13-040505-CLN-01

***TO: DISTRIBUTION***
***FROM: C NEUMEYER***
***SUBJECT: PRELIMINARY ANALYSIS OF PF4 ENERGIZATION***

***References:***

[1] NSTX-CALC-13-020-1, "PF Coil Axial and Radial Force Calculation", C. Neumeyer
[2] 13_031205_CLN_01.doc, "PF4 and PF5 Forces w/PF4 Energization", C. Neumeyer

*Summary*

This memo revisits the calculation of axial forces on the PF coils with PF4 energization, and provides a preliminary assessment of the ability of the support structure to withstand same. Since PF4 and PF5 are situated very close to one another, and since their diameters are large, they are the most vulnerable to axial loads.

Modifications to the hardware associated with the support structure will be necessary in order that PF4 can be energized to a useful level. Specifically, the studs on the PF4 coil support clamps, and the bolts on the PF5 turnbuckle struts need to be upgraded to high strength materials (tensile yield ≥ 95ksi).

With these changes, operation to the desired level with IPF4 at –20kA and IPF5 at +10kA, with the other PF coils at present limits, will be allowable.

Ultimately, implementation of digital coil protection can account for the combination of PF currents in effect at any time and can maintain safe conditions while allowing an operating envelope greater than the one described herein which is based on simultaneous maximum allowable currents in all PF circuits.

The preliminary findings described herein need to be refined using more detailed analysis.

<u>Force Calculation</u>

The original design basis force calculation, rev. 0 of ref. [1], produced influence matrices which contain coefficients relating the force on each PF coil due to the current in each of the other coils. One matrix describes radial force, the other vertical force. This result was derived using ANSYS. It was the basis for the results reported in [2] for the forces on

PF4 and PF5. The writer has since revisited this calculation and found discrepancies, mainly in the loads on the outer coils, probably due to the use of early information concerning PF5 dimensions which later changed. Therefore the calculation has now been revised [1]. The new calculation is based on FEMLAB, and was checked using a separate FORTRAN code based on filaments which calculates for one source coil at a time the field at each coil due to current in the source coil. The new calculation predicts significantly higher vertical forces on PF4 and PF5 than the original one.

Of primary interest are the forces in the vertical direction. Since the coils are mounted on supports which are designed to slide in the radial direction, radial forces are taken by the coils themselves in hoop tension.  And, in general, even with PF4 energization, the resultant stresses are not of concern.

The influence matrix for vertical forces is as follows [1]…

**TABLE I: Influence Matrix for Vertical Force**

| Fz(lbf/kA) | OH | PF1aU | PF1aL | PF1b | PF2U | PF2L | PF3U | PF3L | PF4U | PF4L | PF5U | PF5L |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| OH | 0 | 10 | -10 | -54 | 55 | -55 | 29 | -29 | 7 | -7 | 6 | -6 |
| PF1aU | -10 | 0 | 0 | 0 | 25 | -1 | 3 | -2 | -3 | -2 | -4 | -2 |
| PF1aL | 10 | 0 | 0 | -98 | 1 | -25 | 2 | -3 | 2 | 3 | 2 | 4 |
| PF1b | 54 | 0 | 98 | 0 | 1 | -19 | 2 | 8 | 2 | 6 | 3 | 6 |
| PF2U | -55 | -25 | -1 | -1 | 0 | -2 | -101 | -7 | -40 | -9 | -43 | -17 |
| PF2L | 55 | 1 | 25 | 19 | 2 | 0 | 7 | 101 | 9 | 40 | 17 | 43 |
| PF3U | -29 | -3 | -2 | -2 | 101 | -7 | 0 | -26 | -228 | -36 | -218 | -67 |
| PF3L | 29 | 2 | 3 | -8 | 7 | -101 | 26 | 0 | 36 | 228 | 67 | 218 |
| PF4U | -7 | 3 | -2 | -2 | 40 | -9 | 228 | -36 | 0 | -52 | -529 | -100 |
| PF4L | 7 | 2 | -3 | -6 | 9 | -40 | 36 | -228 | 52 | 0 | 100 | 529 |
| PF5U | -6 | 4 | -2 | -3 | 43 | -17 | 218 | -67 | 529 | -100 | 0 | -200 |
| PF5L | 6 | 2 | -4 | -6 | 17 | -43 | 67 | -218 | 100 | -529 | 200 | 0 |

The force on any coil is computed according to the following expression…

$$Fz_i = I_i * \sum_{j=1,12} \left[ M_{i,j} * I_j \right]$$

where  $Fz_i$ is the total vertical force (lbf) on the coil in row i, $M_{i,j}$ is the influence matrix value from row i and column j, $I_i$ is the current (kA) in coil i and $I_j$ is the current (kA) in coil j.

Of interest are the worst case forces which push the coils away from the midplane, and the worst case forces which push the coils toward the midplane. The former place loads on the support pad weldments and the clamping rods, and the latter on the support pad weldments and (in the case of PF5) the turnbuckle struts which link the upper and lower coils.

The machine is not fully symmetric about the midplane due to PF1b so that the worst case condition sometimes occurs on the upper coils and sometimes on the lower coils.

The following table shows the worst case combinations, assuming OH and PF currents at their present operating limits, and IPF4 and IPF5 at the levels desired for the upcoming experiments…

**TABLE II: Worst Case Force Calculations**

| Ckt | Ipf Limits (kA) | | | PF4 Away from MP | Ipf Case | PF4 Toward MP | Ipf Case | PF5 Away from MP | Ipf Case | PF5 Toward MP |
|---|---|---|---|---|---|---|---|---|---|---|
| | (-) | (+) | I(kA) | FzPF4L (lbf) | I(kA) | FzPF4U (lbf) | I(kA) | FzPF5U (lbf) | I(kA) | FzPF5L (lbf) |
| OH | -24.0 | 24.0 | 24.0 | -3552 | -24.0 | -3552 | -24.0 | 1549 | 24.0 | 1549 |
| PF1aU | -10.0 | 3.5 | -10.0 | 340 | 3.5 | -196 | 3.5 | 136 | -10.0 | -215 |
| PF1aL | -10.0 | 3.5 | -10.0 | -560 | 3.5 | 119 | 3.5 | -75 | -10.0 | 389 |
| PF1b | -5.0 | 0.0 | -5.0 | -560 | -5.0 | -190 | -5.0 | 143 | -5.0 | 317 |
| PF2U | -20.0 | 20.0 | -20.0 | 3680 | 20.0 | -15960 | 20.0 | 8767 | -20.0 | -3380 |
| PF2L | -20.0 | 20.0 | -20.0 | -15960 | 20.0 | 3680 | 20.0 | -3380 | -20.0 | 8767 |
| PF3U | -5.0 | 20.0 | -5.0 | 3610 | 20.0 | -91120 | 20.0 | 44614 | -5.0 | -3446 |
| PF3L | -5.0 | 20.0 | -5.0 | -22780 | 20.0 | 14440 | 20.0 | -13786 | -5.0 | 11153 |
| PF4U | -20.0 | 0.0 | -20.0 | 20760 | -20.0 | 0 | 0.0 | 0 | -20.0 | -20402 |
| PF4L | -20.0 | 0.0 | -20.0 | 0 | -20.0 | -20760 | 0.0 | 0 | -20.0 | 108318 |
| PF5U | 0.0 | 10.2 | 10.2 | -20402 | 0.0 | 0 | 10.2 | 0 | 10.2 | 20990 |
| PF5L | 0.0 | 10.2 | 10.2 | -108318 | 0.0 | 0 | 10.2 | -20990 | 10.2 | 0 |
| | | | Σ | -143742 | Σ | -113539 | Σ | 16978 | Σ | 124040 |

Assuming that the OH and PF coils other than PF4 and PF5 will operate at the above levels, equations of the following form can be used to calculate the PF4 and PF5 forces for the above four worst case combinations with arbitrary values of current in PF4 and PF5…

$$Fz_x = aI_x + bI_xI_y + cI_x^2$$

… where x and y are PF4 and PF5.

Values of the coefficients for the four cases are as follows…

**TABLE III: Coefficients for PF4 and PF5 Vertical Force Calculation**

| | | PF4 Away from MP | | | PF4 Toward MP | | | PF5 Away from MP | | | PF5 Toward MP |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | FzPF4L | | | FzPF4U | | | FzPF5U | | | FzPF5L |
| a | 1789 | lbf/ka | a | 4639 | lbf/ka | a | 3707 | lbf/ka | a | 1478 | lbf/ka |
| b | 628 | lbf/ka^2 | b | -628 | lbf/ka^2 | b | 429 | lbf/ka^2 | b | -429 | lbf/ka^2 |
| c | 52 | lbf/ka^2 | c | -52 | lbf/ka^2 | c | -200 | lbf/ka^2 | c | 200 | lbf/ka^2 |

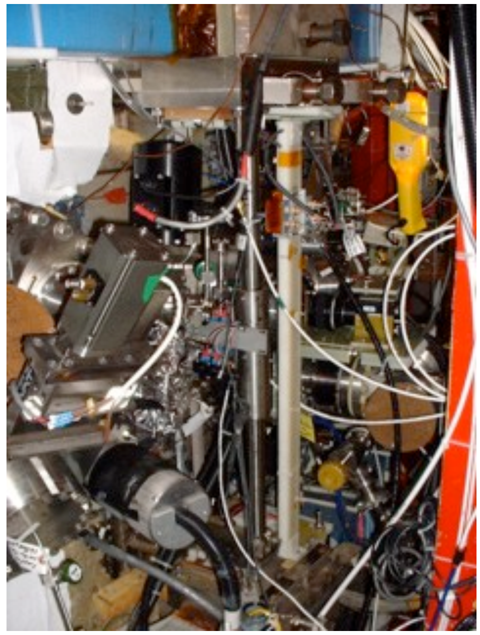
This formulation may be useful in assessing different combinations of PF4 and PF5 current limits.

Structural Supports

The following photo shows the typical PF coil support pad, clamp, and hardware.

There are six pads per coil, and four 1/2”-13 threaded rods per clamp. An important feature to note is that, while the stud end away from the midplane is attached via a nut, the opposite end is threaded into the base metal where it is 3/4” thick. Due to limited space, nuts and washers are not feasible. The pads are welded to the VV (not visible in the photo above, hidden behind the thermal insulation).

The following photos show the turnbuckle strut which links the PF5 U and L coils, including a zoom of the attachment anchor.



The strut is necked down to a cross section of approximately 1" x 3/4" where it engages the clevis and shear bolt which is 3/4" diameter. Thickness of clevis fingers are 1/4".

All of the fastener structural parts are 300 series stainless steel with tensile yield of 30ksi.

Analysis of Forces and Stresses

1. Threaded Rods

Allowable load on the threaded rods is as follows for the case of 300 series stainless steel and a proposed high strength A193 stainless steel material.

| | 300 series | A193 | |
|---|---|---|---|
| Threaded Rod Diameter | 0.500 | 0.500 | in |
| Threads/in. | 13 | 13 | |
| Pitch Diameter | 0.468 | 0.468 | in |
| Tensile Area | 0.142 | 0.142 | sq in |
| Tensile Yield Strength | 30000 | 95000 | psi |
| Tensile Allowable (2/3 yield) | 20000 | 63333 | psi |
| Allowable Load/rod | 2838 | 8987 | lbf |
| #Rod/Pad | 4 | 4 | |
| #Pad | 6 | 6 | |
| Safety Factor | 1.50 | 1.50 | |
| Total Allowable Load | 45408 | 143791 | lbf |

Due to space constraints, one end of the rods are threaded into the base plates of the pads. Therefore, the pull-out strength of the base material could be limiting. However, this appears not to be the case, even compared to the load per rod with the proposed high strength material.

| | | |
|---|---|---|
| Thread Engagement Length | 0.750 | in |
| Shear Area | 0.826 | sq in |
| Tensile Yield Strength | 30000 | psi |
| Shear Allowable (1/2 yield) | 15000 | psi |
| Allowable Load/rod | 12392 | lbf |

With the existing 300 series rods, the strength of the assembly is quite limiting. For example, it would allow $|I_{PF4}| \leq 12.5$kA with $|I_{PF5}| \leq 4$kA. These levels of current are probably not useful.

However, comparing the result with the high strength material to the forces calculated in Table II, for the scenarios which push the coils away from the midplane, it is concluded that the desired operating level with $|I_{PF4}| \leq 20$kA with $|I_{PF5}| \leq 10$kA can be achieved if the rods are changed to the high strength material on PF4. The existing rods appear to be adequate for PF5.

2. PF5 Struts

Worst case loads on the struts occur when PF5U and L are forced toward the midplane, as indicated in the fourth case in Table II. At issue is the compression in the strut at its necked down region, the shear in the strut bolts, and the bearing loads on the clevis fingers.

An unknown is the load sharing between the two load paths for the attractive force. One path is via the cantilevered pads, through their welds, and through the VV. The other is through the struts. Here is is assumed that the two paths share the loads equally. Analysis of the stresses is given in the following.

| | | |
|---|---|---|
| #Strut | 6 | |
| Load Fraction to Strut | 0.50 | |
| Load/Strut | 10337 | lbf |
| Min CSA per Strut | 0.75 | sq in |
| Compressive Yield Strength | 30000 | psi |
| Tensile Allowable (2/3 yield) | 20000 | psi |
| Allowable Load/Strut | 15000 | lbf |
| Strut Safety Factor | 1.5 | |
| Strut Bolt Dia | 0.75 | in |
| #Shear Planes/Bolt | 2.00 | |
| Strut Bolt Shear CSA | 0.88 | sq in |
| Tensile Yield Strength | 30000 | psi |
| Shear Allowable (1/2 yield) | 15000 | psi |
| Allowable Shear Load/bolt | 13254 | lbf |
| Strut Bolt Safety Factor | 1.3 | |
| Clevis Finger Thickness | 0.250 | in |
| #Fingers | 2 | |
| Shear Load per Finger | 20673 | lbf/in |
| E | 29000000 | psi |
| Clevis/Shear Bolt Gap*2 | 4.78E-04 | in |
| Stress | 13332 | psi |
| Clevis Bearing Safety Factor | 1.5 | |

This result shows that, with the assumed load sharing, the necked down region of the strut has an adequate safety factor. The strut bolts are a bit low at 1.3, and should therefore be upgraded to high strength material.

For the clevis bearing, a variable is the difference between the bolt diameter and the holes in the clevis fingers. The above result shows that these parts must be tight fitting in order for the stresses to fall below allowables. Another interpretation is that the mating surfaces will experience plastic deformation until equilibrium is achieved. From a practical perspective, this would correspond to a small (10's of mils?) decrease in the gap between PF5U and PF5L and bending of their supports as the bearing surfaces come into equilibrium and the load sharing adjusts itself accordingly.

From this result it is concluded that the strut bolts should be changed to a higher strength material. Consideration could also be given to modifying the clevis fingers to provide more area for load bearing (e.g. install inserts wider than the 1/2" thick fingers.

3. Additional Considerations

A more detailed analysis should be performed to assess various aspects of this situation, some of which have already been mentioned. These includes…

- determination of load sharing between PF5 load paths
- deformation of PF4 and PF5 coils between support pads, and associated stresses including shear in the insulation
- loads on welds which attach support pads to VV

*Summary*

Force calculations have been updated, and algorithms provided to guide choice of PF4 and PF5 current limits. To obtain useful levels of current, the threaded rods on the PF4 clamps need to be upgraded to high strength material. In addition, the shear bolts on the PF5 struts should be changed to high strength material. Pending the outcome of additional analysis to determine the load sharing between the two PF5 load paths, modifications to the clevis fingers may also be appropriate. Additional detailed analysis is recommended to address the issues mentioned herein.

| | | | | |
|---|---|---|---|---|
| M Bell | J Chrzanowski | L Dudek | T Egebo | P Heitzenroeder |
| C Jun | J Menard | M Ono | S Ramakrishnan | |
| A Von Halle | M Williams | R Woolley | I Zatz | |