

DC0304 Turn-to-Turn Short
J. Strait
12/17/90

During the collar keying operation of DC0304 on 12/12/90 the lower inner coil (17M-1008) developed a turn-to-turn short. The short was detected before key insertion and the magnet has been disassembled. Before assembly the conductor of coil 17M-1008 was observed to be delaminated from the wedge over a distance of about ± 1 inch from the joints between 30 inch wedge segments. The pattern of delamination was what would be expected if the coil had been twisted. It is not known if this is related to the insulation fault discussed here.

Table I shows the resistance of the upper and lower half coils as a function of increasing press load. Above a hydraulic system pressure $P_H = 5000$ psi the lower coil resistance began to decrease, but this was not immediately noted. At $P_H = 8500$ psi the resistance monitoring equipment was removed and a series of hi-pots (coil to ground, heaters to ground, upper to lower coil) was successfully performed. When the resistance monitor was reconnected the upper-lower coil resistance difference exceeded 1% and the computer monitoring system set an alarm.

Resistance measurements were performed and the short was isolated to the lower inner coil. Its resistance was monitored as the press was de-energized and the data are shown in Table II. The resistance did not return to its initial value until the press was at almost zero load.

The following day the resistance was measured turn by turn using the voltage taps at $P_H = 0$ and $P_H = 8000$ psi. The data were shown in Table III; Figure 1 shows the locations of the taps. The resistance of the uninstrumented section (turns 1-9) was monitored during the loading of the press (Table IV) and was found to be constant. The resistance of turns 11 (taps 10B-11B) and 12 (taps 11B - 12B) are reduced indicating a short between them. Because the turn 11 resistance is effected more it is evident that the short is not too far towards the non-lead end from taps 10B and 11B. The sum of the turn 11 and 12 resistances is larger than that of a single turn indicating that there is non-zero resistance in the short itself.

To determine the precise location of the short the coil was modeled as the resistor network shown in Figure 2. The sum of $R_a + R_b = R_t = 86.4\text{m}\Omega$, the resistance of one turn. The resistance of the short R_s can be determined from the sum

$$\begin{aligned} R_{11} + R_{12} &= R_a + (R_b + R_a) \parallel R_s + R_b \\ &= R_t + (R_t \parallel R_s) \\ \frac{1}{R_s} &= \frac{1}{R_{11} + R_{12} - R_t} - \frac{1}{R_t} \end{aligned}$$

where $R_{11} = I V_{11}$ and $R_{12} = I V_{11}$. This yields $R_s = 2.11 \text{ m}\Omega$

The values of R_a and R_b are determined by solving the following equations:

$$V_{12} = I R_a + (I - I_s) R_b = I R_a + (I - I_s) (R_t - R_a)$$

$$V_{11} = I R_b + (I - I_s) R_a = I (R_t - R_a) + (I - I_s) R_a$$

$$I_s R_s = (I - I_s) (R_b + R_a) = (I - I_s) R_t$$

These have the solution:

$$I_s = I \frac{R_t}{R_s + R_t}$$

$$R_a = R_{12} - R_s \left(1 - \frac{R_{12}}{R_t} \right) = 84.3 \text{m}\Omega$$

$$R_b = R_{11} - R_s \left(1 - \frac{R_{12}}{R_t} \right) = 2.1 \text{m}\Omega.$$

That is, the short is 2.4 % of the distance from tap 10B to 11B. Taking the estimated uncertainty in each resistance measurement to be 0.1 - 0.2m Ω and the errors to be uncorrelated yields the uncertainty in R_a and R_b to be 0.5 - 0.8m Ω or the uncertainty in the distance of the short from the taps to be 0.6 - 0.9 % of a turn. One turn is about 1300 inches, so the short is about 30 ± 10 inches from the taps or 50 ± 10 inches from the boundary between the wedges and the lead end spacers on the side with the mid-plane lead.

Table I
Coil Resistance (ohms)

P_H (psi)	Coil Resistance (ohms)	
	Upper	Lower
-11	3.241	3.248
355	3.241	3.248
998	3.240	3.248
2001	3.238	3.247
2996	3.238	3.247
3996	3.238	3.246
5018	3.238	3.242
5992	3.238	3.243
6982	3.238	3.244
7993	3.238	3.241
8478	3.238	3.235

Table II

P_H (psi)	R (LI) ($m\Omega$)
8500	1334
7000	1335
6000	1337
5000	1348
4000	1355
3000	1362
2000	1369
1000	1374
350	1377
0	1377

Table III

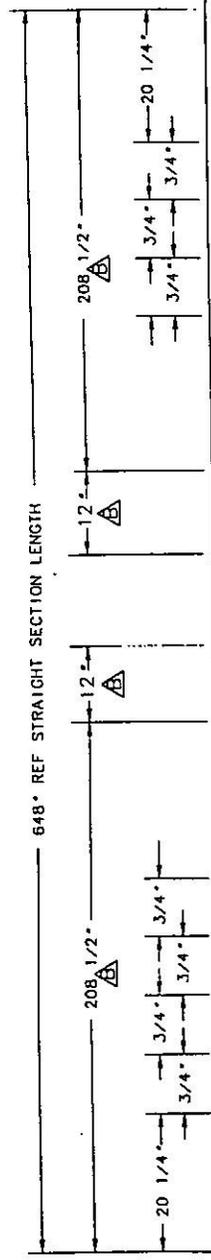
Turn	Taps	Resistance ($m\Omega$)	
		$P_H=0$	$P_H=8500$ psi
16	16A-15B	85.0	83.3
15	15B-14B	86.4	86.5
14	14B-13B	86.3	86.3
13	13B-12B	86.4	86.4
12	12B-11B	86.3	85.8
11	11B-10B	86.5	61.9
10	10B-9B	86.5	86.5

Table IV
Turns 1-9 Resistance

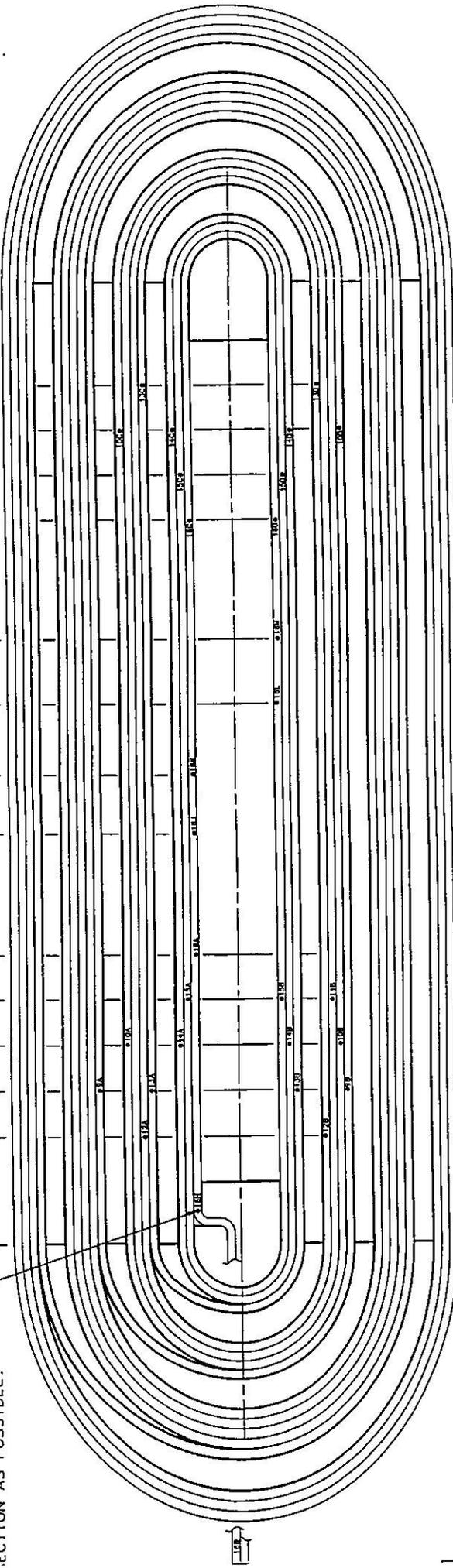
P_H (psi)	R ($m\Omega$)
1000	780.6
2000	780.6
3000	780.6
4000	780.7
5000	780.7
6000	780.7
7000	780.8
8000	780.8

ORIGINAL DRAWING DATE: 1982

- A C. ADDED 6 NEW VOLTAGE TAP.
- DELETED FOUR TAP LOCATIONS AND
- A ADDED 2. ADDED 208 1/2" .12" DIMS.



TAP TO BE LOCATED AS CLOSE TO BEGINNING OF STRAIGHT SECTION AS POSSIBLE.



ITEM	PART NO.	DESCRIPTION OR SIZE	0
PARTS LIST			
UNLESS OTHERWISE SPECIFIED:			
1.	ALL DIMENSIONS ARE IN MILLIMETERS, TOLERANCES ARE IN MILLIMETERS BASED UPON ANSI Y14.5M-1982.	ORIGINATOR	STRAIT/KOSKA
2.	1/4 INCH DIMENSIONS ARE FOR REFERENCE ONLY. DO NOT SCALE DRAWING.	DRAWN	R. DIXON
3.	ALL SURFACES UNLESS OTHERWISE SPECIFIED.	CHECKED	
4.	ALL DIMENSIONS ARE FOR REFERENCE ONLY. DO NOT SCALE DRAWING.	APPROVED	
5.	BREAK ALL SHARP EDGES. DO NOT SCALE DRAWING.	USED ON	
6.	ALL SURFACES UNLESS OTHERWISE SPECIFIED.	MATERIAL	
7.	ALL DIMENSIONS ARE IN MILLIMETERS, TOLERANCES ARE IN MILLIMETERS BASED UPON ANSI Y14.5M-1982.		5/12

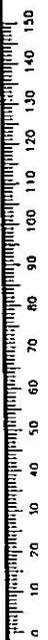
FERMI NATIONAL ACCELERATOR LABORATORY
UNITED STATES DEPARTMENT OF ENERGY
SSC

VOLTAGE TAPS
SSC LONG INNER COIL
MOD 2

SCALE	FILMED	DRAWING NUMBER	0
NONE		0102-MC-263900	
CREATED WITH I-DEAS 4.1			USER NAME: SPUD

1. VOLTAGE TAP WIRES FOR TAPS 0A, 16B, AND THE HALF COIL TAP ARE #22 AWG TEFLON INSULATED.
2. THE REMAINING VOLTAGE TAP WIRES ARE #32 AWG TEFLON INSULATED.
3. TAP WIRES WITH THE SAME NUMBER AT EACH END SHOULD FORM A TWISTED PAIR (A-B AND C-D).
4. VOLTAGE TAP WIRE SHOULD FOLLOW THE CABLE TO WHICH THEY ARE SOLDERED UNTIL THEY MEET AND ARE TWISTED WITH THEIR 'MATE'.
5. COIL AS VIEWED FROM INSIDE.

Figure 1



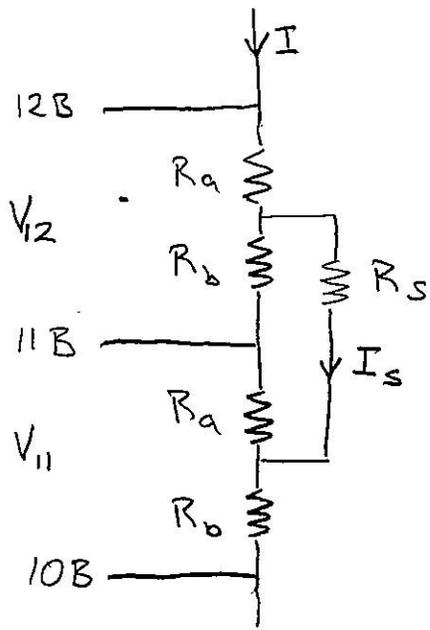


Figure 2

Distribution:

R. Bossert
J. Carson
S. Delchamps
M. Gordon
S. Gourlay
W. Koska
M. Lamm
R. Sims
G. Tassotto
M. Wake
M. Winters

From: FNAL::JBS 13-DEC-1990 18:02:47.70
To: CARSON
CC: BOSSERT, DELCHTS, GOURLAY, HANFT, KOSKA, KUCHNIR, LAMM, MANTSCH, MAZUR, PEWITT, WAKE, MYSELF
Subj: Location of DC0304 short

By performing resistance measurements on the lower inner coil of DC0304 under stress in the collaring press (8000 psi hydraulic pressure) we have located the short to be between turns 11 and 12 (not adjacent to a wedge!) relatively close to taps 10B and 11B. From the individual turn resistance values the short appears to be about 30" from taps 10B and 11B towards the return end, or about 50" from the lead end of the wedges on side with the mid-plane lead. I would guess the uncertainty of the determination is on the order of +/-10". While yesterday the short resistance decreased steadily with increasing press pressure and the short was clearly present at hydraulic pressure of 1000 psi, today it required 6500 psi to make the short visible. This is far in excess of the capacity of the hydraulic C-clamp and I therefore see no purpose in using it to compress one collar pack at a time. If the press pressure is assumed to be distributed equally among the two sides of the two coils, 6500 psi in the hydraulic system corresponds to 14 kpsi in the coil. It therefore may be difficult to detect the short with the coil sizing gauge unless considerably higher loads than normal are used. I believe that the next step is to begin disassembly of the magnet. The crew on the floor is awaiting your command to begin.

I will place the original data sheets on which the resistance measurements were recorded into the DC0304 traveller and will attempt to make a more detailed writeup of the measurements in the next day or two.

DC0304 Turn-to-turn Short Inspection

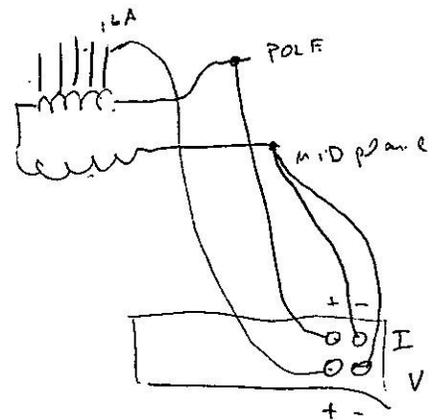
12/13/90
 J. Strait
 Page 1 of 3

1) With press unloaded, perform voltage tap resistance measurements:

Using Valhalla meter perform 4-wire resistance measurements. Attach the current leads to the mid-plane (-) and pole (+) leads of the lower inner coil. Power the coil with 1 A from the Valhalla. Place the negative voltage lead also at the mid-plane lead of the lower inner coil. Attach the positive voltage lead sequentially on the following voltage taps and record the resistances to 0.1 milliohm.

14:30

Tap	Resistance	delta-R
Pole lead	1387.6	
16A	1385.5	2.1
15A	1299.2	86.3
14A	1212.9	86.1
13A	1126.7	86.2
12A	1040.3	86.4
11A	N.A.	
10A	867.3	173.
9A	780.9	86.4



In the column "delta-R" record the difference between one resistance and the one below it in the table. This is the resistance of each turn.

- 2) Leave the Valhalla current and voltage leads connected as above with the positive voltage lead attached to tap 9A. Record the resistance from 9A to the mid-plane lead as a function of press hydraulic pressure.

Hydraulic Pressure	Resistance (9A)
1000	780.6
2000	780.6
3000	780.6
4000	780.7
5000	780.7
6000	780.7
7000	780.8
8000	780.8

DC0304 Turn-to-turn Short Inspection

3) Repeat step (1) with the press at 8000 psi.

Tap	Resistance	delta-R
Pole lead	1362.2	
16A	1361.7	0.5
15A	1275.0	86.7
14A	1188.2	86.8
13A	1101.8	86.4
12A	1015.4	86.4
11A	NA	
10A	866.8	148.6
9A	780.6	86.2

In the column "delta-R" record the difference between one resistance and the one below it in the table. This is the resistance of each turn.

Jill Strait X 2240

DC0304 Turn-to-turn Short Inspection

3) Repeat step (1) with the press at 8000 psi.

15:40

~~15:40~~

15:55

Tap	Resistance	delta-R		
Pole lead	1366.2			
16XB	NA			
15XB	1281.2	85	16A - 15B	83.3
14XB	1195.0	86.2	15B - 14B	86.5
13XB	1109.7	85.3	14B - 13B	86.3
12XB	1022.8	86.9	13B - 12B	86.4
11XB	NA 937.1	85.7	12B - 11B	85.8
10XB	870.1	67	11B - 10B	61.9
9XB	783.6	86.5	10B - 9B	86.5

In the column "delta-R" recored the difference between one resistance and the one below it in the table. This is the resistance of each turn.

Jim Strait X2240

DC0304 Turn-to-turn Short Inspection

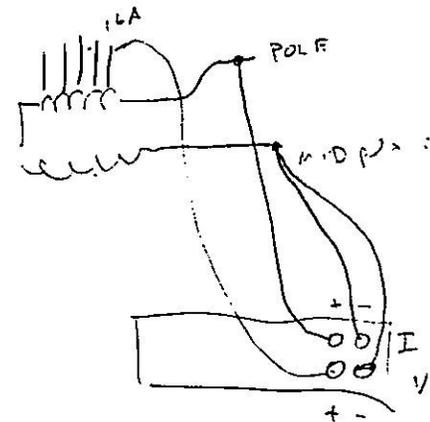
12/13/90
 J. Strait
 Page 1 of 3
 4

1) With press unloaded, perform voltage tap resistance measurements:

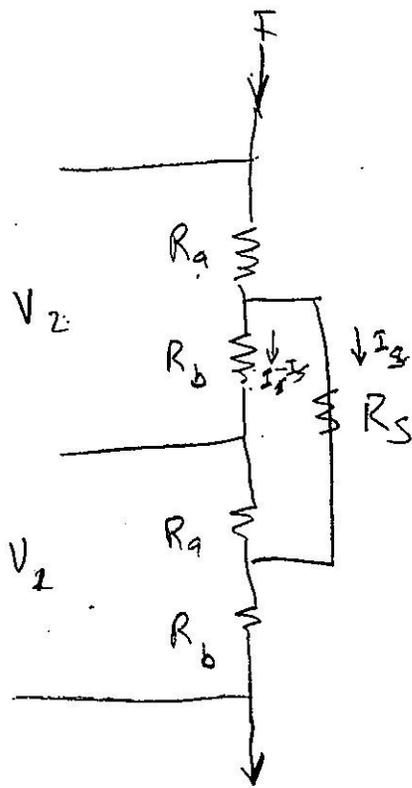
Using Valhalla meter perform 4-wire resistance measurements. Attach the current leads to the mid-plane (-) and pole (+) leads of the lower inner coil. Power the coil with 1 A from the Valhalla. Place the negative voltage lead also at the mid-plane lead of the lower inner coil. Attach the positive voltage lead sequentially on the following voltage taps and record the resistances to 0.1 milliohm.

15:30

Tap	Resistance	delta-R
Pole lead	1386.7	
16XB	— N/A —	
15XB	1301.7	85.0
14XB	1215.3	86.4
13XB	1129.0	86.3
12XB	1042.6	86.4
11XB	1056.3 956.3	86.3
10XB	869.8	86.5
9XB	783.3	86.5



In the column "delta-R" record the difference between one resistance and the one below it in the table. This is the resistance of each turn.



$$R_1 = 61.9 \text{ m}\Omega$$

$$R_2 = 85.8 \text{ m}\Omega$$

$$R_1 \equiv \frac{V_1}{I}$$

$$R_2 \equiv \frac{V_2}{I}$$

$$R_a + R_b = R_T = 86.4 \text{ m}\Omega$$

~~$R_1 + R_2$~~

$$R_1 + R_2 = R_T + R_T \parallel R_S$$

$$(R_1 + R_2) - R_T = R_T \parallel R_S = \left(\frac{1}{R_T} + \frac{1}{R_S} \right)^{-1}$$

$$\frac{1}{(R_1 + R_2 - R_T)} - \frac{1}{R_T} = \frac{1}{R_S}$$

$$R_S = 211 \text{ m}\Omega$$

$$R_b = R_{11} - \left(\frac{1}{R_{11} + R_{12} - R_T} - \frac{1}{R_T} \right)^{-1} \left(1 - \frac{R_{11}}{R_T} \right)$$

$$\frac{dR_b}{dR_{11}} = 1 - \left[\frac{1}{(R_{11} + R_{12} - R_T)^2} \left(1 - \frac{R_{11}}{R_T} \right) + \right.$$

$$\left. 1 - \left\{ + \left(\frac{1}{R_{11} + R_{12} - R_T} - \frac{1}{R_T} \right)^{-2} \left(+ \frac{1}{(R_{11} + R_{12} - R_T)^2} \right) \left(1 - \frac{R_{11}}{R_T} \right) + \left(\frac{1}{R_{11} + R_{12} - R_T} - \frac{1}{R_T} \right)^{-1} \left(-\frac{1}{R_T} \right) \right\} \right]$$

$$= 1 - \left\{ \frac{R_S^2}{(R_{11} + R_{12} - R_T)^2} \left(1 - \frac{R_{11}}{R_T} \right) - \frac{R_S}{R_T} \right\} = 0.918(6)$$

$$\frac{dR_b}{dR_T} = + R_S^2 \left(+ \frac{1}{(R_{11} + R_{12} + R_T)^2} + \frac{1}{R_T^2} \right) \left(1 - \frac{R_{11}}{R_T} \right) =$$

$$- R_S \frac{R_{11}}{R_T^2} = 3.302(7)$$

$$\frac{dR_b}{dR_{12}} = - R_S^2 \frac{1}{(R_{11} + R_{12} - R_T)^2} \left(1 - \frac{R_{11}}{R_{12}} \right) = -3.360(0)$$

$$\sigma_b^2 = \sigma_{11}^2 \left(\frac{dR_b}{dR_{11}} \right)^2 + \sigma_{12}^2 \left(\frac{dR_b}{dR_{12}} \right)^2 + \sigma_T^2 \left(\frac{dR_b}{dR_T} \right)^2 = (0.8 \text{ m}\Omega)^2$$

$$\text{for } \sigma_{11} = \sigma_{12} = 0.7 \\ \sigma_T = 0.1$$

$$= (0.5 \text{ m}\Omega)^2 \text{ for}$$

$$\sigma_{11} = \sigma_{12} = \sigma_T = 0.5 \text{ m}\Omega$$

$$V_2 = I R_a + (I - I_s) R_b$$

$$V_1 = I R_b + (I - I_s) R_a$$

$$I_s R_s = (I - I_s) R_T$$

$$I_s (R_s + R_T) = I R_T$$

$$I_s = I \frac{R_T}{R_s + R_T}$$

$$I - I_s = I \left(1 - \frac{R_T}{R_s + R_T} \right)$$

$$= I \left(\frac{R_s}{R_s + R_T} \right)$$

$$\cancel{V_2 = I} R_2 = R_a + R_b \frac{R_s}{R_s + R_T}$$

$$R_2 = R_b + R_a \frac{R_s}{R_s + R_T}$$

$$R_1 = R_b + (R_T - R_b) \frac{R_s}{R_s + R_T} = R_b \left(\frac{R_T}{R_s + R_T} \right) + \left(\frac{R_T R_s}{R_T + R_s} \right)$$

$$R_b = \left[R_1 - \left(\frac{R_T R_s}{R_T + R_s} \right) \right] \frac{R_s + R_T}{R_T} = 2.1 \text{ m}\Omega$$

$$R_a = \left[R_2 - \frac{R_T R_s}{R_T + R_s} \right] \frac{R_s + R_T}{R_T} = 84.3 \text{ m}\Omega$$

$$\frac{dR_s}{dR_T} = -R_s^2 \left(\frac{1}{(R_{11} + R_{12} - R_T)^2} - \frac{1}{R_T^2} \right) = 5.884 \quad (6)$$

$$\frac{dR_s}{dR_{11}} = \frac{dR_s}{dR_{12}} = +R_s^2 \left(\frac{1}{(R_{11} + R_{12} - R_T)^2} \right) = 11.849 \quad (7)$$

$$\sigma_{R_s}^2 = \sigma_T^2 \left(\frac{dR_s}{dR_T} \right)^2 + 2 \sigma_{11}^2 \left(\frac{dR_s}{dR_{11}} \right)^2 = (1.08 \text{ m}\Omega)^2 \text{ for all } \sigma_R = 0.1 \text{ m}\Omega$$

$$= (3.4 \text{ m}\Omega)^2 \text{ for}$$

$$\sigma_{R_{11}} = \sigma_{R_{12}} = 0.2$$

$$\sigma_{R_T} = 0.1$$

$$\frac{dR_b}{dR_{11}} = 1 + \frac{R_s}{R_T} = 3.442 \frac{dR_b}{dR_s} = \frac{R_{11}}{R_T} = 0.716 \quad (3) \quad \frac{dR_b}{dR_T} = -\frac{R_s R_{11}}{R_T^2} = 1.750 \quad (4)$$

$$\sigma_b^2 \approx \sigma_{11}^2 \left(\frac{dR_b}{dR_{11}} \right)^2 + \sigma_s^2 \left(\frac{dR_b}{dR_s} \right)^2 + \sigma_T^2 \left(\frac{dR_b}{dR_T} \right)^2$$

=

$$\frac{2.1 \pm 0.5 \text{ m}\Omega \quad (0.8)}{86.4 \pm 0.1 \text{ m}\Omega} = (2.4 \pm 0.6) \% \quad (0.9)$$

$$\Rightarrow 31 \pm 8 \quad (12)$$

