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Determination of the Complete Penetration Magnetic Field of a HTS Pellet from the Measurements of the Magnetic Field at its Top-Center Surface

Bruno Douine, Kévin Berger, Frédéric Trillaud, Mohamed Elbaa, El Hadj Ailam

Abstract— Our basic method to characterize HTS pellets, which has been presented in earlier publications, is based on the measurement of their complete penetration magnetic flux density B_P . The method allows assessing the critical current density J_C and the n -value through the classical power law model modeling the magnetic behavior of pellets and the direct measurement of B_P . A first method used two slightly axially separated HTS disks to determine B_P in the gap between the disks. However, this first method exhibits two main disadvantages. The first disadvantage is that the magnitude of the derived values depends on the spacing e between the two pellets. The second one is that the two pellets ought to be strictly identical for the method to lead to representative values of a given pellet. To overcome those constraints and limitations, we have been looking for a new improved method that relies only on the measurement involving a single pellet. The following work introduces the principle of this new method. The main idea is thus to deduce B_P from the magnetic flux density measured at the center of the top surface when the applied magnetic flux density B_a equals B_P . The maximum magnetic flux density produced by the SC pellet B_{ZSCM} is deduced from the measurement and multiply by an analytical coefficient to deduce B_P .

Index Terms—Superconductors, magnetic field diffusion, critical current density.

I. INTRODUCTION

A LOT of projects of superconducting motors, generators or magnetic levitation systems have been studying on the base of high temperature superconductor (HTS) bulks because of increasing of critical current density and improvement of cryogenics [1]-[7]. The critical state model (CSM) is commonly used [8] to calculate magnetization, strength and other physic parameters. In the CSM, the current

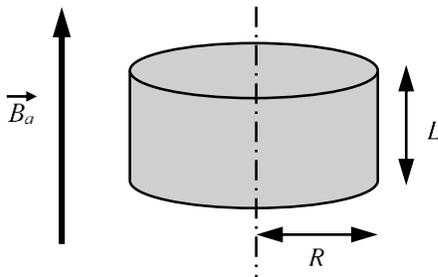


Fig. 1. Cylindrical bulk superconducting pellet submitted to a uniform axial magnetic field $B_a(t)$.

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density J can only be equals to 0 or the critical current density J_C independent on the rate of variation of the externally applied magnetic field. Thanks to CSM, J_C can be simply determined by experiments [9]-[10].

If a uniform axial magnetic field $B_a(t)$ is applied to a cylindrical HTS pellet, Fig. 1, the magnetic flux density at the center of the pellet $B_0(t)$ starts to rise after some time delay T_P , related to the moment at which B_a reaches B_P , Fig. 2. Biot-Savart law, assuming CSM, allows to calculate an analytic expression for the complete penetration field, named B_{PB} , for cylinders, i.e. [10]-[12]:

$$B_{PB} = \frac{\mu_0 J_C L}{4} \ln \left(\frac{\sqrt{R^2 + \left(\frac{L}{2}\right)^2} + R}{\sqrt{R^2 + \left(\frac{L}{2}\right)^2} - R} \right) \quad (1)$$

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

The power law model (PLM) (2) is commonly used for HTS for temperatures above 50 K, instead of CSM [11], [12].

$$E = E_C \left(\frac{J}{J_C} \right)^n = \frac{E_C}{J_C} \left(\frac{J}{J_C} \right)^{n-1} J \quad (2)$$

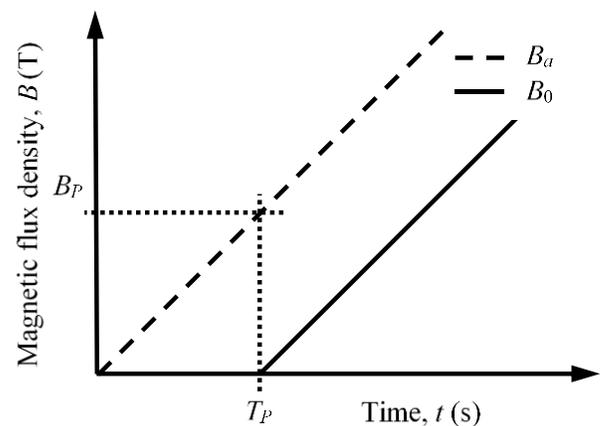


Fig. 2. Linearly growing applied magnetic field (B_a) and theoretical magnetic field (B_0) at the center of the pellet versus time (t).

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The calculation of the magnetization of superconducting samples assuming PLM generally requires numerical simulations. The method of determination of the J_C and n parameters using PLM is given in [11]. It has been shown that the complete penetration magnetic field B_P depends on the n -value and the applied magnetic field rising rate V_b , Fig.2:

$$B_P = B_{PB} \left(1 + \frac{\alpha \ln V_b + \beta}{n} \right) \quad (3)$$

with $\alpha = 1.2$ and $\beta = 3.4$ [11].

In [12], it has been shown that there is no influence of geometrical parameters R and L on these values of α and β for commonly used HTS pellets.

Based on (3) PLM, J_C and n -value of a cylindrical sample are calculated from experimental measurements using two identical pellets [11], the magnetic field being measured by axial Hall probe between the two HTS pellets Fig. 3. In this paper a method of determination of B_P of a unique HTS pellet from the measurements of the magnetic field at its top-center surface is presented. This could be a simpler and cheaper method than the previous method using two pellets. This method uses one Hall probe placed at a distance d from the top-center surface of the pellet (Fig. 3). In this case the issue is to know the relationship between the measured magnetic flux density by Hall probe and B_P . From B_{P1} and B_{P2} measured at two rise rates of applied magnetic field V_{b1} and V_{b2} , n -value, B_{PB} and finally J_C can be deduced [11], Fig. 4.

II. NUMERICAL AND ANALYTICAL CALCULATIONS OF THE RELATIONSHIP BETWEEN THE MEASURED MAGNETIC FLUX DENSITY BY HALL PROBE AND B_P

A combination of numerical simulations and analytical calculations has been used to determine the relationship between the measured magnetic flux density by Hall probe and B_P .

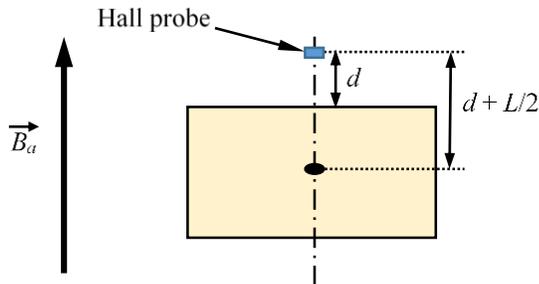


Fig. 3. Hall probe location above the HTS pellet.

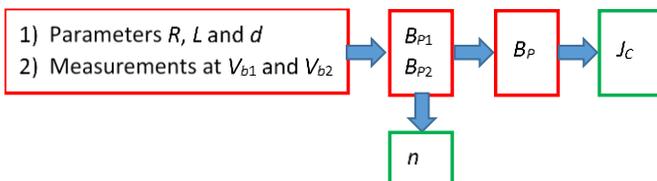


Fig. 4. Determination of J_C and n -value.

A. Numerical simulations

Firstly, numerical simulations of a HTS pellet submitted to linearly rising applied magnetic field. This allows to determine the magnetic flux density along the axis, especially at the center pellet $B_0(t)$ and at the position of the Hall probe $B_z(d,t)$. In these simulations, $R = 10$ mm and $L = 10$ mm as in [11]. For $n = 15$ $B_a(t)$ and $B_z(d=0.5\text{mm}, t)$ are represented in Fig. 5 for constant J_C and equals to 100 A/mm². The difference $B_a(t) - B_z(d=0.5\text{mm}, t)$ represented in Fig. 5 is the magnetic flux density produced by the induced current inside the superconducting pellet $B_{ZSC}(d, t)$. Fig. 5 shows that $B_{ZSC}(d=0.5\text{mm}, t)$ reaches a maximum value B_{ZSCM} than before $B_a(t) - B_0(t)$ reaches B_P . It seems obvious in Fig. 5 that B_{ZSCM} is directly linked to B_P through geometrical parameters R and L .

B. Analytical calculation of the magnetic flux density along the pellet axis

In the case of the magnetic field complete penetration and CSM, the magnetic flux density along the axis of the cylindrical pellet B_{ZSCB} can be calculated using Biot–Savart law in the same way as the B_{PB} (1). B_{ZSCB} is produced by homogenous and constant critical current J_C in the volume of the pellet, Fig. 6. The formula of B_{ZSCB} is obviously similar to (1):

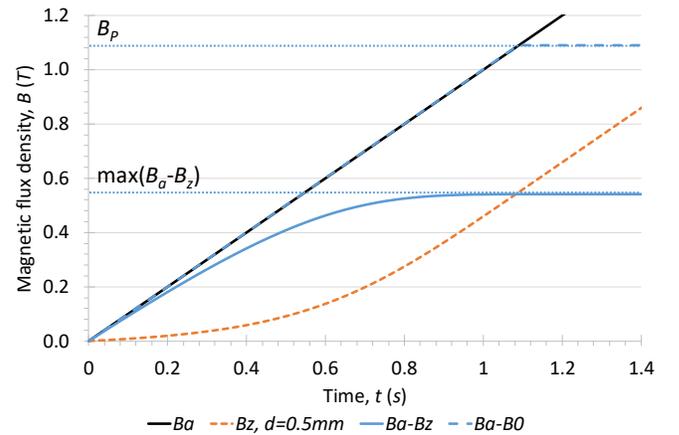


Fig. 5. Numerical calculation of $B_a(t) - B_z(d=0.5\text{mm}, t)$ and $B_a(t) - B_0$, with $n = 15$, $V_b = 1\text{T/s}$.

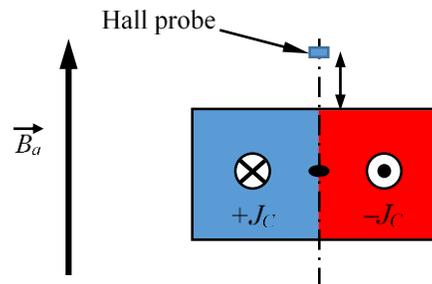


Fig. 6. Complete penetration of the current density with CSM.

$$B_{ZSCB}(d, R, L) = \frac{\mu_0 \cdot J_C}{4} \left[(d+L) \cdot \text{Ln} \left(\frac{1 + \frac{R}{\sqrt{(d+L)^2 + (L/2)^2}}}{1 - \frac{R}{\sqrt{(d+L)^2 + (L/2)^2}} \right) \right] - \frac{\mu_0 \cdot J_C}{4} \left[d \cdot \text{Ln} \left(\frac{1 + \frac{R}{\sqrt{d^2 + (L/2)^2}}}{1 - \frac{R}{\sqrt{d^2 + (L/2)^2}} \right) \right] \quad (4)$$

Fig. 7 shows B_{ZSCB} versus d for realistic values of d due the thickness of Hall probes.

C. Comparison of analytical and numerical calculation of B_{ZSCM}/B_P for complete penetration case

The last question is to know if the numerically calculated ratio $B_{ZSCM}(d)/B_P$ and the analytically calculated ratio $B_{ZSCB}(d)/B_{PB}$ are equivalent or different? $B_{ZSCB}(d)/B_{PB}$ has been numerically calculated with various n -value from 15 to 50 and various magnetic field rise rate from 1 T/s to 1000 T/s. Fig. 8 clearly shows that these two ratios are equivalent for these numerous values of these both parameters. It means that $B_{ZSCB}(d)/B_{PB}$ is relevant to deduce B_P from $B_{ZSCM}(d)$ drawn from

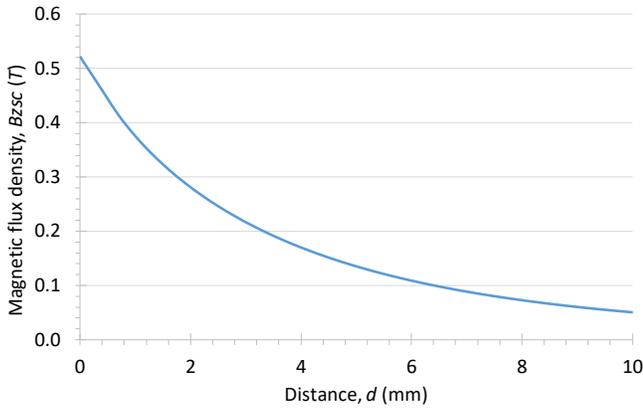


Fig. 7. Analytical calculation of B_{ZSC} along the axis of the pellet in complete penetration case.

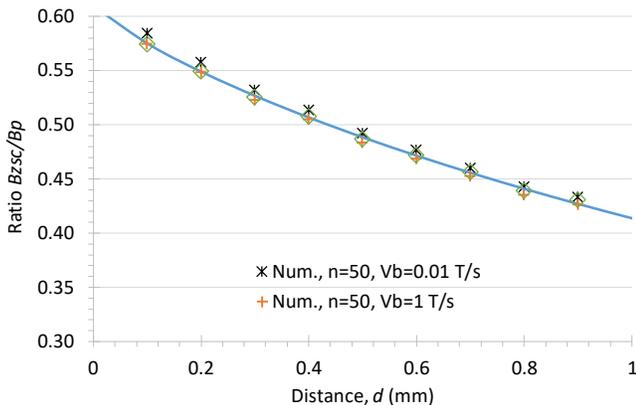


Fig. 8. Comparison of numerical calculation of B_{ZSCM}/B_P and analytical calculation of B_{ZSCB}/B_{PB} .

measurement whatever n -value and V_b :

$$B_P = \frac{B_{ZSCM}(d)_{measured}}{(B_{ZSCB}(d)/B_{PB})_{analytical}} \quad (5)$$

It should be added that the ratio $B_{ZSCB}(d)/B_{PB}$ is J_C independent and depends only on geometrical parameters R and L .

D. Influence of $J_C(B)$ on results of this determination method

The most important assumption made in this method is constant J_C . In this section the influence of $J_C(B)$ is analyzed. Numerical simulations of a HTS pellet submitted to linearly rising applied magnetic field has been made using $J_C(B)$ as:

$$J_C(B) = \frac{J_{C0}}{1 + (|B|/B_{C0})^3} \quad (6)$$

with $J_{C0} = 200$ A/mm² and $B_{C0} = 1$ T.

J_{C0} and B_{C0} are arbitrarily chosen to have huge variation of $J_C(B)$, represented in Fig. 9, around $B_P = 1.1$ T which has been previously calculated with constant J_C . These numerical calculation has been made with the same dynamics parameters as those in Fig. 5, namely $n = 15$ and $V_b = 1$ T/s.

The results of this simulations shown in Fig. 10 that the magnetic flux density produced by HTS pellet $B_{ZSC}(t)$ represented by the difference $B_a(t) - B_z(t)$ presents a unique maximum value B_{ZSCM} instead of a saturation plateau as in the

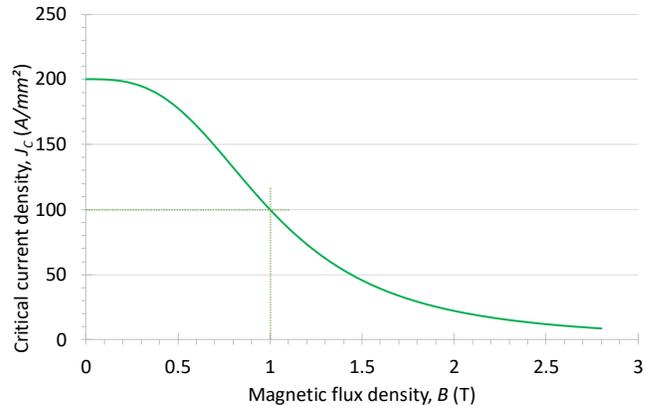


Fig. 9. $J_C(B)$ used in numerical simulations.

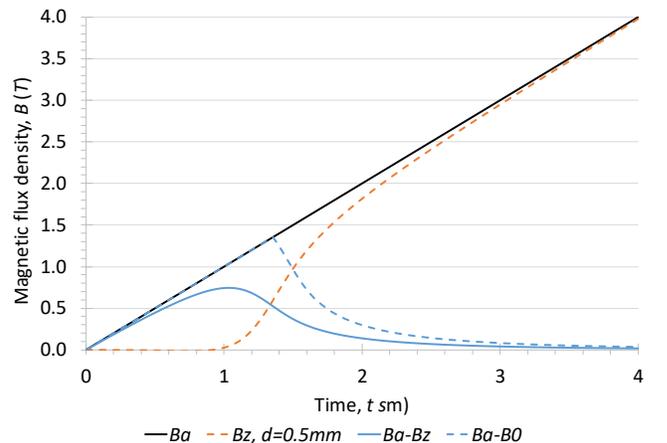


Fig. 10. Numerical calculation of $B_a(t) - B_z(d=0.5\text{mm}, t)$ and $B_a(t) - B_0$, with $n = 15$, $V_b = 1$ T/s and $J_C(B)$.

constant J_C case, in Fig. 5. B_P is the maximum value of $B_d(t) - B_0(t)$ and equals 1.35 T, in Fig. 10. For $d = 0.5$ mm, the calculated B_{ZSCM} is 0.745 T and it corresponds to $B_{ZSCM}(d)/B_P = 0.55$ instead of 0.49 for constant J_C case, Fig. 8. This difference is due to the non-homogeneity of the magnetic flux density and current density inside the HTS pellet. In this case (4) has to be recalculated which is not analytically possible with Biot-Savart law and can only be made by numerical simulations. This remaining work has to be done in the next step of our work.

III. CONCLUSION

The main idea of this paper is to determine B_P from the measurement of the maximum magnetic flux density at the top-center surface B_{ZSCM} . Analytical calculated ratio $B_{ZSCB}(d)/B_{PB}$ similar as numerically calculated ratio $B_{ZSCB}(d)/B_{PB}$ allows to simply determine B_P . The influence of $J_C(B)$ of this B_P , n -value and J_C determination method has to be studied further in next studies to improve the relevance of our method. The comparison of this method with previous ones [13]-[15] has to be done too.

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