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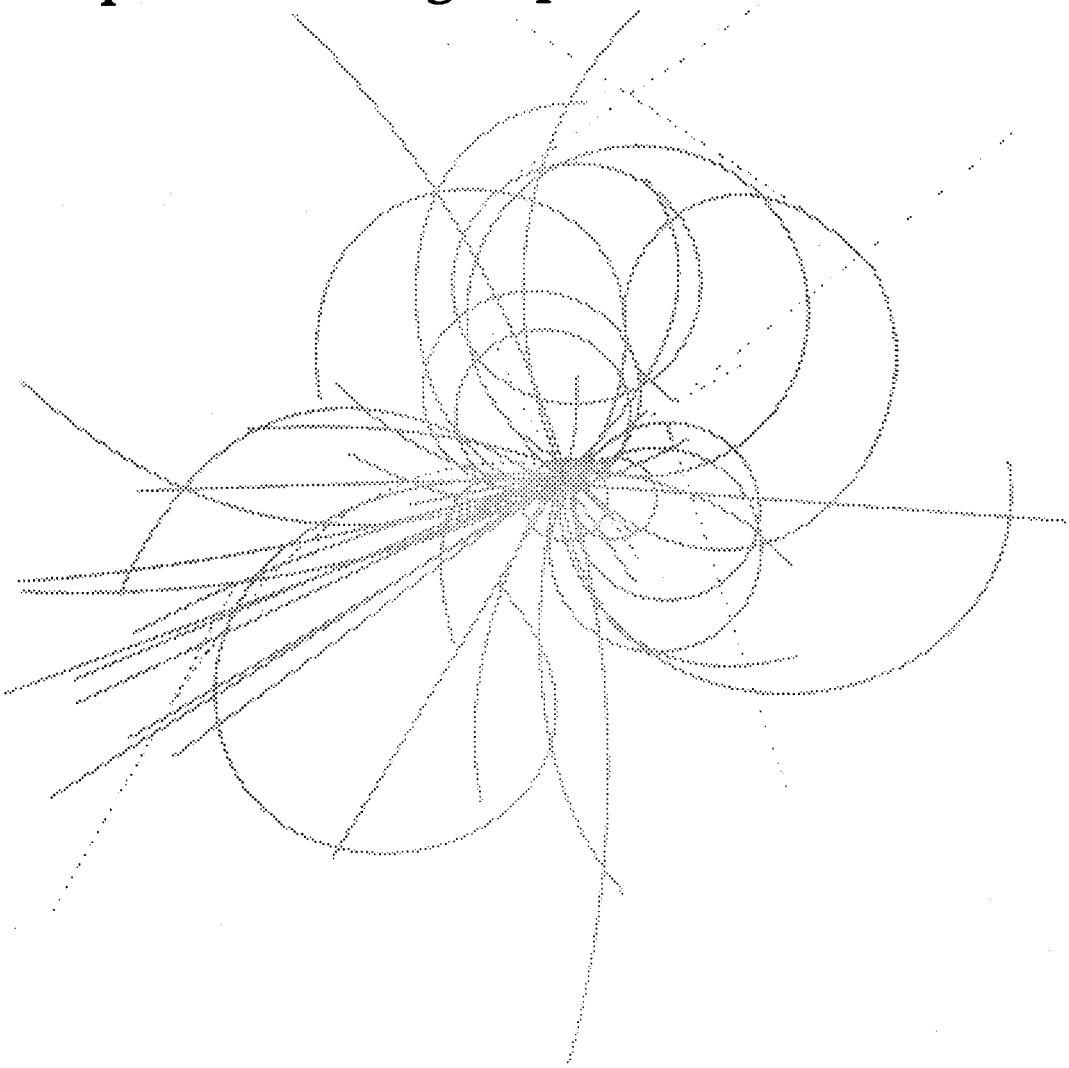
Superconducting Super Collider Laboratory



Quantification of Systematic Error in I_C Testing

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QUANTIFICATION OF SYSTEMATIC ERROR IN I_c TESTING

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Abstract: Critical current (I_c) testing of the superconducting wire for the Superconducting Super Collider (SSC) is an important Quality Assurance concern due to its significance in magnet variability. Established industrial QA procedures to quantify measurement variability have been adapted to I_c measurements. To implement these ideas, a round robin experiment was developed and six test sites were invited to participate in the evaluation of I_c measurement uncertainty. An SSCL Quality Assurance representative witnessed all measurements performed in this program. The definition of each component of variability, the test plan procedure that quantified each component, preliminary findings, and future plans are reported. Preliminary results show that four of the six round robin participants achieved accuracy within +/- 2% of the National Institute of Standards and Technology critical current Standard Reference Material value. Reproducibility results show that five of six test sites have a 2% or less uncertainty, with one test site as high as 6.5%. In addition, the repeatability results show that only one participant has less than 2% uncertainty; the remaining labs falling within 2–5%. Cumulative uncertainty is determined to be 3–10% depending on the method used to calculate repeatability.

INTRODUCTION

In order to make good management decisions from reported I_c measurement data, gage calibration must be guaranteed by all testing sources. By measuring and controlling test error, the Superconducting Super Collider (SSC) Laboratory hopes to ensure that long-term accurate I_c values are reported from all possible sources during the entire SSC construction program. This is vital to implement the current philosophy of cable strand mapping.[5,6] Strand I_cs from different billets are to be intermixed into cable to minimize variation from magnet to

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magnet. In the enclosed test plan, the systematic error has been broken down into components which include accuracy, linearity, reproducibility, and repeatability. These components take into account both the device-specific and operator-induced error experienced in I_c testing. Of particular interest is the component of variability due to operator technique. To our knowledge, this element has never been quantified. This method of error evaluation is based on an established Quality Assurance model for measurement calibration and, to our knowledge, has never been performed for this particular application.[1-4]

DEFINITION/PROCEDURE

Accuracy

Measurement accuracy is defined as the difference between the observed average of measurements and the true average of the same parts using precision instruments.

Linearity

Measurement linearity is defined as the difference in the accuracy over the expected operating range.

To determine this portion of the uncertainty, each participant was given a National Institute of Standards and Technology Standard Reference Material (SRM) 1457. SRM 1457 is a NbTi superconducting wire certified by NIST as an I_c standard.[7,8] The SRMs were purchased consecutively, guaranteeing that each came from the same section of the parent billet.

One certified operator from each site mounted the SRM onto the sample holder and lowered the sample into a liquid helium-cooled superconducting magnet. The magnet was ramped up to 8.0 T and three voltage vs. current curves were generated at this same applied field. The applied magnetic field in the magnet was not changed between the three tests. The critical current was then calculated from each curve using a resistivity criterion that was converted from the SRM certified electric field criterion of 0.2 μV/cm.[7,8] The same operator repeated the same procedure at magnetic fields of 7.0, 6.0, 5.6, and 4.0 T.

The I_c measurement accuracy was determined by taking the difference between each field's SRM value and the observed average of three measurements for the laboratory. The difference was converted to percent uncertainty by dividing by the SRM value. The linearity for the test site was computed using the accuracy values determined above. The field with the lowest percent uncertainty was subtracted from the field with the greatest percent uncertainty.[1,2]

The SRM I_c value was corrected for each test site's liquid helium bath temperature using the I_c temperature correction table in NBS Special Publication 260-91, which was received with the SRM.[8] The liquid helium bath temperature was computed from the absolute atmospheric pressure at the time of the test.[9] Because the SRM is certified only at even fields, the 5.6 and 7.0 T values were determined by interpolation from the even fields.[8] This method is valid because the I_c vs. magnetic field curve is nearly linear at the fields in question. Sample self field corrections on the I_c were included only if the test site typically corrects the measurements that it submits.

Reproducibility

Measurement reproducibility is defined as the range between the average of the I_c measurements made by different operators using the same test facility when measuring

identical wire samples. All certified I_c measurement operators were invited to take part in this test. Each operator was given a contiguous SSC-type 1.3:1 inner grade wire sample (from the same source spool) which he/she mounted to the I_c sample holder. Three voltage vs. current curves were produced by each operator at 7.0 T, and the I_c was determined using a resistivity criterion of 10^{-14} Ω-m. The magnetic field of 7.0 T was chosen for data comparison as it is the SSC inner grade wire specified test field. The field was held consistent for all three measurements.

To determine reproducibility, first the average I_c value was calculated separately for each operator. The range in amperes was determined by subtracting the smallest average I_c from the largest average I_c. This value was then converted to percent uncertainty by dividing the average I_c range by the grand average of all the operators' I_c results in the given facility.[1,2]

Repeatability

Measurement repeatability is defined as the variation in measurements obtained when one certified operator uses the same test facility for measuring the I_c of the same source sample. One certified test site operator was given three contiguous 1.3:1 type inner grade SSC wire samples which he/she mounted on an I_c sample holder. Three voltage vs. current curves were produced at 7.0 T for each sample, and the I_cs were determined, again using a resistivity criterion of 10^{-14} Ω-m. A total of nine measurements were made on the same source wire by each test site.

Repeatability was determined using the two methods described below. Both assume that the I_c measurement variation is normally distributed, an assumption that has been verified by the data.

Method I

The I_c range in amperes was determined for each of the three samples, and the average range was computed from the three ranges. The average range was divided by d_2, which is a factor to estimate the standard deviation of the population using the range.[10] The 95% (+/- 1.96 sigma) spread was determined by multiplying the estimated standard deviation by two times the respective Z factor. Finally, the spread was converted to percent uncertainty by dividing the +/- 1.96 sigma spread by the average I_c of the test site's nine measurements, then multiplying by 100.[2-4]

Method II

The calculation in Method II is similar to Method I except that the standard deviation was determined from all nine measurements directly. To compare results with Method I, the 95% spread was calculated (as in Method I) and converted to % uncertainty by dividing the +/- 1.96 sigma spread by the average of the nine measurements and multiplying by 100.[10]

The reason for calculating the percent uncertainty using Method II is that currently the I_c data is taken using the "1-test-per-1-spool-of-wire" technique. Although the Method I test plan was performed by taking three I_c tests per sample, Method II looks at the data as if there were nine separate measurements, any one of which could have been reported had this been a typical industry verification. Method II uncertainty can be compared to that determined using Method I where the range of three tests was used to estimate the population standard deviation.

Miscellaneous Data

In addition to the critical current results, other pertinent data were collected such as the strand diameter and the length between voltage taps on the sample holder. The copper to non-copper ratio was calculated using both the chemical method and the electrical resistance method on one sample of each type of wire. This data will not be presented in this paper, but each method will eventually be statistically evaluated.

Note: The test sites listed in the following results are identified by an arbitrary number (1-6). This number has no bearing on the outcome or rating of the test sites. Another paper[12] presented at the 1991 IISSC uses colors instead of numbers to identify certain test sites. For comparison, the number with its corresponding color is given: 2 = brown, 3 = blue, 5 = black, 6 = purple.

RESULTS

Table 1 lists all the participants accuracy data for each tested field.

Figure 1 graphically compares the percent uncertainty for each laboratory at all fields. Currently, a limit has not been determined for an acceptable accuracy uncertainty, but if a +/- 2% limit is arbitrarily picked, two of the six laboratories would fail. Test Site 2 was the only participant that corrected its measurements for self field and, as seen by the data, produced the lowest percent uncertainty due to accuracy. The SRM does not assume the application of self field corrections, however.

The accuracy results also show that the temperature dependence of I_c (SRM I_c variation) is significant, and that a temperature correction should be included when I_c data is reported. This confirms previously reported results.[9]

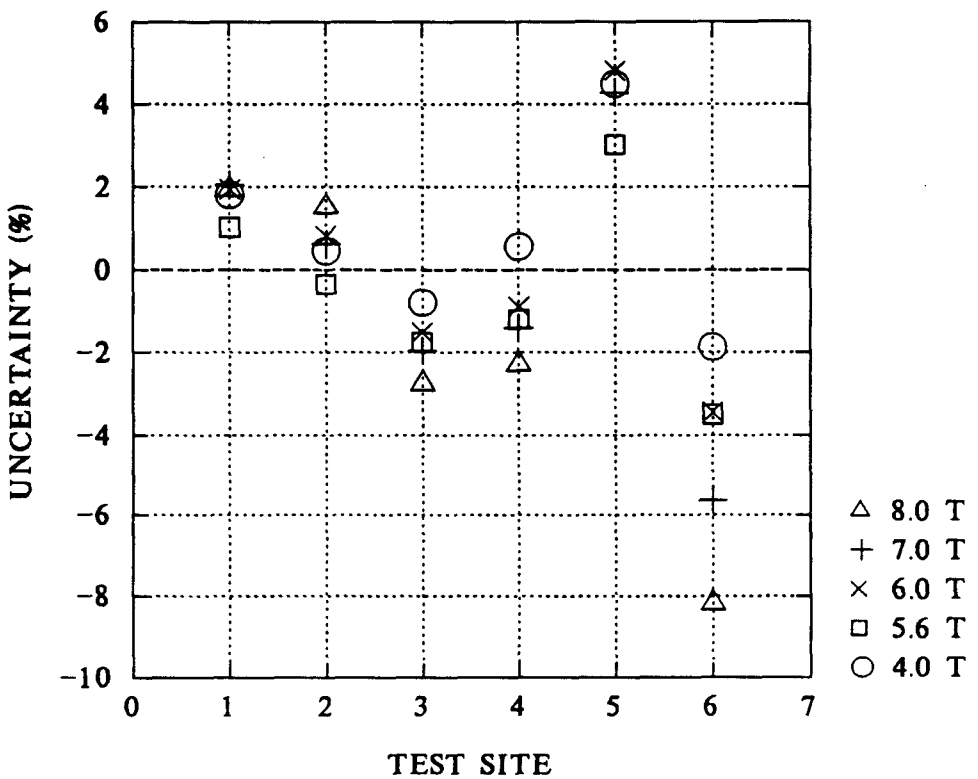

Figure 1. Accuracy percent uncertainty for each test site.

Table 1. Accuracy.

4.0 T LAB	I_c AVERAGE (Amps)	SRM I_c (Amps)	% DIFFERENCE
1	191.27	187.88	1.803
2	186.87	186.03	0.450
3	185.00	186.48	-0.794
4	187.87	186.82	0.563
5	195.00	186.63	4.485
6	182.67	186.16	-1.874
5.6 T LAB			
1	139.13	137.72	1.026
2	135.50	135.98	-0.353
3	134.00	136.41	-1.767
4	135.07	136.72	-1.209
5	140.67	136.55	3.015
6	131.33	136.10	-3.502
6.0 T LAB			
1	127.60	125.18	1.933
2	124.47	123.47	0.806
3	122.00	123.89	-1.526
4	123.10	124.20	-0.886
5	130.00	124.03	4.813
6	119.33	123.59	-3.444
7.0 T LAB			
1	99.67	97.68	2.034
2	96.57	95.98	0.611
3	94.50	96.39	-1.961
4	95.33	96.71	-1.418
5	100.67	96.54	4.280
6	90.67	96.10	-5.652
8.0 T LAB			
1	71.53	70.17	1.943
2	69.53	68.50	1.516
3	67.00	68.90	-2.758
4	67.63	69.21	-2.278
5	N/A	N/A	N/A
6	63.00	68.61	-8.177

Figure 2 lists each test site's linearity using the above accuracy data.

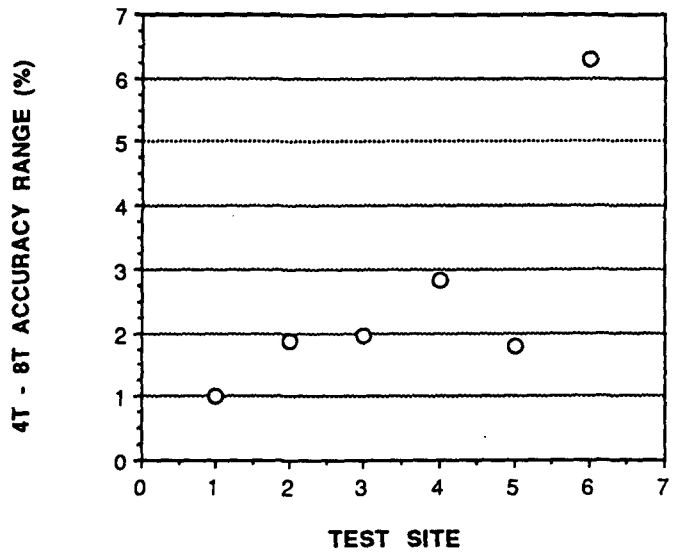

Figure 2. Linearity for each test site over the magnetic fields of 4–8 T.

If a test site exhibited a 0% range in accuracy over the fields measured, this would mean that the error (or lack of error) was consistent at all fields, i.e., all the I_c values deviated by the same amount. Applying an arbitrary 2% limit, again two labs failed, with three others near the limit. This suggests that the variation in I_c with field is not consistent for most of the test sites, and that causes of field-dependent error should be found and corrected.

Table 2 lists the reproducibility data for each participant.

Table 2. Reproducibility Data.

LAB/OPERATOR	I_c AVG. (Amps)	RANGE (Amps)	% UNCERTAINTY
1/A	392.27		
1/B	386.87	5.40	1.39%
2/A	364.97		
2/B	367.20		
2/C	390.10	25.13	6.72%
3/A	375.33		
3/B	373.00	2.33	0.62%
4/A	375.97		
4/B	382.20	6.23	1.64%
5/A	396.67		
5/B	398.00	1.33	0.34%
6/A	377.33		
6/B	374.00	3.33	0.89%

These results can be seen in Figure 3.

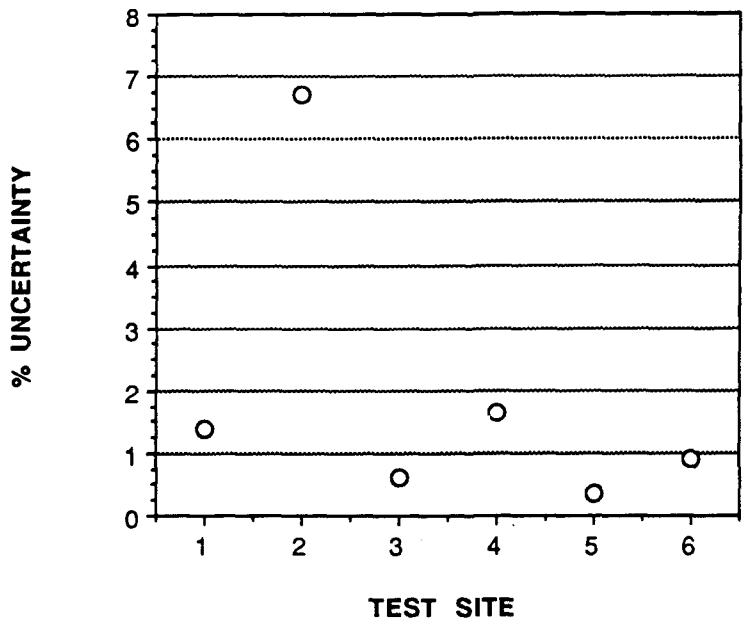

Figure 3. Percent uncertainty due to reproducibility for each test site.

From Figure 3, it appears that Lab B has a very large percent uncertainty due to reproducibility. This demonstrates that Lab B needs to carefully evaluate operator technique. All of the other remaining labs have roughly the same percent uncertainty (< 2%). An even better 1% limit appears to be attainable by five of the six test sites through further process control.

Table 3 lists the repeatability data in tabular form.

Table 3. Repeatability.

Method I (95% spread = (I_C Avg Range/d_2) * 1.96_Z * 2)

LAB/SAMPLE	I_C AVG. (Amps)	95% SPREAD (Amps)	% UNCERTAINTY
1/A	392.27		
1/B	384.67		
1/C	390.20	4.13	1.06%
2/A	364.97		
2/B	360.93		
2/C	364.67	13.51	3.72%
3/A	375.33		
3/B	373.00		
3/C	373.00	0.74	0.20%
4/A	375.97		
4/B	381.33		
4/C	376.40	3.10	0.82%
5/A	396.67		
5/B	395.67		
5/C	397.67	11.07	2.79%
6/A	377.33		
6/B	376.67		
6/C	377.33	8.86	2.35%

Table 3. Repeatability (Continued).

Method II (95% spread = sample $\sigma * 1.96_z * 2$)

LAB	I_c AVG. (Amps)	95% SPREAD (Amps)	% UNCERTAINTY
1	388.76	13.84	3.56%
2	363.71	17.64	4.85%
3	373.81	4.71	1.26%
4	378.26	10.44	2.76%
5	397.15	12.55	3.16%
6	376.78	7.95	2.11%

The results of Table 3 can be seen in Figure 4.

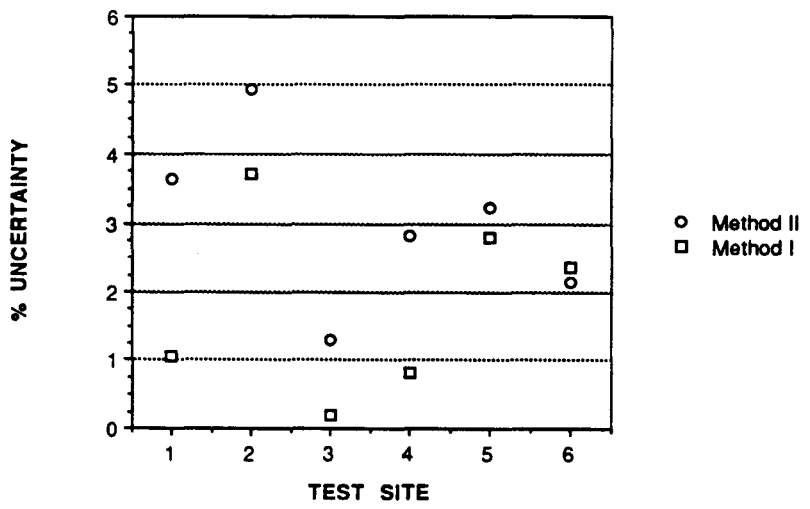

Figure 4. Percent uncertainty due to repeatability for each test site.

Figure 4 shows that if an arbitrary 2% limit is applied to the data, five of six participants fail when calculating the repeatability using Method II and three of six fail using Method I. These results suggest that one way to decrease uncertainty would be to increase the number of measurements per sample and to report the average.

Figure 5 shows the sum of the uncertainty measured for each lab. The mid-point for each test site is the relative accuracy determined with the SRM. The spread around accuracy is based on the repeatability plus the reproducibility. The repeatability method depicted uses the standard deviation of all nine measurements (Method II) to simulate the error of one I_c test per spool.

The sum of the absolute uncertainty is given in Figure 6. The ASTM B714-82 procedure for I_c measurements states that using the procedure should give an I_c accurate to within 5%.[11] It is unclear, however, how ASTM is defining "accuracy." If the 5% benchmark is used on the total uncertainty, four of six labs would fail.

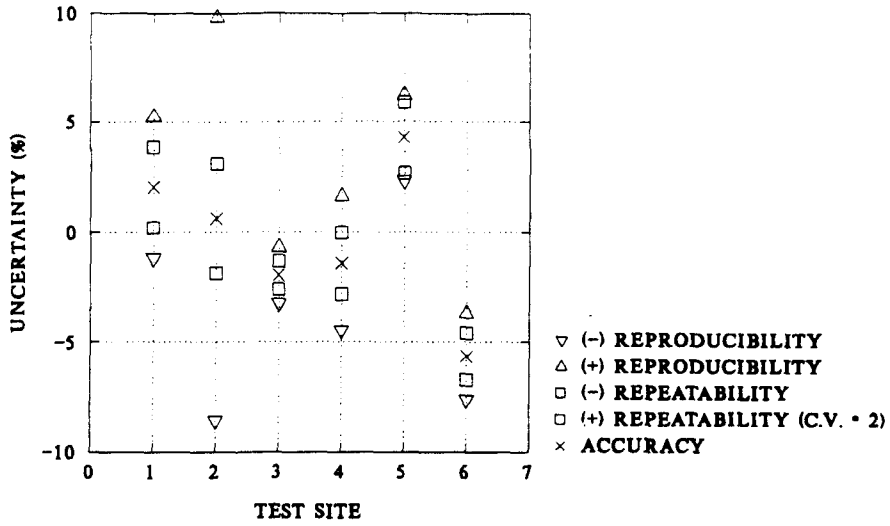

Figure 5. The sum of uncertainty for each test site.

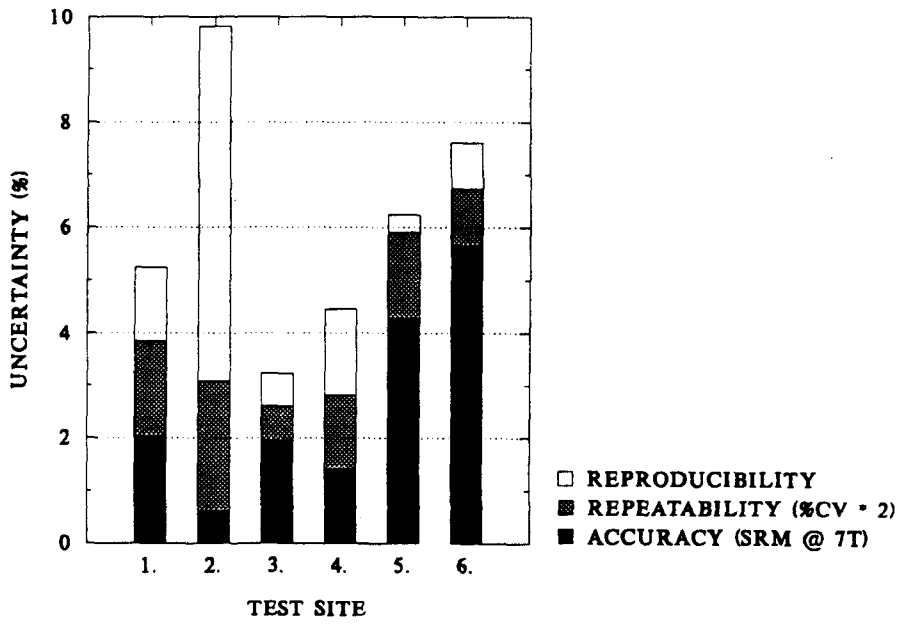

Figure 6. The sum of absolute uncertainty for each test site.

Impact on Cable Mapping

Figure 7 is a plot of the one sigma variation of several inner and outer grade SSC superconducting billets produced by one of the test sites. It also lists the one σ uncertainty for that particular test site due to reproducibility and repeatability. Upon comparison, it appears that uncertainty in the measurement is nearly equal to the variation about the billet mean for the samples measured. This condition suggests that it may be difficult to determine whether the variation was due to local differences in the wire or to measurement error.

TEST UNCERTAINTY (LAB 5)	%	
REPEATABILITY	0.807	(1 * Sigma / Mean) * 100, n = 9
REPRODUCABILITY	0.335	(Avg. Tech Range / Avg. Ic)
R&R	1.141	(Repeatability + Reproducability)

Billet Ic Variation								
Wire Type	IN	OUT	OUT	OUT	OUT	OUT	OUT	OUT
Number of Samples	55	29	55	28	17	83	29	48
Mean	369.6	311.4	313.4	305.5	310.6	315.8	325.1	323.0
Standard Deviation	5.68	3.51	3.42	4.76	4.35	3.49	6.28	7.09
Coefficient of Variation (C.V.)	0.015	0.011	0.011	0.016	0.014	0.011	0.019	0.022
% C.V.	1.54	1.13	1.09	1.56	1.40	1.10	1.93	2.19

Materail - Measurement Difference								
BILLET %C.V. - R&R (%)	0.39	-0.02	-0.05	0.42	0.26	-0.04	0.79	1.05

Figure 7. Repeatability and Reproducibility vs. Billet Variation.

IMPLICATIONS OF THE RESULTS

- Temperature dependence on I_c measurement is significant; a correction should be included when reporting I_c data.
- It is difficult to determine whether variation in I_cs is due to local wire variation or to measurement error.
- The implications of measurement error should be considered when evaluating I_cs near the specification limit.
- The significance or validity of single data point measurements in I_c performance studies may be in question.
- The number of measurements needed to determine source I_cs may have to be increased to reduce the uncertainty due to repeatability.
- The relative accuracy of the source should be considered when comparing or judging the results from different sources.

FUTURE PLANS

The strategy to be used in evaluating the test sites will be to first determine an agreeable uncertainty for both the components and the total variability, and compare it to each participant's error. The results will then be reviewed with each participant. Causes of unacceptable uncertainty will be identified and corrective action taken. Finally, participants with unacceptable uncertainty will be asked to repeat certain portions of the test plan after corrective action has been taken.

SUMMARY

Two of six labs have uncertainty due to accuracy of less than 2%.

Two of six labs have large variation over their applied field, suggesting that their error is not consistent at all fields.

The reproducibility of five of six labs was less than 2%, with the other lab exceeding 6% uncertainty for this component.

The 95% spread for repeatability using the range to estimate the standard deviation (Method I) was between 0.2% and 4%, while the 95% spread using the sample standard deviation of the nine measurements (Method II) was between 1% and 5%.

The total percent uncertainty for each lab fell within the range of 3% to 10% (Method II repeatability). Four of six labs have greater than a 5 % uncertainty.

ACKNOWLEDGMENTS

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