Evaluation of film thickness dependency of the reversible fluxoid motion in the third harmonic voltage method

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Abstract

Significant overestimation of the critical current density J_c is found for the third harmonic voltage measurement method for thin YBCO superconductors. This is caused by a reversible flux motion in pinning potentials, which is known to be significant for superconductors of thickness comparable to or smaller than Campbell's AC penetration depth. In this paper the effect of reversible flux motion on the estimation of J_c by this method with different thicknesses is also theoretically investigated by using the Campbell model for the force-displacement characteristics of flux lines. Although the factor of overestimation can be approximately explained by the Campbell model, agreement is not satisfactory. It is considered that the variation in the flux motion from reversible to irreversible states seems to take place much faster than assumed in the Campbell model.

Keywords: critical current density, YBCO coated conductor, third harmonic voltage, reversible flux motion
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1 Introduction

Recently long YBCO coated-conductors with high critical current density are successfully fabricated [1]. Hence, simple and reliable measurement methods are required for the critical current density of long coated conductors. The measuring method of the third harmonic voltage seems to be suitable for the purpose, since the measurement can be done without any contact with specimens. The critical current density J_c of a superconducting thin film can be estimated by measuring the third harmonic voltage induced in a pick-up coil put on the film which is exposed to AC magnetic field [2]. Since the third harmonic voltage rapidly grows when the AC magnetic field penetrates through the film, J_c can be directly measured from the threshold value of AC magnetic field at which the third harmonic voltage appears. In addition, the DC E-J characteristic can be estimated by changing the frequency of AC magnetic field.

However, when the film thickness d is comparable to or smaller than Campbell's AC penetration depth λ_0', a reversible flux motion becomes remarkable and J_c is overestimated by this method [3]. In our previous study, the simplified Campbell model was applied to explain the overestimation factor with that of experimental results [4]. This model assumes a reversible and linear relationship between the pinning force and the displacement of flux lines and an irreversible constant force for the displacement larger than the interaction distance d_i. However, the observed overestimation factor at large λ_0' is significantly lower than the theoretical prediction by the simplified Campbell model. This seems to be caused by the too simplified assumption that the flux motion is completely reversible until u reaches d_i. Thus, it is necessary to analyse by

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using the original Campbell model.

In this study, the E-J characteristic is measured with using the third harmonic voltage method for YBCO films with different thicknesses. The overestimation factor of J_c which is compared with J_c of four terminal method at the same electric field criteria is estimated as a function of the film thickness, and the result is compared with the analysis with the original Campbell model which describes the reversible flux motion.

2 Experiments

The measured specimens were YBCO coated tapes made by IBAD/PLD method. The J_c was measured with using the third harmonic voltage method for different thicknesses of specimens in the magnetic field range of 0–3 T. The film thickness was in the range of 0.5–1.5 μm. The specifications of these specimens are listed in Table 1. The specimen was cooled by liquid nitrogen at 77.3 K and a DC magnetic field was applied along the c-axis normal to the tape surface. The AC coil made of a copper wire was mounted just above the superconducting tape surface with its axis normal to the surface as shown in Fig. 1 in which the size and configuration of the coil and the thin film are illustrated. AC drive current $I_0 \cos 2\pi f t$ of the frequency f of 130–1024 Hz was given to the coil to apply the AC magnetic field $H_0 \cos 2\pi f t$ to the tape. The voltage induced by the penetrating magnetic flux in the pick-up coil was measured by a lock-in amplifier. Appreciable third harmonic voltage was generated when an AC magnetic flux penetrates through the superconducting film. In this situation, the current density is given by [2]

$$J = \frac{2K}{d} I_{\mathrm{th}}, \tag{1}$$

where d is the film thickness and I_{th} is the threshold coil current at which the third harmonic voltage is generated in the coil and $K (= 3872\ \mathrm{m}^{-1})$ is a constant determined by the coil geometry and distance between the coil and the film surface. At the same time the electric field is estimated as

$$E = \frac{3\sqrt{3}}{8}\mu_0 f J d^2. \tag{2}$$

Then, V_3-I_0 characteristics were measured. From these characteristics, the E-J characteristics were obtained.

The magnetic relaxation was measured in a DC magnetic field along the c-axis at 77.3 K using a SQUID magnetometer in the range of low electric field [4] range of $E = 10^{-10}$–10^{-8} V/m. The four terminal method was also used in the magnetic field parallel to the c-axis to measure the E-J characteristics in the range of usual electric field range of $E = 10^{-4}$–10^{-2} V/m at 77.3 K.

3 Theory

In order to understand the effect of the reversible flux motion on the estimation of $J_{\rm c}$, the relationship between the third harmonic voltage and the coil current is analysed using the Campbell model [5] for the force-displacement characteristics of flux lines. In this model, the relationship between the pinning force density F and the displacement of flux lines u from an equilibrium position is assumed as

$$F = J_{\rm c}B\left[1 - \exp\left(-\frac{u}{d_{\rm i}}\right)\right], \tag{3}$$

where $J_{\rm c}B$ is the usual irreversible pinning force density. When the magnetic field is applied along the z-axis and the flux lines move to x-axis, the continuity equation of flux lines is described as

$$\frac{{\rm d}u}{{\rm d}x} = -\frac{b}{B}, \tag{4}$$

where b is a variation in the magnetic flux density due to the flux motion from the equilibrium state. This variation causes the variation in the Lorentz force, and the force balance equations is written as

$$F + \frac{B}{\mu_0}\cdot\frac{{\rm d}b}{{\rm d}x} = 0. \tag{5}$$

Elimination of the displacement of flux lines u leads to

$$\frac{\mathrm{d}^2 b}{\mathrm{d}x^2} - \frac{b}{\lambda_0'^2}\left(1 + \frac{1}{\mu_0 J_\mathrm{c}} \cdot \frac{\mathrm{d}b}{\mathrm{d}x}\right) = 0, \tag{6}$$

where λ_0' is the Campbell's AC penetration depth. λ_0' is given by [5]

$$\lambda_0' = \left(\frac{B a_\mathrm{f}}{2\pi \mu_0 J_\mathrm{c}}\right)^{1/2} \tag{7}$$

for the pinning by pointlike defects, where a_f is the flux line spacing given by

$$a_\mathrm{f} = \left(\frac{2\phi_0}{\sqrt{3}B}\right)^{1/2} \tag{8}$$

with ϕ_0 denoting a flux quantum.

In this paper, Eq. (6) was solved numerically, and the third harmonic voltage was calculated as a function of the AC field amplitude $\mu_0 H_\mathrm{m}$ for various film thicknesses. Then, the critical current density was estimated from the relationship between the third harmonic voltage and $\mu_0 H_\mathrm{m}$ with a certain threshold of the third harmonic voltage, as in experiments. The critical current density defined in this way with $E_\mathrm{c} = 3.0 \times 10^{-6}$ V/m is denoted by J_c'.

4 Results and Discussion

Fig. 2 shows the E-J characteristics of specimens measured by the four terminal method, the DC magnetization method and the third harmonic voltage method at 77.3 K. It is found that the E-J curves obtained by the third harmonic voltage method at medium electric fields are shifted to the direction of higher J, suggesting an overestimation of J value, in comparison with those by other two methods.

The factor of overestimation is now defined by the ratio of J_c' to J_c obtained by extrapolating the E-J curve of the four terminal method to $E_\mathrm{c} = 3.0 \times 10^{-6}$ V/m. Fig. 3 shows the magnetic field dependence of the factor of overestimation for each specimen at 77.3 K. It is found that although the factor of overestimation is almost constant in thick film #3, it increases with increasing the magnetic field at thin films #1 and #2.

Fig. 4 shows the calculated V_3 vs. $\mu_0 H_\mathrm{m}$ relationship. It is found that V_3 appears gradually with increasing $\mu_0 H_\mathrm{m}$ and that the threshold value of $\mu_0 H_\mathrm{m}$ becomes larger when λ_0'/d becomes larger. Thus, it shows that the overestimation of J_c occurs when J_c is determined with the certain threshold voltage V_3th as shown in Fig. 4. Although V_3 is not predicted to appear for $H_\mathrm{m} < J_\mathrm{c}\lambda_0'$ by the simplified Campbell model, V_3 appears gradually at H_m smaller than $J_\mathrm{c}\lambda_0'$ in the Campbell model. Fig. 5 shows the factor of overestimation in the Campbell model as a function of λ_0'/d with various values of V_3th. Thus, the theoretical factor of overestimation is simply given by the ratio of J_c' to J_c in Eq. (3). It is found that the factor of overestimation drastically changes by the choice of V_3th-value. In addition, an appreciable underestimation of J_c is predicted when V_3th is reduced.

The experimental factor of overestimation is compared with the theoretical ones using the simplified Campbell model and the original Campbell model in Fig. 6. Here, λ_0' is calculated by Eq. (7) using the J_c values extrapolated from the E-J curves of the four terminal method to $E_\mathrm{c} = 3.0 \times 10^{-6}$ V/m. It is found that the factor of overestimation increases with increasing λ_0'/d at thin films #1 and #2. This is due to the effect of the reversible flux motion and the influence of the reversible flux motion is caused by large λ_0' at high magnetic fields. The underestimation of J_c predicted by the Campbell model for $\lambda_0'/d < 1$ is not observed in this measurement. This may be attributed to the penetration of AC magnetic field by the coil from the other surface of the specimen, because the specimen size is finite. The overestimation factor predicted by the simplified Campbell model is significantly higher than the observed one for large λ_0'/d. On the other hand, the prediction of the Campbell model with $V_\mathrm{3th} = 0.01$ is closer to the experiments. Thus, the influence of the reversible flux motion can be more accurately treated in the original Campbell model. However, the factor of overestimation is still larger than the experiments and does not meet in a single curve being different for each specimen as predicted theoretically. This means that the behavior of flux lines is not correctly described by the Campbell model. That is, the variation of the flux motion from reversible to irreversible states seem to take place much faster than expected in Eq. (3). This is considered to be caused by the wide distribution width of pinning forces in high temperature supercondutors. Thus, it is necessary to find out a correct F-u characteristic.

5 Summary

E-J characteristics are measured using the third harmonic voltage method for YBCO films with different thicknesses, and the factor of overestimation of J_{c} by this method is obtained by comparing the results with the E-J characteristics of the four terminal method. It is found that the factor of overestimation increases with increasing λ_0'/d in thin specimens. To investigate the influence of the reversible flux motion to the overestimation factor the third harmonic voltage is calculated using the Campbell model for the F-u characteristic. Although the obtained overestimation factor agrees qualitatively with the experimental results, quantitative agreement is not satisfactory. It is expected that the behavior of flux lines is not correctly described by the Campbell model. Thus, a new model is required which describes the F-u characteristic correctly.

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Table 1: Specification of specimens.

Specimen	Thickness d (μm)	Size (mm)	J_{c} (A/m^2)
#1	0.5	5×5	2.60×10^{10}
#2	1.0	10×10	2.02×10^{10}
#3	1.5	10×10	1.53×10^{10}

Figure captions

Fig. 1 Schematic illustration of arrangement of coil and superconducting thin film.

Fig. 2 E-J characteristics of (a)#1, (b)#2 and (c)#3 measured by 4 terminal method, SQUID and third harmonic voltage method.

Fig. 3 Overestimation factor of (a)#1, (b)#2 and (c)#3 which J_{c} is defined by the result of four terminal method and J'_{c} is measured by third harmonic voltage method at $E_{\mathrm{c}} = 3.0 \times 10^{-6}$ V/m .

Fig. 4 V_3-$\mu_0 H_{\mathrm{m}}$ characteristics by theoretical analysis by the Campbell model.

Fig. 5 Overestimation factor in the Campbell model as a function of λ'_0 normalized by the thickness with various $V_{3\mathrm{th}}$.

Fig. 6 Factor of overestimation as a function of λ'_0/d estimated from experimental results and theoretical estimation.

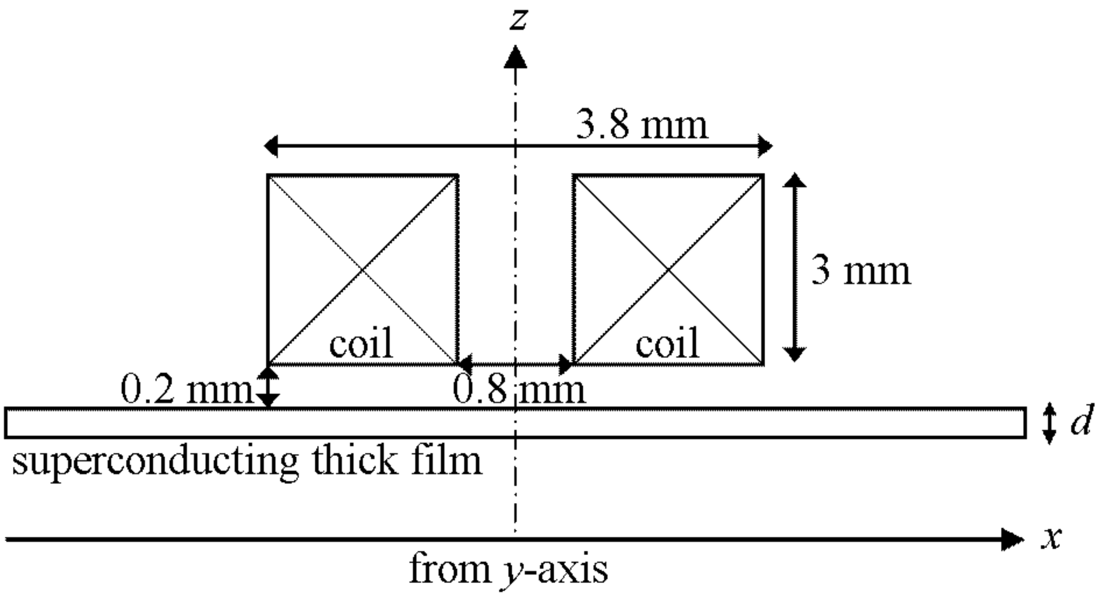


Fig. 1: T. Yoshida *et al.* WTP–20/ISS2006

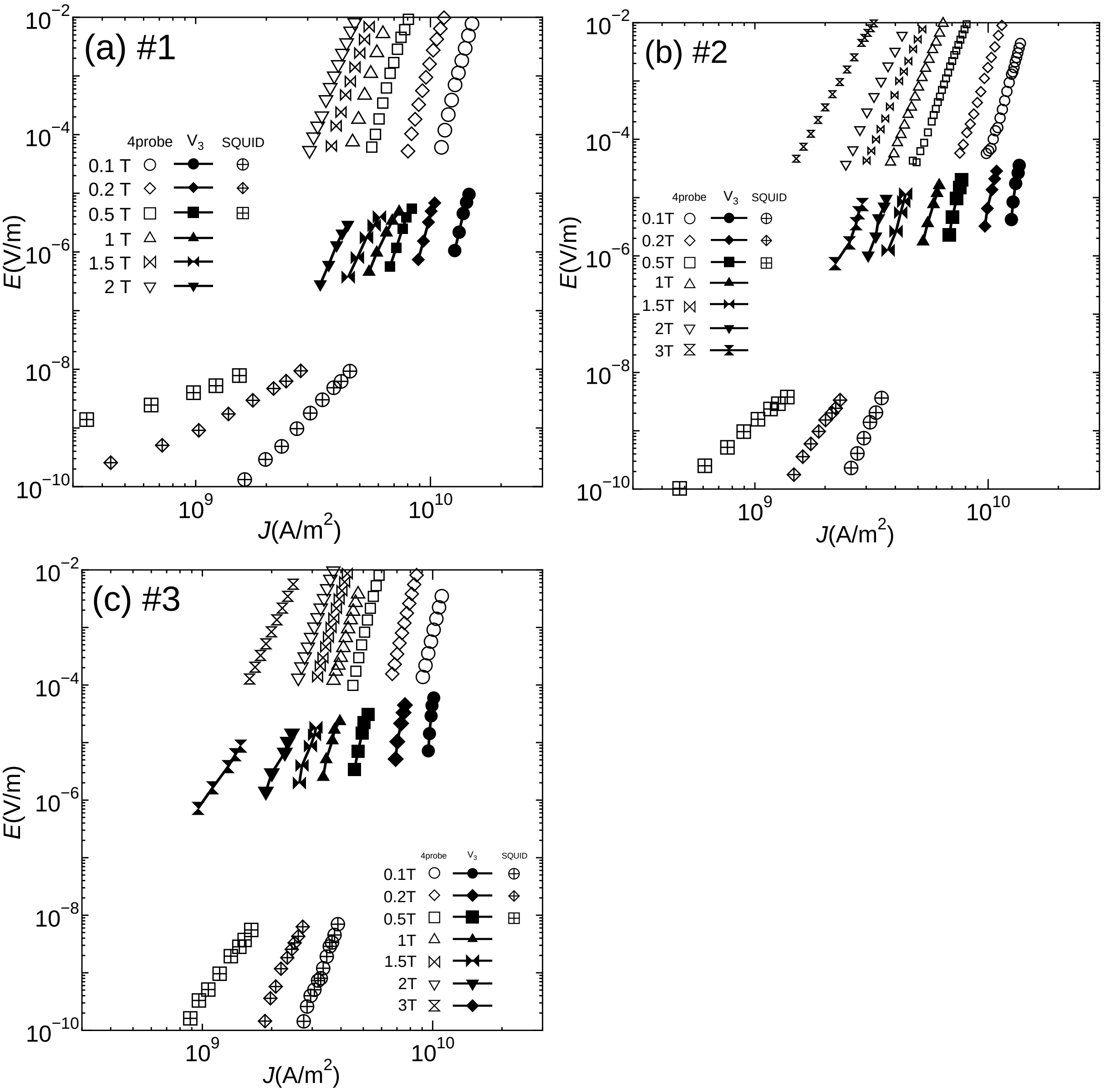
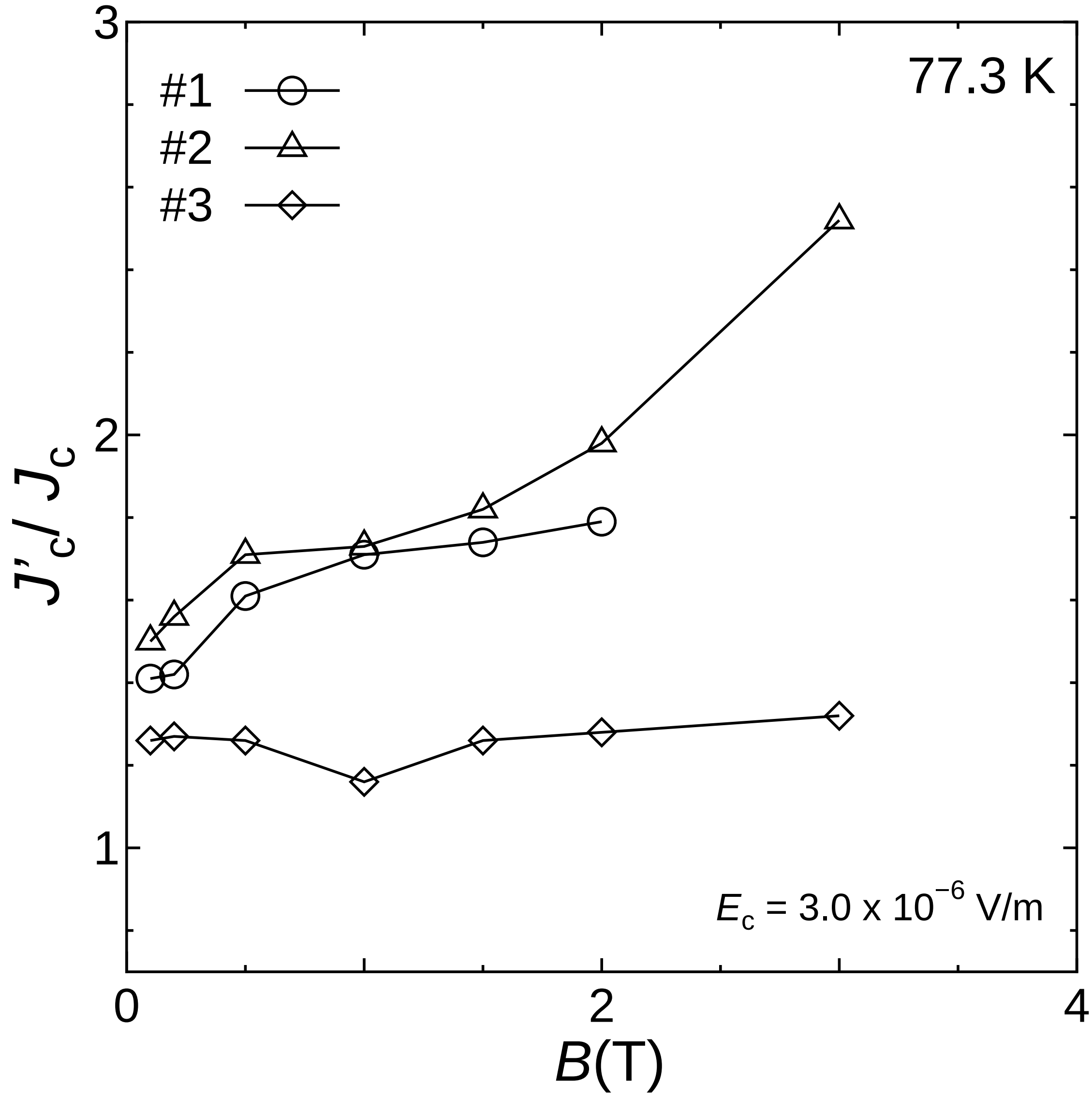


Fig. 2: T. Yoshida *et al.* WTP–20/ISS2006



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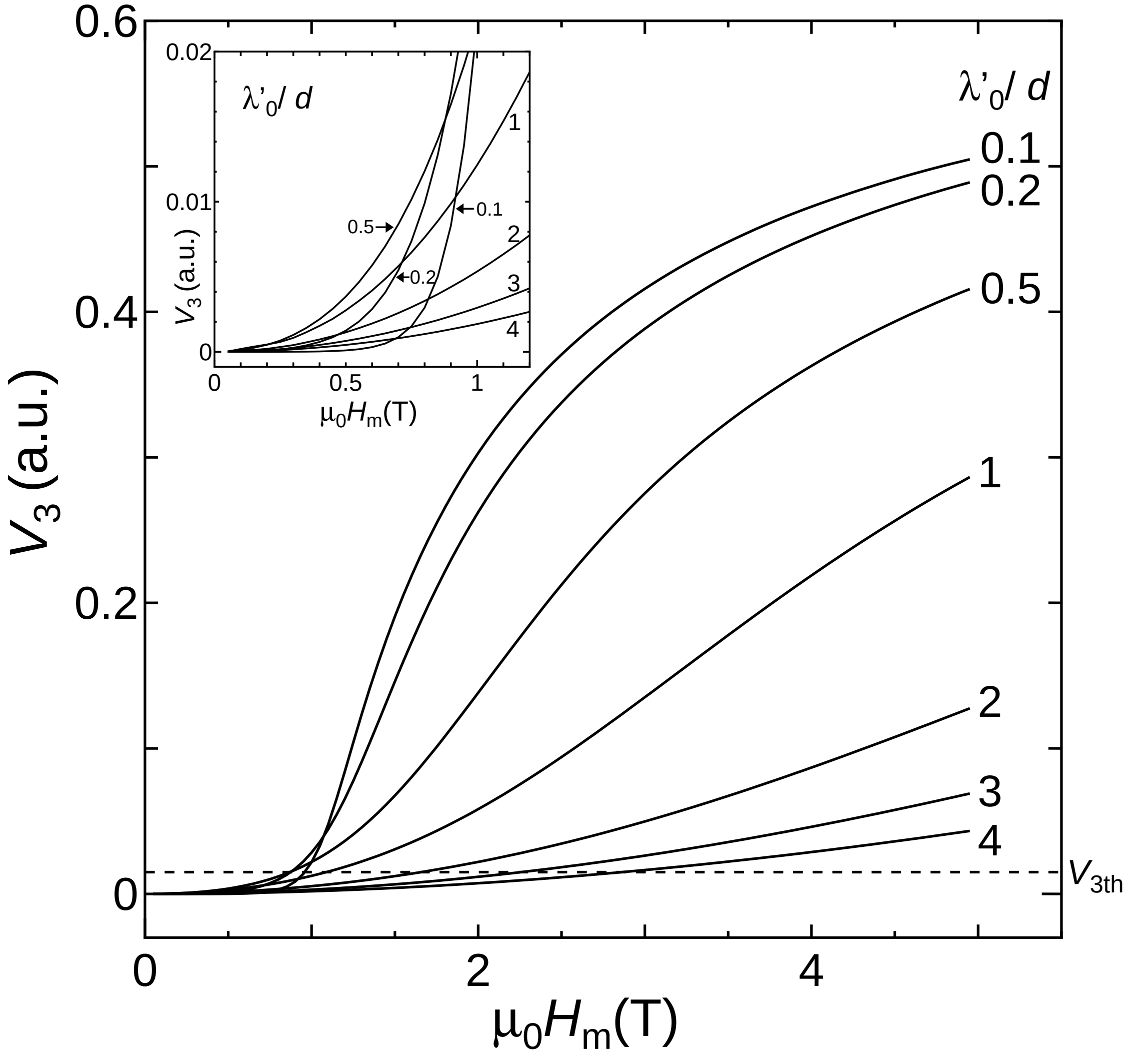

Fig. 4: T. Yoshida *et al.* WTP–20/ISS2006

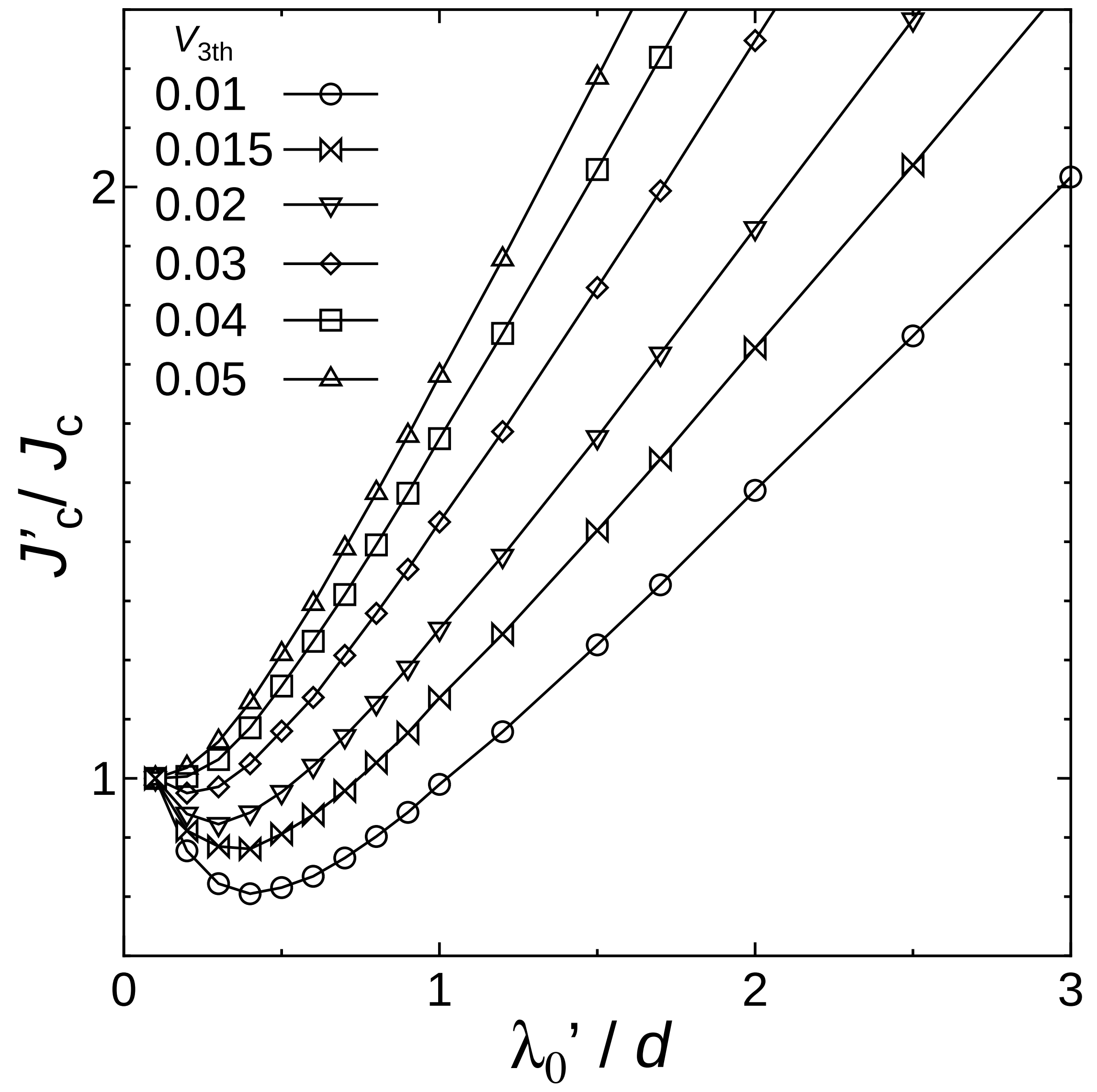

Fig. 5: T. Yoshida *et al.* WTP–20/ISS2006

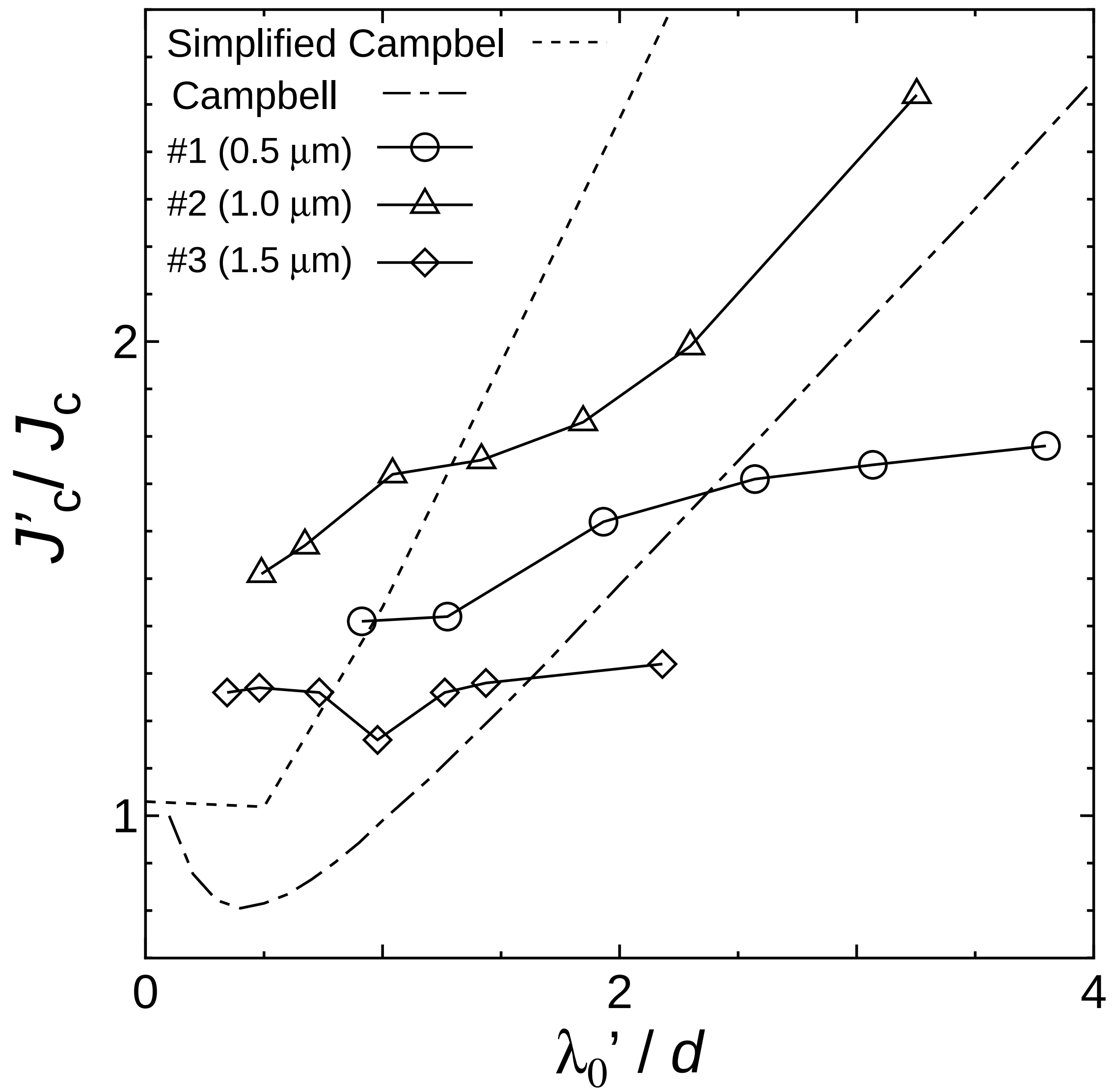

Fig. 6: T. Yoshida *et al.* WTP–20/ISS2006