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The Effects of Manufacturing Errors on Field Quality of a CCT Twin Aperture Beam Orbit Corrector

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1. Introduction

A set of twin aperture beam orbit correctors with Canted-Cosine-Theta (CCT) dipoles will be developed in China. Cooperating with CERN, twin aperture correctors are being fabricated as the prototypes before the series production. During the fabrication of the CCT coils, certain manufacturing errors including winding error, rotation error and concentricity error and were appeared, which affect the field harmonic components. This study analyzed the effects on field harmonic components by these manufacturing errors, and the production process of the prototype was introduced. Suggestions from the analysis results are provided the further series production of the 2.2-m orbit correctors.

2. Theory

- The position of the center of the powered cable for one of the two coils of the CCT is described by

$$x = R\cos\theta$$
$$y = R\sin\theta$$
$$z = \sum_{n_B}\left[\frac{R\sin(n_B\theta)}{n_B\tan\alpha_{n_B}} + \frac{\omega}{2\pi}\theta\right] + \sum_{n_A}\left[\frac{R\cos(n_A\theta)}{n_A\tan\alpha_{n_A}} + \frac{\omega}{2\pi}\theta\right] \quad (1)$$

where R is the radius of the cylinder, ϑ is the azimuthal angle, ω is the axial pitch length, n_A and n_B are the skew and normal multipoles (n_B=1 is the dipole component), α_{nA} , α_{nB} is the skew angles.

- For a normal dipole, the CCT coil winding path is described by

$$x = R\cos\theta$$
$$y = R\sin\theta$$
$$z = \sum\left[\frac{R\sin(\theta)}{\tan\alpha_{n_B}} + \frac{\omega}{2\pi}\theta\right] \quad (2)$$

- For dipole, the harmonics can be calculated by

$$B_\rho(\rho,\varphi,z) = \sum_{n=0}^{\infty} a_n\cos(n\varphi) + \sum_{n=0}^{\infty} b_n\sin(n\varphi)$$
$$B_\varphi(\rho,\varphi,z) = \sum_{n=0}^{\infty} a_n\sin(n\varphi) + \sum_{n=0}^{\infty} b_n\cos(n\varphi) \quad (3)$$

where, ρ is the radius, φ is the azimuthal angle, z is the coordinate in the longitudinal direction, B_ρ is magnetic flux densities in the radial direction, B_φ is magnetic flux densities in the azimuthal direction, n is the order for field components.

3. Analysis

- The parameters of CCT Corrector are shown in Table I.

Table I. Parameters of CCT Corrector

Items	Values
Iron yoke size (mm)	Φ614/ L500
Diameter of aperture (mm)	167
CCT skew angle β (center-center)	30°
No. of turns per layer	55
Slot size in former (mm)	2mm x 5mm
Spacing per turn (mm)	5.2
Diameter of the slot (mm)	1st layer:109/119 2nd layer:123/133
Reference radius (mm)	35
Current (A)	422
Central field without/with yoke (T)	1.86/2.64
Peak field in coil/yoke (T)	2.90/1.89
Integral field (T· m)	0.77

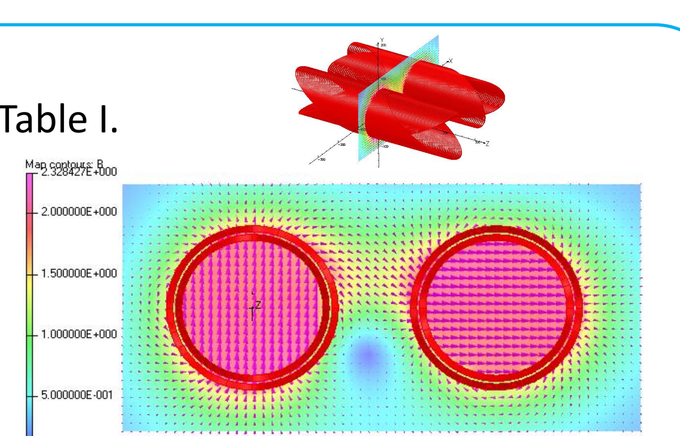


Fig.1 Magnetic flux distribution

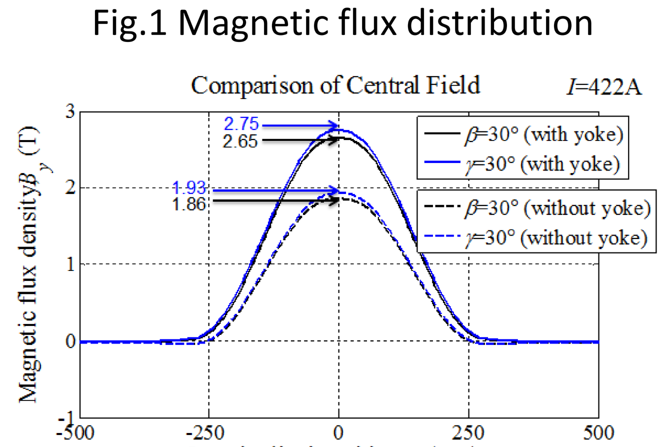


Fig.2 Magnetic flux density

- As the harmonics in twin CCT coils will affect each other greatly , the results of harmonics of single CCT coil are shown in Table II.

Table II. The result of harmonics of single CCT coil

n	Harmonics @z = 0, a_n	Harmonics @z = 0, b_n	Integral harmonics, z=[-500 : 500] a_n	Integral harmonics, z=[-500 : 500] b_n	Unit (a_n)	Unit (b_n)
0	0	-4.36E-16	0	2.85E-14	0	5.59E-13
1	1.879	-8.45E-16	509	-3.15E-14	10000	-6.19E-13
2	6.49E-06	-5.07E-16	1.20E-04	-6.92E-15	2.36E-03	-1.36E-13
3	-1.00E-03	-6.53E-16	-1.09E-04	3.14E-14	-2.14E-03	6.15E-13
4	3.57E-06	9.34E-17	9.42E-07	5.14E-14	1.85E-05	1.01E-12
5	-9.42E-06	6.55E-16	5.38E-07	4.18E-14	1.06E-05	8.20E-13
6	-5.87E-07	-2.20E-16	1.43E-06	-5.32E-14	2.81E-05	-1.04E-12
7	3.40E-06	1.21E-16	7.78E-07	7.70E-14	1.53E-05	1.51E-12
8	8.08E-08	-5.15E-17	1.93E-06	-3.75E-14	3.79E-05	-7.37E-13
9	-3.87E-07	-1.02E-15	1.04E-06	-5.58E-14	2.04E-05	-1.10E-12

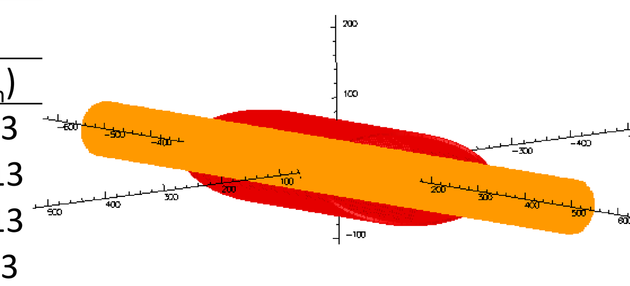


Fig.3 Integral harmonics of single CCT coil

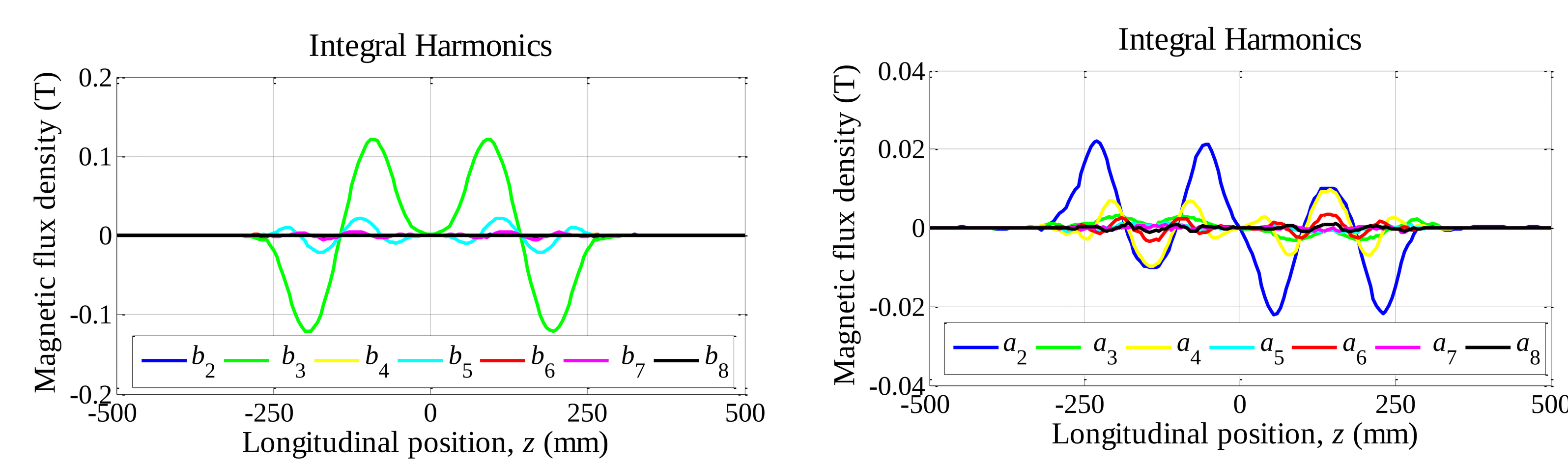


Fig.4 Harmonics b_n and a_n distribution in z direction

- Analysis of manufacturing errors on harmonics

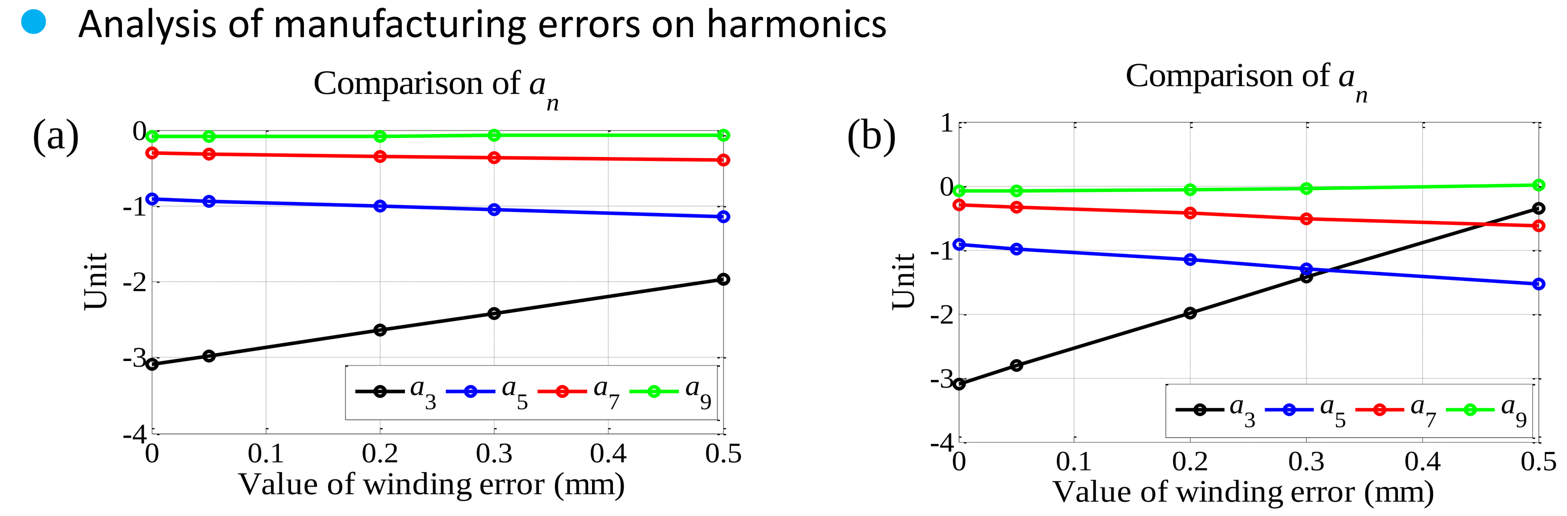


Fig.5 Winding error on harmonics. (a) Only outer layer has winding error (b) Both inner and outer layer

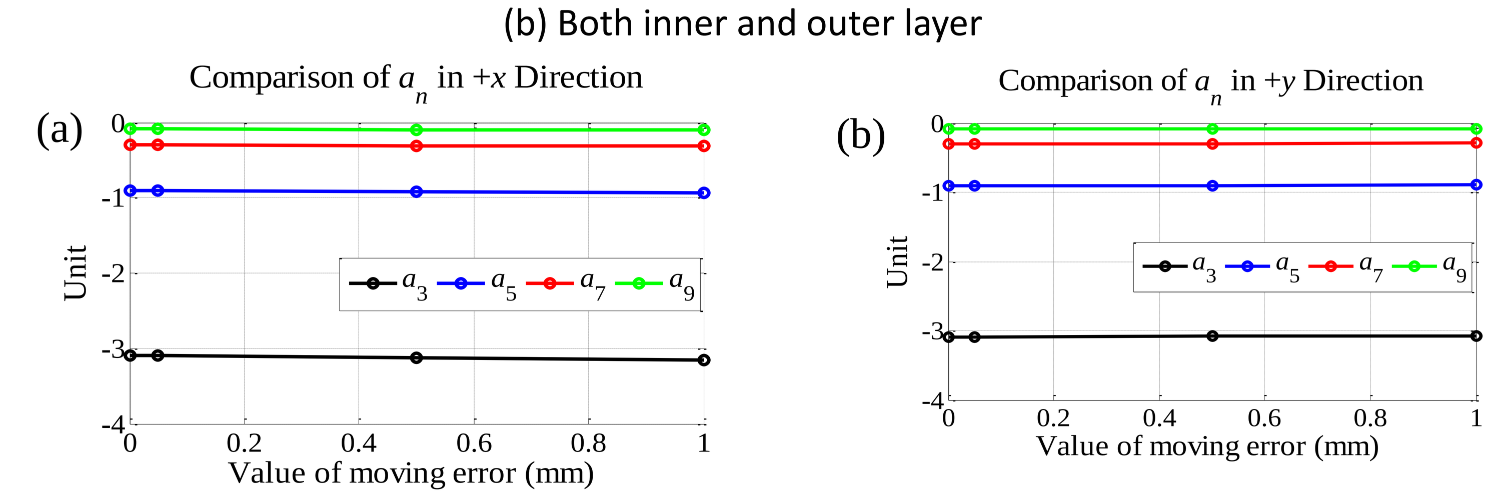
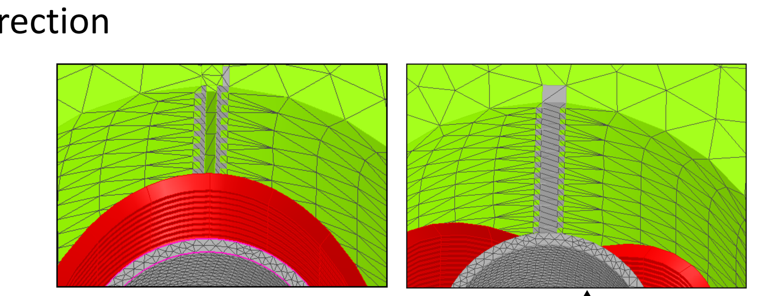
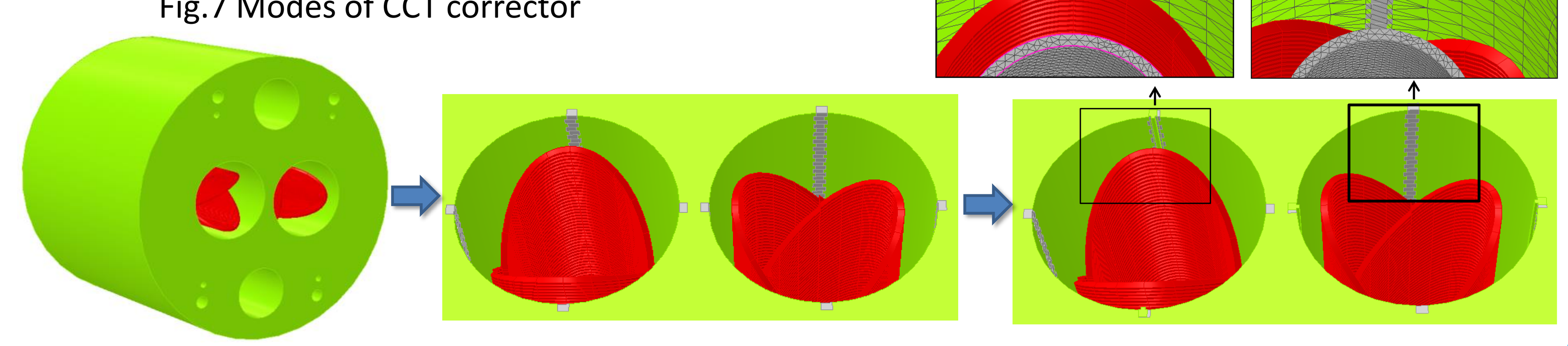


Fig.6 Rotating error on harmonics. (a) Rotating error in x direction (b) Rotating in y direction

- Integral harmonics comparison of CCT corrector

Fig.7 Modes of CCT corrector





Case 1: Simple yoke   Case 2: Yoke key cut out   Case 3: Yoke key

Table III. The harmonics comparison results of CCT correctors

Comparison of integral harmonics b_3 with B_φ				
Model	APH		APV	
	Value	Unit	Value	Unit
Case 1: Simple yoke	0.191	2.539	0.111	1.477
Case 2: Yoke key cut out	0.389	5.176	0.432	5.746
Case 3: Yoke key	-0.250	-3.323	-0.082	-1.087

- 50 μm concentricity error

✓Case A : 50 μm error at both ends of the rotating coil

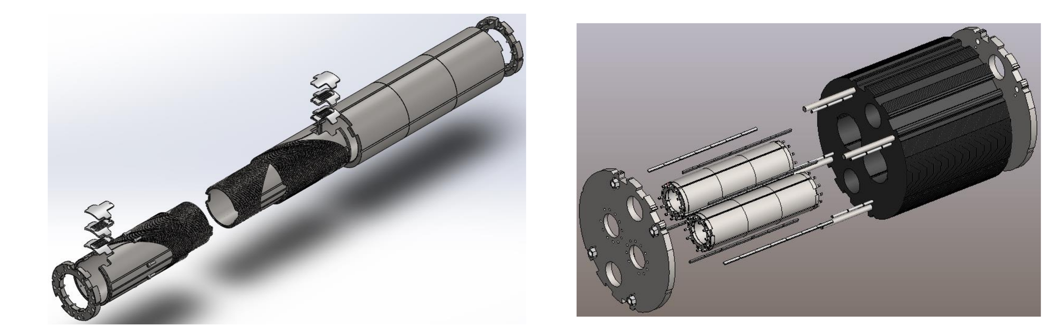
✓Case B : 50 μm error at one end of the rotating coil

Table IV. The effect of 50 μm concentricity error

Comparison of integral harmonics b_3 with B_φ				
Model	APH		APV	
	Value	Unit	Value	Unit
Original	-0.250	-3.323	-0.082	-1.087
Case A: Plane xoz	-0.250	-3.329	-0.082	-1.096
Case A: Plane yoz	-0.250	-3.325	-0.082	-1.092
Case B: Plane xoz	-0.250	-3.331	-0.082	-1.099

4. Manufacture

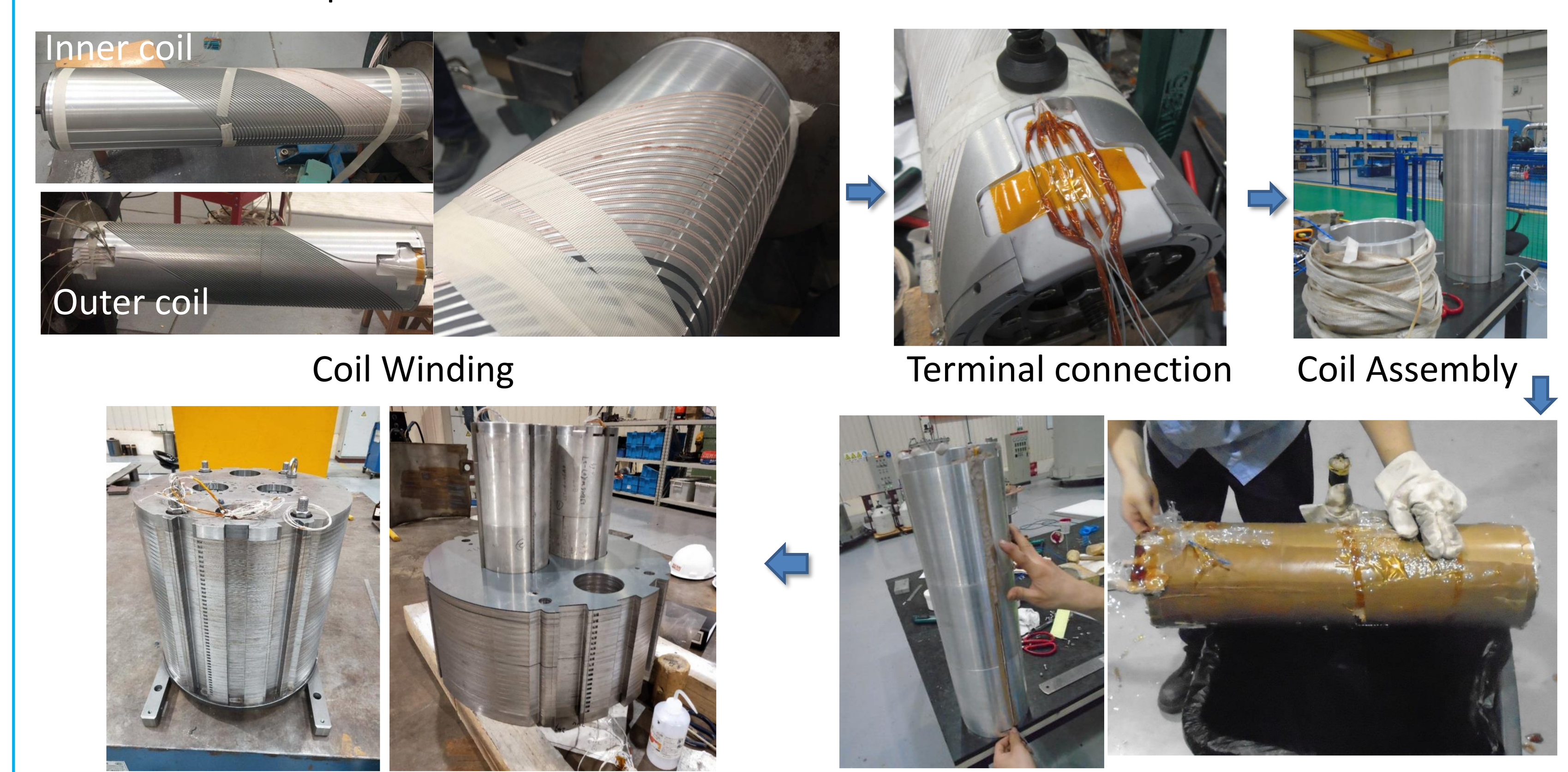
- Structure of prototype



(a)   (b)

Fig.8 Structure of CCT corrector prototype (a) Coil structure (b) Magnet structure

- Manufacture process



Coil Winding   Terminal connection   Coil Assembly

Magnet assembly   The whole-structure vacuum impregnation

Fig.9 Manufacture process of CCT corrector prototype

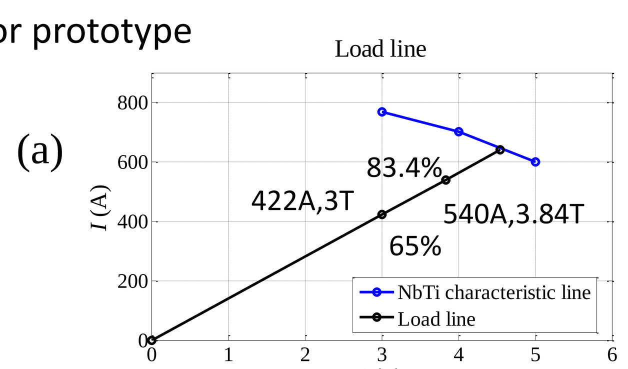
- Cold test @4.2K

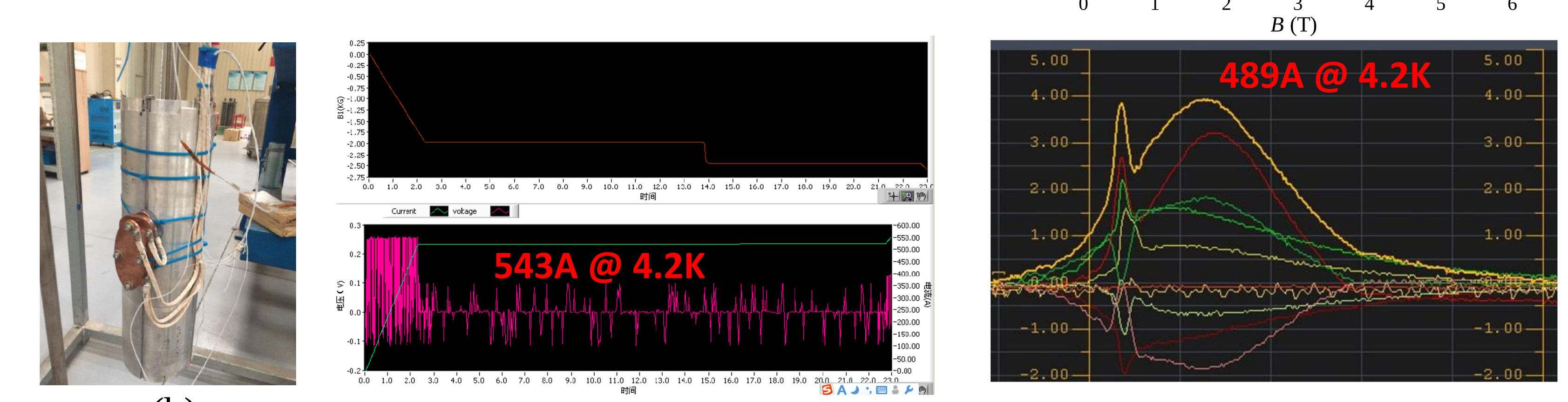
After 5 quench, the 1# coil reached 543A @ 4.2 K

After 5 quench, the 2# coil reached 489A @ 4.2 K

Design current I = 422A @1.9K (I=394A @1.9K)

(a)





(b)   (c)   (d)

Fig.10 Cold test (a) Load line (b)one coil (c)1# coil (d) 2# coil (c) load line

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