# Comparison between T-A formulation and uniform current assumption for the critical current calculation of high temperature superconductor ReBCO coils

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## Introduction

In this paper,

1) Two methods of calculating critical current of ReBCO coils are studied and compared, including a critical state model based on T-A formulation and E-J power law, and a magnetic field model based on uniform current assumption.
2) The critical current of three circular coils with different parameters are measured, the calculation results are compared with the measurement.
3) The effect of inner diameter, number of turns and number of pancakes on the calculation results are studied.

## Modeling

1) T-A critical state model:

The superconducting layer is treated as a thin shell without thickness. T is defined as the current vector potential:

$$\mathbf{J} = \nabla \times \mathbf{T}$$

The governing equation in the superconducting shell is derived from Faraday's law of electromagnetic induction:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

The governing equation in the 3D domain is given by Ampere circuital theorem:

$$\begin{cases} \nabla \times \mathbf{B} = \mu \mathbf{J} \\ \mathbf{B} = \nabla \times \mathbf{A} \end{cases}$$

The E-J relationship is expressed as:

$$\mathbf{E}(\mathbf{J}) = E_0 \left( \frac{|\mathbf{J}|}{J_c(\mathbf{B})} \right)^{n-1} \frac{\mathbf{J}}{J_c(\mathbf{B})}$$

2) Magnetic field model:

A The current is assumed to be uniformly distributed in the ReBCO tape, the magnetic field is calculated by Biot-Savart law:

$$d\mathbf{B} = \frac{\mu_0}{4\pi} \frac{Id\mathbf{l} \times \mathbf{r}}{r^3}$$

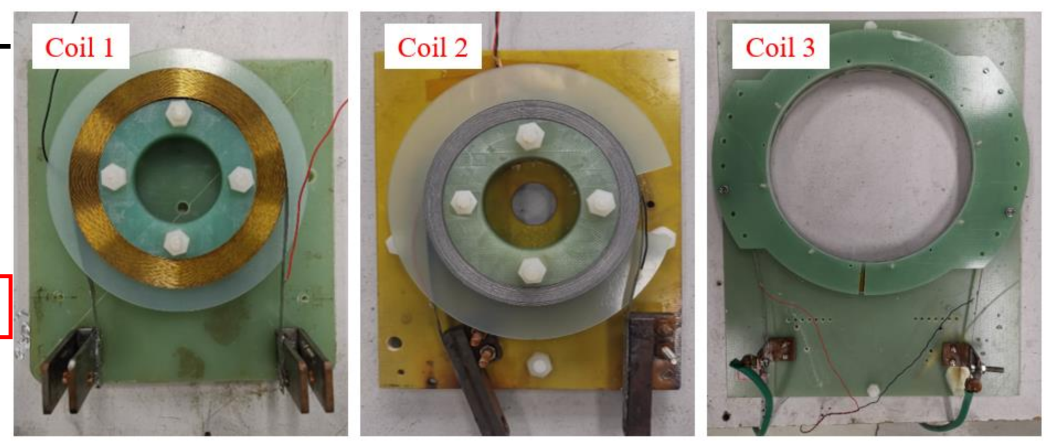
The critical current of each turn is calculated by:

$$J_c(\mathbf{B}) = \frac{J_{c0}}{\left[ 1 + \sqrt{(kB_{par})^2 + B_{per}{}^2} \Big/ B_c \right]^b}$$

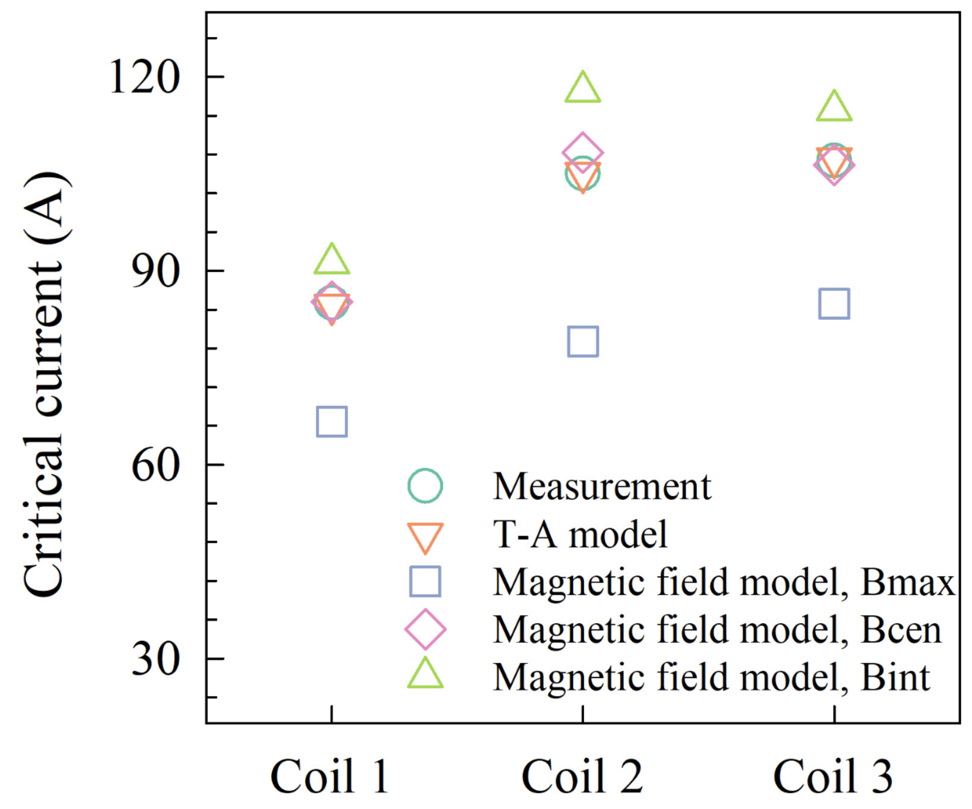
3) The critical current of three circular coils with different parameters are measured.

TABLE I
PARAMETERS OF THE TESTED COILS

| Parameters | Coil 1 | Coil 2 | Coil 3 |
|---|---|---|---|
| Insulation | insulated | no-insulation | insulated |
| Inner/outer diameter | 70/96.6mm | 70/84.4mm | 244/294mm |
| Number of turns, DP | 40 × 2 | 40 × 2 | 59 × 2 |
| Self-inductance | 0.582mH | 0.688mH | 6.92mH |
| Ic of coil, @77K | 85A | 105A | 107A |
| Ic of tape, @77K | 150.8A | 213.4A | 200.0A |
| Width of tape | 6mm | 6mm | 4mm |
| Thickness of tape | 360μm | 180μm | 430μm |




## Results and analysis




1) In the magnetic field model, three methods of selecting the magnetic field are compared:

$B_{max}$: The maximum magnetic field on the ReBCO tape

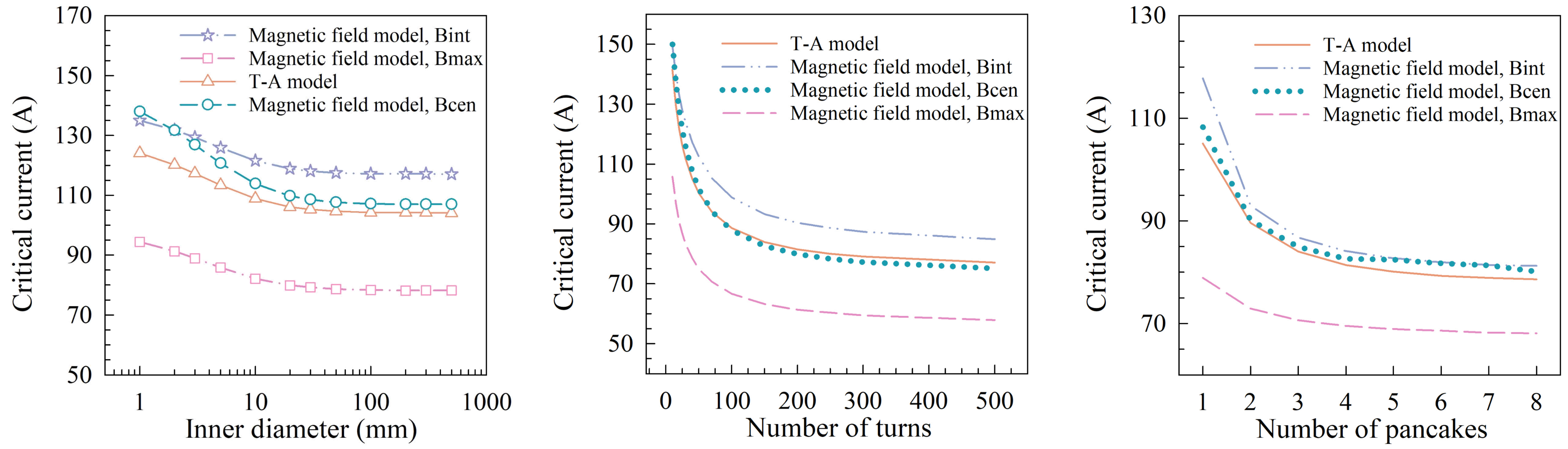
$B_{cen}$: The central magnetic field in the tape width direction

$B_{int}$: Dividing the ReBCO tape into micro elements from width direction, and calculating the critical current of each element. The tape's critical current is the integral of each micro element.

Results from T-A model shows the best agreement with the measurement, with a discrepancy lower than 0.35%.

Results from magnetic field model calculated by $B_{cen}$ is close to the measurement, with a discrepancy lower than 3.14%. Results calculated by $B_{int}$ is 12.1% higher than the measurement, results calculated by $B_{max}$ is 21.7% lower than the measurement.

2) Influence of coil parameters:




At high inner diameters, results from magnetic field model calculated by $B_{cen}$ is close to the T-A model, with a discrepancy of 2.88%. Higher calculation error occurs at low inner diameters.

For coils with more than 25 turns, the relative error between the magnetic field model $B_{cen}$ and the T-A model is lower than 3.7%.

At different number of pancakes, the relative error between the magnetic field model $B_{cen}$ and the T-A model is lower than 3.14%.

## Conclusion

1) T-A critical state model has the most accurate calculation of the critical current of ReBCO coil, but the high calculation cost restricts its application in large size coils.
2) The magnetic field model calculated by $B_{cen}$ shows better agreement with T-A model at larger coil size, which can be a simplified method for estimating critical current of large sized coils and special sized coils.