National Spherical Torus eXperiment Upgrade

NSTX-U

Pulse Currents and EM Forces During Power Testing of Inner PF Coils

NSTXU-CALC-131-09-00

Charles L. Neumeyer
Digitally signed by Charles L. Neumeyer
DN: cn=Charles L. Neumeyer, o=PPPL, ou, email=neumeyer@pppl.gov, c=US
Date: 2018.05.01 11:29:49 -04'00'

Prepared By
C. Neumeyer

Peter H. Titus
Digitally signed by Peter H. Titus
Date: 2018.05.01 12:51:45 -04'00'

Reviewer Appointed By – Analysis Technical Authority
P. Titus

Yuhu Zhai
Digitally signed by Yuhu Zhai
Date: 2018.05.01 13:13:49 -04'00'

Reviewed By
Y. Zhai

Mike Kalish
Digitally signed by Mike Kalish
Date: 2018.05.01 13:07:13 -04'00'

Approved By – Responsible Engineer
M. Kalish

NSTX-U CALCULATION
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Record of Changes

Rev.	Date	Description of Changes	Revised by
0	5/1/18	Initial Release	

1 Purpose of Calculation

The Inner PF Coils (one prototype and all production coils) will be power tested to satisfy DOE notable outcomes and to demonstrate ability to withstand pulse currents before installation in NSTX-U. The testing will be performed in the Field Coil Power Conversion (FCPC) building using a power supply circuit formed using standard FCPC components including a Transrex AC/DC converter and a DC Current Limiting Reactor (CLR). The coils will be installed on a Test Stand located in the PF Reactor Enclosure of the FCPC building.

The coils will be incrementally pulsed until they reach their rated current and temperature. The coils will produce a stray field and will be exposed to the stray field of the CLR. The stray field from the coils will interact with the reinforcing bar (rebar) in the concrete floor.

The purpose of this calculation is to:

- Develop a sequence of test pulses that meet the objectives
- Estimate the forces on the coils to confirm adequacy of the test stand and to determine requirements for attachment of coils to the test stand

2 References

[1] PF1A Prototype Coil Assembly, E-DC11053
[2] PF1A Coil Assembly, E-DC11102
[3] PF1B Coil Assembly, E-DC11100
[4] PF1C Coil Assembly, E-DC11101
[5] PF Coils Test Stand Assembly, E-DC11061
[6] PF1AU/CHI CWD, B-4F1005 sh. 1575
[7] Field Coil Power Conversion Building First Floor Framing Plan & Substation Foundation Plan & Sections, EMDRAC 6426-449
[8] Design Point Calculations for NSTX Center Stack Upgrade, NSTX-U-CALC-10-03-00
[9] PPPL Magnetics Library – ICC subroutine

3 Assumptions

3.1 Coil pulsing

- Use Design Point Spreadsheet (DPSS) G-function [8] for coil heating calculations based on adiabatic conductor heating

- Use DPSS hoop stress formula [8] for coil stress

- Assume Analog Coil Protection (ACP) in FCPC set to 5% over nominal targets for current and I2T

- Assume inlet water temperature 25^{o}C

3.2 Forces on coils

- Represent behavior of rebar in floor based on an image current flowing in an annulus with radius R and width dR same as coil under test, height dZ equal to the floor thickness, and Z = -1/2 of the floor thickness

- Estimate resistance of rebar current loop based on fraction of cross section of annulus filled by steel rebar material in direction of current flow

- Estimate radial field produced by rebar current loop over coil winding pack based on a dipole moment at the center of the image current loop

- Estimate radial field produced by CLR over coil winding pack based on a dipole moment at the center of the CLR

- Assume 2kV power supply voltage minus circuit resistive voltage drop at full current applied to circuit inductance to determine rate of change of coil current

- Neglect effect of rebar current loop on circuit inductance

- Neglect ferromagnetic effect of rebar (conservative, would tend to offset repulsive force)

- Assume resistive solution for current in rebar loop

- Compute coil forces based on full current in coil and rebar loop current driven by maximum available inductive voltage at full load current

4 Calculation

Calculations are performed using XL sheet “Inner_PF_Testing_180501.xlsx”.

4.1 Power testing pulse currents

The basic strategy for power testing is as follows.
Initial pulse sequence, first prototype coil, all production coils:

Pulse 1: 1/3 hoop stress, low heating, 1kV, 100mS ramp
Pulse 2: 2/3 hoop stress, low heating, 1kV, 100mS ramp
Pulse 3: full hoop stress, 1/3 heating, 1kV, 100mS ramp
Pulse 4: full hoop stress, 2/3 heating, 1kV, 100mS ramp
Pulse 5: full hoop stress, full heating, 1kV, 100mS ramp

Repeated pulse train (20 pulses) production coils only:

Pulse 6: full hoop stress, full heating, 2kV, 25mS ramp

An example of the set of 6 pulses is given in **Figure 1.**

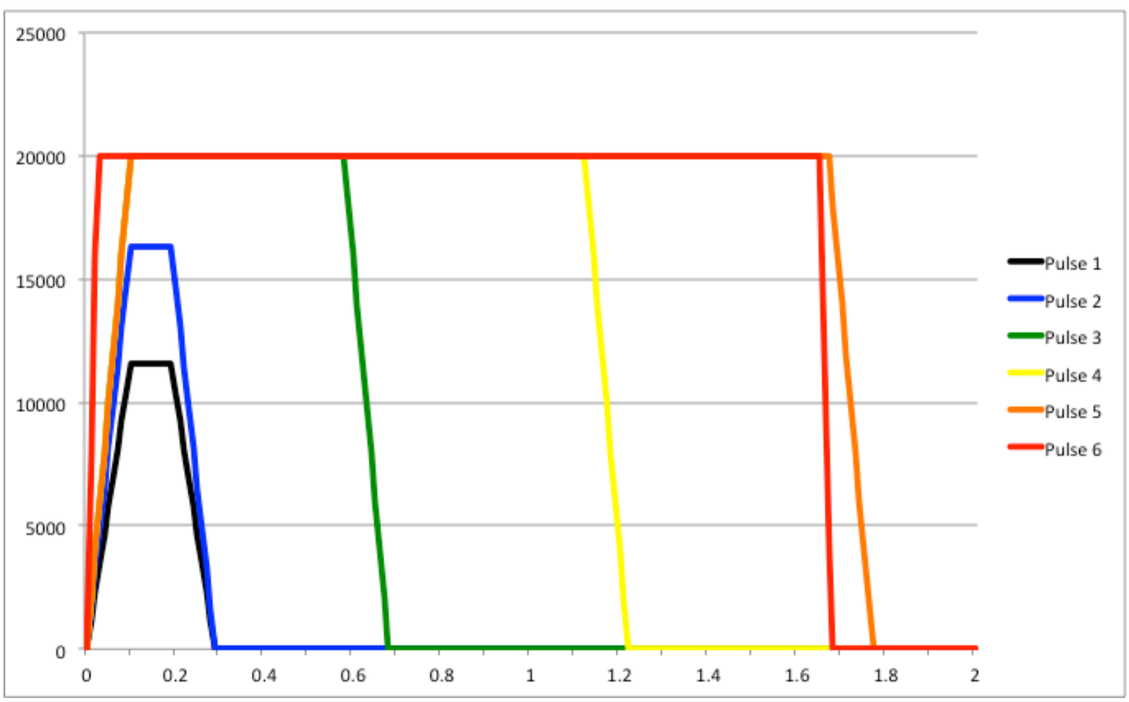


Figure 1 – Typical set of Power Testing pulses (Proto coil)

The “full heating” pulse will bring the coil to the same end-of-pulse conductor temperature that it is designed for in normal NSTX-U service. Since the FCPC cooling water temperature is 25^{o}C whereas the NSTX Test Cell cooling water is 12^{o}C, the temperature rise during these tests will be less than in service by 25 – 12 = 13^{o}C. The alternative would be to deliver the full I2T “action integral” and in doing so, allow the coil temperature during test to exceed its service temperature. This is judged imprudent, so the end-of-pulse temperature limit is chosen.

The full heating pulse is applied only once to the prototype coil, because it will not be equipped with a preload mechanism and is therefore not equipped to handle repetitive cooling waves. The current per turn is set to 20kA, slightly more than the PF1A production coil rating (19.67kA) but was the prototype coil design basis. The peak conductor temperature target is 60^{o}C which is consistent with the design basis of the PF1A production coil.

The “full hoop stress” pulse will bring the coil to a level of conductor hoop stress corresponding to the full rated current and the self-field of the coil, but in absence of a background magnetic field. Therefore the stress level during test will be less than that in service.

In the first set of 5 pulse waveforms, 100mS rise and fall times all are chosen. The power supply voltage required to drive the current waveform will be V = I*R + L*dI/dt, reaching a maximum during the ramp up, just prior to flat-top, when both I and dI/dt are maximum. As will be confirmed in the calculations, the available power supply voltage at 1kV is sufficient to drive the pulse. For the repetitive pulse waveform run at 2kV, 25mS rise and fall times are chosen such that a maximum available voltage is applied to the coil. Note that, in service, additional series filter inductors will absorb some of the power supply voltage so that voltages in excess of those during these tests is unlikely. Between the 1kV and 2kV modes a broad range of voltages, including 6-pulse and 12-pulse harmonics, are applied to the coils, well representative of service on NSTX-U.

With the pulse currents ~ 20kA, the apparent power demand will be ~ 1kV*20kA = 20MVA in pulses 1-5 and ~ 2kV*20kA = 40MVA in pulse 6. Although these levels should be available with direct pulsing of the grid, the use of one MG set is recommended for the 2kV, pulse 6 testing.

The test setup in FCPC includes an “Analog Coil Protection” (ACP) device that trips the power supplies on overcurrent and I2T. Settings of 1.05 above nominal rating will be used. Small excursions above design-basis coil temperature are possible and are calculated herein, assuming that the FCPC water is at the maximum allowable 25^{o}C.

If an overcurrent occurs then the hoop stress will go to $1.05^2 = 1.1$ over the intended test rating but this is not an issue because design basis, that considers background fields, is considerably higher. Moreover, infrequent overloads are allowed by the design criteria.

Calculations of pulse current waveform parameters are performed on the XL worksheets "Proto_Pulsing", "PF1A_Pulsing", "PF1B_Pulsing" and "PF1C_Pulsing". The methodology and equations are the same as used in the DPSS calculations [8]. Yellow cells are inputs. The values of flat top current to achieve 1/3 and 2/3 hoop stress are automatically calculated. The values flat top durations are calculated for the full heating case using the XL "goal seek" to set the target cells (green color) to the desired temperature. The flat top duration for the 1/3 and 2/3 heating cases is calculated such that the total waveform I2T for those cases is 1/3 and 2/3 of the full heating case.

A summary of the test pulse parameters is given in Table 1.

Table 1 – Power Testing Pulse Parameters

	Pulse No.	**1**	**2**	**3**	**4**	**5**	**6**
	NS	1	1	1	1	1	2
Proto	I_ft (amp)	11547	16330	20000	20000	20000	20000
	t_ft (sec)	0.100	0.100	0.480	1.027	1.574	1.630
	ESW (sec)	0.233	0.233	0.740	1.469	2.198	2.198
	t1 (sec)	0.100	0.100	0.100	0.100	0.100	0.025
	t2 (sec)	0.200	0.200	0.580	1.127	1.674	1.655
	t3 (sec)	0.300	0.300	0.680	1.227	1.774	1.680
	T_max (°C)	26	27	36	48	60	60
PF1A	I_ft (amp)	11358	16062	19672	19672	19672	19672
	t_ft (sec)	0.100	0.100	0.272	0.611	0.950	1.006
	ESW (sec)	0.233	0.233	0.463	0.915	1.367	1.367
	t1 (sec)	0.100	0.100	0.100	0.100	0.100	0.025
	t2 (sec)	0.200	0.200	0.372	0.711	1.050	1.031
	t3 (sec)	0.300	0.300	0.472	0.811	1.150	1.056
	T_max (°C)	27	29	36	48	60	60
PF1B	I_ft (amp)	11547	16330	20000	20000	20000	20000
	t_ft (sec)	0.100	0.100	0.137	0.341	0.546	0.602
	ESW (sec)	0.233	0.233	0.283	0.555	0.827	0.827
	t1 (sec)	0.100	0.100	0.100	0.100	0.100	0.025
	t2 (sec)	0.200	0.200	0.237	0.441	0.646	0.627
	t3 (sec)	0.300	0.300	0.337	0.541	0.746	0.652
	T_max (°C)	31	37	48	71	97	97
PF1C	I_ft (amp)	11547	16330	20000	20000	20000	20000
	t_ft (sec)	0.100	0.100	0.138	0.343	0.548	0.604
	ESW (sec)	0.233	0.233	0.284	0.558	0.831	0.831
	t1 (sec)	0.100	0.100	0.100	0.100	0.100	0.025
	t2 (sec)	0.200	0.200	0.238	0.443	0.648	0.629
	t3 (sec)	0.300	0.300	0.338	0.543	0.748	0.654

	T_max (°C)	27	28	32	38	45	45

4.2 Forces

4.2.1 Rebar model

As shown in Figure 2 the coil under test is mounted to a test stand that is mounted to the floor in the PF Reactor Area of the FCPC building.

Figure 2 – Test set up

(Note floor markings showing rebar pattern based on eddy current tester)

Based on the FCPC architectural drawing [7] the FCPC floor consists of a 8” thick slab with two layers of rebar. See Figure 3 for excerpt from drawing.

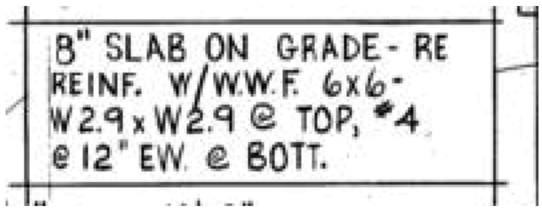


Figure 3 – Rebar spec from drawing

This translates to the following[1,2]:

- WWF 6 x 6 - W2.9 x W2.9 is a call-out for woven wire fabric with 6” x 6” grid spacing and wire size with cross section of 29 hundredths square inches

- #4 @ 12” is a call-out for a grid formed by #4 size rebar with a 12” x 12” spacing

The diameter of the wire in the WWF works out to 0.192” while the #4 rebar is 0.5” diameter. To simulate the resistance of the rebar current loops an average resistivity is calculated based on the net effect of individual rebar wires over an 8” x 12” grid section as depicted in Figure 4.

[1] Woven wire fabric https://en.wikipedia.org/wiki/Welded_wire_mesh
[2] Rebar wire sizes https://en.wikipedia.org/wiki/Rebar

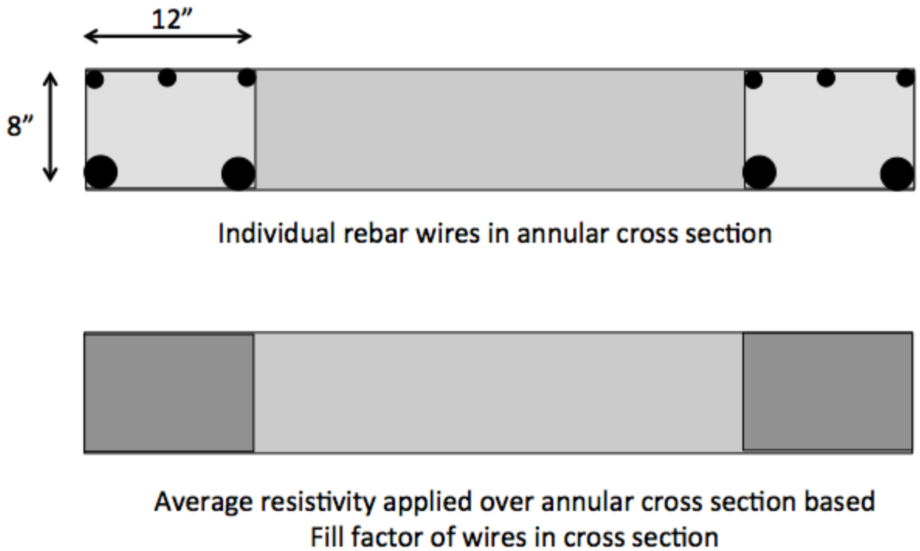


Figure 4 – Model used to approximate rebar loop resistivity

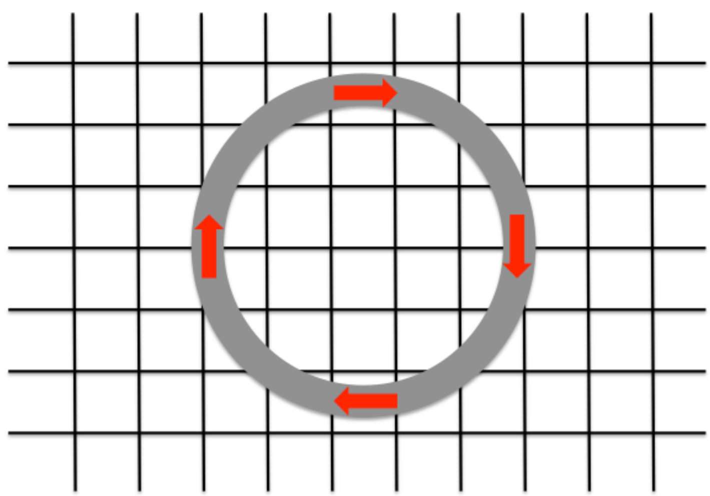


Figure 5 – Image current path through rebar grid

Per Figure 5, note that a circular current path would only align with the direction of the wires in the grid and four angles around the loop. At other angles the resistance would be higher because the current would flow along wires on both sides of the grid cells. The model shown in Figure 4 is therefore conservative because the actual current path would exhibit higher resistance than a path that is aligned with the grid. It also assumes that there is good electrical contact between all of the rebar wires which is certainly true for the wire fabric (WWF) but may not be true for the simple wire (W).

Calculation of the average resistivity across the section is given in XL worksheet “Rebar”, resulting in a value of 3.22E-05 ohm-m (as compared to the resistivity of steel which is 1.61E-07 ohm-m).

4.2.2 CLR model

The Current Limiting Reactor (CLR) designated EOH1-IND-2 is part of the load circuit [6] that is energized with the coil under test. Layout is shown in Figure 6. Per [6] , positive current enters terminal A2 and exits A1, flowing clockwise when viewed from above.

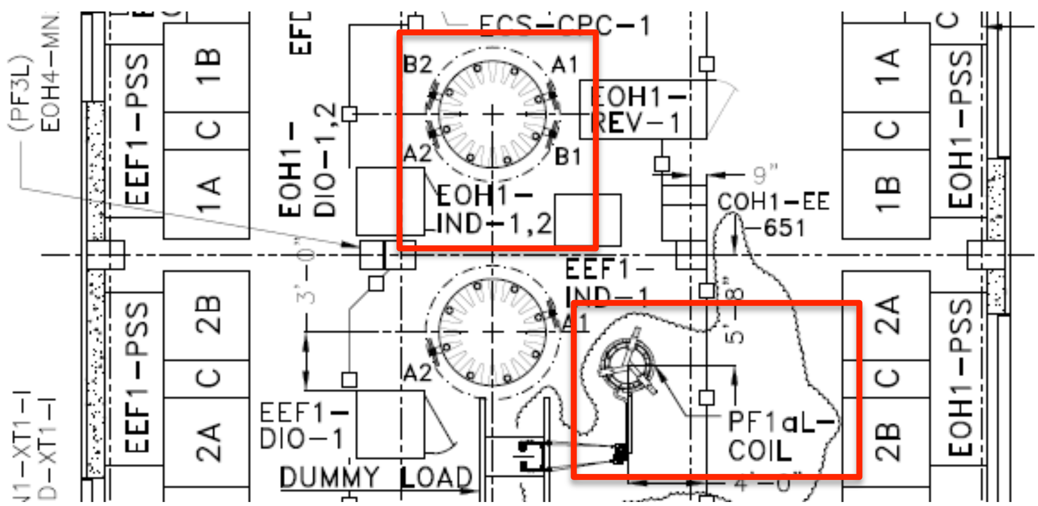
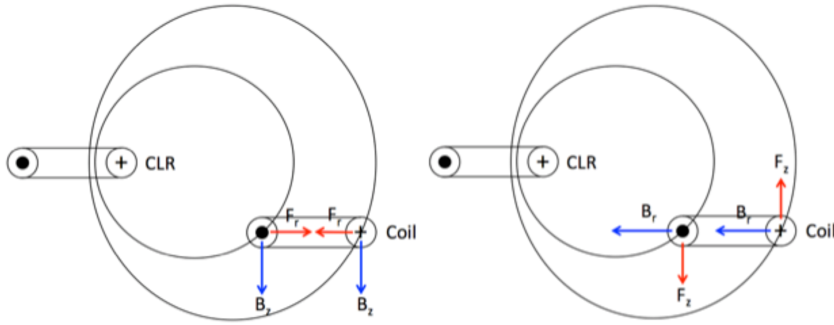


Figure 6 – Layout of CLR and coil under test

The CLR is a 265 microH, 1mOhm inductor. The dimensions are given in XL worksheet “CLR” (28 turns, current center of 0.350 m). The CLR midplane is 1.067 m above the floor, and the distance between vertical axes of the CLR and the coil under test is 4.5 m.

The radial field from the CLR interacts with the current in the test coil as follows:

- Adding or subtracting hoop stress per $F_{r\text{-}coil} = J_{coil} \times B_{z\_clr}$ depending on polarity of coil and CLR currents
- Creating a moment along the axis of the coil per $F_{z\text{-}coil} = J_{coil} \times B_{r\_clr}$ depending on offsets in elevation (z) of the coil current centers (if both at the same elevation there is no radial field from the CLR at the coil current center)



$F_r = J \times B_z$ $F_z = J \times B_r$

Figure 7 – CLR + Coil Interaction

The field is estimated based on the formula for magnetic field of a dipole moment in r, z coordinates[3] with reference to the center of the dipole:

$$M = \pi R^2 NI$$

$$\rho = \sqrt{r^2 + z^2}$$

$$B_r = \frac{\mu_0 M}{4\pi\rho^3}\frac{3\sin(2\theta)}{2}$$

$$B_z = \frac{\mu_0 M}{4\pi\rho^3}\frac{(1 - 3\cos(2\theta))}{2}$$

$$|B| = \frac{\mu_0 M}{4\pi\rho^3}\sqrt{(1 + 3\sin^2\theta)}$$

R = radius of current center
NI = amp-turns
θ = poloidal angle measured with respect to a horizontal plane

4.2.3 Overall configuration

Key dimensions are shown in Figure 8.

[3] Interaction of Tokamak Building Structures With ITER Magnetic Field, ITER_D_2FGN9P

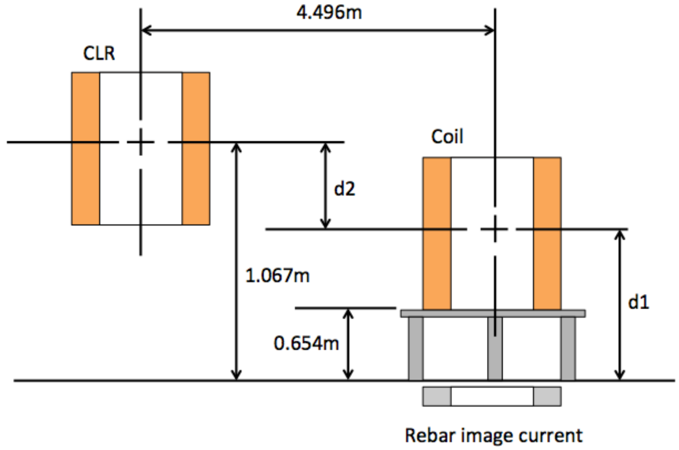


Figure 8 – Key dimensions

4.2.4 Estimation of current in rebar

See the XL worksheets "Proto_Forces", "PF1A_ Forces", "PF1B_ Forces" and "PF1C_ Forces".

The rebar current is estimated based on the mutual inductance between the image current and the coil under test, calculated by the PPPL Magnetics Library code ICC [9] and the resistance using the resistivity calculated per 4.2.1. The dimension of the annulus is set to the width (dR) of the coil and the depth (dZ) of the concrete with the radius (R) of the current center set to the radius of the coil.

The voltage applied to the rebar loop is calculated as follows where M is the mutual inductance between the coil and the rebar loop, V_{ps} is the maximum power supply voltage, I_{coil} is the current in the coil, and R_{loop} and L_{loop} are the inductance and resistance of the power supply circuit.

$$V_{rebar} = M * \frac{dI_{coil}}{dt} = M * \frac{V_{ps} - I_{coil} R_{loop}}{L_{loop}}$$

Then the rebar current is calculated simply as V_{rebar}/R_{rebar}, based on the conservative assumption that the time constant of the rebar loop is very short.

4.2.5 Estimate of forces on coil

See the XL worksheets "Proto_Forces", "PF1A_ Forces", "PF1B_ Forces" and "PF1C_ Forces".

The vertical force (upward) on the coil due to the current in the rebar loop is calculated as follows.

$$F_{z-coil-rebar} = \int J_{coil} B_{r-rebar}(z) dV_{coil}$$

Where $B_{r\text{-}rebar}(z)$ is the radial field from the rebar loop as a function of elevation (z) at the center of the coil winding pack, calculated using the dipole moment formula.

Interaction with the CLR produces insignificant forces owing to the large spacing between the coils. For example the |B| in the prototype coil bore due to the CLR is only 24mT, as compared to the self-field which is 3.5T (factor of 150x).

4.2.6 Summary of forces

A summary of the forces is given in Table 1.

Table 2 – Vertical Force Summary

	Proto	PF1A	PF1B	PF1C
Copper weight (lb)	-902	-702	-158	-325
Sling weight (lb)	0	-271	-74	0
Rebar force (lb)	82	82	155	493
Net force (lb)	-820	-891	-77	168

The prototype coil does not come with a sling assembly but the production coils will be equipped with their full support structure during testing. This additional weight will serve to reduce the net vertical force (launching load), but the weights are not known at the present time.

Small radial forces will exist due to the CLR and the leads and power cable connection, depending on they are routed and supported.

5 Conclusion

Results for the test pulses given in Table 1 provide guidance on how the tests should be conducted.

Since the prototype coil will not have a preload mechanism, the end-of-pulse temperatures given in Table 1 that will interact with the incoming cooling water at 20 ~ 25^{o}C should be assess from a cooling wave perspective. However, only one pulse is planned at the full level.

Estimate of forces indicates that launching loads will not exceed the dead weight of the coils with the possible exception of PF1C, depending on the weight of the sling assembly.