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MAGNETIC MEASUREMENTS OF HTc SUPERCONDUCTORS

ABSTRACT *Selected methods for measuring magnetic quantities in HTc superconductors are discussed in the paper. Considered methods base on an analysis of the magnetic hysteresis curves, as well as rely on the investigations of the current-voltage characteristics in slowly varying magnetic field.*

Keywords: *measurements, magnetism, superconductivity*

2. INTRODUCTION

Superconducting materials, including especially high temperature oxide superconductors are characterised not only by vanishing resistivity but also by peculiar magnetic properties, allowing to treat them as very effective magnetic materials. They are ideally diamagnetic for low applied magnetic field but also very efficient permanent magnets in trapped magnetic flux state. Magnetic characteristics of superconductors are related to very peculiar form of penetration of a magnetic flux into these materials that is as a form of vortices – – flux line or pancake shape. Each of these vortices transports lowest known

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value of quantized magnetic flux equal to $\Phi_0 = 2{,}067 \cdot 10^{-15}$ Wb, which enables the usage of superconducting materials for construction of ultra sensitive devices detecting the smallest magnetic fields. Therefore elaborating new methods for magnetic measurement of superconductors is an important goal.

In present paper two methods for detecting magnetic quantities in HTc superconductors are discussed: first one is described by the magnetization hysteresis curves measurements and the second for which only first results were received until now, is based on the dynamic current-voltage characteristics measurements.

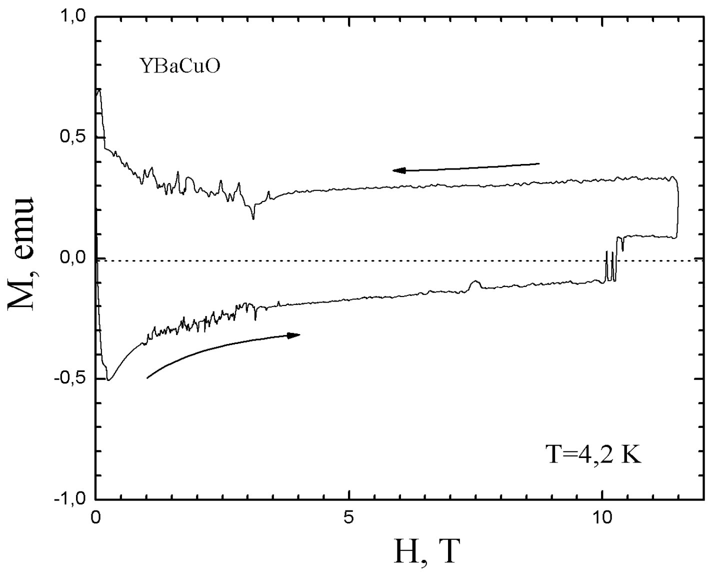

Fig. 1. Hysteresis loop of the magnetization curve in high magnetic field, for sintered HTc superconductor $YBa_2Cu_3O_{7-x}$ as a function of applied magnetic induction, with shown small flux jumps instabilities. Arrows indicate the direction of variation of applied magnetic field
Measurement performed by dr D. Gajda from MLSPMiNT.

2. EXPERIMENTAL RESULTS

An example of the magnetic hysteresis curve measured by the author on a synthetized sample $YBa_2Cu_3O_{7-x}$ HTc superconductor is shown in Figure 1. Ceramic sample was prepared by the method of melting powdered oxides of all components in resistive furnace, in air atmosphere and finally slowly cooling and annealing for few days. Irreversibility of hysteresis loop is observed here as well as numerous instabilities of magnetic induction distribution, which in uncontrolled way can lead to rapid transition of superconductor into normal state. These partial flux jumps in superconductors indicate therefore some analogy to Barkhausen noises appearing in magnetic materials. Magnetization measurements allow to determine most of the magnetic quantities of HTc superconducting materials, including magnetic critical fields but also critical currents, magnitude of trapped magnetic induction, magnetic hysteresis losses and other parameters. These parameters are measured in an indirect way, so appropriate pinning force model [1-3] should be then applied for a proper evaluation of the above quantities from experimental data. In order to receive these results precise and simple method for magnetization measurements of superconductors should be applied. A widely applied experimental method for magnetization curves measurements lies in using vibrating sample magnetometer. According to the IEC EN 61788-13 standard, in this method a sample is vibrating in a slowly varying longitudinal magnetic field generated by a superconducting electromagnet, as it shows Figure 2. The signal induced in the pick-up coils directly proportional to the magnetic moment of the superconductor is passed onto a power amplifier. It is registered in a computer unit for each value of applied magnetic field. The signal is then elaborated in a computer in appropriate way that gives required magnetic quantity, such as run versus magnetic field of the magnetic hysteresis curve, magnetic hysteresis losses or trapped flux. According to requirements of the above mentioned standard an accuracy of the measurements should be better than 99,5%, for acceptable non-homogeneity of the magnetic field of the range 0,1%. Proper calibration of this device is assured by using nickel balls of the diameter 2,3 mm, prepared especially at NIST (USA). For low frequencies of vibration of the range 100 Hz, measured signal should be insensitive to the frequency variation.

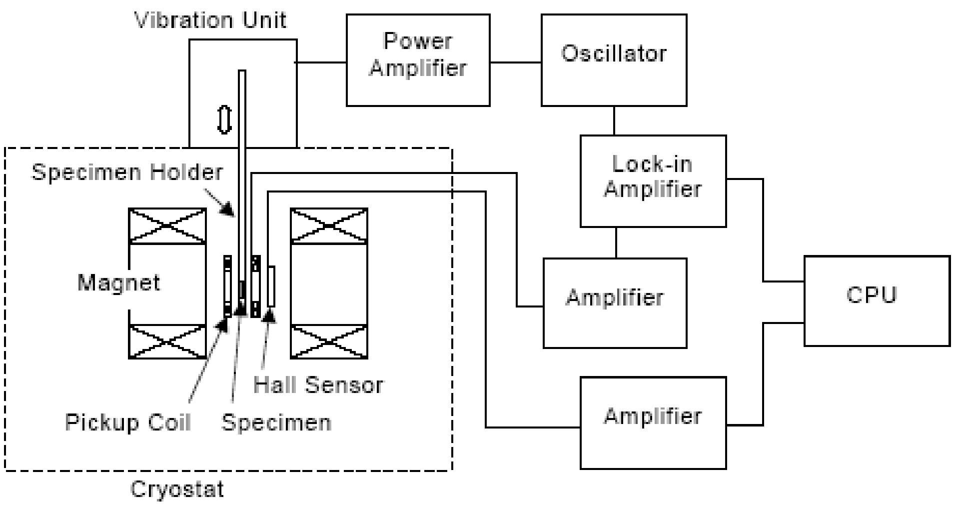

Fig. 2. Scheme of a typical experimental setup for measuring the magnetic hysteresis curves of superconductors using VSM (Vibrating Sample Magnetometer) method

Area of the hysteresis loop of the magnetization curve shown in Figure 1 determines the losses generated in a bulk superconductor during the cycle of the magnetic field. Irreversibility of this magnetization describes the critical current density of the superconductor j_c, according to the relation joining the hysteretic magnetization of the superconducting pellet of the diameter D with its critical current density: $M = j_c \cdot D$. It follows from the Bean's critical state model [1]. Magnetization M is an important magnetic quantity allowing to determine also the levitation force F between two magnetic materials characterized by the magnetization values M_1 and M_2 respectively, which is an essential parameter of the superconducting bearings: $F = M_1 M_2 /(2\mu_0)$, where μ_0 is magnetic permeability.

According to these considerations it is also clear that superconducting macromolecules, which can reach the dimension even up to 10 cm are the most attractive to be used in the superconducting bearings and generally levitating devices. The diamagnetic features of the superconductors, observed especially in a low magnetic field, are useful for construction of the magnetic shields, allowing to homogenize the magnetic induction distribution of the superconducting electro-magnets. An example of measurements of a magnetic induction profile, inside the superconducting coil with the superconducting HTc shield, is shown in Figure 3. The subsequent curves concern the cases of increasing magnetic field and indicate the usefulness of this method. The observed small steps in magnetic induction profile are especially interesting, they are well seen for low applied magnetic field, which reflects the structure of this superconducting shield, wound from the single layer of HTc superconducting tape of the first generation in the solenoid form. The length of the tape L, of the width b and thickness a, necessary for construction of HTc superconducting shield of the inner radius R, thickness $T = \dfrac{\Delta Bab}{\mu_0 I_C}$ and length C screening magnetic induction ΔB, is connected with critical current I_C of this tape according to the relation:

$$L = \frac{2\pi Cb\Delta B}{\mu_0 I_C}\left(R + \frac{a}{2}\left(\frac{b\Delta B}{\mu_0 I_C} - 1\right)\right) \quad (1)$$

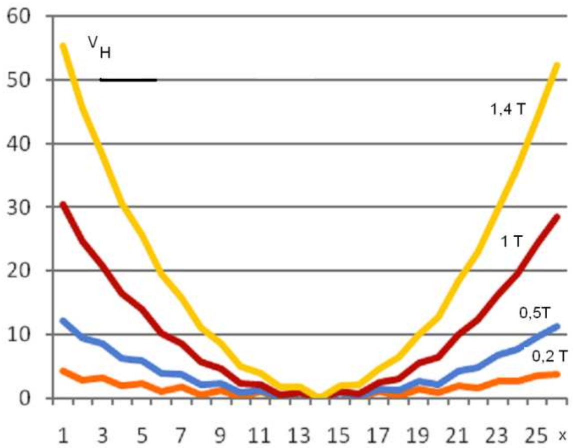

Fig. 3. Profiles of the magnetic induction distribution, described by Hall sensor signal, along an axis of superconducting coil with HTc shield, for various maximal value B_m, given at each curve. X is number of the measured point along an axis of the coil, V_H is Hall probe signal, while all curves are pinned at their maximal values

3. MODELING OF DYNAMIC CURRENT-VOLTAGE CHARACTERISTICS OF HTc SUPERCONDUCTORS IN VARYING MAGNETIC FIELD

In the previous clause the measurements of magnetic hysteresis were described. They allow to determine the essential electro-magnetic quantities characterizing the HTc superconductors, as for instance critical current in inductive way. The critical current is usually also determined directly in resisitive way from current-voltage characteristics: I-V curves. We observed that for slowly varying magnetic induction, the dynamic current-voltage characteristics lead to existence of the dynamical normal and inverse anomalies [4], shown in Figure 4. These anomalies should be useful as a new tool for detecting magnetic quantities in superconductors – especially describing the magnetic flux penetration and therefore concerning the stability behavior of magnetic induction in HTc superconducting materials.

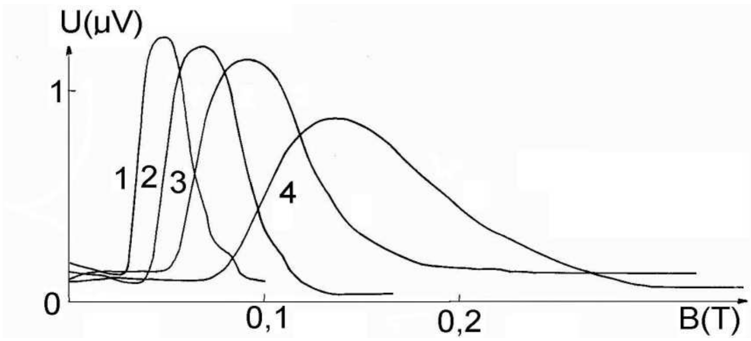

Fig. 4. Measured dynamical anomalies of the I-V curves on YBaCuO superconductor for various values of the linearly sweeping magnetic field: 1) 1 mT/s; 2) 5 mT/s; 3) 10 mT/s; 4) 15 mT/s

A new approach to the interpretation of these anomalies is given in this clause. It is based on an analysis of the magnetic diffusion equation for the case of HTc superconducting plate inserted into linearly varying magnetic field:

$$\frac{\partial B}{\partial t} = \frac{1}{D}\frac{\partial^2 B}{\partial x^2} \qquad (2)$$

This equation, in the present case describes diffusion of the magnetic induction B in the form of vortices into the superconductor with the diffusion coefficient D, which is characteristic feature of superconductors [5]. In order to describe the experimental case of an applied linearly varying magnetic induction, parallel to the surface of superconductor, solution of the diffusion Eq. 2 has been chosen in the following form:

$$B(x,t) = \frac{D\dot{B}}{2}x^2 + bx + B(t) \tag{3}$$

Symbol $\dot{B} = \frac{\partial B}{\partial t}$ denotes time derivative of induction on the surface, which according to the experimental situation is constant. $B(t)$ is time dependence of an applied magnetic induction, while parameter x is the depth inside the sample. The choice of the form of the parameter b describes the physical character of the given process. Present case concerns super-conductors, for which critical current should decrease with magnetic field. Critical current, according to Maxwell's equation, is described now for plate geometry, by the derivative $\partial B/\partial x = D\dot{B}x + b$. In order to fulfill the condition of decreasing critical current with magnetic field at each point of superconductor, parameter b has been selected in the following form: $b = -\alpha D\dot{B}/B$. It leads then from physical reasons to the necessary modification of the solution of the basic diffusion equation, dependent on the magnitude of the parameter α. Magnetic induction increasing with time penetrates the superconducting sample and reaches its half-thickness x_m at time t_1 given by the relation:

$$t_1 = \frac{-(0,5D\dot{B}x_m^2 + \Delta B) + \sqrt{(\frac{D\dot{B}x_m^2}{2} + \Delta B)^2 + 4D\dot{B}\alpha x_m}}{2\dot{B}} \tag{4}$$

Relation (4) takes into account the shift of magnetic induction on the sample surface connected with the flow of transport current. Electric field E is then generated in the centre of a sample, its sign depends on the respective orientation of magnetic field and transport current density, while module is:

$$E = \frac{1}{(\dot{B}t)^2 t^2}\left[\dot{B}^3 x_m t^4 + \frac{\dot{B}^2 D\alpha x_m^2 t^2}{2} + \dot{B}\alpha\Delta B t^2 - D\alpha^3 + (\dot{B}^2 t^3 + D\alpha^2)\sqrt{\frac{D\alpha^2 - 2\dot{B}^2 t^3 - 2\dot{B}\Delta B t^2}{D}}\right] \tag{5}$$

ΔB appearing in Eqs. 4-5 is just mentioned magnetic induction shift on surface of superconductor connected with transport current flow, while $-\Delta B$ respectively, is the value of the shift of induction on the opposite cover of the sample, x_m is sample half-thickness.

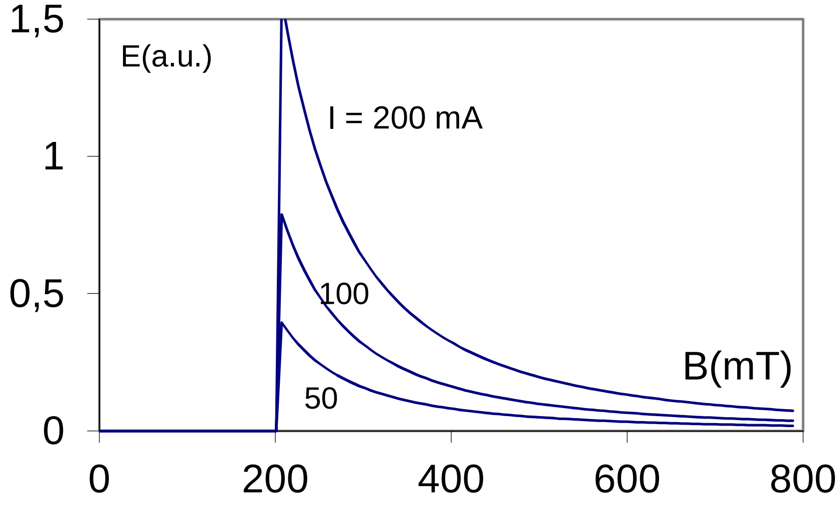

Fig. 5. Enhancement of the calculated maximum of the dynamical anomalies with transport current

Eq. 5 describes non-saturated case, in which magnetic induction penetrates from one side of superconductor up to the depth $x_1 < x_c$. x_1 is given here by the relation:

$$x_1 = \frac{\alpha}{B} - \frac{1}{\dot{B}}\sqrt{(\frac{\alpha}{t})^2 - \frac{2\dot{B}}{D}(B + \Delta B)} \tag{6}$$

while $x_c(t)$ is expressed by the relation:

$$x_c = x_m + \frac{\Delta B}{D\left(\frac{\alpha}{t} - \dot{B}x_m\right)} \tag{7}$$

$x_c(t)$ is the function of time and describes the depth inside the sample onto which join themselves together the magnetic fluxes coming from both ends of sample. This case is called the saturated one. The connection of two branches of magnetic induction leads to the variation of the penetration of magnetic flux through the middle of the sample, where voltage taps are put and therefore variation of the generated electric field equals:

$$E = \frac{\alpha \Delta B}{2D^2 x_m \left(\dot{B} x_m t - \alpha \right)^4} \left\langle \begin{array}{l} \dot{B}^3 D^2 x_m^5 t^2 - \dot{B}^2 D x_m^2 t (2D\alpha x_m^2 + t(2\alpha + \Delta B x_m)) + \\ \dot{B} x_m \left[D^2 \alpha^2 x_m^2 + 2D\alpha t (2\alpha + \Delta B x_m) - (\Delta B t)^2 \right] - D\alpha^2 (2\alpha + \Delta B x_m) \end{array} \right\rangle + \frac{\Delta B}{D x_m} \tag{8}$$

Time t_2 in which appears the transition from unsaturated to saturated case is given by the condition:

$$D\left(x_m + \frac{\Delta B t_2}{D(\alpha - x_m \dot{B} t_2)}\right) \left\langle \dot{B}\left(x_m + \frac{\Delta B t_2}{D(\alpha - x_m \dot{B} t_2)}\right) - \frac{2\alpha}{t_2} \right\rangle + 2\left(\dot{B} t_2 + \Delta B \right) = 0 \tag{9}$$

In Figure 5 is shown the result of the calculations of the influence of the transport current amplitude on the dynamical anomalies of the current voltage characteristics, which indicates an increase of magnitude of anomalies with transport current.

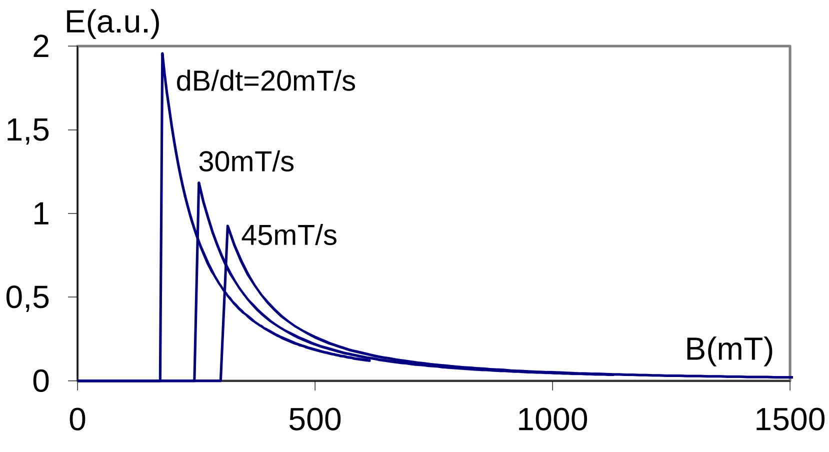

Fig. 6. Theoretically predicted influence of the magnetic field sweep rate on the dynamical anomalies of the current-voltage characteristics for HTc superconductors

This dynamical effect has really been observed experimentally. The Figure 6 shows the influence, calculated according to this model, of the change of magnetic field sweep rate on the dynamical current-voltage characteristics anomalies. For larger external magnetic field time variation the anomalies are shifted into higher magnetic field, which result is in accordance with experimental data shown in Figure 4.

A parallel theoretical analysis of this phenomenon has been performed basing on critical state model, developed previously and presented in [3]. The critical current magnetic field dependence is described then as:

$$\mu_0 j_c = \pm \frac{\alpha}{\left(B(x) + B^0\right)^{\gamma}} \tag{10}$$

where μ_0 is magnetic permeability α and B^0 material parameters, while $\gamma = 1$ gives Kim's critical state model and $\gamma = 0$ describes Bean's approach.

As in previous case the generated electric field has been calculated separately for non-saturated and saturated cases. In non-saturated case, it is when both branches of the magnetic induction do not meet together and superconductor is not penetrated fully by magnetic flux, the generated electric field is equal:

$$E = \frac{\dot{B}}{\alpha}\left(B + \Delta B + B^0\right)^{\gamma} \cdot \left\langle \left[\left(B + \Delta B + B^0\right)^{1+\gamma} - \alpha(1+\gamma)x_1\right]^{\frac{1}{1+\gamma}} - B^0 \right\rangle \tag{11}$$

For total penetration of magnetic induction into the HTc superconductor, it is in saturated case, the electric field is:

$$E = \frac{\dot{B}}{\alpha}\left\langle \left(B + \Delta B + B^0\right)^{\gamma} \cdot \left(\left[\left(B + \Delta B + B^0\right)^{1+\gamma} - \alpha(1+\gamma)x_1\right]^{\frac{1}{1+\gamma}} - B_{av}(x_m)\right) + B^{\otimes}\left(B_{av}(x_m) - B^0\right)\right\rangle \tag{12}$$

In Eq. 12 have been introduced magnetic inductions defined according to:

$$B^{\otimes} = \frac{\left(B + \Delta B + B^0\right)^{\gamma} - \left(B - \Delta B + B^0\right)^{\gamma}}{2} \tag{13}$$

$$B_{av}(x_m) = \left[\frac{\left(B + \Delta B + B^0\right)^{1+\gamma} + \left(B - \Delta B + B^0\right)^{1+\gamma}}{2} - \alpha(1+\gamma)x_m\right]^{\frac{1}{1+\gamma}} \tag{14}$$

Figure 7 shows the results of calculations of the anomalies of the dynamical current-voltage characteristics according to relations 10-14. This model explicitly takes into account the magnetic parameters describing HTc superconductor. The calculated dependence of the dynamic anomalies of the current-voltage characteristics on the electromagnetic parameters, such as transport current amplitude and material magnetic parameter B^0, describing magnetic field dependence of the critical current allows then to treat this effect as new tool for detecting magnetic quantities of the superconductors. While the previously described magnetization measurements, allowed to determine static magnetic parameters of superconductors, this new method is sensitive as results from Figure 4 to dynamics of the magnetic flux penetration into these materials. Therefore this method should bring new information on velocity of flux penetration and generally stability behavior, which is an important parameter of the superconducting devices.

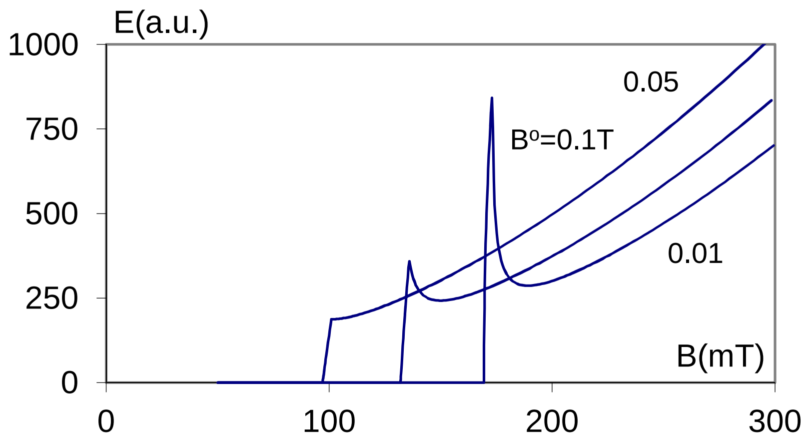

Fig. 7. Influence of material, magnetic parameter B^0 appearing in Eq. 10 on dynamic I-V curves anomalies in slowly varying magnetic field

Acknowledgment

Authors are grateful to Prof. N.N. Agapov for hospitality and to Dr V.I. Datskov and Dr D. Gajda for experimental collaboration.

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Manuscript submitted 20.03.2012

POMIARY MAGNETYCZNE NADPRZEWODNIKÓW WYSOKOTEMPERATUROWYCH

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STRESZCZENIE *W artykule przedyskutowano wybrane metody badania wielkości magnetycznych w nadprzewodnikach wysokotemperaturowych. Rozważono metody oparte na analizie krzywych histerezy magnetycznej, jak rownież polegające na badaniach charakterystyk prądowo-napięciowych nadprzewodników w wolnozmiennym polu magnetycznym.*

Słowa kluczowe: *pomiary, magnetyzm, nadprzewodnictwo*