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SUBJECT: UPDATE OF NSTX INFLUENCE MATRICIES AND EM LOADS

Reference:

[1] NSTX-CALC-13-020, "PF Coil Axial and Radial Force Calculation", R1, 5/3/4

This memo presents results from an analysis performed to generate influence matrices for calculation of in-plane loads on the OH and PF coils as well as the out-of-plane loads on the TF coil inner bundle elements. It supercedes the prior revision of the reference calculation, which only addressed the PF coils. In addition to the inclusion of the TF, it also includes the revised PF1a coil geometry.

The finite element analysis program FEMLAB was used to model the PF coils using the 2-d axi-symmetric magnetics mode. Sub-domains were created to represent regions of the TF coil so that fields and forces could be calculated based on interaction with the OH and PF. However, the TF conductors do not effect the in-plane field calculations, which are generated only by the out-of-plane currents in OH and PF. Figure 1 shows an example field plot.

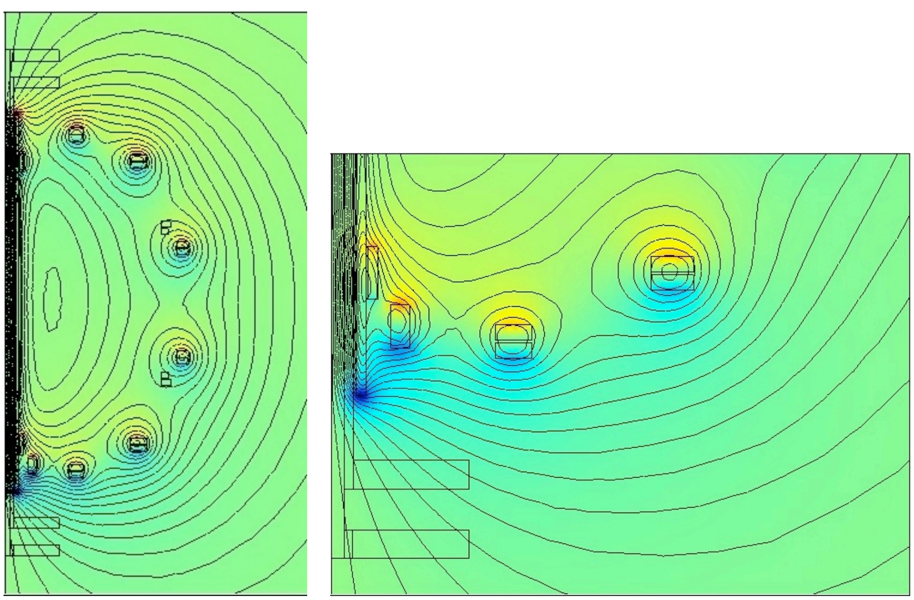

Figure 1 – FEMLAB Model Including Zoom View of Region in Lower Half Plane (B_r and flux shown for the case with rated current in each coil, except PF4)

Characteristics of the PF and TF coils in each half plane are given in Table 1 below.

TABLE 1: PF Coil Summary

Coil	R (center)	ΔR	Z (center)	ΔZ	Turns
	(in)	(in)	(in)	(in)	
OH	5.2088	1.7335	41.7490	83.4980	482
PF1a	7.2403	1.6265	62.6215	9.1820	20
PF1b	11.9768	3.3055	71.8570	7.5030	32
PF2a	31.4634	6.4060	76.1225	2.6760	14
PF2b	31.4634	6.4060	72.9385	2.6760	14
PF3a	58.8370	7.3400	64.3114	2.6760	15
PF3b	58.8370	7.3400	61.1274	2.6760	15
PF4b	70.6540	3.6040	31.7800	2.6760	8
PF4c	71.1210	4.5380	34.9640	2.6760	9
PF5a	78.5280	5.3500	25.6840	2.6980	12
PF5b	78.5280	5.3500	22.7440	2.6980	12
PFAB1	16.9530	0.8565	69.1550	2.6725	48
PFAB2	24.8750	0.8565	75.8210	2.6725	48
TF Inner	1.1090	2.2180	55.7500	111.5000	12
TF Inner Flag	13.8590	20.2820	109.0000	5.0000	12
TF Inner Flag Stub	2.9680	1.5000	109.0000	5.0000	12
TF Outer	3.0750	1.5460	49.6875	99.3750	24
TF Outer Flag	13.9240	20.1520	96.8750	5.0000	24
Coil	R (center)	ΔR	Z (center)	ΔZ	Turns
	(cm)	(cm)	(cm)	(cm)	
OH	13.2302	4.4031	106.0425	212.0849	482
PF1a	18.3902	4.1313	159.0586	23.3223	20
PF1b	30.4209	8.3960	182.5168	19.0576	32
PF2a	79.9170	16.2712	193.3510	6.7970	14
PF2b	79.9170	16.2712	185.2637	6.7970	14
PF3a	149.4460	18.6436	163.3510	6.7970	15
PF3b	149.4460	18.6436	155.2637	6.7970	15
PF4b	179.4612	9.1542	80.7212	6.7970	8
PF4c	180.6473	11.5265	88.8086	6.7970	9
PF5a	199.4611	13.5890	65.2374	6.8529	12
PF5b	199.4611	13.5890	57.7698	6.8529	12
PFAB1	43.0606	2.1755	175.6537	6.7882	48
PFAB2	63.1825	2.1755	192.5853	6.7882	48
TF Inner	2.8169	5.6337	141.6050	283.2100	12
TF Inner Flag	35.2019	51.5163	276.8600	12.7000	12
TF Inner Flag Stub	7.5387	3.8100	276.8600	12.7000	12
TF Outer	7.8105	3.9268	126.2063	252.4125	24
TF Outer Flag	35.3670	51.1861	246.0625	12.7000	24

Since the PF1b coil is located in the lower half plane only, the calculations for TF were performed in the lower half plane only, since that represents the worst case. Radial extent of the flag elements given above is noted to extend out to the mipoint of the flex links at approx. 24”

For the force coefficients on the PF and OH coils an excitation current was imposed one at a time in each of the PF and OH coils, and the total radial (JxB_v) and vertical (JxB_r) force on each of the other coils, per unit of current, was calculated. This involves the integration of the field over the cross section of the coil, multiplied by the circumference and divided by the area of the coil…

$$C_{xy} = \frac{2\pi r_x}{\Delta r_x \Delta z_x} \iint B_y dr dz$$

where C_{xy} is the coefficient of force on coil “x” due to the current in coil “y”. The resultant influence matricies are given in Tables 2 and 3.

TABLE 2: Radial Force Coefficients (lbf/kA^2)

Fr	OH	PF1aU	PF1aL	PF1b	PF2U	PF2L	PF3U	PF3L	PF4U	PF4L	PF5U	PF5L
OH	24620	1069	1069	1681	972	972	1017	1017	660	660	896	896
PF1aU	-19	129	0	1	95	1	67	5	24	6	28	11
PF1aL	-19	1	129	179	2	95	5	67	6	24	11	28
PF1b	-76	1	10	545	4	374	12	192	15	61	27	70
PF2U	-19	-6	1	2	444	6	443	19	112	25	129	47
PF2L	-19	1	-6	-73	6	444	19	443	25	112	47	129
PF3U	-17	-3	1	3	-113	9	575	33	222	43	266	85
PF3L	-17	1	-3	-18	9	-113	33	575	43	222	85	266
PF4U	-11	0	1	2	-4	7	14	28	189	38	612	80
PF4L	-11	1	0	-1	7	-4	28	14	38	189	80	612
PF5U	-17	0	1	2	-3	8	7	36	-300	46	392	105
PF5L	-17	1	0	-1	8	-3	36	7	46	-300	105	392

TABLE 3: Vertical Force Coefficients (lbf/kA^2)

Fz	OH	PF1aU	PF1aL	PF1b	PF2U	PF2L	PF3U	PF3L	PF4U	PF4L	PF5U	PF5L
OH	0	6	-6	-72	54	-54	27	-28	7	-7	6	-6
PF1aU	-6	0	0	0	11	0	0	0	-1	0	-2	-1
PF1aL	6	0	0	-88	0	-11	0	0	0	1	1	1
PF1b	72	0	90	0	1	-20	2	10	2	7	3	8
PF2U	-55	-11	0	-1	0	-2	-99	-7	-39	-9	-41	-16
PF2L	55	0	11	21	2	0	7	99	9	39	16	41
PF3U	-28	-1	-1	-2	99	-7	0	-26	-225	-36	-214	-66
PF3L	28	1	1	-9	7	-99	26	0	36	225	66	214
PF4U	-7	1	-1	-2	39	-9	228	-36	0	-52	-533	-100
PF4L	7	1	-1	-6	9	-39	36	-228	52	0	100	533
PF5U	-6	2	0	-3	42	-15	214	-65	530	-99	0	200
PF5L	6	0	-2	-8	15	-42	65	-214	99	-530	200	0

The above results are noted to differ from the prior revision of the reference calculation as a result of the changed geometry of PF1a. Using these results the force on coil "x" due to its current and the currents in the other "y" coils is is calculated as follows…

$$F_x = \sum_y C_{xy} I_x I_y$$

where the currents are in kA and the resultant force in lbf.

For the TF coil, the forces and moments (taken w.r.t. machine axis) of interest are:

F_{inner} = total force generated on an inner flag due to J_{TF} x B_v
F_{outer} = total force generated on an outer flag due to J_{TF} x B_v
M_{inner} = total moment generated on inner flag due to J_{TF} x B_v
M_{outer} = total moment generated on outer flag due to J_{TF} x B_v
R_{eff_inner} = effective radius of F_{inner}
R_{eff_outer} = effective radius of F_{outer}
$M_{inner\ bundle}$ = moment on inner turn in bundle due to J_{TF} x B_r and reacted by hub
$M_{outer\ bundle}$ = moment on outer turn in bundle due to J_{TF} x B_r and reacted by hub
M_{bundle} = total moment generated on 12 inner and 24 outer turns and reacted by hub
M_{flag} = total torsional moment generated on 12 inner and 24 outer flags J_{TF} x B_v
M_{net} = net moment of bundle and flags transmitted through vacuum vessel

Equations for the influence matrix coefficients are as follows…

Flags:

$$C_{F\_inner,outer} = w \iint J_{TF} B_v \, drdz$$ where w is the width of the flag (1")

$$C_{M\_inner,outer} = w \iint J_{TF} B_v \, rdrdz$$

$$R_{eff\_inner,outer} = \frac{C_{M\_inner,outer}}{C_{F\_inner,outer}}$$

Bundle:

$$C_{Mbundle\_inner} = 2\pi \iint J_{TF} B_r r^2 \frac{z}{z_{\max}} drdz + w \iint J_{TF} B_r r \frac{z}{z_{\max}} drdz$$

$$C_{Mbundle\_outer} = 2\pi \iint J_{TF} B_r r^2 \frac{z}{z_{\max}} drdz$$

where z_{max} is the turn height in a half plane. The z/z_{max} term is used to approximate the amount of torsional load taken out at the hub end of the bundle as if it was a fixed boundary. The remainder is taken by the bundle twist. Note also that the second term in the inner calculation accounts for the flag stub.

The resultant matrix is given in Table 4.

TABLE 4: TF Influence Coefficients (forces: lbf/kA^2, moments: lbf-in/kA^2, radii: inches)

Note: Moments taken about NSTX machine axis

	OH	PF1aU	PF1aL	PF1b	PF2U	PF2L	PF3U	PF3L	PF4U	PF4L	PF5U	PF5L
F_Inner	0.222	0.003	0.024	0.175	0.011	0.652	0.037	0.655	0.049	0.195	0.092	0.240
F_Outer	0.471	0.004	0.048	0.382	0.015	1.178	0.048	0.890	0.063	0.260	0.115	0.310
M_Inner	2.7	0.0	0.3	2.1	0.1	8.5	0.5	8.9	0.7	2.7	1.2	3.3
M_Outer	5.1	0.1	0.6	4.3	0.2	15.7	0.7	12.2	0.9	3.6	1.6	4.2
Reff_Inner	12.2	13.3	12.7	12.3	13.5	13.1	13.6	13.5	13.6	13.7	13.5	13.6
Reff_Outer	10.7	13.1	12.1	11.4	13.5	13.3	13.7	13.8	13.7	13.7	13.9	13.7
∑M_Bundle	-188	-0.2	-8	-10	-0.5	0.1	-1	-1	-1	-2	-2	-3
∑M_Flag	154	2	17	130	7	478	22	400	29	117	53	141
∑M_Net	-34	2	10	120	6	478	21	399	27	115	51	138

Maximum values for the TF forces and moments are given in Table 5. These values result from all coils being at maximum current with the same polarity, and are equivalent to prior published results, except for M_bundle. Prior results reported the total torque integrated along the bundle without accounting for the load sharing according to the z/z_{max} term. The calculation methodology given here, under maximum possible conditions, finds the total torque magnitude to be 36 ft-klbf and, with the inclusion of the z/z_{max} term, 30 ft-klbf loading to the hub/spline/vacuum vessel load path.

TABLE 5: TF Forces and Moments for Maximum Possible Conditions

F_Inner_TF_Flag	3077	lbf
F_Outer_TF_Flag	5077	lbf
M_Inner_TF_Flag	40	in-klbf
M_Outer_TF_Flag	65	in-klbf
Reff_Inner_TF_Flag	13	in
Reff_Outer_TF_Flag	13	in
∑M_TF_Bundle	-30	ft-klbf
∑M_TF_Flag	171	ft-klbf
∑M_TF_Net	141	ft-klbf

Maximum values for the TF and PF forces under realistic maximum conditions are given in Table 6. These forces result from the coils being in worst case current combination within the range indicated in Table 7, which is constrained by the polarity considerations associated with normal plasma operation. Specific worst case current combinations were derived for each case and are given in Table 8. Note that PF4 energization is not included; this is a special case to be treated separately. Cases shown are limited to those relevant to the limiting structural support clamp designs, i.e. forces away from the midplane, except for PF5, whose struts must react the forces toward the midplane as well.

TABLE 6: TF and PF Forces and Moments for Realisitic Maximum Conditions

F_Inner_TF_Flag	1848	lbf
F_Outer_TF_Flag	2765	lbf
M_Inner_TF_Flag	25	in-klbf
M_Outer_TF_Flag	36	in-klbf
Reff_Inner_TF_Flag	13	in
Reff_Outer_TF_Flag	13	in
∑M_TF_Bundle	-28	ft-klbf
∑M_TF_Flag	96	ft-klbf
∑M_TF_Net	78	ft-klbf
Fz_OH	35	klbf
Fz_PF1a (max toward MP)	11	klbf
Fz_PF1b (max toward MP)	82	klbf
Fz_PF2 (max away from MP)	92	klbf
Fz_PF3 (max away from MP)	156	klbf
Fz_PF5 (max away from MP)	144	klbf
Fz_PF5 (max toward MP)	157	klbf

TABLE 7: Realistic Maximum Current Range

	Min	Max
Ioh	-24.0	24.0
Ipf1a	-24.0	5.0
Ipf1b	-20.0	0.0
Ipf2	-20.0	0.0
Ipf3	-20.0	20.0
Ipf4	0.0	0.0
Ipf5	0.0	20.0
Itf	0.0	71.2

TABLE 8: Worst Case Currents (kA) for Various Limiting Conditions

	OH Launch	PF1a Away	PF1b Away	PF2 Away	PF3 Away	PF5 Away	PF5 Toward	TF (all except M_Net)	TF (M_Net)
Ioh	24	24	-24	24	24	-24	24	24	-24
Ipf1a	-24	5	-24	5	5	5	-24	5	5
Ipf1b	-20	-20	-20	0	-20	-20	-20	0	0
Ipf2	-20	-20	0	-20	-20	0	-20	0	0
Ipf3	-20	20	-20	20	-20	20	-20	20	20
Ipf4	0	0	0	0	0	0	0	0	0
Ipf5	0	20	0	20	20	20	20	20	20
Itf	71	71	71	71	71	71	71	71	71

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