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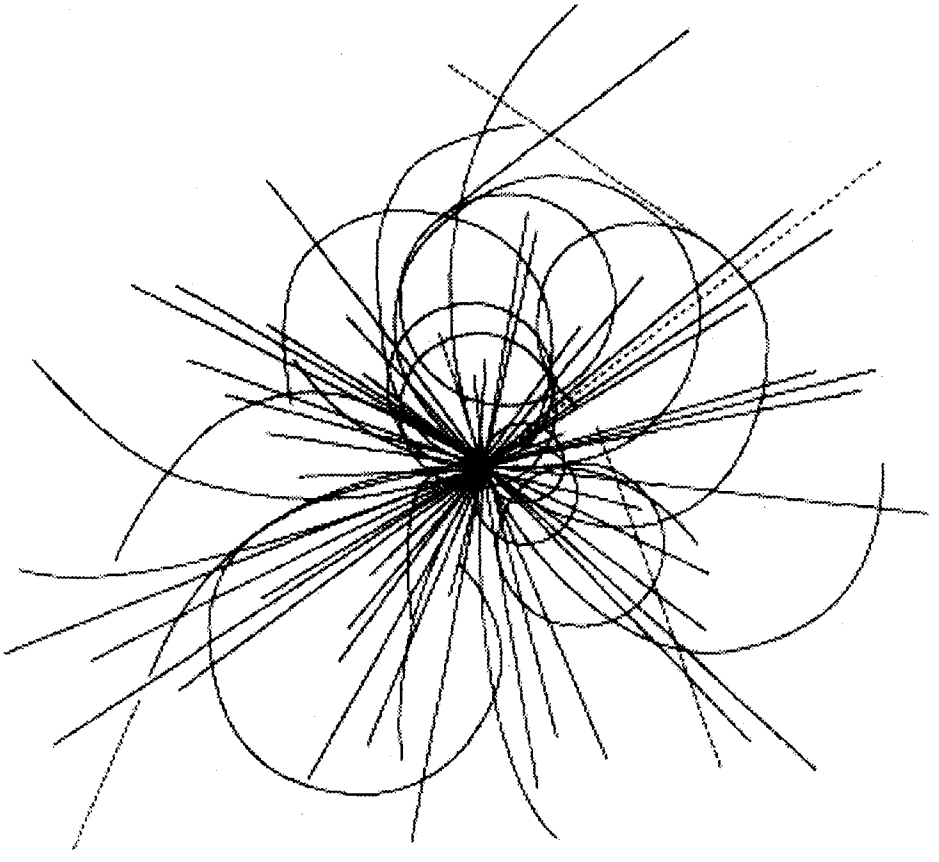

Superconducting Super Collider Laboratory

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Experimental Young's Modulus Calculations*

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EXPERIMENTAL YOUNG'S MODULUS CALCULATIONS

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INTRODUCTION

Coil is a very important magnet component. The turn location and the coil size impact both mechanical and magnetic behavior of the magnet. The Young's modulus plays a significant role in determining the coil location and size. Therefore, Young's modulus study is essential in predicting both the analytical and practical magnet behavior.

To determine the coil Young's modulus, an experiment has been conducted to measure azimuthal sizes of a half quadrant QSE101 inner coil under different loading. All measurements are made at four different positions along an 8-inch long inner coil. Each measurement is repeated three times to determine the reproducibility of the experiment. To ensure the reliability of this experiment, the same measurement is performed twice with a "dummy coil", which is made of G10 and has the same dimension and similar azimuthal Young's modulus as the inner coil. The difference between the G10 azimuthal Young's modulus calculated from the experiments and its known value from the manufacturer will be compared. Much effort has been extended in analyzing the experimental data to obtain a more reliable Young's modulus. Analysis methods include the error analysis method and the least square method.

THE EXPERIMENTS

Experiments are implemented based on the SSC MSD Process Control Specification : "QSE Coil Size Measurements." Step (1): pole stress of a steel inner coil master is increased from 0 to –10.08Mpa, –20.16Mpa, –30.24Mpa, –45.35Mpa and –60.47Mpa† (calculated from applied hydraulic load); then the pole stress is decreased through the same path. All corresponding azimuthal sizes measured are recorded. Step (2): The inner coil master is replaced with an 8-inch long half quadrant inner coil, then step (1) is repeated every other 2 inches along the coil. Step (3): Step (2) is repeated twice. Step (4): Step (2) is repeated twice with a G10 tube.

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† 60.47Mpa is about 130% designed inner coil pole stress for QSE101 magnet.

YOUNG'S MODULUS CALCULATION

In this experiment, the following equation aids in evaluating the local azimuthal Young's modulus.

$$E_{ij\ up/dn} = \Delta\sigma_j \ / \ (\Delta L_{ij\ up/dn} / L) \qquad (1)$$

where, E is a local azimuthal Young's modulus; $\Delta\sigma_j = \sigma_{j+1} - \sigma_j$, and σ_{j+1}, σ_j are consecutive pole stresses; $\Delta L_{ij\ up/dn} = [(SZC_{ij+1} - SZM_{j+1})_{up/dn} + SM_{j+1}] - [(SZC_{ij} - SZM_j)_{up/dn} + SM_j]$, is the change of the azimuthal deflection resulting from the change between two consecutive pole stresses, where SZC and SZM are respectively the azimuthal sizes of the coil/G10 tube and the master, $SM_j = \sigma_j * L / E_{steel}$ is the calculated master deflection in which E_{steel} = 195,000 Mpa; L=18.0681 mm (711.35 mil) is the middle arc length of the half quadrant inner coil cross-section designed for QSE101 also. "i" $\in \{1, 2, 3, 4\}$ denotes a position along the coil/G10 tube, "j" denotes a state at a certain pole stress, "up" denotes the branch of increasing pole stress, and "dn" denotes the branch of decreasing pole stress.

Based on equation (1), local Young's moduli for the coil at decreasing pole stress is bigger than that at increasing pole stress. This is primarily because the coil is a composite material; thus, different materials in the coil expand back differently when decreasing the compressing pole stress.[1] Therefore, this hysteresis of the coil deflections in loading and unloading results the hysteresis of its Young's modulus. This phenomena is more obvious at high pole stress. This is because the coil azimuthal size is measured shortly after decreasing pole stress, so that the coil has not been sitting long enough to complete the relaxation for the pole stress drop from the process of increasing pole stress; therefore the deflection change is very small, resulting a jump in Young's modulus. Further study on coil relaxation is necessary in order to obtain realistic coil azimuthal Young's moduli at decreasing pole stress. Thus, at this stage, only the coil azimuthal Young's moduli at increasing pole stress are presented. All the moduli from EQ. (1) are shown in Table 1 and Table 2.

Table 1. Coil Azimuthal E

P (psi)	500	1000	1500	2250
σ (Mpa)	10.08	20.16	30.24	45.35
Position	E (Mpa) - 1st			
1 up	5796	6921	8536	23901
2 up	5363	6311	11203	19555
3 up	5796	6921	10146	19555
4 up	4665	6921	9272	23901
	E (Mpa) - 2nd			
1 up	6040	7660	12506	23901
2 up	5571	9742	11819	21511
3 up	5571	7660	14152	19555
4 up	5571	8577	12506	16547
	E (Mpa) - 3rd			
1 up	5571	6921	14152	19555
2 up	5169	7660	12506	23901
3 up	5571	7660	12506	23901
4 up	6040	6921	12506	19555

P : pump load
σ : pole stress

Table 2. G10 Azimuthal E

P (psi)	500	1000	1500	2250
σ (Mpa)	10.08	20.16	30.24	45.35
Position	E (Mpa) - 1st			
1 up	8083	9742	14152	11950
1 dn	8566	12236	12153	14835
2 up	8083	9742	16296	13444
2 dn	9729	13377	13701	13878
3 up	8566	10452	16296	11950
3 dn	9729	13377	14633	14835
4 up	8566	11274	16296	11950
4 dn	10437	16445	13701	13878
	E (Mpa) - 2nd			
1 up	8083	9742	13278	11321
1 dn	8270	12896	14152	16547
2 up	9729	9742	15148	11950
2 dn	13869	10930	15148	14340
3 up	9111	10274	16296	12653
3 dn	10000	12896	15148	14340
4 up	9111	9742	17632	11950
4 dn	9345	14170	15148	13444

From Tables 1 and 2, it is clear that the coil azimuthal Young's modulus increases as the pole stress increases, which means that coil becomes stiffer at high pole stresses than at low pole stresses. The G10 azimuthal Young's modulus does not vary as much as the coil's does, and the hysteresis of its modulus is smaller than the coil's.

A. The Error Analysis For Young's Modulus

The azimuthal size measurement for coil/G10 tube involves several mechanical instruments, which may bring errors to the data recorded and result in errors in calculating the azimuthal Young's modulus from EQ. (1). Therefore, the error bar analysis is performed to predict the range of possible azimuthal Young's moduli. In these measurements, errors that might occur are: 50 psi reading error from the pump pressure meter and 0.05 mil reading error for the size measurement from the LVDT reader. Since EQ. (1) is used to calculate each azimuthal Young's modulus, the error of the calculated Young's modulus can be evaluated as following:

$$\Delta E_{ij\ up/dn} = [\delta(\Delta\sigma)/\Delta\sigma_j + \delta(\Delta L)/\Delta L_{ij\ up/dn}] * E_{ij\ up/dn} \qquad (2)$$

where $\delta(\Delta\sigma)$ = 100 psi and $\delta(\Delta L)$ = 0.1 mil denote respectively the maximum pump pressure error and size measurement error. The first term represents the Young's modulus error from pump pressure and the second term represents that from size measurement. The results of the error analysis from EQ. (1) and EQ. (2) are representatively shown in Figures 1 through 3, where each plot shows the calculated azimuthal Young's modulus with its error bar versus pole stress at a certain position along the coil/G10 tube. For coil, the higher the pole stress is, the bigger the error bar is. This is because the coil becomes very stiff at high pole stress so that its deflection change due to the pole stress change is very small, thus the error from the second term in EQ.(2) becomes large. The Young's modulus error at low pole stress is dominated by the pump pressure error; while at high pole stress, it is dominated by the coil size measurement error. For G10, the Young's modulus error at different pole stresses is quite uniform simply because its modulus at different pole stresses is nearly constant.

B. The Least Square Analysis For Young's Modulus

From the size data recorded, the deflection curve for G10 is nearly linear (refer to Figure 4); therefore, the least-square method is used for the coil/G10 azimuthal Young's modulus calculation, determining an average modulus. In Figure 4, a linear line is drawn by using the least-square criterion in a plot of relative deflection versus pole stresses. Then the product of the line reciprocal slope and the middle arc length L=18.0681 mm gives a constant modulus. Each relative deflection in each plot is the average relative deflection from repeated measurements. All constant moduli calculated in this way are recorded in Table 3 for both coil and G10 tube.

In Table 3, the hysteresis of the azimuthal Young's modulus is obvious and is bigger for coil than for G10 tube. In this experiment, the G10 azimuthal deflection is more linear than the coil's; therefore, the G10 azimuthal Young's moduli from the least square method are more reliable than the coils'.

Table 3. Azimuthal Young's Modulus from the Least Square Method

Position	1 up	1 dn	2 up	2 dn	3 up	3 dn	4 up	4 dn
Coil E (Mpa)	9854	15364	9995	15125	10043	15338	9624	14628
G10 E (Mpa)	11045	12482	11953	13236	12344	13417	12264	13476

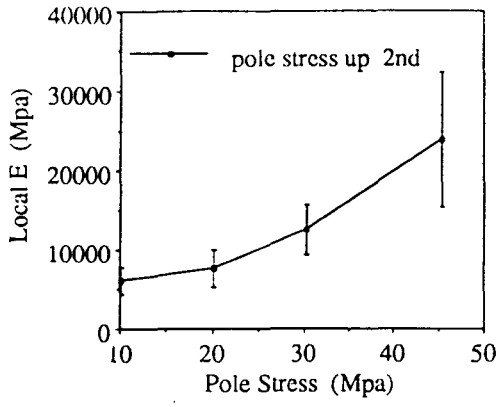

Figure 1. Local Inner Coil Azimuthal Young's Modulus for loading - Position 1

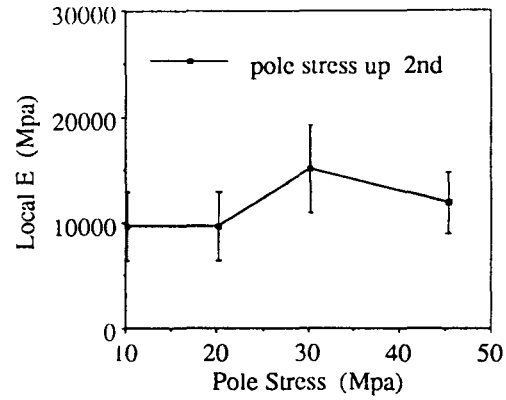

Figure 2. Local G10 Azimuthal Young's Modulus for loading - Position 1

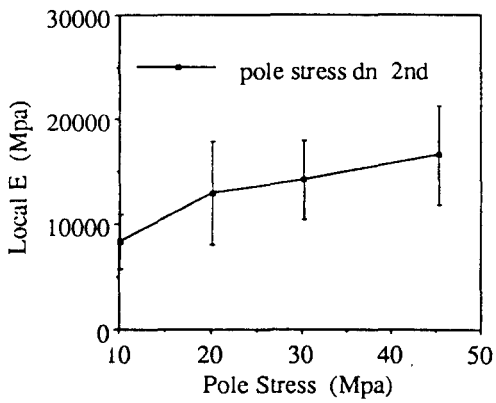

Figure 3. Local G10 Azimuthal Young's Modulus for unloading - Position 1

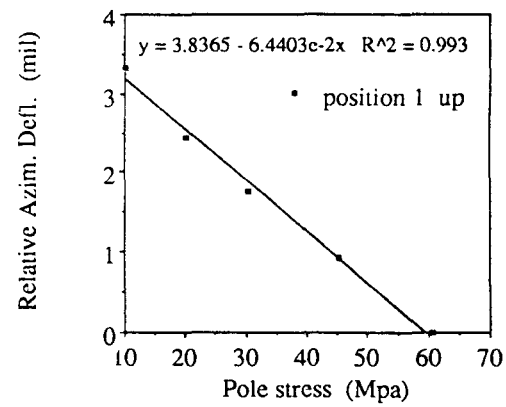

Figure 4. Relative G10 Azimuthal Deflection Vs. Pole Stress for loading G10 - Position 1

CONCLUSION

This paper presents a practical method to evaluate coil's azimuthal Young's modulus during the process of increasing pole stress. The results obtained yield several conclusions. First, coil's azimuthal Young's modulus increases as pole stress increases, in other words, the coil becomes stiffer. Secondly, the calculated G10's azimuthal Young's modulus shown in Tables 9 through 11 are very close to the known value from the manufacturer, which is 14,000 Mpa.[1] This proves that this experiment can be conducted to estimate inner coil's azimuthal Young's modulus. Finally, data from repeated measurements are reproducible, which ensures the reliability of the results.

The coil's azimuthal Young's modulus during the process of decreasing pole stress can be calculated in the same way. However, the coil size measuring technique needs to be improved upon further study of coil relaxation.

REFERENCES

1. Private conversation with S. Krishna.