# NSTX

# ANALYSIS OF TF OUTER LEG

**NSTX-CALC-13-03-00**

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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**

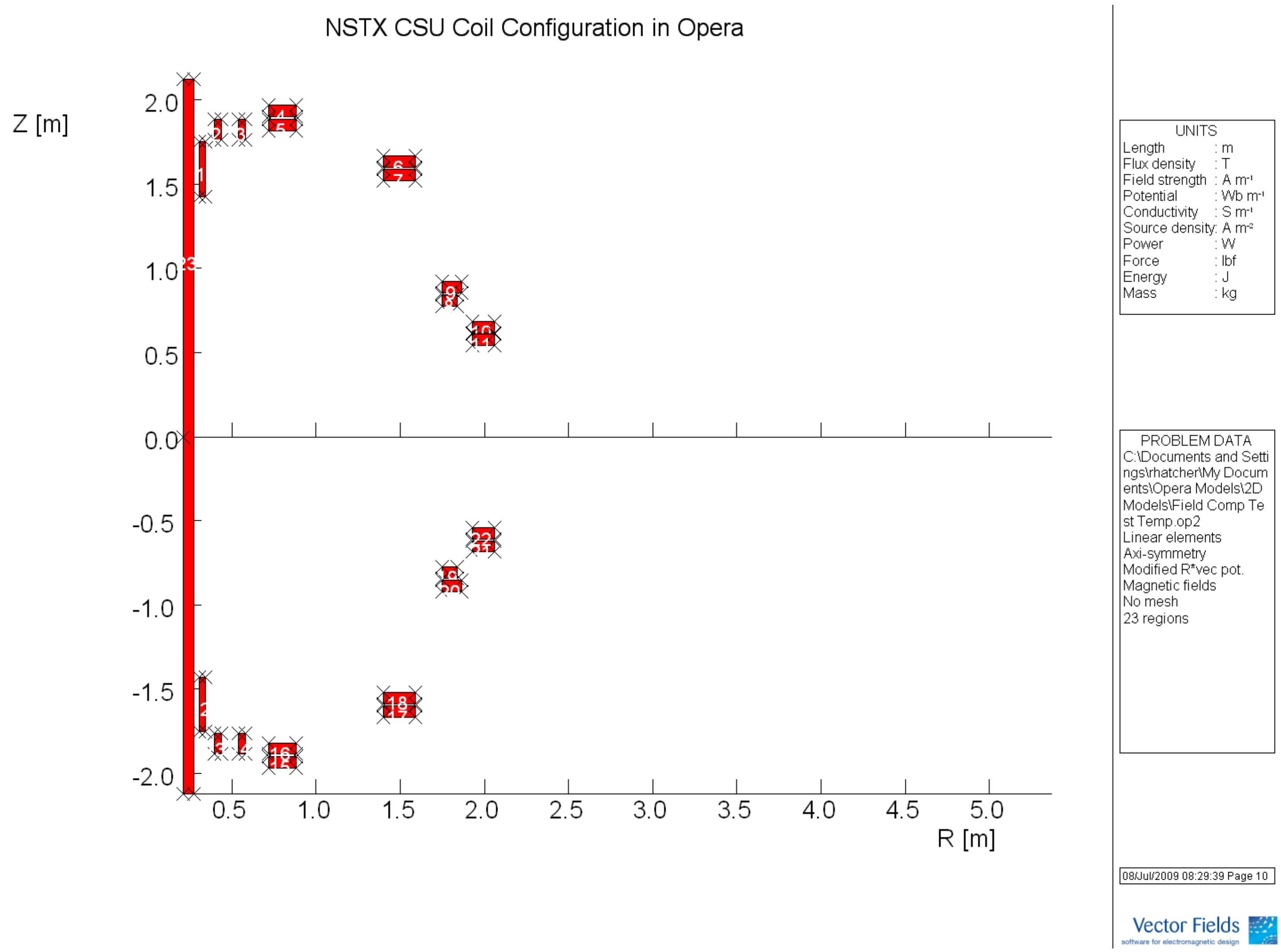


**Figure 1 - Operaa Model for NSTX CSU Influence Matrix Calculation**

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**

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