INVESTIGATION ON MOTION OF IONS IN ALIVE TISSUE UNDER INFLUENCE OF TOROIDAL LOW FREQUENCY MAGNETIC FIELD

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Abstract

The application of low frequency magnetic field can be meet in many procedures of physiotherapy. Often one pair of coils are enough for application of low frequency magnetic field. But in this case the number of "appropriate" pathologies is limited. Because of that usually more than one pair of coils are used for the procedures. The different coils can be situated at different part of the human body, according to the physician's recommendations. The procedure would be user friendly if some mechanical devices can be used for providing of space dispositions of coils.

One very useful disposition of coils is this one when the space configuration of magnetic field is like toroidal magnetic field.

1. INTRODUCTION

In the process of design of multifunctional flexible system for physiotherapy a bed for "running" low frequency magnetic field has been designed (Fig.1)

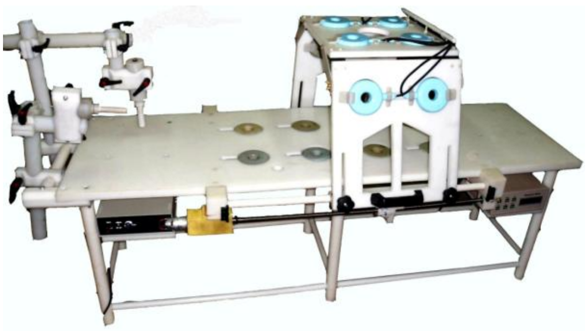

Fig. 1. Patient's bed

Two devices for acupressure are situated on the "magnetic". Therefore it's possible to be used acupressure together with magnetotherapy as one new method for therapy, which can provide a good results of therapy for a short time. The coils are situated on the plane of bed and on special mechanical trapezium stand. Because of that the coils on the bed (under trapezium stand) together with the coils on the trapezium stand provide magnetic field which space configuration is approximately like toroidal magnetic field. It's clear that during the process of therapy the ions of human body are under influence of toroidal magnetic field.

2. MOTION OF IONS IN ALIVE TISSUE UNDER INFLUENCE OF TOROIDAL LOW FREQUENCY MAGNETIC FIELD

Let us consider a magnetic field wich in cylindrical coordinates has only a component B_φ and wich is uniform in the $\varphi-$and $z-$direction. In the absence of volume currents it follows from the 2^{nd} Maxwell equation that

$$\frac{\partial B_\varphi}{\partial r} = -\frac{B_\varphi}{r}. \qquad (1)$$

In this coordinate system the velocity of the particle can be represented as

$$\vec{v}_c = \vec{v}_r + \vec{v}_z, v_{\parallel} = v_\varphi .$$

Equation of drift velocity of the center of gyration of charged particle is

$$\vec{u}_c = -\varphi_0 \times r_0 \frac{1}{r\frac{e}{mc}B_\varphi}\left(\tfrac{1}{2}v_c{}^2 + v_\varphi{}^2\right) \qquad (2a)$$

$$u_{\parallel} = v_\varphi . \qquad (2b)$$

As equation (2a) involves the value of the charge e carried by the particle, it follows that the u_c

drift for negatively charged particles in a direction opposite to the drift of positively charged particles. It's interesting to note that the component of the drift associated with the speed v_c arises

From the radial non-uniformity of B_φ, whereas the component associated with v_ε derives from the centrifugal force $mv_\varphi^{\ 2} / r$ of the circulating particle. This latter component can be also calculated directly from a force-balance equation

$$\vec{r}_0 \frac{mv_\varphi}{r} = \frac{e}{c} \vec{u} \times \vec{B} \tag{3}$$

which gives:

$$u = \frac{mc}{e} \frac{v_\varphi^{\ 2}}{rB_\varphi} \text{ (cm/sec)} \tag{3a}$$

A beam of particles injected tangentially into the field B_φ will spiral around the axis whilst individual particles will also spiral on tube of flux. The trajectory of individual particles is, therefore, a double helix. The problem of how the injection speed $v_{\varphi 0}$ is divided into v_c and v_φ of the spiral is outside the scope of this paper.

3. MOTION OF IONS IN THE FIELD OF A MAGNETIC LENS

The motion of charged particles in the field of a simple cylindrical magnetic lens can be considered from two extreme points of view. One is that of electron optics, in which it is usually assumed that the lens changes the momentum of the particles only by a small amount. The other view is found in plasma physics, where one usually assumes that the lens is so strong that the Larmor radius of particles is much smaller than the dimensions of the lens and that most of the particles to be studied have their velocities oriented at least in two dimensions. Somewhere between these extremes is the subject of cosmic ray interactions with the magnetic fields of cosmic clouds, of stars and of planets. In this section we shall deal with the motion for which

$$p \equiv \frac{mv}{\frac{e}{c} B} \ll d$$

where d is some characteristic dimension of lens. The description of the motion of such a particle can be based on the drift-velocity formulae. However, in order to apply these equations, information is required on v_c and $v_\parallel$. This can be derived from the invariance of the total kinetic energy of the particle, which is

$$W = \frac{1}{2} m \left(v_c^{\ 2} + v_\parallel^{\ 2} \right) = const. \tag{4}$$

and from the adiabatic invariance of the magnetic moment μ of the particle defined as

$$\mu = \frac{\frac{1}{2} m v_c^{\ 2}}{B} \tag{5}$$

The magnetic moment μ is only approximately invariant and its variation $\Delta\mu$ is critically dependent on ratio

$$\frac{v / L}{eB_0 / 2\pi mc} = \frac{\tau_c}{\tau_t}, \tag{6}$$

where τ_c is period of the cyclotron motion and τ_t is the transit time of the particle through a non-uniformity whose dimension is L. It can be shown that

$$\frac{\Delta\mu}{\mu} = \exp\left(a \frac{\tau_c}{\tau_t} \right) \tag{7}$$

and a is a factor depending on the relative amplitude $\Delta B / B_0$ of the non –uniformity.

The consequence of assuming that the magnetic moment is constant is that, apart from drift motion of center of gyration, a charged particle is bound to a surface of a tube of constant flux. Thus

$$\frac{\frac{1}{2} m^2 v_c^{\ 2}}{B^2} \frac{B}{m} = const. or \ p^2 B = const.$$

and as $\pi p^2 = \phi$ where ϕ is the magnetic flux, it follows that the orbit of the particle links a constant amount of magnetic flux.

Let us consider the motion of a charged particle on a converging tube of flux of rotational symmetry. Here from

$$\bar{u}_c = \frac{\vec{B} \times gradB_z}{B^2 \omega_c} \left(\tfrac{1}{2} v_c^{\ 2} + v_\parallel^{\ 2} \right)$$

gives

$u_c = 0$ owing to $\vec{B} \times gradB_z = 0$.

The equation for $u_\parallel$ does not contain any information as $u_\parallel = v_\parallel$. It is, therefore, necessary to find an equation for $v_\parallel$. This is

$$\frac{d}{dt}v_{\parallel}=\frac{F_{\parallel}}{m} \tag{8}$$

where $F_{\parallel}$ is a force on the particle in the direction of the vector $\vec{B}$. This force is the component of the Lorentz force in this direction. Thus

$$F_{\parallel}=\left|\frac{e}{c}\vec{v}\times\vec{B}\right|_{\parallel}=\frac{e}{c}v_c B_r.$$

The component B_r is related to B_z through $div\vec{B}=0$. Thus

$$\frac{\partial\left(rB_r\right)}{\partial r}=-r\frac{\partial B_z}{\partial z}. \tag{9}$$

Assuming that for $r \ll p, \partial B_z/\partial z$ is independent of r one obtains on integrating this equation with respect to r:

$$B_r=-\frac{1}{2}p\frac{\partial B_z}{\partial z}.$$

Substituting this into equation (9) yields

$$F_{\parallel}=-\frac{1}{2}\frac{e}{c}v_c p\frac{\partial B_z}{\partial z}$$

$$F_{\parallel}=-\frac{\frac{1}{2}mv_c^{2}}{B}\frac{\partial B_z}{\partial z} \tag{10a}$$

or expressed in a vector form

$$F_{\parallel}=-\vec{\mu}.gradB. \tag{10b}$$

The equation of motion in the B-direction becomes

$$\dot{v}_{\parallel}=\dot{u}_{\parallel}=-\frac{\vec{\mu}}{m}.gradB_z \tag{11}$$

This equation shows that charged particles, incident on a region of strong magnetic field experience deceleration in the direction of $\vec{B}$ and in some cases are reflected. However, as their total kinetic energy remains constant, it follows that as $v_{\parallel}$ decreases v_c increases and vice versa. This can be expressed mathematically using eq. (4) as

$$v_c^{2}=\frac{2W}{m}-v_{\parallel}^{2} \tag{12}$$

The condition of reflection is that $v_{\parallel}=0$. When this is so v_c reaches a maximum

$$v_{cM}=\sqrt{\frac{2W}{m}} \tag{13}$$

Assuming the magnetic moment to be invariant it follows that

$$\mu=\frac{\frac{1}{2}mv_{cM}^{2}}{B_M}=\frac{W}{B_M}. \tag{14}$$

It is clear that the smaller the magnetic moment, for a given total energy W, the further will the charged particle penetrate along the converging flux tube. A more general problem is represented by the motion of charged particle in a magnetostatic field whose flux tubes form a convergining and bent bundle (fig. 4)

This is the configuration off axis of a cylindrical lens.

If B varies only slowly with respect to z one has $\vec{B}\times gradB_z \approx B.\partial B_z/\partial r$ and equation (11) become

$$u_{\varphi}=\left[\left(\frac{\partial B_z}{\partial r}\right)/\left(\frac{eB^2}{mc}\right)\right]\left(\frac{1}{2}v_c^{2}+v_{\parallel}^{2}\right) \tag{15}$$

$$\dot{v}_{\parallel}=\frac{1}{2}v_c^{2}B_z^{-1}\frac{\partial B_z}{\partial z} \tag{16}$$

The reflection condition remains approximately the same as formulated in equation (14).

However, the particle does not return after the reflection along the same tube of flux but processes in the φ-direction during the reflection process.

Let us study this precession in the case of a magnetic mirror .This is a particular case of a lens geometry in which

$$B=B_0 \text{ for } z<a,\ B=B_1 \text{ for } z>b$$

where $B_1>B_0$ and b>a.

It follows from equation (14) that particles for which

$$\mu>\frac{W}{B_1}$$

will be reflected. Let us divide this inequality by $\left(v_{\parallel}^2\right)_0$ where $\left(v_{\parallel}\right)_0=v_{\parallel}$ for $z<a$. Then

$$\frac{\left(\frac{v_c}{v_{\parallel}}\right)_a^2}{B_0}>\frac{\left(\frac{v_c^2}{v_{\parallel}^2}\right)+1}{B_1}.$$

Putting

$$\left(\frac{v_c}{v_{\parallel}}\right)_0 = \tan\theta$$

where θ is the angle between the vector $\vec{v}_0$ and $\vec{B}_0$,one can write the condition for reflection as

$$\sin^2\theta > \frac{B_0}{B_1}. \qquad (17)$$

We shall follow a typical particle which satisfies this inequality. The angle of precession φ of such a particle will be

$$\varphi = 2\int_0^{\tau}\frac{u_{\varphi}}{r}dt = 2\frac{c}{e}\int_0^{\tau}\frac{\partial B_r/\partial z}{rB}\left(\frac{2W}{B}-\mu\right)dt \qquad (18)$$

This can be written as

$$\varphi = 2\frac{c}{e}\int_a^{z-a}\frac{\partial B_r/\partial z}{rB}\left(\frac{2W}{B}-\mu\right)\frac{dz}{v_{\parallel}}.$$

From eq. (16) it follows that

$$v_{\parallel}\dot{v}_{\parallel} = \frac{\mu}{m}\frac{\partial B_z}{\partial t}$$

or

$$v_{\parallel} = \left[2\frac{\mu}{m}\left(B_z - B_0\right) + v_{\parallel 0}{}^2\right]^{\frac{1}{2}}. \qquad (19)$$

Also near the z-axis (i.e. for $r < b-a$) one can expand B_z as

$$B_z\left(r_1, z\right) \cong B_A - \tfrac{1}{4}r^2 B_A''$$

where

$$B_A = B_A\left(0_1, z\right), B''_A = \frac{\partial^2}{\partial z^2}B_{A.}. \qquad (20)$$

Using this expression and equation (20) one obtains

$$\varphi \cong -\frac{c}{e}\int_a^{z-a}\frac{B_A''\left(\frac{2W}{B_z}-\mu\right)dz}{B_z\left[2\frac{\mu}{m}\left(B_z-B_0\right)+v_{\parallel 0}{}^2\right]^{\frac{1}{2}}} \qquad (21)$$

which can be easily evaluated for a specific field geometry. It can be appreciated that owing to B''_A changing sign in the interval (a, b) the sign of φ may be either positive or negative.

The field of a magnetic dipole can be also regarded as a magnetic lens of the type discussed in this section. However, as the field strength of a dipole depends on the distance r from the center of the dipole as $1/r^3$, the motion of a charged particle in this field cannot be always correctly represented by the drift motion of its center of gyration .In particular , the theorem of conservation of the magnetic moment μ of the particle breaks down when the radius of gyration ρ becomes larger than the distance r.

CONCLUSION

A mathematical description of motion of ions under influence of toroidal low frequency magnetic field is done in the paper, The space configuration of approximately toroidal magnetic field depends to the currents in the coils, which consists "toroid". These currents can be managed using appropriate software. Therefore the space configuration of toroidal magnetic field can be managed also.

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