Dependence of induced third harmonic voltage on width of superconducting coated conductor

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Abstract

When an AC magnetic field of a suitable magnitude by a small coil is applied locally to a surface of a superconducting Coated Conductor (CC) tape, a third harmonic voltage (V_3) is induced in the coil. The critical current density (J_c) of the film is evaluated from AC magnetic field dependence of V_3. In this study, a minimum width of the film for evaluation of correct J_c is numerically investigated using Finite Element Method. It is found that the correct measurement can be done when the width is more than 1.2 times as large as the outer diameter of the coil. This shows that the third-harmonic voltage method is useful for the J_c measurement of narrow CC tapes.

Keywords: critical current, third harmonic voltage, FEM
PACS: 74.25.Sv, 74.76.-w, 02.70.Dh

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1 Introduction

Fabrication of large area superconducting films with high and uniform critical current density is desired for various applications. The critical current density, J_c, is one of the most important parameters for such applications, and a nondestructive and contactless method to measure the distribution of J_c is needed to characterize large-area films. Claassen *et al.* proposed a method to measure the local J_c of films by detecting a third harmonic voltage induced by an applied AC magnetic field [1]. In this method, an amplitude, V_3, of the third harmonic voltage induced in a small coil is measured as a function of an amplitude of AC current, I_0, applied to the coil to generate the AC field. Usually coils of several mm in diameter are used. J_c is proportional to the threshold value (I_{c0}) of I_0 above which nonzero V_3 appears. Hence, J_c can be estimated from I_{c0}. The theoretical analysis by Mawatari *et al.* [2] based on the critical state model in a simplified geometry showed that the above principle is correct. Our previous study with Finite Element Method (FEM) [3] clarified a validity of this principle even in a practical arrangement of coil and thin film.

Recently relatively long Y-123 coated-conductor (CC) tape with high J_c has been successfully fabricated [4] and its application at liquid nitrogen temperature is expected. The use of present inductive method is considered to be very useful for a continuous on-line measurement of J_c of a long CC tape, since it is a contactless and nondestructive method.

In this method, it is required for safety of the measurement that the width of superconductor, D, should be more than twice as large as the outer diameter of the coil to eliminate the edge effect. However, the application of the present method to narrow CC tape is desired. Hence, it is necessary to clarify the applicable limit of the width of superconductor for the present inductive method.

In this paper, the magnetic field distribution in a superconducting thin film with various width was numerically calculated by FEM to estimate the third harmonic voltage V_3, and the threshold amplitude of current I_{c0} is obtained from V_3-I_0 characteristics. Discussion is given on the relationship between I_{c0} and the width of the superconducting thin film. In addition, the effect of distance between the coil and the film on I_{c0} was also investigated, since the distance between the coil and the CC tape might be changed in real contactless measurement. The optimal condition on the distance is discussed.

2 Simulation

JMAG studio version 7 of Japan Research Institute was used for the calculation in FEM. A following circumstance was assumed: a single coil of inner and outer diameters of 2 mm and 5 mm and a height of 1 mm is mounted at a position of 0.2 mm or 2 mm apart from the surface of a thin film of thickness 0.6 μm. The width of the film, D, was changed from twice of outer diameter of the coil, 10 mm, down to 2 mm. The value of J_c of the film is 1.0×10^{10} A/m^2. The number of turns of windings in the coil is 400. An AC magnetic field is applied normal to a wide surface of the film by a sinusoidal driving current $I_0 \cos \omega t$. The magnetic flux density distribution in the space including the film and coil system is calculated by FEM in each phase of AC field assuming the critical state model. Because of symmetry of the system, we calculated the field and current distributions inside 1/2 of the whole system as shown in

Fig. 1.

The voltage induced in the pick-up coil was derived from the magnetic flux which interlinked the pick-up coil. The amplitude, V_3, and phase, θ_3, of the third harmonic voltage were derived by Fourier analysis. The threshold current, I_{c0}, at which V_3 began to appear was estimated from V_3-I_0 characteristics.

3 Results and Discussion

Fig. 2 shows the V_3-I_0 curves for various values of the film width, D. V_3 starts to appear when I_0 increases beyond some threshold current, I_{c0}. Dependence of I_{c0} on D is shown in Fig. 3. It is found that I_{c0} takes a constant value of 70 mA in the range of 6–10 mm. The theoretical estimation by Mawatari *et al.* [2] for an infinity wide thin film in a parallel AC field predicts I_{c0} to be 64 mA. Hence, it can be said that the present method is applicable down to the film width of 6 mm, i.e., 1.2 times larger than the outer diameter of the coil. Thus, this method is applicable even in severer condition than expected. When D is smaller than 6 mm, I_{c0} decreases monotonically with decreasing D. This comes from easier penetration of AC field due to limited shielding current in the film.

Fig. 4 shows the distribution of the shielding current at $I_0 = 70$ mA, the critical amplitude, in the cases of $D = 10, 5, 2$ mm. When the width is 10 mm, circular shielding current flows in the middle of the film and the current does not flow in the outer region. Hence, the same situation is considered to occur in the film wider than 6 mm. On the other hand, when the width is shorter than 6 mm, the shielding current flow is limited by the film width, resulting in the penetration of the AC field. This leads to the smaller I_{c0}.

A similar calculation was done for a different distance between the coil and the film surface to look for the effect of distance on the measurement. The width dependence of I_{c0} for the case of distance of 2 mm is shown in Fig. 5. It is found that I_{c0} starts to decrease with D at $D = 7$ mm. This critical size is slightly larger than in the previous case of 0.2 mm in the distance. This is caused by a spread of AC magnetic field in a wider area by making the distance large. At the same time, the saturated value of $I_{c0} = 600$ mA for a large width is about one order of magnitude larger than the previous case, suggesting that much larger current is necessary to reach a full penetration of AC field.

When the distance between the coil and the film surface is increased, the applicable range of the film width is diminished and the larger current source is needed. On the other hand, the dependence of I_{c0} on the distance becomes lower at the larger distance. In the case of continuous J_c measurement of long CC tape the distance between the fixed coil and moving CC tape might be slightly changed, resulting in an error in estimated J_c-value. This error becomes larger for the shorter distance between the coil and surface of CC tape. Hence, the optimal condition of this distance should be investigated in more detail for the J_c measurement of CC tape.

4 Summary

The effect of the width of thin film on the measurement of the critical current density using the third harmonic voltage is investigated by numerical calculation by FEM. The following results are obtained.

1. It is found that the evaluation of J_c is possible when the film width is more than 1.2 times as larger as the outer diameter of the coil. Hence, this measuring method is useful for narrow CC tapes.
2. The threshold current, I_{c0}, decreases when the film width is less the above critical value, because of the decrease in shielding current in the film resulting in a penetration of AC field from the film edge.
3. It is found that the minimum film width increases and much larger current is needed to evaluate J_c when the distance between the coil and the film surface is long. From the viewpoint of safety against the error due to the movement of the film, the optimal condition of the distance should be investigated in detail.

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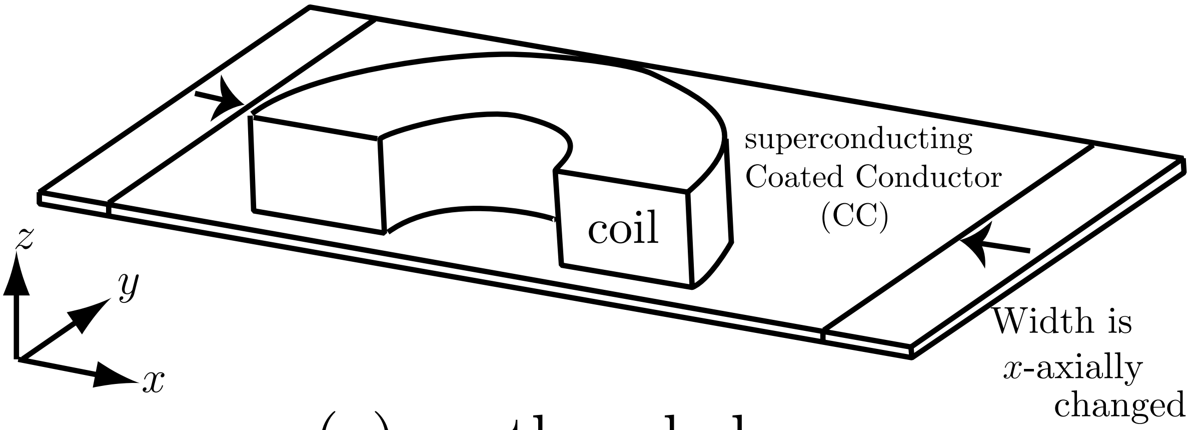
Fig 1 Schematic illustration of arrangement of coil and thin film for calculation by FEM.

Fig 2 third harmonic voltage amplitude V_3 dependence of Driving current amplitude I_0 vs for various values of film width.

Fig 3 Threshold current I_{c0} vs film width.

Fig 4 Distribution of shielding current on the film surface when the film width is 10, 5 and 2 mm.

Fig 5 Threshold current I_{c0} vs film width when the distance between coil and and film surface is 2 mm.



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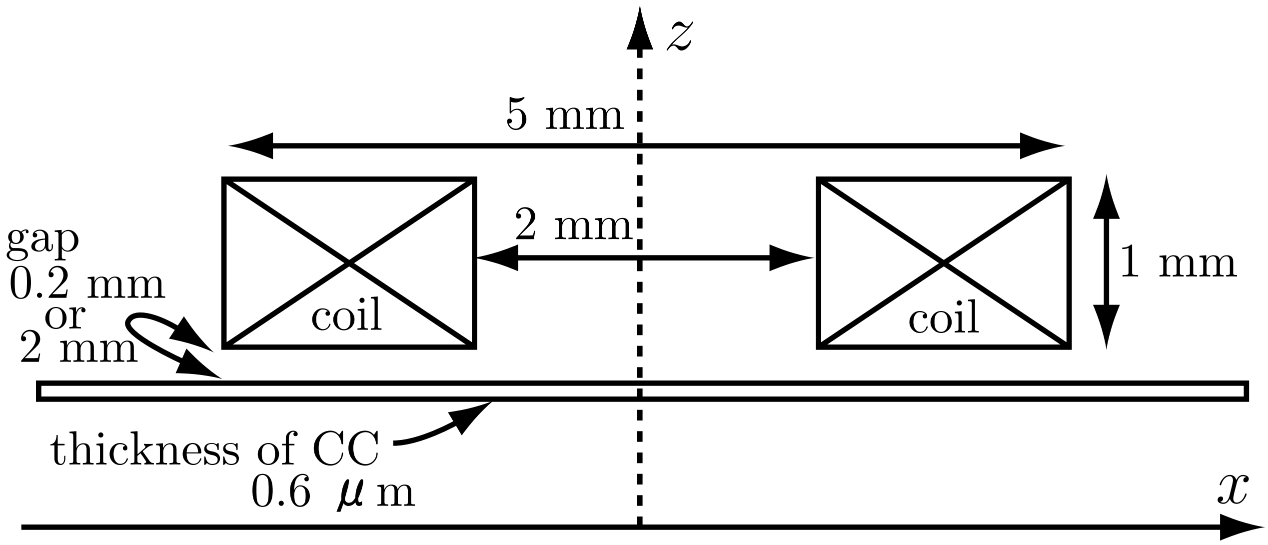

(b) from y-axis

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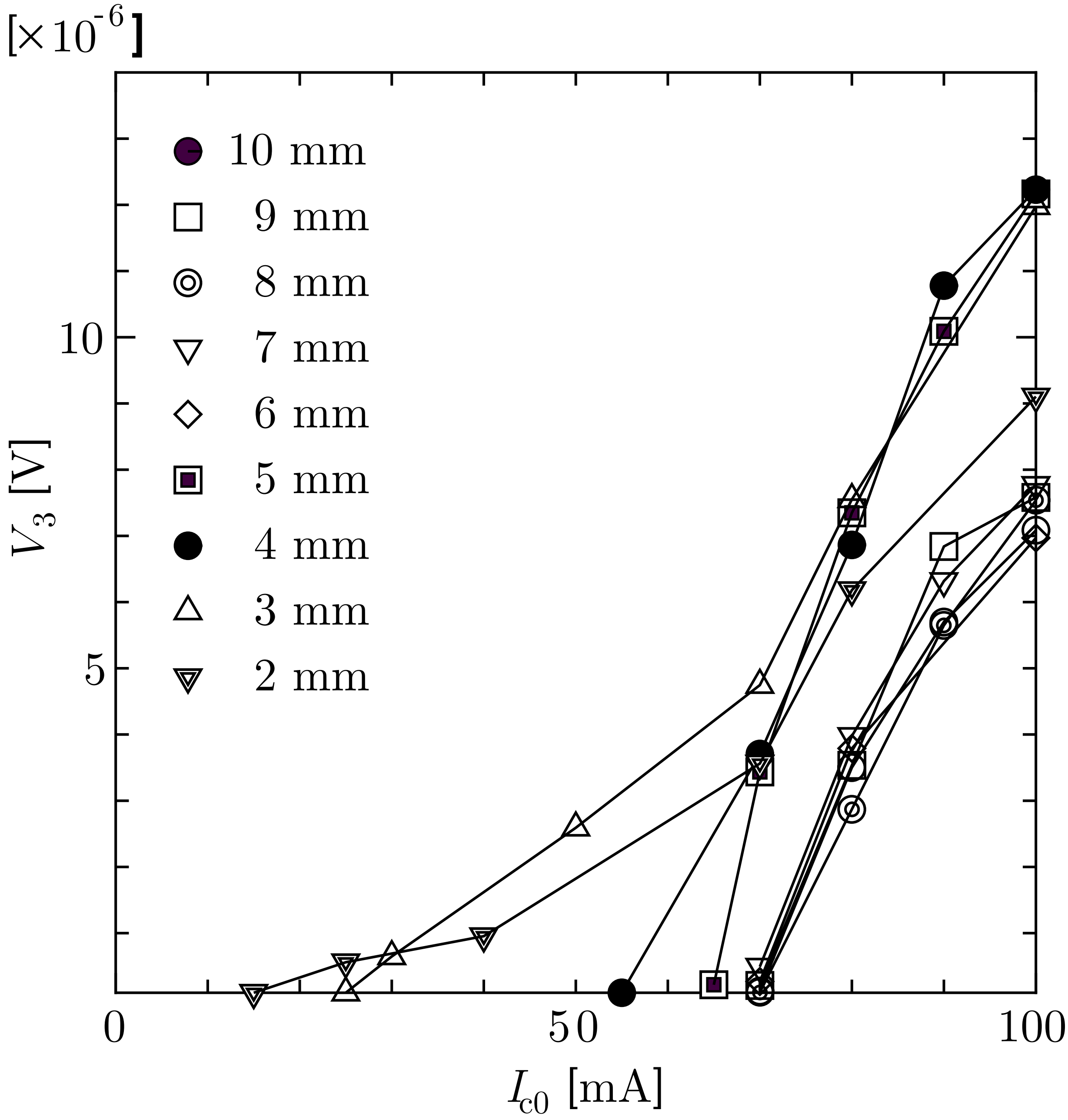

Fig. 2: T. Nadami *et al.* WSP–34/ISS2003

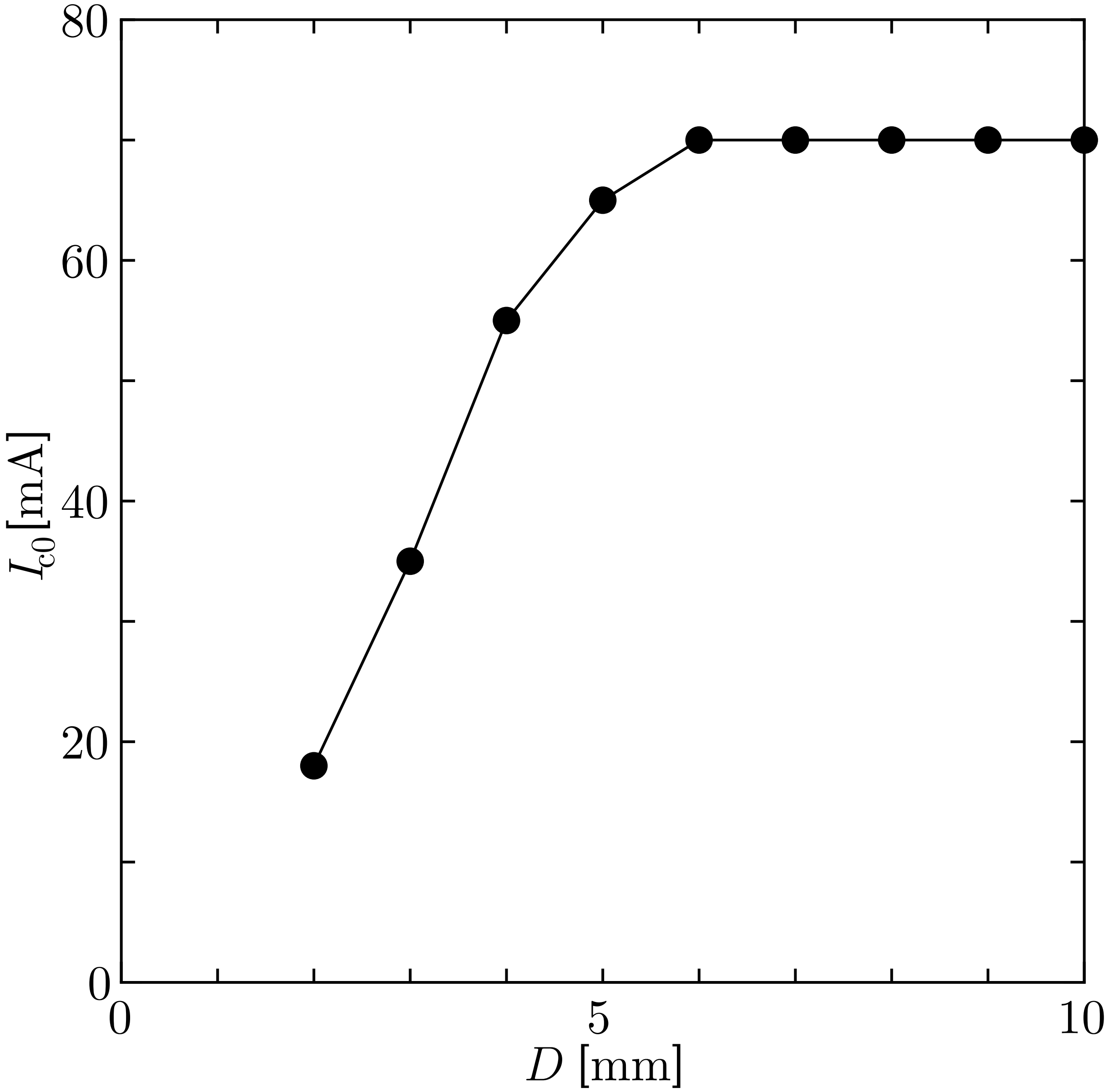

Fig. 3: T. Nadami *et al.* WSP–34/ISS2003

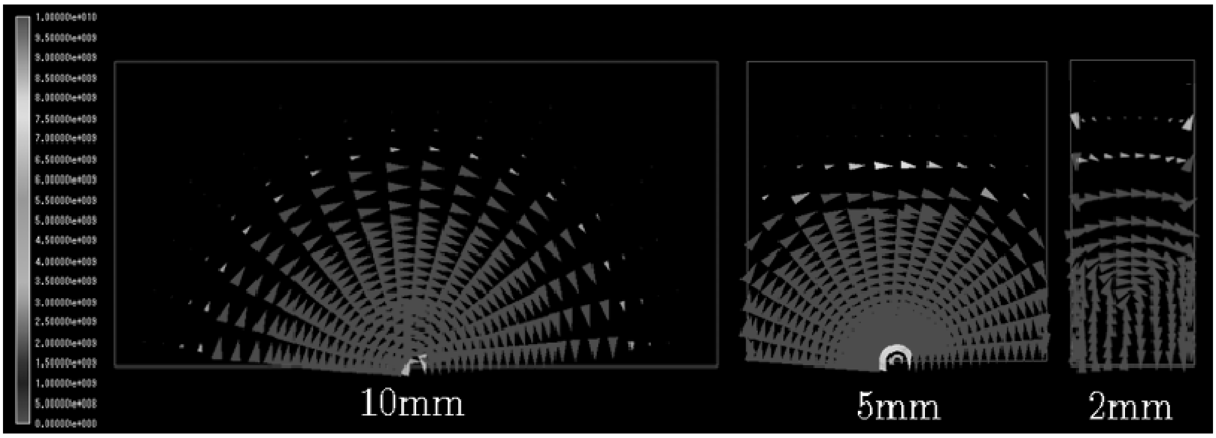

Fig. 4: T. Nadami *et al.* WSP–34/ISS2003

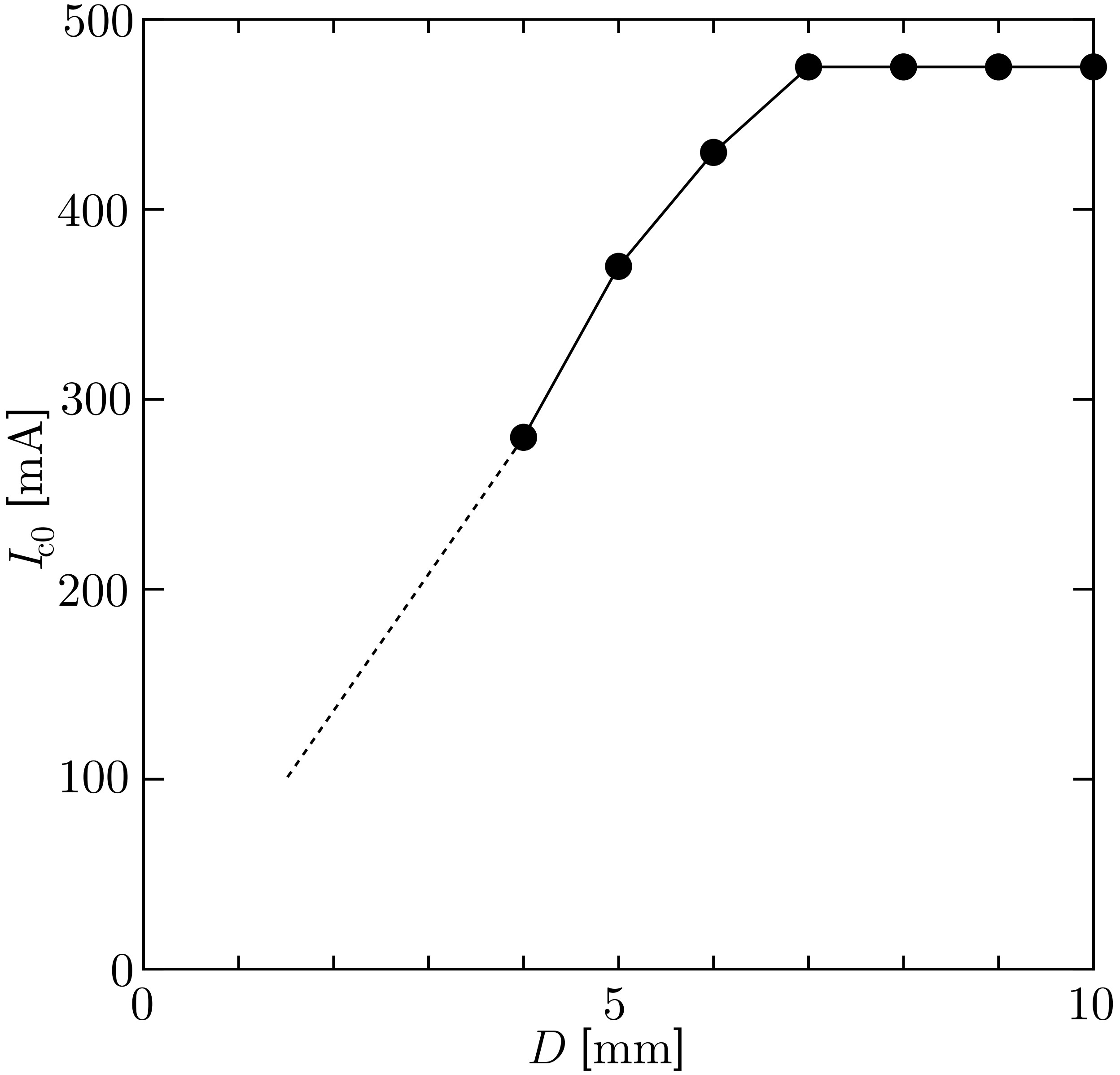

Fig. 5: T. Nadami *et al.* WSP–34/ISS2003