71-970421-CLN-01

TO: DISTRIBUTION
FROM: C NEUMEYER
SUBJECT: FAR FIELD CALCULATIONS

References:

(1) 72-970129-SMK-02, "Plasma Initiation"

(2) 72-970206-SMK-01, "Disruption Modeling, Revised"

This memo presents estimates of the maximum magnetic field in the vicinity of NSTX, its derivative, and the resultant voltages and currents in nearby conducting loops. The purpose is to provide general guidance with regard to the placement of equipment (I&C racks, motors, etc.) in the stray static fields created by NSTX, and to assess the possible impact of conducting loops formed by I-beams, reinforcing bar in concrete, etc.

Contour plots of the field were made for a region contained by z = +0/-12 meters (with respect to the NSTX midplane), and r = 12 meters. A. Brooks supplied the code, which is constructed from standard PPPL Magnetics Library routines. The code assumes that no magnetic material is present, which strictly speaking, is not true in the context of the subject work (far from the machine) due to structural materials in the floors and walls of the building.

It is noted that the NSTX midplane is located roughly 4 meters above the floor of the hot cell, and that the floor of the hot cell is roughly 1 meter thick (at the thickest points were the I-beams are located). The basement mezzanine is about 8 meters below the midplane, and the basement floor about 11 meters. Horizontal lines are drawn on the contour plots corresponding to the midplane, the hot cell floor, the basement ceiling, the mezzanine, and the basement floor.

Three cases were examined as follows:

Case 1 - All Fields On

This case includes the contributions of the OH and all PF coils at peak rated currents, all in the same direction, and is used to estimate the peak static field. The plasma is excluded since the presence of the plasma would tend to decrease the net field.

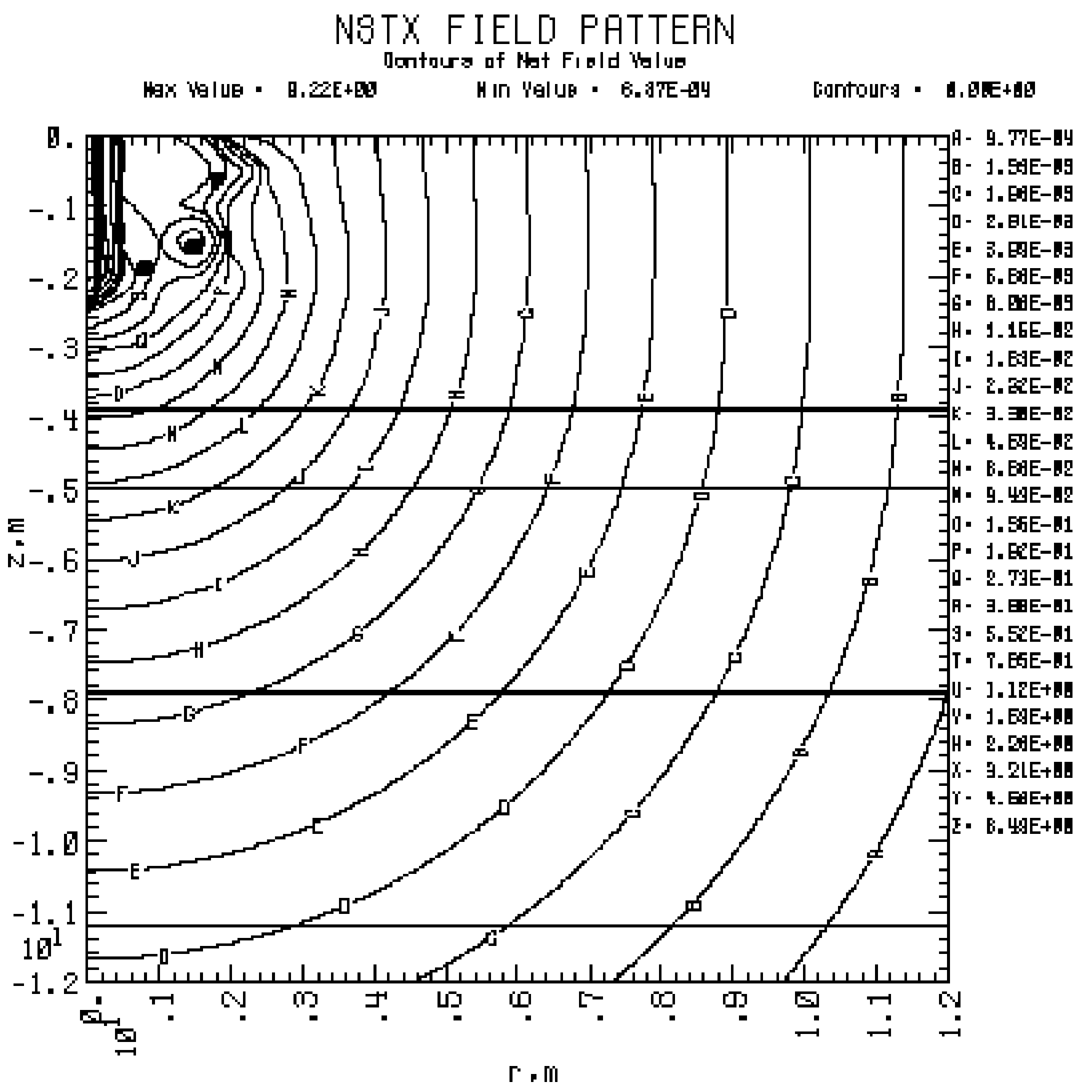
Case 2 - OH Only

This case includes the field from the OH only at I_{oh} = 24kA, and is considered in the determination of maximum field derivative, since the rate of change of OH magnetic flux due to plasma initiation is large.

Case 3 - Plasma Only

This case includes the plasma only (modeled at a 1MA filament at R_o = 0.854m), and is considered in the determination of maximum field derivative, since the rate of change of magnetic flux due to plasma current decay during disruption is large.

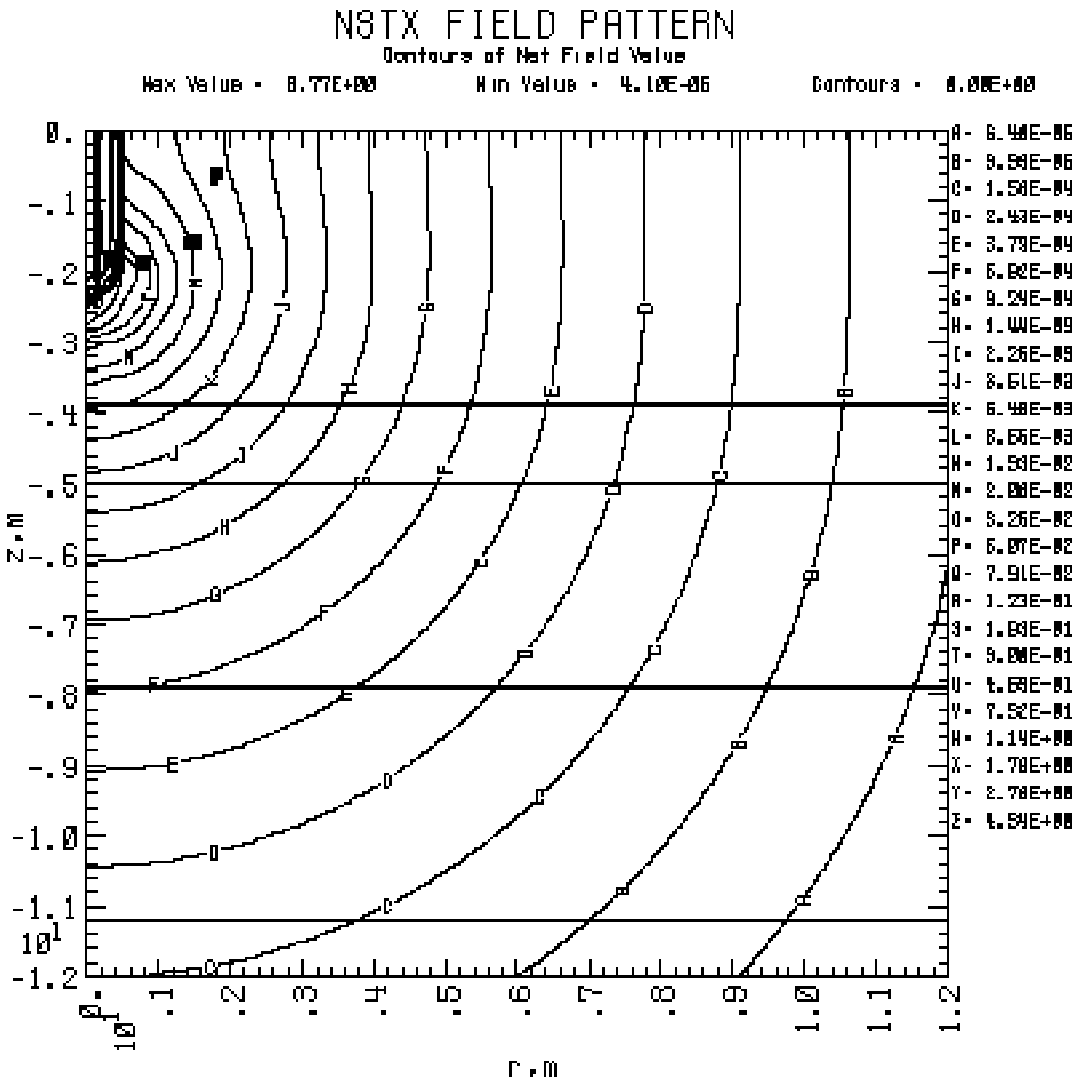
Case 1 is depicted in the following figure.

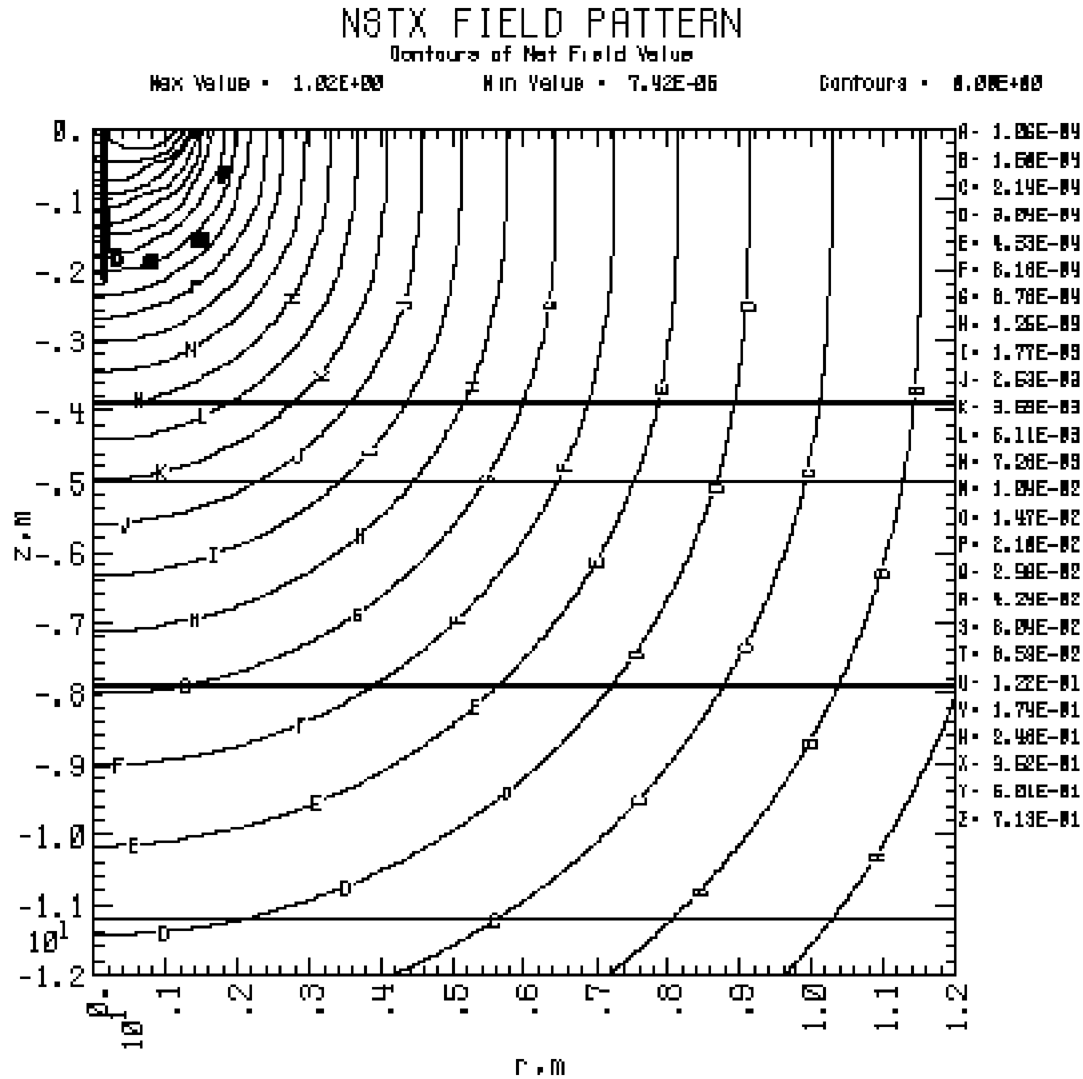


The maximum field in the basement is roughly equal to contour L @ 469 gauss. The 100 gauss line corresponds roughly to contour H @ 115 gauss, the 50 gauss line to contour F @ 57 gauss, and the 10 gauss line to contour A @ 9.7 gauss.

It is recommended that sensitive electrical equipment (e.g. I&C racks, motors, etc.) be located beyond contour F.

Cases 2 and 3 are depicted in the following figures.





To determine which of the above cases (2 or 3) will cause worst case induced voltages we need to compare the resultant dB/dt due to each. Let us neglect the shielding effect of eddy currents in conducting loops (e.g. the vacuum vessel) in terms of the rate of change in flux at points far away from the machine (this will yield conservative results). Let us assume further that the field is perpendicular with the surface of incidence for any remote conducting loop of interest.

Let us assume that the plasma initiation event corresponds to a decay of I_{oh} from 24 to 20kA in 10ms (400kA/second) (ref. 1), so that the rate of flux change per second will be proportional to (24-20)/24/10ms = 16.66 per unit per second. Similarly let us assume that a plasma disruption event from 1 mA to zero occurs in 10mS (ref.2), corresponding to 1/10mS = 100 per unit per second.

So, the rate of change of the field at any point can be determined by taking the field from the contour plot and then multiplying by the above factors. For example, consider contour L (B = 8.56e-3 Tesla), from case 2, which is the maximum field at the hot cell floor due to I_{oh} = 24kA. The maximum field derivative here will be dB/dt = (8.56e-3) * 16.66 = 0.143 T/second.

Similarly contour M (B = 7.26e-3 Tesla) is seen to be the maximum field at the hot cell floor due to I_p = 1MA. The maximum field derivative here will be dB/dt = (7.26e-3) * 100 = 0.726 T/second.

Although the field patterns from the OH and from the plasma current are not identical, they are similar enough to draw the conclusion that, based on the above comparision at the surface of the hot cell floor, the induced voltage due to plasma disruption will exceed that due to plasma initiation (roughly by a factor of .726/.142 ≈ 5).

Now, the voltage induced in any conducting loop can be estimated by multiplying the rate of change of field by the area enclosed. So, at the surface of the test cell floor the voltage induced in a 1 m^2 loop would be (1.0 m^2) * (0.726 T/sec) = 0.726 volt.

For loops with insulating breaks, the insulation must be able to withstand the induced voltage.

For loops without insulating breaks, current flow will be induced. Assuming that the induced voltage is constant over the 10mS interval associated with plasma disruption, and neglecting mutual coupling to any other loops, then the peak induced current will be...

$$I = V/R * (1 - \exp(-tR/L))$$

where:

I	=	induced current (amps)
V	=	induced voltage (volts)
t	=	time (seconds)
R	=	loop resistance (Ω)
L	=	loop inductance (henries)

A formula[1] for calculating the inductance of a rectangular loop formed from a circular conductor is...

$$L = 0.004 * [a * \ln(2a/r) + b * \ln(2b/r) + 2 * \mathrm{sqrt}(a^2+b^2) - a* \sinh^{-1}(a/b) - b* \sinh^{-1}(b/a) - 2*(a+b)+\mu_r/4*(a+b)]$$

where:

L	=	inductance (μH)
a	=	length of one side of rectangle (cm)
b	=	length of one side of rectangle (cm)

[1]"Inductance Calculations", F. W. Grover, p. 60, formula # 58

r	=	radius of conductor
μ_r	=	relative permeability of conductor (equal to 1 for non-magnetic)

The resistance of the conductor is...

$$R = \rho * l / A$$

where:

ρ	=	resistivity (≈ 1.7 μΩ-cm (Cu), 2.7 (Al), 10.0 (Fe), 18.0 for steel)
l	=	length of conductor
A	=	conductor cross section

Let us consider for example a loop which will be formed in the hot cell floor from the concrete reinforcing bar (a.k.a. "rebar"). Per the architechtural drawings the rebar type is #5 (0.625" diameter) in a 12" x 12" mesh. Further, assume that the steel is unsaturated and $\mu_r = 500$. Using the above formulae the inductance and resistance are roughly 31 μH and 1.1 mΩ, and the time constant 28 mS. The loop area is 0.09m and the voltages induced by plasma disruption and initiation are 67mV and 13mV, respectively. For the plasma disruption case the peak current would be 18 amps, and for the plasma initiation case roughly 1/5 of that, around 3.5 amps. The energy per plasma initiation pulse is very small (< 1/1000 Joule) so that temperature rise will not be an issue. Since the current is so small, even if the loop in question was to be isolated from the overall mesh (which results in cancellation to a large degree the local currents in each limb of the loop) the resultant field error would be very small.

Next let us consider the I-beams in the hot cell floor. Per the architechtural drawings there are rectangular loops formed in the area below NSTX which are comprised of type W14x48 and type W36x230 structural steel I-beams with cross sectional areas of 14.1 and 67.7 in^2, respectively. The lengths are roughly 97" and 62", respectively. Again, assuming $\mu_r = 500$, and using an equivalent radius (3.35") for a circular conductor with constant cross section around the loop the calculated inductance and resistance are 206 μH and 64.3 μΩ, and the time constant is 3.2 seconds. For the plasma disruption case the peak current would be 137 amps, and for the plasma initiation case roughly 26 amps. Again, the energy dissipation is trivial.

Finally, let us consider the aluminum I-beams which support the machine platform. Calculations per the method described above estimate the induced voltage to be 12.6 and 0.32 volts for disruption and initiation, respectivly, which would, if insulating breaks were not included, result in currents of 23kA and 588 A, respectively. Clearly the insulating breaks in these elements are essential.

The aforementioned calculations are described in the following table. Additional columns are included with the assumption that the rebar and I-beam materials are made of non-magnetic steel ($\mu_r = 1$) to gauge the effect of the μ_r assumption. However the $\mu_r = 500$ assumption is considered to be the valid one for unsaturated common grade steel.

	Rebar	Rebar	I-beams	I-beams	Platform	
conductor radius	0.79	0.79	8.49	8.49	2.69	cm
side a	30.48	30.48	246.18	246.18	121.92	cm
side b	30.48	30.48	158.26	158.26	243.84	cm
material	steel	steel	steel	steel	aluminum	
μr	500	1	500	1	1	
inductance	3.12E-05	7.62E-07	2.06E-04	4.21E-06	5.25E-06	H
rho	1.80E-05	1.80E-05	1.80E-05	1.80E-05	1.80E-05	μΩ-cm
loop length	121.92	121.92	808.89	808.89	731.52	cm
conductor area	1.98	1.98	226.28	226.28	321.50	cm^2
resistance	1.11E-03	1.11E-03	6.43E-05	6.43E-05	4.10E-05	Ω
tau	0.0281	0.0007	3.2020	0.0654	0.1281	sec
loop area	929.03	929.03	38961.56	38961.56	29728.97	cm^2
Bo (disruption)	7.26E-03	7.26E-03	7.26E-03	7.26E-03	4.24E-02	Tesla
Bo (initiation)	8.56E-03	8.56E-03	8.56E-03	8.56E-03	6.48E-03	Tesla
V(disruption)	0.07	0.07	2.83	2.83	12.61	volt
V(initiation)	0.01	0.01	0.56	0.56	0.32	volt
time duration	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	sec
t/tau	0.3556	14.5549	0.0031	0.1528	0.0781	
I(disruption)	18.20	60.83	137.08	6230.23	23111.66	amp
I(initiation)	3.58	11.95	26.94	1224.33	588.71	amp
W(initiation)	0.0001	0.0016	0.0005	0.9645	0.1419	Joule

The presence of the magnetic materials (rebar and I-beams) introduces a level of uncertainty and complexity, since the far field pattern is no doubt influenced by their presence. Although the presence of these materials is not in conflict with the GRD requirement (no magnetic materials ($\mu_r > 1.03$) within r = 3 m and Z = +/- 3m) there will be non-axisymmetric field errors resulting. This needs further study. It may turn out that we can minimize errors by positioning the machine centerline at the intersection of I-beams in the floor, for example.

cc:

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NSTX File