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Investigation of Microcoils for High Magnetic Field Generation

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Introduction

Pulsed magnetic field generation technologies have become commonly used in many areas of fundamental and applied sciences and in general laboratory facilities include a high voltage power supply, a capacitor bank, high power switch, pulsed coil and apparatus for control and experimental data registration [1].

A compact pulsed magnetic field generator consisting of 80 kJ capacitor bank, 4 kV high voltage power supply, 50 kA thyristor switch and reinforced pulsed coil was designed in Vilnius Magnetic Field Centre. Discharging the capacitor bank through pulsed coil a sinusoid shape pulse of magnetic field up to 50 T and 1-10 ms in duration can be generated [2].

Recently electrical and magnetic properties of manganite thin films are investigated intensively due to their potential application in the development of spin-electronics devices and magnetic field sensors [3]. Investigating magnetotransport phenomenon in manganite thin films a relaxation of magnetoresistance was observed [4]. Therefore further measurements of transient characteristics of such structures in microsecond and sub-microsecond range should be done to clear time limits of sensors response to rapidly changing magnetic field.

Standard high voltage thiristor switches are capable to switch tens of kiloampers, but their application for microsecond and sub-microsecond pulse generation is strongly limited due to low current rise rate and relatively slow turn-on, turn-off switching characteristics. Presently a progress of solid-state switches design has changed a situation in general and conventionally used spark gaps, optically triggered air gap switches, thyratrons, ignitrons and other ignition devices can be replaced successfully with semiconductor switches in many high power applications [5].

High power IGBT and MOSFET transistors have good switching characteristics in microsecond and sub-microsecond range but single transistors cannot be used for high-pulsed power applications due to their relatively low operation voltage and switching current. Therefore transistors are connected in parallel and series and combined in compact low-inductance modules. Such modules can be applied in magnetic field generators with microcoils [6].

Subject description

It is important to evaluate technical possibility to generate short magnetic field pulses with microcoils driven by IGBT and MOSFET transistors and to specify the structure of prototype for further experimental investigations. Initial conditions can be as following: operation voltage 3 kV, current 1 kA, pulse rise time 50 ns, pulse duration 500 ns.

According to Biot-Savart's law as shown in Fig.1, a current *I* flowing in segment *dl* create a magnetic field with flux density *dB* at a point *r* as [7]

$$\mathbf{dB} = \frac{\mu_0}{4\pi} I \frac{1}{r^2} \mathbf{dl} \times \mathbf{r} . \qquad (1)$$

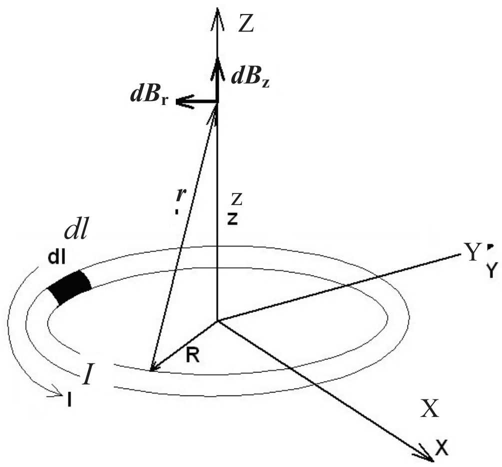


Fig. 1. Principle of magnetic field generation by single loop

In case of circular single loop with radius R axial magnetic flux density can be expressed as

$$B(z) = \frac{\mu_0}{4\pi} I \frac{2\pi R^2}{\left(R^2 + z^2\right)^{3/2}} , \qquad (2)$$

here $\mu_0 = 4\pi \cdot 10^{-7}$ is a magnetic constant and z is the distance on the axis.

Magnetic flux density in the centre (z = 0) of the loop is expressed as

$$B(0) = \frac{\mu_0 I}{2R}. \quad (3)$$

In a case of calculation the magnetic flux density of uniformly wound microcoil of length L and N turns it is necessary to multiply the magnetic flux density of one turn by the density of turns N/L and integrate over the length.

The equation of magnetic flux density looks as follow

$$B(z) = \frac{\mu_0 IN}{2L}\left(\frac{z+L/2}{\sqrt{R^2+(z+L/2)^2}} - \frac{z-L/2}{\sqrt{R^2+(z-L/2)^2}}\right). \quad (4)$$

And magnetic flux density at the centre of microcoil can be found as:

$$B(0) = \frac{\mu_0 IN}{2}\frac{1}{\sqrt{R^2+(L/2)^2}}. \quad (5)$$

These formulas are useful to express evaluation of maximal value of magnetic flux density. For example for microcoil with inner radius $R = 0,5$ mm, $N = 10$, $I = 1$ kA magnetic field up to 10 T can be expected.

In real case due to non-homogeneous distribution of current in the conductor and the influence of other parameters analytical evaluation of magnetic field becomes complicated and a mismatch of results takes place.

For configuration of microcoils different from elementary circular single loop a finite element method (FEM) successfully can be used [8].

Magnetic field evaluation involves magnetic field analysis in the space around the coil. Magnetic analysis, for the given current density the magnetic flux density **B** can be found from the Maxwell's equations [9]:

$$\nabla \times \mathbf{H} = \mathbf{J}, \quad (6)$$

$$\nabla \cdot \mathbf{B} = 0, \quad (7)$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \quad (8)$$

here **H** is magnetic field intensity vector, **B** – is magnetic flux density vector, **E** is electric field intensity vector, **J** is applied source current density vector, while ∇ is notation of the divergence operator of a vector.

Maxwell equations also can be governed by introducing magnetic vector potential **A** as:

$$\mathbf{B} = \nabla \times \mathbf{A}, \quad (9)$$

$$\mathbf{E} = -\frac{\partial \mathbf{A}}{\partial t}. \quad (10)$$

The finite element method analysis of axial magnetic field is based on the numerical model [10]

$$\left[C^{\mathrm{M}}\right]\dot{\mathbf{A}} + \left[K^{\mathrm{M}}(\mathbf{A})\right]\mathbf{A} = \mathbf{J}, \quad (11)$$

here $\left[K^{\mathrm{M}}\right]$ and $\left[C^{\mathrm{M}}\right]$ are coefficient matrices of Maxwell equations, $\dot{\mathbf{A}}$ is the first time derivative of magnetic vector potential. The model can be validated performing quantitative comparison of numerical results with experimental measurements and analytical solutions.

The magnetic problem is coupled with thermal analysis by the induced Joule heat vector $\mathbf{Q}^J(\mathbf{A})$. The solution can be performed in the coupled fashion considering all advantages of multi-physical approach. The heat flow acting over surface S is specified as [11]

$$\mathbf{n} \cdot [\mathbf{K}] \nabla T = q, \quad (12)$$

here $\boldsymbol{n}$ is normal vector, q is specified heat flow, which vanishes in case of thermally isolated surfaces, $[\mathbf{K}]$ is conductivity matrix which might be ortothropic or temperature dependent, $\hat{q}$ is heat generation rate per unit volume which is computed from induced Joule heat as

$$\mathbf{Q}^J = R\mathbf{J} \cdot \mathbf{J}. \quad (13)$$

Magneto thermal analysis is obligatory in microcoil design because huge current flowing in very limited area can overheat or even evaporate a microcoil. As shorter magnetic pulse is generated the closer coil heating is to adiabatic process and dissipation of heat becomes insignificant. Coil heating strongly influences the maximum value of generated magnetic field. To avoid the overheating a thermal capacity of a microcoil can be increased constructively or using pre-cooling of coil before every shot. Further results of simulation of operation temperature and magnetic field distribution are presented.

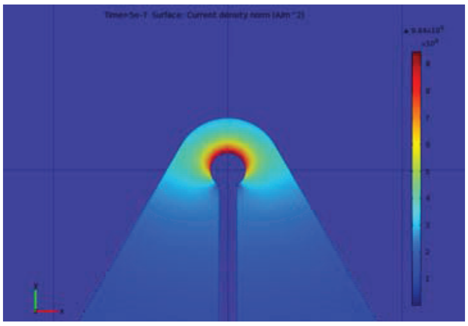
Simulation results

A prototype of microcoil with inner diameter of 1,0 mm can be made by photolithography planar technology using single or double surface metallized dialectic substrate. Simulation results of current density and temperature of single microcoil are shown in Fig. 2.

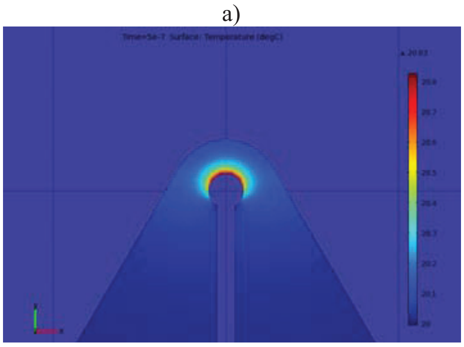
The maximal value of magnetic flux density in the centre of microcoil is 0,75 T. If a stronger field is necessary an inner diameter of a coil should be decreased or current increased. But in any case a great non-homogeneity of magnetic field takes places. Due to Joule heating the temperature is increased 20 degrees only and therefore additional pre-cooling or an increase of cross-section of a microcoil conductor is not necessary.

A dual or Helmholtz's construction of microcoils can be used. The view of dual microcoil construction is shown in Fig. 4.

Driving a microcoil with separate switches a double effect as an increase of a maximal value and homogeneity of a magnetic field can be achieved. Such construction can be made from two surfaces metallized dielectric polyamide glass fibre reinforced plate.



a)



b)

Fig. 2. Current density (a) and temperature (b) of planar single microcoil

Results of simulation of axial field distribution B_z is shown in Fig. 3.

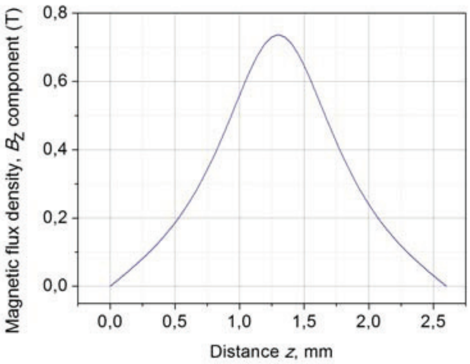


Fig. 3. Distribution of axial magnetic field of a microcoil

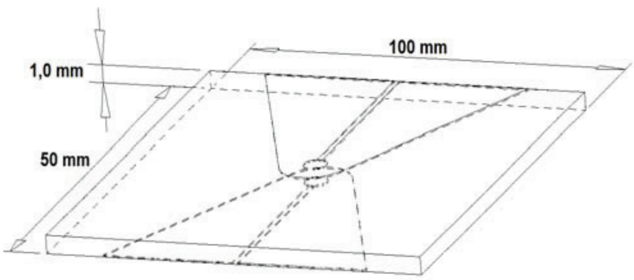


Fig. 4. Dual or Helmholtz's microcoil construction

Resulted magnetic field in centre z_h of dual microcoil is determined as superposition of parts as [12]

$$B_{SUM}(z) = B_1(z) + B_2(z) \tag{14}$$

and a non-homogeneity of magnetic field is calculated as

$$h(z_h) = \left(B_{SUM\max}(z_h) - B_{SUM\,av}(z_h)\right) / B_{SUM\,av}(z_h), \tag{15}$$

here $B_1(z), B_2(z)$ magnetic flux density generated by first and second microcoil, $B_{SUM\max}(z_h)$ is maximum of superposition of magnetic fields, $B_{SUM\,av}(z_h)$ is the average of magnetic field in z_h area. Simulation results of magnetic field distribution of dual microcoil driven by two separate 1 kA MOSFET switches are shown in Fig. 5.

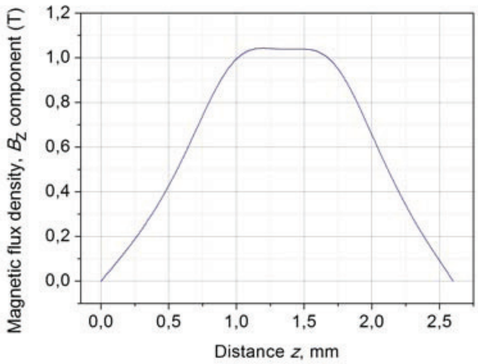


Fig. 5. Axial magnetic field distribution of dual planar microcoil

Obtained results show the advantage of such construction. It becomes attractive enough in experimental facilities when homogeneity is necessary. Calculated non-homogeneity in central is limited by 0,5 mm area and does not exceed 1-2 %, what is acceptable in various solid state physics and material science investigations.

With a goal to get microsecond range pulsed magnetic fields a multiturn microcoil construction can be evaluated also. A schematic view of such construction and simplified principle of operation of pulsed generator are shown in Fig. 6.

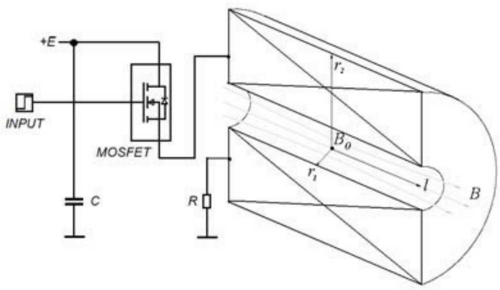


Fig. 6. Schematic view of multiturns construction of microcoil

A pulsed generator consists of high voltage supply, low self-inductance capacitor bank, solid-state 1 kA switch and pulsed microcoil. For first estimation of maximal value of magnetic flux density in the centre of microcoil a following equation can be used [13]

$$B = \mu_0 \frac{NI}{r_1} \frac{1}{2(\alpha - 1)} \ln \frac{\alpha + \sqrt{\alpha^2 + \beta^2}}{1 + \sqrt{1 + \beta^2}}, \tag{16}$$

here $\alpha = {r_2}/{r_1}$, $\beta = {l}/{2r_1}$ are coil geometrical parameters, N is number of turns, μ_0 is magnetic constant.

For computer simulation a prototype of a microcoil with an inner radius $r_1 = 0{,}5$ mm, outer radius $r_2 = 1{,}0$ mm, length l = 10 mm and N = 100 turns was used. Axial magnetic field distribution of multiturn microcoil was found and is shown in Fig. 7.

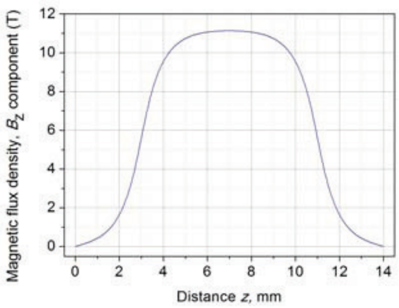


Fig. 7. Axial magnetic field distribution in multiturn microcoil

A non-homogeneity in order of 1-2 % is achieved in 2 mm central area what is acceptable in most pulsed magnetic field applications.

Conclusions

Available prototypes of microcoils for pulsed magnetic field generation have been analysed using finite element method and analytical formulas for current, temperature, magnetic field distribution evaluation. Single turn coil with inner diameter of 1 mm made by photolithography planar technology and driven by 1 kA switch can generate pulsed magnetic field up to 1 T. A dual or Hermholtz's construction of microcoils driving with separate switches allow to increase twice maximal value and homogeneity of a magnetic field. Multiturn microcoil construction can be used in microsecond range if there are no special requirements for rise time and shape of magnetic pulse.

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Microcoils design for high pulsed magnetic field generation is described. A possibility to generate micro and sub–microsecond magnetic field pulses in 1 – 10 T range is analyzed. Pulsed facilities consisting of high voltage power supply, low self–inductance capacitor bank and fast high voltage solid state switches connected in parallel and in series are able to generate high power 1 kA, 0,5–1,0 μs pulses. Three different prototypes of single, dual and multiturn microcoils are investigated. Analytical and finite element methods are used for modelling of transient electromagnetic and thermodynamic processes. Computer simulation results of current density, thermal overloads and calculations of axial magnetic flux density are presented and recommendations for further experiments are offered. Ill. 7, bibl. 13 (in English; abstracts in English and Lithuanian).

A. Grainys, J. Novickij. Stipriems impulsiniams magnetiniams laukams generuoti skirtų mikroričių tyrimas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2011. – Nr. 3(109). – P. 63–66.

Išanalizuota galimybė generuoti mikro– ir submikrosekundinės trukmės 1–10 T magnetinius impulsus. Impulsinio magnetinio lauko generatorius, susidedantis iš aukštosios įtampos maitinimo šaltinio, mažą parazitinį induktyvumą turinčių kondensatorių ir greitų didelės galios MOSFET raktų, sujungtų lygiagrečiai bei nuosekliai, gali sukurti didelės galios 0,5–1,0 μs 1 kA impulsus. Pateikta mikroritės skirtingų konstrukcijų, skirtų stipriesiems impulsiniams magnetiniams laukams generuoti, analizė bei trijų ričių – vienos apvijos ritės, dviejų apvijų ritės (Helmholtz ritė) ir daugiasluoksnės ritės – skaitinių tyrimų rezultatai. Pereinamiesiems elektromagnetiniams ir termodinaminiams vyksmams modeliuoti taikomi analitinis ir baigtinių elementų metodai. Kompiuterinio modeliavimo būdu gauti srovės, šilumos ir magnetinio lauko pasiskirstymo skaičiavimo rezultatai. Il. 7, bibl. 13 (anglų kalba; santraukos anglų ir lietuvių k.).