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Magnetic flux trapping in porous high-T_c superconductors

Denis Gokhfeld

Kirensky Institute of Physics, Krasnoyarsk Scientific Center, Siberian Branch, Russian Academy of Sciences, Krasnoyarsk, Russia

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ABSTRACT

Porosity affects the properties of high-T_c superconductors and can improve their performance by enhancing oxygenation, cryocooling, etc. Among other factors, the presence of pores plays a significant role in the process of magnetic flux trapping. Relationships with the porosity manifest in the irreversibility field, the full penetration field, and the remnant magnetization of the samples. To account for the effect of porosity on the trapped magnetic flux into type-II superconductors, a simple toy model is suggested. Generally, as the porosity increases, the trapped flux and related parameters tend to diminish. However, in the case of microscopic samples, porosity can enhance magnetic flux trapping.

1. Introduction

Effective cooling is crucial for many applications of superconductors. In the case of overheating, stable functioning is hindered, and the superconductor can even be damaged [1,2]. An improvement in cooling can be achieved by perforation, which provides a coolant to infiltrate the sample and to withdraw the emitted heat. Moreover, perforation can increase oxygenation and prevent cracking during sample synthesis [3–6]. The same positive effects can be provided by macroscopic pores forming long percolation clusters into superconductors.

Porous superconductors are a special class of novel materials [7–9]. They have properties inherent both bulk 3D and quasi 2D systems [10,11] because pores are defects with high specific surfaces. The pinning of vortices and the critical current density depend on the concentration, form, and size of defects. Earlier works concerning pinning focused on defects of about the superconductor coherence length [12,13]. Larger defects are believed to depress the critical current due to distortions of current trajectories [14]. Moreover, the coolant percolation requires infinite pore clusters and a pore diameter of approximately 0.1–1 mm [15]. Porous high-T_c superconductors are realized in the form of foams, fibers, fabrics, and polycrystals [9]. Superconducting foams, which have been investigated since 2002 [16], have a high porosity (up to 80%) and 1 mm pores. For such samples, a high porosity provides chemical uniformity and effective cryocooling.

Describing these systems is complicated [9,17] because the trajectories of currents and vortex configurations in porous superconductors are tangled [18–20]. The simplified model of the porous superconductor is a long perforated cylinder, and this is considered in [21–23]. This model accounts for perforated holes trapping a magnetic flux due to their surface barriers [24–26]. The corresponding entrance field for magnetic vortices is about a value of the thermodynamical critical field of the superconductor [25]. It was found that perforated samples have the maximum trapped magnetic flux for some effective area of holes [22,23].

The present work focuses only on the effect of the pores on the trapped magnetic flux. An optimal porosity is expected analogous to the optimal hole area in perforated superconductors [22,23]. The aim is to estimate this optimal porosity. The effects of porosity on oxygenation, cracking, and cooling, which are important for superconducting performance, are not considered here.

2. Model

Previously, a toy model of magnetic flux trapping by the surface barrier of perforated holes in a cylindrical superconductor was constructed [24]. Now, let us consider a cylindrical type–II superconductor with nearly spherical pores of different diameters. The sample has a much larger size than the London penetration length λ. The relevant pore diameters are much smaller than the sample sizes but larger than λ.

The cross-section of a porous cylinder perpendicular to its major axis looks like the same cross-section of the perforated sample. However, the voids corresponding to the cross-section of the pores are different in size, and the arrangement of the voids depends on the position of the cross-section plane. Additionally, the magnetic field distribution depends on

E-mail address: gokhfeld@iph.krasn.ru.

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the coordinate z. However, the average trapped flux is independent of the z value. We propose considering an average cross-section characterized by an area S, which is the area of the cylindrical sample end face, and the areal density of voids φ_v. The average diameter of the voids D_v is smaller than the average pore diameter D_p; the simple math gives $D_v = \pi D_p/4$. In the considered case of porous media with a random structure, the porosity φ is equal to φ_v [27], and $\varphi = \pi^3 N_v D_p^2/(64S)$, here N_v is a number of the pores intersected by the cross section. The porosity in the units of pores per inch can be expressed as $P_{PPI} \approx 0.0254\sqrt{N_v/S} \approx 0.029\sqrt{\varphi}/D_v$.

The magnetic field distributions realized in the cross section of a porous superconductor and in the cross-section of a perforated superconductor are practically equivalent. Due to the elasticity of superconducting vortex lines [13,28], each line can warp and skewer many pores to minimize the vortex energy [29,30]. Pores as well as perforated holes decrease the useful area and the number of inner pinning centers. At the same time, pores trap an excess magnetic field due to the surface barriers [25]. The excess magnetic field is characterized by the parameter $k_h = B_h/B_{pin0}$, where B_h is the average magnetic field in the pores, $B_{pin0} = \Phi_{pin0}/S$, and Φ_{pin0} is the magnetic flux trapped in the pore-free sample. The value of k_h for pores is assumed to be the same as that for holes [24]: $k_h \approx [(B_s/B_{pin0})^2 + 1]^{1/2}$, where $B_s = \Phi_0/(4\pi\lambda\xi)$, ξ is the coherence length of the superconductor, and $\Phi_0 = 2.07\times10^{-15}$ Wb.

The correspondence between the perforated and porous samples allows us to express the trapped flux for porous media in the same way as for perforated superconductors [24]:

$$\Phi \approx \Phi_{pin0}(1-\varphi)(1+k_h\varphi). \tag{1}$$

The three important parameters φ_{lim}, φ_{max}, and Φ_{max} result from (1). The porosity should be lower than the limit value φ_{lim} to improve the trapped magnetic flux. That is, $\Phi > \Phi_{pin0}$ when $\varphi < \varphi_{lim}$, with

$$\varphi_{lim} = 1 - \frac{1}{k_h}. \tag{2}$$

The optimal porosity, which corresponds to the maximum trapped flux, is

$$\varphi_{max} = \frac{1}{2}\left(1 - \frac{1}{k_h}\right). \tag{3}$$

The corresponding maximum value of the trapped flux is

$$\Phi_{max} = \frac{\Phi_{pin0}}{4}\left(2 + k_h + \frac{1}{k_h}\right). \tag{4}$$

3. Results

The application of the model to the practically interesting case of large-grain REBCO samples at 77 K is considered in this section.

3.1. Influence of the porosity on samples of different sizes

The trapped magnetic flux Φ depends on the critical current density, sample size, and porosity. The dependence of Φ on φ for a cylindrical YBCO sample with $D = 2$ cm is demonstrated in Fig. 1a. Using $B_{pin0} \approx \mu_0 j_c D/6$ for the considered cylinder geometry and given the typical parameters of large-grain bulk REBCO samples ($j_c = 10^8$ A/m^2 and $B_s = 0.17$ T at 77 K), one obtains $k_h \approx 1.08$ for $D = 2$ cm. The trapped magnetic flux is increased by increasing the porosity of the sample until $\varphi = 0.036$ (see inset in Fig. 1a). The increase in Φ is negligible in this case. As the porosity increases, the trapped flux decreases.

A low value of k_h means that the flux trapping on the pores is negligible in large single-grain superconductors. In addition, thermal fluctuations can further suppress the surface barrier in high-T_c superconductors [31] and additionally decrease k_h.

Higher values of k_h can be realized in porous superconductors only for smaller sizes or smaller critical current densities. Fig. 1b demonstrates the $\Phi(\varphi)$ dependence for a cylindrical YBCO sample with $D = 10$ μm. For this sample, $k_h \approx 833$, and the increase in Φ is significant. The maximum position shifts to greater φ, and the peak corresponds to $\varphi = 0.499$. Note that the latter case is not grounded because $D = 10$ μm is near the lower limit of the model's applicability.

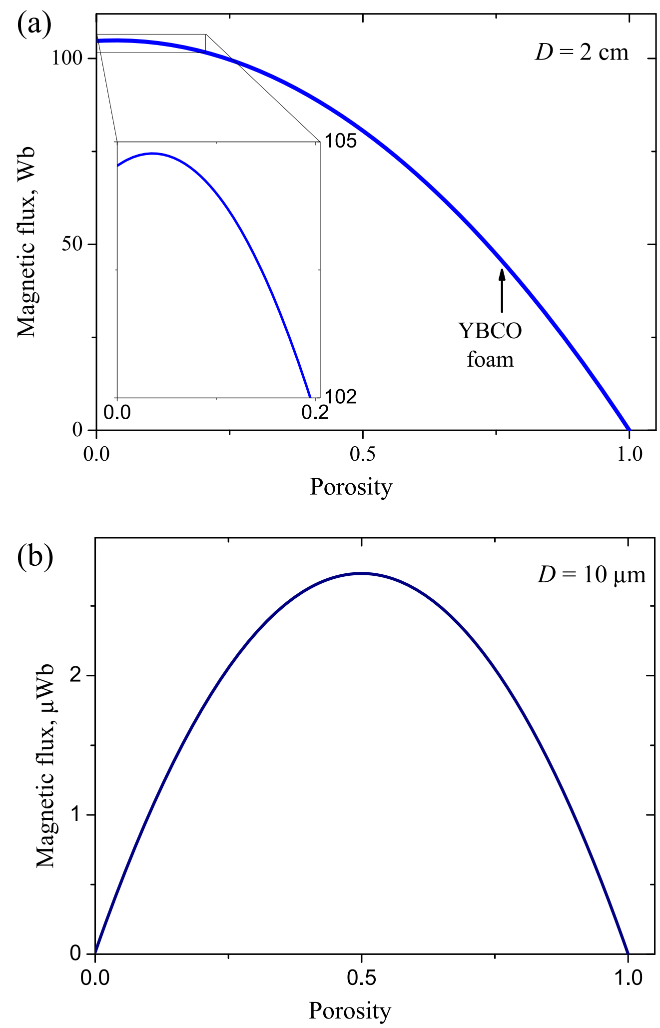

Fig. 1. Effect of the porosity φ on the trapped magnetic flux Φ for the 2 cm sample (a) and the 10 μm sample (b); $j_c = 10^8$ A/m^2 for both samples. Arrow indicates the porosity of YBCO foam. Insert (a) demonstrates the $\Phi(\varphi)$ dependence for small values of φ.

We apply the model to YBCO foam, which is quasi single-crystalline [32]. The porosity of the YBCO foam is 0.75 [16] or about 30 PPI, which is much greater than the optimal value φ_{max} (see arrow in Fig. 1a). This means that the trapped flux is diminished in this material. Indeed, the trapped flux in this foam was found to be two orders of magnitude smaller than that in single crystals of YBCO [19,33].

3.2. Maximum trapped flux

Fig. 2 shows the effect of the sample diameter on the maximum increase in the trapped magnetic flux Φ_{max}/Φ_{pin0}. It can be concluded that the magnetic field trapped in the pores has almost no positive effect on the trapped flux for macroscopic samples ($D \geq 0.001$ m). However, as shown in Fig. 2, smaller microscopic samples can significantly increase Φ due to porosity. The effect of porosity is more pronounced for superconductors with lower j_c values because B_{pin0} is low in this case, and k_h can be very high.

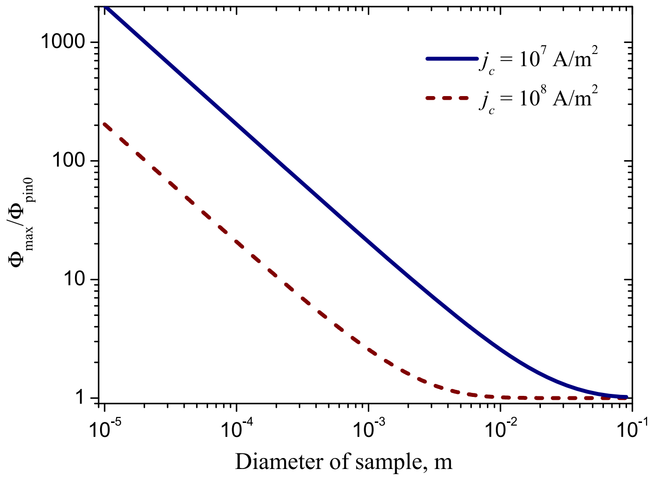

Fig. 2. Maximum achievable improvement in trapped magnetic flux.

3.3. *Magnetic hysteresis loops*

The potential effects of porosity on the sample magnetization are considered in tis subsection. i) Pores can facilitate the movement of magnetic flux into the sample interior and correspondingly reduce the full penetration field and the magnetization width ΔM [21]. ii) The specific surface increases with increasing porosity. This increases the surface equilibrium magnetization and decreases the bulk nonequilibrium magnetization of the superconductor [34,35]. Thus, increasing the porosity makes the magnetization hysteresis loops more asymmetric along the H axis and decreases the irreversibility field (Fig. 3). iii) When equation (2) is satisfied, the remnant magnetization increases due to the excess flux trapped in the pores. This effect is expected only for microscopic samples ($D < 0.1$ mm) and samples with low j_c. iv) If (2) is not satisfied, the remnant magnetization decreases.

4. Discussion

Any effects of sample demagnetization or local demagnetization on the pore scale are neglected in the above considerations. The trajectories of currents flowing through porous superconductors can be three-dimensional [19], and this deviation from 2D is also neglected. We do not expect that these geometric effects drastically change the dependence (1). Therefore, the main results should not be dependent on the sample geometry. The model claims the negative effect of macroscopic porosity on the trapped magnetic flux for macroscopic high-T_c superconductors. This result explains the decrease in Φ due to the porosity observed in a resent experimental study of macroscopic YBCO samples [36]. For the smaller superconducting samples ($D < 0.1$ mm), if the condition (2) is satisfied, the porosity can likely enhance the trapped flux.

The applicability of the model to the cases of polycrystalline superconductors and superconducting fabrics [7,9] is questionable. These materials are two-level superconductors [37]. At high fields, most of the magnetic flux is trapped by defects into granules and crystallites. Pores between granules can trap the excess magnetic field only in small magnetic fields up to the lower critical field of the granules. A similar case of the magnetic flux trapping by Josephson loops was considered in [38].

The model can be useful for expectable room-temperature superconductors. Room-temperature superconductors are expected to have low values of j_c at high temperatures [39]. It means that k_h can be sufficient high, and these materials can be significantly facilitated by porosity.

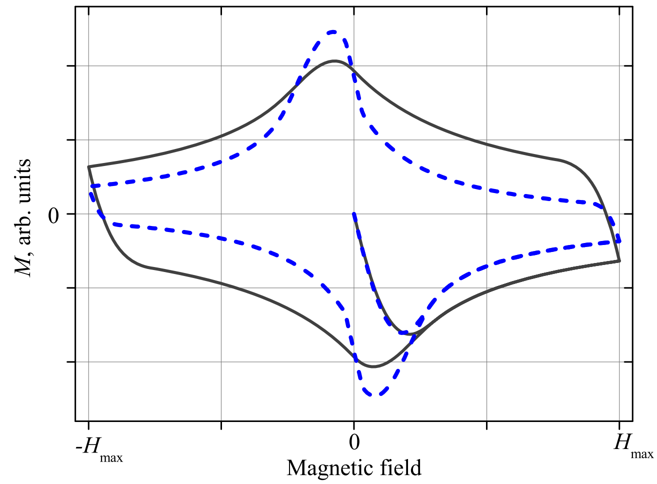

Fig. 3. The hysteresis magnetization loops of a pore-free superconductor (solid line) and a porous superconductor (dashed line). The curves were calculated using the extended critical state model [34] with different contributions of the surface magnetization.

5. Conclusions

The magnetic properties of superconducting samples are significantly influenced by porosity. The simple toy model presented here is used to answer the following question: is there a positive effect of porosity itself on the trapped flux? It is found that the optimal porosity depends on the sample size and the critical current density. However, for macroscopic samples, the positive effect of porosity on the excess flux trapping is found to be negligible. Thus, the increasing porosity in single-crystal REBCO samples decreases the trapped magnetic flux. Moreover, increasing porosity should increase the asymmetry of the magnetic hysteresis loop of type-II superconductors and decrease the irreversibility field.

CRediT authorship contribution statement

Denis Gokhfeld: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

[1] S.S. Fetisov, V.S. Vysotsky, V.V. Zubko, HTS tapes cooled by liquid nitrogen at current overloads, IEEE Trans. Appl. Supercond. 21 (2011) 1323–1327, https://doi.org/10.1109/TASC.2010.2093094.

[2] S. Lee, V. Petrykin, A. Molodyk, S. Samoilenkov, A. Kaul, A. Vavilov, V. Vysotsky, S. Fetisov, Development and production of second generation high T_c

superconducting tapes at SuperOx and first tests of model cables, Supercond. Sci. Technol. 27 (2014) 044022, https://doi.org/10.1088/0953-2048/27/4/044022.
[3] F. Antončík, M. Lojka, T. Hlásek, I. Valiente-Blanco, J.L. Perez-Diaz, O. Jankovský, Artificially perforated single-grain YBCO bulks: dependence of superconducting properties on the bulk thickness, J. Am. Ceram. Soc. 103 (2020) 5169–5177, https://doi.org/10.1111/JACE.17279.
[4] K. Zmorayová, P. Diko, D. Volochová, V. Antal, T. Hlásek, V. Plecháček, F. Antončík, Complex microstructural analysis of YBCO single-grain bulks with artificial holes: effect on superconducting properties, Ceram. Int. 49 (2023) 22177–22186, https://doi.org/10.1016/J.CERAMINT.2023.04.046.
[5] J.G. Noudem, S. Meslin, D. Horvath, C. Harnois, D. Chateigner, B. Ouladdiaf, S. Eve, M. Gomina, X. Chaud, M. Murakami, Infiltration and top seed growth-textured YBCO bulks with multiple holes, J. Am. Ceram. Soc. 90 (2007) 2784–2790, https://doi.org/10.1111/j.1551-2916.2007.01841.x.
[6] Y. Zhao, Y. Yang, The effect of thermal stress on crack-inclusion problem in inhomogeneous superconducting cylinder, Eur. Phys. J. B. 96 (2023) 148, https://doi.org/10.1140/EPJB/S10051-023-00619-7.
[7] M.R. Koblischka, A. Koblischka-Veneva, Porous high-T_c superconductors and their applications, AIMS Mater. Sci. 5 (2018) 1199–1213, https://doi.org/10.3934/matersci.2018.6.1199.
[8] M.R. Koblischka, A. Koblischka-Veneva, S.Pavan Kumar Naik, D. Gokhfeld, M. Murakami, Porous high-T_c superconducting cuprates: advantages and applications, J. Phys. Conf. Ser. (2019) 1293, https://doi.org/10.1088/1742-6596/1293/1/012009.
[9] D.M. Gokhfeld, M.R. Koblischka, A. Koblischka-Veneva, Highly porous superconductors: synthesis, research, and prospects, Phys. Met. Metallogr. 121 (2020) 936–948, https://doi.org/10.1134/S0031918×20100051.
[10] A.A. Bykov, D.M. Gokhfeld, N.E. Savitskaya, K.Y. Terentjev, S.I. Popkov, A. A. Mistonov, N.A. Grigoryeva, A. Zakhidov, S.V. Grigoriev, Flux pinning mechanisms and a vortex phase diagram of tin-based inverse opals, Supercond. Sci. Technol. 32 (2019) 115004, https://doi.org/10.1088/1361-6668/AB3DB7.
[11] D.M. Gokhfeld, S.I. Popkov, A.A. Bykov, Analog of the intertype superconductivity in nanostructured materials, Phys. C Supercond. Its Appl. 566 (2019), https://doi.org/10.1016/j.physc.2019.1353526.
[12] R. Willa, A.E. Koshelev, I.A. Sadovskyy, A. Glatz, Strong-pinning regimes by spherical inclusions in anisotropic type-II superconductors, Supercond. Sci. Technol. 31 (2018) 014001, https://doi.org/10.1088/1361-6668/aa939e.
[13] S. Eley, A. Glatz, R. Willa, Challenges and transformative opportunities in superconductor vortex physics, J. Appl. Phys. 130 (2021) 050901, https://doi.org/10.1063/5.0055611.
[14] E. Bartolomé, X. Granados, T. Puig, X. Obrados, E.S. Reddy, S. Kracunovska, Critical state of YBCO superconductors with artificially patterned holes, IEEE Trans. Appl. Supercond. 15 (2005) 2775–2778, https://doi.org/10.1109/TASC.2005.848210.
[15] S.L. Qi, P. Zhang, R.Z. Wang, L.X. Xu, Single-phase pressure drop and heat transfer characteristics of turbulent liquid nitrogen flow in micro-tubes, Int. J. Heat Mass Transf. 50 (2007) 1993–2001, https://doi.org/10.1016/J.IJHEATMASSTRANSFER.2006.09.032.
[16] E.S. Reddy, G.J. Schmitz, Superconducting foams, Supercond. Sci. Technol. 15 (2002) L21–L24, https://doi.org/10.1088/0953-2048/15/8/101.
[17] M.R. Koblischka, A. Koblischka-Veneva, Q. Nouailhetas, G. Hajiri, K. Berger, B. Douine, D. Gokhfeld, Microstructural parameters for modelling of superconducting foams, Materials (Basel) 15 (2022) 2303, https://doi.org/10.3390/ma15062303.
[18] D.A. Balaev, I.L. Belozerova, D.M. Gokhfeld, L.V. Kashkina, Y.I. Kuzmin, C. R. Michel, M.I. Petrov, S.I. Popkov, K.A. Shaikhutdinov, Current-voltage characteristics of a foamed $Bi_{1.8}Pb_{0.3}Sr_2Ca_2Cu_3O_x$ high-temperature superconductor with fractal cluster structure, Phys. Solid State 48 (2006) 207–212, https://doi.org/10.1134/S1063783406020016.
[19] M.R. Koblischka, S.P.K. Naik, A. Koblischka-Veneva, M. Murakami, D. Gokhfeld, E. S. Reddy, G.J. Schmitz, Superconducting YBCO foams as trapped field magnets, Materials (Basel) 12 (2019) 853, https://doi.org/10.3390/ma12060853.
[20] A.L. Pessoa, A. Koblischka-Veneva, C.L. Carvalho, R. Zadorosny, M.R. Koblischka, Microstructure and paramagnetic Meissner effect of $YBa_2Cu_3O_y$ nanowire networks, J. Nanoparticle Res. 22 (2020) 360, https://doi.org/10.1007/S11051-020-05076-2.
[21] G.P. Lousberg, M. Ausloos, P. Vanderbemden, B. Vanderheyden, Bulk high-T_c superconductors with drilled holes: how to arrange the holes to maximize the trapped magnetic flux? Supercond. Sci. Technol. 21 (2008) 025010 https://doi.org/10.1088/0953-2048/21/02/025010.
[22] A.N. Maksimova, V.A. Kashurnikov, A.N. Moroz, D.M. Gokhfeld, Trapped field in superconductors with perforations, J. Supercond. Nov. Magn. 35 (2022) 283–290, https://doi.org/10.1007/s10948-021-06067-7.
[23] D.M. Gokhfeld, A.N. Maksimova, V.A. Kashurnikov, A.N. Moroz, Optimizing trapped field in superconductors with perforations, Phys. C Supercond. Its Appl. 600 (2022) 1354106, https://doi.org/10.1016/j.physc.2022.1354106.
[24] D.M. Gokhfeld, Surface barrier of holes drilled in a type-II superconductor, J. Supercond. Nov. Magn. 36 (2023) 1481–1484, https://doi.org/10.1007/s10948-023-06599-0.
[25] J.R. Clem, A Model for Flux Pinning in Superconductors, in: Low Temp. Physics-LT 13, Springer US, Boston, MA, 1974, pp. 102–106, https://doi.org/10.1007/978-1-4684-2688-5_17.
[26] F. Sernetz, Flux pinning in porous type II superconductors, J. Low Temp. Phys. 24 (1976) 85–103, https://doi.org/10.1007/BF00659197.
[27] F.A.L. Dullien, Porous Media. Fluid Transport and Pore Structure, Academic Press, 1992, https://doi.org/10.1016/c2009-0-26184-8.
[28] E.H. Brandt, The flux-line lattice in superconductors, Reports Prog. Phys. 58 (1995) 1465–1594, https://doi.org/10.1088/0034-4885/58/11/003.
[29] G.S. Mkrtchyan, V.V. Shmidt, Interaction between a cavity and a vortex in a superconductor of the second kind, JETP 34 (1972) 195–197.
[30] K. Matsumoto, P. Mele, Artificial pinning center technology to enhance vortex pinning in YBCO coated conductors, Supercond. Sci. Technol. 23 (2010) 014001, https://doi.org/10.1088/0953-2048/23/1/014001.
[31] L. Burlachkov, Magnetic relaxation over the Bean-Livingston surface barrier, Phys. Rev. B. 47 (1993) 8056–8064, https://doi.org/10.1103/PhysRevB.47.8056.
[32] E. Bartolomé, X. Granados, T. Puig, X. Obradors, E.S. Reddy, G.J. Schmitz, Critical state in superconducting single-crystalline $YBa_2Cu_3O_7$ foams: local versus long-range currents, Phys. Rev. B. 70 (2004) 144514, https://doi.org/10.1103/PhysRevB.70.144514.
[33] M.R. Koblischka, S.Pavan Kumar Naik, A. Koblischka-Veneva, D. Gokhfeld, M. Murakami, Flux creep after field trapping in $YBa_2Cu_3O_x$ foams, Supercond. Sci. Technol. 33 (2020) 044008, https://doi.org/10.1088/1361-6668/ab72c3.
[34] D.M. Gokhfeld, An extended critical state model: asymmetric magnetization loops and field dependence of the critical current of superconductors, Phys. Solid State. 56 (2014) 2380–2386, https://doi.org/10.1134/S1063783414120129.
[35] D.X. Chen, R.W. Cross, A. Sanchez, Effects of critical current density, equilibrium magnetization and surface barrier on magnetization of high temperature superconductors, Cryogenics (Guildf) 33 (1993) 695–703, https://doi.org/10.1016/0011-2275(93)90022-G.
[36] J. Baumann, Y. Shi, A.R. Dennis, J.H. Durrell, D.A. Cardwell, The influence of porosity on the superconducting properties of Y–Ba–Cu–O single grains, Supercond. Sci. Technol. 36 (2023) 085020, https://doi.org/10.1088/1361-6668/ACE480.
[37] L. Ji, M.S. Rzchowski, N. Anand, M. Tinkham, Magnetic-field-dependent surface resistance and two-level critical-state model for granular superconductors, Phys. Rev. B. 47 (1993) 470–483, https://doi.org/10.1103/PhysRevB.47.470.
[38] A.A. Bykov, K.Y. Terent'ev, D.M. Gokhfeld, N.E. Savitskaya, S.I. Popkov, M. I. Petrov, Superconductivity on interfaces of nonsuperconducting granules La_2CuO_4 and $La_{1.56}Sr_{0.44}CuO_4$, J. Supercond. Nov. Magn. 31 (2018) 3867–3874, https://doi.org/10.1007/s10948-018-4668-x.
[39] M.R. Beasley, Will higher T_c superconductors be useful? Fundamental issues from the real world, MRS Bull 36 (2011) 597–600, https://doi.org/10.1557/MRS.2011.159.