



53-970609-CLN-01

TO: DISTRIBUTION
FROM: C NEUMEYER
SUBJECT: SIMULATION OF NSTX PLASMA INITIATION

References:

- [1] 72-970129-SMK-02, "Plasma Initiation"
- [2] 72-970130-SMK-01, "Stray Fields in NSTX"
- [3] 13-970214-JMB-01, "Eddy Currents in TF Cross Section [inner leg]"
- [4] NSTX-RQMT-GRD-018-00, "NSTX General Requirements Document"
- [5] 53-970609-CLN-02, "Comparision of Simulation Code with CDX-U Measurements"

Introduction

This memo presents results of a simulation of plasma initiation in NSTX, continuing the work and depending on various assumptions described in references [1], [2], and [3]. The work presented herein uses a newly developed code, and includes models of the power supplies which are more realistic than those used in the references.

The results indicate that the field null and loop voltage required by the GRD [4] can be obtained based on the 24kA precharge of the OH coil and the use of the PF3 coil for compensation of the OH stray field. GRD requirements are as follows:

"2.6.1 Plasma Initiation

- a. The NSTX PF/OH magnets and power systems shall be designed to produce a loop voltage $\geq 3.0V$ and a field null (≤ 2 Gauss) region ≥ 40 cm diameter for ≥ 2 mS."

The current required in the PF3 coil for compensation is opposite in polarity to that required for the plasma equilibria. Therefore the PF3 power supply must be bipolar.

The simulation uses an axisymmetric model of the coils, vacuum vessel, center stack casing, and passive plates. Based on arguments presented in [2],[3] the time constants of the TF inner leg conductor eddy currents are short enough that they can be excluded from the modeling. The same is true for the tension cylinder which threads the bore of the OH coil.

The passive plates are modeled as axisymmetric with resistance included to simulate the gap resistance. Several values of gap resistance were evaluated, and it was found that the required performance can be achieved with toroidal gap resistance associated with the passive plate mounting brackets.

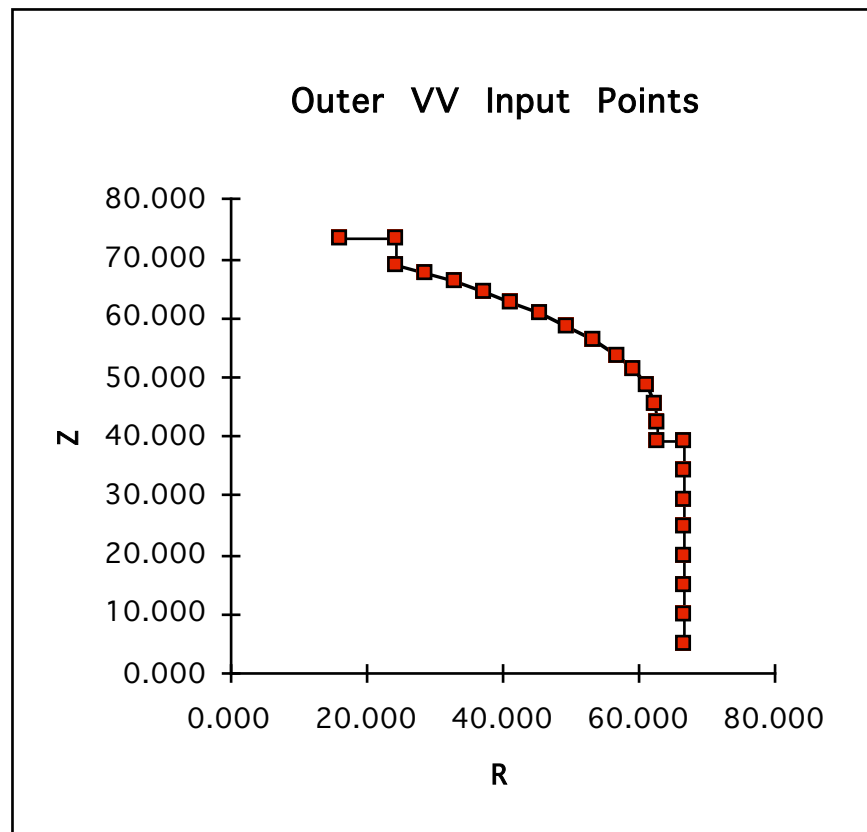
Symmetry about the midplane is assumed for all coils and all structures.

The simulation has been benchmarked against measurements taken on CDX-U [5]. The calculations and simulation code described herein will be formally documented and checked as part of the WBS5 Power Systems design review process. This is appropriate since further refinement will take place between now and then.

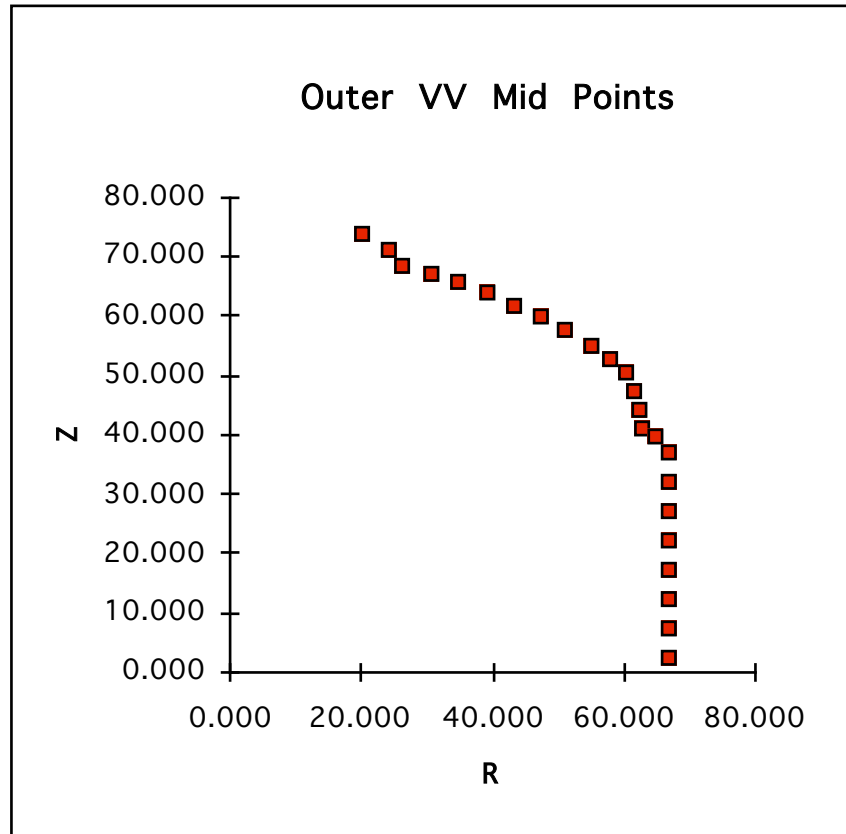
Coil and Structure Modeling

The PF coil set described in "PF Coils 4/14/97" was used. All coils except PF1b were included. All upper and lower coils were assumed in series with the same current direction. Sub-coils (e.g. PF2a, PF2b, etc.) were assumed in series, except that the PF4a sub-coils were separated from the PF4b and PF4c subcoils to investigate options involving such separation.

The outer vacuum vessel shape was obtained from H. M. Fan based on the finite element model description being used for mechanical studies. Points are shown in the following figure (dimensions in inches).



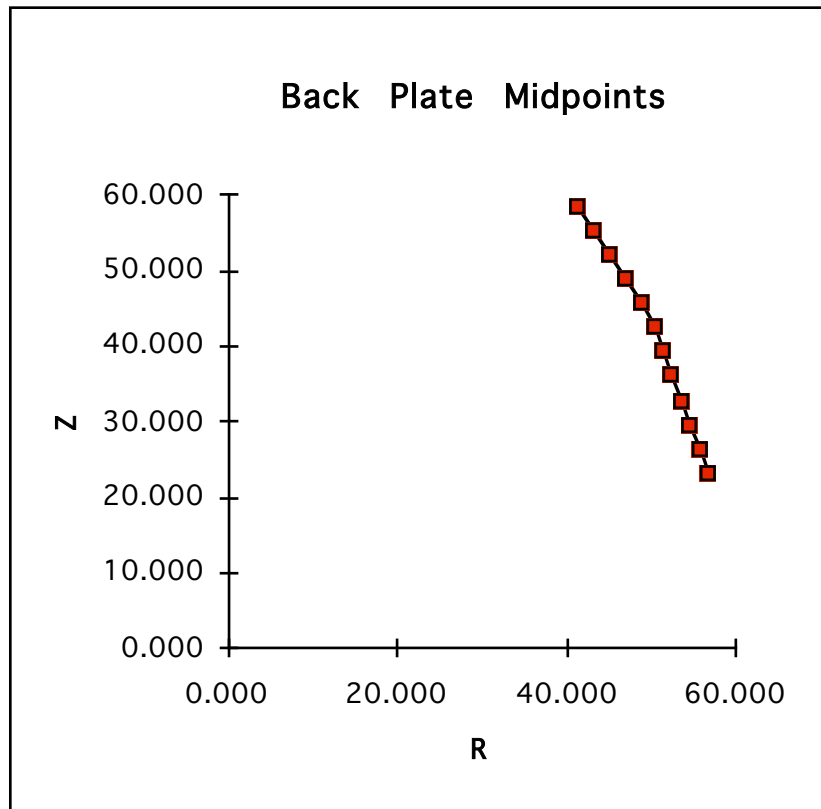
The vessel was modeled using 24 elements of square cross section with centers located at the midpoints of the segments between the input points and with cross section equal to that of the segment of the vessel which it represents. Stainless steel resistivity was assumed $77.0 \mu\Omega\text{-cm}$. Centers are shown in the following figure (dimensions in inches).



The location of the front face of the PFCs associated with the passive plates was obtained from J. Spitzer as follows:

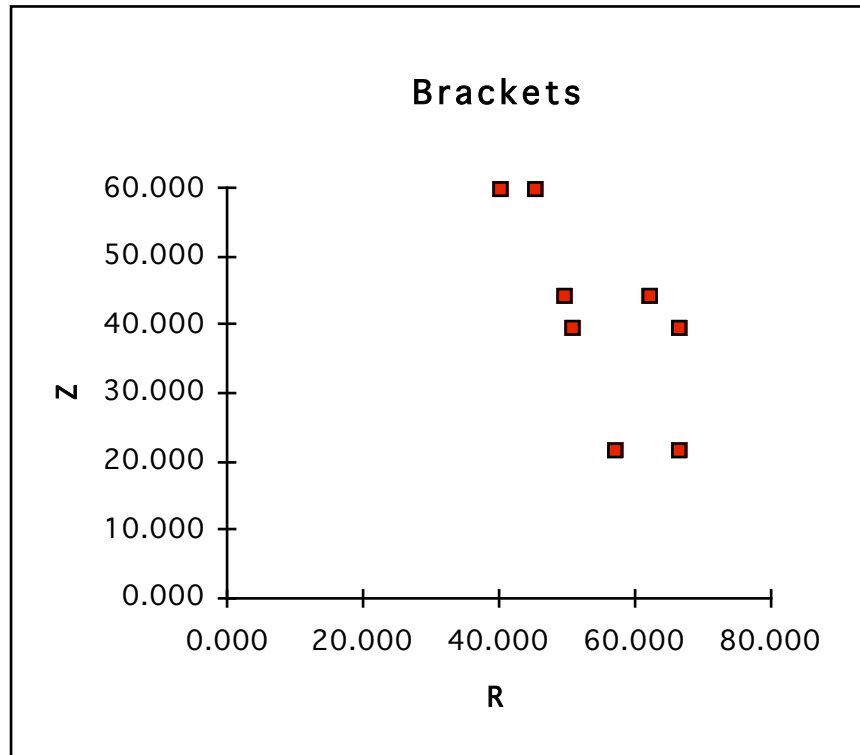
R (in)	Z (in)	Plate
39.370	59.055	Upper
43.307	53.150	Upper
47.244	46.063	Upper
48.702	43.657	Intsct
51.181	36.220	Lower
55.118	24.409	Lower
56.299	20.866	Lower

Given that the PFCs are 1" thick and the copper backing plate 0.5" thick, a set of 12 equally spaced points through the centerline of the plate was derived as depicted below.



Square cross sections of the 12 elements representing the plates were chosen such that the area of each element is equal to the segment which it represents. Copper resistivity was assumed to be $1.72 \mu\Omega\text{-cm}$.

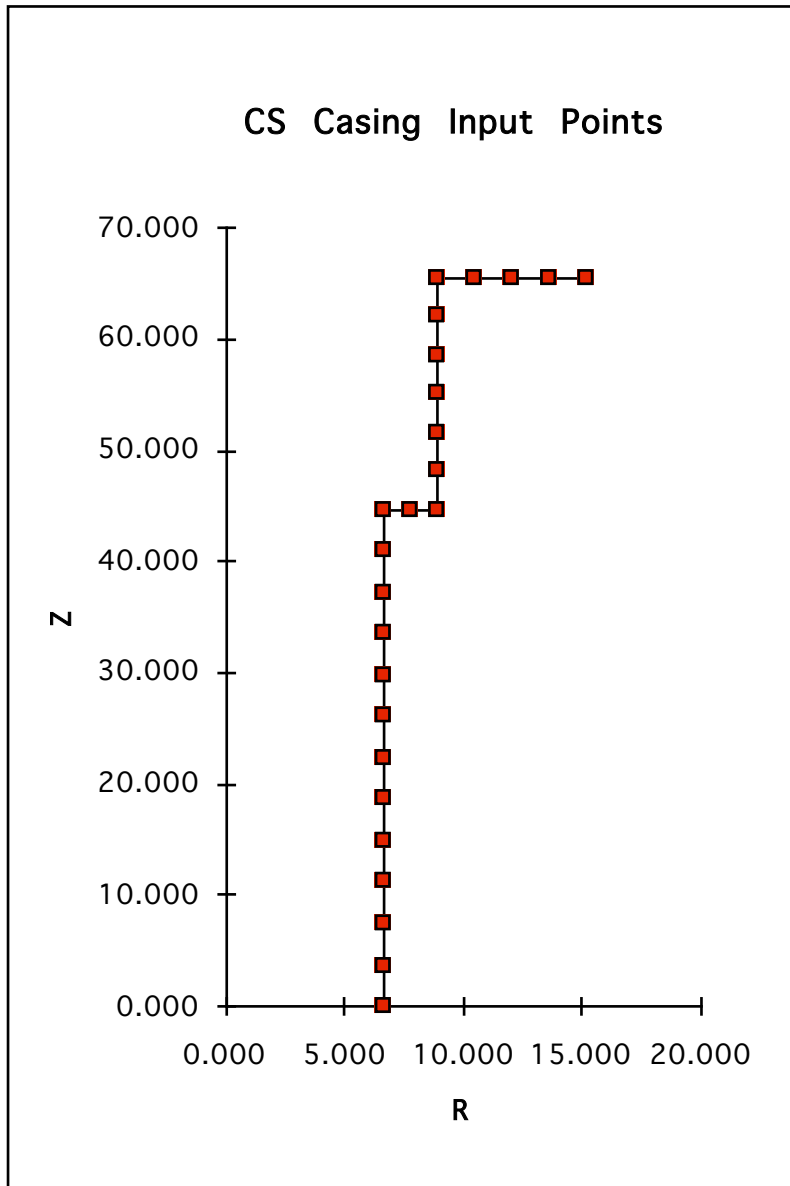
To determine the minimum toroidal gap resistance associated with the passive plate support brackets an assumed bracket shape was used, with the inboard edge of the bracket matching up to the backplate shape, and with the outboard edge matching up to the vacuum vessel shape. The outline of the assumed brackets is depicted below.



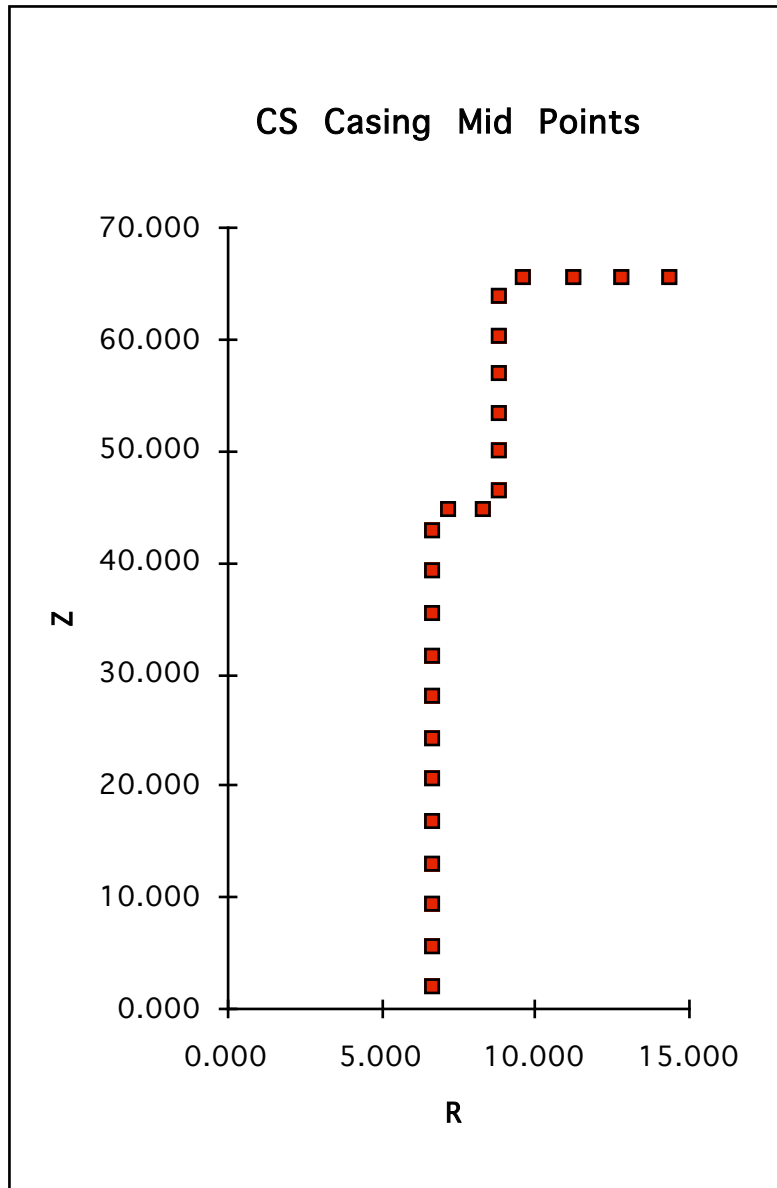
Assuming no holes in the brackets, and assuming 0.5" thick stainless steel, the calculated resistance (in the radial direction) of the upper bracket is $37.5\mu\Omega$, and that of the lower bracket $37.0\mu\Omega$. This is based on the equivalent resistance of several (8 in the top bracket, and 6 in the bottom bracket) radial slices of the plates, all in parallel, with stainless steel resistivity equal to $77.0\mu\Omega\text{-cm}$.

In the simulation, the toroidal gap resistance was included using external circuit resistances introduced equally into each of the 12 elements used to simulate the passive plates.

The center stack casing input points were obtained from drawing NSTX 13.E0110.0 and are depicted below.



Midpoint locations were derived based on the segments between the input points taken from the drawing. For each of the 24 elements a square cross section was used such that the area is equal to that of the segment which it represents. Inconel resistivity was assumed equal to $130.0 \mu\Omega\text{-cm}$.



Since the electrical circuit elements which represent the passive structure elements are symmetric about the midplane and are short circuited, they are connected in series in the simulation. The result is identical to that which would be obtained if the upper and lower short circuit loops were treated as separate circuits. The advantage is that the total number of circuits to be simulated is reduced.

The total number of individual circuits used in the work described herein was 6 coil circuits (OH, PF1a, PF2, PF3, PF4a, PF4b&c), plasma, plus 60 passive structure elements (representing a total of 120 elements considering that the upper and lower elements are combined into single circuits), for a total of 67.

Preparation of Simulation Input Data

Using the data (r , z , Δr , Δz , etc.) for the coils and passive structure elements as described above, along with an additional filament ($r = 0.8$ m, $z=0$) to measure the loop voltage available for plasma initiation, the PPPL Magnetics Library code "ICC" is used to determine the mutual inductance matrix and resistance vector which is placed into file "cntmtx.d".

External circuit resistances are placed in a file "ecr.d". As described above, each of the passive plate circuit elements includes an external circuit resistance due to the toroidal gap resistance, such that the net parallel equivalent yields the desired effective value. The coil circuits, which are driven by power supplies, include an external circuit resistance which simulates the power supply regulation (voltage drop under load). A value of 14.6 m Ω is used per 1kV D-site power supply section such that the full load (24kA) voltage is on the order of 660 volts. This corresponds to the configuration where 2 sections (comprising a 12-pulse rectifier) are active on a feeder.

In order to calculate the vertical field at the center of the field null region during the simulation, the contribution of each circuit element per amp of current is calculated in advance using a standard PPPL subroutine (drvgrn) which solves Greens function. In determining the field due to each coil circuit, the contribution due to each coil turn for each coil in the circuit is calculated, and the result is summed up (with due consideration of the contribution of both the upper and lower half plane coils). This data is placed into file "b.o".

Other simulation control data is placed in file "sim.d". This includes run time instructions (time duration, time step, linear breakpoint data for driven circuits, etc.). Power supply voltage limits are prescribed for circuits which will be driven in a feedback mode. Maximum positive and negative voltages are input, so that the reduced voltage magnitude available in inversion (negative voltage) can be simulated.

Simulation

The simulation solves the matrix equation...

$$[V] = [M]*[dI/dt] + [R]*[I]$$

The method used is to solve for the current derivatives and apply an Euler integration....

$$[X] = [M]^{-1}$$

$$[Y] = [V - R*I]$$

$$[dI/dt] = [X]*[Y]$$

$$[\mathbf{I}]_{k+1} = [\mathbf{I}]_k + [d\mathbf{I}/dt]_{k+1} * \Delta t$$

Each circuit is specified in the input data file to be one of the following types....

- 0 = voltage specified
- 1 = current specified
- 2 = open circuited
- 3 = short circuited
- 4 = voltage feedback controlled
- 5 = current feedback controlled

For type 0 (voltage specified) the waveform specified in "sim.d" is interpreted as a voltage and applied to the circuit.

For type 1 (current specified) the waveform specified in "sim.d" is interpreted as a current and the voltage required to produce that current is calculated each time step and then applied to the circuit such that the specified current is achieved.

For type 2 (open circuited) the circuit is not included in the simulation (since its current will always be zero), but the induced voltage is calculated each time step.

For type 3 (short circuited) zero voltage is applied to the circuit.

For type 4 (voltage feedback controlled) the waveform specified in "sim.d" is interpreted as a voltage and used as a reference against a proportional-integral (PI) feedback control loop. The resultant requested voltage is subject to rate limiting and (+) and (-) limits per the input specifications before being applied to the coil. Rate limit is such that changes in voltage (in either direction) occur at a rate equal to $V_{\max}/(1/60/4)$. In other words the minimum time to change from V_{\max} to zero is 1/4 of a cycle at 60Hz. This is consistent with the behavior of the D-site power supplies.

For type 5 (current feedback controlled) the waveform specified in "sim.d" is interpreted as a current and used as a reference against a proportional-integral (PI) feedback control loop. The resultant requested voltage is subject to rate limiting and (+) and (-) limits per the input specifications before being applied to the coil. Rate limit is as per type 5 above.

Another feature is the selection of circuits for stray field compensation duty. One or more type 5 circuits can be selected. Each is signed a weighting factor. At each time step the net vertical field at the field null target due to all circuits except for the compensating circuits is calculated. Then a reference current is determined for each compensating circuit based on the vertical field to be canceled, the weighting factor, and the vertical field per amp data from file "b.o". This current is used then as the reference current, overriding any waveform data from sim.d.

Subject to the array dimensioning in the source code any number of output voltages and currents can be saved (present limit is 16).

The net stray field at the field null target is saved in an output file.

At two time points specified in "sim.d" a complete set of all circuit currents is saved. This feature is intended for saving the current distribution at the Start of Initiation (SOI) and the End of Initiation (EOI) for later use in field plotting.

Field Plotting

A routine supplied by A. Brooks (contpf2) provides plots of the flux, vertical and radial field contours, and net field contour. This code is based on subroutines from the PPPL Magnetics Library. By confirming the presence of the field null this code essentially checks the input data and processing associated with "b.d" and "b.o" as described above.

Simulation Results

Several schemes were evaluated for creating the field null as follows. Toroidal gap resistance was assumed at the nominal values resulting from the resistance of the passive plate support brackets as described earlier.

a. Compensation via PF4a only

This was found to be feasible from a voltage and current point of view but was found to produce too small of a null (field gradient too high). The required current would be bipolar.

b. Compensation via PF3 only

This was found to work very well and produce a large field null. The required PF3 current is bipolar, and the required voltage magnitude is within the capability of two series connected D-site power supply sections (2kV).

c. Bias via PF4a, compensation via PF3 only

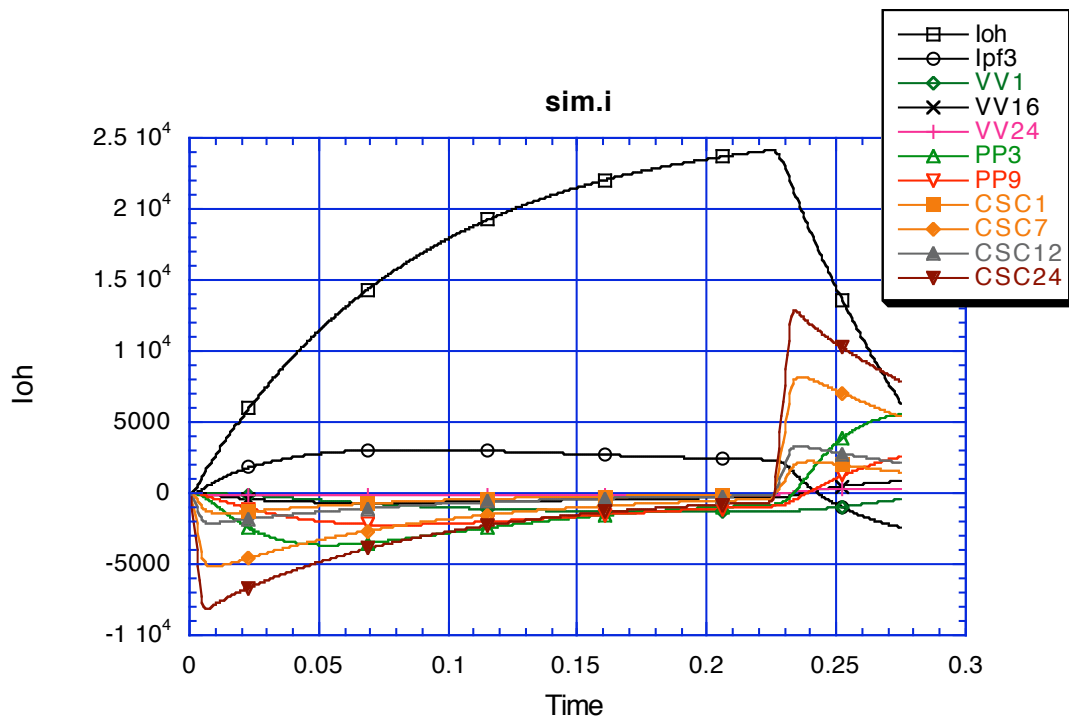
In an attempt to keep the PF3 current unidirectional, a bias field was introduced using PF4a, so that the role of PF3 was to reduce the bias sufficiently to create the null. Although feasible from a voltage and current point of view this approach was again found to produce too small of a null.

As a result of the above it was decided to adopt the PF3-only compensation scheme.

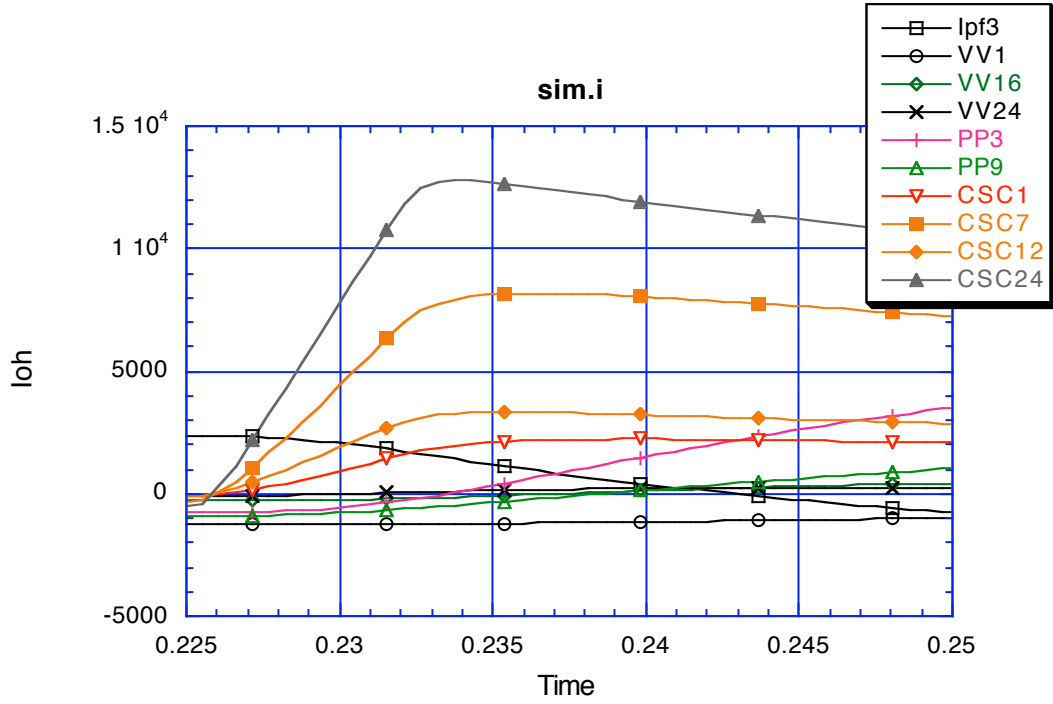
So, simulation results using a 4kV OH power supply, 2kV PF3 power supply, and nominal toroidal gap resistance are given in the following figures.

Following figure shows the evolution of the OH current along with the PF3 compensation current and selected passive structure currents. The variable names for the passive structure currents (e.g. VV1) refer to the vacuum vessel

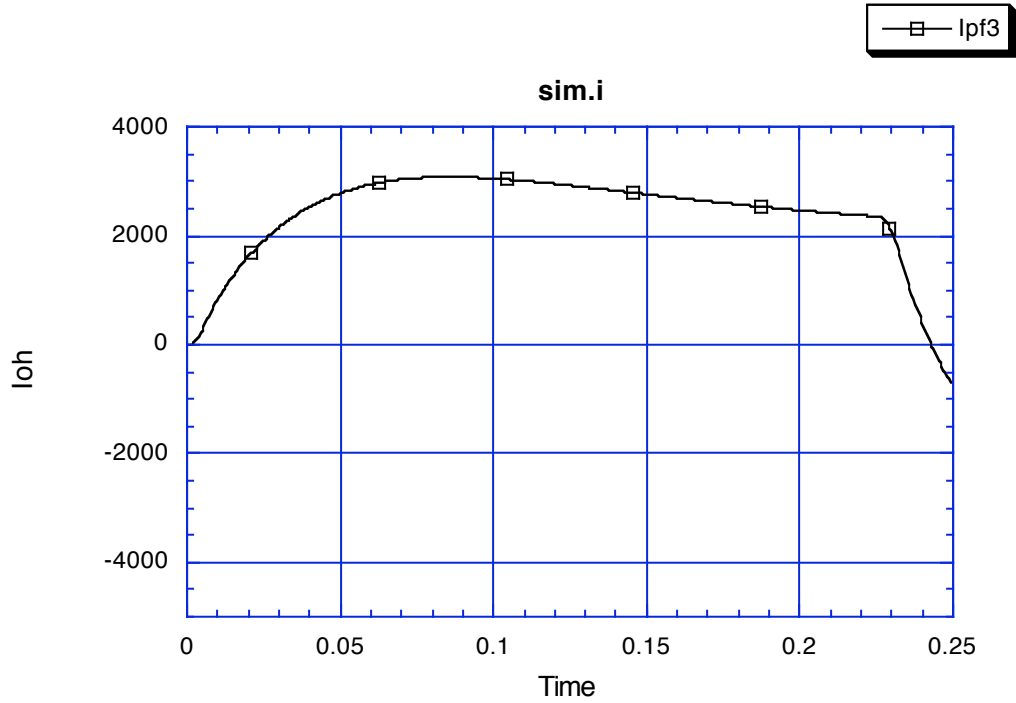
(VV), passive plate (PP) and center stack casing (CSC) element numbers as described earlier.



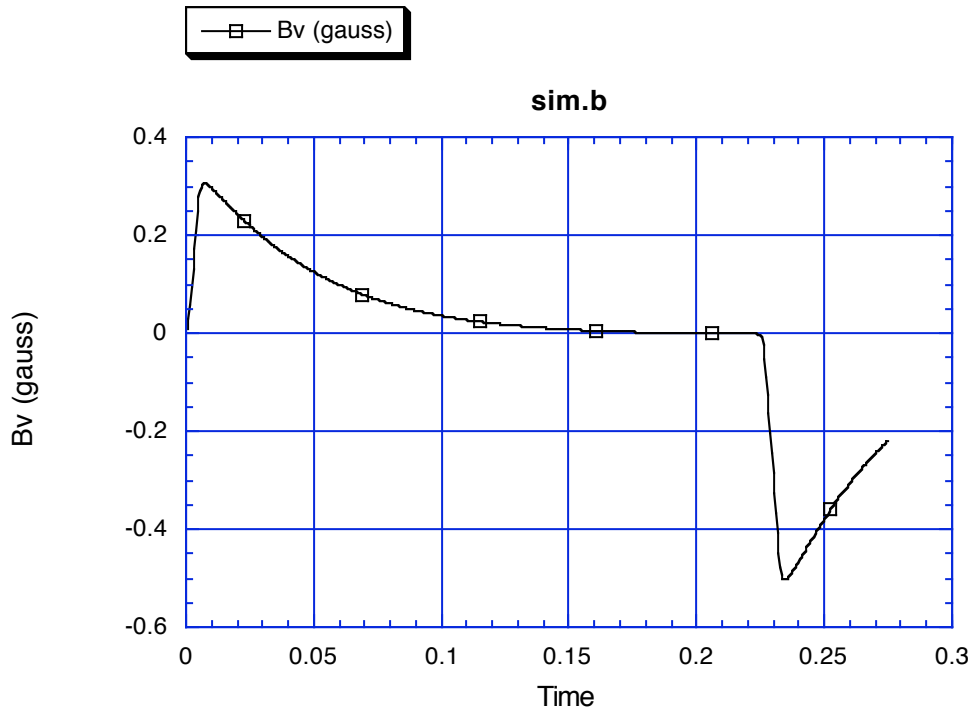
Following curve show a zoom of the currents during the plasma initiation interval (0.225 to 0.235 seconds).



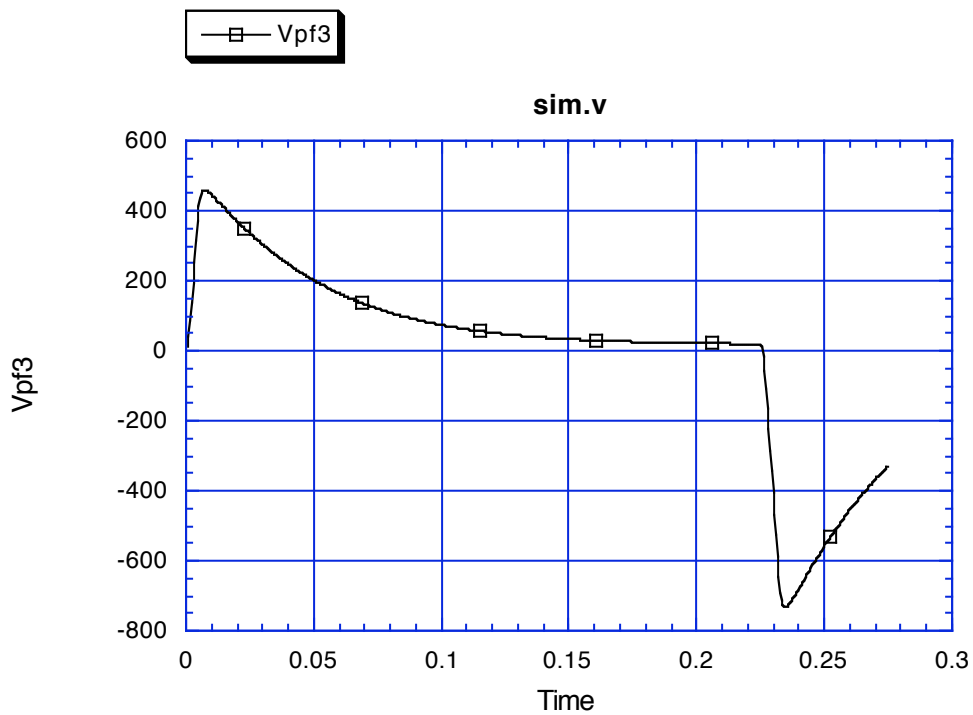
Following curve shows the compensation current required of PF3.



Following curve show the net vertical field (in gauss) at the field null target.



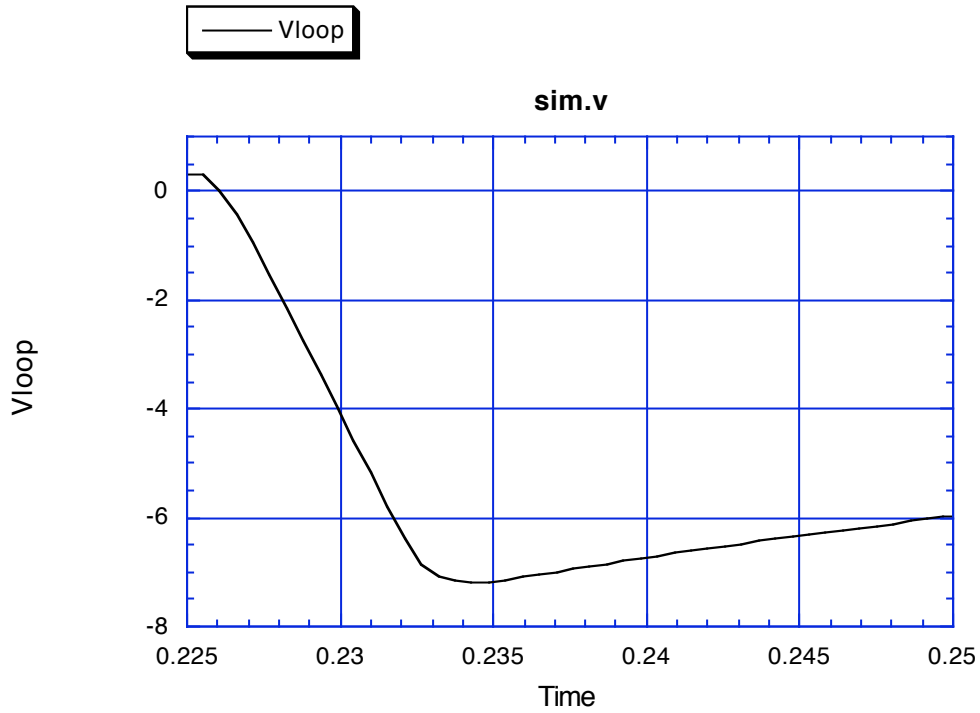
Following curve shows the voltage demanded of PF3.



It is noted that the full available voltage (2kV) was not demanded. If the feedback gains were set higher, more voltage could be supplied and the field at the null

could be reduced somewhat. Further work can be performed to determine best feedback gains.

Following curve shows the plasma loop voltage during the initiation interval. It is noted that the main contributors are the OH power supply, the voltage drop due to the OH coil resistance, and the PF3 power supply.



Following curve shows the flux at the start of initiation (t=0.225 sec).

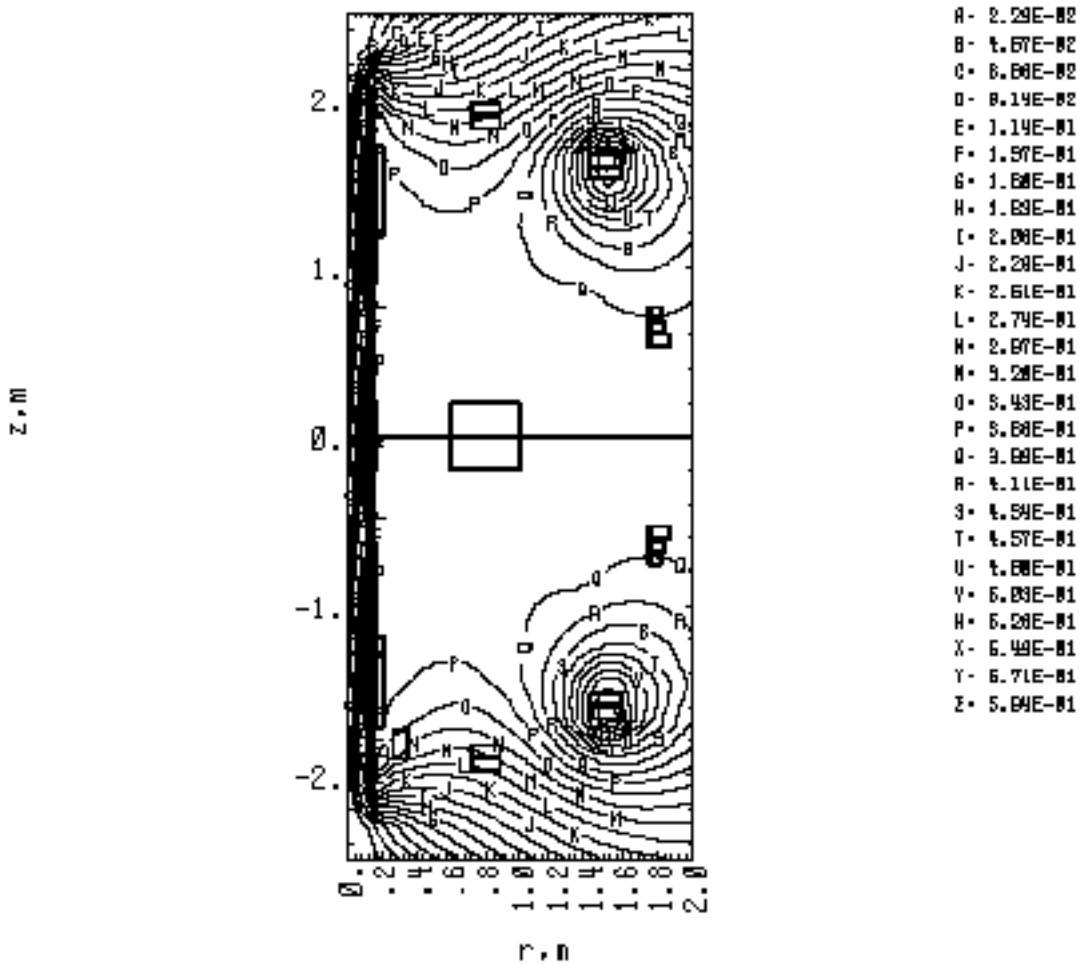
NSTX FIELD PATTERN

Contour of Flux

Max Value • 8.17E-01

Min Value • 0.00E+00

Contours • 2.20E-02



Following curve shows the flux at the start of initiation, zoomed into the area of interest. The drawn box is 40 cm x 40 cm with the target ($r = 0.8$ m) at the center.

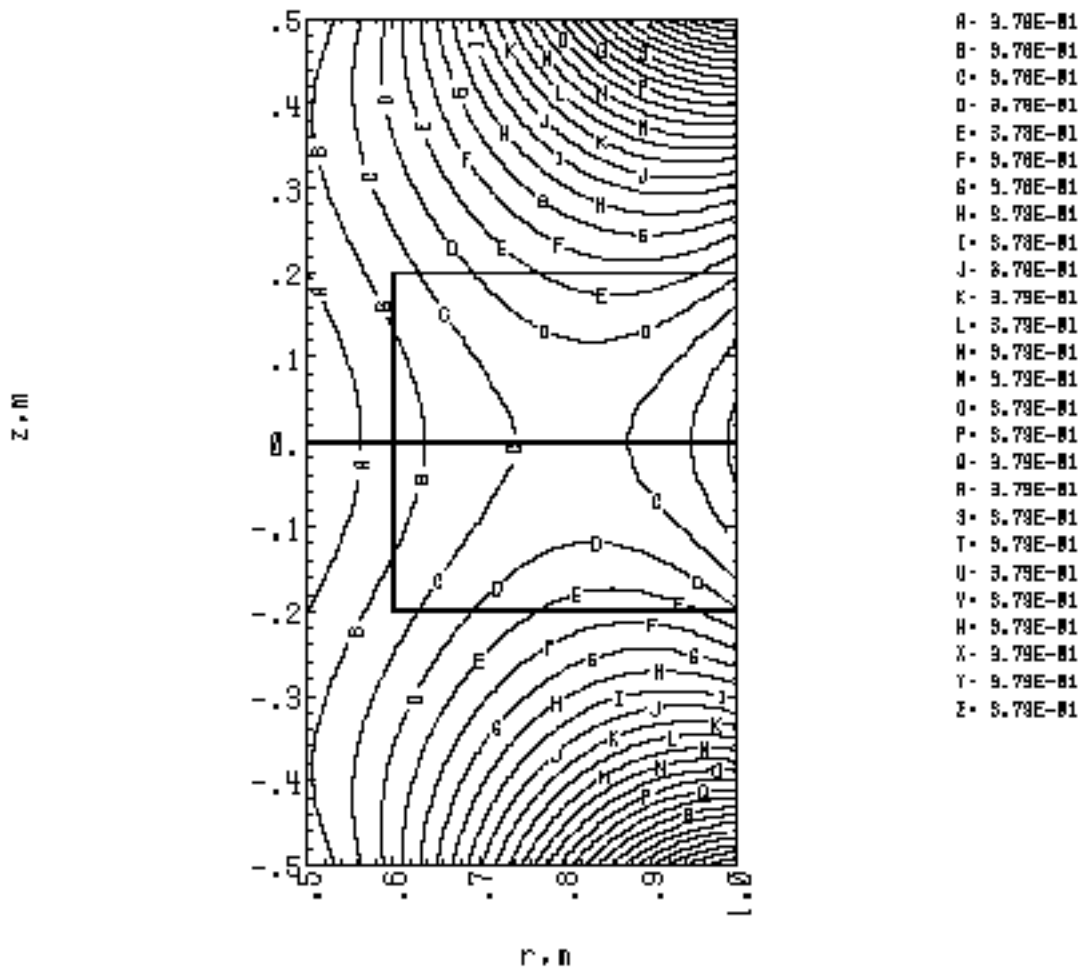
NSTX FIELD PATTERN

Contours of Flux

Max Value • 9.79E-01

Min Value • 9.78E-01

Contours • 3.79E-05



Following curve shows the contours of net field at the start of initiation. Contour G is ≈ 2 gauss.

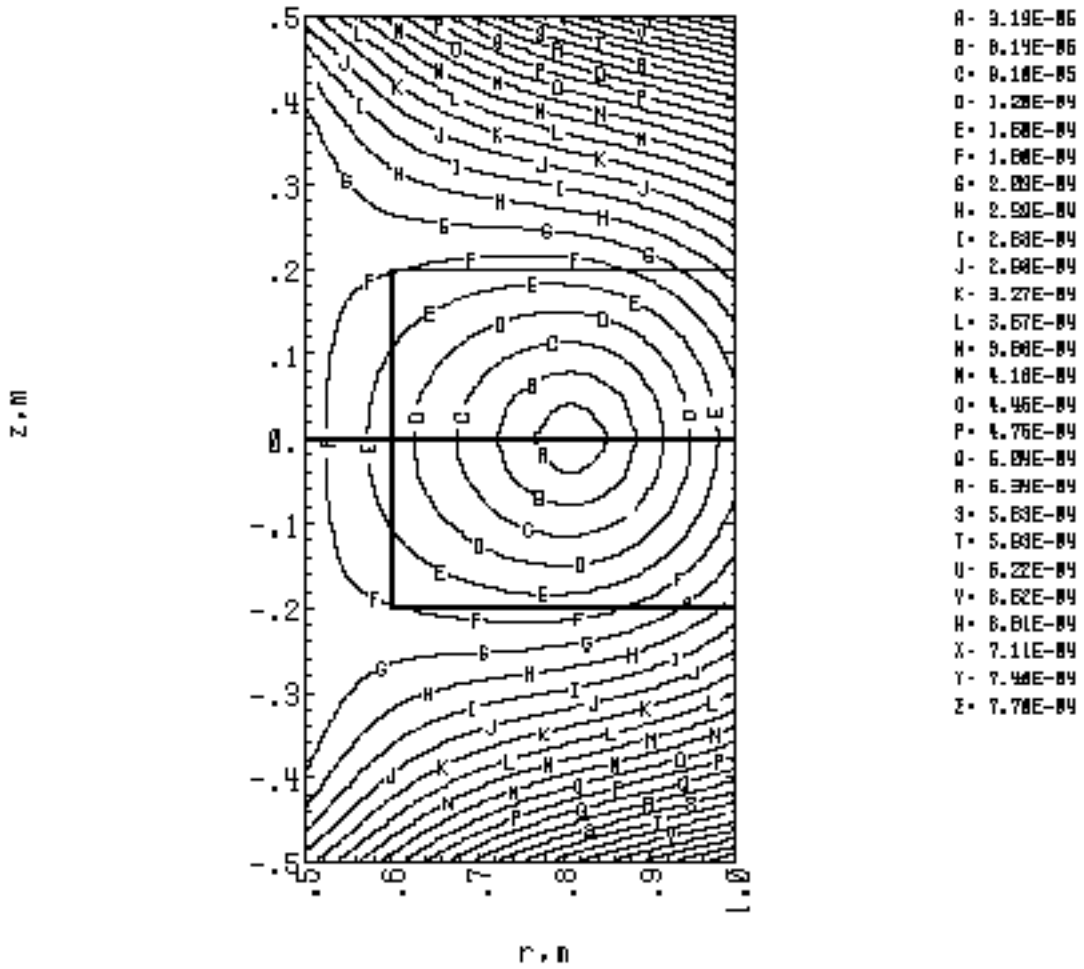
NSTX FIELD PATTERN

Contours of Net Field Value

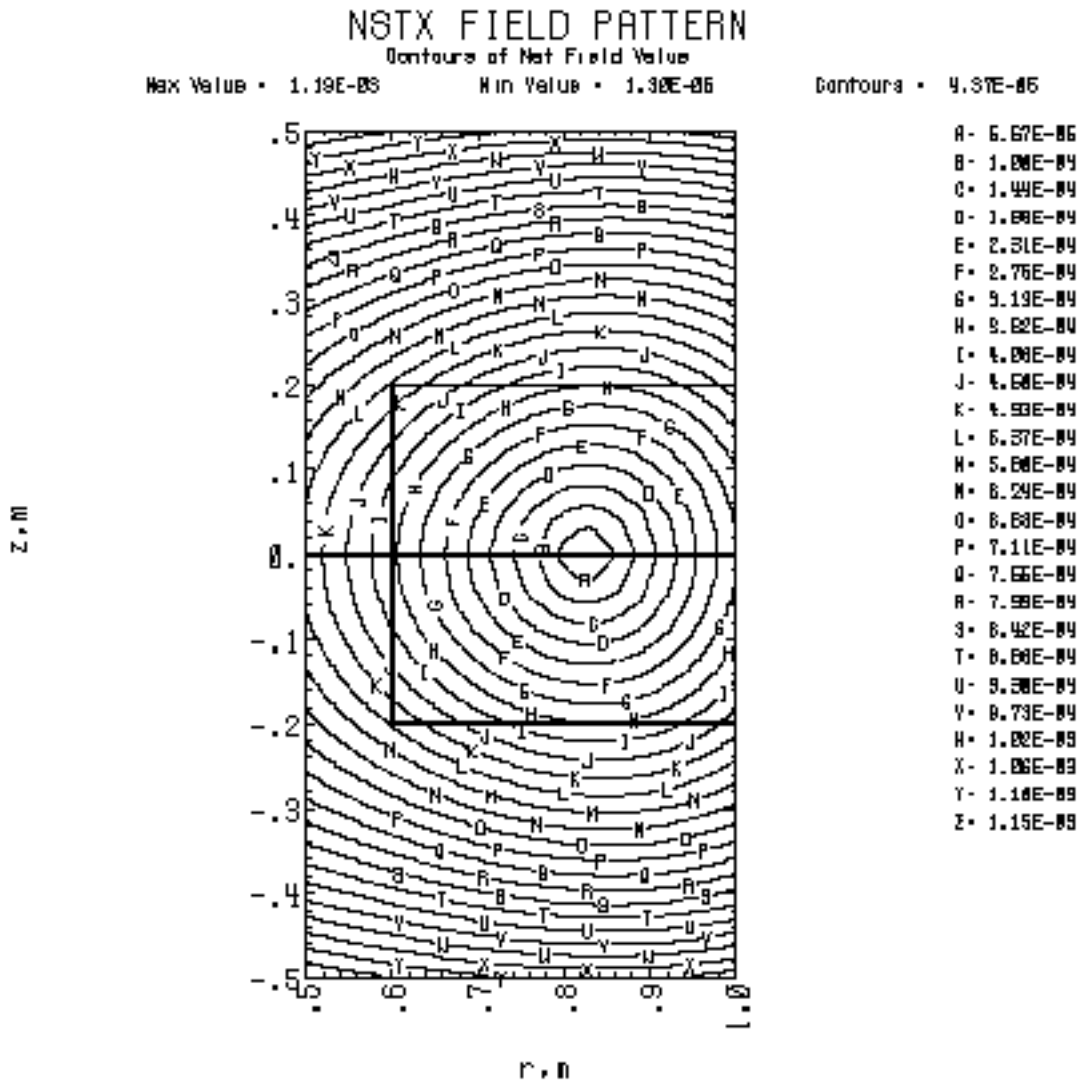
Max Value • 8.00E-04

Min Value • 2.39E-08

Contours • 2.90E-05

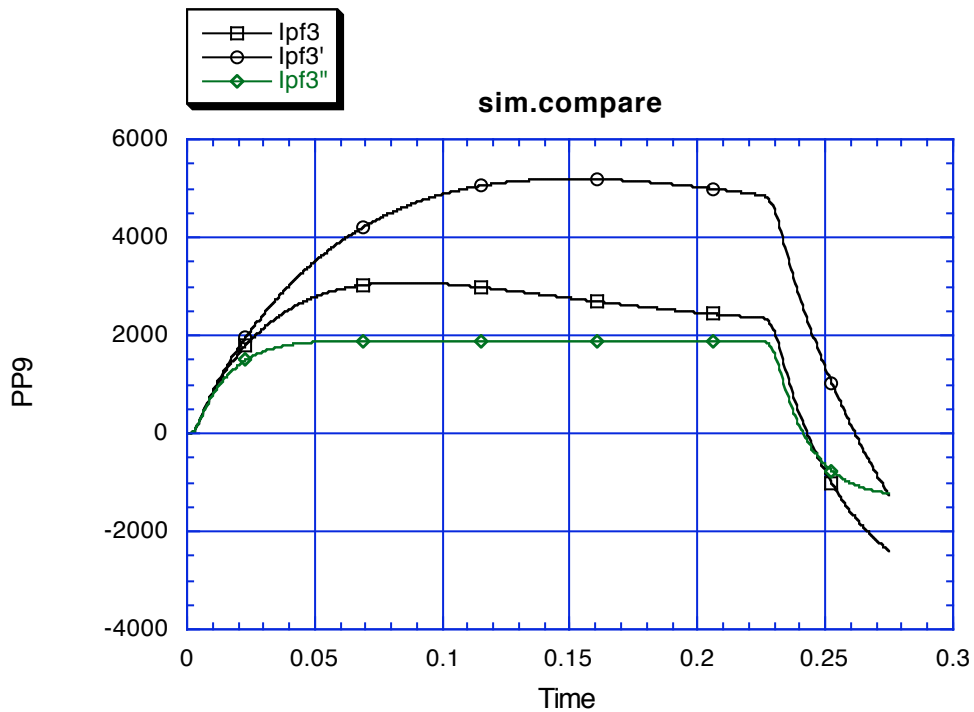
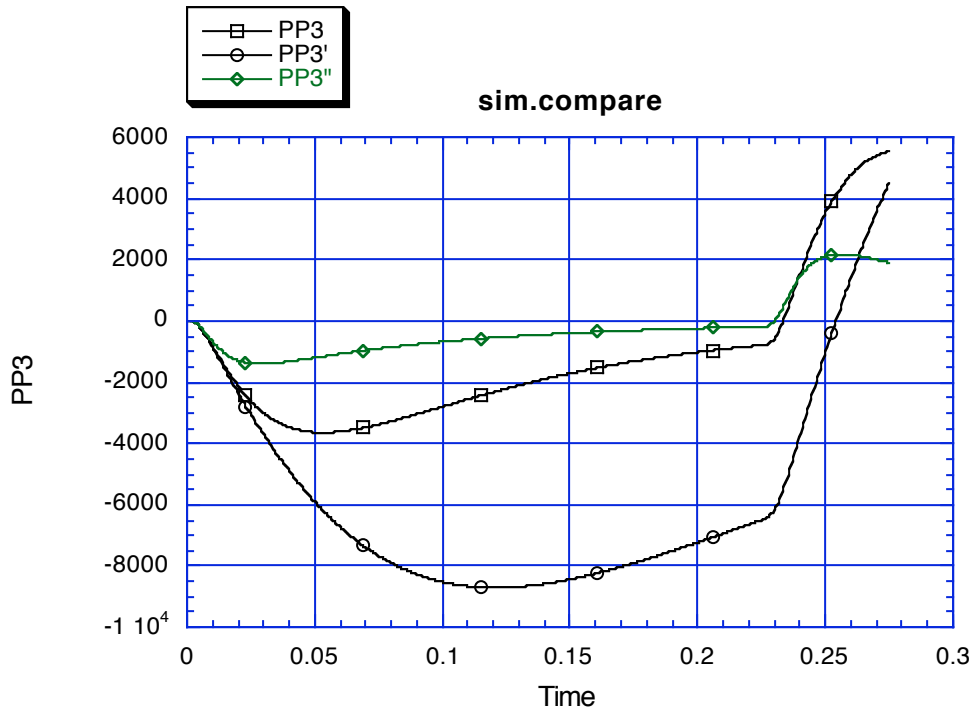


Following curve shows the contours of net field at the end of initiation (t=0.235).
The 2 gauss contour is between D and E.



To study the effect of different toroidal gap resistances, three cases were compared, namely the nominal ($37\mu\Omega$) case described above, a low resistance case ($1\mu\Omega$), and a high resistance case ($150\mu\Omega$). These numbers are to be compared with the toroidal resistance of the copper plates which is on the order of $10\mu\Omega$ for each pair in each half plane.

Insignificant differences in the loop voltage waveform were observed. Similarly, insignificant differences in the extent or shape of the field null area were observed. The most significant differences were in the plate currents and the current required from PF3 to create and maintain the null. These results are given in the following figures, where the (') variable naming corresponds to the low resistance case and the (") naming to the high resistance case.

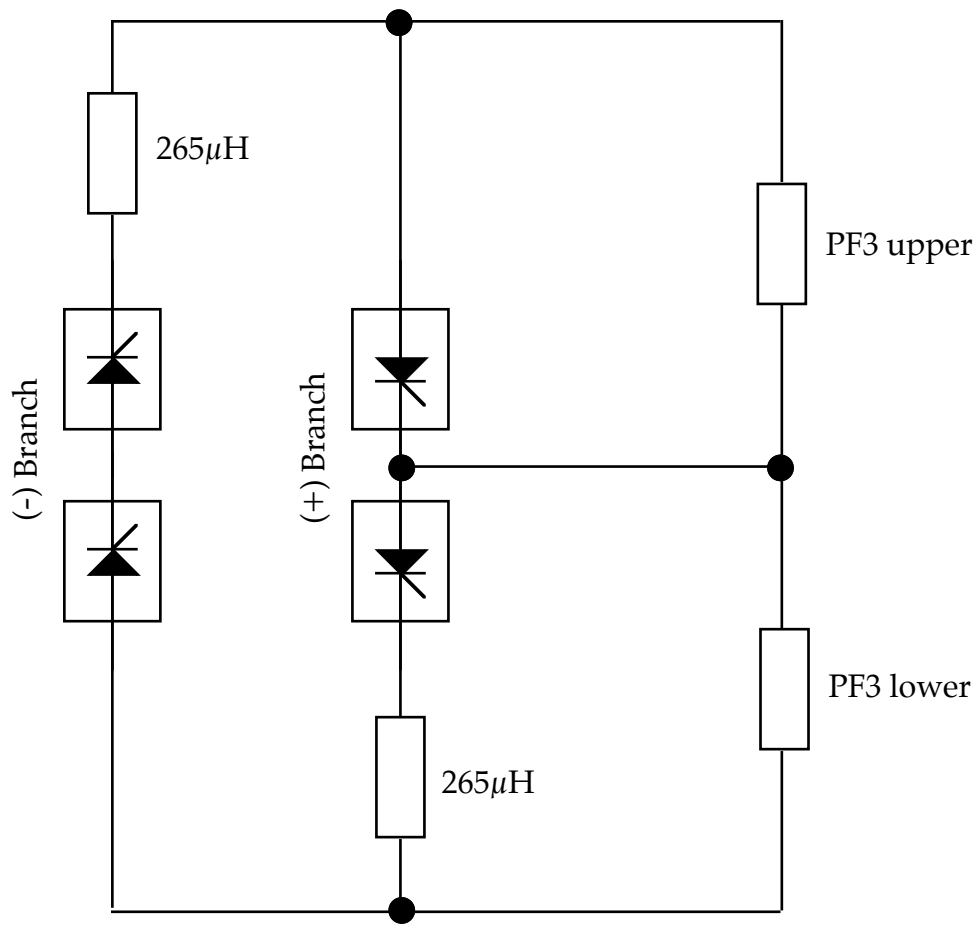


Proposed Power Supply Circuit for PF3

According to the results described herein PF3 requires a 1kV bipolar power supply circuit for the compensation. However, assuming that PF3 will be used for vertical position control during the scenario, the power supply must be also

be able to produce a difference current between the upper and lower PF3 coils. Difference current and driving voltage requirements are unknown at this time; these requirements will be determined later by Project Physics.

The circuit depicted in the figure below is proposed for PF3.



Two D-site power supply sections ($\pm 1\text{kV}$, $+24\text{kA}$ -6sec/300sec each) are connected in series in each of two anti-parallel branches. Each branch contains a $265\mu\text{H}$ inductor for limiting circulating current and rate of rise of fault current.

During plasma initiation, the (-) branch drives the current in the required direction for compensation. The voltage is set on the (+) branch to exclude any current flow. The current in the upper and lower coils is exactly equal since they are in series, so no radial field error is produced.

Following initiation the current reverses and flows in the (+) branch. The voltage is set in the (-) branch to exclude the current. Difference currents can be produced between the upper and lower coils, of either polarity, in order to produce a radial field for vertical position control.

The proposed circuit differs somewhat from the baseline presently assumed by the WBS 5 power systems, not in terms of the number of power supply sections

but instead the manner of connection and control. Further study will be required to determine the most cost effective implementation. Issues to contend with are...

- Need for independent control of the power supply sections (presently, pairs of power supply sections (two 6-pulse bridges which form a 12-pulse rectifier) are subject to common control). If the topology shown in the above figure is adopted, then modifications would be required to permit independent control of the two sections from each power supply unit.

- Need for matched AC phasing and source impedance. The phase angle of the AC voltages which feed the anti-parallel connected rectifiers as well as the AC source impedance must be matched for balanced operation. Further investigation will be required to determine if the present rectifier selection meets this criteria, which was not relevant when the rectifiers were to be series connected.

- Placement of $265\mu\text{H}$ reactors. The circuit shown above is not symmetric in terms of the reactors. It may be desirable add another $265\mu\text{H}$ reactor in the upper half of the (+) branch, or move the $265\mu\text{H}$ reactor from the lower half of the (+) branch to the midpoint connection, or to remove the $265\mu\text{H}$ reactor from the lower half of the (+) branch to achieve symmetry.

- Spare power supply sections. The circuit shown does not have any spare units; all the units shown must be available in order to operate as prescribed.

Other Power Supply Options

In case the proposed PF3 circuit is found for some reason not acceptable for both compensation and vertical control duties, another option would be to transfer the vertical control duty to the PF4a coils, with the upper and lower turns connected in anti-series to produce a radial field. In this case PF4a would be used for vertical control, and PF4b&c would be used for radial control.

The PF3 power supply would still have to be bipolar, but a 1kV configuration could be used.

The PF4a power supply would have to be bipolar, but hopefully the existing D-site bipolar supply (+/- 1kV, +/-5kA-6sec/300sec) would be adequate.

cc:

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NSTX File