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A New Direct Magnetic Method for Determining J_C in Bulk Superconductors from Magnetic Field Diffusion Measurements

Bruno Douine, Frédéric Sirois, *Senior member IEEE*, Jean Leveque, Kevin Berger, Charles-Henri Bonnard, The-Cuong Hoang and Smail Mezani

Abstract— The knowing the critical current density J_C is important to calculate AC losses in superconducting applications. Usually J_C can be obtained from magnetization measurements or electric measurements based on global quantities as the magnetic flux or the voltage. In this paper a quick and direct magnetic method for determining J_C is proposed. It is based on direct measurements of local magnetic field in the gap between two bulk HTS pellets. Field penetration measurements were carried out on HTS pellets at 77 K by applying increasing axial magnetic fields with a quasi constant sweep rate. This determination of J_C is theoretically based on Bean model. J_C is deduced from the complete penetration magnetic field B_p . B_p is deduced from the delay T_p between the applied magnetic field $B_a(t)$ and the magnetic field at the center between the two pellets $B_0(t)$. Numerical calculations allow deducing J_C more precisely from theoretical calculations and measurements. The numerical calculations are made with the power law $E=E_C(J/J_C)^n$. For the determination of J_C the influence of the gap due to Hall probe sensor and the applied magnetic field rise rate are taken into account. The influence of thermal is also studied.

Index Terms— Superconductor, magnetic field diffusion, critical current density

I. INTRODUCTION

The value of J_C can be derived from different experimental techniques as transport current, magnetization cycle [1], [2] or ac susceptibility [3]. The electrical transport method is not valid in the case of pellet because this method practically only works for wire. Magnetic methods are called indirect method because relation between measurement and J_C is not direct. Magnetization methods need complex and expensive devices as Physical Properties Measurement System or other set up [1], [2]. For AC susceptibility method the relation between measure and J_C is complicated because it needs calculation of demagnetizing factor, integration and so on [3], [4].

The main contribution of the present work is to propose a

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new direct magnetic J_C determination method. In this method HTS sample is submitted to an axial applied magnetic field $B_a(t)$ (Fig. 1). $B_a(t)$ is considered as linear function of times even if the shape of $B_a(t)$ does not matter with Bean model:

$$B_a(t) = V_b \cdot t \quad (1)$$

At the center of the pellet the magnetic field begins to increase with delay time T_p when B_a reaches the complete magnetic field B_p (Fig. 2). For short cylinders and with the Bean model [5], an explicit expression of the penetration magnetic field B_p can be calculated as the axial magnetic field created in the center of solenoid of null internal radius [6]:

$$B_p = \frac{\mu_0 J_C \cdot L}{4} \cdot \ln \left(\frac{\sqrt{R^2 + \left(\frac{L}{2}\right)^2} + R}{\sqrt{R^2 + \left(\frac{L}{2}\right)^2} - R} \right) \quad (2)$$

L is the length of the cylinder and R its radius.

(2) is equivalent of B_p formula given by different authors [2], [7], [8].

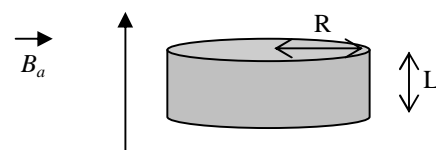


Fig. 1. A cylindrical superconducting sample with axis parallel to the applied magnetic field

The principle of this method is measuring B_p and deducing J_C . In this paper, firstly, experimental results are presented and discussed. Secondly, computational method is exposed. Thirdly numerical simulations with COMSOL Multiphysic 4.1 software allow studying the influence of Hall probe depth and rise rate.

II. EXPERIMENTAL SETUP AND RESULTS

Some authors already used Hall probes to determine magnetic field distribution in superconducting sample [9]-[13]. In our method the complete penetration magnetic field

is detected with an axial Hall probe placed between two HTS pellets (Fig. 3) at the center of pellet. At this point the magnetic field has only axial component so magnetic field is well measured with this Hall probe. These two pellets are theoretically considered as one pellet. So in a first time the influence of the Hall probe thickness e is neglected. Discussion about this hypothesis will be done in section IV.

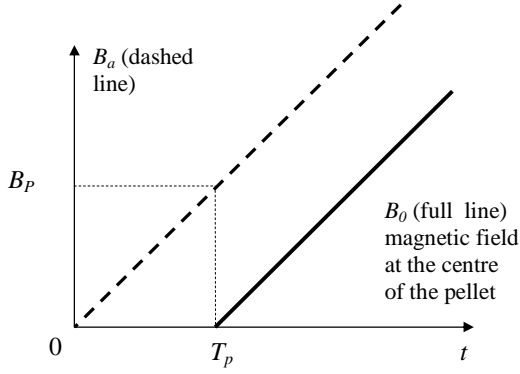


Fig. 2. Linear magnetic applied field B_a and theoretical magnetic field at the center of the pellet B_0 versus time

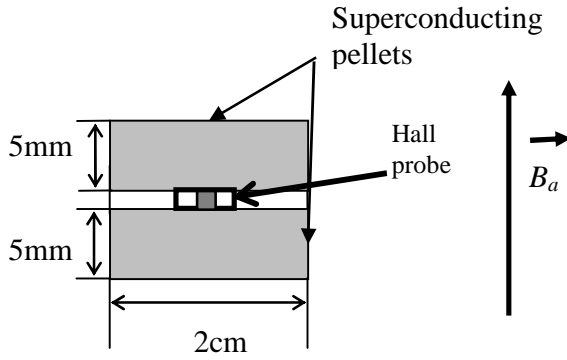


Fig. 3. Hall probe location and HTS pellet dimensions

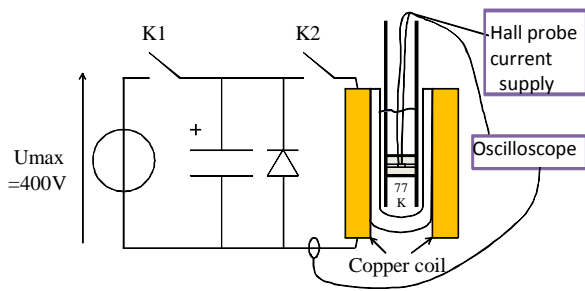


Fig. 4. Experimental set up

Fig. 4 shows our experiment with the pulsed field magnetization process [14] that is used to apply magnetic field with a copper coil. A previously charged capacitor is discharged through this copper coil. It allows obtaining quasi constant rise rate V_b equals to 660 T/s. With this process there is no need of superconducting coil in order to obtain high magnetic field of several Tesla. The applied magnetic field $B_a(t)$ is deduced from copper coil current and the magnetic field at the center of the two pellets $B_0(t)$ is

measured with Hall probe. Figure 5 shows the experimental results. As you can see in surrounded part of Figure 5, the beginning of $B_0(t)$ has not exactly the same shape as the beginning of $B_a(t)$. As it will be confirmed in section IV, this is due to the necessary space between pellets to place Hall probe. So the determination of the penetration time T_p is done as follow. The measured magnetic field curve at the pellet center is modified around T_p to be a copy of applied magnetic field $B_a(t)$ (dotted line in Fig. 5). All along time the difference between curves is constant and equal to T_p . T_p determined then B_p is deduced from the curves.

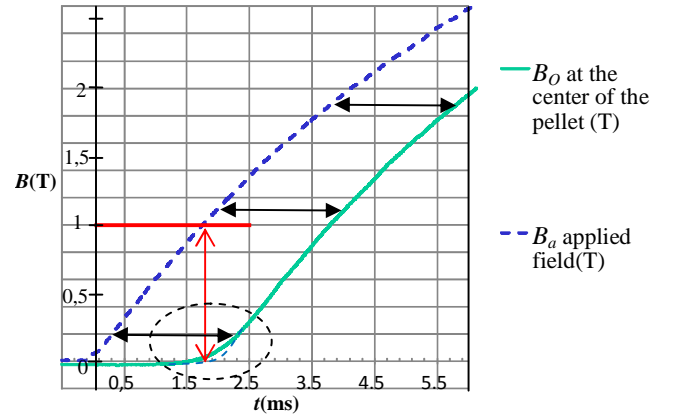


Fig. 5. Applied magnetic field and measured magnetic induction at the center of the pellet

For our two YBCuO pellets (Fig.3), measured B_p is 1 T (Fig.5). J_C deduced from B_p and (2) is 110 A/mm². It seems a realistic value of J_C at 77 K.

Three questions remain. What are the influence of Hall probe depth and the influence of rise rate on this J_C determination? What about thermal effect? To answer these questions numerical simulation is necessary.

III. COMPUTATIONAL METHOD

Pellet magnetization with axial applied magnetic is a 2D axisymmetric problem. PDE interface of COMSOL 4.1 is used with or without heat transfer module. The field profiles can be computed by Faraday's law, Ampere's theorem and constitutive laws of superconducting material usually used for numerical simulation [14]-[15]:

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad (3)$$

$$\nabla \times \vec{H} = \vec{J} \quad (4)$$

$$E = \rho(J).J \text{ with } \rho(J) = \frac{E_C}{J_C} \left(\frac{|J|}{J_C} \right)^{n-1} \quad (5)$$

$$B = \mu_0 H \quad (6)$$

To allow computing convergence a small value ρ_0 , equals $1e-3 \times E_C / J_C$, is added to $\rho(J)$ [16]. The common parameters

used in these simulation are the value of n ($=15$ as realistic value for HTS at 77 K) and the dimensions of pellet ($R = 1$ cm and $L = 1$ cm for one pellet study or 2×0.5 cm for two pellets study). In PDE interface the applied magnetic field $B_a(t)$ is a condition applied at the external boundary. For thermal study convection cooling is used in heat transfer module. Thermal parameters are taken from [14].

IV. INFLUENCE OF RISE RATE, THERMAL EFFECT AND SENSOR THICKNESS.

To answer to the three questions of section II, three sets of simulation are made.

The value of rise rate V_b changes the distribution of magnetic field and current density due to the power law (5) instead of Bean model [17]. So the measured B_p value must depend on rise rate. To study this phenomena (Fig. 6) simulation is made with one pellet with constant rise rate V_b equals 1, 10 and 100 T/s and with $J_C = 1$ A/m². For this value of J_C , B_p equals 9.1 mT.

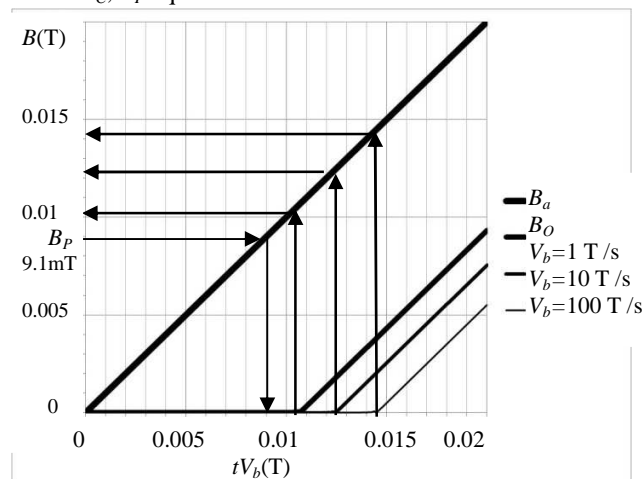


Fig. 6. Applied magnetic field and magnetic induction at the center of the pellet for different rise rates.

To allow comparison between rise rates on one figure, magnetic field in Figure 6 is represented versus tV_b . The measured B_p increases with V_b . This is due that J in superconductor is higher than J_C until almost two times for 100 T/s (Fig. 7). So if J is higher T_p and B_p are also higher. To correctly using (2), based on Bean model, small values of rise rate, lower than 1 T/s, are necessary. Future experiments with superconducting coil and low rise rate will be made to confirm this.

To study the influence of Hall probe thickness e (Fig. 8) simulation is made with two pellets with two different thicknesses ($e = 0.5$ and 1 mm) typical of Hall probe depth and compare with one pellet without hall probe ($e = 0$ mm). Figure 8 shows that measured T_p and B_p increase with e . It is due to the shape of the current density distribution near the centre of the pellets [Fig.9]. Without Hall probe (one pellet on Fig.7) the null current density area has circular shape. But due to Hall probe, this null current area becomes two areas with almost circular shape. So with Hall probe

current density penetrates quicker than without probe (Fig.8). As expected the probe depth should be maximally reduce but with numerical simulation B_p and J_C values can be corrected.

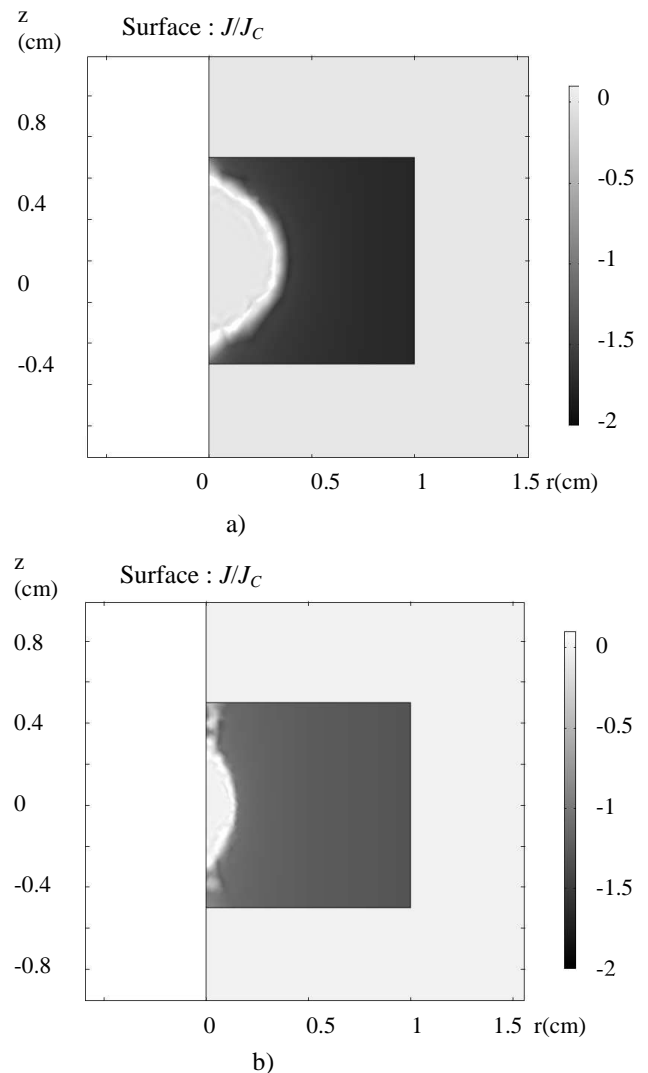


Fig. 7. Current density distribution in superconducting pellet at $V_b = 100$ T/s a) and $V_b = 1$ T/s b) for $B_a = B_p$.

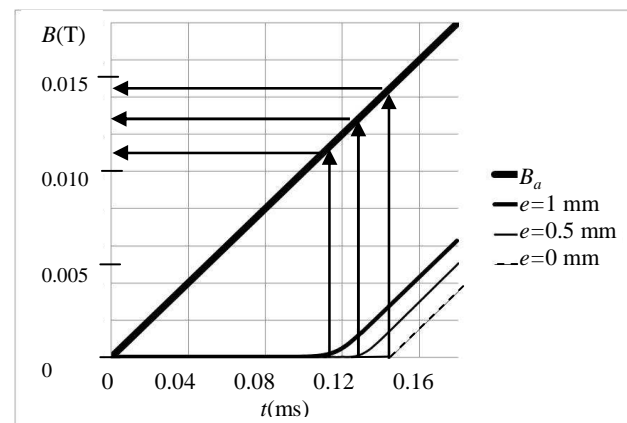


Fig. 8. Applied magnetic field and magnetic field at the center of the pellet for different Hall probe thicknesses.

Thermal effects on J_C determination are also numerically studied. For this $J_C(T)$ is taken and heater module is used in COMSOL.

$$J_C(T) = J_C \left(\frac{T_C - T}{T_C - T_0} \right) \quad (7)$$

$T_0 = 77$ K is the liquid nitrogen bath constant temperature and $T_C = 100$ K [14].

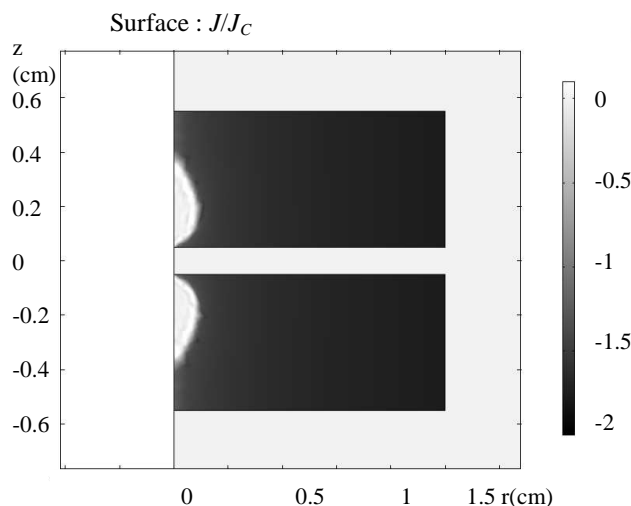


Fig. 9 Current density distribution in superconducting pellet for $e = 1$ mm.

Quicker rise rate is higher thermal effects are. So the value of V_b taken for simulation is a quick rise rate 660 T/s and corresponds to measurement. For this value and for J_C equals 100 A/mm², thermal effects are negligible on B_p because temperature rising in superconductor is weak about 1° K or 2° K. As a result the J variation in superconductor due to thermal effects is also weak during the magnetic field penetration phase. In this J_C determination method thermal effects can be neglected.

Finally, the best J_C value are numerically determine to have closest numerical and experimental results of $B_0(t)$. For n -value fixed at 15, e fixed at 0.5 mm, the found best J_C equals 55 A/mm². It is about half of measured one (110 A/mm²) mainly because rise rate is very high.

V. CONCLUSION.

In this article a new direct J_C determination method is presented. The experimental set up is relatively simple because it needs only one copper coil and one capacitor bank. It is a relatively precise method but it is important taking into account rise rate and sensor depth. Thermal effects can be neglected. The corrected value of J_C is lower than measured one mainly because of high experimental rise rate. The influence of n -value has to be studied because it is related to the influence of rise rate. A negative point is this method does not allow to determine $J_C(B)$ but it is a good method to quickly obtain a first value of J_C for bulk HTS samples.

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