NSTX Upgrade Project

CALCULATED POLOIDAL MAGNETICS QUANTITES FOR THE MAY 2010 DESIGN OF THE NSTX CS UPGRADE

NSTXU-CALC-131-03-00

December 17, 2010

Prepared By:

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Reviewed By:

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Reviewed By:

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PPPL Calculation Form

Calculation # **NSTXU-CALC-131-03** Revision # **00** ___ WP #, if any **1672** (ENG-032)

Purpose of Calculation: (Define why the calculation is being performed.)
This is essentially a reissuance of Ref.(4) with updated explanatory text and file names to reflect the project adoption of the February 2010 Provisional design as the May 4, 2010 official design, which as of today remains the most recent design point iteration. I have recentely reviewed the calculations of Ref. (4) and confirmed that they do indeed fully apply to the present (May 4, 2010) design point. Included are the:
(1) Mutual Inductance matrix connecting 14 circuits (12 PF, 1 OH, 1 Plasma)
(2) Radial Force influence coefficient from 14 circuit currents to 24 "windings"
(3) Vertical Force influence coefficients from 14 circuit currents to 24 "windings"
(4) Moment (i.e., torque) influence coefficients from 14 circuit currents to 24 "windings"

References (List any source of design information including computer program titles and revision levels.)

(1) R. Woolley, "Magnetics_20100504Design.xls", 17 December 2010 Excel file containing results of Poloidal Magnetics Calculations, distributed in conjunction with this present memo. (This replaces the Excel file distributed with Ref.4)
(2) R. Woolley, "NSTX_CSU Poloidal Magnetics-8Sept2009 Design", 1 November 2009, memo 13-011109-RDW-01
(3) Smythe, Static and Dynamic Electricity, McGraw-Hill Book Co., 1968
(4) R. Woolley, "Calculated Poloidal Magnetics Quantites for the February2010 Provisional Design of the NSTX CS Upgrade", 26 April 2010 memo 13-250410-RDW-01

Assumptions (Identify all assumptions made as part of this calculation.)

See attached memo 13-171210-RDW-01

Calculation (Calculation is either documented here or attached)
See attached information that follows:

- Calculated Poloidal Magnetics Quantites for the May 4, 2010 Design of the NSTX CS Upgrade
- Ip=4 High Precision Magnetics Results:(171712 tiles representing windings)

Conclusion (Specify whether or not the purpose of the calculation was accomplished.)
This is essentially a reissuance of Ref.(4) with updated explanatory text and file names to reflect the project adoption of the February 2010 Provisional design as the May 4, 2010 official design, which as of today remains the most recent design point iteration. I have recentely reviewed the calculations of Ref. (4) and confirmed that they do indeed fully apply to the present (May 4, 2010) design point.

Cognizant Engineer's printed name, signature, and date

____

I have reviewed this calculation and, to my professional satisfaction, it is properly performed and correct.

Checker's printed name, signature, and date

____

13-171210-RDW-01

To: Distribution | Date: 17 December2010

From: R. Woolley | Subject: Calculated Poloidal Magnetics Quantites for the May 4, 2010 Design of the NSTX CS Upgrade **NSTXU-CALC-132-03-00**

References:

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Summary

This is essentially a reissuance of Ref.(4) with updated explanatory text and file names to reflect the project adoption of the February 2010 Provisional design as the May 4, 2010 official design, which as of today remains the most recent design point iteration. I have recentely reviewed the calculations of Ref. (4) and confirmed that they do indeed fully apply to the present (May 4, 2010) design point.

Greens function methods were used to calculate poloidal magnetics quantities for the May 4, 2010 design. The purpose was to accurately estimate parameters needed for the design of coil protection algorithms. Numerical results include calculated ***mutual inductance matrices*** linking windings and/or circuits of the PF coils, OH coils and plasma, and also the corresponding calculated ***influence matrices*** for ***vertical forces***, for ***radial forces***, and for ***moments*** (i.e., *torques*). The numerical results are not direcly included herein but instead are stored in Ref.1 tables.

This memo discusses the analytical and numerical methods employed in these poloidal magnetics calculations, and also explains how to interpret the resulting numerical tables of Ref. 1. For force influence matrices, the methods used herein are the same as those that were used in Ref.2. The calculations of the present memo were themselves carried out using MATLAB software, and the detailed MATLAB/MSWORD code cells implementing these calculations are documented in this memo's included Appendix.

The plasma was represented for these calculations by an idealized conctant-current-density single-turn winding of rectangular cross section, with height Δz=2.00 m and radial width Δr=1.10 m, centered on the z=0 midplane at r=1.07 m. Rectangle width matches plasma width and rectangle height was chosen (as per J. Menard's suggestion) so that rectangle area roughly matches the area enclosed within the last closed flux surface of plasma equilibria.

Calculation Methods

The greens function methods used to calculate magnetic field rely on the closed-form solution for the magnetic field of a circular loop, as presented on pages 290-291 of Ref.3. For a circular loop carrying *I* amperes of coaxial current in the azimuthal (i.e., toroidal) direction at cylindrical coordinate location, (r, z), the magnetic vector potential is everywhere purely in the azimuthal (i.e., toroidal) direction. At any cylindrical coordinate location (ρ,ζ) its magnitude is as follows:

$$A_\varphi(\rho,\zeta) = \frac{\mu_0 I}{\pi k}\sqrt{\frac{r}{\rho}}\left(\left(1-\frac{k^2}{2}\right)K(k) - E(k)\right) \qquad (1)$$

where

$$k = \sqrt{\frac{4r\rho}{(r+\rho)^2 + (\zeta - z)^2}} \qquad (2)$$

and where *E* and *K* are the complete elliptic integral functions of the first and second kinds respectively. The magnetic field's cylindrical components are determined as the curl of the magnetic vector potential, and the poloidal magnetic flux function is the vector potential times the local circumference of a loop:

$$B_r(\rho,\zeta) = -\frac{\partial A_\varphi}{\partial \zeta} = \frac{\mu_0 I}{2\pi\rho}\frac{(\zeta - z)}{\sqrt{(r+\rho)^2 + (\zeta - z)^2}}\left(-K(k) + \frac{r^2+\rho^2+(\zeta-z)^2}{(r-\rho)^2+(\zeta-z)^2}E(k)\right) \qquad (3)$$

$$B_z(\rho,\zeta) = \frac{1}{\rho}\frac{\partial(\rho A_\varphi)}{\partial \rho} = \frac{\mu_0 I}{2\pi}\frac{1}{\sqrt{(r+\rho)^2 + (\zeta - z)^2}}\left(K(k) + \frac{r^2-\rho^2-(\zeta-z)^2}{(r-\rho)^2+(\zeta-z)^2}E(k)\right) \qquad (4)$$

$$\Phi(\rho,\zeta) = 2\pi\rho A_\varphi = \frac{2\mu_0 I}{k}\sqrt{r\rho}\left(\left(1-\frac{k^2}{2}\right)K(k) - E(k)\right) \qquad (5)$$

Eqs. (3), (4), and (5) serve as greens functions for calculation of the magnetic field and poloidal flux for distributions of current in PF and OH coils and in the plasma. For any arbitrary distribution of azimuthal (i.e., toroidal) current density, *J(r,z)*, Eqs (3), (4), and (5) are replaced by the following greens function integrals:

$$B_r(\rho,\zeta) = \iint drdz J(r,z)\frac{\mu_0}{2\pi\rho}\frac{(\zeta - z)}{\sqrt{(r+\rho)^2 + (\zeta - z)^2}}\left(-K(k) + \frac{r^2+\rho^2+(\zeta-z)^2}{(r-\rho)^2+(\zeta-z)^2}E(k)\right) \qquad (6)$$

$$B_z(\rho,\zeta) = \iint drdz J(r,z)\frac{\mu_0}{2\pi}\frac{1}{\sqrt{(r+\rho)^2 + (\zeta - z)^2}}\left(K(k) + \frac{r^2-\rho^2-(\zeta-z)^2}{(r-\rho)^2+(\zeta-z)^2}E(k)\right) \qquad (7)$$

$$\Phi(\rho,\zeta) = \iint drdz J(r,z)\frac{2\mu_0}{k}\sqrt{r\rho}\left(\left(1-\frac{k^2}{2}\right)K(k) - E(k)\right) \qquad (8)$$

For constant current density PF coil models *J(r,z)*,is constant and so is factored out. However, the present calculations must estimate vertical and radial forces on a coil instead of the average field in a coil body. Thus, the integrands of the source integrals in Eqs. (6) and (7) must be multiplied by the local circumference, 2πρ, before integrating again over the winding cross section in (ρ,ζ) and the signs must be adjusted to absorb the vector cross product operation, This results in Eqs. (9) and (10) in which i represents the coil body whose force is being calculated while j represents the interacting coil body.

$$F_z = -\mu_0 J_i J_j \iint_i d\rho d\zeta \iint_j drdz \frac{(z-\zeta)}{\sqrt{(r+\rho)^2+(\zeta-z)^2}}\left(-K(k)+\frac{r^2+\rho^2+(\zeta-z)^2}{(r-\rho)^2+(\zeta-z)^2}E(k)\right) \quad (9)$$

$$F_r = +\mu_0 J_i J_j \iint_i d\rho d\zeta \iint_j drdz \frac{\rho}{\sqrt{(r+\rho)^2+(\zeta-z)^2}}\left(K(k)+\frac{r^2-\rho^2-(\zeta-z)^2}{(r-\rho)^2+(\zeta-z)^2}E(k)\right) \quad (10)$$

It has been identified that it would be useful to also have tabulated influence coefficients for the "***moments***" on coils, so they have been included. Note that what is really sought is a quantity expressing the moment on each coil winding's cross-section due to the spatial distribution of Lorenz forces within the winding. The sought quantities are developed, calculated, and tabulated herein. Similar to the Fr quantities which also have a net vector sum of zero when taken over the entire axisymmetric coil winding, the moment quantities are valid in the sense that a small fraction of each quantity gives the toroidal moment on the wedge-shaped cross sectioon of that coil having the same fraction of a circle. For instance, the toroidally directed moment vector on a 1-degree thick poloidal plane section of a PF coil winding is 1/360 of the value determined from the tabulated moment influence coefficients.

Moments of the Lorenze forces calculated here are taken about the cross-sectional centroid of each coil winding body. In principle, the quantity calculated is given by the following integral taken in the poloidal plane over a winding.

$$M_{\text{winding}} = \iint_{\text{winding}} (\vec{\mathrm{r}} - \vec{\mathrm{r}}_{\mathrm{C}}) \times \left(J\hat{\varphi}\times\vec{B}_{Poloidal}\right)2\pi r drdz = 2\pi J\hat{\varphi} \iint_{\text{winding}} \left[(\mathrm{r}-\mathrm{r_C})b_r(\vec{r})+(\mathrm{z}-\mathrm{z_C})b_z(\vec{r})\right]rdrdz$$

Using the variables employed in Eqs.(1) through (10), this can be rewritten as follows:

$$M = \mu_0 J_i J_j \iint_i d\rho d\zeta \iint_j drdz \left[\begin{array}{l} \dfrac{(\rho-\rho_C^{(i)})(z-\zeta)}{\sqrt{(r+\rho)^2+(\zeta-z)^2}}\left(-K(k)+\dfrac{r^2+\rho^2+(\zeta-z)^2}{(r-\rho)^2+(\zeta-z)^2}E(k)\right) \\ +\dfrac{(\zeta-\zeta_C^{(i)})\rho}{\sqrt{(r+\rho)^2+(\zeta-z)^2}}\left(K(k)+\dfrac{r^2-\rho^2-(\zeta-z)^2}{(r-\rho)^2+(\zeta-z)^2}E(k)\right)\end{array}\right] \quad (11)$$

The mutual inductance between two distinct circuits is the magnetic flux produced by unit current flowing in one circuit that is enclosed within the second circuit. That definition and Eq. (8) would be appropriate if the second circuit were modeled as filamentary, but for actual real finite-thickness coil windings it is necessary to represent how the current density is distributed over the winding's cross section and then integrate over that cross section. For real constant current density axisymmetric coaxial coil windings, the proper muual inductance formula to use becomes as follows:

$$L_{ij} = n_i n_{j,} \iint_i d\rho d\zeta \iint_j drdz \frac{2\mu_0}{k} \sqrt{r\rho} \left(\left(1 - \frac{k^2}{2} \right) K(k) - E(k) \right) \tag{12}$$

where n_i denotes the number of turns in the i^{th} winding.

Equations (9) through (12) are also technically valid for the case where i=j, i.e., for self-force coefficients and self-inductances. In practice, however, their integrands all have a logarithmic discontinuity approaching infinity wherever (r,z)=(ρ,ζ), a condition which cannot be analytically avoided if i=j.

For the present computations, these iterated double integrals over the rectangular cross sections of two interacting windings are carried out numerically by first tiling each of the two coil cross sections with a set of smaller subrectangles. The complete iterated integrals over windings i and j are then approximated as a finite sum of smaller terms estimated for each pair of subrectangles. The integrand for each such subrectangle pair is computed as the average of four integrand values having (ρ,ζ) points representing the four corners of the subrectangle from winding i and a common (r,z) point at the midpoint of the subrectangle from winding j. That average integrand value is then used as a constant for the integration over that particular subrectangle pair.

It is important to note that this numerical procedure, in which current filaments are placed at the centers of rectangular tiles while magnetic field and flux are evaluated at the corners of rectangular tiles, has the property that (r,z) is always different from (ρ,ζ) at all integrand evaluation points. This situation positively avoids the numerical difficulties with the integrand's logarithmic discontinuity. It can be shown that in the limit of an infinite number of infinitesimal rectangular tiles, the Riemann sum converges to the actual finite integral limit, even for the cases where i=j in which the integral is improper.

For the present calculations the initial subtiling into rectangles is as listed in Table 1. This initial subtiling was chosen to have all subrectangles tiling of PF and OH coil windings and plasma of about the same cross section area and of about the same vertical/radial aspect ratio.

It can be shown that this numerical method based on rectaangular subtilings converges to the exact integral quantities in the infinite limit of progressively smaller subrectangles tiling the winding cross sections. In the present set of calculations, the initial substiling was designated as lp=1, where lp stands for "level of precision". Each tile was then further subdivided into 2^(lp-1) horizontal and 2^(lp-1) vertical subrectangles for different calculations using successive levels of precision, for lp=1, 2, 3, and 4 values. Results from all four lp levels of precision are included in the associated Excel file in order to assess the approach of the computed results towards the precise limit. The lp=4 values are the most precise results calculated herein and are recommended for engineering uses.

Table 1: Subtiling of Poloidal Plane Winding Cross-setions for Calculations

Number	**Coil Winding Name**	**LevelPrecision=1**		**LevelPrecision=2**		**LevelPrecision=3**		**LevelPrecision=4**	
		# tiles height	**# tiles width**	**# tiles height**	**# tiles width**	**# tiles height**	**# tiles width**	**# tiles height**	**# tiles width**
1	**PF1AU**	**13**	**2**	**26**	**4**	**52**	**8**	**104**	**16**
2	**PF1BU**	**6**	**1**	**12**	**2**	**24**	**4**	**48**	**8**

3	PF1CU	5	1	10	2	20	4	40	8
4	PF2AU	2	5	4	10	8	20	16	40
5	PF2BU	2	5	4	10	8	20	16	40
6	PF3AU	2	6	4	12	8	24	16	48
7	PF3BU	2	6	4	12	8	24	16	48
8	PF4BU	2	4	4	8	8	16	16	32
9	PF4CU	2	4	4	8	8	16	16	32
10	PF4BL	2	3	4	6	8	12	16	24
11	PF4CL	2	4	4	8	8	16	16	32
12	PF5AU	2	4	4	8	8	16	16	32
13	PF5BU	2	4	4	8	8	16	16	32
14	PF5AL	2	4	4	8	8	16	16	32
15	PF5BL	2	4	4	8	8	16	16	32
16	PF3BL	2	6	4	12	8	24	16	48
17	PF3AL	2	6	4	12	8	24	16	48
18	PF2LA	2	5	4	10	8	20	16	40
19	PF2LB	2	5	4	10	8	20	16	40
20	PF1CL	5	1	10	2	20	4	40	8
21	PF1BL	6	1	12	4	24	8	48	16
22	PF1AL	13	2	26	4	52	8	104	16
23	OH	117	3	234	6	468	12	936	24
24	PL	56	31	112	62	224	124	448	248

Excel File Table Contents

The first worksheet, named 'Design', summarizes geometric details of the NSTX CS Upgrade February 2010 Provisional Design which were used to carry out the magnetics calculations. The second worksheet, 'CoilCircuits', shows which coil windings are included in which series electrical circuits by means of a 24X14 matrixc of ones and zeros. The remaining 16 worksheets are divided into 4 groups, in which the level of precision variable for the calculation subtiling is lp=1, 2, 3, and 4, respectively. Within each precision group, the four worksheets are "L" including calculated mutual inductance matrices, "Fr" including calculated radial force influence matrices, "Fz" including calculated vertical force influence matrices, and "M" including moment (i.e. torque) influence matrices.

Within the "L" worksheets, Table 3 contains a 24X24 matrix of mutual inductances calculated between windings via Eq. (12). Values were calculated by modeling 1 ampere successively in coils listed for each row, and then determining the flux enclosed by the coils listed for each column. Table 2 contains a 14X14 matrix of mutual inductances between the electrical circuits, obtained by pre-multiplying and post-multiplying the L Table 3 matrix by the CoilCircuits matrix and its transpose. Table 1 was formed by averaging the Table 2 matrix with its transpose.

Radial and vertical force and moment matrices between windings, expressed in SI units and dimensioned 24X24, were calculated by numerically evaluating Eqs. (9), (10) and (11) using the MATLAB routines. These matrices have not been included in Ref. 1. Instead, Tables 1 of the Fr, Fz, and M worksheets, which are dimensioned 24X14, were obtained by postmultiplying the respective calculated Fr, Fz, and M 24X24 matrices by the 24X14 CoilCircuits matrix of coil connections. The included respective Table 1 24X14 matrices are useful because they are in a form ready for matrix multiplication by the 14X1 vector of coil & plasma circuit currents (in amperes per turn), then by the current (also in amperes per turn) in the winding of interest. The force or moment algorithms can be written in scalar form as follows:

$$[Fr, Fz, \text{or } M]_k = I_{i_k} \sum_j A_{(i_k, j)} I_j \tag{13}$$

Here, the indexed index, i_k , signifies the particular circuit number (1 through 14) which contains winding number k, and $A_{i,j}$ represents a force or moment influence coefficient. To calculate the entire 24X1 vector of force components or moments on "windings" representing PF coils, OH coil and the plasma, this can be expressed in the following more complicated vector-matrix form, in which the function diag[] of a 24X1 vector is the 24X24 matrrix having that vector on its diagonal and zeros elsewhere.

$$[\underline{Fr}, \underline{Fz}, \text{or } \underline{M}] = diag[(CoilCircuits)\underline{I}]\underline{\underline{A}}\underline{I}$$

Tables 2 of the Fr and Fz worksheets were obtained from the Tables 1 by converting from Newtons to pounds force and from amperes to kiloamperes. This brings their influence coeffieicnts into the hybrid combination of various nonstandard units used in the past for certain NSTX engineering calculations.

APPENDIX: MATLAB NOTEBOOK CALCULATIONS

<u>MATLAB m-file subroutines used</u>

The m-file subroutine used for axisymmetric field and flux calcalculations was

```
function [br,bz,flux]=poloidal_fieldy(rho,zeta,r,z);
```

which I had previously coded and extensively tested. Its coding is as follows:

```
function [br,bz,flux]=poloidal_fieldy(rho,zeta,r,z);
% Axisymmetric poloidal magnetic field and flux are calculated
% at locations specified in matrices rho and zeta, normalized to
a
% total source current of one ampere uniformly distributed
between
% circular loop filament locations specified by matrices r and
z.
% Matrix sizes must match between r and z which may be 1D or 2D
arrays.
% Sizes of rho and zeta must also match each other but they may
be ND
% arrays. SI units are used.
%
if size(r)~=size(z)
    error('r and z filament description matrices must be of same
size')
end
if size(rho)~=size(zeta)
    error('rho and zeta field calc location description arrays
must be of same size')
end
br=zeros(size(rho));bz=br;flux=br;aphi=flux;
%The following uses linear indexing for rho,zeta,br,bz,aphi,flux
%Note that aphi is the vector potential and flux is integrated
over two pi radians.
for i=1:numel(br)
        rhot=rho(i);zetat=zeta(i);
% First confirm this evaluation location misses all filaments.
        disc=(r-rhot).^2+(z-zetat).^2;
        if (isempty( find( disc==0 ) ) );
        m=4*rhot*r./((rhot+r).^2+(zetat-z).^2);
        [K,E]=ellipke(m);
        bz(i)=         mean(mean((2e-7).*(K+((r.^2-rhot^2-(zetat-
z).^2)./disc).*E)...
```

```
        ./sqrt((rhot+r).^2.+(zetat-z).^2)  )');
        if rhot==0
            br(i)=0.;
            aphi(i)=0.;
        else
            br(i)=mean(mean(2e-7*(z-
zetat)./sqrt((rhot+r).^2+(zetat-z).^2).*(-K+...
            (r.^2+rhot^2+(zetat-z).^2)./disc.*E)/rhot)');
            aphi(i)=mean(mean(4e-7*sqrt(r/rhot).*((1.-m/2).*K-
E)./sqrt(m))');
        end
        flux(i)=2*pi*rhot*aphi(i);
        else
            bz(i)=NaN;
            br(i)=NaN;
            aphi(i)=NaN;
            flux(i)=NaN;
        end
end
```

This m-file calculates the magnetic field components, br and bz, and the total magnetic flux included inside the complete 2π radian circle(s) about the z-axis passing through location(s) specified by (rho, zeta). Providing they have the same size, rho and zeta may be specified either as single scalars, as 1-D vectors, as 2-D matrices, or even as ND-arrays with 3 or more dimensions. The magnetic results variables, br, bz, and flux, have the same dimensions size as the field evaluation location specifiers, rho and zeta.

The calculated field is modeled as though it is produced by current flowing in a set of coaxial curcular loops passing through poloidal half-plane location(s) (r, z), where r and z are variable arrays having the same dimensional size as each other and also may optionally be dimensioned as single scalars, as 1-D vectors, as 2-D matrices, or even as ND-arrays with 3 or more dimensions. Obviously, r and rho may have completely different array size dimensions. The model assumes one ampere of current is equally *divided* between the different loops specified in (r, z), so that the total modeled current flowing is 1 ampere-turn.

The m-file routine uses exact formulae for the field and flux of an idealized circular filament, employing Elliptic Integral functions exactly as given in Smythe's textbook on Electromagnetism. To use this for actual PF coils we must first represent each PF coil by coaxial circular filaments. Using a single central current filament is pretty accurate far from the coil, but its error increases at locations closer to the coil. The filament's field strength theoretically approaches an infinite limit at a sequence of locations approaching the filament's location, whereas an actual PF coil's field remains finite everywhere. If you ask the m-file to calculate field at a (rho, zeta) location which precisely matches a current loop's (r, z) location, it returns NaN (not a number) instead of a numerical value for that evaluation location and it also warns about dividing by zero. To obtain better accuracy close to a coil, the coil should be represented by multiple nearby filaments.

To automate this generation of multiple filaments to represent PF coils, I wrote the following m-file:

```
function [r,z]=filamentize(rmin,rmax,zmin,zmax,m,n)
```

It is coded as follows:

```
function [r,z]=filamentize(rmin,rmax,zmin,zmax,m,n)
% Calculates filament matrix to represent rectangular xsection
pf coils.
% Rectangle is divided into subrectangles; filaments are located
at
% subrectangle centers.
%
r=zeros(m,n);z=r;
for j=1:n;
    r(:,j)=rmin+(rmax-rmin)/n*(j-0.5);
end
for i=1:m;
    z(i,:)=zmin+(zmax-zmin)/m*(i-0.5);
end
```

The first four arguments specify the rectangular cross section dimensions of a PF coil. The other two arguments state the (integer) number if subrectangle "tiles" to partition it into, with m being the number in the z direction and n the number in the r direction. The rho and zeta quantities it returns are each m-by-n matrices containing the radial and axial coordinates of centers of rectangles subdividing the PF coil cross-section.

With the multiple filament approximateion of PF coils, magnetic fields and fluxes calculated close to, but outside of, PF coil bodies are quite accurate provided that several filaments are used to represent each coil. However, that is not true for arbitrary locations inside the coils. Arbitrary internal locations for field evaluation may approach modeled current filaments arbitrarily closely, and for field evaluation locations arbitarily close to one of the modeled filaments, the calculated field strength may be arbitrarily large. So, for arbitrary locations inside PF coils, the magnetic field as calculated by my straight combination of filamentize.m and poloidal_fieldx.m could be wildly in error. A different calculational approach is therefore taken for fields evaluation at locations within coils.

Calculation error is small at locations exactly midway between filaments in the uniform rectangular array of filaments used for coil modeling. Since the filaments are located at the centers of tiled subrectangles, I evaluate field at each of the *corners* of those same subrectangles. Thus, if the PF coil cross section partition was into an m-by-n array of subrectangles and thus resulted in m*n filament locations, then this approach defines an associated rectangular mesh of (m+1)-by-(n+1) locations in the coil with field known by accurate calculation. For other internal locations inside the coil, 2-D interpolation of those meshpoint field values is used.

To help implement this scheme the following (almost trivial) m-file was written:

```
function [rho,zeta]=filamentize_corners(rmin,rmax,zmin,zmax,m,n)
% Calculates matrices of field evaluation locations in
rectangular xsection pf coils.
% Rectangle is divided into subrectangles; eval. locations are
at their
% corners.
%
rpoints=linspace(rmin,rmax,n+1);
zpoints=linspace(zmin,zmax,m+1);
[rho,zeta]=meshgrid(rpoints,zpoints
```

A single worksheet EXCEL document, **NSTX_CSU_Assumed_Feb2010-Design_PFSystem.xls**, was manually prepared to specify the conductor geometry of the PF coil system design by decomposing each coil into a set component windings each having a regular rectangular matrix of turns as its cross section. Data used in this file were obtained from the 'Provisional_DesignPoint' file, NSTX_CS_Upgrade_100201.xls. The file's single worksheet has been copied into the Ref.1 Excel file as its 'Design' worksheet.

MATLAB code for these calculations follows:

```
[num,txt] =
xlsread('F:\Documents\NSTXCSUGstuff\DesignPointExcelFiles\NSTX_CSU_Assumed_Fe
b2010-Design_PFSystem-1.xls', 'B5:J28');




coil_name=txt(:,1)
winding_name=txt(:,2)
winding_r=num(:,1)
winding_dr=num(:,2)
winding_z=num(:,3)
winding_dz=num(:,4)
winding_m=num(:,5)
winding_n=num(:,6)
winding_mn=num(:,7)

coil_name =
    'PF1AU'
    'PF1BU'
    'PF1CU'
    'PF2U'
    ''
    'PF3U'
```

```
    ''
    'PF4'
    ''
    ''
    ''
    'PF5'
    ''
    ''
    ''
    'PF3L'
    ''
    'PF2L'
    ''
    'PF1CL'
    'PF1BL'
    'PF1AL'
    'OH'
    'PLASMA'
winding_name =
    'PF1AU'
    'PF1BU '
    'PF1CU '
    'PF2AU'
    'PF2BU'
    'PF3AU'
    'PF3BU'
    'PF4BU'
    'PF4CU'
    'PF4BL'
    'PF4CL'
    'PF5AU'
    'PF5BU'
    'PF5AL'
    'PF5BL'
    'PF3BL'
    'PF3AL'
    'PF2LA'
    'PF2LB'
    'PF1CL'
    'PF1BL'
    'PF1AL'
    'OH'
    'PL'
winding_r =
                     31.93
                    40.038
                    55.052
                   79.9998
                   79.9998
                   149.446
                   149.446
                  179.4612
                  180.6473
                  179.4612
                  180.6473
                  201.2798
```

```
                   201.2798
                   201.2798
                   201.2798
                    149.446
                    149.446
                    79.9998
                    79.9998
                     55.052
                     40.038
                      31.93
                    24.2083
                        107
winding_dr =
                     5.9268
                       3.36
                     3.7258
                    16.2712
                    16.2712
                    18.6436
                    18.6436
                     9.1542
                    11.5265
                     9.1542
                    11.5265
                    13.5331
                    13.5331
                    13.5331
                    13.5331
                    18.6436
                    18.6436
                    16.2712
                    16.2712
                     3.7258
                       3.36
                     5.9268
                      6.934
                        110
winding_z =
                     159.06
                     180.42
                     181.36
                   193.3473
                     185.26
                   163.3474
                     155.26
                    80.7212
                    88.8086
                   -80.7212
                   -88.8086
                    65.2069
                    57.8002
                   -65.2069
                   -57.8002
                    -155.26
                  -163.3474
                  -193.3473
```

```
                  -185.26
                  -181.36
                  -180.42
                  -159.06
                        0
                        0
winding_dz =
                  46.3533
                  18.1167
                  16.6379
                    6.797
                    6.797
                    6.797
                    6.797
                    6.797
                    6.797
                    6.797
                    6.797
                    6.858
                    6.858
                    6.858
                    6.858
                    6.797
                    6.797
                    6.797
                    6.797
                  16.6379
                  18.1167
                  46.3533
                   424.16
                      200
winding_m =
    16
    16
    10
     2
     2
     2
     2
     4
     2
     4
     2
     2
     2
     2
     2
     2
     2
     2
     2
    10
    16
    16
   221
     1
```

```
winding_n =
                          4
                          2
                          2
                          7
                          7
                        7.5
                        7.5
                          2
                        4.5
                          2
                        4.5
                          6
                          6
                          6
                          6
                        7.5
                        7.5
                          7
                          7
                          2
                          2
                          4
                          4
                          1
winding_mn =
    64
    32
    20
    14
    14
    15
    15
     8
     9
     8
     9
    12
    12
    12
    12
    15
    15
    14
    14
    20
    32
    64
   884
     1
```

Before going any further, all dimensional information must first be converted into meters units, since subsequent magnetics calculations assumes that distances arfe expressed in the SI system. Since input data from the spreadsheet were expressed in centimeters, we must divide their values by 100.

```
winding_r=winding_r/100
winding_z=winding_z/100
winding_dr=winding_dr/100
winding_dz=winding_dz/100
```

```
winding_r =
                    0.3193
                   0.40038
                   0.55052
                  0.799998
                  0.799998
                   1.49446
                   1.49446
                  1.794612
                  1.806473
                  1.794612
                  1.806473
                  2.012798
                  2.012798
                  2.012798
                  2.012798
                   1.49446
                   1.49446
                  0.799998
                  0.799998
                   0.55052
                   0.40038
                    0.3193
                  0.242083
                      1.07
winding_z =
                    1.5906
                    1.8042
                    1.8136
                  1.933473
                    1.8526
                  1.633474
                    1.5526
                  0.807212
                  0.888086
                 -0.807212
                 -0.888086
                  0.652069
                  0.578002
                 -0.652069
                 -0.578002
                   -1.5526
                 -1.633474
```

```
               -1.933473
                 -1.8526
                 -1.8136
                 -1.8042
                 -1.5906
                       0
                       0
winding_dr =
                0.059268
                  0.0336
                0.037258
                0.162712
                0.162712
                0.186436
                0.186436
                0.091542
                0.115265
                0.091542
                0.115265
                0.135331
                0.135331
                0.135331
                0.135331
                0.186436
                0.186436
                0.162712
                0.162712
                0.037258
                  0.0336
                0.059268
                 0.06934
                     1.1
winding_dz =
                0.463533
                0.181167
                0.166379
                 0.06797
                 0.06797
                 0.06797
                 0.06797
                 0.06797
                 0.06797
                 0.06797
                 0.06797
                 0.06858
                 0.06858
                 0.06858
                 0.06858
                 0.06797
                 0.06797
                 0.06797
                 0.06797
                0.166379
                0.181167
                0.463533
                  4.2416
```

```
                        2
```

Then save the winding description data to a matlab data file.

```
save NSTXCSU_windings.mat   coil_name winding_name winding_r winding_dr
winding_z winding_dz winding_m winding_n winding_mn


clear
load NSTXCSU_windings.mat
whos

  Name                  Size              Bytes  Class     Attributes

  coil_name            24x1               1560  cell
  winding_dr           24x1                192  double
  winding_dz           24x1                192  double
  winding_m            24x1                192  double
  winding_mn           24x1                192  double
  winding_n            24x1                192  double
  winding_name         24x1               1672  cell
  winding_r            24x1                192  double
  winding_z            24x1                192  double
```

Next, for the purposes of calculating inductance, force ond moment matrices for PF coils and plasma, we will allocate some storage arrays for intermediate calculated quantities. We have defined 14 "circuits", i.e., 13 OH and PF coil circuits and the plasma as the 14th. We also have defined 24 rectangular winding packs, i.e., 23 for the OH&PF coils and 1 for the plasma. Magnetics calculations are carried out using the 24 defined rectangular winding pack geometries and numbers of turns. Magnetics calculations for the 14 circuits are then obtained by summing the winding pack results over thse winding packs that are connected in series within each circuit.

The calculation of the inductance between one poloidal field winding pack or OH coil winding pack and another winding pack assumes one ampere-turn flowing through a coaxial set of circular filaments uniformly distributed over the first winding pack, calculates the resulting magnetic fluxes enclosed within a set of coaxial circular filaments uniformly distrbibuted over the second winding pack, averages those flux values, and then finally multiplies by the product of turns in the two winding packs. The calculation of vertical force influence coefficients between winding packs similarly assumes one-ampere-turn uniformaly distributed in the first winding pack, evaluates the product, $2\pi r B_r(r,z)$, for each coaxial circular fiklament in the second winding pack, then averages these values, and finally multiplies by the product of turns in the two winding packs. The calculation of radial "force" influence coefficients similarly evaluates the product, $-2\pi r B_z(r,z)$, for each coaxial circular fiklament in the second winding pack, then averages these values, and finally multiplies by the product of turns in the two winding packs.

Note the magnetics calculations are initially done here as though each winding was single-turn, and the actual number of turns per winding is then handled as a multiplicative adjustment made later. Note that the initial number of filaments for each winding (at the coarsest level of precision) is obtained by the following procedure. First, the minimum dr or dz of all winding packs is found, then that minimum dimension is divided into the width and height of each winding pack, then the "ceiling" of each result is taken, i.e., by rounding up to the next whole integer. This provides the initial tilings. Higher precision tilings are obtained by successive doublings of the numbers of filaments in both radial and vertical directions.

```
T1=zeros(24,24,6);T1turns=T1;
Mcw=zeros(24,24,6); Fz=Mcw;Fr=Fz;L=zeros(14,14,6);
small=min(min(winding_dr),min(winding_dz));
mz=ceil(winding_dz/small);
nr=ceil(winding_dr/small);
[mz winding_dz  nr  winding_dr]
```

```
ans =
  Columns 1 through 3
                        14                    0.463533
2
                         6                    0.181167
1
                         5                    0.166379
2
                         3                     0.06797
5
                         3                     0.06797
5
                         3                     0.06797
6
                         3                     0.06797
6
                         3                     0.06797
3
                         3                     0.06797
4
                         3                     0.06797
3
                         3                     0.06797
4
                         3                     0.06858
5
                         3                     0.06858
5
                         3                     0.06858
5
                         3                     0.06858
5
                         3                     0.06797
6
                         3                     0.06797
6
                         3                     0.06797
5
```

```
                         3                          0.06797
5
                         5                         0.166379
2
                         6                         0.181167
1
                        14                         0.463533
2
                       127                           4.2416
3
                        60                                2
33
  Column 4
                  0.059268
                    0.0336
                  0.037258
                  0.162712
                  0.162712
                  0.186436
                  0.186436
                  0.091542
                  0.115265
                  0.091542
                  0.115265
                  0.135331
                  0.135331
                  0.135331
                  0.135331
                  0.186436
                  0.186436
                  0.162712
                  0.162712
                  0.037258
                    0.0336
                  0.059268
                   0.06934
                       1.1
```

```
lp=1;
for iwinding=1:24;
rwindingmin=winding_r(iwinding)-winding_dr(iwinding)/2;
rwindingmax=winding_r(iwinding)+winding_dr(iwinding)/2;
zwindingmin=winding_z(iwinding)-winding_dz(iwinding)/2;
zwindingmax=winding_z(iwinding)+winding_dz(iwinding)/2;

[rwinding,zwinding]=filamentize(rwindingmin,rwindingmax,zwindingmin,zwindingm
ax, mz(iwinding)*2^(lp-1),nr(iwinding)*2^(lp-1));

for jwinding=1:24;

rwindingminj=winding_r(jwinding)-winding_dr(jwinding)/2;
rwindingmaxj=winding_r(jwinding)+winding_dr(jwinding)/2;
zwindingminj=winding_z(jwinding)-winding_dz(jwinding)/2;
zwindingmaxj=winding_z(jwinding)+winding_dz(jwinding)/2;
```

```
[rhoj,zetaj]=filamentize_corners(rwindingminj,rwindingmaxj,zwindingminj,zwind
ingmaxj,mz(jwinding)*2^(lp-1),nr(jwinding)*2^(lp-1) );

[br,bz,flux]=poloidal_fieldy(rhoj,zetaj,rwinding,zwinding);

Mcw(iwinding,jwinding,lp)= mean(mean((flux(1:end-1,1:end-1)+flux(2:end,1:end-
1)+flux(1:end-1,2:end)+flux(2:end,2:end))/4)');
rhojbz=rhoj.*bz;

Fr(iwinding,jwinding,lp)=+2*pi*mean(mean((rhojbz(1:end-1,1:end-1)
+rhojbz(2:end,1:end-1)+rhojbz(1:end-1,2:end)+rhojbz(2:end,2:end))/4)');
rhojbr=rhoj.*br;

Fz(iwinding,jwinding,lp)=-2*pi*mean(mean( (rhojbr(1:end-1,1:end-
1)+rhojbr(2:end,1:end-1)+rhojbr(1:end-1,2:end)+rhojbr(2:end,2:end))/4)');

r1=(rhoj(1:end-1,1:end-1)+rhoj(2:end,1:end-1))/2;
r2=(rhoj(1:end-1,2:end)+rhoj(2:end,2:end))/2;
z1=(zetaj(1:end-1,1:end-1)+zetaj(1:end-1,2:end))/2;
z2=(zetaj(2:end,1:end-1)+zetaj(2:end,2:end))/2;

Br_avg=(br(1:end-1,1:end-1)+br(2:end,1:end-1) +br(1:end-
1,2:end)+br(2:end,2:end))/4;

Br_dif=(-br(1:end-1,1:end-1)-br(2:end,1:end-1)+br(1:end-
1,2:end)+br(2:end,2:end))/4;

Bz_avg=+(bz(1:end-1,1:end-1)+bz(2:end,1:end-1)+bz(1:end-
1,2:end)+bz(2:end,2:end))/4;

Bz_dif=+(-bz(1:end-1,1:end-1)-bz(2:end,1:end-1)+bz(1:end-
1,2:end)+bz(2:end,2:end))/4;

rc=winding_r(jwinding);
zc=winding_z(jwinding);

T1(iwinding,jwinding,lp)=mean(mean( ( Br_avg .*((r1+r2)/2-rc)
+Bz_avg.*((z1+z2)/2-zc) ) .* (r1+r2)/2)')*2*pi;

end
end
Mcw;
Fr;
Fz;



lp=2;
for iwinding=1:24;
rwindingmin=winding_r(iwinding)-winding_dr(iwinding)/2;
rwindingmax=winding_r(iwinding)+winding_dr(iwinding)/2;
zwindingmin=winding_z(iwinding)-winding_dz(iwinding)/2;
zwindingmax=winding_z(iwinding)+winding_dz(iwinding)/2;
```

```
[rwinding,zwinding]=filamentize(rwindingmin,rwindingmax,zwindingmin,zwindingm
ax, mz(iwinding)*2^(lp-1),nr(iwinding)*2^(lp-1));

for jwinding=1:24;

rwindingminj=winding_r(jwinding)-winding_dr(jwinding)/2;
rwindingmaxj=winding_r(jwinding)+winding_dr(jwinding)/2;
zwindingminj=winding_z(jwinding)-winding_dz(jwinding)/2;
zwindingmaxj=winding_z(jwinding)+winding_dz(jwinding)/2;
[rhoj,zetaj]=filamentize_corners(rwindingminj,rwindingmaxj,zwindingminj,zwind
ingmaxj,mz(jwinding)*2^(lp-1),nr(jwinding)*2^(lp-1) );

[br,bz,flux]=poloidal_fieldy(rhoj,zetaj,rwinding,zwinding);

Mcw(iwinding,jwinding,lp)= mean(mean((flux(1:end-1,1:end-1)+flux(2:end,1:end-
1)+flux(1:end-1,2:end)+flux(2:end,2:end))/4)');
rhojbz=rhoj.*bz;

Fr(iwinding,jwinding,lp)=+2*pi*mean(mean((rhojbz(1:end-1,1:end-1)
+rhojbz(2:end,1:end-1)+rhojbz(1:end-1,2:end)+rhojbz(2:end,2:end))/4)');
rhojbr=rhoj.*br;

Fz(iwinding,jwinding,lp)=-2*pi*mean(mean( (rhojbr(1:end-1,1:end-
1)+rhojbr(2:end,1:end-1)+rhojbr(1:end-1,2:end)+rhojbr(2:end,2:end))/4)');

r1=(rhoj(1:end-1,1:end-1)+rhoj(2:end,1:end-1))/2;
r2=(rhoj(1:end-1,2:end)+rhoj(2:end,2:end))/2;
z1=(zetaj(1:end-1,1:end-1)+zetaj(1:end-1,2:end))/2;
z2=(zetaj(2:end,1:end-1)+zetaj(2:end,2:end))/2;

Br_avg=(br(1:end-1,1:end-1)+br(2:end,1:end-1) +br(1:end-
1,2:end)+br(2:end,2:end))/4;

Br_dif=(-br(1:end-1,1:end-1)-br(2:end,1:end-1)+br(1:end-
1,2:end)+br(2:end,2:end))/4;

Bz_avg=+(bz(1:end-1,1:end-1)+bz(2:end,1:end-1)+bz(1:end-
1,2:end)+bz(2:end,2:end))/4;

Bz_dif=+(-bz(1:end-1,1:end-1)-bz(2:end,1:end-1)+bz(1:end-
1,2:end)+bz(2:end,2:end))/4;

rc=winding_r(jwinding);
zc=winding_z(jwinding);

T1(iwinding,jwinding,lp)=mean(mean( ( Br_avg .*((r1+r2)/2-rc)
+Bz_avg.*((z1+z2)/2-zc) ) .* (r1+r2)/2)')*2*pi;

end
end
Mcw;
Fr;
Fz;
```

```
lp=3;
for iwinding=1:24;
rwindingmin=winding_r(iwinding)-winding_dr(iwinding)/2;
rwindingmax=winding_r(iwinding)+winding_dr(iwinding)/2;
zwindingmin=winding_z(iwinding)-winding_dz(iwinding)/2;
zwindingmax=winding_z(iwinding)+winding_dz(iwinding)/2;

[rwinding,zwinding]=filamentize(rwindingmin,rwindingmax,zwindingmin,zwindingm
ax, mz(iwinding)*2^(lp-1),nr(iwinding)*2^(lp-1));

for jwinding=1:24;

rwindingminj=winding_r(jwinding)-winding_dr(jwinding)/2;
rwindingmaxj=winding_r(jwinding)+winding_dr(jwinding)/2;
zwindingminj=winding_z(jwinding)-winding_dz(jwinding)/2;
zwindingmaxj=winding_z(jwinding)+winding_dz(jwinding)/2;
[rhoj,zetaj]=filamentize_corners(rwindingminj,rwindingmaxj,zwindingminj,zwind
ingmaxj,mz(jwinding)*2^(lp-1),nr(jwinding)*2^(lp-1) );

[br,bz,flux]=poloidal_fieldy(rhoj,zetaj,rwinding,zwinding);

Mcw(iwinding,jwinding,lp)= mean(mean((flux(1:end-1,1:end-1)+flux(2:end,1:end-
1)+flux(1:end-1,2:end)+flux(2:end,2:end))/4)');
rhojbz=rhoj.*bz;

Fr(iwinding,jwinding,lp)=+2*pi*mean(mean((rhojbz(1:end-1,1:end-1)
+rhojbz(2:end,1:end-1)+rhojbz(1:end-1,2:end)+rhojbz(2:end,2:end))/4)');
rhojbr=rhoj.*br;

Fz(iwinding,jwinding,lp)=-2*pi*mean(mean( (rhojbr(1:end-1,1:end-
1)+rhojbr(2:end,1:end-1)+rhojbr(1:end-1,2:end)+rhojbr(2:end,2:end))/4)');

r1=(rhoj(1:end-1,1:end-1)+rhoj(2:end,1:end-1))/2;
r2=(rhoj(1:end-1,2:end)+rhoj(2:end,2:end))/2;
z1=(zetaj(1:end-1,1:end-1)+zetaj(1:end-1,2:end))/2;
z2=(zetaj(2:end,1:end-1)+zetaj(2:end,2:end))/2;

Br_avg=(br(1:end-1,1:end-1)+br(2:end,1:end-1) +br(1:end-
1,2:end)+br(2:end,2:end))/4;

Br_dif=(-br(1:end-1,1:end-1)-br(2:end,1:end-1)+br(1:end-
1,2:end)+br(2:end,2:end))/4;

Bz_avg=+(bz(1:end-1,1:end-1)+bz(2:end,1:end-1)+bz(1:end-
1,2:end)+bz(2:end,2:end))/4;

Bz_dif=+(-bz(1:end-1,1:end-1)-bz(2:end,1:end-1)+bz(1:end-
1,2:end)+bz(2:end,2:end))/4;

rc=winding_r(jwinding);
zc=winding_z(jwinding);

T1(iwinding,jwinding,lp)=mean(mean( ( Br_avg .*((r1+r2)/2-rc)
+Bz_avg.*((z1+z2)/2-zc) ) .* (r1+r2)/2)')*2*pi;

end
```

```
end
Mcw;
Fr;
Fz;


lp=4;
for iwinding=1:24;
rwindingmin=winding_r(iwinding)-winding_dr(iwinding)/2;
rwindingmax=winding_r(iwinding)+winding_dr(iwinding)/2;
zwindingmin=winding_z(iwinding)-winding_dz(iwinding)/2;
zwindingmax=winding_z(iwinding)+winding_dz(iwinding)/2;

[rwinding,zwinding]=filamentize(rwindingmin,rwindingmax,zwindingmin,zwindingm
ax, mz(iwinding)*2^(lp-1),nr(iwinding)*2^(lp-1));

for jwinding=1:24;

rwindingminj=winding_r(jwinding)-winding_dr(jwinding)/2;
rwindingmaxj=winding_r(jwinding)+winding_dr(jwinding)/2;
zwindingminj=winding_z(jwinding)-winding_dz(jwinding)/2;
zwindingmaxj=winding_z(jwinding)+winding_dz(jwinding)/2;
[rhoj,zetaj]=filamentize_corners(rwindingminj,rwindingmaxj,zwindingminj,zwind
ingmaxj,mz(jwinding)*2^(lp-1),nr(jwinding)*2^(lp-1) );

[br,bz,flux]=poloidal_fieldy(rhoj,zetaj,rwinding,zwinding);

Mcw(iwinding,jwinding,lp)= mean(mean((flux(1:end-1,1:end-1)+flux(2:end,1:end-
1)+flux(1:end-1,2:end)+flux(2:end,2:end))/4)');

rhojbz=rhoj.*bz;

Fr(iwinding,jwinding,lp)=+2*pi*mean(mean((rhojbz(1:end-1,1:end-1)
+rhojbz(2:end,1:end-1)+rhojbz(1:end-1,2:end)+rhojbz(2:end,2:end))/4)');
rhojbr=rhoj.*br;

Fz(iwinding,jwinding,lp)=-2*pi*mean(mean( (rhojbr(1:end-1,1:end-
1)+rhojbr(2:end,1:end-1)+rhojbr(1:end-1,2:end)+rhojbr(2:end,2:end))/4)');

r1=(rhoj(1:end-1,1:end-1)+rhoj(2:end,1:end-1))/2;
r2=(rhoj(1:end-1,2:end)+rhoj(2:end,2:end))/2;
z1=(zetaj(1:end-1,1:end-1)+zetaj(1:end-1,2:end))/2;
z2=(zetaj(2:end,1:end-1)+zetaj(2:end,2:end))/2;

Br_avg=(br(1:end-1,1:end-1)+br(2:end,1:end-1) +br(1:end-
1,2:end)+br(2:end,2:end))/4;

Br_dif=(-br(1:end-1,1:end-1)-br(2:end,1:end-1)+br(1:end-
1,2:end)+br(2:end,2:end))/4;

Bz_avg=+(bz(1:end-1,1:end-1)+bz(2:end,1:end-1)+bz(1:end-
1,2:end)+bz(2:end,2:end))/4;

Bz_dif=+(-bz(1:end-1,1:end-1)-bz(2:end,1:end-1)+bz(1:end-
1,2:end)+bz(2:end,2:end))/4;
```

```
rc=winding_r(jwinding);
zc=winding_z(jwinding);

T1(iwinding,jwinding,lp)=mean(mean( ( Br_avg .*((r1+r2)/2-rc)
+Bz_avg.*((z1+z2)/2-zc) ) .* (r1+r2)/2)')*2*pi;

end
end
Mcw;
Fr;
Fz;



Mturns=Mcw;
for lp=1:4;
Mturns(:,:,lp)=diag(winding_mn)*Mcw(:,:,lp)*diag(winding_mn);
end
L_refined=zeros(14,14,4);
CoilCircuits=[
1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1
];
for lp=1:4;
L_refined(:,:,lp)=CoilCircuits*Mturns(:,:,lp)*CoilCircuits';
end
format long g
Frturns=Fr(:,:,1:4);Fzturns=Fz(:,:,1:4);
for lp=1:4;
Frturns(:,:,lp)=diag(winding_mn)*Fr(:,:,lp)*diag(winding_mn);
Frturns_ckts(:,:,lp)=CoilCircuits*Frturns(:,:,lp);
Frturns_ckts_lbs=Frturns_ckts*0.224808943;
Fzturns(:,:,lp)=diag(winding_mn)*Fz(:,:,lp)*diag(winding_mn);
Fzturns_ckts(:,:,lp)=CoilCircuits*Fzturns(:,:,lp);
Fzturns_ckts_lbs=Fzturns_ckts*0.224808943;
T1turns(:,:,lp)=diag(winding_mn)*T1(:,:,lp)*diag(winding_mn);
end
ckt_name=coil_name([1 2 3 4 6 8 12 16 18 20 21 22 23 24])
T=zeros(14,24,4);
for lp=1:4;
T(:,:,lp)=CoilCircuits*T1turns(:,:,lp);
end
```

```
ckt_name =
    'PF1AU'
    'PF1BU'
    'PF1CU'
    'PF2U'
    'PF3U'
    'PF4'
    'PF5'
    'PF3L'
    'PF2L'
    'PF1CL'
    'PF1BL'
    'PF1AL'
    'OH'
    'PLASMA'
```

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Windings in Coil Circuits'}, 'CoilCircuits', 'A1')
xlswrite('F:\Documents\NSTXCSUGstuff\Magnetics_Feb2010Design.xls',{'CC Table
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xlswrite('F:\Documents\NSTXCSUGstuff\Magnetics_Feb2010Design.xls',{'CIRCUITS'
}, 'CoilCircuits', 'B4')
xlswrite('F:\Documents\NSTXCSUGstuff\Magnetics_Feb2010Design.xls',{'WINDINGS'
}, 'CoilCircuits', 'A5')
xlswrite('F:\Documents\NSTXCSUGstuff\Magnetics_Feb2010Design.xls', ckt_name',
'CoilCircuits', 'B5:O5')
xlswrite('F:\Documents\NSTXCSUGstuff\Magnetics_Feb2010Design.xls',
winding_name, 'CoilCircuits', 'A6:A29')
xlswrite('F:\Documents\NSTXCSUGstuff\Magnetics_Feb2010Design.xls',
CoilCircuits','CoilCircuits', 'B6:O29')
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Warning: Added specified worksheet.
> In xlswrite>activate_sheet at 269
  In xlswrite at 228
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xlswrite('F:\Documents\NSTXCSUGstuff\Magnetics_Feb2010Design.xls',{'lp=4 High
Precision Magnetics Results:(171712 tiles representing windings)'}, 'L;lp=4',
'A1')

xlswrite('F:\Documents\NSTXCSUGstuff\Magnetics_Feb2010Design.xls',{'L4 Table
1: Mutual Inductance Matrix Between Circuits-Sanitized Symmetric'}, 'L;lp=4',
'A3')
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xlswrite('F:\Documents\NSTXCSUGstuff\Magnetics_Feb2010Design.xls', ckt_name,
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xlswrite('F:\Documents\NSTXCSUGstuff\Magnetics_Feb2010Design.xls',
L_refined(:,:,4), 'L;lp=4', 'B22:O35')

xlswrite('F:\Documents\NSTXCSUGstuff\Magnetics_Feb2010Design.xls',{'L4 Table
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'A37')
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winding_name, 'L;lp=4', 'A39:A62')
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winding_name,'Fz;lp=4','A36:A59')
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T(:,:,4)','M;lp=4', 'B6:O29')
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Warning: Added specified worksheet.
> In xlswrite>activate_sheet at 269
  In xlswrite at 228
Warning: Added specified worksheet.
> In xlswrite>activate_sheet at 269
  In xlswrite at 228
Warning: Added specified worksheet.
> In xlswrite>activate_sheet at 269
  In xlswrite at 228
Warning: Added specified worksheet.
> In xlswrite>activate_sheet at 269
  In xlswrite at 228
```

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xlswrite('F:\Documents\NSTXCSUGstuff\Magnetics_Feb2010Design.xls',{'lp=3
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'A3')
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winding_name,'Fz;lp=3','A36:A59')
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Warning: Added specified worksheet.
> In xlswrite>activate_sheet at 269
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  In xlswrite at 228
Warning: Added specified worksheet.
> In xlswrite>activate_sheet at 269
  In xlswrite at 228
Warning: Added specified worksheet.
> In xlswrite>activate_sheet at 269
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Warning: Added specified worksheet.
> In xlswrite>activate_sheet at 269
  In xlswrite at 228
```

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lp=4 High Precision Magnetics Results:(171712 tiles representing windings)

M4 Table 1: Moment Coefficients (Newton-metera per A^2)

	CIRCUITS													
WINDINGS	PF1AU	PF1BU	PF1CU	PF2U	PF3U	PF4	PF5	PF3L	PF2L	PF1CL	PF1BL	PF1AL	OH	PLASMA
PF1AU	1.72E-20	0.000448	0.000123	6.6E-05	1.07E-07	-8.7E-06	-1.1E-05	-1.7E-06	-4.4E-07	-1.7E-07	-1.5E-07	-2.6E-07	-4.5E-05	-3.8E-07
PF1BU	3.89E-05	-1.7E-20	3.07E-06	4.76E-06	-9.3E-07	-8.1E-07	-9.9E-07	-1.2E-07	-3.3E-08	-1.3E-08	-1.1E-08	-1.8E-08	-2.6E-06	-2.4E-08
PF1CU	7.02E-06	1.92E-06	-5.5E-21	8.62E-06	-8.7E-07	-6E-07	-7.1E-07	-8.5E-08	-2.2E-08	-8.5E-09	-7.4E-09	-1.2E-08	3.72E-07	-1.6E-08
PF2AU	-1.3E-06	-1.3E-06	-3.4E-06	2.62E-06	1.67E-06	4.91E-07	5.7E-07	5.88E-08	1.5E-08	5.69E-09	4.95E-09	7.88E-09	-8.1E-07	8.68E-09
PF2BU	-1.3E-06	-6E-07	-1.5E-06	-2.6E-06	1.49E-06	5.26E-07	6.06E-07	6.31E-08	1.61E-08	6.13E-09	5.35E-09	8.55E-09	-5.9E-07	9.71E-09
PF3AU	-3.9E-08	1.37E-07	2.09E-07	1.34E-06	3.92E-06	1.9E-06	2.03E-06	1.31E-07	3.1E-08	1.11E-08	9.53E-09	1.38E-08	-2.8E-07	1.72E-09
PF3BU	3.46E-08	1.87E-07	2.75E-07	1.44E-06	-3.9E-06	2.33E-06	2.32E-06	1.39E-07	3.27E-08	1.17E-08	1E-08	1.45E-08	-2.4E-07	3.68E-10
PF4BU	1.05E-08	6.94E-09	8.21E-09	2.07E-08	8.58E-08	-1.4E-06	1.81E-06	1.13E-08	2.08E-09	6.06E-10	4.77E-10	3.69E-10	-2.6E-09	-2E-09
PF4CU	2.78E-08	1.96E-08	2.36E-08	6.31E-08	3.34E-07	-3E-06	3.42E-06	2.8E-08	5.33E-09	1.6E-09	1.28E-09	1.14E-09	-8.8E-09	-6.2E-09
PF4BL	-3.7E-10	-4.8E-10	-6.1E-10	-2.1E-09	-1.1E-08	1.37E-06	-1.8E-06	-8.6E-08	-2.1E-08	-8.2E-09	-6.9E-09	-1.1E-08	2.58E-09	1.98E-09
PF4CL	-1.1E-09	-1.3E-09	-1.6E-09	-5.3E-09	-2.8E-08	3.02E-06	-3.4E-06	-3.3E-07	-6.3E-08	-2.4E-08	-2E-08	-2.8E-08	8.83E-09	6.16E-09
PF5AU	3.92E-08	2.56E-08	3.01E-08	7.79E-08	4.04E-07	6.11E-06	1.57E-06	3.69E-08	4.72E-09	5.76E-10	1.98E-10	-2.1E-09	-1.4E-08	-6E-09
PF5BU	3.71E-08	2.32E-08	2.71E-08	6.77E-08	3.18E-07	4.2E-06	-1.2E-06	3.49E-08	3.7E-09	6.69E-11	-2.7E-10	-3.1E-09	-1.1E-08	-5.1E-09
PF5AL	2.12E-09	-2E-10	-5.8E-10	-4.7E-09	-3.7E-08	-6.1E-06	-1.6E-06	-4E-07	-7.8E-08	-3E-08	-2.6E-08	-3.9E-08	1.37E-08	5.99E-09
PF5BL	3.08E-09	2.72E-10	-6.7E-11	-3.7E-09	-3.5E-08	-4.2E-06	1.21E-06	-3.2E-07	-6.8E-08	-2.7E-08	-2.3E-08	-3.7E-08	1.12E-08	5.11E-09
PF3BL	-1.4E-08	-1E-08	-1.2E-08	-3.3E-08	-1.4E-07	-2.3E-06	-2.3E-06	3.92E-06	-1.4E-06	-2.7E-07	-1.9E-07	-3.5E-08	2.41E-07	-3.7E-10
PF3AL	-1.4E-08	-9.5E-09	-1.1E-08	-3.1E-08	-1.3E-07	-1.9E-06	-2E-06	-3.9E-06	-1.3E-06	-2.1E-07	-1.4E-07	3.9E-08	2.84E-07	-1.7E-09
PF2LA	-7.9E-09	-5E-09	-5.7E-09	-1.5E-08	-5.9E-08	-4.9E-07	-5.7E-07	-1.7E-06	-2.6E-06	3.43E-06	1.33E-06	1.29E-06	8.13E-07	-8.7E-09
PF2LB	-8.5E-09	-5.3E-09	-6.1E-09	-1.6E-08	-6.3E-08	-5.3E-07	-6.1E-07	-1.5E-06	2.62E-06	1.54E-06	5.96E-07	1.32E-06	5.91E-07	-9.7E-09
PF1CL	1.22E-08	7.44E-09	8.5E-09	2.2E-08	8.46E-08	5.95E-07	7.14E-07	8.72E-07	-8.6E-06	-5.5E-21	-1.9E-06	-7E-06	-3.7E-07	1.57E-08
PF1BL	1.83E-08	1.11E-08	1.27E-08	3.27E-08	1.24E-07	8.07E-07	9.9E-07	9.31E-07	-4.8E-06	-3.1E-06	-1.7E-20	-3.9E-05	2.61E-06	2.45E-08
PF1AL	2.59E-07	1.54E-07	1.75E-07	4.44E-07	1.65E-06	8.74E-06	1.13E-05	-1.1E-07	-6.6E-05	-0.00012	-0.00045	1.72E-20	4.46E-05	3.77E-07
OH	0.036211	0.017744	0.009472	0.010114	0.007022	-6.5E-19	1.08E-18	-0.00702	-0.01011	-0.00947	-0.01774	-0.03621	5.06E-18	-6.3E-21
PL	2.25E-07	2.23E-07	2.75E-07	8.08E-07	3.85E-06	-5.9E-21	-8.5E-22	-3.9E-06	-8.1E-07	-2.8E-07	-2.2E-07	-2.2E-07	-7.5E-23	-1.4E-24