Time varying magnetic flux simulations of the NSTX and HIT-II experiments

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ABSTRACT

As part of the Coaxial Helicity Injection (CHI) collaboration between the University of Washington and the Princeton Plasma Physics Laboratory, a method for modeling the time varying magnetic geometry in a low aspect ratio tokamak has been developed. The model includes mutual inductance effects of an arbitrarily shaped conducting shell, poloidal field coils, a saddle coil with finite gap resistance, and a single element, distributed plasma current. The plasma current distribution is specified using EFIT results, and remains unchanged during the simulation, while the magnitude of the plasma current can be changed linearly over time. The model can be utilized to predict the tracking capabilities of the poloidal field coil feedback mechanisms for a given demand of flux boundary conditions. The resulting simulations are used to verify power supply requirements for the National Spherical Torus Experiment (NSTX) under CHI operation. Results from simulations of NSTX and the Helicity Injected Torus II (HIT-II) are shown.

Overview

- Motivation
- Theory & Equations
- Feedback mechanisms on HIT-II and NSTX
- Implementation of the SOAK code
- Results for HIT-II
- Results for NSTX
- Summary

Motivation

The University of Washington in collaboration with the Princeton Plasma Physics Laboratory has proposed a three-year program to study Coaxial Helicity injection (CHI) on the National Spherical Torus Experiment (NSTX) as a method of formation and sustainment of a spherical tokamak. CHI is a steady state method of current drive that does not require a transformer and is compatible with low aspect ratio tokamaks[1]. The Helicity Injected Torus (HIT) experiment at the University of Washington has achieved plasma currents of up to 250kA with an injector current of about 20kA in a low aspect ratio (A=1.5) geometry [2]. On NSTX it is planned to use CHI to startup the spherical tokamak and to drive the edge plasma during sustained operation. In order to determine whether or not the power supplies intended for use on NSTX will be capable of maintaining desirable flux boundary conditions throughout the discharge, a computational model of the time varying magnetic field geometry is needed. Similar calculations have been performed for the HIT-II experiment at the University of Washington.

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[1] T. R. Jarboe, “Formation and steady-state sustainment of a tokamak by coaxial helicity injection.”, *Fusion Technology*, **15**, 7 (1989).

[2] B. A. Nelson, T.R. Jarboe, D J. Orvis, L. McCullough, J. Xie, C. Zhang, and L. Zhou, *Phys. Rev. Lett*. 72, 3666 (1994).

Theory & Equations

The simulation code models the interaction between all conducting material elements on the experiment, assuming toroidal symmetry in all elements except for the saddle coil. There are 4 different element types which are considered:

1. vessel elements (passive)

   $\tilde{R} = 0, \tilde{V} = 0, R \neq 0, V \neq 0$

2. driven coils (active)

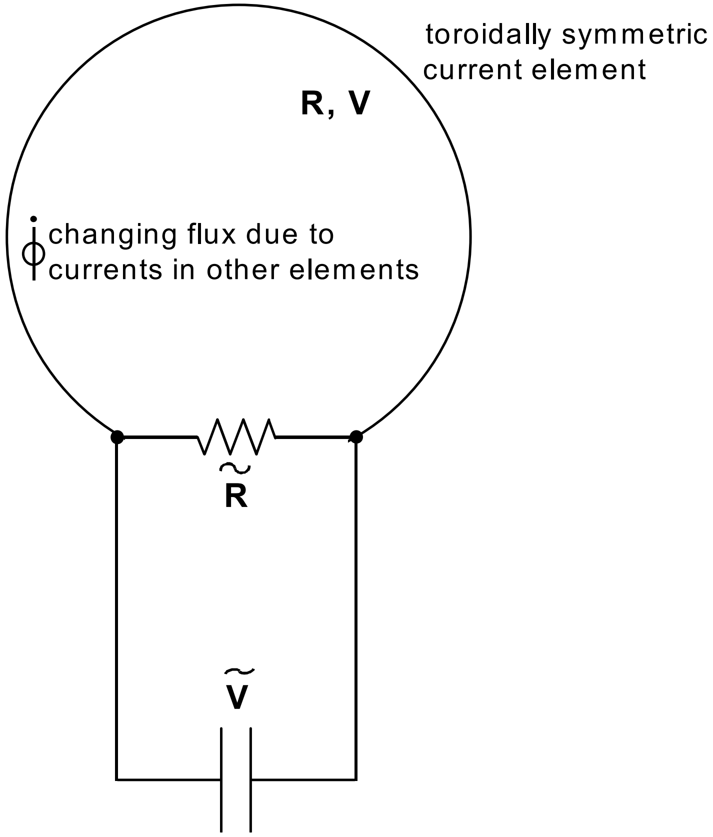
   $\tilde{R} = \infty, \tilde{V} \neq 0, R \neq 0, V \neq 0$

3. saddle coil elements (passive)

   $\tilde{R} \neq 0, \tilde{V} \neq 0, R \neq 0, V \neq 0$

4. plasma current (modeled as a single, distributed, driven coil; equivalent to item 2 - active)

The plasma curent distribution is taken from EFIT results and remains unchanged during the simulation. The total plasma current is increased linearly over time to simulate the effect of a CHI driven plasma.



Theory & Equations (continued)

To find the current generated by two time-varying DC voltage sources, the contributions of each voltage source is super-imposed.[3] V is the voltage due to self and mutual inductance. M is defined as a matrix that contains the mutual inductance values for all elements.[4]

In order to utilize the equations in a computational simulation they need to be discretized over each time-step, where the voltage ($\tilde{I}R_i$) is held constant over the time-step.

Power supply contributions are separated in V_{app}. The saddle coil contributions are incorporated into a single matrix factor (S).

$$IR = V - \tilde{V}$$

$$\sum_{j=1}^{n}\left(\frac{M_{ij}}{R_i}\right) = \tau_{ij} \qquad \tilde{I}_i = \frac{\tilde{V}_i}{R_i}$$

$$\vec{I}_{j+1} = e^{-\tau^{-1}\cdot\Delta t}\left(\vec{I}_j + \vec{\tilde{I}}_{j+1}\right) - \vec{\tilde{I}}_{j+1}$$

$$\vec{I}_{j+1} = e^{-\tau^{-1}\Delta t}\left[\vec{I}_j + \left(\frac{\vec{V}_i^{app}}{R_i}\right)_{j+1}\right] - \left(\frac{\vec{V}_i^{app}}{R_i}\right)_{j+1} + \left(e^{-\tau^{-1}\Delta t} - \vec{1}\right)\left(\vec{a}\cdot\vec{I}_{j+1}\right)\cdot\left(\frac{\vec{R}_{eq}}{R_i}a_i\right)$$

$$\vec{I}_{j+1} = \overleftrightarrow{S}^{-1}\left[e^{-\tau^{-1}\Delta t}\left(\vec{I}_j + \left(\frac{\vec{V}_{app}}{R_i}\right)_{j+1}\right) - \left(\frac{\vec{V}_{app}}{R_i}\right)_{j+1}\right]$$

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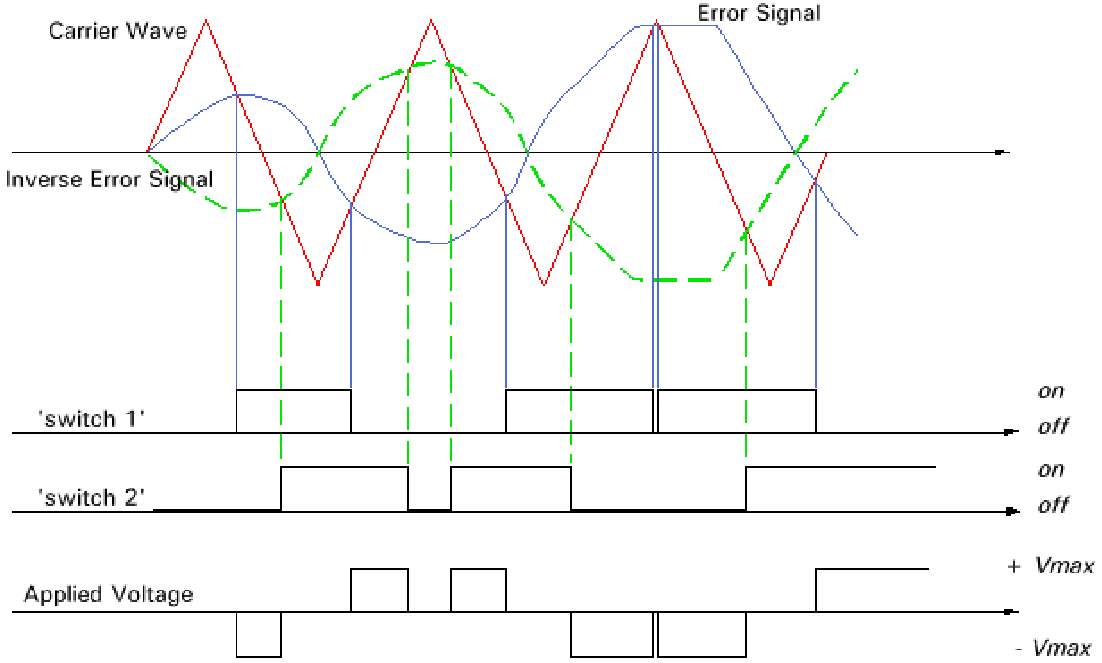
[3] D. E. Johnson, *et all*, “Basic Electric Circuit Analysis”, 5th Edition, !995, Prentice-Hall, pp.198.

[4] D. J. Griffiths, “Introduction to Electrodynamics”, 2nd Edition, 1989, Prentice-Hall, pp. 293

Feedback mechanisms on HIT-II and NSTX

HIT-II: Pulse Width Modulation

- Voltage is constant
- Coils are driven by pulses of varying duration
- Pulse length is determined by the error between flux demand and measured flux
- Error is 'sampled' by a carrier frequency



NSTX: Voltage Amplitude Modulation

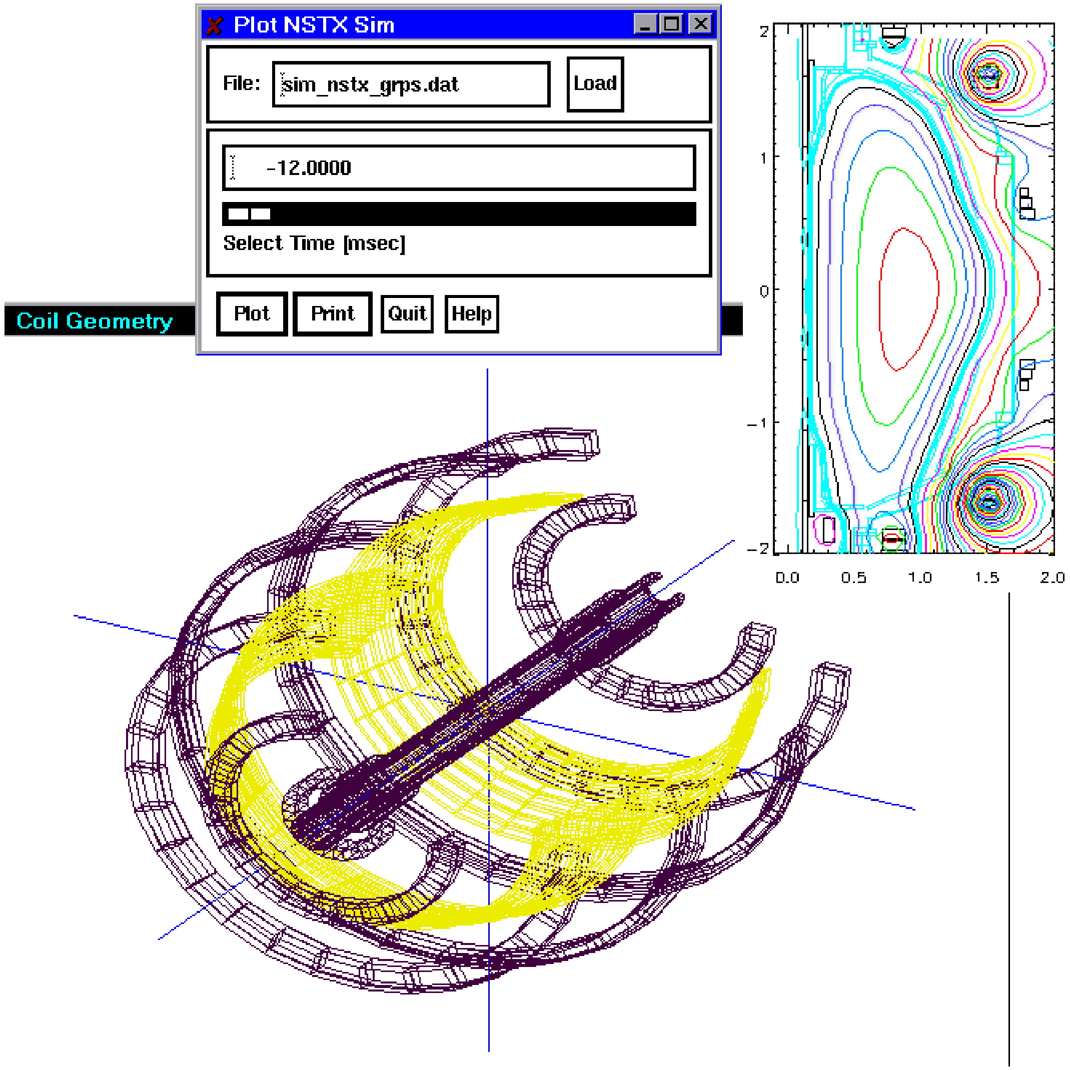
- Voltage varies smoothly over time
- Coils are driven continuously
- Amplitude is determined by the error and its derivative, clipped to reflect hardware capabilities

$$\text{Error} = \frac{\Phi_{\text{demand}} - \phi_{\text{error}}}{\left|\phi_{\text{demand}}\right| + \exp\left(-0.01\left|\phi_{\text{demand}}\right|\right)}$$

$$V_{\text{app}} = \text{G1}\left(\left(1 - \text{G2}\right)\text{Error} + \text{G2}\frac{\partial}{\partial t}\text{Error}\right)$$

Implementation of the SOAK code

- Geometry setup in IDL
- Green Functions calculations in FORTRAN
- Simulation Parameter Setup in IDL
- Output visualization in IDL



File: sim_nstx_grps.dat

-12.0000

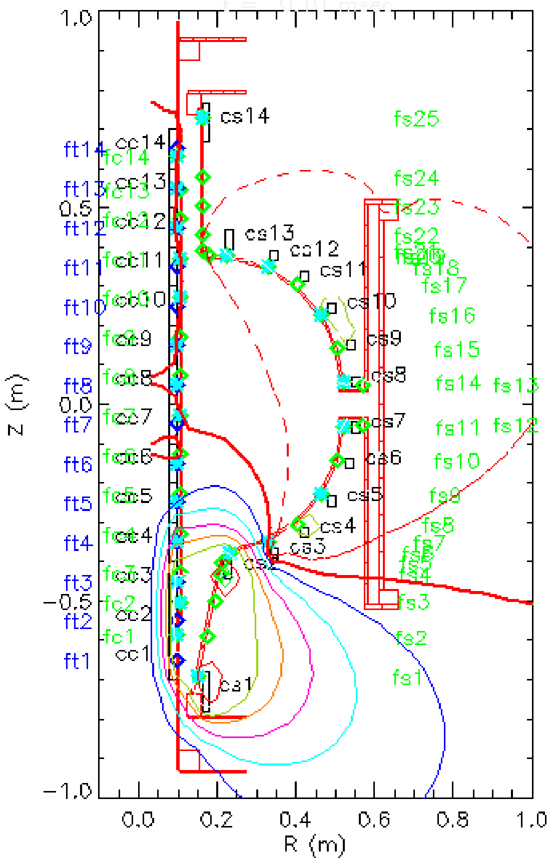
Select Time [msec]

NSTX
Soak
Through
Simulation

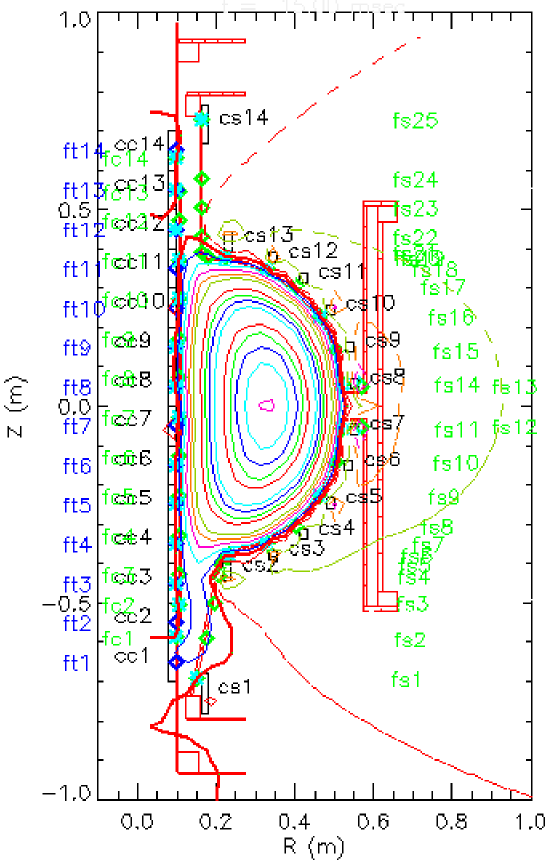
University of Washington &
Princeton Plasma Physics Lab
CHI Collaboration

Results for HIT-II

Vacuum Magnetic Flux Geometry

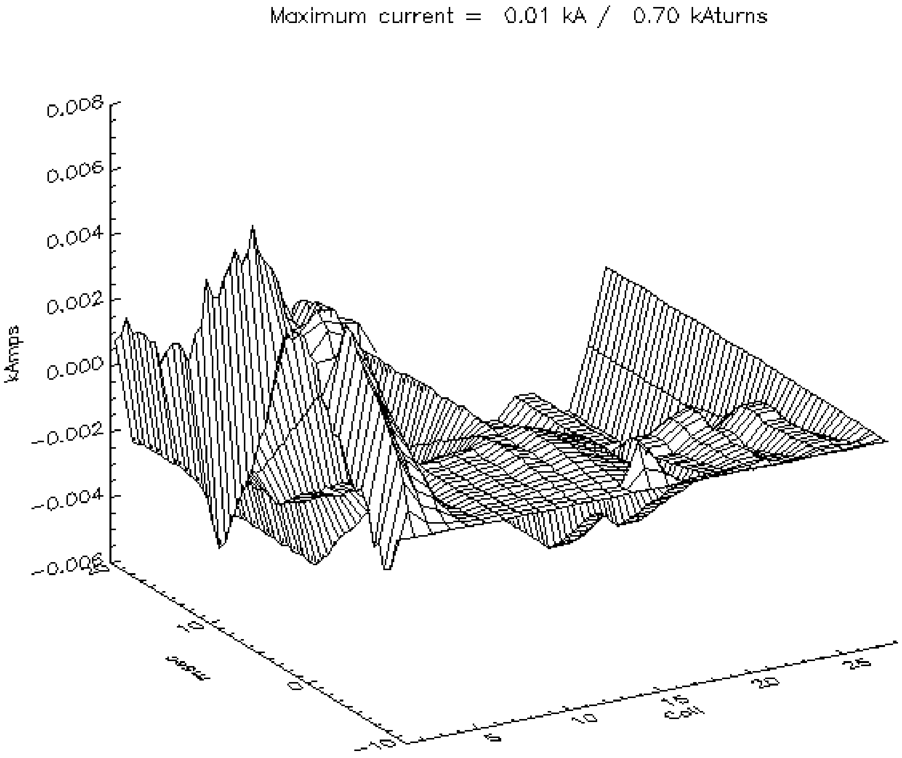


325 kAmps Plasma Current

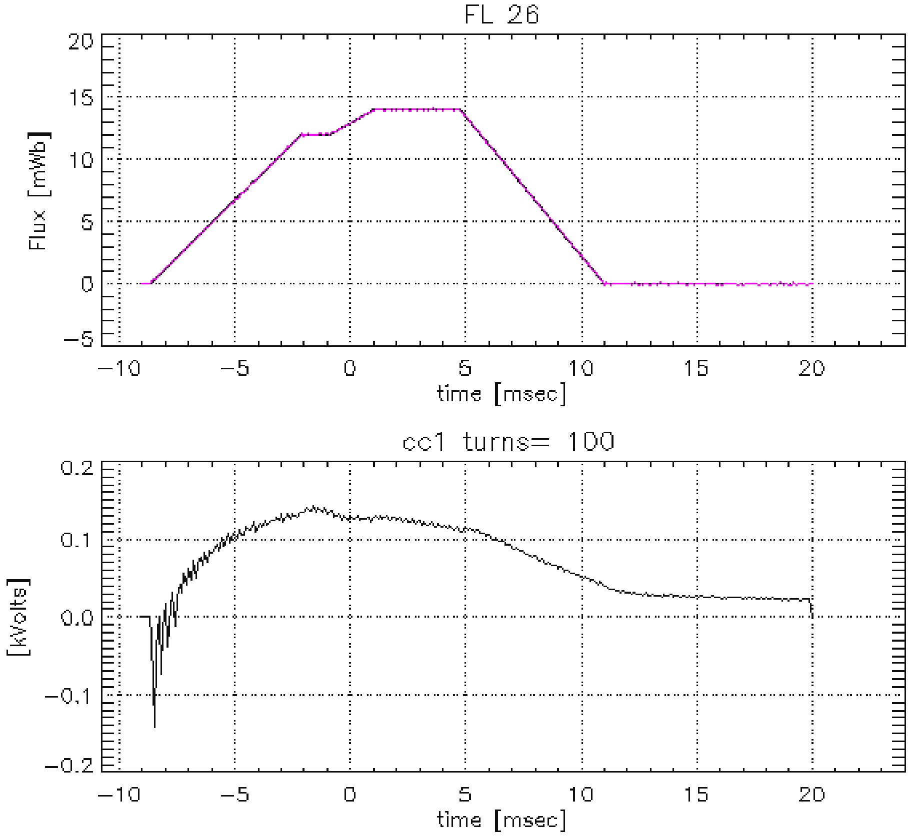


Results for HIT-II (continued)

HIT-II Coil Currents

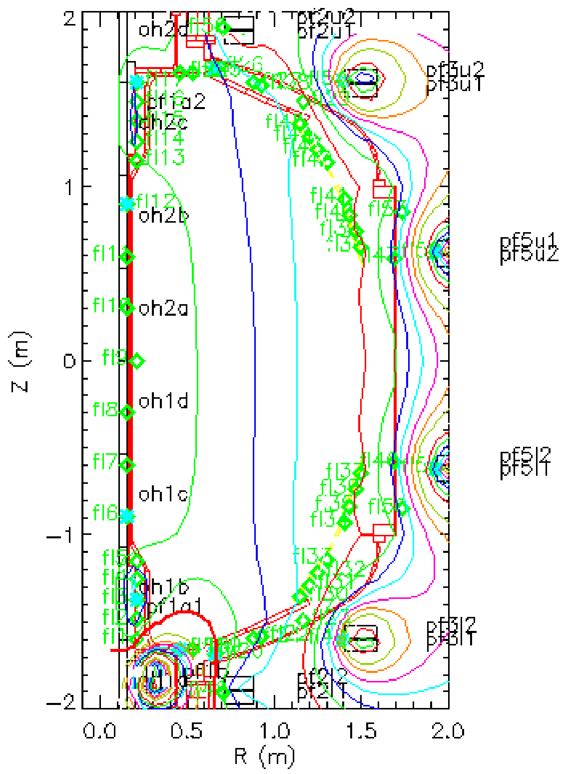


Flux Demand / Output for CC1, PFC A



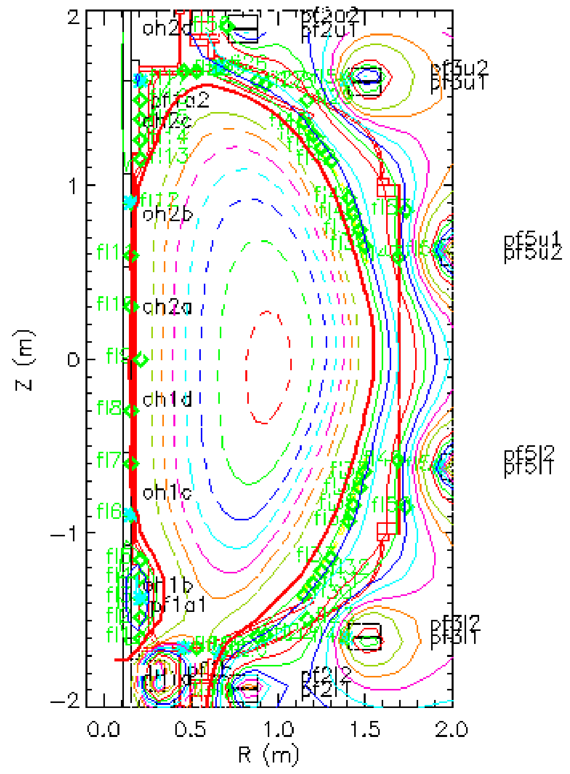
Results for NSTX

Vacuum Magnetic Flux Geometry



PF1B:	-18.13 kA / -507.6 kA-turns	PF1A1:	8.67 kA / 416.18 kA-turns
PF2L:	0.95 kA / 28.60 kA-turns	OH1:	0.55 kA / 265.10 kA-turns
PF3L:	1.65 kA / 50.40 kA-turns	OH2:	0.57 kA / 274.74 kA-turns
PF5L:	1.62 kA / 38.88 kA-turns	PF1A2:	5.07 kA / 243.36 kA-turns
PF5U:	1.61 kA / 38.64 kA-turns		
PF3U:	1.75 kA / 52.50 kA-turns	time:	0.00 msec
PF2U:	1.39 kA / 38.92 kA-turns	plasma:	0.00 kA

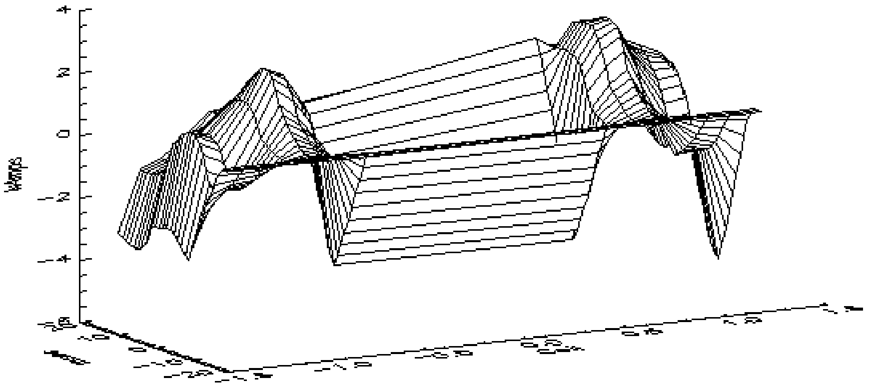
810 kAmps Plasma Current

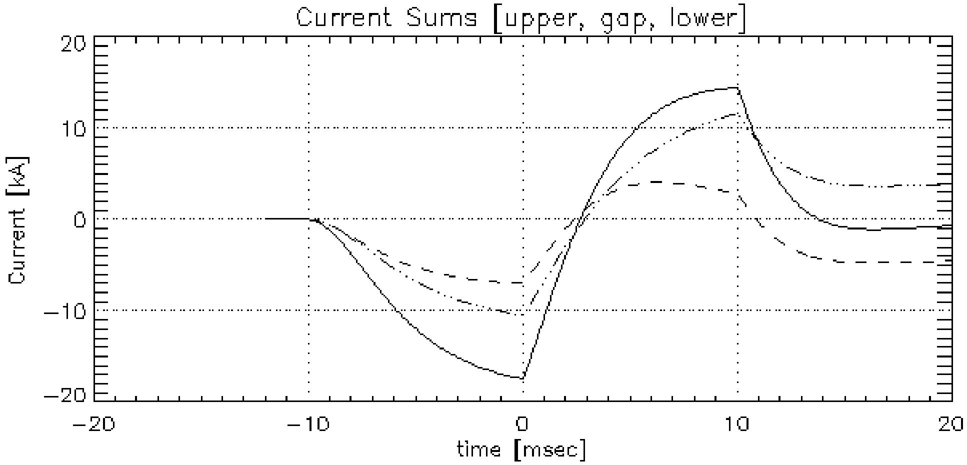


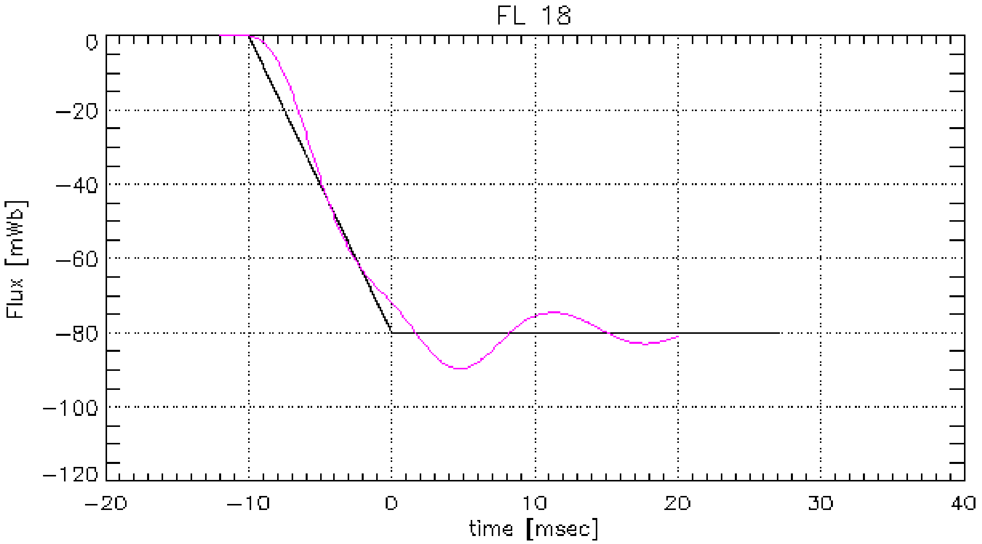
PF1B:	-11.75 kA / -329.0 kA-turns	PF1A1:	7.44 kA / 357.12 kA-turns
PF2L:	4.82 kA / 129.36 kA-turns	OH1:	1.56 kA / 751.92 kA-turns
PF3L:	1.46 kA / 43.80 kA-turns	OH2:	1.60 kA / 771.20 kA-turns
PF5L:	1.75 kA / 42.00 kA-turns	PF1A2:	2.73 kA / 131.04 kA-turns
PF5U:	1.75 kA / 42.00 kA-turns		
PF3U:	1.65 kA / 49.50 kA-turns	time:	10.0 msec
PF2U:	3.31 kA / 92.68 kA-turns	plasma:	-823.77 kA

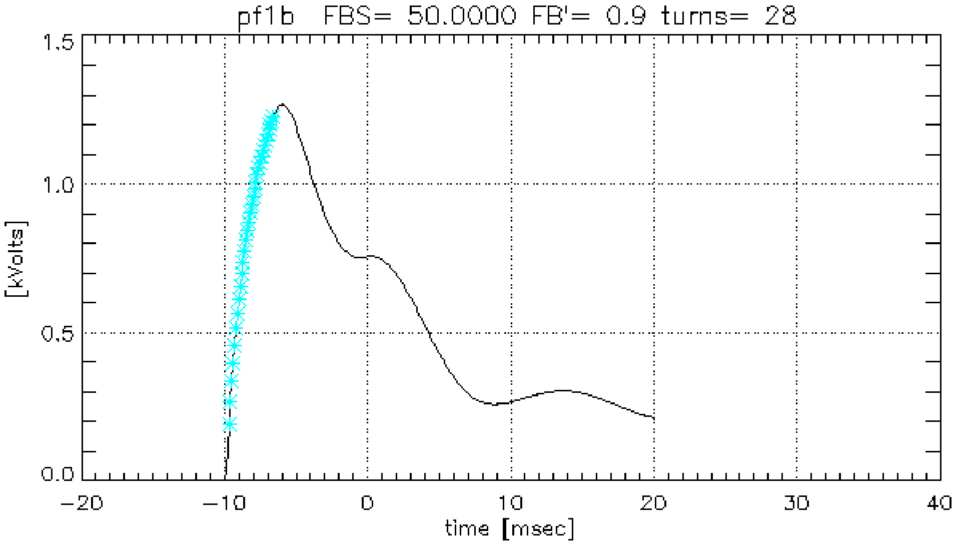
Results for NSTX (continued)

Saddle Coil Currents [kAmps vs. msec, m]









Summary

A code for simulating the time varying magnetic geometry in HIT-II and NSTX was developed. The model includes mutual inductance effects of the conducting shell, poloidal field coils, a saddle coil with finite gap resistance (NSTX only), and a single element, distributed plasma current. The plasma current distribution is obtained from EFIT results and remains unchanged during the simulation, while the total plasma current value is ramped linearly over time to simulate CHI current drive on the plasma. Results from simulations of NSTX and HIT-II are shown, incorporating 810 kAmps and 250 kAmps of plasma current respectively, as well as vacuum flux configurations.

The resulting simulation code is a useful tool to predict power supply requirements, and obtain first order estimates of the magnetic flux geometry in the experiment for a given set of flux boundary conditions. The model does not have the capability to recalculate the plasma current distributions for each time-step. However, ohmic current drive effects can be estimated, since the total current value in the plasma current 'coil' will respond to inductive effects from other current carrying elements.

Acknowledgements:

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