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 intital 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

$$R_{11} + R_{12} = R_a + \left(R_b + R_a\right) \parallel R_s + R_b$$

$$= R_t + (R_t \parallel R_s)$$

$$\frac{1}{R_s} = \frac{1}{R_{11} + R_{12} - R_t} - \frac{1}{R_t}$$

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 - 0.2mΩ and the errors to be uncorrelated yields the uncertainty in $R_a$ and $R_b$ to be 0.5 - 0.8mΩ 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) (mΩ) |
|---|---|
| 8500 | 1334 |
| 7000 | 1335 |
| 6000 | 1337 |
| 5000 | 1348 |
| 4000 | 1355 |
| 3000 | 1362 |
| 2000 | 1369 |
| 1000 | 1374 |
| 350 | 1377 |
| 0 | 1377 |

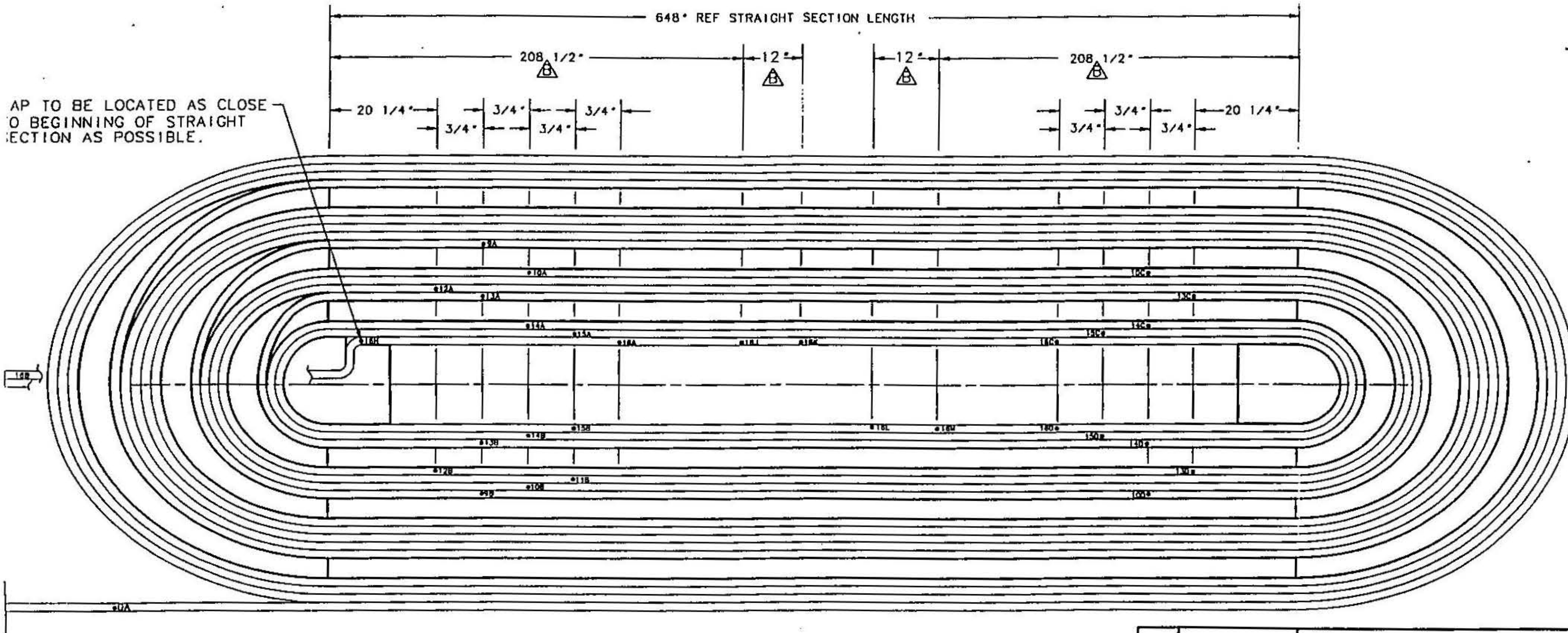
Table III

| | | Resistance (mΩ ) | |
|---|---|---|---|
| Turn | Taps | $P_H$=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 (mΩ) |
|---|---|
| 1000 | 780.6 |
| 2000 | 780.6 |
| 3000 | 780.6 |
| 4000 | 780.7 |
| 5000 | 780.7 |
| 6000 | 780.7 |
| 7000 | 780.8 |
| 8000 | 780.8 |

| | |
|---|---|
| A | CHANGE DRAWING SIZE ... C. ADDED 6 NEW VOLTAGE TAPS |
| A | DELETED FOUR TAP LOCATIONS AND ADDED 2. ADDED 208 1/2",12" DIMS. |




E:

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

| ITEM | PART NO. | DESCRIPTION OR SIZE | |
|---|---|---|---|
| | | PARTS LIST | |

| | | | |
|---|---|---|---|
| UNLESS OTHERWISE SPECIFIED: 1. ALL DIMENSIONS ARE IN MILLIMETERS. 2. TOLERANCES: ± 1 mm. 3. DIMENSIONS BASED UPON ANSI Y14.5M-1982. 4. INCH DIMENSIONS ARE FOR REFERENCE ONLY. 5. BREAK ALL SHARP EDGES. 6. DO NOT SCALE DRAWING. 7. MAX. ALL MACH. SURFACES √ 8. DIMENSION IDENTIFICATION: MILLIMETER/INCH :MILLIMETER/INCH | ORIGINATOR | STRAIT/KOSKA | |
| | DRAWN | R.DIXON | 5/1/ |
| | CHECKED | | |
| | APPROVED | | |
| | USED ON | | |
| | MATERIAL | | |

FERMI NATIONAL ACCELERATOR LABORATO
UNITED STATES DEPARTMENT OF ENERGY
SSC

VOLTAGE TAPS
SSC LONG INNER COIL
MOD 2

| SCALE | FILMED | DRAWING NUMBER |
|---|---|---|
| NONE | | 0102-MC-263900 |

CREATED WITH I-DEAS 4.1 | USER NAME: SPUD

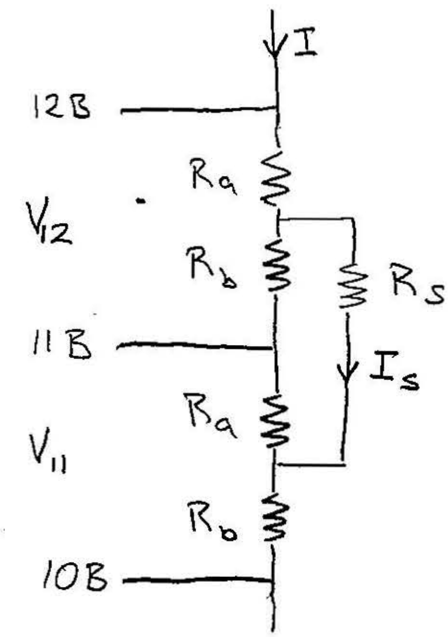



Figure 2

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

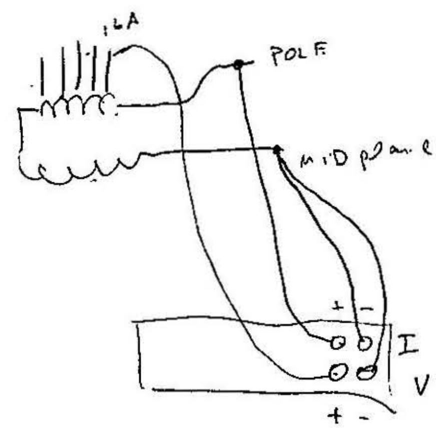
12/13/90
J. Strait


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" recored 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 |

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 | N.A | |
| 10A | 866.8 | 148.6. |
| 9A | 780.6 | 86.2 |

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 x 2240

~~15:40~~

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

15:40 15:55

| Tap | Resistance | delta-R | | |
|---|---|---|---|---|
| Pole lead | 1366.2 | | | |
| 16~~A~~ B | NA | | | |
| 15~~A~~ B | 1281.2 | 85 | 16A-15B | 83.3 |
| 14~~A~~ B | 1195.0 | 86.2 | 15B-14B | 86.5 |
| 13~~A~~ B | 1109.7 | 85.3 | 14B-13B | 86.3 |
| 12~~A~~ B | 1022.8 | 86.9 | 13B-12B | 86.4 |
| 11~~A~~ B | 937.1 | 85.7 | 12B-11B | 85.8 |
| 10~~A~~ B | 870.1 | 67. | ← 11B-10B | 61.9 |
| 9~~A~~ B | 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
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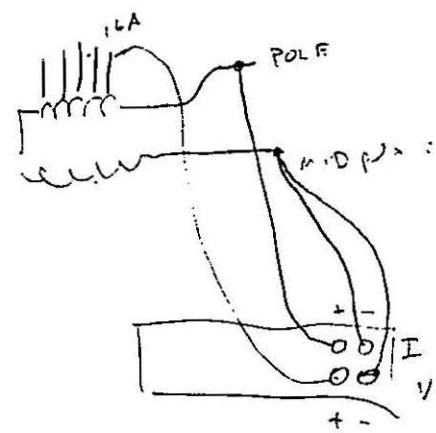
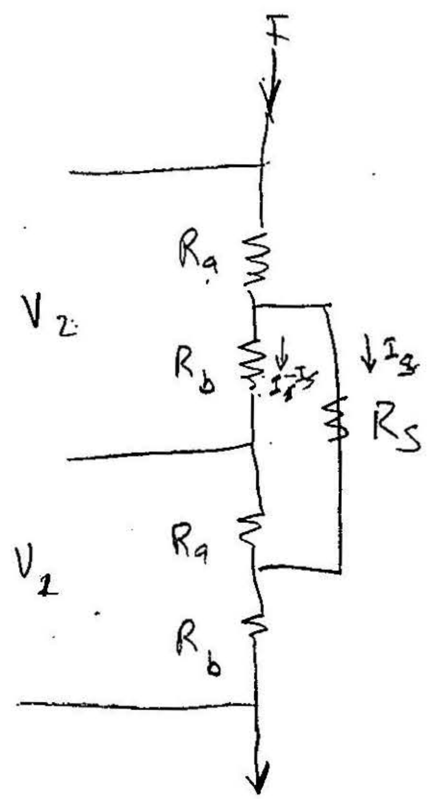
15:30

| Tap | Resistance | delta-R |
|---|---|---|
| Pole lead | 1386.7 | |
| 16~~A~~B | — NA — | |
| 15~~A~~B | 1301.7 | 85.0 |
| 14~~A~~B | 1215.3 | 86.4 |
| 13~~A~~B | 1129.0 | 86.3 |
| 12~~A~~B | 1042.6 | 86.4 |
| 11~~A~~B | 956.3 | 86.3 |
| 10~~A~~B | 869.8 | 86.5 |
| 9~~A~~B | 783.3 | 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.




$$\boxed{\begin{aligned} R_1 &= 61.9\,m\Omega \\ R_2 &= 85.8\,m\Omega \end{aligned}}$$

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

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

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

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

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

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

$$\boxed{R_S = 211\,m\Omega}$$

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

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

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

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

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

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

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

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

for $\sigma_{11} = \sigma_{12} = 0.2$
$\sigma_T = 0.1$

$= (0.5\ m\Omega)^2$ for
$\sigma_{11} = \sigma_{12} = \sigma_T = 0.1\ m\Omega$

$$V_2 = I\,R_a + (I - I_s)\,R_b$$
$$V_1 = I\,R_b + (I - I_s)\,R_a$$

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

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

$$R_1 = R_b + R_a\,\frac{R_s}{R_s + R_T}$$

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

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

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

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

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

$$\sigma_{s}^2 = \sigma_T^2\left(\frac{dR_s}{dR_T}\right)^2 + 2\,\sigma_{11}^2\left(\frac{dR_s}{dR_{11}}\right)^2 = (1.8\,m\Omega)^2 \text{ for all}$$

$\sigma_R = 0.1\,m\Omega$

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

$\sigma_{R11} = \sigma_{R12} = 0.2$

$\sigma_{RT} = 0.1$

---

$$\frac{dR_b}{dR_{11}} = 1 + \frac{R_s}{R_T} = \overset{(0)}{3.442} \quad \frac{dR_b}{dR_s} = \frac{R_{11}}{R_T} = 0.716\ (3) \quad \frac{dR_b}{dR_T} = -\frac{R_s R_{11}}{R_T^2} = 1.750\ (.0)$$

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

$=$

$$\frac{2.1 \pm \overset{(0.8)}{0.5}\ \mathrm{m\Omega}}{86.4 \pm .1\ \mathrm{m\Omega}} = \left(2.4 \pm \overset{(0.9)}{0.6}\right)\%$$

$$\Rightarrow 31 \pm \underset{(12)}{8}$$