High intense pulsed magnetic field for focusing ion beams and stressing biological materials

D. Delle Side, G. Buccolieri, M. Di Giulio, E. Giuffreda, V. Nassisi

LEAS, Department of Mathematics and Physics, University of Salento and INFN sect. of Lecce, SS Monteroni-Lecce – 73100 Lecce, Italy

Abstract

High intensity magnetic fields are employed to focus ion beams and they represent novel stress to study the behaviour of biological samples. In this work we present the realization of a magnetic pulser formed by a capacitor of 150 nF (50 kV) connected to ground by means of a pulsed high-voltage switch and solenoids for high current. The capacitor and the solenoid form a LC circuit oscillating at 210 kHz, 30 µs, at a maximum repetition rate of 2 Hz. The solenoids were realized by a copper wire by 8 mm (11 rings) and 5 mm (20 rings) in diameter. The corresponding inductances were 3.6 and 16 µH and the maximum currents generated at 50 kV of charging voltage of capacitor reached values up to 12 and 4.5 kA. The measurements determined a magnetic field at the centres of solenoid of 0.85 T for the less inductive solenoid and 0.5 T for the other one. The current diagnostic was performed by two systems: a self-integrating Rogowski coil and an integrator connected to a current transformer, both suitable for pulses longer than 1µs.

Introduction

Recently, many researches are in progress in the world to realize novel ion beams [1]. But the focusing of such beams is very complex due to their intensity and to short propagating length [2]. Moreover, different researches are investigating the possibility to study the behaviour of intense magnetic pulses on biological matter. Such an interest raised up with the increasing role played by these fields in our lives, so that it's obvious to investigate under which conditions they are not lethal for the living beings.

In classical electrodynamics theory, it's easy to show a variation along the radius of a solenoid gives rise to a force which can trap the particles in a magnetic field [3]. In a cylindrical symmetry, supposed the magnetic field B is axisymmetric, that means in cylindrical coordinates $B_\vartheta = 0$ and $\partial B / \partial \vartheta = 0$, it's possible to know from Maxwell's equation $\vec{\nabla} \cdot \vec{B} = 0$ written in cylindrical coordinates (r, ϑ, z) ,

$$B_r = -\frac{1}{2} r \left[\left(\frac{\partial B_z}{\partial z} \right)_{r=0} \right] \quad (1)$$

assuming a negligible variation of the field with r.

Since the expression for a magnetic field for $r \to 0$ in a finite solenoid is known, it's possible to get the expression for the average force along the z axis as well as its radial component:

$$\overline{F_z} = -\frac{1}{2}\frac{mv_\perp^2}{B}\left(\frac{\partial B_z}{\partial z}\right)_{r=0}$$

$$\overline{F_r} = \frac{mv_\perp^2}{r_L B} B_z \tag{2}$$

where $v_\perp$ is the speed lying in the plane perpendicular to B, depending on the particle q charge through the relation $v_\perp = \frac{|q| r_L B}{m}$, where r_L is the Larmor radius of the particle trajectory.

The focusing of the ions is however not perfect. It depends on many factors, but our work can be simplified by the following considerations: a particle with $v_\perp = 0$ has no magnetic moment which is $\mu = \frac{1}{2}\frac{mv_\perp^2}{B}$, and won't feel any force along B. A particle with small rate between speed perpendicular and parallel to B will also escape if the maximum value of the magnetic field B is not large enough. That's why we can only focus on the maximum values reached by the magnetic field in the solenoid in order to check how good its focusing skills will be.

Instead, in presence of matter the magnetic field interacts with magnetic moment. The magnetic moment of matter is governed by the quantum mechanics and the ferromagnetic and paramagnetic molecules which are the molecules more sensible. The diamagnetic molecules, characteristic of all matter, are sensible to the derivate of the magnetic flux due to the Lenz law. During the interaction of magnetic field with paramagnetic matter, this last is undergone to a mechanical moment corresponding to $\vec{N} = \vec{M} \times \vec{B}$, where $\vec{M}$ represents the magnetic moment and $\vec{B}$ the magnetic field. Inside the matter the mechanics moment can provokes a variation in orientation and a changing in energy of the molecule expressed by:

$$E_B = -\vec{M} \cdot \vec{B}$$

The study of exposed living samples is very hard due to the membrane structure complexity. In these cases, it reasonable to suppose that magnetic fields can influence the charge and energy transport through the membrane. Considering only the electronic moment, the change energy can be negative or positive due to the electron spin number (±½). It is given by:

$$E_B = \pm g \mu_B B m$$

where g is the Landé factor which is close to 2.00 for free electrons and most organic radicals[4], μ_B is the Bohr magneton, B is the magnetic field and m is the quantum constant.

On the earth, it is well known that the geomagnetic field is relevant for many living organism even if its intensity is very low, about 0.005 mT. Generally, fields more intense are used in laboratory experiments and they are called moderate and ranging from 1 to 1000 mT.

In this work we developed a high voltage circuit able to generate high pulse currents to get intense magnetic fields. To get the value of the magnetic intensity, we also developed the diagnostic system to record the current pulses.

Experimental apparatus

The magnetic field is generated by a LC circuit with a main pulse lasting 30 µs. To generate it we connected a solenoid to a pulser composed by a capacitor of 150 nF and a spark gap as fast switch. The capacitor is charged by a high-voltage power supply up to 50 kV. Considering the internal non – zero resistance of the circuit, the discharge occurs in the pulser with a time dependence for the current *i(t)*:

$$i(t) = \frac{V}{\omega L} e^{-\frac{Rt}{2L}} \sin \omega t$$

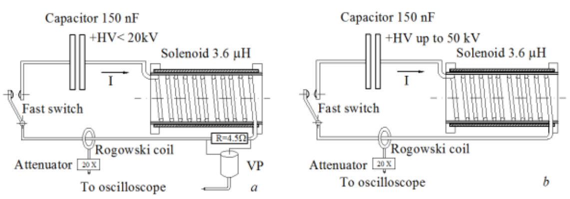
where $\omega = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$ and V is the applied voltage on capacitor.

The first solenoid we tested was made by 11 rings made of a 0.8 cm diameter copper tube. It has a length of 12 cm and a radius of 3 cm. Fig. 1 shows the sketch of the high voltage pulser.

The discharge current was recorded by a fast Rogowski coil, composed of 140 rings with a resulting inductance of $L = 11\,\mu H$. Closing the inductor to a load resistor $R_L = 0.5\Omega$, the detector system becomes an auto-integrator for pulse times $\ll 10\mu s$[9]. The Rogowski coil was calibrated using the same discharge circuit working at 20 kV.

The diagnostic system was characterized by an attenuation factor, that is generally time - dependent. To record the peak value of the field it is necessary that the system exhibits a constant attenuation factor (times shorter than 2 μs). To ensure a better measure of the current in the calibration procedure, an additional power resistor of 4.5 Ω was inserted, Fig. 1a. By theoretical considerations, without the power resistor, the circuit impedance, defined as $\sqrt{L/C}$, becomes 4.9 Ω and by this value we can expect to reach peaks of current of the order kA.

Fig. 1: Sketch of the high voltage pulser. a) configuration to calibrate the Rogowski coil; b) to irradiate the samples



Recording the output signal by the voltage probe (PPE20kV Le Croy) and the output signal form by the Rogowski coil, we determinate the attenuation factor of the Rogowski coil at the peak (at about 1 μs) of 250 A/V, can be seen by Fig. 2.

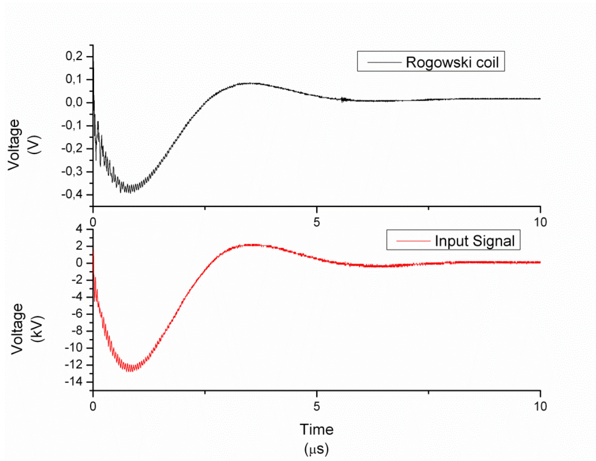


Fig. 2: Calibration of Rogowski coil by means of a charging voltage of 20 kV. The input signal was recorded by the voltage probe.

By the Ampère law we can calculate theoretically the magnetic field by:

$$B = \mu_o k \frac{N}{l} I$$

where k is a correcting factor depending on the system geometry, μ_0 is the magnetic permeability in vacuum, N is the number of rings and l is the length of the solenoid. Then, in order to get fields of the order of Tesla, high currents in the range of kA are necessary. By our pulser the maximum current we can obtain is the one with maximum charging voltage applied to the capacitor of 50 kV. Under treated this condition the maximum current is 9 kA and the magnetic field of 0.85 T. In fact, to characterize distribution of the magnetic field inside the solenoid, we fed the solenoid with a current of 10 A and detected the field by a Hall probe (GM07). The linear dependence of the field on the current allows to extrapolate the values of the magnetic field in the high – current regime from the ones obtained with low – intensity currents. Fig. 4 shows magnetic field versus longitudinal direction of the solenoid.

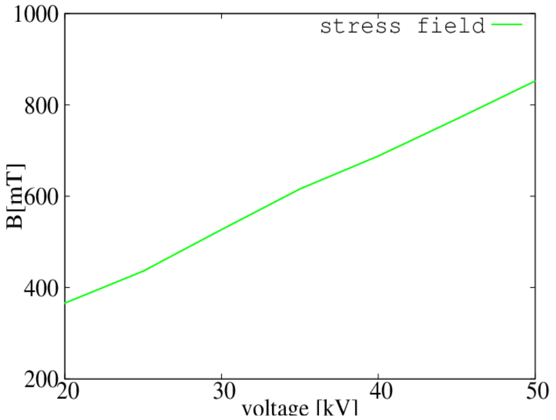


Fig. 3: Map of the maximum magnetic field inside the solenoid versus the external applied voltage.

Typical waveform of the field obtained with 23 kV, 4 kA is shown in Fig. 5. Its maximum value is 400 mT.

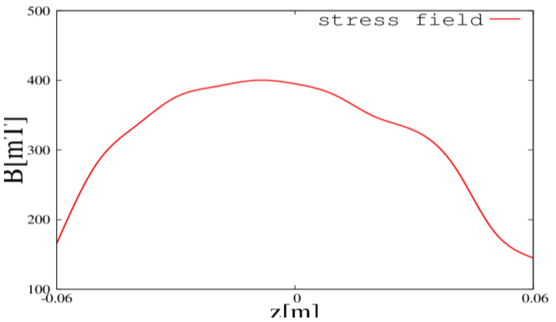


Fig. 4: magnetic field versus longitudinal direction used for the biological stress.

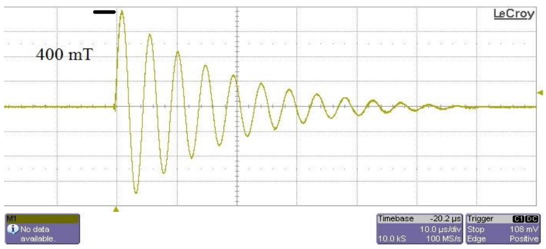


Fig. 5: Waveform of magnetic field versus the time.

As the theory predicts, the output waveform signal is a damped sinusoid with frequency of 210 kHz with a main pulse lasting 2 μs. The time range taken under consideration owing to the significant field is about 30 μs. this value has been calculated by fitting the waveform of the voltage signal recorded with HV probe. Fixing the capacitance value 150 μF the total resistor value was of 5 Ω. By this result, we can estimate the internal resistance of the circuit, due to spark gap, electric contacts and copper resistivity, of about 0.4 Ω. Utilising the Eq.1 the damping time of the circuit is 15.2 μs.

Results

Preliminary tests were performed with a high magnetic field 400 mT to Drosophila adult males. The flies were left under magnetic field up to a sub-lethality condition that were achieved after 2.5 h. The applied magnetic field has got a repetition rate of 1 Hz [10]. Treated testes spermatocytes did not exhibit the presence of any crystalline aggregates which should denote deregulation of repetitive sequences. Instead, the tests of flies subjected to magnetic field do not exhibit the presence of the Stellate-made crystalline aggregates. Since any time that the deregulation of the Stellate sequences occurs, the activation of the (transposable elements (TEs) also takes place, we can hypothesize that the magnetic field treatment does not produce effects on the deregulation of repetitive sequences in the germ line of Drosophila and for this reason we did not analyze the expression of the TEs.

After this observation, our attention moves to look at the chromatin state of the chromosomes in individuals subjected to stress, because it has been previously found that static magnetic fields can affect Escherichia coli and human cells, resulting in changes of the chromatin conformation.

In order to analyze the state of the chromatin condensation at the polytene chromosomes of the flies subjected to the magnetic field, a tube containing third stage larvae of Drosophila has been subjected to the same conditions of magnetic stress of adult flies, described above.

We observed that specific regions of the polytene chromosomes showed specific regions of decondensation (also called "puffs"). These decondensed regions were firstly identified after the "heat shock" and actually represent regions of transcriptionally active chromatin coding for the Heat Shock proteins.

These data indicate that the applied field produces changes in the structure of the chromatin.

We further analyzed the state of chromatin examining the distribution of a specific protein, HP1, on the chromosomes of stressed individuals. Heterochromatin Protein 1 (HP1) is a conserved protein involved in heterochromatin formation and gene silencing in different species including humans.

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