I. Introduction

In April 2019 LBNL acquired a Leica AT960-MR Laser Tracker with T-Probe ("Leica system") to measure the physical dimensions of the MQXFA coils. Previously we had been measuring the coil physical dimensions using a Zeiss Accura Bridge-Type Measuring Machine with a 1.6 x 3.0 x 1.4 m measuring range ("Zeiss system" or "CMM").

Figure 1: Coil on Zeiss Accura (left) Leica Laser Tracker and handheld T-Probe measuring coil

The Leica system provides several advantages over the Zeiss system. Namely,

1. Coil does not need to be transported across the street, this means that after arrival at LBNL it can be maneuvered solely with the crane and crane lifting fixture
2. Coil can be measured in one set-up
3. Coil inner radius can be measured in that same one set-up
4. The Leica system is not shared with other projects, so the project has more control over scheduling measurements

Per the manufacturer's specifications, the Leica system is less accurate than the Zeiss system. This Technical Note analyzes whether the Leica system's accuracy is still appropriate for the use.

II. Manufacturer Guaranteed Specifications

Zeiss

Length measuring uncertainty: 3.5µm + L (in mm)/350

For example, over 160mm coil width uncertainty = 3.957 µm and over 3 m measuring box uncertainty = 12.071 µm

Leica

Full range measurement uncertainty: 15 µm + 6 µm/m
Uncertainty within a 2.5 x 5 x 10 m volume: 10 µm + 5 µm/m
T-probe additional uncertainty: 35 µm

Working over 5 meters, uncertainty = 35 µm (AT960) + 35 µm (T-Probe) = 70 µm
We set up the Leica system in the middle of the coil, about a meter away.
At 3 meters, uncertainty = 25 µm + 35 µm = 60 µm.
At 1 meter uncertainty = 15 µm + 35 µm = 50 µm

Note: Other possible sources of error include that the axial position of measurements taken with the Leica is manually set (and can vary ~1 mm even using a guide) vs. the highly accurate positioning of the Zeiss, and the Zeiss is set up in a room with highly controlled temperature vs. the Leica measurements being taken in a high bay with less temperature control.

III. Description of Practical Test

When four coils are assembled into the coil pack, all 4 need to see the same amount of pressure. That pressure is a factor of the coil outer radius and the arc length (or whether the coil's arc is a full 90 degrees). Shimming can be used on the outer radius or on the midplane to adjust. Shims are 0.002" to 0.005" (50-125 µm, increments of 25 µm). Therefore if the radius and midplane offset measurements taken with the Leica system match the radius and midplane offset measurements taken with the Zeiss system within 25 µm, then the Leica system can be said to be sufficiently accurate.

Coil 116 and Coil 207 were measured using both the Zeiss system and the Leica system according to drawing 27K975 "MQXFA Coil CMM Profile Measurement Locations". 14 cross-sections were measured.

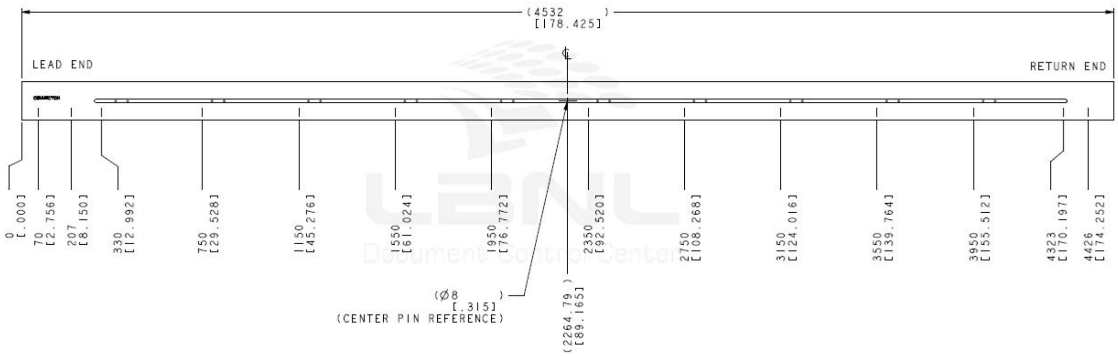

Figure 2: Drawing 27K975 shows where to measure the coil profile

The Zeiss data was pre-processed using the Calypso program, then the data from both the Zeiss and Leica systems were imported into Spatial Analyzer for processing.

Each cross-section was treated individually. The Outer Diameter and midplanes were best fit to the model with equal weighting, allowing rotation but no movement in the axial direction.

IV. Results from Coils 116 and 207

The arc length excess (or midplane offset) calculation was only performed for coil 207. The average distance from the model's midplane to the data was calculated, then the left and right average distance were summed to get the arc length excess.

The graph in Figure 3 shows the arc length excess for each cross-section.

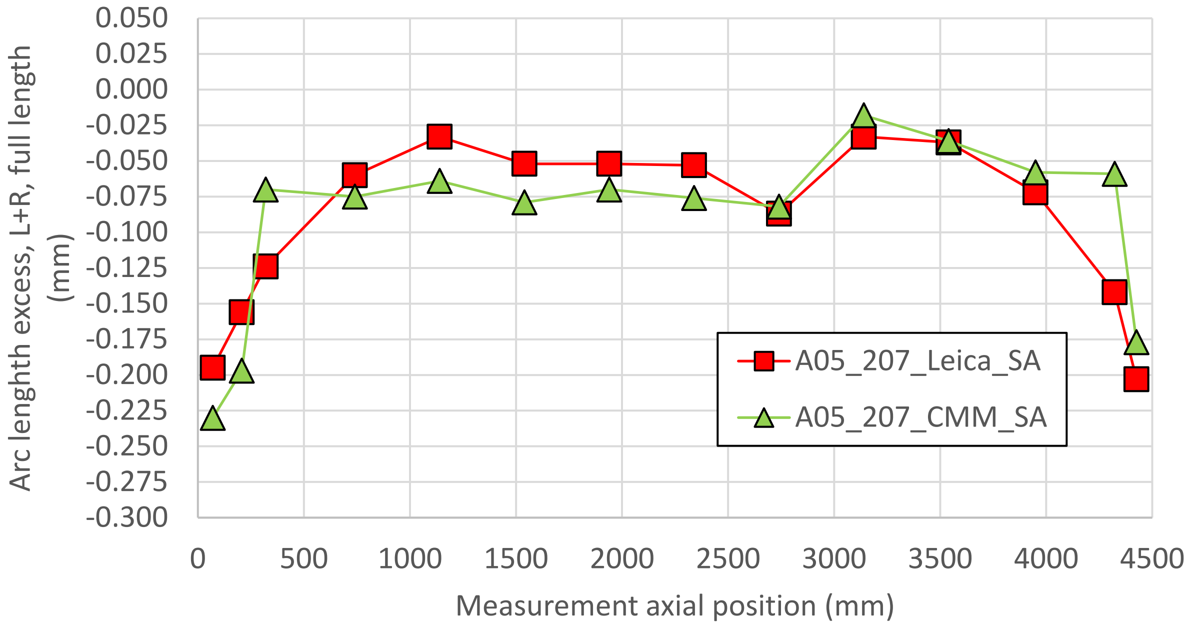

Figure 3: Arc length excess for Coil 207 taken with the Leica (red square) and Zeiss (green triangle) systems

The average of these 14 cross-sections using the Zeiss system is -0.092 mm, the average using the Leica system is -0.093 mm. 7 individual measurements differ by more than 0.025 mm and 2 individual measurements differ by more than 0.050 mm.

The radius measurements on the end sections were quite different from the rest of the coil. The first two and last one point will be disregarded in subsequent analysis, but are shown in Figure 4 for reference.

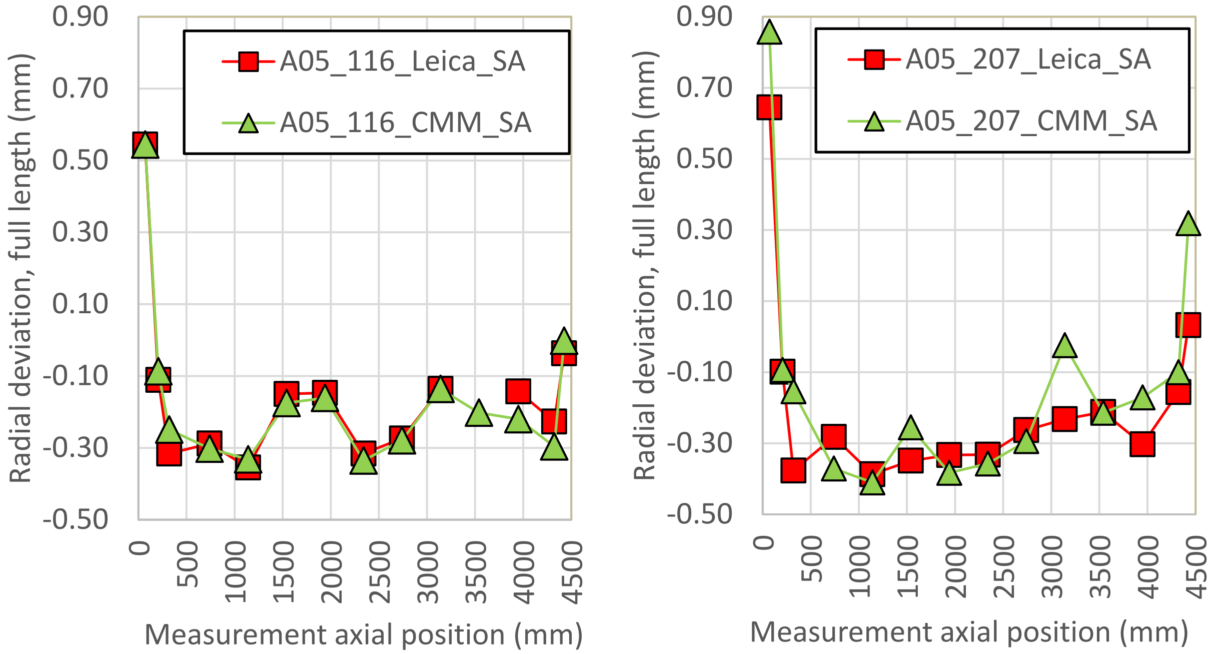

Figure 4: Full length coil radius difference measurements for coil 116 and coil 207

Figure 5 is a graph of the difference between the nominal radius and the radius of the circle fit to the OD of coil 116 at each cross-section measured by both the Zeiss and Leica systems.

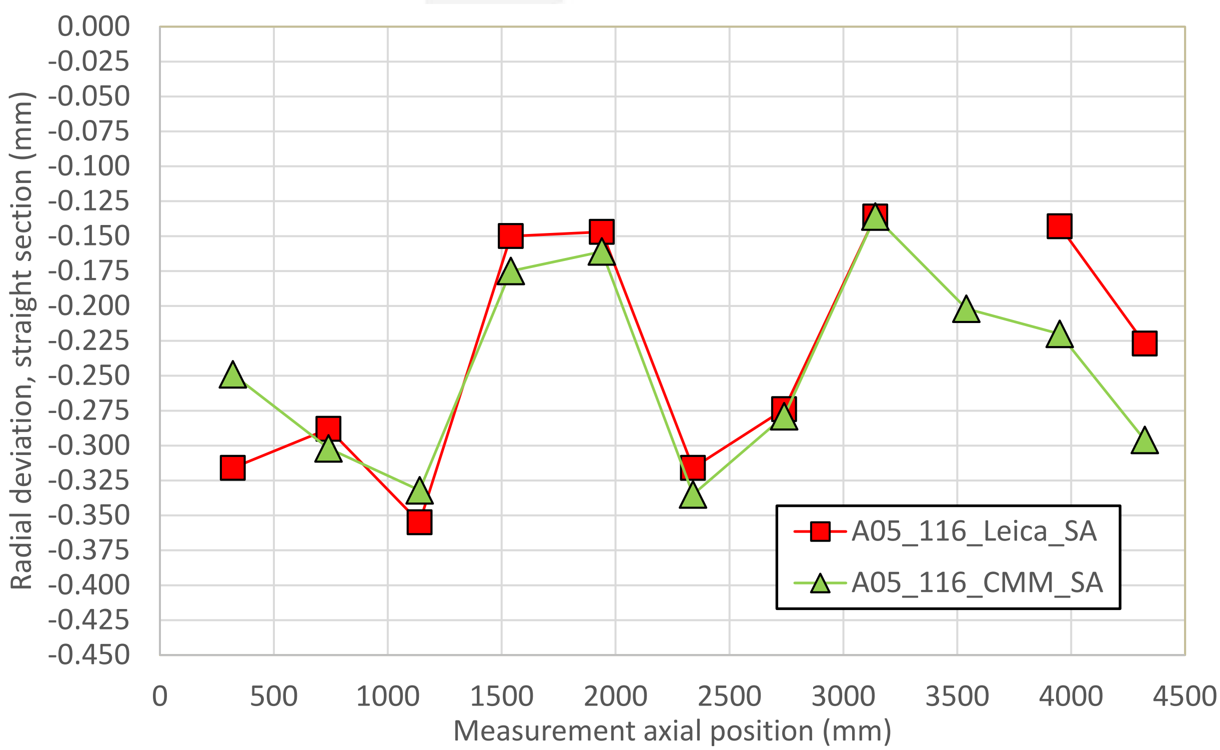

Figure 5: Coil 116 radius difference from nominal coil radius of 113.376 mm measured with both Zeiss and Leica system

Below is the same graph for coil 207, Figure 6, with an extra line for a modified version of the Zeiss/CMM data that will be discussed below.

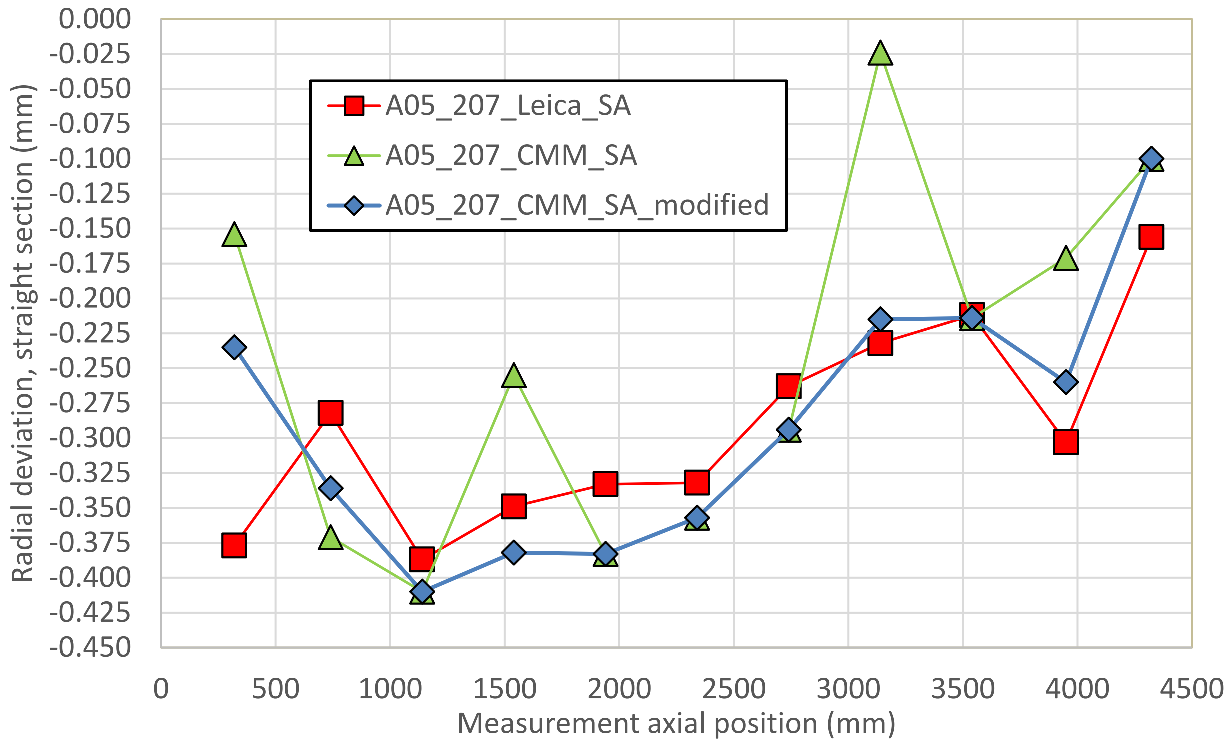

Figure 6: Coil 207 radius difference from nominal coil radius of 113.376 mm measured with both Zeiss and Leica system

Table 1 shows the average of the 11 cross-sections of the straight section of coils 116 and 207 measured by both the Zeiss and Leica systems and the difference between them.

Table 1: Average radial offset, 2 coils, 2 systems

	Zeiss	Leica	Difference
Coil 116	-0.244 mm	-0.235 mm	0.009 mm
Coil 207	-0.248 mm	-0.293 mm	0.045 mm
Modified Coil 207	-0.290 mm	-0.293 mm	0.003 mm

"Modified Coil 207" is a modification to the measurement of 5 cross sections of the Zeiss data. (Cross-sections at 330, 750, 1550, 3150 and 3950). When we looked at the difference vectors between the model and the data for both the Zeiss and Leica data, we noticed that the Zeiss registered some large bumps that were absent in the Leica data. See Figure 7 below (Zeiss in green, Leica in rainbow). The difference was 80-140 µm in some spots. We theorize that these bumps are delaminations of the top layer of the coil that the Zeiss can measure because it does not press as hard as the handheld T-Probe.

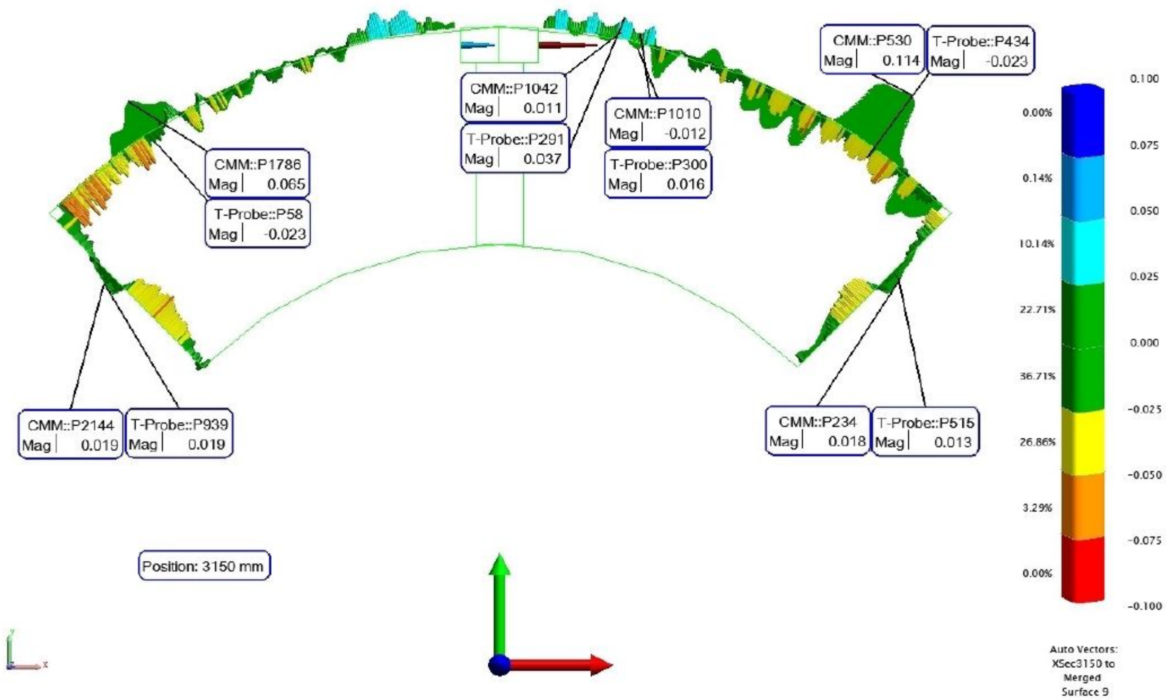

Figure 7: Cross-section at 3150 mm of Coil 207, both Zeiss (in green) and Leica (rainbow) there are two bumps that the Zeiss registered and the Leica did not. "Modified Coil 207" data removes the bumps from the calculation of the radius.

For the 5 cross-sections in question, a circle was fit to the points excluding these "delamination bumps" and the radius of the circle was plotted as "modified coil 207".

V. Summary and Conclusion

For the measurements of interest, the average arc length and the average coil radius, we got very good matching between the two systems. The average arc length matched within a micron for the one coil measured. The average radius matched within 10 microns for both coils measured.

Based on the initial results comparison of two coils we believe that this Leica system provides sufficient accuracy for the coil CMM measurements required. We expect to build up more statistics as we measure more coils that should strengthen these results.