PRINCETON UNIVERSITY: PLASMA PHYSICS LABORATORY

Electrical Design Branch

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FROM: R. E. Hatcher **SUBJECT: NSTX-CSU Force Influence Matrix**

INTEROFFICE MEMORANDUM

This memo documents the results of an analysis to generate force influence matrices for the calculation of in-plane (F_r, and F_z) loads on the NSTX CSU poloidal field coil system (including the OH coil). These matrices must recalculated if the details of the coil geometry change. Most geometry changes (positions and/or numbers of turns) can be easily assimilated into the current model with re-calculation of new matrices taking 1- 2 hours.

A 2-d axisymmetric model of the coil system was generated using the Opera electromagnetic design package by Vector Fields Limited. The coils are modeled as conducting regions in the model. The effect of multiple turns is included in the current densities used by the analysis.

The following table and figure details the coil configuration used in this analysis. Note that all of the coils, with the exception of the OH coil, have a mirrored coil in the lower z half- plane. The OH coil was modeled as a single entity to simplify some of the bookkeeping required.

Coil	R (center)	ΔR	Z (center)	ΔZ	Turns
	(cm)	(cm)	(cm)	(cm)	
OH	24.30	6.55	0	424.16	1029
PF1a	32.39	4.13	159.06	32.65	28.00
PF1b	41.42	4.20	182.53	12.06	10.00
PF1c	56.00	4.20	182.53	12.06	10.00
PF2a	79.92	16.27	193.35	6.80	14.00
PF2b	79.92	16.27	185.26	6.80	14.00
PF3a	149.45	18.64	163.35	6.80	15.00
PF3b	149.45	18.64	155.26	6.80	15.00
PF4b	179.46	9.15	80.72	6.80	8.00
PF4c	180.65	11.53	88.81	6.80	9.00
PF5a	199.46	13.59	65.24	6.85	12.00
PF5b	199.46	13.59	57.77	6.85	12.00

Table 1 - Coil configuration parameters used for NSTX CSU influence matrix coefficient calculation

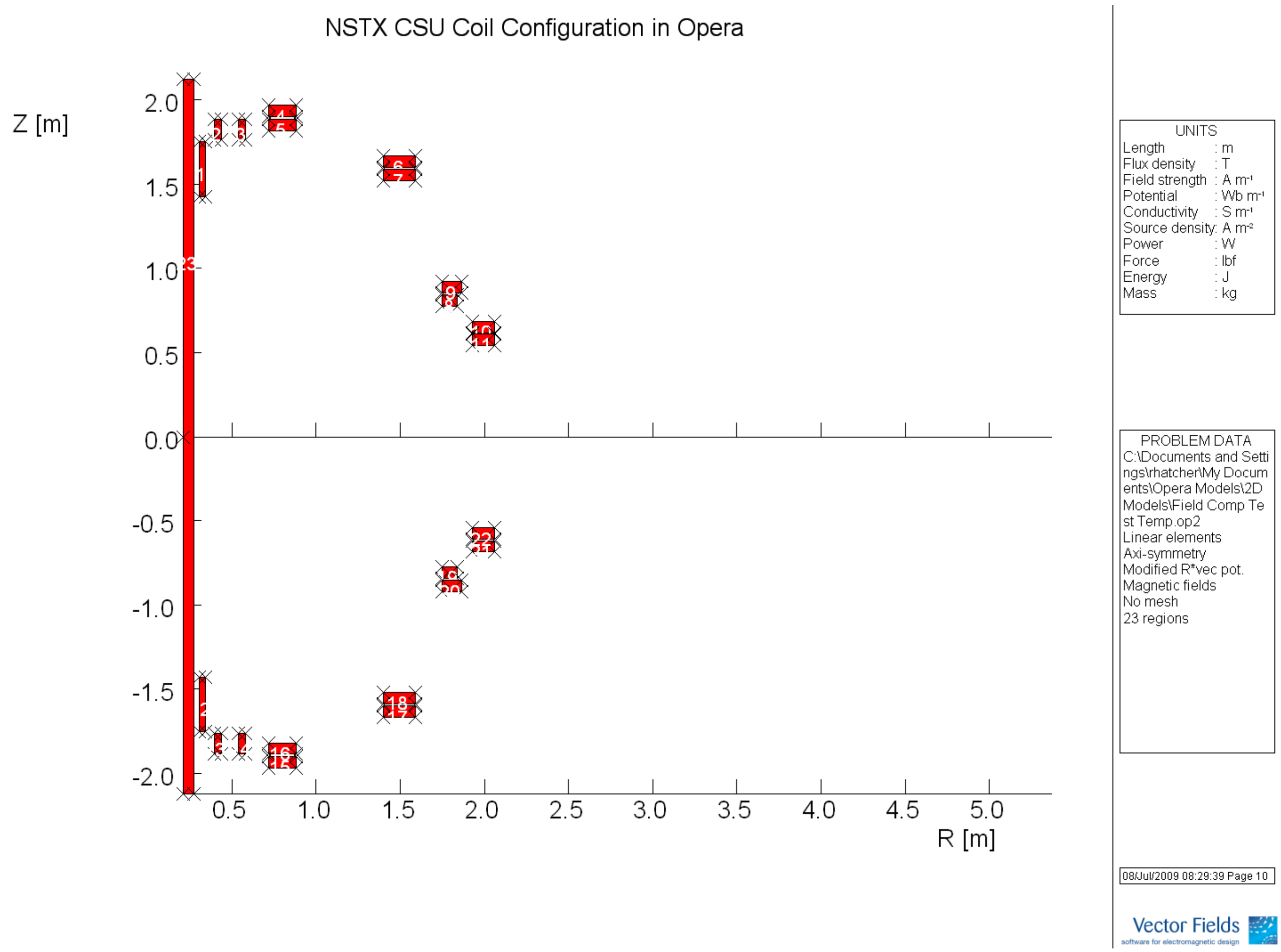

Figure 1 - Operaa Model for NSTX CSU Influence Matrix Calculation

In Opera, forces for axisymmetric problems are calculated by integrating 2π r J x B over current carrying regions ($F = \iint 2\pi\, r\, J \times B\, dr\, dz$, where "x" in this expression indicates the vector cross product). There is a built-in function for this which can be accessed either from menus in the gui or via a command which can be used in a statement as part of a program. The function returns the result of the integration as r- and z- force components.

The program written for this analysis loops over all possible pairs of conducting elements and computes the static field for the case where each of the elements has a current density equivalent to 1 A of current flowing in its associated coil. At each step, the force integral described above is executed for both elements of the pair and the results saved. It should be noted that the force integral does not calculate the quantity that we actually desire (F_{ij} the force on element i due to 1 A (equivalent density) of current in element j). This would be $\iint 2\pi\, r_i\, J_i \times B_j\, dr\, dz$ where the integration is over the i^{th} region (which carries the current) and the field is due to the j^{th} current (which supplies the field). The integral computed is actually $\iint 2\pi\, r_i\, J_i \times (B_i + B_j)\, dr\, dz$ where the self field from the i^{th} element contributes to the total field and hence, to the force (this is actually the self-force term due to 1 A (equivalent density) flowing in the i[th] element). So for each F_{ij} result we get, we have to subtract off the F_{ii} term (which was computed as part of the area integral). This bit of bookkeeping is somewhat offset by the fact that we get F_{ji} from the same static calculation.

A Matlab™ routine was written to read the output from Opera and produce contracted F_R and F_Z influence matrices. Contraction is necessary as most of the coils are made from multiple elements in the model.

	OH	**1AU**	**1BU**	**1CU**	**2U**	**3U**	**4U**	**5U**	**1AL**	**1BL**	**1CL**	**2L**	**3L**	**4L**	**5L**
OH	47683	2736	856	780	1839	1909	1225	1690	2736	856	780	1839	1909	1225	1690
1AU	-134	266	115	117	236	162	58	66	1	0.28	1	3	10	14	26
1BU	-68	-2	49	114	158	73	22	25	0.22	0.10	0.18	1	4	5	10
1CU	-50	-17	-52	54	273	103	30	34	0.28	0.13	0.24	1	5	7	13
2U	-78	-29	-44	-112	380	436	109	125	1	0.45	1	4	18	24	45
3U	-67	-19	-10	-20	-116	495	219	263	2	1	1	7	32	43	84
4U	-44	-3	-1	-2	-5	12	179	617	1	1	1	6	27	37	80
5U	-61	-3	-1	-1	-3	6	-300	353	1	1	1	8	37	47	108
1AL	-134	1	0.28	1	3	10	14	26	266	115	117	236	162	58	66
1BL	-68	0.22	0.10	0.18	1	4	5	10	-2	49	114	158	73	22	25
1CL	-50	0.28	0.13	0.24	1	5	7	13	-17	-52	53	273	103	30	34
2L	-78	1	0.45	1	4	18	24	45	-29	-44	-113	382	436	109	125
3L	-67	2	1	1	7	32	43	84	-19	-10	-20	-116	495	219	263
4L	-44	1	1	1	6	27	37	80	-3	-1	-2	-5	12	178	617
5L	-61	1	1	1	8	37	47	108	-3	-1	-1	-3	6	-300	354

Table 2 - NSTX CSU Radial Force Influence Matrix

Multiplication of the influence matrix by a current vector (in this case given in kA) results in a column vector of coil forces in lbf. As an example, if we have PF4 and PF5 currents of 10 and 20 kA respectively (note that the upper and lower portions of PF4 and PF5 are in series and thus carry the same current) the resulting radial forces are $F_{R,PF4U/L}$ = 16087 and $F_{R,PF5U/L}$ = 6710 lbf respectively (which is why we typically don't run them together in NSTX).

Because of the series connection of PF4U/L and PF5U/L it is possible to contract the matrix further. In this case the forces are for the total coil (i.e., upper and lower combined). While for most cases of interest the matrices with the U/L portions of PF4 and PF5 will suffice, there may be some off-normal cases where combining them would obscure the true force behavior. For this reason, both are supplied.

	OH	1AU	1BU	1CU	2U	3U	4U	5U	1AL	1BL	1CL	2L	3L	4L	5L
OH	6	73	77	78	201	98	23	22	-73	-78	-78	-201	-98	-23	-22
1AU	-73	-0.02	84	43	52	0	-6	-7	-0.11	-0.05	-0.08	-0.41	-2	-2	-4
1BU	-77	-84	0.10	-0.09	14	-5	-4	-4	-0.05	-0.02	-0.04	-0.18	-1	-1	-2
1CU	-78	-43	-0.02	1	48	-11	-7	-8	-0.08	-0.04	-0.07	-0.33	-1	-2	-3
2U	-203	-52	-14	-48	-1	-102	-40	-43	-0.42	-0.18	-0.33	-2	-7	-9	-17
3U	-104	-0.46	5	10	96	-7	-228	-219	-2	-1	-1	-6	-26	-36	-68
4U	-25	6	3	6	38	222	-3	-530	-2	-1	-2	-9	-35	-52	-100
5U	-25	7	4	7	40	210	527	-2	-3	-2	-3	-15	-65	-99	-201
1AL	73	0.11	0.05	0.08	0.41	2	2	4	0.36	-84	-43	-52	0.27	6	7
1BL	77	0.05	0.02	0.04	0.18	1	1	2	84	0.08	0.10	-14	5	4	4
1CL	78	0.08	0.04	0.07	0.33	1	2	3	43	0.03	-1	-48	11	7	8
2L	203	0.42	0.18	0.33	2	7	9	17	52	14	49	1	102	40	43
3L	104	2	1	1	6	26	36	68	0.46	-5	-10	-96	7	228	219
4L	25	2	1	2	9	35	52	100	-6	-3	-6	-38	-222	1	530
5L	25	3	2	3	15	65	99	201	-7	-4	-7	-40	-210	-526	2

Table 3 - NSTX CSU Vertical Force Influence Matrix

	OH	1AU	1BU	1CU	2U	3U	PF4	PF5	1AL	1BL	1CL	2L	3L
OH	47683	2736	856	780	1839	1909	2449	3380	2736	856	780	1839	1909
1AU	-134	266	115	117	236	162	72	92	1	0.28	1	3	10
1BU	-68	-2	49	114	158	73	27	35	0.22	0.10	0.18	1	4
1CU	-50	-17	-52	54	273	103	37	47	0.28	0.13	0.24	1	5
2U	-78	-29	-44	-112	380	436	133	170	1	0.45	1	4	18
3U	-67	-19	-10	-20	-116	495	262	347	2	1	1	7	32
PF4	-87	-2	-0.45	-1	1	40	432	1393	-2	-0.45	-1	1	40
PF5	-121	-2	-0.11	-0.03	4	43	-506	924	-2	-0.11	-0.03	4	43
1AL	-134	1	0.28	1	3	10	72	92	266	115	117	236	162
1BL	-68	0.22	0.10	0.18	1	4	27	35	-2	49	114	158	73
1CL	-50	0.28	0.13	0.24	1	5	37	47	-17	-52	53	273	103
2L	-78	1	0.45	1	4	18	133	170	-29	-44	-113	382	436
3L	-67	2	1	1	7	32	262	347	-19	-10	-20	-116	495

Table 4 - Further Contracted Radial Force Influence Matrix

	OH	1AU	1BU	1CU	2U	3U	PF4	PF5	1AL	1BL	1CL	2L	3L
OH	6	73	77	78	201	98	0.00	0.01	-73	-78	-78	-201	-98
1AU	-73	-0.02	84	43	52	-0.27	-8	-11	-0.11	-0.05	-0.08	-0.41	-2
1BU	-77	-84	0.10	-0.09	14	-5	-5	-6	-0.05	-0.02	-0.04	-0.18	-1
1CU	-78	-43	-0.02	1	48	-11	-9	-11	-0.08	-0.04	-0.07	-0.33	-1
2U	-203	-52	-14	-48	-1	-102	-49	-60	-0.42	-0.18	-0.33	-2	-7
3U	-104	-0.46	5	10	96	-7	-265	-287	-2	-1	-1	-6	-26
PF4	0.00	8	4	8	46	257	-2	-0.06	-8	-4	-8	-46	-257
PF5	0.00	10	5	10	55	275	0.37	-0.06	-10	-5	-10	-55	-275
1AL	73	0.11	0.05	0.08	0.41	2	8	11	0	-84	-43	-52	0.27
1BL	77	0.05	0.02	0.04	0.18	1	5	6	84	0.08	0.10	-14	5
1CL	78	0.08	0.04	0.07	0.33	1	9	11	43	0.03	-1	-48	11
2L	203	0.42	0.18	0.33	2	7	49	60	52	14	49	1	102
3L	104	2	1	1	6	26	265	287	0	-5	-10	-96	7

Table 5 - Further Contracted Vertical Force Influence Matrix

Distribution: C. Neumeyer, P. Titus, P. Heitzenroeder, L. Dudek, R. Simmons, J. Menard