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The Investigation of Magnetic Field Distribution of Dual Coil Pulsed Magnet

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Introduction

Non-destructive pulsed magnetic systems have become a common tool for scientific investigations and pulsed magnetic field applications in engineering science, physics, biology and other areas are rapidly expanded [1]. As higher magnetic field can be generated as greater possibilities for investigators take place. But the increase of magnetic field value is accompanied with a quadratic increase in thermal and mechanical loads and the maximum of available magnetic field is limited by thermal and mechanical strength of available materials [2]. There are many techniques to generate pulsed magnetic field and the discharge of capacitor bank by thyristor switch via reinforced solenoid is most convenient. By this way high magnetic field in 40-60 T range has become applicable in many scientific laboratories and recently non-destructive facilities up to 100 T are under development [3].

In Vilnius Magnetic Field Centre pulsed magnets up to 50 T were constructed. A pulsed magnetic field generator consisting of 50 kJ capacitor bank, thyristor switch and reinforced solenoid with inner diameter of 12 mm was enough to arrange various scientific experiments for investigations of condensed matter properties. Investigations of magnetoresistance of manganite thin films in pulsed magnetic fields were some of them [4].

Last decade the interest for investigations of quantum dots, quantum wells, quantum wires and other small dimensional objects is increased very much and top level magnetic laboratories in Europe, US, Japan and other countries are under constant competition in this modern scientific area [5]. For such experiments laboratory facilities as pulsed magnets and cryogenic vessels should have a possibility to install parallel (Faraday configuration) and perpendicular (Voigt configuration) optical channels [6]. One of convenient ways is to split a pulsed coil into two semi or completely separate coils. Last one can be designed as a system of dual coils which will allow to use standard cryogenic vessels and spectroscopy methods for further experiments with minimal improvements. Magnetic field distribution of dual coil system can be found as a superposition of two separate magnetic field sources.

The structure of the experimental equipment

The structure of the prototype of developed pulsed magnetic field generator with closed cycle helium cryostat [7] and pulse registration units is shown in Fig. 1.

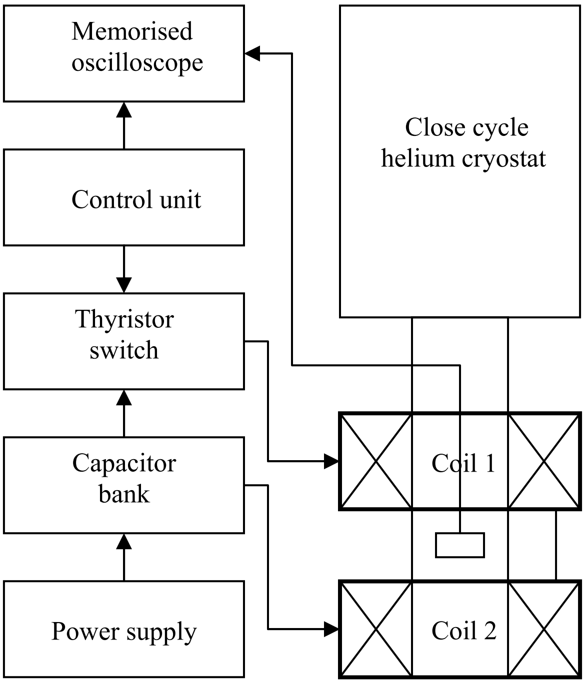

Fig. 1. The structure of the prototype of developed pulsed magnetic field generator with closed cycle helium cryostat and pulse registration units (optical components are not shown)

Pulsed magnetic generator consists of the control unit with optical channels, 4 kV high voltage power supply, 10,8 mF capacitor bank, 50 kA thyristor switch, double reinforced coil, sensor and memorized oscilloscope to control an amplitude and shape of generated magnetic field pulse. The capacitor bank depending on charging time is able to store 86,4 kJ electric energy. Discharging the capacitor bank through the inductive coils electric energy is transformed into magnetic energy and a sinus shaped magnetic field pulse can be generated.

The analysis of transient processes in dual coil magnet

Dual coil magnet consists of two identical separate coils positioned axially as Helmholtz coils to insure maximal homogeneity of magnetic field in central area. Last fact is very important because any distortion of magnetic field can dramatically change results of measurements. Magnetic field homogeneity of the system of two separate coils depends on the distance between coils and their own geometry. But this task is not such easy as looks by the first glance because the development of a pulsed magnets is a multidimensional task where thermodynamic, electromagnetic and electromechanical processes occurring during the pulse have to be analyzed in order to improve and pick up inductor‘s geometry, construction technology, materials with appropriate electrical, thermal and mechanical parameters. Only the complete analysis of major processes in pulsed coils during the pulse may lead to good results and improvements. The simplified structure of pulsed magnetic field generator consists of capacitor bank, switch and pulsed coils. Capacitor bank is charged up to U_0 voltage. Self inductance, resistance of capacitor bank, thyristor switch and connectors should not be taken into consideration because capacitor bank's capacitance C and self inductance and resistance L_1, R_1, L_2, R_2 of coils are dominant parameters. An equivalent circuit of wire wound coils is like an inductance and resistance connected in series. Surely when there are two nearly positioned coils a mutual inductance $M_{12}=k\sqrt{L_1L_2}$ also has to be taken into account. The value of coupling coefficient k depends on coil's geometry and the distance between of them. In our case inner diameter of coils with identical geometry is limited by outer diameter of cryostat vessel and it is equal 60 mm. For first estimation a gap between coils can be about 10-20 mm and $k=(0{,}15\div 0{,}20)$. The discharge of a capacitor bank through the dual coil magnet can be defined according to equation:

$$U_0=\left(R_1+L_1\frac{di(t)}{dt}\right)+\left(R_2+L_2\frac{di(t)}{dt}\right)+2M_{12}\frac{di(t)}{dt}+$$
$$+\frac{1}{C}\int i(t)dt=2\left(R_{1,2}+L_{1,2}\frac{di(t)}{dt}+kL_{1,2}\frac{di(t)}{dt}\right)+\frac{1}{C}\int i(t)dt.\ (1)$$

Using Laplace transformation for this equation we can obtain a transfer function in a form:

$$W(s)=\frac{I(s)}{U_0(s)}=\frac{\dfrac{1}{2(L(1+k)s+R)}}{1+\dfrac{1}{2((1+k)Ls+R)}\dfrac{1}{Cs}},\qquad (2)$$

where Laplace operator $U_0(s)$ is an input and circuit current $I(s)$ is an output; L, R – self inductance and resistance of one part of dual coil; k – coupling coefficient. Actually, obtained transfer function is similar with one already applied for transient processes modelling in pulsed solenoids [8]. This model in *Matlab*® *Simulink*® programming environment can be adapted for further analysis of transient processes in dual coil magnet too. It is necessary to specify initial parameters only. In our case operating temperature is close to room temperature. The operation cycle of a pulsed coil consist of rapid flow of high current during few milliseconds and next cooling during 10-30 minutes to avoid thermal overloads. Operation temperature is 290-300 K and is close to room temperature. Maximal available capacitor bank is 10,8 mF, voltage 4 kV. Main parameters of material used for coil winding is shown in Table 1.

Table 1. Winding's parameters

Parameter	Value
Material	CuNb
Dimensions	4.2x2.37 mm
Composition	82% Cu
σ,% IACS	63 (293K)
Winding Insulation	S2 glass fiber/*Kapton*®, 0.3 mm
Interlayer reinforcement	*Zylon*® + Epoxy, 0.23 mm

Insulations used for pulsed inductors loose their properties when kept in temperatures over T_{max}=500 K, and the yield strength of the mechanically weakest element CuNb wire is approximately σ_{VM}=850 MPa. If maximum stress in inductor does not exceed the yield strength of the weakest material, inductor will not fail mechanically. Assuming this, the criteria for inductor optimization is selected and figured in Table 2.

Table 2. Optimization criteria for pulsed inductor

Criteria	Value
B_z maximum	0 T < B_z < 100 T
Transient process duration	$t_{t.p.}$ < 10 ms
Maximum winding temperature	T_{max} <500 K
Maximum Von Misses stress	σ_{VM} < 800 MPa

Inputs for the optimization would be: number of winding in one layer n_1=var=2:20; number of layers n_2=var=2;4;6;8, inner diameter of coil a_1 = 30 mm, outer diameter of coil $a_2=\alpha a_1$, coil length $l=2\beta a_1$, coil geometric factors α, β. Outputs would be: maximal magnetic field density $B_z(\alpha,\beta)$, pulse duration $t_{t.p.}$ (α,β), maximum temperature $T_{max}(\alpha,\beta)$, mechanical stress $\sigma_{VM}(\alpha,\beta)$. The structure of model for the optimization is shown in Fig. 2.

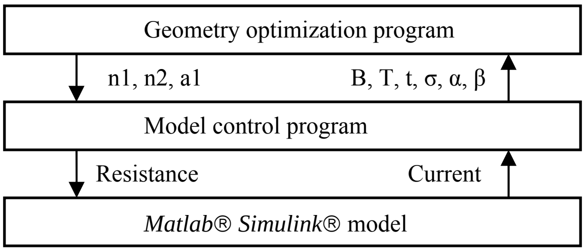

Fig. 2. Inductor optimization process structure

The result of coil optimization is the definition of coil “life-zone” where the maximum stress, induced by

Lourence force and maximal temperature do not exceed the yield strength and thermal overloads limits. Determined "life-zone" of pulsed coil fulfilled above mentioned conditions is shown in Fig. 3.

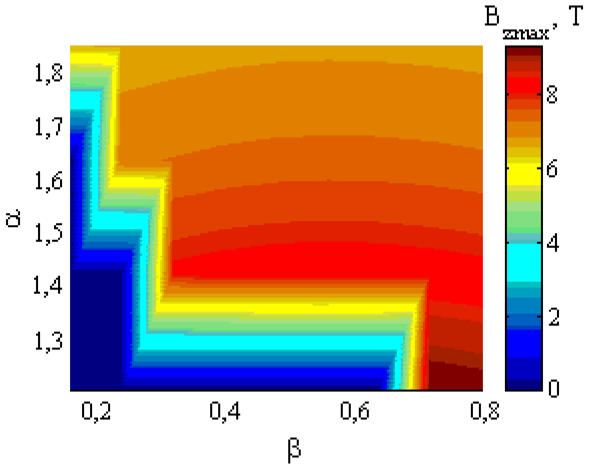

Fig. 3. Determined "life-zone" of pulsed coil

Coil geometry was chosen with following parameters: $(\alpha,\beta)=(1{,}64{,}0{,}48),(n_1,n_2)=(6{,}6)$. Such coil can generate maximal magnetic field up to 7,6 T at room conditions. Transient processes of pulsed current and temperature inside a coil are shown in Fig. 4.

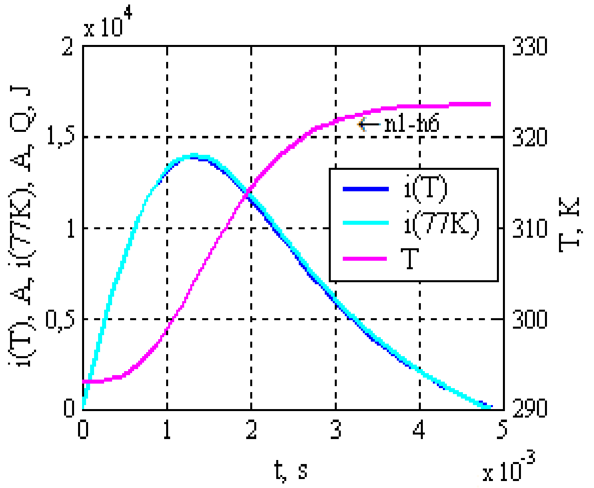

Fig. 4. Transient processes of pulsed current and temperature inside a coil

The maximal value of pulsed current is 13,4 kA and rise time 1,3 ms. Temperature inside a pulsed coil after first pulse has increased up to 323 K discarding 86 kJ capacitor bank.

Total mechanical stress was calculated by Von Misses stresses criteria and was about 60 MPa only, so that designed coil has enough reserve and can operate for a long time without disintegration.

The analysis of magnetic field distribution of dual coil

There are two ways to evaluate magnetic field distribution of dual coil. The first way is the modelling of general magnetic field distribution of two coils system. Another one is to calculate magnetic field of one separate coil with further superposition of two identical fields. We have used the last one due to its simplicity. For the beginning the analysis of magnetic field distribution of separate coil was done. Magnetic field in any point can be determined as a result of equivalent current loops. If a coil has n_1 windings in a layer and n_2 layers, the distribution of axial and radial magnetic fields can be calculated as [9]

$$B_z(r,z)=\sum_{i=1}^{n2\cdot cz}\sum_{j=1}^{n1\cdot cr}B_{z,ji}(r,z), \tag{3}$$

$$B_r(r,z)=\sum_{i=1}^{n2\cdot cz}\sum_{j=1}^{n1\cdot cr}B_{r,ji}(r,z), \tag{4}$$

where cz, cr – multiplication factors; $B_z(r,z), B_r(r,z)$ are axial and radial magnetic fields of every current loop given point can be found as:

$$B_z(r,z)=(\mu_0/2\pi)I_{\max}\frac{1}{\sqrt{(a+r)^2+z^2}}\left(\frac{a^2-r^2-z^2}{(a-z)^2+z^2}E(m)+K(m)\right), \tag{5}$$

$$B_r(r,z)=(\mu_0/2\pi)I_{\max}\frac{1}{\sqrt{(a+r)^2+z^2}}\left(\frac{a^2+r^2+z^2}{(a-z)^2+z^2}E(m)-K(m)\right), \tag{6}$$

where r, z – radius and height of any point where B is calculated (from the inductor centre point (0,0)); a – radius of a current loop; $E(m), K(m)$ – elliptic first and second order integrals, when $m=4ar/((a+r)^2+z^2)$.

Taking into account that the radial non-homogeneity of pulsed magnetic field is at least two times less than the axial one, the determination of the non-homogeneity of generated magnetic field inside the pulsed magnet can be reduced only to the estimation of axial non-homogeneity.

The distance between parts of dual coil can be determined from the minimum field distortion criteria in centre of dual coil. In most experiments non-homogeneity of magnetic field less than 0,01% is enough. The resulted field in centre z_h of dual coil is $B_{SUM}(z)=B_1(z)+B_2(z)$. Non-homogeneity of magnetic field was calculated as

$$H(z_h)=\left(B_{SUM\,\max}(z_h)-B_{SUM\,av}(z_h)\right)/B_{SUM\,av}(z_h), \tag{7}$$

where $B_1(z), B_2(z)$ – magnetic flux density generated by first and second coil; $B_{SUM\,\max}(z_h)$ – maximum of superposition of magnetic fields; $B_{SUM\,av}(z_h)$ – the average of magnetic field in z_h area. The cycle of simulation was stopped when the non-homogeneity of magnetic field has become less than $h=0{,}01\,\%$ in area of $z_h=10$ mm. It was found that the gap between dual coil parts should be $z_e=15{,}3$ mm. This is shown in Fig. 5.

The maximum value of magnetic flux density of dual coil is $B=(10{,}5\pm0{,}01\,\%)$ T in $z_h=10$ mm central area.

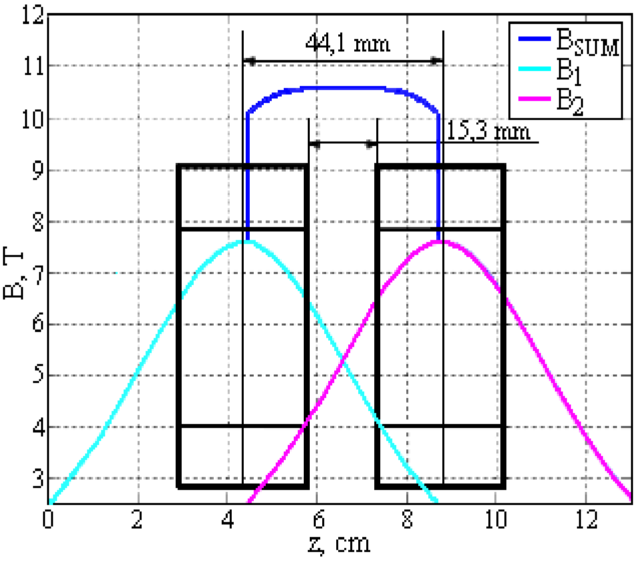

Fig. 5. Magneti field distribution in dual coil pulsed magnet

Conclusions

The magnetic flux in central area was evaluated as a result of superposition of magnetic fluxes of two separate coils. Coil geometry was found by simulating transient of electromagnetic, magneto mechanical ant thermodynamic processes using *Matlab*® *Simulink*® and *Matlab*® software. The result of coil optimization allowed to determine coil "life-zone" where the maximum stress, induced by Lourence force and maximal temperature do not exceed the yield strength and thermal overloads limits. The distance between parts of dual coil has been determined from the minimum field distortion criteria in centre of dual coil. The non-homogeneity of magnetic field does not exceed 0,01% in 10 mm area.

Acknowledgements

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The evaluation of magnetic field distribution of dual coil pulsed magnet has been performed. Coil geometry was found by the simulation of transient electromagnetic, magneto mechanical ant thermodynamic processes using *Matlab*® *Simulink*® and *Matlab*® software. The result of optimization has allowed to determine of coil "life-zone" where the maximum mechanical stress and temperature do not exceed the yield strength and thermal overloads limits. The distance between parts of dual coil has been determined from the minimum field distortion criteria in centre of dual coil. The non-homogeneity of magnetic field does not exceed 0,01% in 10 mm central area. Ill. 5, bibl. 9 (in English; summaries in English, Russian and Lithuanian).

С. Барткевичюс, Ю. Новицкий. Исследование распределения магнитного поля импульсного магнита из двух катушек // Электроника и электротехника. – Каунас: Технология, 2009. – № 4(92). – С. 23–26.

Представлены результаты исследования распределения магнитного поля в центральной области магнитной системы из двух импульсных катушек. Геометрия катушек найдена с учетом результатов анализа элекромагнитных, термодинамических и магнитомеханических процессов. Моделирование проведено с помощью *Matlab*® и *Simulink*® программных пакетов. Найдена область параметров, при которых суммарные механические напряжения и температура внутри катушек не превышают предельно допустимых. Расстояние между катушками найдено из условия максимально допустимой (0,01%) неоднородности поля. Ил. 5, библ. 9 (на английском языке; рефераты на английском, русском и литовском яз.).

S. Bartkevičius, J. Novickij. Impulsinio dviejų ričių magneto magnetinio lauko pasiskirstymo tyrimas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2009. – Nr. 4(92). – P. 23–26.

Pateikti impulsinio dviejų ričių magneto magnetinio lauko pasiskirstymo skaičiavimo rezultatai. Ričių geometrija rasta analizuojant elektromagnetinius, termodinaminius, magnetomechaninius procesus. Procesų modeliavimas atliktas *Matlab*® *Simulink*® programų paketu. Rastos geometrinių parametrų sritys, arba ritės „gyvavimo zona“, kur mechaniniai įtempiai bei darbo temperatūra neviršija medžiagų tamprumo ir maksimaliai leistinų šiluminių perkrovų ribų. Kiekvienos ritės magnetinio lauko pasiskirstymas buvo skaičiuojamas atskirai, magnetinės sistemos suminis laukas nustatytas superpozicijos principu. Atstumas tarp dviejų ričių apskaičiuotas atsižvelgiant į magnetinio lauko maksimaliai leistiną (0,01 %) lauko nehomogeniškumą. Il. 5, bibl. 9 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).