

Magnetic Analysis of Magnetic Rotating Field Devices for Studies about the Molecular Effects in Blood Cells

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The study of the molecular level effects in blood cells of the variable magnetic field requires the design of appropriate magnetic devices. In this article, four immobile configurations are analyzed: Helmholtz coils, Gramme coils, quadrupole magnet, and sextupole magnet. These devices can create a rotational magnetic flux density, intense (up to hundreds of mT), of high frequency (up to 1 MHz) and with an appropriate degree of homogeneity (minimum 95%) in the bioreactor area of 1 cm in diameter. The rotational field is created by supplying the component coils by currents having shifted phases. The comparative numerical analysis with the help of COMSOL software highlighted the effect of the device geometry, the type of core and conductor, correlated with the working frequency, on the magnetic flux density level in the area of the blood cells.

Index Terms— Biological cells, Electrical engineering computing, Magnetic analysis, Magnetic cores, Rotating high frequency magnetic field.

I. INTRODUCTION

THE EFFECTS of the magnetic flux density on biological cells has been intensively studied [1], but most of the scientific works refer to usual levels of the order of tens of mT. Strong magnetic fields have been addressed in particular in the field of particle acceleration (e.g., in [2]) but the main parameter is the field gradient, not the magnetic flux density level. In the case of a multipole electromagnet, ensuring a uniform field in the area of the biological sample requires a careful design of the poles so that the field lines do not close through the neighboring poles, but cross the sample. This problem has long been avoided by using coreless sources of uniform magnetic field, such as Helmholtz coils. The increased interest in biomedical studies in intense, rotating magnetic field and at the highest possible frequencies has led to new core configurations being proposed: Gramme coils [3] or multipolar electromagnets [4]-[6].

This study is focused on four configurations (Helmholtz coils, Gramme coils, quadrupole magnet and sextupole magnet) in which the coils are powered in such a way as to create a rotational field of the greatest possible amplitude in area of interest occupied by blood cells placed in a 1 cm diameter bioreactor. The geometry and the used materials were initially designed through the analytical optimization of the magnetic flux closure paths, in order to have uniformity in the bioreactor area and the necessary access space to it. The results of the magnetic analysis highlight the correlation between the magnetic core (geometry and materials), the coil conductor, the working frequency, and the level of magnetic flux density in the bioreactor area (1 cm diameter) with a degree of homogeneity of at least 95%. This homogeneity was evaluated by a relative volume root mean square (rVRMS), used in magnetic resonance imaging (MRI) quality recommendations.

II. DESIGNED DEVICES

Four magnetic flux density sources were considered to produce homogeneous field in the working area (1 cm diameter).

Their structures were heuristically optimized, starting from the analytical methods for calculating the magnetic flux density (magnetic circuits, Biot-Savart-Laplace formula, average length of magnetic flux lines). Later, the respective structures were modeled in COMSOL Multiphysics and were tested for different frequencies, magnetic yoke materials and conductor sections. The 3D models are further detailed and shown in Fig. 1. The conductor section was correlated with the penetration depth corresponding to the frequency, the diameter being 1 mm for 400 Hz, 0.2 mm for 300 kHz and 0.125 mm for 1 MHz.

A. Helmholtz coils

Two pairs of Helmholtz coils (Fig. 1.a) spaced at 30 cm and 50 cm respectively, fed with alternating current of variable frequency, with phases shifted by 90 degrees, were used to generate the rotating magnetic flux density. The section of each coil is (2 cm x 2 cm).

B. Gramme coils

The device shown in Fig. 1.b has a square-shaped magnetic yoke with sides of 24 cm (outside) and 16 cm (inside), the thickness being 4 cm. The materials tested for the magnetic core were M-15 Steel (0.635 mm sheets), ferrite and Supermalloy (0.3 mm sheets). The four coils are fed in such a way that a rotating magnetic flux density is generated in the middle area (occupied by the biological sample).

C. Quadrupole electromagnet

A quadrupole structure with two pairs of poles, frequently used in particle acceleration, was adapted to ensure the homogeneity of the magnetic flux density in the middle area occupied by the bioreactor. The quadrupole electromagnet shown in Fig. 1.c has two section coils for an optimal use of the core windows and to create a maximum field. The magnetic core, made of materials similar to those tested for Gramme coils, has a side of 22 cm and a thickness of 2 cm. The coils' power supply is two-phased, with a phase difference of 90 degrees to ensure the rotational field.

D. Sextupole electromagnet

The last structure uses three pairs of poles with three-phase powered coils to generate a rotating magnetic flux density in the middle area occupied by the biological sample – see Fig. 1.d.

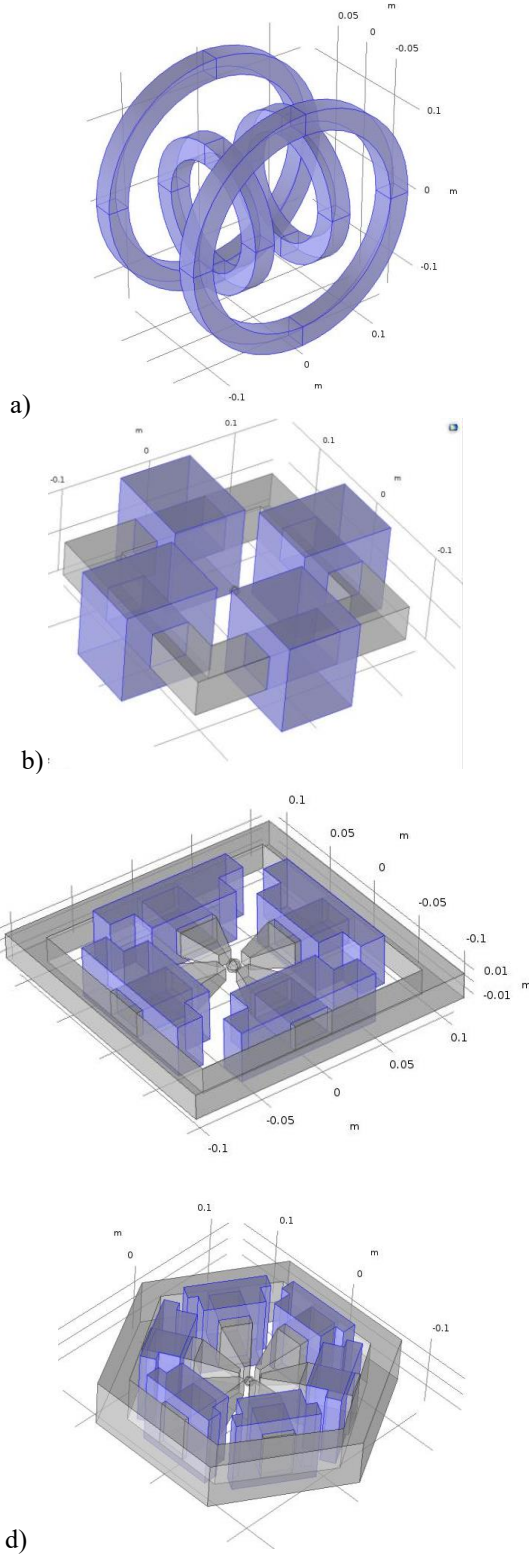


Fig. 1. Magnetic rotating field devices: a) Helmholtz coils; b) Gramme coils; c) quadrupole electromagnet; d) sextupole electromagnet.

TABLE I
AVERAGE MAGNETIC FLUX DENSITY B IN THE BIOREACTOR ZONE

Device	Frequency [kHz]	Core	Coil current [Amp-turns]	B [mT]
Helmholtz	0.4	-	1250	38.9
	300	-	1250	38.9
	1000	-	1254	24.4
Gramme	0.4	M15 Steel	7200	90.8
	300	M15 Steel	7200	81.4
	1000	M15 Steel	7200	66.4
	1000	Ferrite	7200	89.1
	1000	Supermalloy	7200	87.1
Quadrupole	0.4	M15 Steel	3600	524.1
	300	M15 Steel	3750	185
	300	Ferrite	3750	257.5
	300	Supermalloy	3750	485.6
Sextupole	0.4	M15 Steel	2025	322.7
	300	M15 Steel	2000	144.6

III. RESULTS

The numerical simulations of the four devices were carried out by COMSOL Multiphysics software, the main results being presented in Table I. It is observed that the dissipation of the magnetic flux density in the case of Helmholtz or Gramme coils leads to tens of mT in the sample area for frequencies below 1 MHz. The use of magnetic cores for multipolar electromagnets lead to an increased level in the bioreactor area up to 500 mT. It should be noted that these values are obtained without saturating the cores. The rVRMS homogeneity of the field in the sample area (radius of 1 cm) is over 95% in all the analyzed configurations, following the appropriate profiling of the poles.

The devices have been designed to operate without cooling, with a maximum of 4 A/mm² in the effective cross section of the conductors, but a detailed thermal study could impose a water cooling. The finalization of the project and the construction of the prototype will be done in the next stage, after the completion of the purchase of all the components necessary to energize the coils.

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