Design of Two Concentrical Pairs of Helmholtz Coils for the Exposure of Cell Cultures to ELF Magnetic Fields

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***Abstract*— In view of starting a research on the effect of Extremely Low Frequency (ELF) magnetic fields on the proliferation of cell cultures, a system of two concentrical pairs of Helmholtz coils was designed, simulated and built. One pair to generate a sine wave magnetic field of 10mT maximum, and the other to generate a magnetostatic field of 500µT maximum. The reason for this design was the possibility to generate fields under the Ion Cyclotron Resonance (ICR) hypothesis that explores intracellular ion resonance through the combination of a magnetostatic field in parallel with a sine wave magnetic field. The system was placed within a commercial CO_2 incubator, used to ensure the growth of cells in culture, generating the magnetic field in the axis perpendicular to the plane of the coils. The following work presents the design of the coils, simulations and measurements of the sine wave magnetic field and magnetostatic field of the system placed inside of the incubator.**

***Resumen*— Con vistas a iniciar una investigación sobre el efecto de los campos magnéticos de Frecuencias Extremadamente Bajas (ELF, según siglas en inglés) en la proliferación de cultivos celulares, se diseñó, simuló y construyó un conjunto de dos pares de bobinas de Helmholtz concéntricas. Un par para generar un campo magnético senoidal de hasta 10mT, y el otro para generar un campo magnetostático de hasta 500µT. La razón de este diseño es la posibilidad de generar campos bajo la hipótesis conocida como Resonancia Iónica Ciclotrón (ICR según siglas en inglés), que explora la resonancia de iones intracelulares mediante la combinación de un campo magnetostático en paralelo con un campo magnético senoidal. El sistema de bobinas se colocó dentro de una incubadora de CO_2 comercial, utilizada para asegurar el crecimiento de las células en cultivo, generando el campo magnético en el eje perpendicular al plano de las bobinas. El siguiente trabajo presenta el diseño de las bobinas, simulaciones y mediciones del campo magnético senoidal y magnetostático del sistema colocado dentro de la incubadora.**

I. Introduction

Almost forty years ago, Bioelectromagnetism emerged as a new and promising discipline. Nowadays there are a large number of researchers and institutes around the world dedicated to the study of the interaction between electromagnetic fields and biological systems [1]. In Argentina, the closest antecedent is the INDEBIO (Institute of Biophysics) which studied biological effects of radar radiation but unfortunately was shut down in the mid eighties [2].

With the aim of recovering the area, a research on the effects on Extremely Low Frequency (ELF) Magnetic Fields (MF) on cell cultures was planned. Therefore, this aim required the design of a custom device to generate a controlled MF inside of a commercial CO_2 incubator, where the cultures are placed to grow. The device should be able to generate not only sine wave MF(MF_{AC}) but also MF under the Ion Cyclotron Resonance (ICR) hypothesis [3] which states that intracellular ions can be influenced through the combination of a Magnetostatic Field (MF_{DC}) in parallel with a MF_{AC} in order to change the biological response of certain biological systems.

Thus the device should include the possibility to generate these combined fields that could also cover others hypothesis [4][5][6]. In general, the Helmholtz coils pair is the most common design because it can produce an acceptable volume of homogeneous MF [7], though there are more complex and improved models [8]. In that regard, we designed, simulated and built a set of two concentrical pairs of Helmholtz coils, one for the MF_{AC} and one for the MF_{DC}. Measurements of MF were performed with the coils inside of the CO_2 incubator and were in good agreement with the simulations.

II. Helmholtz Coils Design and Simulation

The equation that defines the MF of a single loop of current in a Z axis perpendicular to the plane of the loop is:

$$B_{z(0,0,z)} = \mu_0 \frac{I}{2} \frac{a^2}{(a^2+z^2)^{3/2}} \qquad (1)$$

Where $\mathbf{B_{Z(0,0,Z)}}$ is the z component of the MF along the Z axis for X and Y equal to 0, μ_0 is the free space permeability = $4\pi.10^{-7}$ $Hy.m^{-1}$, **I** is the current through the loop in Ampers, **a** is the radius of the loop in meters and **z** is the point where the MF is being evaluated. In order to calculate de MF of several concentrical loops with the same current and phase, superposition could be applied. In that case, the total MF along de Z axis will be the sum of the field created by each loop. Then, if every loop can be define by a radius **a**(i,j) and its **z** coordinate **z**(i,j) where **i** and **j** are correspondently the row and column of the n,m matrix depicted by every wire of the loops (Fig. 1), the equation 1 becomes:

$$B_{z(i,j)}(0,0,z) = \mu_0 \frac{I}{2} \frac{a_{(i,j)}^2}{\left(a_{(i,j)}^2 + (z - z_{(i,j)})^2\right)^{3/2}} \quad (2)$$

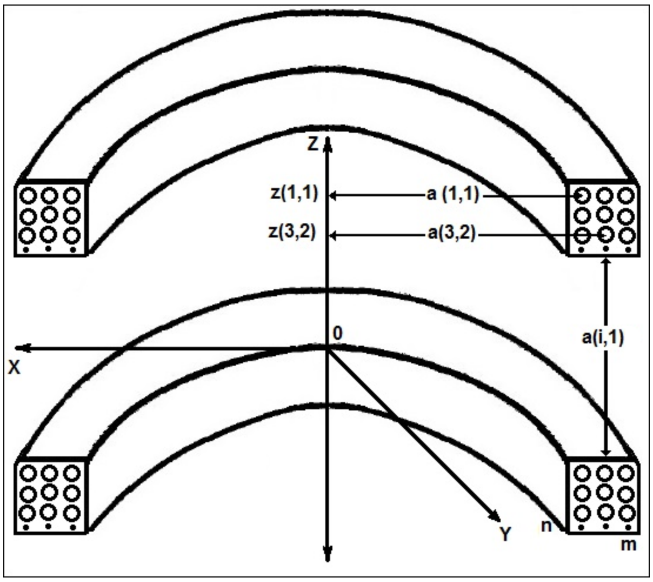

Figure. 1. (n,m) Matrix of the wires of each loop with its correspondent radius a and position z.

And the total MF $\mathbf{B_Z}$ (0,0,z) is

$$\boldsymbol{B_z}(0,0,z) = \sum_{i=1}^{n} \sum_{j=1}^{m} \boldsymbol{B_{z(i,j)}}(0,0,z) \quad (3)$$

Helmholtz coils pair requires that the coils be separated one radius distance (the minimum radius, **a**(i,1)), thus obtaining, in the Z axis, a homogenous field of half the radius. This way, the Helmholtz pair for the MF_{AC} was designed with a 0.6mm diameter enamelled copper wire (approximately 65.26Ω/Km, 20ºC), considering a radius of 80mm for **a**(i,1) and a separation between coils of 80mm, what should give a homogenous field of 40mm in the Z axis. The required relation between the current and the MF_{AC} was 10mT/A in order to be able to generate fields as low as those measured under a typical power line and as high as those generated by commercial magnet therapy devices. Equation 3 was used to calculate in MatLab the (n,m) matrix of the wires which determines the number of turns per each coil. Results obtained for **n**=23 and **m**=46 (1058 turns per coil), **I** = 1A are shown in Fig. 2.

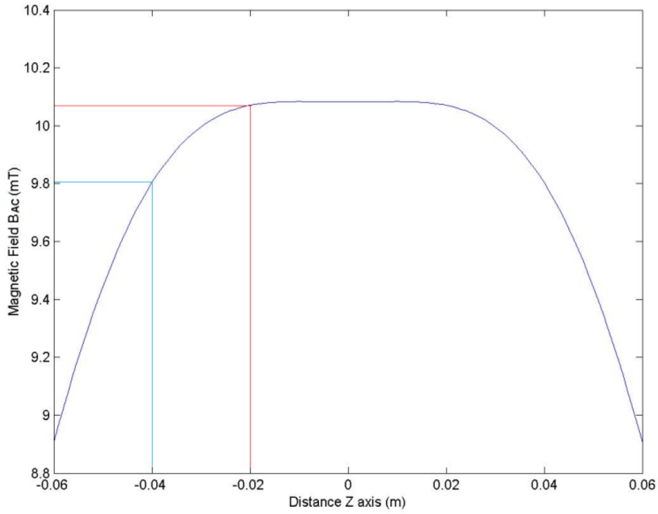

Figure. 2. Simulation in MatLab of the Helmholtz pair to generate the MF_{AC} for 1058 turns per coil and I=1A.

As can be seen, the maximum field value for a current of 1A is 10.08mT. The red line shows the field value at 20mm from the centre (homogenous theoretical limit) which is only a 0.13% less than the maximum and the light blue line shows the value at 40mm (coil level) which is only 2% less than the maximum. The resistance was calculated considering the total length of the wire, obtaining a RB_{AC}=81.9Ω. An approximation of the inductance was also calculated considering that the field was uniform in the whole area of each loop and equal to the value in the Z axis, thus obtaining the total inductance of the Helmholtz pair LB_{AC}=443.1mHy. Because of this consideration, an actual higher value was expected.

The same procedure was follow for the design of the MF_{DC} Helmholtz pair. In this case, we used a 0.25mm diameter copper wire (approximately 338.5Ω/Km, 20ºC), considering a radius of 62mm for **a**(i,1) and a separation between coils of 62mm, what should give a homogenous field of 31mm in the Z axis. The required relation between the current and the MF_{DC} was 500µT/160mA (3.125µT/mA). Higher currents could damage the wire and with this field intensity, most of the target ions could be tuned according to ICR hypothesis. Results obtained for **n**=14 and **m**=16 (224 turns per coil), **I** = 160mA are shown in Fig. 3.

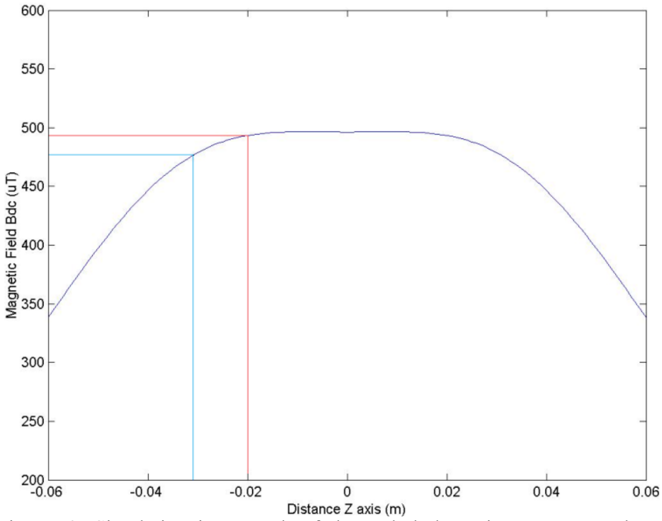

Figure. 3. Simulation in MatLab of the Helmholtz pair to generate the MF_{DC} for 224 turns per coil and I=160mA.

The maximum field value for a current of 160mA is 497.4µT. The red line shows the field value at 20mm from the centre which is only a 0.58% less than the maximum and the light blue line shows the value at 31mm (coil level) which is 5.1% less than the maximum.

The calculated resistance was RB_{DC}=61Ω. Inductance was not calculated in this case because these coils were only meant for DC current.

In order to analyse the field distribution in the radius line (XZ or YZ plane), a simulation of the MF_{AC} Helmholtz pair was run on Wipl-D Pro (Fig. 4).

Certain considerations had to be taken into account when simulating at 50Hz, regarding it's a software designed for higher frequencies. The coils were simulated with only one turn and the current was raised in order to replace the number of turns in the actual design. Results for the Z component of the MF strength (H) are presented in Fig. 4.

According to the simulation, a 2% variation is obtained within a radius of 30mm and 5% variation within 44mm.

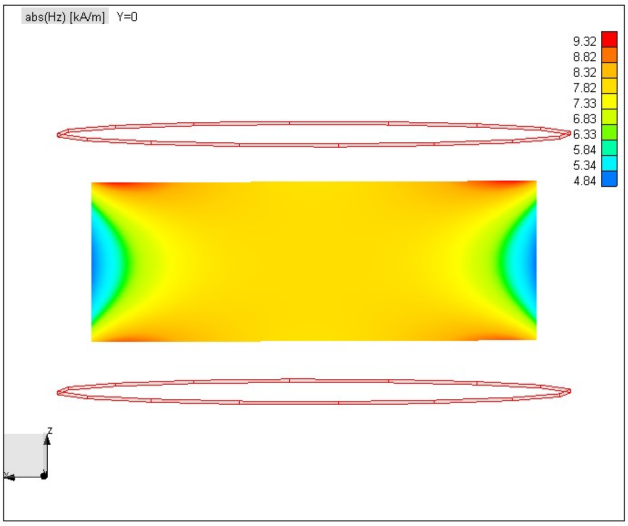

Figure. 4. Simulation in Wipl-D Pro of the MF_{AC} Helmholtz pair in the XZ plane.

III. SYSTEM CONSTRUCTION AND CHARACTERISATION

After the simulations, we built a model of both Helmholtz pairs with an acrylic core (not hollow at the centre). Both winding were shielded with aluminum paper, leaving a short gap, to reduce parasitic electric fields [8] (Fig. 5).

Figure. 5. Shielded MF_{AC} and MF_{DC} coils that compose the Helmholtz pairs.

The Helmholtz pairs were assembled using non ferromagnetic metals. MF_{AC} and MF_{DC} were measured in the homogenous region with the system place within the commercial CO_2 incubator. The incubator belongs to the Institute of Basic Science and Experimental Medicine (ICBME) of the Italian Hospital of Buenos Aires

[9], where a research in the effects of ELF MF on cells proliferation has recently started. One engineer of this team is performing all the experiments there, as a part of his Ph.D thesis plan.

The MF_{DC} was measured using a fluxgate magnetometer (Applied Physics System, model 428C) (Fig. 6).

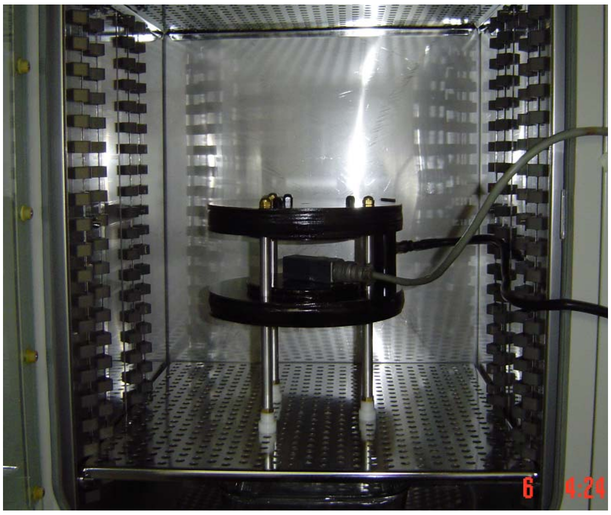

Figure. 6. Measurement of the MF_{DC} of the system within the incubator.

The MF_{DC} was measured without current (geomagnetic field) and then several points were assessed in order to calculate the relation between the MF and the current supplied. Results are shown in Fig. 7. No appreciable difference could be measured along the Z axis.

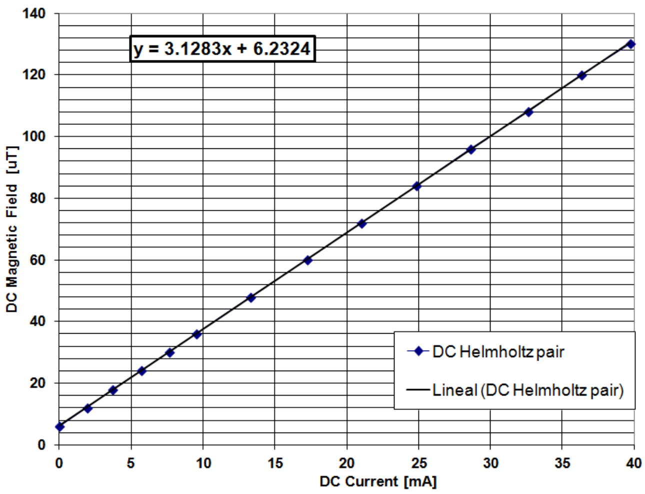

Figure. 7. Measured MF_{DC} of the system within the incubator.

The measured MF_{DC} inside the incubator due to the geomagnetic field in the Z axis was 6.23µT and the relation between the field and the applied current was 3.128µT/mA, which was in good agreement with the simulation.

Correspondingly, the MF_{AC} was measured in the calculated homogenous region with a magnetic field meter (Spectran-NF5035, Aaronia AG, Fig. 8).

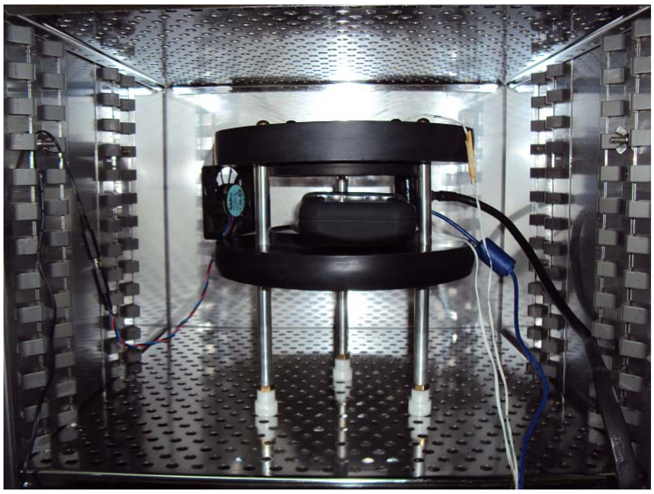

Figure. 8. Measurement of the MF_{AC} of the system within the incubator.

The results of the measurement are shown in Fig. 9. The relation between the MF and the current applied was 10.11µT/mA = 10.11mT/A which is in perfect agreement with the calculated relation.

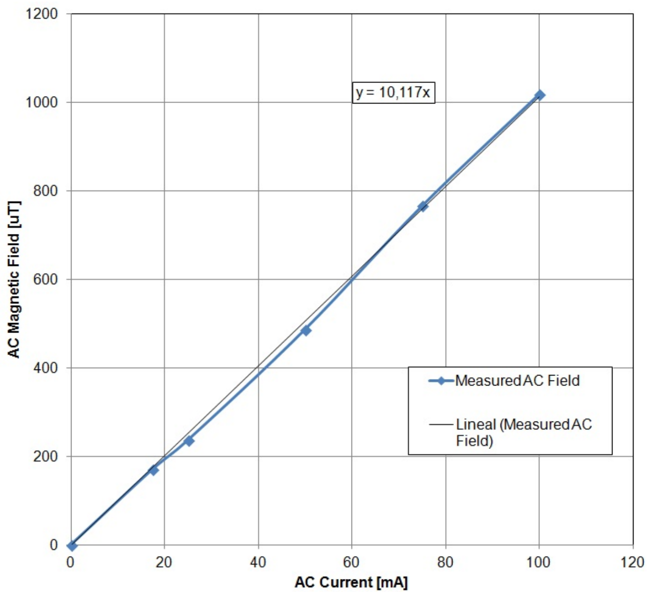

Figure. 9. Measured MF_{AC} of the system within the incubator

Also the resistance and inductance of the MF_{AC} coils were measured, obtaining a

RB_{AC}=83Ω and LB_{AC}=628mHy. Though the resistance was in good agreement the inductance was 41% higher than the calculated value, a fact that had already been expected. The measured resistance of the MF_{DC} coils was RB_{DC}=63Ω, again in good agreement with calculated value.

IV. CONCLUSION

According to simulations and measurements the system of two concentrical pairs of Helmholtz coils is a useful solution when the aim is exposing cells to MF under the ICR hypothesis or any other hypothesis that requires a combination of DC and AC fields. In this manner, it's easier to control the DC and AC currents separately. This system is at the moment being used for researching in the area of biological effects of ELF MF on the proliferation of cells in culture, in the Institute of Basic Science and Experimental Medicine of the Italian Hospital of Buenos Aires.

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