\right)^{5/2} R^3}$$

[See Ref. 1,2,4]

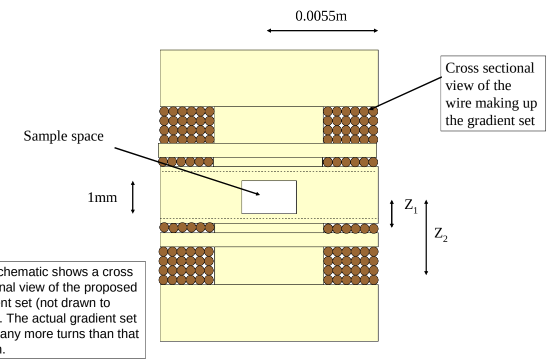
Current	I	200 Amperes
Permeability of free space	μ	$4\pi \times 10^{-7}$ N/A^2
Distance between the loops	2z	0.001 meters
Gradient	G	6664.4 Gauss/cm

Comments:

- With a single turn, this gradient is non-linear due to the presence of higher order terms.
- In order to generate a stronger, more linear gradient and simultaneously eliminate higher order terms, additional turns are required.

Schematic cross sectional view of a gradient set

3



The schematic shows a cross sectional view of the proposed gradient set (not drawn to scale). The actual gradient set has many more turns than that shown.

Geometric condition necessary for producing a linear gradient:

$$z_1 = 0.44R \quad z_2 = 1.19R \quad \frac{S_2}{S_1} = 7.47$$

Citations:

[1] B.H. Suits and D.E. Wilken. Improving magnetic field gradient coils for NMR imaging, J. *Phys. E: Sci. Instrum.* 22 (1989) 565-573.

[2] W. Zhang and D.G. Cory. Pulsed gradients NMR probes for solid state studies. *J. Magn. Reson.* 132, (1998) 144-149.

Parameters used in this design

Gradient field for first set of turns:

$$G_1[G/cm] = \sum_{n=1}^{46} \frac{3z\mu I}{\left(1+\left(\frac{z}{R_n}\right)^2\right)^{5/2} R_n^3}$$

Method used here involved pair wise summation of gradients generated by each turn of wire

Current	I	200 Amperes
Permeability of free space	μ	$4\pi \times 10^{-7}$ N/A^2
Radius of first loop	R_{int}	0.001 m
Increments in summation (wire radius)	R_n	0.0001 m
Total number of turns	n	46
Distance from center of sample to center of first set of turns	Z_1	0.00143 m
Gradient field	G_1	129, 834.5 Gauss/cm

4

Gradient field for second set of turns:

$$G_2[G/cm] = \sum_{n.m} \frac{3z_m\mu I}{\left(1+\left(\frac{z_m}{R_n}\right)^2\right)^{5/2} R_n^3}$$

Current	I	200 Amperes
Permeability of free space	μ	$4\pi \times 10^{-7}$ N/A^2
Radius of first loop	R_1	0.001 m
Distance from center of sample to center of first set of turns		0.002968m
Total number of turns	n, m	504
Wire Gauge		0.0001m
Gradient field	G_2	429015.3 Gauss/cm
Total gradient generated	**$G_1 + G_2$**	**558,849.8 Gauss/cm**

Temperature increase of the gradient set

$$\Delta T = 0.055\frac{V^2\Delta t}{n^2 D^2}$$ [See Ref. 2]

Minimizing the temperature increase is important when high currents are used in order to achieve reproducible gradient waveforms. For example, the change in temperature of the gradient set is 0.04°C for the parameters above with a 100 μs long pulse.

Voltage	V
Gradient pulse length	Δt
No. of Maxwell pairs	n
Average coil diameter	D
Temperature change (°C)	ΔT

Citations:

[3] W. Zhang and D.G. Cory. First direct measurement of spin diffusion rates in a homogenous solid. *Phys. Rev. Lett.* 80, (1998) 13-24.

[4] Jin, Jianming. Electromagnetic analysis and design in magnetic resonance imaging. CRC press LLC, 1999.

[5] G.S. Boutis, D. Greenbaum, H. Cho, D.G. Cory, and C. Ramanathan. Spin diffusion of correlated two spin states in a dielectric. *Phys. Rev. Lett.* 92, (2004) 137-201.

Conclusions

5

In this poster we presented an analysis performed to generate a strong magnetic gradient field over a sample volume of approximately 1 mm^3. The techniques used relied on already developed methods by W. Zhang and D. G. Cory[2]. A pulsed gradient field of approximately 500,000 G/cm can readily be generated with these coils, with a suitable power supply that can deliver approximately 200 Amperes of current. In the past a set of car batteries were used for this application [2,5] resulting in a pulsed field gradient of approximately 50,0000 G/cm.

Acknowledgments

Y. Rumala thanks the support of the National Science Foundation Louis Stokes Alliance for Minority Participation (LSAMP) program and the Department of Education McNair Scholars program at York College of CUNY. E. S. Mananga thanks the National Science Foundation sponsored Minority Access/Graduate Networking in the Sciences, Engineering and Mathematics (MAGNET) program at CUNY.