DØ ENGINEERING NOTE

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ESTIMATES OF THE DEFLECTIONS AND STRESSES OF THE TOSHIBA COLD MASS SUPPORT SYSTEM

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A handwritten signature in black ink, appearing to be 'R. P. Smith', is written over a horizontal line. The signature is stylized with a large, sweeping 'S' and a long horizontal stroke extending to the right.

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1 INTRODUCTION

Tensile stresses in the Toshiba cold mass support links generated by the loadings the coil is subject to, and the deflections the the coil experiences as a result of these loadings, are estimated in the following note.

2 LOADINGS AND GEOMETRY

The Fermilab TS specified the loadings the cold mass support system must sustain during all modes of normal and abnormal operation, plus "shipping and handling loadings to be defined by the subcontractor". Toshiba has specified that they will design for shipping and handling loadings of up to 2g in any direction. It is convenient to summarize these loadings in the following table:

TABLE 1: SPECIFIED LOADINGS				
Condition	Weight	Magnetic	Seismic	Total
Upward Loading				
Operate		410	150	0.6×10^3
Ship	2g			3.0×10^3
Downward Loading				
Operate	1500	410	150	2.1×10^3
Ship	1500 + 2g			4.5×10^3
Right/Left Loading				
Operate		410	150	0.6×10^3
Ship	2g			3.0×10^3
Axial Loading				
Operate		1430	150	1.6×10^3
Ship	2g			3.0×10^3

Toshiba drawing 1KN002015A (10/4/95) shows an axial link with FRP section 10 mm in diameter and 250 mm long. Three of these links are provided at each end of the cold mass. Those at the south end are at 12:00, 4:00, and 8:00 o'clock, and those at the north end are at 2:00, 6:00, and 10:00 o'clock. The links at the south end of the magnet support compression and tension, and those at the north end support tension only. Toshiba is considering a preload scheme for the axial links.

3.1 Upward Motion

If there is no preload in the links only the lower diagonal links (4, 5) would participate. In fact the coil weight acts as a preload in the vertical links (3,6) so they also participate in restraining upward motion of the coil. The free-body force diagram for the coil, and the strain diagram for e.g. link 5, are:

In the force diagram F_l is the force in the link produced by a vertical upward motion of the coil generated by a vertical force F_v .

There are 4 diagonal links at the bottom of the coil (2 at each end) so $F_v = 4F_l \sin \theta$. Now $F_l = K_l \Delta l$ where K_l is the stiffness of the link and Δl its extension due to the force F_l . Hence

$$F_v = 4K_l \Delta l \sin \theta. \quad (1)$$

In the strain diagram it is seen that a vertical displacement Δy produced by the force F_v extends the link l to a new length l' :

$$l'^2 = l^2 + \Delta y^2 - 2 l \Delta y \cos \alpha. \quad (2)$$

Expressing α in terms of θ and ignoring the second-order terms Δy^2 , and Δl^2 , we have, with $\Delta l = l' - l$,

$$\Delta l \approx \Delta y \sin \theta. \quad (3)$$

Inserting this in equation 1 we have for the lower links

$$F_v = 4K_l \Delta y \sin^2 \theta. \quad (4)$$

The coil weight generates a preload $F_{weight} = W/4$ in each of the vertical links (3,6) where the factor 4 accounts for the pairs at each end of the coil and W is the weight of the coil. The weight deflection in the vertical links is just $\Delta_{weight} = F_{weight}/K_l = (1500 \text{ kg}/4)/530 \text{ kg/mm} = 0.71 \text{ mm}$. By assumption this deflection is established before the lower links (4,5) are snugged up. The initial weight stress in the links (3,6) is

$$\sigma_{weight}(3,6) = (\Delta l/l)E = (0.71/380) \times 4000 = 7.5 \text{ kg/mm}^2. \quad (5)$$

The application of an external vertical upward force F_v on the coil (equal or less than the weight of the coil) is equilibrated by the loss of the weight preload in the vertical links plus the load in the lower links:

3.1.2 Shipping Loads

The shipping load in Table 1 for upward loading completely unloads the vertical supports (reduces the weight deflection to zero) and continues the vertical deflection 0.22 mm for the preloaded case. This total motion generates a stress in links (4,5) of 6.0 kg/mm^2 , which added to the preload is 9.0 kg/mm^2 . The corresponding motion is 0.93 mm. Since Toshiba intends to use auxiliary shipping supports this matter will not be considered further in this note.

3.2 Downward Motion

For downward motion the two vertical links (3,6) provide the majority of the restraint at each end and if there is no preload only the two top links (1,2) add a small amount of additional restraint. The free-body diagram for link 3 in this case is:

Since there are a total of four such links on the coil, $F_y = 4F_{3l} + 4F_{2l} \sin \theta = 4K_l \Delta y + 4K_l \Delta y \sin^2 \theta$. Hence

$$K_y = F_y / \Delta y = 4K_l (1 + \sin^2 \theta), \quad (13)$$

and for $\theta = 38^\circ$, $K_y = 4 \times 530 \times 1.379 = 2920 \text{ kg/mm}$.

Assuming the deflection in link 3 due to the weight is not included (by omitting the weight shown in the loading table above),

$$\Delta_{\text{operate}}^{\text{downward}} = F_y / K_y = (0.6 \times 10^3 \text{ kg}) / (2920 \text{ kg/mm}) = 0.21 \text{ mm}. \quad (14)$$

and

$$\sigma_{\text{operate}}(1,2) = (\Delta l / l) E = (.21 \times .616 \times 4000) / 380 = 1.4 \text{ kg/mm}^2. \quad (15)$$

Since $F_{l3} = \text{weight} + K_l \Delta_{\text{operate}}$,

$$\sigma_{\text{operate}}(3,6) = [1500/4 + (530 \times 0.21)] / 50.3 = 7.5 + 2.2 = 9.7 \text{ kg/mm}^2, \quad (16)$$

3.2.1 Preload

If there were preload in links (1,2) generated by preload in the links (4,5) then these latter links would participate in restraining downward motion increasing the stiffness to

$$K_y = 4k_l(1 + 2\sin^2 \theta) = 3727 \text{ kg/mm}^2. \quad (17)$$

operating load likewise reduces to half its unpreloaded value. Choosing a preload of 3.0 kg/mm^2 , the total stress (preload plus operating) is 5.1 kg/mm^2 . Again the idea of preloading looks advantageous.

It should be noted that for sideward motion the weight load in the vertical links is not altered, so the stress in them remains 7.5 kg/mm^2 . The loads in the diagonal links remain below this value.

3.4 Motion at Some Intermediate Angle

It is instructive to look at intermediate angles to see what motions and stresses will occur. For a force F at an angle of 38 degrees upward and to the right (parallel to link 1 and perpendicular to link 2), the coil is acted upon by equivalent forces (f_x, f_y) where $f_x = F \cos \theta = 0.788F$ and $f_y = F \sin \theta = 0.616F$. The effects of upward and sideward forces for the case where the links are preloaded have already been analyzed. From Table 1 F is 600 kg so $f_x = 473 \text{ kg}$, $f_y = 369 \text{ kg}$ and from section 3.1.1 we have for f_y :

$$K_y = 3727 \text{ kg/mm}, \quad (23)$$

$$\Delta_{\text{preload}}^{\text{upward}} = 369/3727 = 0.1 \text{ mm}; \quad (24)$$

$$\Delta l(4) = \Delta y \sin \theta = 0.06 \text{ mm}; \quad (25)$$

$$\sigma_{op}(4) = (0.06/380) \times 4000 = 0.6 \text{ kg/mm}^2; \quad (26)$$

$$\sigma_{tot}(3,6) = 7.5 - (0.1/380) \times 4000 = 6.4 \text{ kg/mm}^2; \quad (27)$$

and from section 3.3.1 we have for f_x :

$$K_x = 1314 \times 2 = 2628 \text{ kg/mm}; \quad (28)$$

$$\Delta_{\text{preload}}^{\text{sideward}} = 473/2628 = 0.18 \text{ mm}; \quad (29)$$

$$\Delta l(4) = \Delta x \cos \theta = 0.14 \text{ mm}; \quad (30)$$

$$\sigma_{op}(4) = (0.14/380) \times 4000 = 1.5 \text{ kg/mm}^2. \quad (31)$$

So finally,

$$\sigma_{tot}(4) = 0.6 + 1.5 = 2.1 \text{ kg/mm}^2 + \sigma_{\text{preload}}, \quad (32)$$

$$\Delta_{tot} = \sqrt{(0.1^2 + 0.18^2)} = 0.21 \text{ mm}. \quad (33)$$

Choosing $\sigma_{\text{preload}} = 3.0 \text{ kg/mm}^2$ (the minimum required by the upward or the sideward loading cases is 2.1 kg/mm^2), we have $\sigma_{tot} = 5.1 \text{ kg/mm}^2$.

3.4.1 Motion at -38°

We can use the same approach to analyze the case of a motion at an angle of -38° . The stress in (5) is the same as in (4, above), but the stress in (3,6) increases to $\sigma_{tot} = 7.5 + 1.1 = 8.6 \text{ kg/mm}^2$. The deflection in the theta direction is the same.

TABLE 3: STRESSES, $[kg/mm^2]$			
Motion	Link(s)	No Preload	Preload
None	(1,2,4,5)	0.0	3.0
None	(3,6)	7.5	7.5
Up	(4,5)	1.4	4.1
Up	(3,6)	5.3	5.8
Down	(1,2)	1.4	4.1
Down	(3,6)	9.7	9.2
Side	(1,5)/(2,4)	4.1	5.1
+38°	(4)	3.8	5.1
+38°	(3,6)	6.1	6.4
-38°	(5)	3.8	5.1
-38°	(3,6)	8.9	8.6

4 STRESSES AND STRAINS: AXIAL MOTION

4.1 Deflections

The axial supports are configured so that those at the south (nozzle) end of the magnet fix its axial location when the magnet is warm (i.e, they support both tension and compression). The links at the north end are installed loose to accommodate the axial shrinkage of the coil during cooldown and designed so that they support only tension thereafter. Again it is assumed that the axial and radial systems are essentially uncoupled, i.e. small motions in one system do not generate significant loads in the other. If the north links are adjusted so that they are just snug after cooldown, then the stiffness of the system for northward motion is just that of the three south links:

$$K_3 = EA/l = (4000 \times 3 \times 78.5)/250 = 3768 \text{ kg/mm}. \quad (34)$$

The operating load for axial motion is $1.6 \times 10^3 \text{ kg}$ so that the operating deflection is just

$$\Delta_{\text{operating}}^{\text{northward}} = F/k = (1.6 \times 10^3)/3768 = 0.42 \text{ mm}. \quad (35)$$

The stress in the south links for such deflections is

$$\sigma_{\text{operate}} = \epsilon E = (0.42/250) \times 4000 = 6.7 \text{ kg/mm}^2. \quad (36)$$

For southward motion, the south links actually support compression so that until they begin to buckle the system is twice as stiff and the deflections (and stresses) are half as large. This means that

$$\Delta_{\text{operating}}^{\text{southward}} = 0.21 \text{ mm}. \quad (37)$$

The stress in the north links in this case is $6.7/2 = 3.4 \text{ kg/mm}^2$.

4.4 Preload

Toshiba has indicated that the axial links will be preloaded. If the links are preloaded to at least $6.7/2 = 3.4 \text{ kg/mm}^2$ then the stiffness of the system is doubled:

$$K_6 = EA/l = 4000 \times 6 \times 78.5/250 = 7536 \text{ kg/mm}. \quad (45)$$

As expected, this reduces the operating deflection (both north and south) by half (the asymmetry between north and south deflections noted for the no-preload case vanishes):

$$\Delta_{\text{operating}} = F/k = 1.6 \times 10^3/7536 = 0.21 \text{ mm}. \quad (46)$$

This means the final position of the south end of the coil is:

$$\Delta z(\text{South})_{\text{cool+operate}} = 0.35 \pm 0.21 \text{ mm}, \quad (47)$$

and the final position of the north end of the coil is:

$$\Delta z(\text{North})_{\text{cool+operate}} = 10.2 \pm 0.21 \text{ mm}. \quad (48)$$

The operating stresses are reduced as well so that the total stress is

$$\sigma_{\text{preload+operating}} \geq 3.4 + 3.4 = 6.8 \text{ kg/mm}^2. \quad (49)$$

Since the south links don't buckle the stiffnesses for north or south deflections are constant during operation.

4.5 Conclusions Regarding Axial Motion

The axial links are conservatively designed and it should be reasonably easy to ensure that the three links at each end of the coil carry approximately equal loads. Small deviations from this ideal should not have great consequence as a system-of-three is somewhat forgiving in this regard. The use of preload makes the north operating deflection equal to the smaller south operating deflection, possibly a convenience when the nozzle design is contemplated. Toshiba has indicated they will establish the desired preload using strain gauges near the warm ends of the links.

TABLE 4: OPERATING CONDITIONS				
Motion Direction	Without Preload		With Preload	
	Stress	Displacement	Stress	Displacement
South	6.7	.21	6.8	.21
North	0	.42	6.8	.21