

Numerical analysis of AC current loss in QMG fault current limiter by finite element method

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Abstract

The AC transport current loss of a meander-shaped fault current limiting device of QMG (Quench Melt Growth) Y-based superconductor was numerically analyzed by finite element method (FEM). The magnetic field and the field-angle dependencies of the critical current density J_c were taken into account as well as a shape of a rectangular cross section. The numerical result shows a good agreement with the experimental result. The reason why Norris's formula fits to the experimental result seems to be because that the effect of the magnetic field dependence of J_c on the AC current loss is compensated by the geometrical effect of the superconductor and the field-angle dependence of J_c .

Keywords: AC current loss, QMG, finite element method

PACS: 61.85, 74.60.J, 74.72.B, 74.80.B, 02.70.D

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1 Introduction

AC application of oxide high temperature superconductors has been developed especially at low fields such as a power transmission cable[1], a transformer[2] and a fault current limiting device[3]. Further decrease of AC loss is needed for realizing a competitive advantage against conventional power electricities. Therefore, measurement and critical analysis of AC transport current loss are important.

For analysis of AC current loss, Norris's formula[4] is used since it often well agrees with experimental results. However, the magnetic field dependence of critical current density is neglected in Norris's formula, while this dependence is strong in high temperature superconductors. Therefore, it is necessary to take into account of the magnetic field dependence in the calculation of AC transport current loss. For example the theoretical formula using Irie-Yamafuji's model[5,6] for $J_c(B)$ was compared with the observed AC current loss of QMG (Quench Melt Growth) processed Y-based superconductor and it was found that deviation from the experimental result was larger than that from Norris's formula[7].

This deviation seems to originate from a geometrical effect of superconducting specimen and complex characteristics in high temperature superconductors, such as field-angle dependence of critical current density. However it is quite difficult to take into account these characteristics in theoretical analysis.

In this study, the AC current loss of a meander-shaped QMG fault current limiter was numerically analyzed by finite element method (FEM) in which dependencies of the critical current density on the intensity and angle of mag-

netic field were taken into account. The theoretical result was compared with Norris's formula and Irie-Yamafuji's formula in which the geometrical effect was disregarded.

2 Analysis Results and Discussion

Finite element method was used for analysis of AC current loss by JMAG studio version 6 of Japan Research Institute[8]. First, it was necessary to confirm if the AC current loss can be correctly calculated by this code, since the calculated result drastically changes and depends on the model and the code in FEM analysis. For this purpose this method was checked for a long superconducting cylinder which carries an AC current. The results of power loss are plotted as a function of time in Fig. 1(a) and 1(b) for Bean's model ($J_c = 10^9$ A/m²) and Kim's model ($J_c = 1.5 \times 10^9 / (1 + B/0.1)$ A/m²), respectively. The first peak of the power loss corresponds to the initial state, and the larger peak is in the periodic state. The power loss can also be numerically calculated using theoretical magnetic flux density distribution in a superconducting cylinder calculated from differential equation. These results are compared with the results of FEM in Fig. 1. A good agreement between theory and FEM results is obtained in the both cases in Fig 1(a) and 1(b).

The result of the AC current loss obtained from the power loss is plotted in Fig. 2. Theoretical results are also plotted in solid and broken lines for comparison. These results agree well with each other for respective models. This shows that FEM is useful to estimate electromagnetic properties in superconductors.

The AC current losses are calculated by FEM for superconductors with dif-

ferent cross sections assuming Bean's model for $J_c(B)$, and the results are shown in Fig. 3. The results are approximately the same between cylindrical and square cross-sections. On the other hand, the result for a rectangular cross-section is slightly higher than other cases. This is probably due to an inhomogeneous distribution of magnetic field in the superconductor. Therefore, the cross section of the superconductor largely influences the AC current loss.

Then, the result of analysis by FEM is compared with experimental AC current loss of a meander-shaped QMG fault current limiter [7]. The meander-shaped specimen was cut from a disk-shaped QMG superconductor, diameter and thickness of which were 45 mm and 15 mm, respectively. The cross section of the linear part of the specimen was 1.5 mm×0.5 mm and the effective length was about 170 mm. The transport AC current was applied to the specimen by a superconducting transformer in which a Bi-2223 tape was used for the secondary winding [9]. The AC current loss measurement was done in liquid N₂.

The observed AC current loss and theoretical results are shown in Fig. 4. The predicted result using Irie-Yamafuji's model and Norris's prediction are shown by solid and dotted lines. The result by Norris's formula fits well to experimental result. On the other hand the result by Irie-Yamafuji's model has a steeper field dependence than observed result with a larger difference at low currents. This reason is seen in Fig. 2, i.e., the critical current density at low magnetic fields at low currents assumed in Irie-Yamafuji's model and Kim's model is larger than that assumed in Bean's model. Therefore, the AC current loss becomes lower and shows the steeper field dependence.

Since the AC current loss density of meander-shaped fault current limiter coincides with the result of short bridge specimen, simply rectangular cross-

section was employed in the model shape in FEM analysis. The field angle dependence of critical current density is simply assumed so that the critical current density is determined by the c -axis component of magnetic field. It is to be noted that the field-angle dependence of J_c is more complicate in Y-based superconductor. The magnetic field dependence of the critical current density was approximated by Kim's model or by a polynomial equation fitted to an experimental result measured by a SQUID magnetometer as shown in Fig 5. The result by the polynomial equation for $J_c(B)$ agrees well with the experimental result. The corresponding result is also obtained in AC current loss calculated using these assumption and compared with experimental result in Fig. 4. It is found that the theoretical result with the polynomial equation coincides to the result by Norris's formula and agrees well with the experimental result. The AC loss based on Kim's model is higher at large AC current amplitude, since the critical current density is smaller than the experimental result at high magnetic fields as shown in Fig. 5.

Hence, it is considered that the geometrical effect and the angular dependence of J_c on the AC loss compensates the effect of the magnetic field dependence of J_c . It is necessary to check if this speculation is correct.

3 Conclusion

In this work, the AC transport current loss of meander-shaped QMG fault current limiter was analyzed by the finite element method. The following results are obtained:

- The AC loss in the rectangular superconductor is higher than that of the cylindrical or square superconductor even when Bean's model is assumed for

the magnetic field dependence of the critical current density. This is considered to originate from an inhomogeneous magnetic flux density distribution in the superconductor.

- The analytic result of the AC current loss of YBCO square rod by FEM in which the magnetic field and the angular dependencies of the critical current density are taken into account agrees well with the experimental result. This result was also close to the predicted result by Norris's formula. This accidental coincide seems to be obtained by the compensation of the field dependence of J_c by the field-angle dependence of J_c and the geometrical effect.

Acknowledgements

This study was partly supported by Industrial Technology Research Grant Program in 2001 from the New Energy and Industrial Technology Development Organization (NEDO) of Japan.

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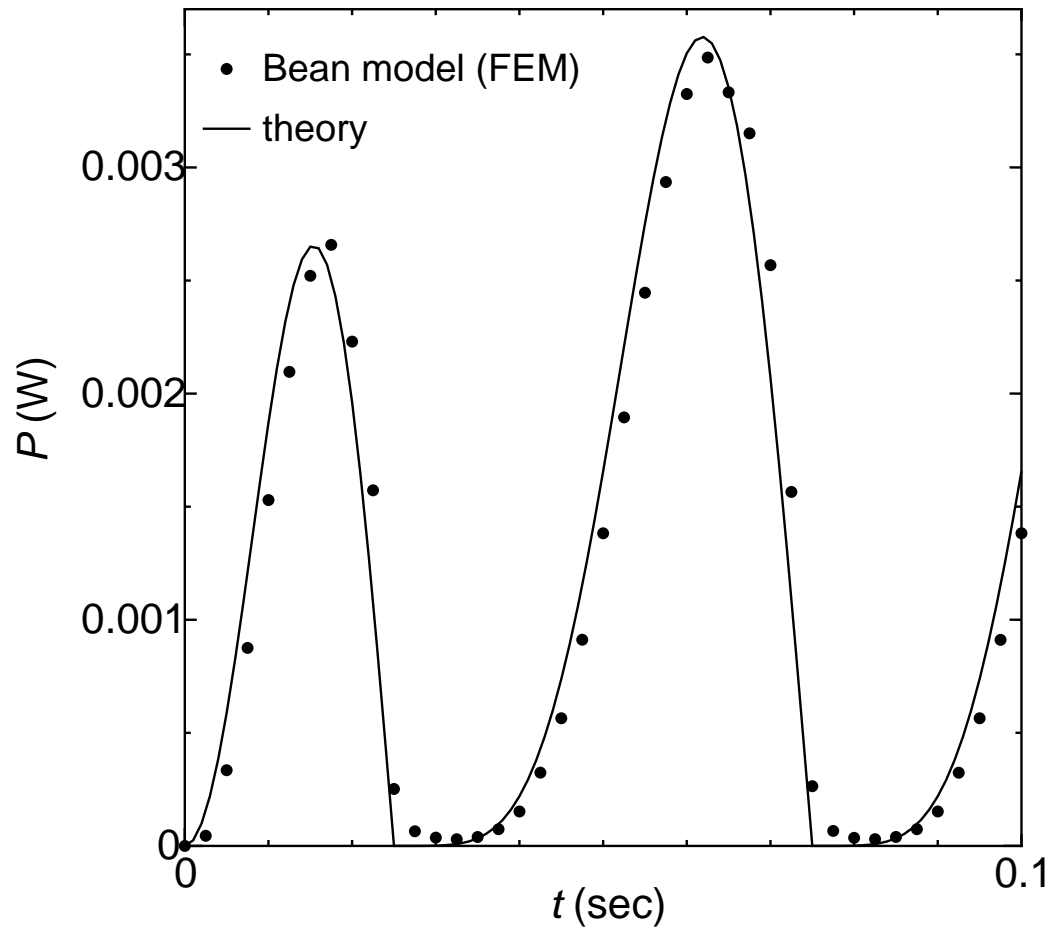


Figure 1(a): E. S. Otabe *et al.*

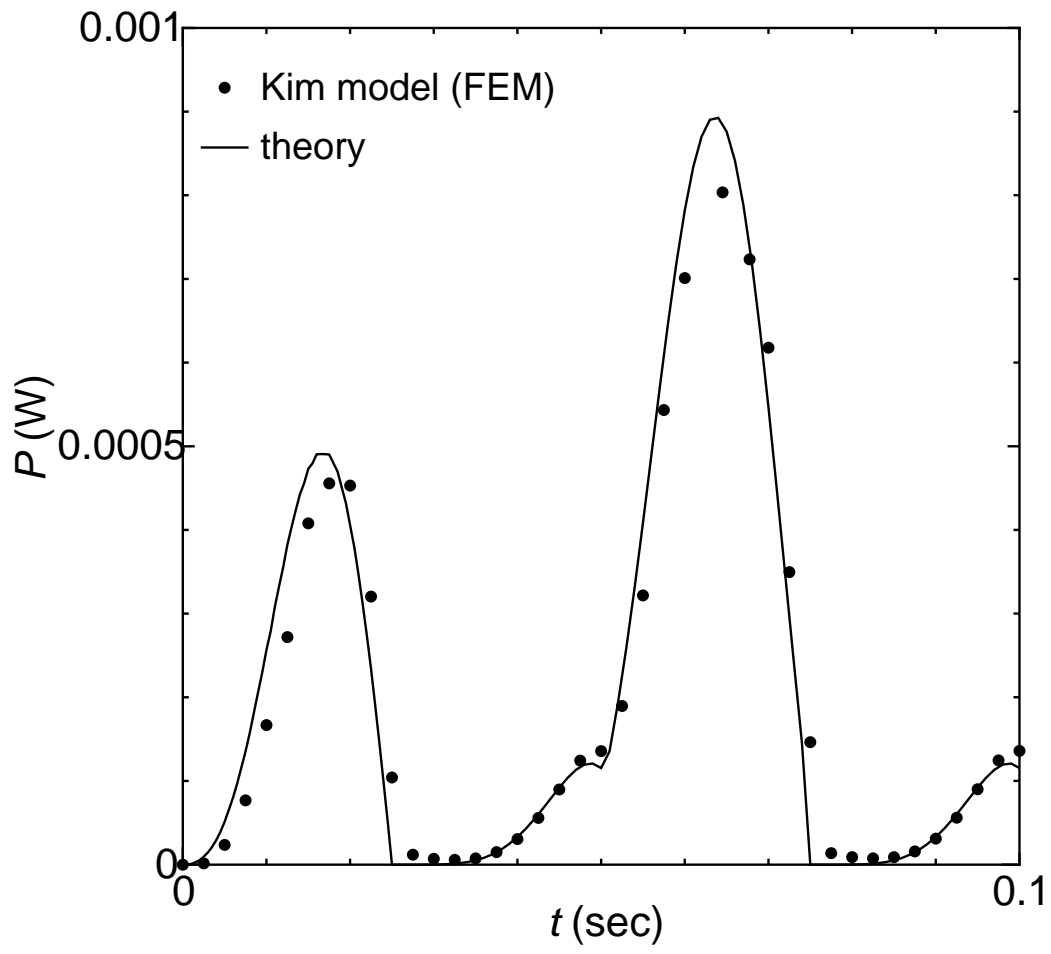


Figure 1(b): E. S. Otabe *et al.*

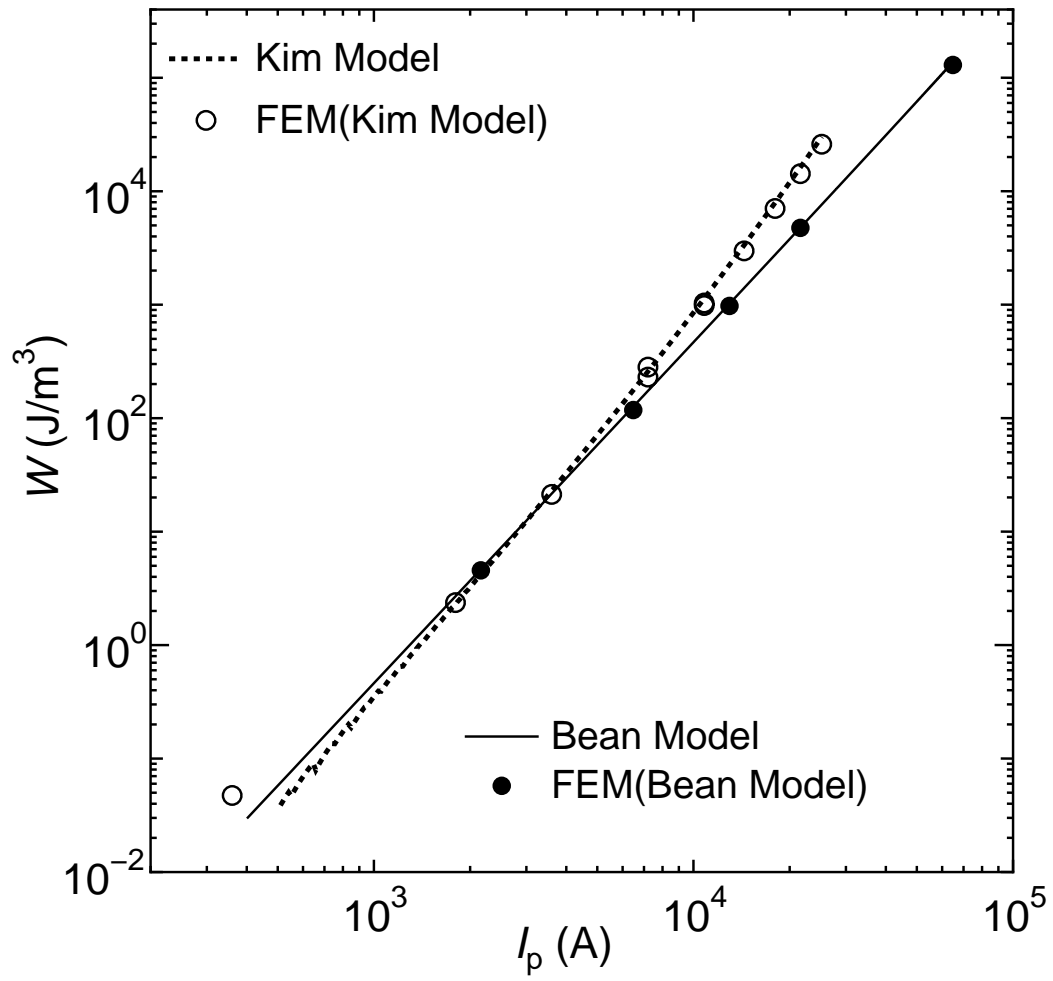


Figure 2: E. S. Otabe *et al.*

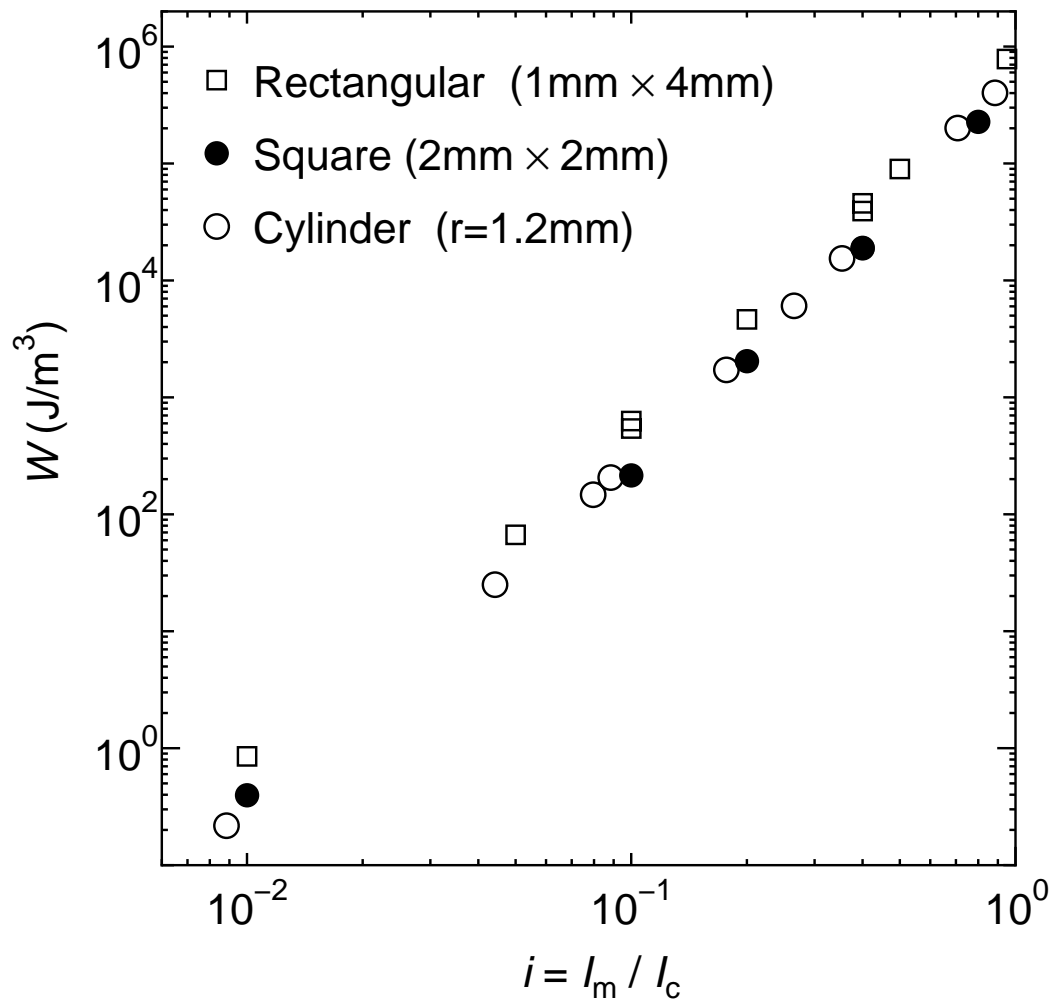


Figure 3: E. S. Otabe *et al.*

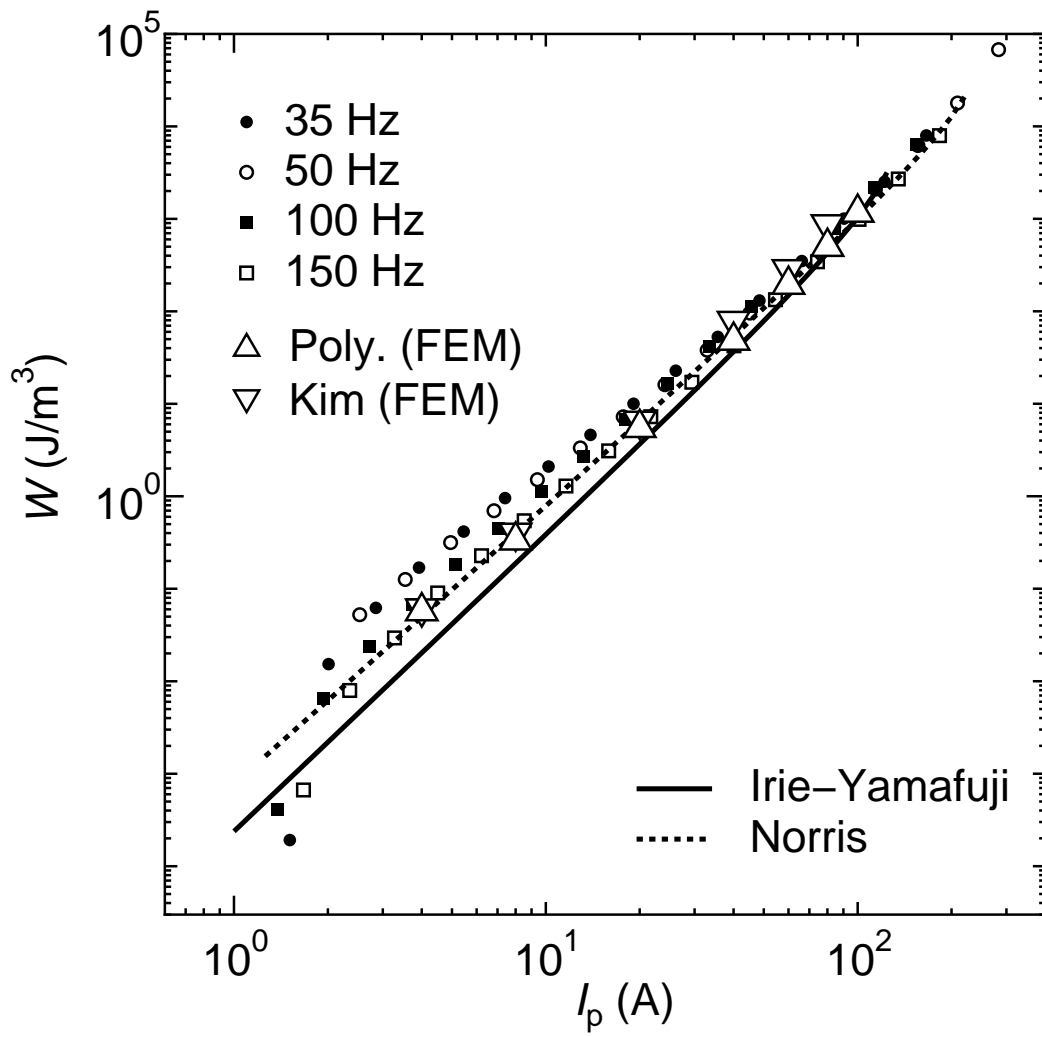


Figure 4: E. S. Otabe *et al.*

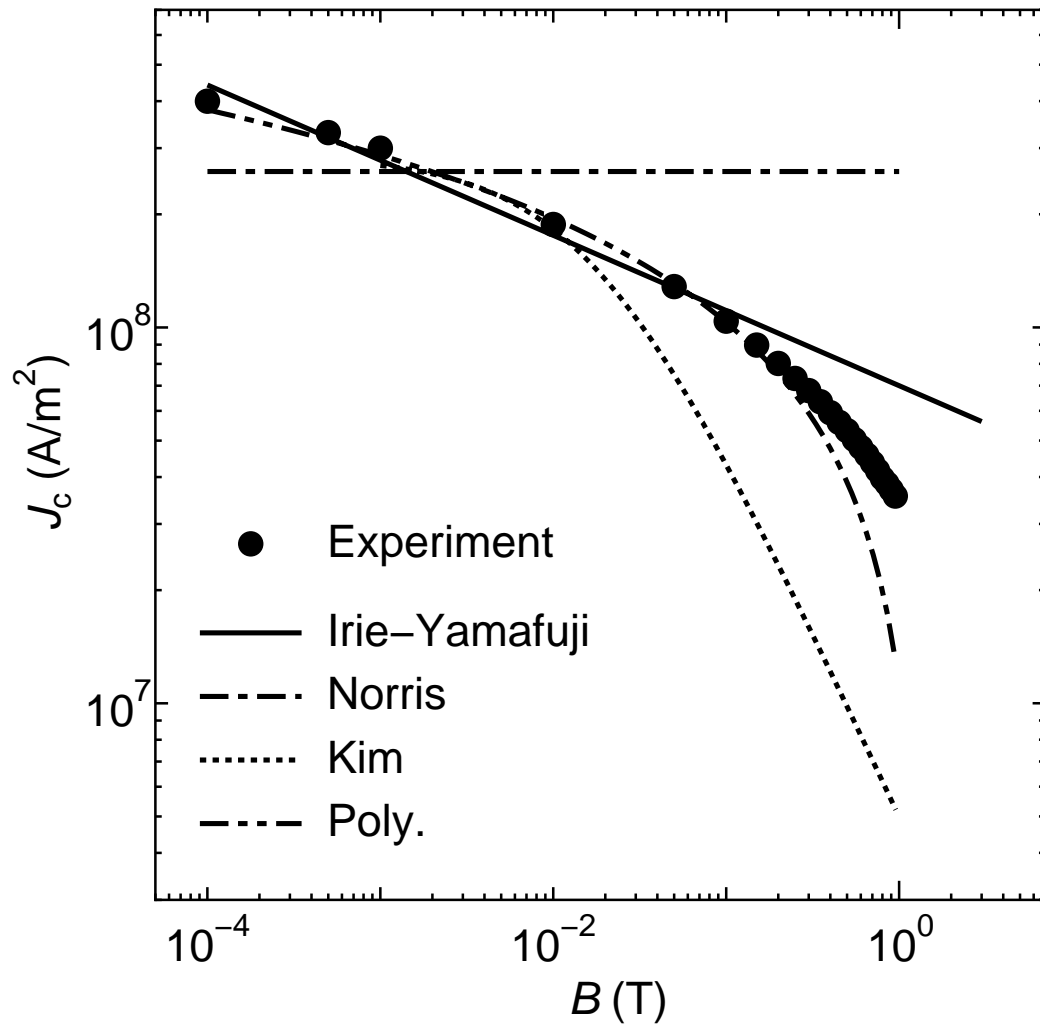


Figure 5: E. S. Otabe *et al.*

Figure caption

Fig. 1. Time dependence of power loss for assumptions of (a) Bean's model ($I_m = 6.5 \times 10^4$ A) and (b) Kim's model ($I_m = 2.5 \times 10^4$ A), respectively for cylindrical superconductor of radius $r = 11$ mm. Solid line represents theoretical result.

Fig. 2. AC current loss of cylindrical superconducting for assumptions of Bean's model and Kim's model.

Fig. 3. AC current loss of different shape of cross section based on Bean's model calculated by FEM.

Fig. 4. AC current loss vs AC current amplitude of meander-shaped QMG fault current limiter with various frequencies and compared with several analyses.

Fig. 5. Magnetic field dependence of critical current density measured by SQUID magnetometer and predicted results by several models.