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TO: DISTRIBUTION
FROM: C NEUMEYER
SUBJECT: OH LAUNCHING LOAD AND AXIAL EXPANSION

Reference:

[1] NSTX-CALC-13-17, "Launching Load Calculations"
[2] PPPL-3446, Engineering Design of NSTX"

This memo addresses concerns related to the subject issues and reflects a consensus reached a meeting on 9/8/00 with the writer, P. Heitzenroeder, J. Chrzanowski, and R. Parsells in attendance. The results have now been documented by the writer in [1].

Introduction

Reference [2] describes an analysis of the axial forces on the PF coils whose outcome was an influence matrix containing coefficients which can be used to predict the force between coils as a function of their currents. The influence matrix M is as follows.

	OH	PF1AU	PF1AL	PF1BL	PF2U	PF2L	PF3U	PF3L	PF4U	PF4L	PF5U	PF5L	PLA	PLB
OH	0	-9.6	9.6	53.3	-54.1	54.1	-27.7	27.7	-4.6	4.6	-5.9	5.9	0	0
PF1AU	9.6	0	0.05	0.05	-24.2	0.26	-2.55	0.96	3.06	1.56	3.51	2.2	0.13	0.09
PF1AL	-9.6	-0.05	0	97.2	-0.26	24.2	-0.96	2.52	-1.56	-3.06	-2.2	-3.51	-0.13	-0.09
PF1BL	-53.3	-0.05	-97.2	0	-0.29	17.9	-1.1	-7.16	-1.84	-4.87	-2.72	-5.81	-0.11	-0.07
PF2U	54.1	24.2	0.26	0.29	0	1.7	99.0	6.56	33.0	11.1	40.29	16.72	0.54	0.35
PF2L	-54.1	-0.26	-24.2	-17.9	-1.7	0	-6.6	-99.0	-11.08	-33.0	-16.7	-40.3	-0.54	-0.35
PF3U	27.7	2.5	0.96	1.1	-99.0	6.6	0	26.0	165.1	44.9	204.6	69.6	1.5	0.95
PF3L	-27.7	-0.96	-2.5	7.2	-6.6	99.0	-26.0	0	-44.9	-165.1	-69.6	-204.6	-1.5	-0.95
PF4U	4.6	-3.06	1.6	1.8	-33.0	11.1	-165.1	44.91	0.01	89.8	189.4	138.0	1.27	0.39
PF4L	-4.6	-1.6	3.1	4.9	-11.1	33.0	-44.9	165.1	-89.8	-0.01	-138.0	-189.4	-1.27	-0.39
PF5U	5.9	-3.5	2.2	2.71	-40.3	16.7	-204.6	69.6	-189.4	138.0	0	225.9	1.31	0.42
PF5L	-5.9	-2.2	3.5	5.81	-16.7	40.3	-69.6	204.6	-138.0	189.4	-225.9	0	-1.31	-0.42
PLA	0	-0.13	0.13	0.11	-0.54	0.54	-1.5	1.5	-1.27	1.27	-1.31	1.31	0	0
PLB	0	-0.09	0.09	0.07	-0.35	0.35	-0.95	0.95	-0.39	0.39	-0.42	0.42	0	0

Thus the axial force between coils i and j is:

$$F_z = I_i I_j M_{ij}$$

Where F_z is the force in pounds, I_i is the current in coil I, I_j the current in coil j, and M_{ij} the coefficient from the matrix.

In terms of the forces on the OH coil , it is seen from the matrix that PF1a does not have a very strong interaction due to the fact that, while it is physically close to the OH coil, it has both upward and downward interactions which tend to cancel out.

PF1b is both close to the OH coil and as an interaction almost fully in one direction. Furthermore there is only a lower PF1b coil so that whenever it is energized in conjunction with OH a relatively large axial force will be generated.

PF2 is similar to PF1b except for the fact that both upper and lower coils exist. Although it is possible that there could be a large difference between PF2 upper and lower coil currents this is not nominally the case (or at least was not assumed so during the design).

Therefore, during the design of NSTX, special concern was associated with the PF1b interaction because during normal operations a large force could be generated.

The OH coil is wound on the "tension tube", essentially a spool with flanges on either end. On the lower end the coil body makes direct contact with the lower flange of the tension tube. On the upper end a "pressure ring", consisting of two split rings with stacks of belleville washers and guide pins in between, is positioned between the coil body and the upper flange. Set screw bolts on the upper flange bear against the pressure ring and are tightened to provide a "preload" force which puts the tension tube in tension and the pressure ring and coil body in compression.

Features of this support scheme are as follows:

- a downward force on the OH coil pushes the coil body against the lower flange;
- an upward force on the OH coil pushes the coil body against the pressure ring in a direction which compresses the belleville washers;
- axial thermal expansion of the OH coil causes it to grow in a direction which compresses the belleville washers.

The dead weight of the OH coil, approximately 2500 lbs., which adds to the initial downward preload force on the coil body.

The main reason for incorporating the pressure rings was to accommodate the axial thermal expansion of the coil. Ideally the belleville washer deflection would take up the full growth of the coil. At the same time, to avoid having the OH coil launched upward and banging against the upper flange, it was deemed prudent to limit the "launching load" force to be less than the initial downward preload.

Launching Load Considerations

There are 10 set screw bolts on the upper flange, each tightened to 375 in-lbs. Calculation of the resultant preload force is as follows, based on the formula for bolting force Force=Torque/0.2/diameter:

Bolt Diameter	0.375	inch
Torque	375.0	inch-lbs
Compression/bolt	5000.0	lb
#Bolts	10.0	
OH Dead Weight	2500.0	lb
Down Force	52500.0	lb

It is noted that the bolting force above is 10x that anticipated in the original design. As a result, even if the OH, PF1b, and PF2l coils are operated at their rated current, the "launching load" upward force will still be less than the downward preload per the following:

Koh-pf1b	53.3	lb/kA^2
Ioh	24000.0	Amp
Ipf1b	15000.0	Amp
Foh-pf1b	19188.0	lb
Koh-pf2l	54.1	lb/kA^2
Ipf2l	20000.0	Amp
Foh-pf2l	25968.0	lb
∑F	45156.0	lb
F/Fdown	0.86	

Therefore it is concluded that, *as assembled, launching load is NOT an issue on NSTX.*

Because of the earlier concerns, a launching load interlock was introduced in both hardware and software, which causes a trip if the product of I_{oh}* I_{pf1b} falls below a setpoint. This is consistent with the fact that opposite current directions in the two coils cause a repulsive force (i.e. the launching load). At present the setpoint is at –50kA^2, which corresponds to an upward force of 50kA^2*53.3lb/kA^2 =2665 lbs., which is approximately equal to the dead weight of the OH coil.

It is proposed to leave this interlock and setpoint as-is for now. It should not adversely impact operations. This is consistent with the fact that the normal usage of the PF1b and OH coil is to produce plasma current I_p with I_{pf1b} in the same direction as I_p to form the CHI X-point, and OH (if it is involved at all) with precharge in the same direction as I_p such that driving OH to zero increases I_p. Hence I_{pf1b} and I_{oh} are in the same direction as I_p and the force between PF1b and OH is attractive.

Thermal Expansion Considerations

The belleville washer used is Solon #10L98177, with the following characteristics.

Overall Height:	0.118″
100% Deflection:	0.023″
100% Load:	3500 lbs.

With the aforementioned preload the compression of the belleville washer stacks is as follows:

Belleville Washer force to flatten	3500	lbs
Belleville Washer full deflection	0.023	in
Series Washers per stack	5	
Parallel Washers per stack	2	
#Stacks	10	
Force per Stack	5000	lbs
Compressive Deflection %	0.714	
Compressive Deflection	0.082	in
Remaining Deflection %	0.286	
Remaining Deflection	0.033	in
∑Remaining Deflection	0.164	in

So, after preload, 0.164″ of deflection remains in the washers to accommodate thermal expansion of the OH coil. Assuming that the coil is all copper (i.e. neglecting the insulation space) the axial thermal expansion is calculated as follows:

Cu Coeff of Expansion	1.69E-05	per degC
Tmax	100.0	degC
Troom	20.0	degC
Delta T	80.0	degC
OH Length at 20C	170.1	in
Delta L	0.230	in

Here it is seen that with the full temperature rise on the coil its axial expansion will exceed the remaining deflection on the belleville washers in the pressure ring assembly. Therefore, as the coil heats up and the washers become flat, the additional growth will be accommodated by yielding and radial growth of the OH coil body in compression and by yielding and axial stretching of the tension tube in tension. Since the cross sectional area of the OH coil body >> that of the tension tube, the compressive stress on the coil copper and insulation will be relatively low, so the main consequence of the thermal expansion will be the stretching of the tension tube.

Properties of the stainless steel tension tube are as follows:

Tube ID	8.18	in
Tube OD	8.496	in
CSA	4.139	in^2
SS Modulus of Elasticity	3.00E+07	psi
SS Yield Strength	30000	psi

The washer preload, full heating, and subsequent cooling of the OH coil assembly will cause it to take on a permanent set with some plastic deformation of the tension tube in the form of stretching to an increased length. This action is estimated in the following calculation which is based on the equation for a column where Force = ΔLength*Area*Elasticity/Initial Length:

	Force	Coil Height	Set Screw	Washer Height	Washer Compression	Tube Height	Tube Stress
Start	0.00	170.079	0.000	0.115	0.000	170.194	0.00
Preload	50000.00	170.079	0.151	0.033	0.082	170.262	12080.95
Coil Expansion to Washer Limit	70000.00	170.139	0.151	0.000	0.115	170.290	16913.33
Tube at Yield Point	124162.40	170.213	0.151	0.000	0.115	170.364	30000.00
Coil Full Expansion	124162.40	170.309	0.151	0.000	0.115	170.459	30000.00
Coil Cooled	18250.00	170.079	0.151	0.085	0.030	170.314	4409.55

An important finding based on the above is that, after cooling, there still remains a preload on the coil body, i.e. the tension tube has not stretched with ΔL greater than the washer ΔL, and the washers do not become loose. Another possible concern might be the stress in the weld which joins the tension tube flanges to the tube cylinder. However, this is a full penetration weld and therefore can be assumed equivalent in strength to the base materials.

Summary and Conclusions

Launching load is not an issue on NSTX, even if both the PF1b and PF2l coils are energized at rated current with unfavorable polarity. The launching load interlock, although not necessary, should not adversely impact normal plasma operations.

When the OH coil is operated up to its temperature limit the tension tube will stretch and take on a permanent set. However, once the coil cools, the belleville washers will still be compressed to some degree and a finite preload will remain.

The situation is different than was intended by the original design philosophy due to the fact that a different washer type with less deflection and higher spring constant was used, such that the initial preload is much higher than anticipated. However, there does not appear to be any serious problem associated with the situation. In fact the launching load concern is alleviated.

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NSTX File