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SUBJECT: ASSUMPTIONS FOR LOAD COMPUTATIONS

This memo presents recommended assumptions for axial (including launching) load computations for toroidal current components, as well as toroidal load computations for axial current components. It is based on a manual procedure of deduction of worst case current combinations. A more rigorous determination, along with force calculations for the axial loads, based on an automated procedure considering all current combinations, will follow at a later date.

Conservative assumptions are made herein. If these lead to unmanageable forces then they can be reconsidered.

Axial loads arise from J x B forces due to toroidal current components and radial field components. Toroidal loads arise from J x B forces due to axial current components and radial field components.

In the NSTX poloidal field magnet system an axial force will be experienced by each turn carrying a toroidal current due to the local radial field in which it is immersed. The local field results from the self-field of magnet as well as the field generated by the other magnets.

The self-field produces axial compression on the magnet due to the radial component of the field as it exits the bore. The field generated by the other magnets may have either polarity relative to the self-field and will therefore serve to either increase or decrease the axial compression. In the latter case the field due to the other magnets could result in axial tension in regions of the magnet.

The net axial force on an individual magnet is due to the sum of the forces on the individual turns. The forces due to the self-field which compress the magnet turns have a zero net value. Thus the net force on an individual magnet is due only to the interaction with the net field produced by the other magnets. This net force may be directed upward or downward depending on the current and field directions. The "launching load" case is that in which the net force on a magnet is directed away from the mid plane, presumably upwards in order to "launch".

The NSTX toroidal field magnets have axial components of current which will react with radial field components causing toroidal forces, e.g. at the top of the inner leg bundle ("torsional force") and at the outer legs. Thus the assumptions used to identify the worst case radial field for the axial load computations for the poloidal field magnets can be extended to the determination of the worst case radial field for the toroidal load computations for the toroidal field magnets.

In principle any combination of circuit currents within the envelope permitted by the protection scheme is possible. For NSTX the protection scheme will likely consist of a simple limit on instantaneous current magnitude in each circuit, unless the need for a more sophisticated scheme is identified.

In practice the machine will be operated as required to produce the required plasma scenarios, but operator errors and control equipment malfunctions will lead to misoperations in which one or more coil circuits are driven by the power supplies to their protection limits. The likelihood that all circuits would be driven to their protection limits simultaneously will be exceedingly small, as long as no common mode failure mechanism is present. So, a reasonable set of conditions to consider in determining worst case loads lies somewhere between the nominal scenarios predicted by physics calculations and the extreme case where all circuits operate at their protection limit.

The present design of NSTX consists of the following circuits each of which may have a unique current of either polarity up to the magnitude indicated.

Circuit	u=upper/ l=lower	#turns above/below mid plane	max lkA/ turnl	max lkA-turnl
OH	u+l	476	24.0	11424.0
PF1a	u	48	10.0	480.0
PF1a	l	48	10.0	480.0
PF1b	l	36	15.0	540.0
PF2a	u+l	14	20.0	280.0
PF2b	u	14	20.0	280.0
PF2b	l	14	20.0	280.0
PF3a	u+l	15	20.0	300.0
PF3b	u	15	20.0	300.0
PF3b	l	15	20.0	300.0
PF4(a+b+c)	u+l	22	20.0	440.0

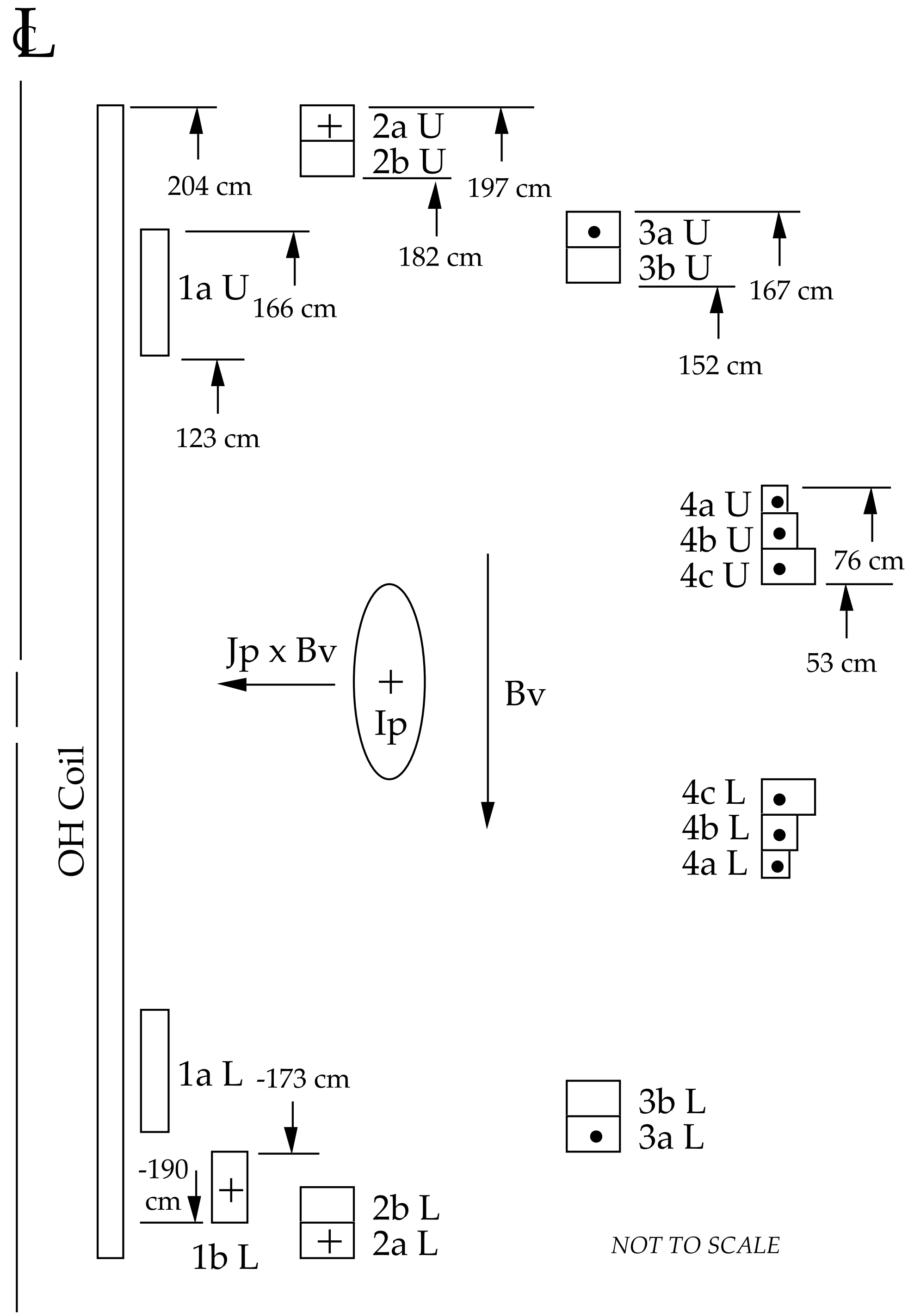
For any magnet, worst case circuit current distributions could be identified which would produce worst case 1) internal compression, 2) internal tension, 3) net force towards the mid plane and 4) net force away from the mid plane. Depending on circumstances there could be four unique current distributions associated with these four cases.

Simplifying assumptions are required in order to reduce the problem to a small set of cases which cover the main areas of mechanical design concern and are limited to reasonably probable misoperations.

As a start, it will be assumed that the relative polarity of a subset of the circuits is fixed as required for plasma operation for a given plasma current polarity. The polarity of these circuits is given in the following figure for the case of a negative plasma current polarity (counterclockwise viewed from above). A (+) symbol indicates current into the page and a (•) symbol current out of the page.

The polarity of the PF4 circuit is fixed since it is required to produce a downward vertical field and inward radial force on the plasma. The polarities of the PF2a and PF3a circuits are fixed since they contribute to the vertical field as they perform their shaping functions (this is confirmed by a review of the equilibria thus far calculated for double null and natural divertor plasma configurations). The polarity of the PF1b circuit is fixed due to its role in shaping the field near the single null X-point as required for CHI.

The polarity of OH cannot be fixed since it is bipolar and a plasma may exist with either OH polarity. The polarity of the PF1a upper and lower circuits may vary depending on the plasma shaping requirement. The polarity of the PF2b and PF3b circuits will vary depending on whether the plasma has an X-point configuration and on the manner in which the radial field, vertical position control is accomplished.



℄
OH Coil
2a U
2b U
204 cm
197 cm
182 cm
3a U
3b U
167 cm
1a U
166 cm
152 cm
123 cm
4a U
4b U
4c U
76 cm
53 cm
Jp x Bv
Ip
Bv
4c L
4b L
4a L
1a L
-173 cm
3b L
3a L
-190 cm
2b L
2a L
1b L
NOT TO SCALE

The following cases are proposed to cover the main areas of mechanical design concern.

1) OH maximum net upward force

2) OH maximum net downward force

3) OH maximum internal compression

4) OH maximum internal tension

5) PF1a maximum net force toward mid plane

6) PF1a maximum net force away from mid plane

7) PF1b maximum net force toward mid plane

8) PF1b maximum net force away from mid plane

9) PF2 (a + b) maximum net force toward mid plane

10) PF2 (a + b) maximum net force away from mid plane

11) PF3 (a + b) maximum net force toward mid plane

12) PF3 (a + b) maximum net force away from mid plane

13) PF4 (a + b + c) maximum net force toward mid plane

14) PF4 (a + b + c) maximum net force away from mid plane

15) Maximum force between subcoils within outer PF coil groups PF2 and PF3

16) Maximum force between subcoils within outer PF coil group PF4

17) Maximum torsional force on TF inner leg bundle

18) Maximum toroidal force on TF outer leg bundle at mid plane

The following is a discussion and proposed set of circuit currents for each case. For all currents the positive sense is clockwise viewed from above.

1) OH maximum net upward force

Since the OH coil turns are uniformly distributed above and below the mid plane, equal and opposite forces will arise from all circuits which are symmetric about the mid plane, so that these circuits need not be considered. Therefore the PF2a, PF3a, and PF4 circuit status is not relevant.

Circuit	u=upper/ l=lower	#turns above/below mid plane	kA/turn	kA-turn
OH	u+l	476	24.0	11424.0
PF1a	u	48	10.0	0.0
PF1a	l	48	-10.0	0.0
PF1b	l	36	-15.0	-540.0
PF2a	u+l	14	0.0	0.0
PF2b	u	14	20.0	0.0
PF2b	l	14	-20.0	0.0
PF3a	u+l	15	0.0	0.0
PF3b	u	15	20.0	0.0
PF3b	l	15	-20.0	0.0
PF4(a+b+c)	u+l	22	0.0	0.0

To the extent that the plasma current centroid is below the mid plane it will contribute to the net upward force on the OH coil. Based on guidance from physics the plasma should be modeled as a filament with Ip = -1.0 MA, r=91.5 cm and z=-21.7 cm.

2) OH maximum net downward force

Assumptions for this case are the same as 1) except with opposite OH polarity.

3) OH maximum internal compression

Worst case compressive forces on the OH solenoid will result from maximum radial field contribution from the other coils at the ends of the solenoid in the same direction as the self-field.

Worst case will occur at the bottom of the OH coil (due to the presence of PF1b) with all coil currents in the same direction as Ioh. PF3a and PF4 currents are assumed zero since they would be of opposite sign and would reduce the force in question. Assume Ip = -1.0 MA r=91.5 cm and z=-21.7 cm.

Circuit	u=upper/ l=lower	#turns above/below mid plane	kA/turn	kA-turn
OH	u+l	476	-24.0	-11424.0
PF1a	u	48	-10.0	-480.0
PF1a	l	48	-10.0	-480.0
PF1b	l	36	-15.0	-540.0
PF2a	u+l	14	-20.0	-280.0
PF2b	u	14	-20.0	-280.0
PF2b	l	14	-20.0	-280.0
PF3a	u+l	15	0.0	0.0
PF3b	u	15	-20.0	0.0
PF3b	l	15	-20.0	0.0
PF4(a+b+c)	u+l	22	0.0	0.0

4) OH maximum internal tension

Assumptions for this case are the same as 3) except with opposite OH polarity.

5) PF1a maximum net force toward mid plane

Assumptions for this case are given below. Worst case occurs on PF1a, lower, due to the presence of PF1b. Forces from PF3 and PF4 are ignored. PF3a, PF4, and Ip are assumed zero because they would tend to reduce the force, given the nominal polarity assumptions.

Circuit	u=upper/ l=lower	#turns above/below mid plane	kA/turn	kA-turn
OH	u+l	476	24.0	11424.0
PF1a	u	48	10.0	480.0
PF1a	l	48	10.0	480.0
PF1b	l	36	-15.0	-540.0
PF2a	u+l	14	-20.0	-280.0
PF2b	u	14	20.0	280.0
PF2b	l	14	-20.0	-280.0
PF3a	u+l	15	0.0	0.0
PF3b	u	15	0.0	0.0
PF3b	l	15	0.0	0.0
PF4(a+b+c)	u+l	22	0.0	0.0

6) PF1a maximum net force away from mid plane

Assumptions for this case are the same as 5) except with opposite PF1a polarity.

7) PF1b maximum net force toward mid plane

Force is due to attraction to OH coil, PF1a, and plasma all with the same polarity as PF1b. PF2a, PF3a, and PF4 would, with nominal polarity, reduce the force so their currents are assumed zero. Assume Ip = -1.0 MA r=91.5 cm and z=-21.7 cm.

Circuit	u=upper/ l=lower	#turns above/below mid plane	kA/turn	kA-turn
OH	u+l	476	-24.0	-11424.0
PF1a	u	48	-10.0	-480.0
PF1a	l	48	-10.0	-480.0
PF1b	l	36	-15.0	-540.0
PF2a	u+l	14	0.0	0.0
PF2b	u	14	-20.0	-280.0
PF2b	l	14	20.0	2800.0
PF3a	u+l	15	0.0	0.0
PF3b	u	15	-20.0	0.0
PF3b	l	15	-20.0	0.0
PF4(a+b+c)	u+l	22	0.0	0.0

8) PF1b maximum net force away from mid plane

Force is due to repulsion from OH and PF1a, and attraction to PF2, lower. If present Ip would be of the same polarity and would reduce the force, so it is assumed zero.

Circuit	u=upper/ l=lower	#turns above/below mid plane	kA/turn	kA-turn
OH	u+l	476	24.0	11424.0
PF1a	u	48	10.0	480.0
PF1a	l	48	10.0	480.0
PF1b	l	36	-15.0	-540.0
PF2a	u+l	14	-20.0	-280.0
PF2b	u	14	20.0	280.0
PF2b	l	14	-20.0	-280.0
PF3a	u+l	15	20.0	300.0
PF3b	u	15	20.0	300.0
PF3b	l	15	20.0	300.0
PF4(a+b+c)	u+l	22	20.0	440.0

9) PF2 (a + b) maximum net force toward mid plane

For PF2 the worst case will occur on the lower coil set) due to the presence of PF1b) under the following conditions. PF3a and PF4 currents are assumed zero since their current would reduce the force in question given the nominal polarity assumptions. Assume Ip = -1.0 MA r=91.5 cm and z=-21.7 cm

Circuit	u=upper/ l=lower	#turns above/below mid plane	kA/turn	kA-turn
OH	u+l	476	-24.0	-11424.0
PF1a	u	48	-10.0	-480.0
PF1a	l	48	-10.0	-480.0
PF1b	l	36	-15.0	-540.0
PF2a	u+l	14	-20.0	-280.0
PF2b	u	14	-20.0	-280.0
PF2b	l	14	-20.0	-280.0
PF3a	u+l	15	0.0	0.0
PF3b	u	15	-20.0	-300.0
PF3b	l	15	-20.0	-300.0
PF4(a+b+c)	u+l	22	0.0	0.0

10) PF2 (a + b) maximum net force away from mid plane

For PF2 the maximum force would result from the case where its current is in the opposite direction from all of the others. However, given the nominal polarity assumption the PF1b and plasma currents would be in the same direction, so they are assumed zero.

Circuit	u=upper/ l=lower	#turns above/below mid plane	kA/turn	kA-turn
OH	u+l	476	-24.0	-11424.0
PF1a	u	48	-10.0	-480.0
PF1a	l	48	-10.0	-480.0
PF1b	l	36	0.0	0.0
PF2a	u+l	14	-20.0	-280.0
PF2b	u	14	-20.0	-280.0
PF2b	l	14	-20.0	-280.0
PF3a	u+l	15	0.0	0.0
PF3b	u	15	-20.0	-300.0
PF3b	l	15	-20.0	-300.0
PF4(a+b+c)	u+l	22	0.0	0.0

11) PF3 (a + b) maximum net force toward mid plane

For PF3 the maximum force would result from the case where PF3, PF4, and OH are carrying current in the same direction, and PF2 is carrying current in the opposite direction. Per the nominal current direction Ip would reduce the force so it is assumed zero. With PF1a, upper, in the positive direction, PF1a, lower in the negative direction, and PF1b in the negative direction, the lower of the PF3 (a + b) coils is the worst case.

Circuit	u=upper/ l=lower	#turns above/below mid plane	kA/turn	kA-turn
OH	u+l	476	24.0	11424.0
PF1a	u	48	10.0	480.0
PF1a	l	48	-10.0	-480.0
PF1b	l	36	-15.0	-540.0
PF2a	u+l	14	-20.0	-280.0
PF2b	u	14	-20.0	-280.0
PF2b	l	14	-20.0	-280.0
PF3a	u+l	15	20.0	300.0
PF3b	u	15	20.0	300.0
PF3b	l	15	20.0	300.0
PF4(a+b+c)	u+l	22	20.0	440.0

12) PF3 (a + b) maximum net force away from mid plane

For PF3 the maximum force would result from interaction with OH, PF1, and the plasma all with currents in the opposite direction. Per the nominal current direction PF1b, PF2, and PF4 would reduce the force so their currents are assumed zero. Assume Ip = -1.0 MA r=91.5 cm and z=-21.7 cm. This will produce the worst case force on the lower PF3 coil set.

Circuit	u=upper/ l=lower	#turns above/below mid plane	kA/turn	kA-turn
OH	u+l	476	-24.0	-11424.0
PF1a	u	48	10.0	480.0
PF1a	l	48	10.0	480.0
PF1b	l	36	0.0	0.0
PF2a	u+l	14	0.0	0.0
PF2b	u	14	0.0	0.0
PF2b	l	14	0.0	0.0
PF3a	u+l	15	20.0	300.0
PF3b	u	15	20.0	300.0
PF3b	l	15	20.0	300.0
PF4(a+b+c)	u+l	22	0.0	0.0

13) PF4 (a + b + c) maximum net force toward mid plane

This case is similar to that for PF3 except, to maximize the inward force on PF4, the PF3a currents would be zero since, given the nominal polarity assumption, their current would tend to reduce the force. Plasma current is zero since it would reduce the force given the nominal polarity convention. Worst case occurs on the lower coil set due to the effect of PF1b.

Circuit	u=upper/ l=lower	#turns above/below mid plane	kA/turn	kA-turn
OH	u+l	476	24.0	11424.0
PF1a	u	48	10.0	480.0
PF1a	l	48	-10.0	-480.0
PF1b	l	36	-15.0	-540.0
PF2a	u+l	14	-20.0	-280.0
PF2b	u	14	20.0	280.0
PF2b	l	14	-20.0	-280.0
PF3a	u+l	15	0	0
PF3b	u	15	20.0	300.0
PF3b	l	15	-20.0	-300.0
PF4(a+b+c)	u+l	22	20.0	440.0

14) PF4 (a + b + c) maximum net force away from mid plane

Due to the opposite polarity of PF1b per the nominal polarity assumption, worst case occurs on the upper PF4 coil set. Assume Ip = -1.0 MA r=91.5 cm and z=-21.7 cm. This will produce the worst case force on the upper PF4 coil set.

Circuit	u=upper/ l=lower	#turns above/below mid plane	kA/turn	kA-turn
OH	u+l	476	-24.0	-11424.0
PF1a	u	48	10.0	480.0
PF1a	l	48	-10.0	-480.0
PF1b	l	36	-15.0	-540.0
PF2a	u+l	14	0.0	0.0
PF2b	u	14	20.0	280.0
PF2b	l	14	-20.0	-280.0
PF3a	u+l	15	20.0	300.0
PF3b	u	15	20.0	300.0
PF3b	l	15	-20.0	-300.0
PF4(a+b+c)	u+l	22	20.0	440.0

15) Maximum force between subcoils within outer PF coil groups PF2 and PF3

In each case the maximum force can be assumed to result from the interaction of the a and b coils at the same polarity (attraction) or opposite polarity (repulsion) with a current magnitude of 20kA/turn.

16) Maximum force between subcoils within outer PF coil group PF4

Since all of the coils, upper and lower, must have the same polarity, the force will be attractive and can be assumed to result from all currents at a magnitude of 20kA/turn.

17) Maximum torsional force on TF inner leg bundle

The same conditions which lead to the maximum compressive force in the OH solenoid will lead to the maximum torsional force on the TF inner leg bundle since the radial field at the ends of the solenoid is maximized under these conditions (see case 3)). Since the toroidal field is required to be capable of operation with either polarity with respect to the plasma current polarity, the subject force can be in either direction.

18) Maximum toroidal force on TF outer leg bundle at mid plane

The symmetric coil sets (OH, PF2a, PF3a, and PF4) will not contribute since they cannot produce a radial field component. The worst case therefore will result from a maximum current asymmetry between upper and lower coils, and from a vertically displaced plasma. Assume Ip = -1.0 MA r=91.5 cm and z=-21.7 cm. Since the toroidal field is required to be capable of operation with either polarity with respect to the plasma current polarity, the subject force can be in either direction.

Circuit	u=upper/ l=lower	#turns above/below mid plane	kA/turn	kA-turn
OH	u+l	476	0	0
PF1a	u	48	10.0	480.0
PF1a	l	48	-10.0	-480.0
PF1b	l	36	-15.0	-540.0
PF2a	u+l	14	0.0	0.0
PF2b	u	14	20.0	280.0
PF2b	l	14	-20.0	-280.0
PF3a	u+l	15	0.0	0.0
PF3b	u	15	20.0	300.0
PF3b	l	15	-20.0	-300.0
PF4(a+b+c)	u+l	22	0	0

Final note: A 1.0 MA plasma has been assumed herein. This is consistent with the present GRD requirements. If 2.0 MA is a serious upgrade possibility as has been mentioned informally, it should be included as a GRD requirement.

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NSTX File