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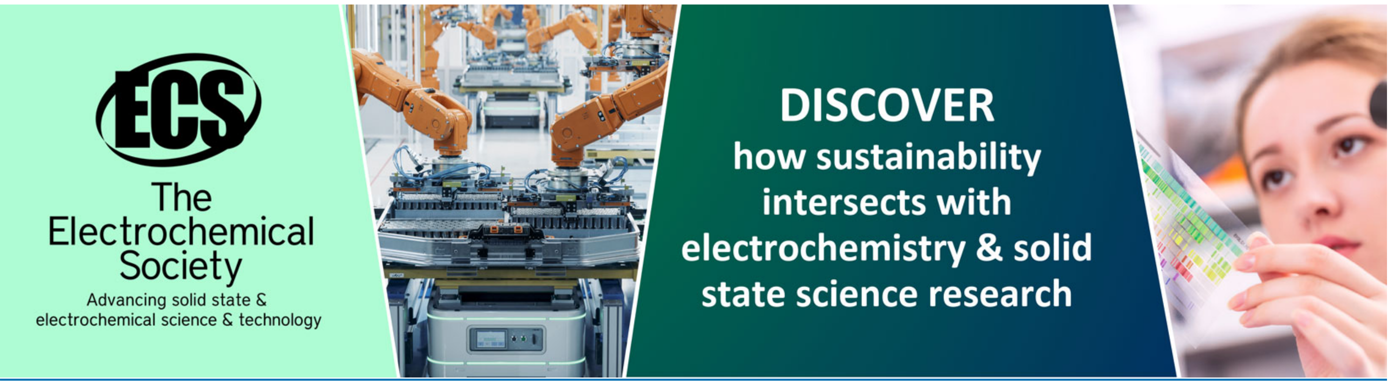

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Investigation of possible electric potential arising from a constant current through a superconductor coil

G G Shishkin[1], A G Shishkin[2], A G Smirnov[1], A V Dudarev[3], A V Barkov[3], P P Zagnetov[1] and Yu M Rybin[1]

[1] Moscow State Aviation Institute, Volokolamskoe sh. 4, Moscow 125871, Russia
[2] Moscow State University, Vorobjovy Gory, Moscow 119899, Russia
[3] Russian Research Center, 'Kurchatov Institute', Moscow, Russia

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Abstract
Edwards *et al* (1976 *Phys. Rev.* D **14** 922) reported that they had observed an I^2-dependent potential resulting from constant current in closed superconducting NbTi, Nb and Pb coils at rest. We have reiterated these experiments and improved them with several variations to understand the nature of Edwards' potentials in more detail. However, at the same time, the current-induced electric field and the potential were not discovered if the Teflon–ground system, which was the base of the superconductor coil assembly, was removed. Our experiments and estimations show that Edwards' potential can arise due to the piezoelectric effects in the Teflon insulator of the superconducting coil assembly. This result is especially important, because papers that cite the results of Edwards *et al* and are based on their conclusions continue to be published to date.

1. Introduction

In this paper, we do not discuss the whole problem of the principal questions of electromagnetism, viz whether a closed circuit carrying constant current can be the source of electric field. Our purpose is to analyse in more detail the phenomena described in [1–3] that are connected with the validity of the conventional Maxwell theory for their experimental configurations.

Edwards and co-workers [1, 2] attempted to prove the possibility of the occurrence of an electric potential on an isolated superconducting closed cylindrical coil with constant current. Based on the not evident suggestion that the module of the moving charge changes in proportion to v^2/c^2 (where v is the charge velocity and c is the speed of light), the authors have obtained the following formula for potential:

$$\phi = \frac{k\alpha L}{\rho C A c^2} I^2, \qquad (1)$$

where L is the circuit length, A is the cross-sectional area of the wire, ρ is the electric charge density ($I = \rho v A$), C is the circuit-to-ground capacitance, $\alpha = (A/I^2)\int J^2\,\mathrm{d}A$ is a factor of the non-uniformity of the conductor cross-section current density (J), and $k \sim 1$ [1] and $k \ll 1$ [2] is a factor that depends on the geometry of the system and some other parameters [1, 2]. Since usually $v \ll c$, the value of this potential should be negligibly small. In this case, the polarity of potential coincides with that of charge carrier. An experiment to check the suggested hypothesis was described in the cited papers. Superconducting bifilar coil (BC) consisting of Nb–Ti wire 701 m long was used as an object for the study in the general part of the experiments. The coil was surrounded by Faraday's cage and placed into the grounded helium cryostat. The use of Teflon allowed one to isolate the coil from all elements of the installation and to reach the insulation resistance over $10^{13}\ \Omega$. The potential between the coil and the grounded cryostat as well as Faraday's cage was measured by an electrometer. In the experiment, a potential up to 100 mV was caused by a 10–20 A current passing through the superconductor coil.

Taking into account the installation parameters (L, A, C, ρ), such a result is in good agreement with equation (1) if the factor $k\alpha$ varies from 60 to 890 [1] and from 18 to 890 [2]. To exclude the boundary and geometry effects, four variations of experiment were carried out. The potential was measured in different parts of the circuit for various temperatures and also at Faraday's cage. For experiments, the potential $\phi \sim I^2$ was always evident.

Edwards *et al* [1] have also concluded that none of the following effects offer a satisfactory explanation: the self-Hall effect, configurational electromagnetic fields, non-steady current effects, thermoelectric effects, flux-flow electromagnetic fields and possible charge transfer on helium bubbles.

On this basis, the conclusion was made that the measured potential could have 'non-Maxwell' origin and was caused by the very movement of Cooper's pairs in superconducting coil. All efforts that followed to explain Edwards' potential were merely suggestions [2, 3, 5–8]. However, we think that other possible sources of the potential were not studied in enough detail. There is, for example, a polarization of the insulator between a BC and the ground or polarization of the superconductor itself. For the first time, the influence of a Teflon polarization was shown in our paper [4], and later some estimations of insulator effects were given by Lemon *et al* [2]. Since Edwards' statement is connected with fundamental physical laws, we have decided to revise it in more detail. This is very important since there are still many publications that use and cite Edwards' results for different theoretical fundamental conceptions [9–17].

2. Experiment

The main part of our installation was the BC. It consists of 705 m of Nb–Ti wire wound in 1660 bifilar turns. The cross-section of the wire was 0.56×10^{-2} cm^2. The electron density was estimated to be 5.6×10^{22} cm^{-3}. At zero external field for a short sample of wire, the critical current was 1500 A. A measured inductance of BC was less than 440 μH.

In agreement with equation (1), a potential on BC was estimated to be about 0.5 V for a current of 500 A and a BC-to-ground screen capacitance of about 100 pF. Two experimental design variations were studied.

Variation I. A schematic diagram of the experimental setup is shown in figure 1. The primary coil consists of $N_1 = 918$ turns of Nb-Ti wire and its inductance is 0.123 mH. The secondary coil consists of $N_2 = 30$ turns with 0.115 mH. This coil and BC were divided by the Teflon insulator with a resistance of more than $10^{14}\ \Omega$. The BC-to-ground screen capacity was in the range of 120 pF and the CR time constant was equal to 1.2×10^4 s. An electrometer with an input resistance of more than $10^{16}\ \Omega$ and an input capacitance of 0.5 pF has been used. Its sensitivity was at least 0.02 mV. Measurements of the potential were taken both at the rising and the falling fronts of the current in the BC.

The current was determined by the Hall probe using several non-bifilar turns in the BC. The cross-section of the coil assembly is shown in figure 2.

The principal difference between the first variation of the setup and Edwards' one is as follows:

(a) the availability of non-conducting current input by means of a superconducting transformer;
(b) the possibility to increase the current to a critical value;
(c) the possibility to change the current rate $\mathrm{d}I/\mathrm{d}t$;
(d) the possibility to measure ϕ in the external magnetic field.

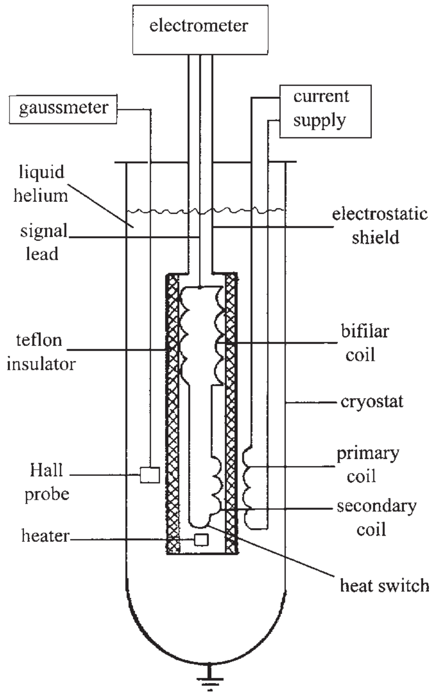

Figure 1. Schematic diagram of the apparatus: Variation I.

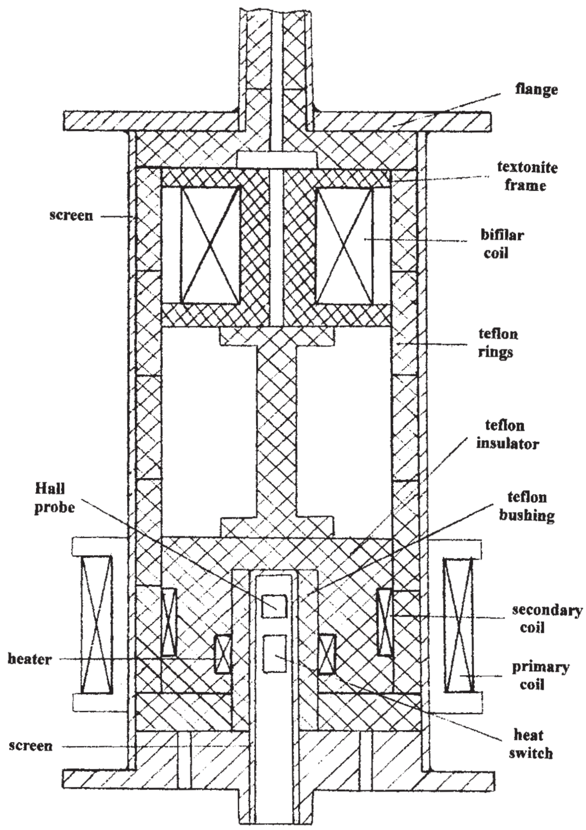

Figure 2. Cross-section drawing of the coil assembly.

Besides, in the experimental configuration of [1] the electrometer input was connected to a cage surrounding the superconducting coil rather than to the coil itself. Any effect that only redistributes the charge on the coil without affecting its total apparent net charge is to be the source of the potential [2]. In our configuration of Variation I of experiments, the electrometer input was connected to the coil itself. Now we describe the general results obtained in Variation I of the experiments.

Figures 3(*a*) and (*b*) illustrate the influence of current magnitude and polarity as well as $\mathrm{d}I/\mathrm{d}t$ on the potential difference between BC and the cage. In our experiment, the value of $\mathrm{d}I/\mathrm{d}t$ = const was realized by the programmed current supply. The circuit relaxation time RC was about 10^4 s. Figures 3(*a*) and (*b*) show that ϕ is negative for current sign '+I' as well as for '$-I$'. For these cases, ϕ is equal to about 300 mV. A small positive potential (upper absciss axis) in the vicinity of $I \approx 0$ arises from the null drift of the electrometer during the experiment (~1400 s). The potential changes in the time interval 0–100 s (figure 3(*b*)) can be connected with transient processes in liquid He after switching the current direction by interchanging the connection of the primary coil. There was no technical possibility to change automatically the current direction of the primary coil in our experimental setup.

The typical dependencies of ϕ versus I are given in figure 4 with the current I_1 in the primary coil as a parameter. Experimental curves $\phi(I)$ can be approximated by the function $\phi \sim I^n$, where $n = 1.78 \pm 0.23$. Figure 4(*a*) shows that the polarity of the potential ϕ is negative if currents I and I_1 have the same direction. The potential ϕ is positive for opposite directions of currents I and I_1, i.e. for $+I$ and $-I_1$ and for $-I$ and $+I_1$ (figures 4 and 5). The signs of I and I_1 are accomplished by the heat switch (figure 5). One can see positive potential changes in figure 5 when the heat switch is open and $I \sim 0$. Different reasons for this 'non-superconductivity' are out of the scope of this paper, but the physical reasons of such potentials can be connected with Teflon polarization from primary coils, final resistance of some part of the superconductor, thermoelectric effects, possible charge transfer on helium bubbles and other effects [1, 2].

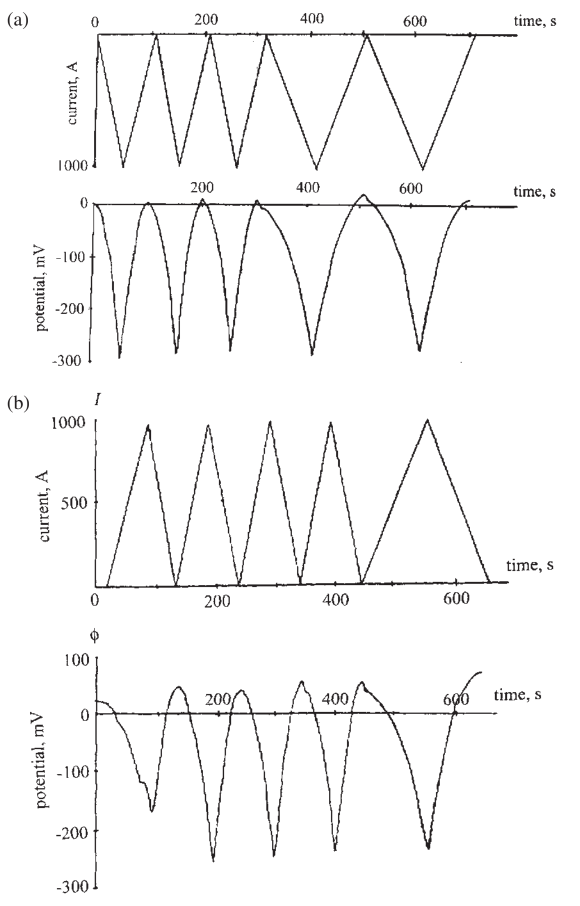

Figure 3. Sample experimental data (I, ϕ versus time) obtained in Variation I. Here I is the current in BC and ϕ is the potential of BC.

If the charge of a moving particle is not conserved, as it was assumed by Edwards, the sign of the potential should not change. In addition, according to the equation (1) the value of ϕ should not depend on the signs of currents I and I_1, but experiments showed that it did. With these contradictions in mind, we investigated the second variation of the experiment. Some years ago, we published primary results of these experiments in [4].

Variation II. A schematic diagram of the apparatus is shown in figure 6. A heat switch was replaced by a magnetically controlled one and the Teflon insulator was withdrawn from the BC vicinity. A magnetic switch was made of $Pb_{0.6}Sn_{0.4}$ superconducting wire 150 mm long with a cross-sectional area of 50 mm^2. Its critical current value was 1000 A and the critical field was 600 G. The normal resistance of the switch was $2.5 \times 10^{-5}\ \Omega$ and I in the superconducting BC could exist for 1 h. The switch gave a negligible charge transfer on helium bubbles for currents less than 650 A. Copper rods were used for the current input with the BC being mounted on them. The BC-to-ground capacitance turned out to be 147 pF and its resistance was more than $10^{14}\ \Omega$. The experimental steps included the following operations.

A magnetic switch was opened by a supercritical field on the control coil and the 500 A current was driven in the BC. Then the switch was closed and the current supply was turned off. An electrometer was connected to one of the current rods. The upper parts of the current rods as well as the signal lead were screened and a zero potential of the BC was established. At the same time, when a magnetic switch was put in its normal (open) state, it was possible to measure current and potential variations (figure 7). The graphs similar to those in figure 7 are described in [4] in detail. The electrometer was terminated in circuit at the time moment t_1. The magnetic switch was opened five times (figure 7) and I was decreased step by step from 500 A to 0. One can see that ϕ changes are not proportional to current changes in BC. The potential ϕ ($\leqslant$7 mV) is very small compared with potentials in Variation I experiments (~350 mV) and determined by the null drift of the electrometer. The value of potential $|\phi|$ continues to increase after switching off the current I. Small abrupt changes of ϕ after time moment t_1 can be explained by transient processes in the circuit in the time of current control by the magnetic switch. As stated above, we expected to obtain BC potential of about 0.5 V for the 500 A current. However, potential deviations were not observed apart from signal noise oscillations and electrometer drifting voltage.

3. Discussion

Part of the results were the same as in Edwards' case, but in the second variation of experiments the potential was found to

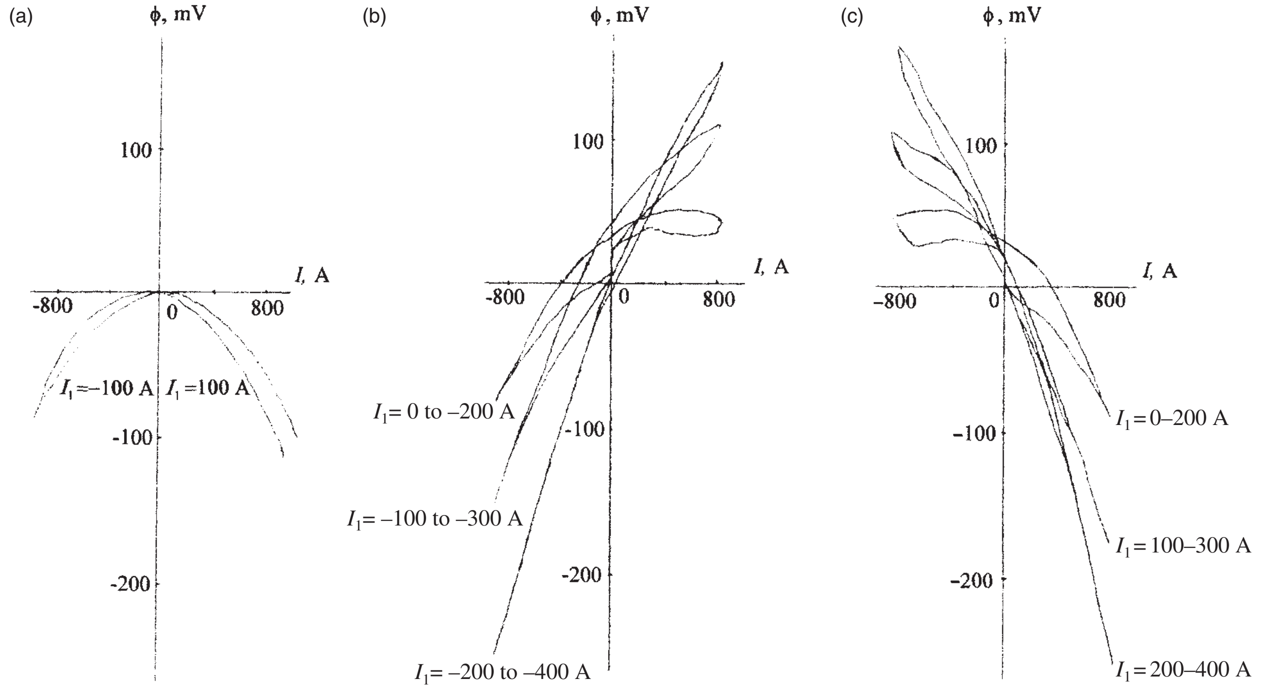

Figure 4. $\phi \sim I^n$ dependence obtained in Variation I: (*a*) data obtained for identical signs of I and I_1; (*b*, *c*) data obtained for various combinations of currents I and I_1.

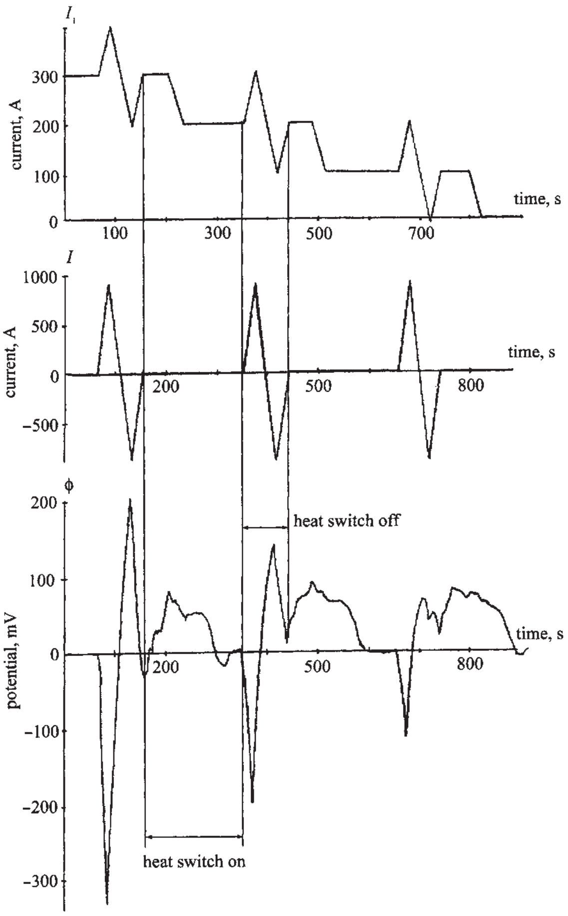

Figure 5. Influence of current directions I and I_1 on potential signs.

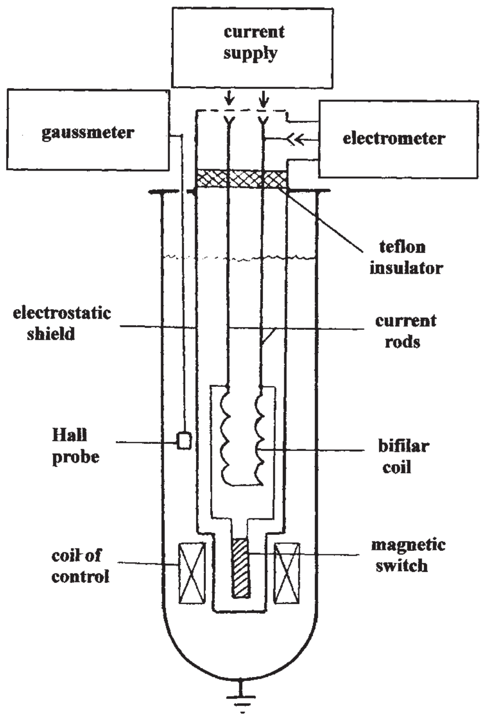

Figure 6. Schematic diagram of the apparatus: Variation II.

be different although the principal characteristics of apparatus (L, A, C, ρ) did not change. Thus, in this case our experiments have led to essentially different results in comparison with Edwards' ones. The second variation of experiments has shown that the current-produced potential did not appear up to current values of 500 A, thereby disproving the hypothesis of non-conservation of a moving particle charge. Regarding the

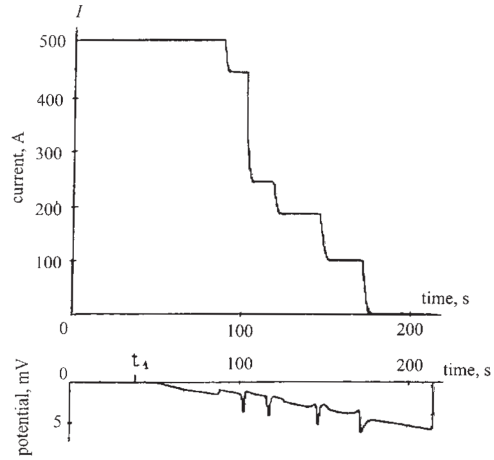

Figure 7. I and ϕ versus time in the circuit without Teflon insulators.

second variation, we suppose that the voltage between the coil and the ground was initiated by a polarization of Teflon under the pressure of the secondary coil caused by the self-magnetic field.

Let us estimate the principal possibility that the measured potential depends on the piezoeffect in Teflon insulation between the secondary coil and the grounded screen. As is known, the piezopotential can be calculated as follows:

$$\phi_p = \frac{Fd}{C}. \quad (2)$$

In our case, d is a Teflon piezoelectric module, C has the same meaning as in equation (1) (the circuit-to-ground capacitance) and its value is 120 pF, and F is the force caused by Teflon deformation. Unfortunately, we do not know the exact value of d for our materials at cryogenic temperatures. However, one can be sure that at positive temperatures (Celsius scale) it does not exceed $d = 1$–$2\ \text{pC N}^{-1}$ for PTFE [18].

In reality, the correct calculation of piezoelectric potentials is complicated for this experimental setup. The rough estimations of a magnetic force on adjacent wires for a long straight wire approximation were carried out by Lemon *et al* [2]. We carried out estimations for different cases that include the radial deformation of windings of the secondary coil, the vertical shift of central surfaces of the primary and secondary coils, the axial shift of windings (axis forces) and the shift of axes of coils. The force caused by the last effect was the largest one. One way to estimate F is as follows. The force F has magnetic nature and is connected with the fact that the axes of primary and secondary coils are shifted at unknown small distance δ. As the primary coil is fastened to the body of the cryostat, the force F leads to the shift of the secondary coil axis in the perpendicular direction of the primary coil axis (figure 8). As a result, the secondary coil presses at the insulated Teflon rings and piezopotential arises. We can estimate F by the following expression:

$$F = I \Delta B N_2 \pi R_2, \quad (3)$$

where $R_2 = 61$ mm and $\Delta B = B' - B''$ (see figure 8) arises due to the shift of coil axes and can be estimated as

$$\Delta B \approx \frac{\mu_0 I_1 N_1}{4}\left(\frac{1}{\Delta R - \delta} - \frac{1}{\Delta R + \delta}\right) \approx \frac{\mu_0 I_1 N_1 \delta}{2\Delta R^2}, \quad (4)$$

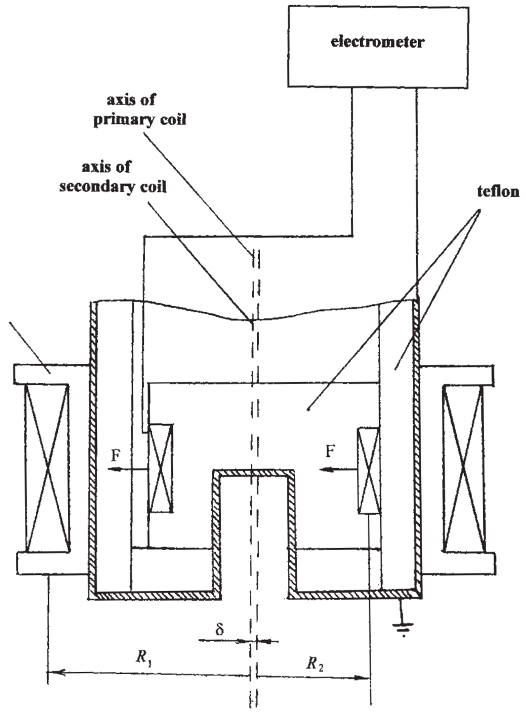

Figure 8. Schematic diagram of the arising ampere force.

where I_1 is the primary current and $\Delta R = R_1 - R_2 = 18$ mm. Hence,

$$\phi_p = \frac{\mu_0 \pi R_2 N_1 N_2 \delta d}{2\Delta R^2 C} I I_1. \quad (5)$$

Thus, similarly to equation (1), $I \sim I_1,\ \phi \sim I^2$.

In the experiment for $I_1 = 100$ A and $I = 1000$ A, the potential ϕ was 250 mV. For these currents and $\delta \approx 2$ mm (which is the greatest possible measured value of δ for our apparatus design), the force F equals 2040 N. Then $d = 0.0147\ \text{pC N}^{-1}$ from equation (2). In principle, it is important to know the product δd in equation (5), so the shift of coil axis can be actually much less in experimental conditions (for example, if $\delta = 0.1$ mm then $d \approx 0.3\ \text{pC N}^{-1}$ for the above-mentioned figures). The range of possible potential changes (~50–500 mV) corresponds to possible changes of $\delta d \sim 0.01$–$0.5\ \text{pC mm N}^{-1}$ for different I and I_1. Thus, these estimations and the dependence like $\phi_p \sim I^2$ as well as $\phi_p \sim I I_1$ support the piezoeffect hypothesis.

4. Conclusions

Thus, if we summarize the results of our analysis of electric fields arising from the current in closed superconductor coils at rest, we can conclude that the observed phenomena are connected with the polarization of Teflon and therefore the conventional Maxwell theory is valid in these experiments.

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