Plasma Confinement Optimization of the Versatile Toroidal Facility for Ionospheric Plasma Simulation Experiments

by
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S.B., Electrical Engineering, Massachusetts Institute of Technology, (1989)

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Abstract

In this thesis, I designed two coil systems for the Versatile Toroidal Facility (VTF) at the Nabisco Laboratory of the Plasma Fusion Center. These coil systems will enable VTF to confine plasmas generated by ECRH,OH, or both, and thereby will enhance its capacity to be versatile enough to run experiments such as ionospheric plasma simulation and high β plasma research. I have carried out elliptic integral calculations to find vacuum field of the coils, and then for the more complete design, I have used ASEQ code in the Cray Supercomputer at the Lawrence Livermore National Laboratory to solve the two-dimensional, nonlinear Grad-Shafranov equation.

Thesis Supervisor: Prof. Min-Chang Lee
Title: Leader, Plasma Fusion Center Ionospheric Plasma Research Group

Acknowledgments

It is difficult to be truly grateful, for the true and sincere gratitude is not in the form of words but of actions. I will make an attempt here to express my appreciation for those who gave me much more than just a helping hand.

First of all, I would like to thank Prof. Min-Chang Lee, my advisor, for his support and guidance over the past four years. He has given me more than what I can ever ask for from any research advisor. It has been a great privilege to write both bachelor's and master's thesis under his supervision. I also thank the fellow students in the Ionospheric Plasma Research Group, who have shown me the great teamwork in action as well as genuine friendship. I feel fortunate that I have had the opportunity to benefit from the interactions with them, especially Keith Groves, Bob Duraski, and Masanori Onozuka. Special thanks go to Dr. S. Wolfe, Dr. M. Gaudreau, and Dr. S. Luckhardt of Plasma Fusion Center for their assistance in working on this thesis.

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Chapter 1

Introduction

The study of nonlinear radio wave propagation and absorption in the ionosphere involves field experiments which require extensive use of radars that are not easily accessible at times. The stringent requirements on time, season, and location of the experiments due to the specific ionospheric conditions necessary for certain ionospheric effects make it even more difficult to conduct these field experiments.

A convenient way to test an ionospheric plasma theory or to confirm a field experiment is to simulate the phenomenon in a more controlled setting, namely in a laboratory environment. To facilitate laboratory simulation of ionospheric plasma, Prof. Min-Chang Lee and his students of the Plasma Fusion Center Ionospheric Plasma Group have built the Versatile Toroidal Facility (VTF). The VTF project has already given the students an ample opportunity to learn the engineering principles and practices by active and direct participation in the building process.

Confinement of plasma in VTF raised a few interesting points. One of them was the issue of which poloidal field (PF) system should be used. MIT has always been building air-core systems for its tokamaks, whereas many of VTF's components came from a discontinued project, ISX-B, of the Oakridge National Laboratory, which had an iron-core system. As a matter of fact, some of the largest parts were from ISX-B, such as inner and outer torque cylinders and toroidal field (TF) coils. Since the dimensions of these two machines are very similar, using the existing iron-core design would be much simpler. However, the material cost of an iron core being so prohibitive and manufacturing cost being one of the most serious concerns in this project, the iron core was not a viable option.

Another issue stemmed from the versatility of the machine. Prof. Lee's objectives were to build the facility to simulate the ionospheric plasmas, but on the other hand, VTF can offer the flexibility to perform experiments other than its primary purposes. To facilitate these experiments, it became clear that VTF should have more than one mode of confinement. In the future, VTF will be able to confine plasmas generated by electron cyclotron resonance heating (ECRH), by ohmic heating (OH), or by both ECRH and OH.

Much of the usage of the VTF being ionospheric plasma research, it was necessary to design a coil system for a non-ohmically heated plamsa. A theory of and the equations for confinement of EC preionized plasma were employed to calculate the coil system that would give a relatively uniform vertical field to counter the $\mathbf{E} \times \mathbf{B}$ drift. A set of coils similar to Helmholtz coils were designed and built according to my vacuum field calculation on a PC using a program containing elliptic integrals on MATLAB, a mathematical software.

The first phase of the poloidal field coil system design for OH operations was also to make vacuum field calculations through which I found the shaping of the magnetic field in the chamber without the plasma. Next, I used ASEQ Code (a free boundary MHD code) to solve the two dimensional and nonlinear Grad-Shafranov equation on the Cray Supercomputing facility at the Lawrence Livermore National Laboratory.

Chapter 2

Theory and Background

In this chapter and the following chapters, the geometric parameters of plamsma are in accordance of the definitions shown in the Figure 2-1.

2.1 Confinement for ECRH Plasma

In the toroidal plasmas, the most serious problem with confinement is $\mathbf{E} \times \mathbf{B}$ drift which is caused by $\nabla\mathbf{B}$ and curvature drifts of electrons and ions. The motions of these particles are given by the following equation for drift velocity:

$$\mathbf{v}_R + \mathbf{v}_{\nabla\mathbf{B}} = \frac{m}{q} \frac{\mathbf{R}_c \times \mathbf{B}}{R_c^2 B^2} [v_{\parallel}^2 + \frac{1}{2} v_{\perp}^2].$$

This causes the slight separation of electrons and ions vertically and thus creates vertical electric field, $\mathbf{E_z}$. This electric field, $\mathbf{E_z}$, and the toroidal magnetic field, $\mathbf{B}_\phi$, cause the $\mathbf{E} \times \mathbf{B}$ drift as is given by the equation,

$$\mathbf{v}_\times = \frac{\mathbf{E_z} \times \mathbf{B}_\phi}{B_\phi^2}.$$

In ohmically heated (OH) plasmas, the induced current due to the vortex electric field provides the poloidal magnetic field in the plasma. This can be shown simply by combining the Ohm's Law and the Ampere's Law (without the dielectric current, $\partial\mathbf{D}/\partial t$), i.e.

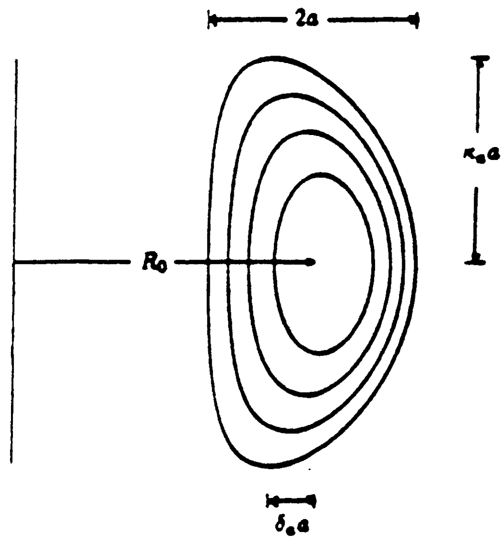

Figure 2-1: Geometric Parameters of Plasma

$$\nabla \times \mathbf{B} = \frac{\mu_o \mathbf{E}}{\eta},$$

where η is the resistivity of plasma.

The slight twist of the toroidal magnetic field lines due to the poloidal field makes the rotational transform, by which the particles traveling along the field lines rotate poloidally as they travel in the toroidal direction. This poloidal motion of the particles effectively reduces the $\nabla \mathbf{B}$ and curvature drifts. (A rotational transform can be approximated as $\iota = 2\pi \frac{R_o B_\theta}{r B_\phi}$).

Now, when the VTF is used for its primary purpose, ionospheric simulations, the plasma will be produced by electron cyclotron resonance heating (ECRH) not by ohmic heating (OH). Since the poloidal field, B_θ, will not be created by the OH system, we need a different mechanism to drive a current in the plasma, and in turn to induce the poloidal magnetic field, B_θ.

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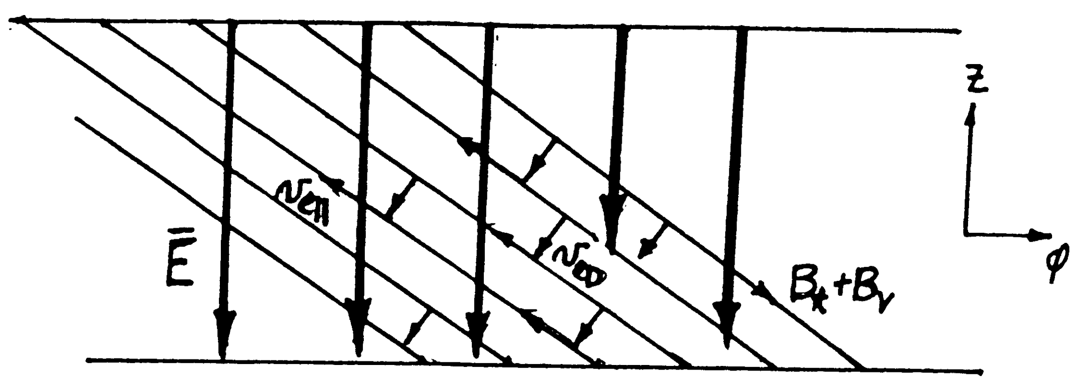


Figure 2-2: Applied Vertical Field in EC Preionized Plasma

of Atomic Energy have worked on the theory of confinement of EC-preionized plasma in a torus with applied toroidal and vertical magnetic fields. [3]

As shown in Figure 2-2, to close the vertical electron circuit, produced by $\nabla\mathbf{B}$ and curvature drifts, we can apply vertical field, B_v. Because of the diffusion along the slanted field lines, as long as the condition, $v_{e\|}|_z \approx -v_{eD}|_z$, is met, the overall vertical drift of electrons can be reduced. For a Maxwellian, this condition can be expressed as

$$|\frac{v_{e\|}B_v}{B}| \approx \frac{m_e v_{th}^2}{eR|B|}.$$

According to the fluid theory, the parallel velocity of electrons, $v_{e\|}$, gives the parallel electric field,

$$E_\| = \frac{m_e}{e} v_{e\|}\nu_{ei},$$

where collisions with neutrals are neglible. The vertical electric field generated is then,

$$E_v = E_{\|}\frac{B}{B_v} \approx \nu_{ei}\frac{m^2}{e^2}\frac{v_{te}^2 B}{RB_v^2}.$$

This electric field gives, $\mathbf{E} \times \mathbf{B}$ drift, which can be written as

$$v_\times = \frac{\nu_{ei} v_{te}^2 m^2}{e^2 R} B_v^{-2}.$$

Another way for the particles to escape is along the field lines:

$$v_{amb} = v_{e\|}|_z = \frac{B_v}{B}\sqrt{\frac{T_e}{m_i}}.$$

The confinement time is then,

$$\tau = \frac{a}{v_\times + v_{amb}}.$$

Noting that

$$v_\times = \frac{2m_e T_e}{e^2 RB_v^2}\nu_{ei} = 2.4 \times 10^{-4}\frac{m_e}{e^2}\frac{n_i}{R}\frac{\ln\Lambda_{ei}}{T_e^{1/2}B_v^2}$$

for quasi-neutral plasma, we can express the confinement time as

$$\tau = \frac{a}{Cn_e T_e^{-1/2} RB_v^{-2} + DT_e^{1/2} B_v B^{1/2}},$$

where

$$C = 2.4 \times 10^{-4}\frac{m_e}{e^2}\ln\Lambda_{ei}$$

$$D = m_i^{-1/2}$$

and a is the minor radius of plasma.

To make a uniform, vertical magnetic field in the plasma region, one should consider a Helmholtz coil as shown in Figure 2-3. The field in the center of the radius and in the middle of the top and the bottom coils is

$$B_z = \frac{3.2 \times 10^{-6}\pi NI}{5^{3/2}R},$$

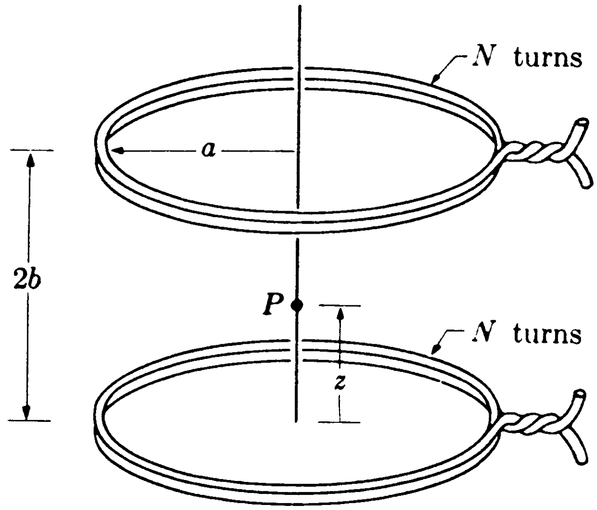


Figure 2-3: Helmholtz Coil

given I in amp, R in meters, and B in Tesla.

2.2 Ohmic Heating Coils

A part of ohmic heating can be simply shown by the principle of a transformer, where the set of ohmic heating coils works as the primary and the plasma the secondary. When the current in the primary coil is turned on, it creates a magnetic field (vacuum field) as shown in the Ampere's Law (without the displacement current), i.e.

$$\nabla \times \mathbf{B} = \mu_o \mathbf{j}.$$

The change of this magnetic field in time (due to the change of the current) causes the current in the plasma, in accordance with the Faraday's Law,

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}.$$

For DC current, the conductivity of plasma is given by

$$\sigma = \frac{50\pi^{1/2}\epsilon_0^2(kT_e)^{3/2}}{m_e{}^{1/2}e^2 Z \ln\Lambda}$$

or

$$\sigma = 1.45 \times 10^{-2}\frac{T_e{}^{3/2}}{Z\ln\Lambda}.$$

Noting that

$$P_\Omega = \frac{j^2}{\sigma},$$

where P_Ω and j are ohmic heating power density and plasma current density, respectively, we can show that

$$P_\Omega = 6.90 \times 10\frac{j_\phi^2 Z\ln\Lambda}{T^{3/2}}.$$

For MHD stability, there is a limit on the value of j_ϕ. The value of this limit is obtained from the following relations:

$$q(r) = \frac{r}{R}\frac{B_\phi}{B_\theta},$$

$$B_\theta(r) = \frac{\mu_o \int_0^r j(r')2\pi r' dr'}{2\pi r},$$

$$< j >_r = \frac{\int_0^r j(r')2\pi r' dr'}{\int_0^r 2\pi r' dr'},$$

and therefore,

$$q(r) = \frac{2B_\phi < j >_r}{\mu_o R}.$$

The volume average, $< j >_r$, is identical to $j_\phi(r)$ at $r = 0$. So the maximum current at the center of the plasm for MHD stability is

$$j_\phi(0) = \frac{2B_\phi}{\mu_o R_o q(0)}.$$

Setting $q(0) = 1$ (consistent with MHD kink stability), the maximum ohmic heating power at $r = 0$ is

$$P_\Omega^{max}(0) = 1.75 \times 10^{14} \frac{Z B_\phi^2 \ln \Lambda}{R_o^2 T_e^{3/2}}.$$

2.3 Equilibrium and Stability

In section 2.1, it was explained how the rotational transform helped confinement of toroidal plasma and how the rotaional transform was produced by providing the poloidal B field, B_θ. One of the ways to create the B_θ is by inducing the plasma current, I_p. The poloidal field created by the plasma current is given by the relation,

$$B_\theta(r) = \frac{\int_0^r 2\pi r' j_\phi(r') dr'}{2\pi r}.$$

Even with the rotational transform, a toroidal plasma tends to expand out. To achieve the equilibrium, it is necessary to provide a vertical field that balances this expanding force.

2.3.1 Vertical Magnetic Field

By separating the two radial forces which expand the plasma, the minor and major radial forces, one can linearize the problem of finding the vertical magnetic field required for equilibrium. (In the following several pages, I will summarize the derivations given in the lecture notes by Prof. Ian Hutchinson for Fusion Energy I and II.) The minor force balance can be approximated by modeling the torus into a cylinder and by using the MHD force balance equation,

$$\nabla p = \mathbf{j} \times \mathbf{B}.$$

With the use of Ampere's equation without the displacement current, i.e.

$$\nabla \times \mathbf{B} = \mu_o \mathbf{J},$$

I can obtain the poloidal beta, which is

$$\beta_p = \frac{2\mu_o < p >}{B_\theta^2(a)}.$$

The major radial force balance is a bit more complicated since we cannot simplify the model as a cylinder like the previous case. This force balance can be, again, divided into two types: 1) self magnetic force of plasma current and 2) pressure force.

The self magnetic force per unit length can be derived to be

$$F_m = \frac{\frac{1}{2}I_p^2}{2\pi R}\frac{dL}{dR}$$

where I_p = plasma current, R = major radius, and L = self inductance.

The pressure force is obtained by using $\Delta W_p = -p\Delta V$, where p and V are pressure and volume of the plasma, respectively. It is given by

$$F_p = \frac{2\pi a^2}{R}p$$

where a is minor radius. Therefore the total outward self-force is

$$F_m + F_p = \frac{\frac{1}{2}I_p^2}{2\pi R}\frac{dL}{dR} + \frac{2\pi a^2}{R}p.$$

The pressure, p, in the above equation is actually an average value $< p >$. Replacing p with $< p >$ and factoring out $\frac{\mu_o I_p^2}{4\pi R}$ in this equation, I get

$$F_m + F_p = \frac{\mu_o I_p^2}{4\pi R}[\frac{1}{\mu_o}\frac{dL}{dR} + \frac{8\pi^2 a^2 < p >}{\mu_o I_p^2}] = \frac{\mu_o I_p^2}{4\pi R}[\frac{1}{\mu_o}\frac{dL}{dR} + \beta_p].$$

Now, the inductance, L, has two parts: 1) the external inductance, L_e, from **B** at $r > a$ and 2) the internal inductance, L_i, from **B** at $r < a$. From an elliptical integral calculation and an approximation for a small inverse aspect ratio, $\epsilon = a/R$, the external inductance can be expressed as

$$L_e = \mu_o R[ln\frac{8R}{a} - 2].$$

The internal inductance is obtained from the relationship,

$$\frac{1}{2}L_i I_p^2 = \int_o^a \frac{B_\theta^2}{2\mu_o} 2\pi r dr 2\pi R.$$

Solving for L_i, and using $I_p = 2\pi a B_\theta(a)/\mu_o$, I find

$$L_i = 2\pi R \frac{\mu_o}{4\pi} \frac{< B_\theta^2 >}{B_\theta^2(a)}.$$

The quantity $< B_\theta^2 > / B_\theta^2(a)$ represents dimensionless form of internal inductance, l_i.

The complete inductance of plasma is

$$L = L_e + L_i = \mu_o R[ln \frac{8R}{a} - 2 + \frac{l_i}{2}].$$

To find $F_m + F_p$, it is necessary to get dL/dR. Since the relationship between the minor and major radii is $a^2 \propto R$, it follows that

$$\frac{da}{dR} = \frac{a}{2R}.$$

Therefore, dL/dR, the change of magnetic inductance due to the change of major radius, is

$$\frac{da}{dR} = \frac{\partial L}{\partial R} + \frac{\partial L}{\partial a}\frac{\partial a}{\partial R} = \mu_o[ln \frac{8R}{a} - \frac{3}{2} + \frac{l_i}{2}].$$

Finally, the force balance equation can be written as

$$F_m + F_p = \frac{\mu_o I_p^2}{4\pi R}[ln \frac{8R}{a} - \frac{3}{2} + \frac{l_i}{2} + \beta_p].$$

Now, this force has to be balanced by a force created by $\mathbf{I}_p \times \mathbf{B}_v$. In other words, it is necessary for equilibrium that

$$\mathbf{I}_p \times \mathbf{B}_v = F_m + F_p.$$

The required magnitude of B_v is

$$B_v = \frac{\mu_o I_p}{2\pi a}\frac{a}{2R}[ln\frac{8R}{a} - \frac{3}{2} + \frac{l_i}{2} + \beta_p].$$

2.3.2 Field Index

If the vertical field, B_v, is straight and does not have any curvature, the toroidal plasma is only marginally stable. To calculate the required shape of B_v, one needs to take into account the toroidicity and noncircularity of the plasma.

Mukhovatov and Shafranov (1971) and Yoshikawa (1964) created a model to simplify this calculation, and it uses an approximation by treating plasma as a thin ($\epsilon \ll 1$) current carrying loop of wire. The approximation also assumes that the internal magnetic flux and the effects of plasma pressure are negligible. The derivation is shown in *Ideal Magnetohydrodynamics* by J. P. Freidberg. [1]

To summarize the steps, I can show the following. Using a potential $\phi(R, Z)$ that satisfies $\mathbf{F}(R, Z) = -\nabla\phi$, one can find the condition for vertical and horizontal stabilities by finding the relations for $\partial F_Z(R_o, Z_o)/\partial Z_o < 0$ and $\partial F_R(R_o, Z_o)/\partial R_o < 0$ respectively, given that the equilibrium occurs at the point R_o, Z_o where $F_R(R_o, Z_o) = F_Z(R_o, Z_o) = 0$.

One can find the equilibrium forces to be

$$F_Z = -LI\frac{\partial I}{\partial Z}$$

$$F_R = -LI\frac{\partial I}{\partial R} - \frac{I^2}{2}\frac{dL}{dR},$$

by the simple model of the potential,

$$\phi(R, Z) = \frac{1}{2}LI^2,$$

where

$$L(R) = \mu_o R[\ln(8R/a) - 2].$$

Noting the the poloidal flux, ψ_p, given by

$$\psi_p(R, Z) = LI - 2\pi \int_0^R B_Z(R', Z) R' \, dR'$$

is constant, one can find

$$B_R(R_o, Z_o) = 0$$

$$B_Z(R_o, Z_o) = \frac{I}{4\pi R_o} \frac{dL}{dR_o}.$$

For vertical stability, it must be satisfied that

$$\frac{\partial F_Z}{\partial Z_o} = \frac{I^2}{2R_o} \frac{dL}{dR_o} \frac{R}{B_z} \left(\frac{\partial B_Z}{\partial R} \right)_{R_o, Z_o} > 0.$$

The field index, $n(R_o, Z_o)$, defined by

$$n(R_o, Z_o) = - \left(\frac{\partial B_Z}{\partial R} \right)_{R_o, Z_o},$$

and it is clear that for vertical stability $n > 0$ must be met.

For the horizontal stability, the condition is given by

$$\frac{\partial F_R}{\partial R_o} = \frac{I^2}{2R_o} \frac{dL}{dR_o} [n - 1 - \frac{1}{2} \frac{d \ln L}{d \ln R_o} + \frac{1}{2} \frac{d \ln(dL/dR_o)}{d \ln R_o}] < 0.$$

Taking the limit $\ln(8R_o/a) \gg 1$, one gets the horizontal stability condition to be

$$n < \frac{3}{2}.$$

2.4 Elliptic Integrals and Vector Potentials

To find the magnetic field (or more precisely, magnetic induction), **B** due to a set of coils, one can first calculate the magnetic field generated by a loop of current and then sum up the fields due to each turn by adding vector components.

The first step is shown on pages 177-8 of *Classical Electrodynamics* by J. D. Jackson. [2]

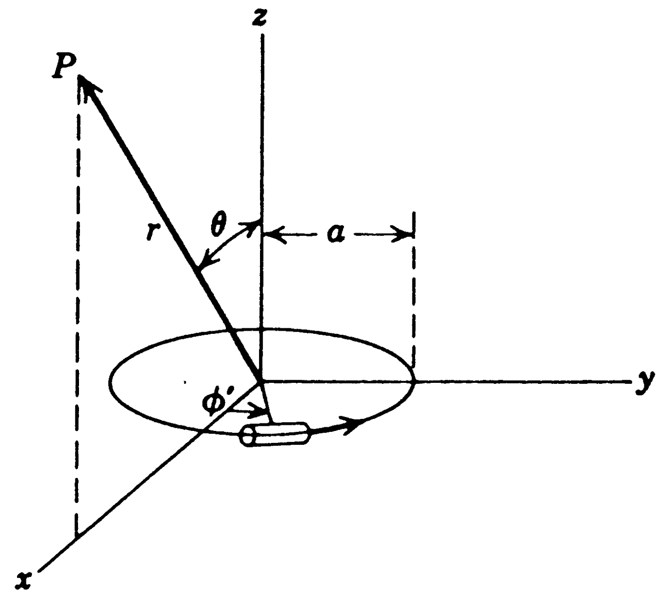


Figure 2-4: Loop of Toroidal Current and Vector Potential

To briefly explain his derivation, I can show that he uses a coordinate system shown in Figure 2-4, and that the loop of current is given as

$$J_\phi = I \sin\theta' \delta(\cos\theta') \frac{\delta(r' - a)}{a},$$

where the vectorial current density, $\mathbf{J}$, is

$$\mathbf{J} = -J_\phi \sin\phi' \mathbf{i} + J_\phi \cos\phi' \mathbf{j}.$$

Integration over the delta function gives the ϕ component, the only nonzero component, of the vector potential, $\mathbf{A}$, to be

$$A_\phi(r,\theta) = \frac{\mu_o I a}{4\pi} \int_0^{2\pi} \frac{\cos\phi' d\phi'}{(a^2 + r^2 - 2ar\ \sin\theta cos\phi')^{1/2}},$$

where I have changed the units from the cgs system to SI. This can be expressed in terms of complete elliptic integrals K and E:

$$A_\phi(r,\theta) = \frac{\mu_o I a}{\pi\sqrt{a^2 + r^2 + 2ar\sin\theta}}[\frac{(2-k^2)K(k) - 2E(k)}{k^2}]$$

where the argument of the integrals, k, is

$$k = \frac{4ar\sin\theta}{a^2 + r^2 + 2ar\sin\theta}.$$

This gives the components of magnetic induction:

$$B_r = \frac{1}{r\sin\theta}\frac{\partial}{\partial\theta}(\sin\theta A_\phi)$$

$$B_\theta = -\frac{1}{r}\frac{\partial}{\partial r}(rA_\phi)$$

$$B_\phi = 0.$$

Chapter 3

Calculation

3.1 Vacuum Field

The first step in the design of the coils was to calculate the profile of the magnetic field inside the vacuum chamber without plasma. There were three separate sets in the vacuum field calculations: Helmholtz coils for ECRH, OH coil system, and EF coil system for OH.

3.1.1 EF Coils for ECRH Mode

In section 2.1, it was shown that the confinement time of a ECRH plasma with a uniform vertical magnetic field can be calculated by this formula:

$$\tau = \frac{a}{Cn_eT_e^{-1/2}RB_v^{-2} + DT_e^{1/2}B_vB^{1/2}},$$

where

$$C = 2.4 \times 10^{-4}\frac{m_e}{e^2}\ln\Lambda_{ei}$$

and

$$D = m_i^{-1/2}.$$

Substituting the values in Table 3.1 for the parameters, I get the profile of con-

$$
\begin{aligned}
a &= 0.27\ cm \\
R &= 0.93\ cm \\
n_e &= 10^{17}\ m^3 \\
T_e &= 10\ eV \\
\ln \Lambda_{ei} &= 13.8 \\
B &= 800 Gauss
\end{aligned}
$$

Table 3.1: Values of Parameters Used for VTF in Parail's Equation

$$
\begin{aligned}
a &= 66'' \\
2b &= 45'' \\
N &= 2\ turns \\
I &= 1.4\ kA
\end{aligned}
$$

Table 3.2: Description of Vertical Field Coils for ECRH Plasma

finement time for different values of vertical field, B_v, as shown in Figure 3-1.

Note the two peaks of confinement time of over 1 millisecond near $B_v = \pm 5$ Gauss. To be on the safe side on the engineering point of view, we have decided to design the coils that would produce three times the value required according to the calculation. I have used the following equation first to find the estimated coil current, with the assumption that we would build a set of coils similar to Helmholtz coils in dimension:

$$NI = \frac{5^{3/2} \times 10 B_z R}{32\pi}$$

where N is number of turns in each of the coils, I current in Ampere, B_z amplitude of vertical magnetic field in Gauss, and R radius of coil in centimeters. Using 10 turns each for top and bottom coils and 65 inches (167.64 cm) for radius, we would need approximately 280 A/turn. It turned out that the field strength began to decay rapidly as the distance from the center approximately reached the half the radius. Unfortunately, that distance was close to the center of the plasma. Therefore, we have placed the top and the bottom coils closer than their radius. The final results

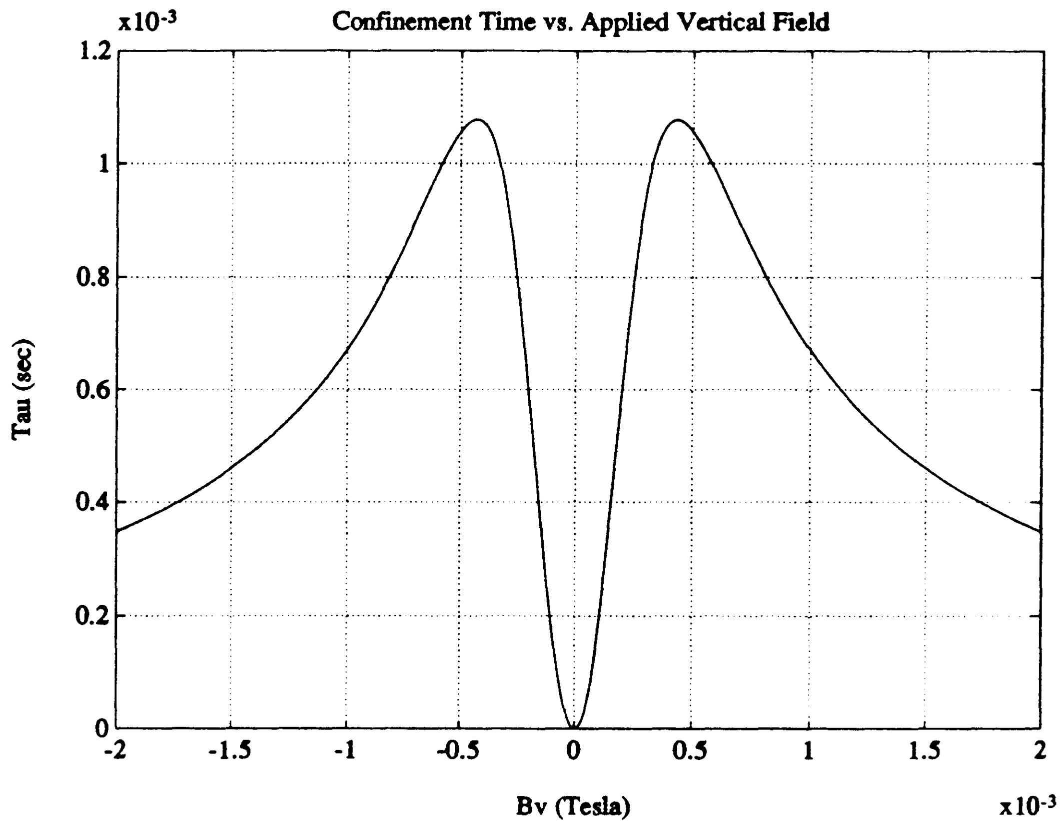


Figure 3-1: Confinement Time of ECRH Plasma with Applied Vertical Field

of the design are given in Table 3.2.

3.1.2 OH Coil System

The main objectives of the OH coil system design were: (1) to maximize the flux linkage between the OH coils and the plasma and (2) minimize the vertical magnetic field (of the OH coils) within the plasma region.

The reason for the first is rather obvious. It makes sense to make as much plasma current with as little coil current as possible. The second objective was for decoupling of OH system from the EF system; the plasma has to be stable while the OH coil current changes rapidly during each shot.

If the cylinder were infinitely long, then the flux linkage would be maximum and there would be no vertical field lines going through the plasma due to OH coils. Given the dimensions of the VTF, this would be more than very difficult to do, however.

To keep the field lines off the plasma, we need more coils (wound toroidally) around the plasma. In the design of the vacuum chamber, there were spaces ($4.25'' \times 2.625''$) on the inner top and bottom sides designated originally for equilibrium field coils (for diverted plasmas). It became necessary that these spaces had to be used for a set of coils to keep the OH coil field lines from entering into the plasma. Because the purpose of these coils was to assist in creating the field null in the plasma, they were called nulling coils.

Even with nulling coils, however, it was still impossible to create the field null. We needed more coils on the outer torque cylinder. These coils were labelled trimming coils, because they were designed to trim out the field lines off the plasma region. The positioning of the trimming coils were not much more flexible than that of the nulling coils; on the outer side of the chamber, there were large ports (typically $19''$ in height) in the middle, which took up almost one-third of the space available. There was another limiting factor: a part of the equilibrium field coils had to be wound on the outer torque cylinder as well. In other words, the space on the outer torque cylinder for the OH trimming coils was very crowded.

The first step in the OH design was to linearize the vertical field strengths of the

$$\begin{aligned} I_{OH} &= 1.4\ kA \\ N_{solenoid} &= 41\ turns \\ N_{null} &= 12 + 12\ turns \\ N_{trim} &= 4 + 4\ turns \end{aligned}$$

Table 3.3: OH Coil Currents

three sets of the OH coils, namely solenoid, nulling, and trimming coils. The profiles of the fields by the coils are shown in Figure 3-2 through Figure 3-4. Without the nulling and trimming coils, the flux due to the solenoid would look like Figure 3-5. As shown in Figure 3-2, also, the vertical component of the **B** would be far from zero in the plasma. I put 10 kA/turn for solenoid and determined the required current in the nulling and trimming coils to achieve the field null. The results are shown in the Table 3.3. The positions of these coils are shown in Figure 3-6. With all three sets of the OH coils in place, the flux and vertical field would be as shown in Figures 3-7 and 3-8. A couple of codes I wrote to carry out these calculations in MATLAB are attached in the Appendix B.

3.1.3 Equilibrium Field Coil System

The next step in the OH system design process was to determine the position and the current of the equilibrium field (EF) coils which would give the plasma a stable equilibrium. The required vertical field for equilibrium is, as has been shown in Chapter 2,

$$B_v = \frac{\mu_o I_o}{4\pi R_o}(\beta_p + \frac{l_i - 3}{2} + \ln\frac{8R_o}{a}).$$

I used the following values for the parameters (some of which were based on assumptions):

$$\begin{aligned} I_o &= 200\ kA \\ R_o &= 0.93\ meters \\ a &= 0.27\ meters \end{aligned}$$

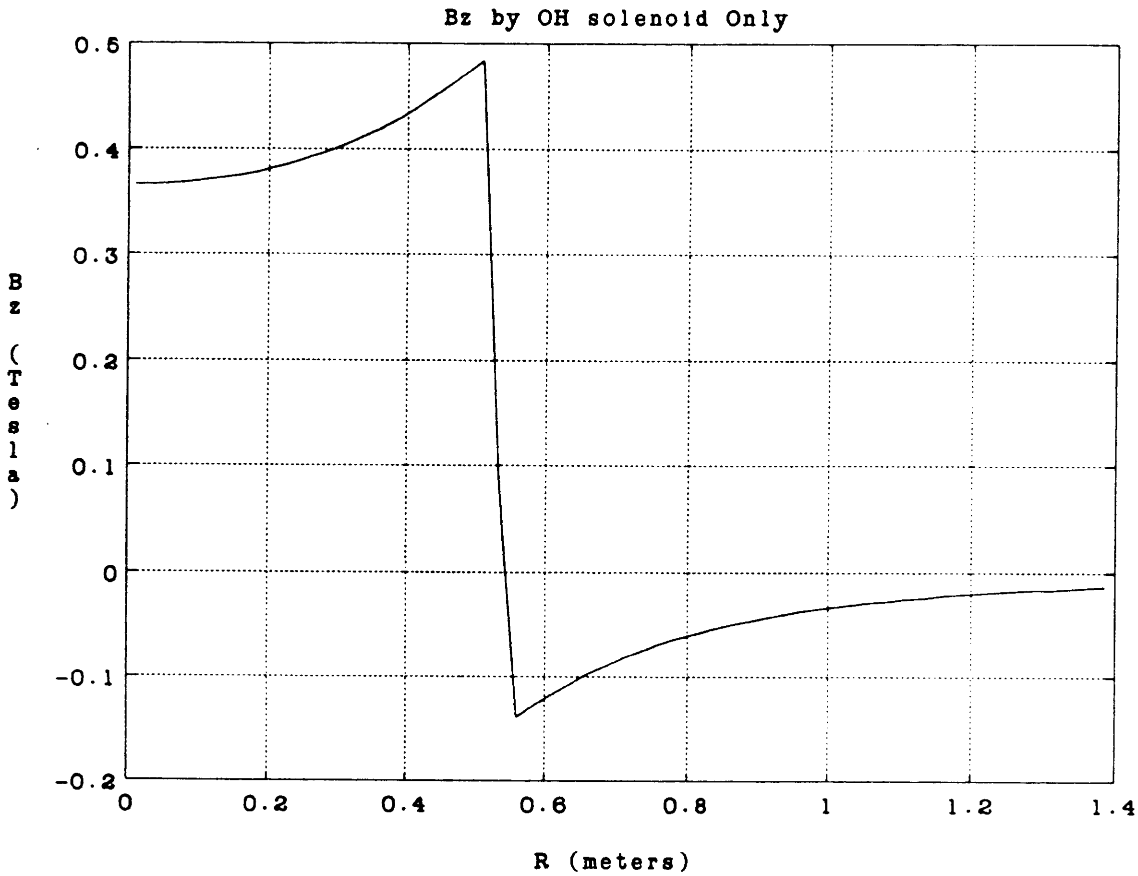


Figure 3-2: B_z at $z = 0$ Induced by Solenoid

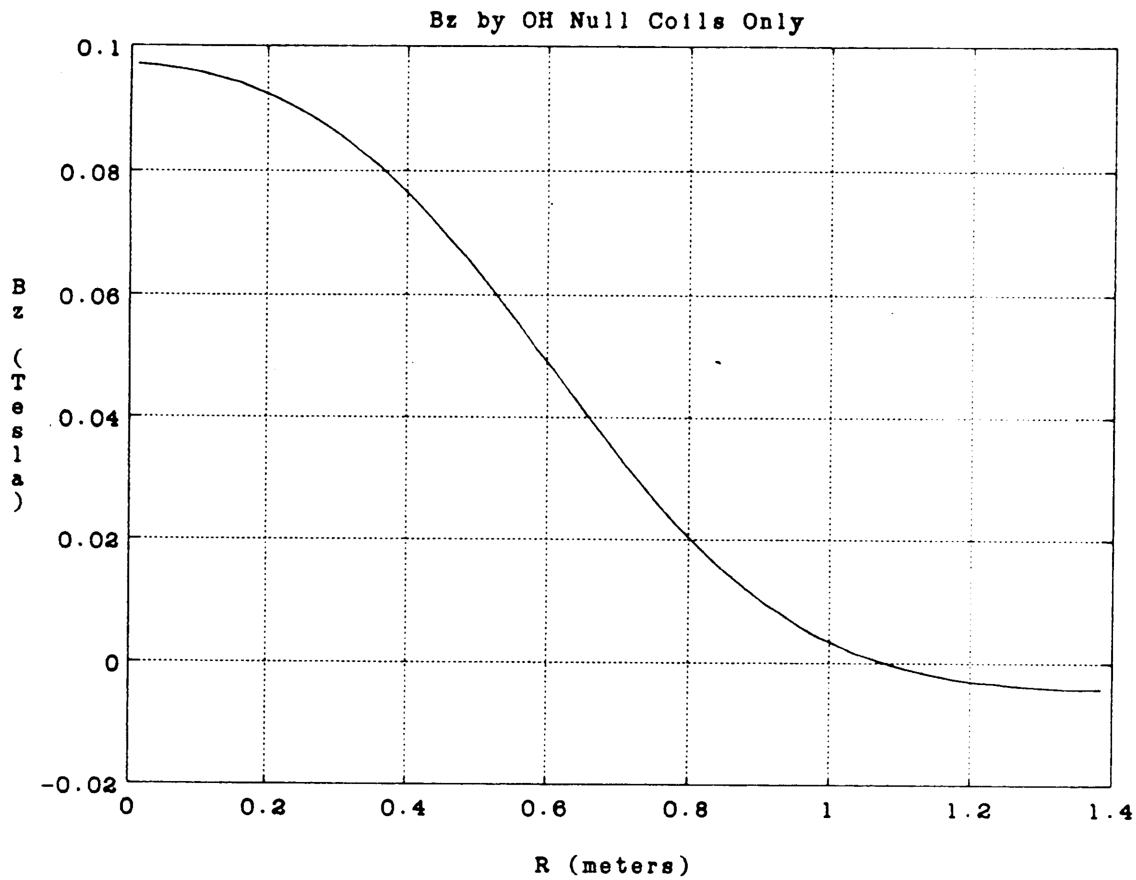


Figure 3-3: B_z at $z = 0$ Induced by Nulling Coils

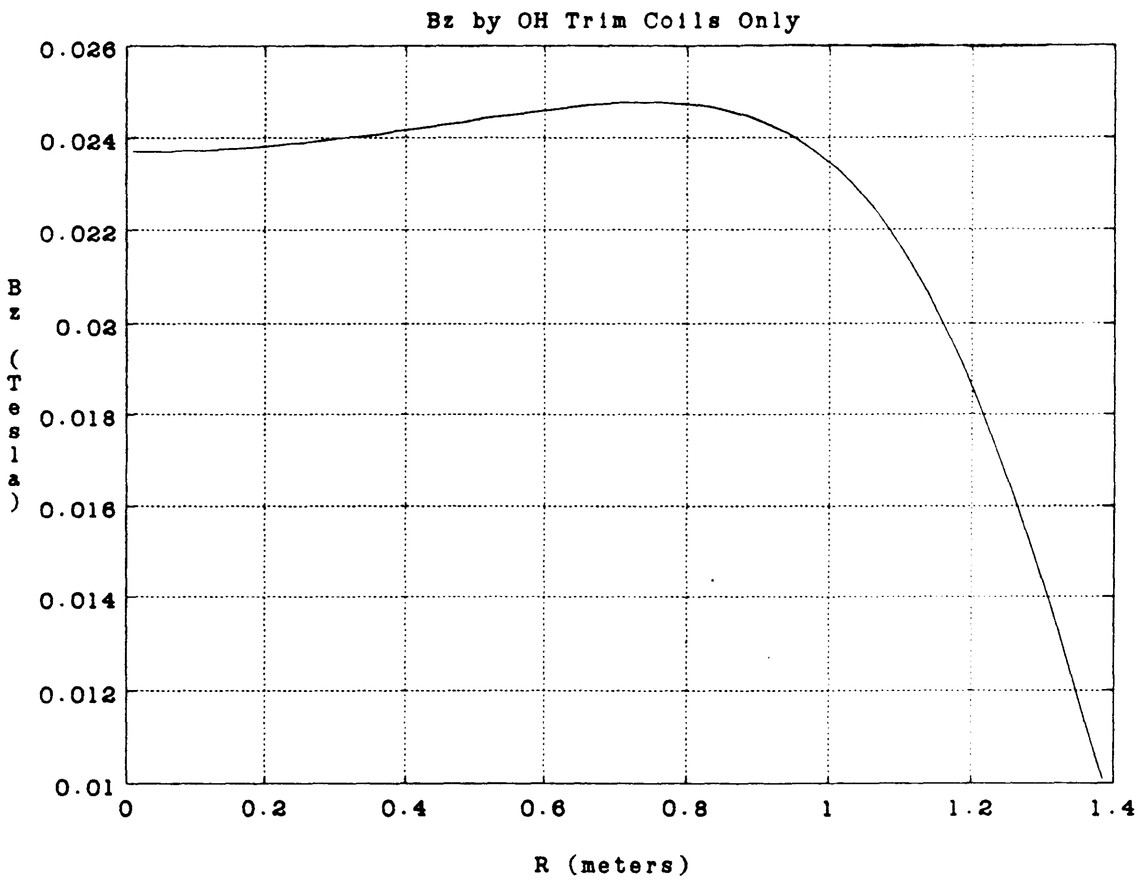


Figure 3-4: B_z at $z = 0$ Induced by Trimming Coils

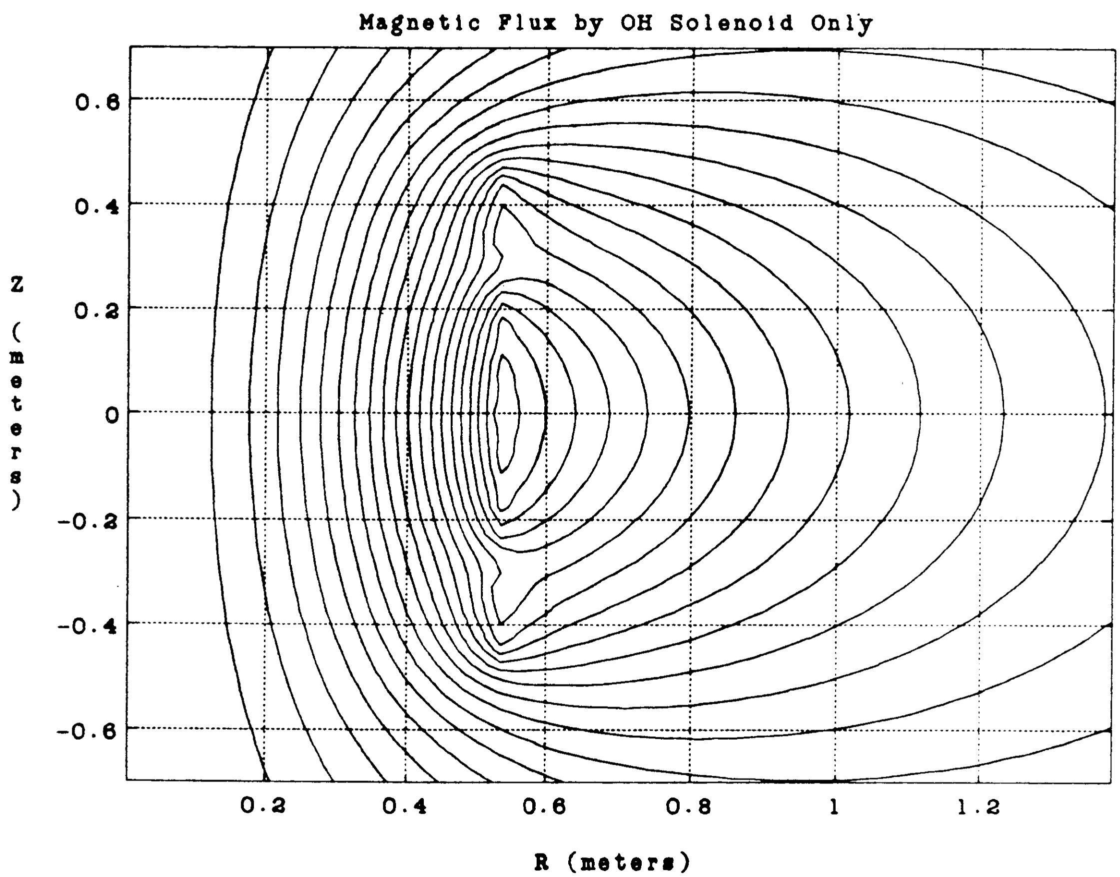


Figure 3-5: Magnetic Flux by Solenoid Only

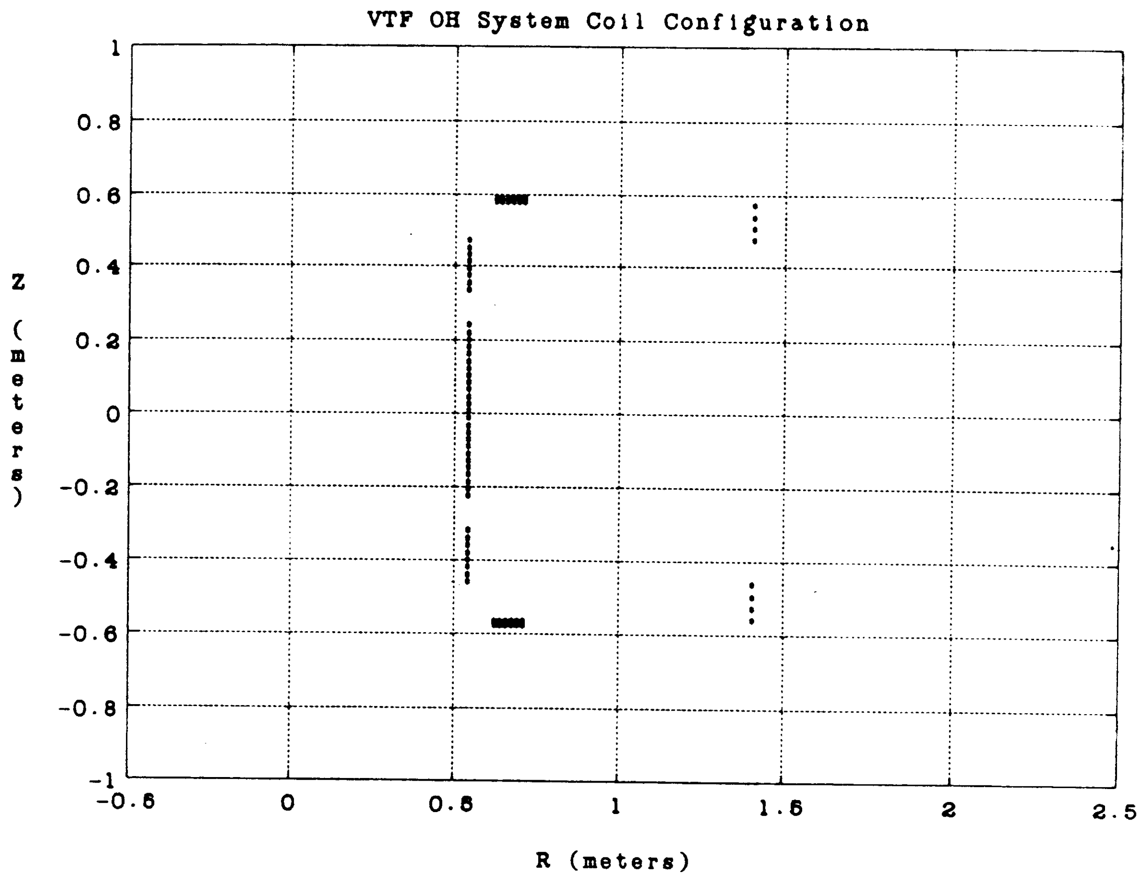


Figure 3-6: VTF OH Coil Positions

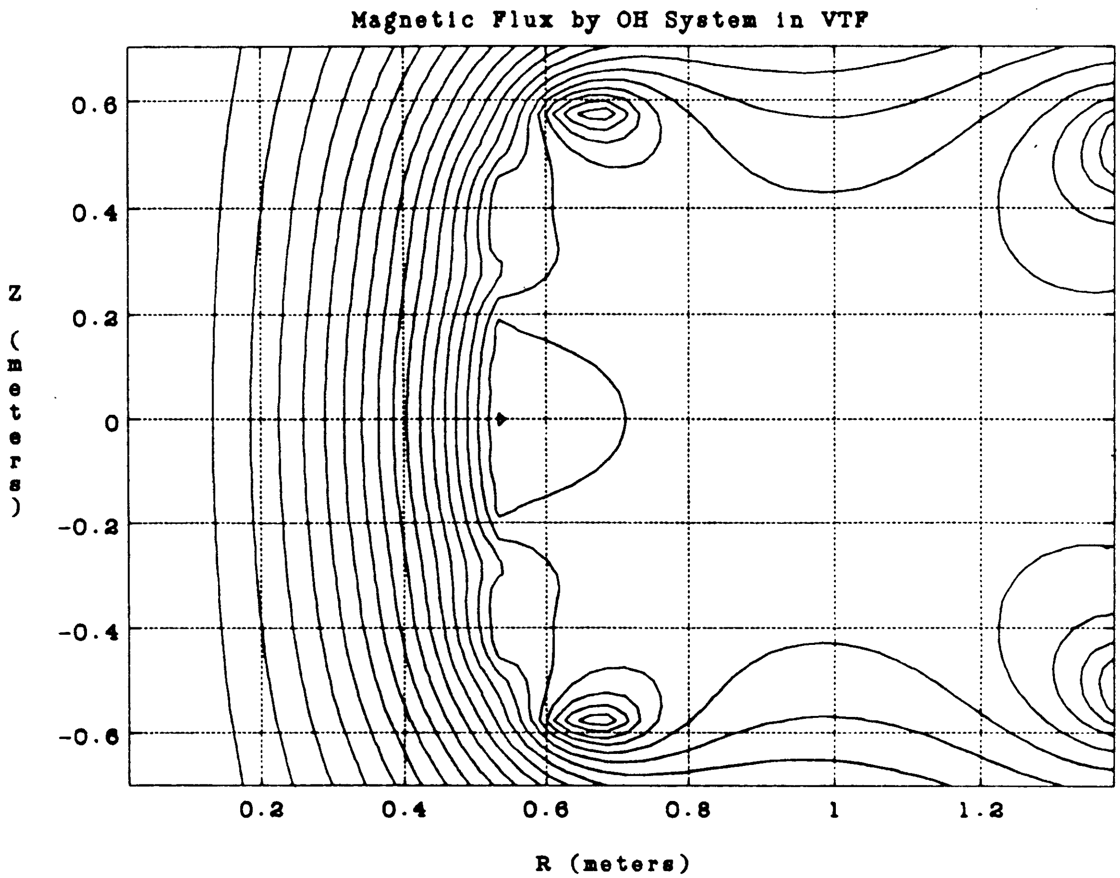


Figure 3-7: Magnetic Flux by OH Coils

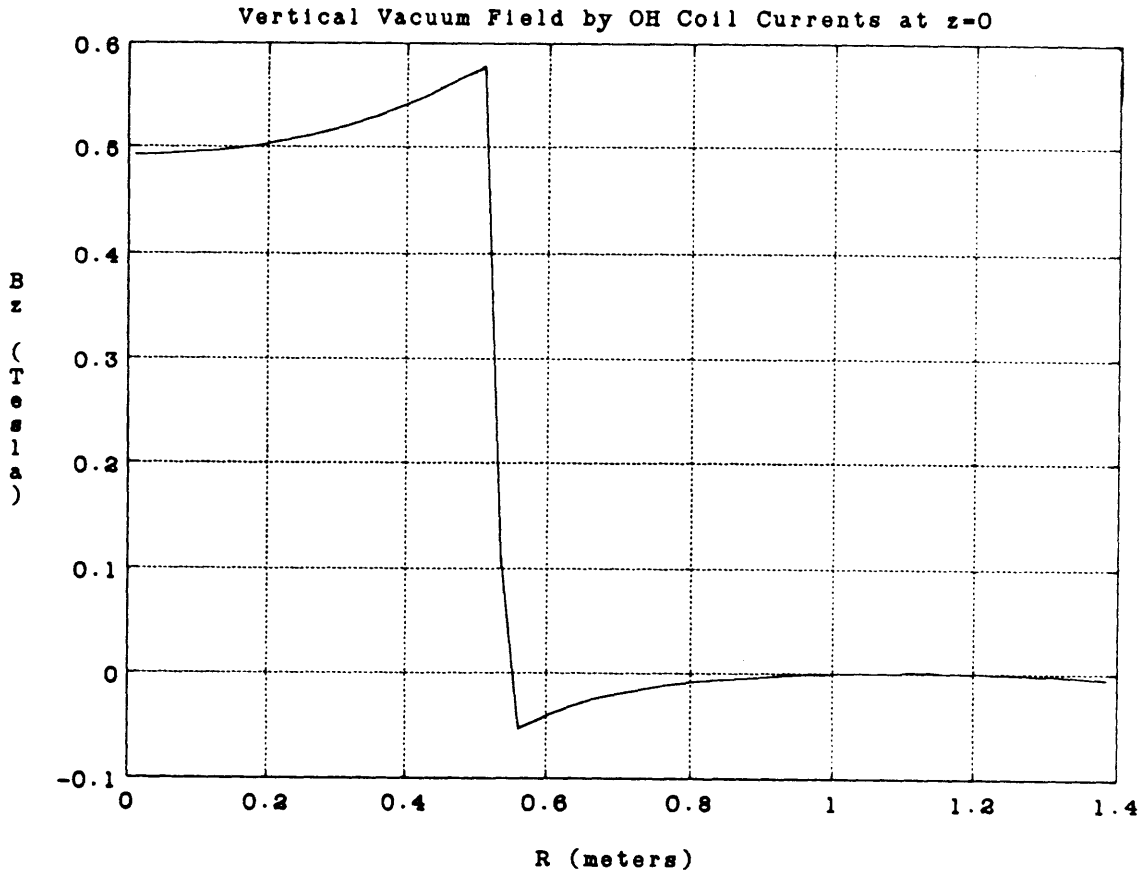


Figure 3-8: B_z at $z = 0$ Induced by OH Coils

$$\beta_p + \frac{l_i}{2} \approx 1.$$

The estimated value of B_v was 606 Gauss.

There were four major considerations to be made in the design of the EF coil system:

1. The vertical field at the center of the plasma would have to be at least 600 Gauss.

2. The field index would have to be positive (for vertical stability) and less than 1.5 (for horizontal stability) in the plasma.

3. The OH coils and the EF coils should have minimum mutual inductance so as to protect the EF system power supply during the OH operation.

4. The EF coils would have to fit in the available spaces on the outer torque cylinder, and they should not block the openings for the port entries of the vacuum chamber.

On the outer torque cylinder, there was only one set of vertically symmetric places to put the EF coils: between the ports and OH trimming coils. But, this did not give an acceptable field, because the field index became negative, which would create vertical instability. There was a region in the plasma, where $\partial B_z/\partial R > 0$, because the distance between the two sets (top and bottom) of loops were smaller than the radius of the loops. (In Helmholtz coils the distance and the radius are equal, making $\partial B_z/\partial R$ equal to zero near the center of the radius.

To keep the field index positive, we needed a set of coils that were separated at a distance greater than the radius. This posed another problem. As a torus, the dimension of VTF is rather wide and short, and therefore such coils would be too far away from the plasma. It was nearly impossible to place them on VTF because of its dimensions. The long distance would also be costly in power, since we would have to put more current in the coils. The best we could do was to put these new coils, which are called farout coils, at approximately the same radius as the far coils (the other coils) but near the top and the bottom of the toroidal field (TF) coils. The coils on the bottom were actually placed on the support beams of the VTF structure, and the top coils were elevated 3.75 inches for the symmetry of the coils.

Fortunately, a set of coils used to decouple the OH and EF coils became helpful in keeping the field index positive. To minimize the mutual inductance between these two coil systems, I had to place the decoupling coils inside the bucking cylinder, which keeps the TF coils from crunching towards the center of the machine due to the $\mathbf{I} \times \mathbf{B}$ forces. The decoupling coils would work in the following manner:

1. The decoupling coils have the same mutual inductance with the OH coils as the rest of the EF coils do.
2. The decoupling coils are connected to the other EF coils in anti-series.

The results of my calculations are shown in Figures 3-9 and 3-10, and the MATLAB code used for the calculations are in Appendix B. The positions of the EF coils are shown in Figure 3-11.

3.2 Free Boundary MHD Code

To find the axisymmetric equilibrium of VTF, it is necessary to solve the Grad-Shafranov equation shown below. [1, pp.110-1]

$$\Delta^* \psi = -\mu_o R^2 \frac{dp}{d\psi} - F \frac{dF}{d\psi}$$

where

$$\mathbf{B} = \frac{1}{R} \nabla \psi \times \mathbf{e}_\phi + \frac{F}{R} \mathbf{e}_\phi$$

$$\mu_o \mathbf{J} = \frac{1}{R} \frac{dF}{d\psi} \nabla \psi \times \mathbf{e}_\phi - \frac{1}{R} \Delta^* \psi \mathbf{e}_\phi,$$

and elliptic operator Δ^* is given by

$$\Delta^* \psi \equiv R^2 \nabla \cdot (\frac{\nabla \psi}{R^2}) = R \frac{\partial}{\partial R} (\frac{1}{R} \frac{\partial \psi}{\partial R}) + \frac{\partial^2 \psi}{\partial Z^2}.$$

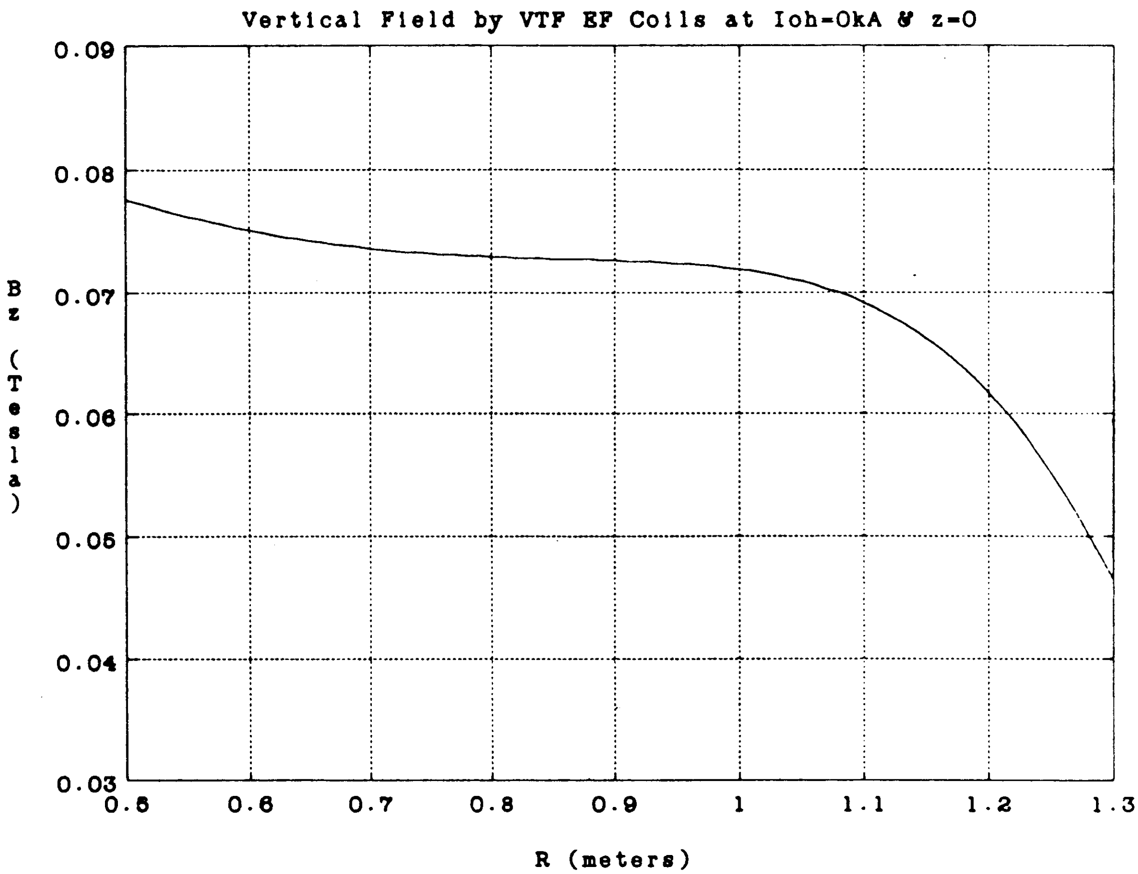


Figure 3-9: B_z at $z = 0$ Induced by EF Coils

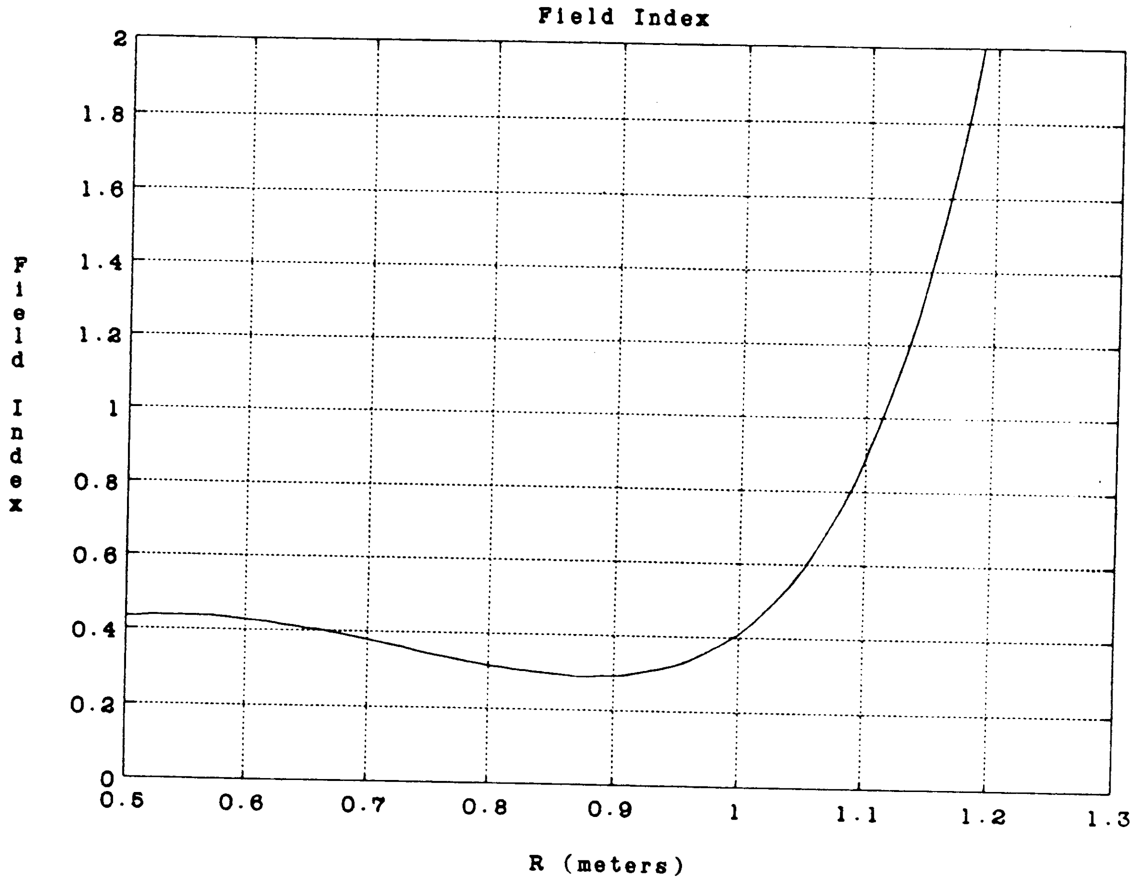


Figure 3-10: Field Index of Equilibrium Field

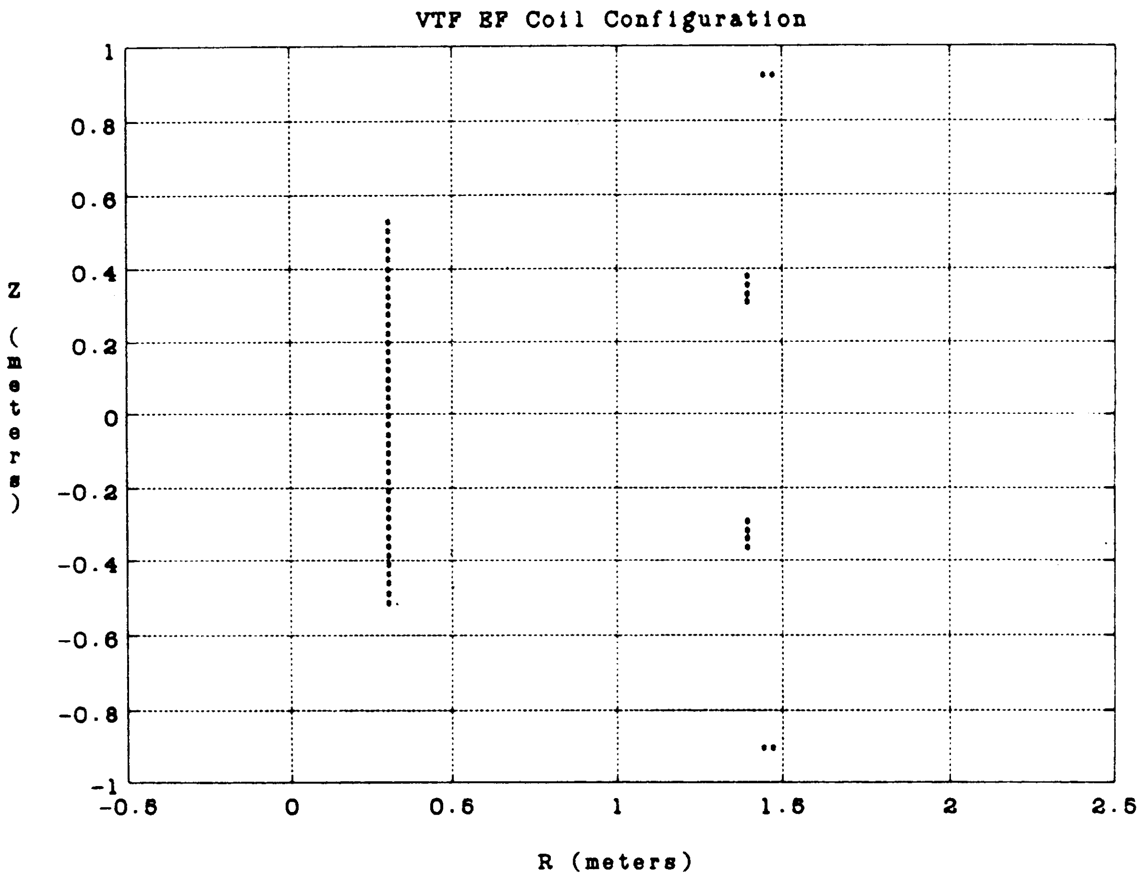


Figure 3-11: VTF EF Coil Positions

The solution to this equation gives a full description of ideal MHD equilibria including radial pressure balance, toroidal force balance, and rotational transform. [1, p. 107] I used *ASEQ*, one of the available codes on the Cray Supercomputer in Lawrence Livermore National Laboratory. The positions of the OH and EF coils are shown in Figure 3-12. Note that the OH coils are shown as 'o' and EF as '*'.

In this code, one can enter the position of the coils and have the flexibility of keeping some coil currents fixed and leaving others to vary so as to find the equilibrium. I have fixed the OH coil currents to ± 8 and 0 kA/turn, to simulate the change in the current during the ohmic heating operation. The values of the EF coil currents were left for the code to determine so that the equilibrium would be met.

Other important variables as inputs to the code were plasma current and location of the plasma minor radius center. These set to 200kA and 0.93 meters respectively.

When the equilibrium is found, several output files are produced. One of the files that I found most useful was *f3eqaa0x*, which can be transferred as tektronix printout format sent to the screen or to the printer.

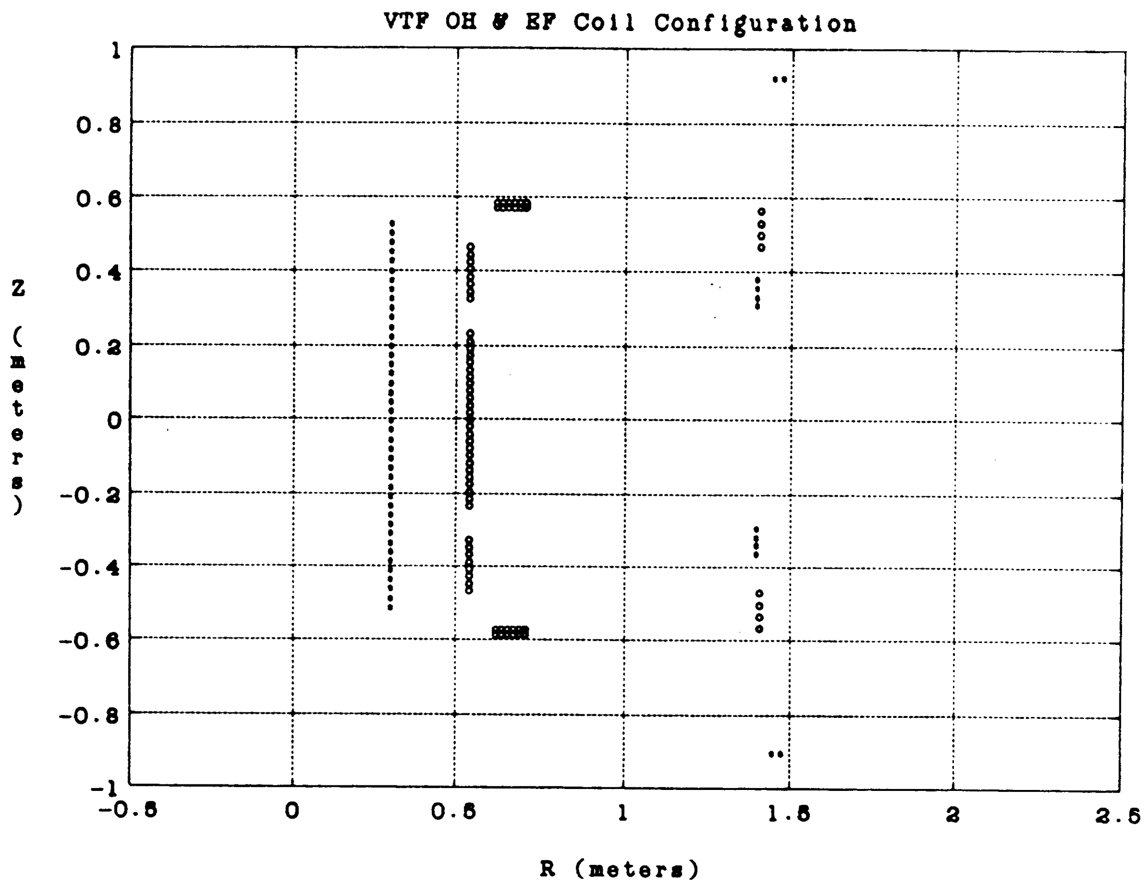


Figure 3-12: VTF OH and EF Coil Positions

Chapter 4

Analysis

4.1 Confinement Time of ECRH Plasma

Without the vertical field coils, the confinement time of 10 eV electrons of VTF would be in the order of 10^{-6} seconds. According to the calculation, the new confinement time would be near 10^{-3} seconds, if the vertical field of 5 Gauss is applied. Without diagnostic instruments available for VTF at present, however, we cannot verify this, yet. Robert Duraski, a graduate student in the Department of Nuclear Engineering will conduct experiments, under the supervision of Prof. Min-Chang Lee of the Plasma Fusion Center, in the near future, to measure the confinement time of the ECRH plasma with applied vertical field.

4.2 Performance of OH and EF Coil Systems

The results from the three cases ($I_{OH} = -8,\ 0,\ +8$ kA/turn) are attached in Appendix A. During the operation of the OH system, the current in the OH coils will build up to +8 kA/turn (without the plasma), and then quickly ramp down to −8kA/turn (with plasma in the chamber). This induces 200 kA of current in the VTF plasma. The OH system provides 0.8757 volt-sec (double swing) at $I_{OH} = 10$ kA and 0.7134 volt-sec (double swing) at $I_{OH} = 8$ kA. As seen in Figures 4-1, 4-2, and 4-3, the shape of plasma changes as the I_{OH} varies from +8 kA to 0 kA to −8 kA. This is

OH Currents	Triangularity	Elongation
$-8\ kA$	8.26×10^{-2}	1.25
$0\ kA$	2.42×10^{-2}	1.09
$+8\ kA$	-3.57×10^{-2}	0.98

Table 4.1: Triangularity and Elongation

because of the incomplete decoupling of OH coil system from the EF coil system.

The field null was given near the center of the plasma, but towards the edge of the plasma, the OH coils give a considerable amount of magnetic field that affects the flux surfaces of the plasma. The comparison of the triangularity and elongation is given in Table 4.1. For the better confinement time, the D-shaped plasma is required , and therefore the plasma at $I_{OH} = 8$ kA/turn poses some problems. This, however, is compensated by the fact that during the OH operation, the actual value of I_{OH} at which the gas will breakdown will be lower than +8 kA/turn. Furthermore, as we use double swing and ramp down the OH coil current to −8 kA/turn, the triangualrity and elongation will be at least 8.3×10^{-2} and 1.25, respectively.

The stability of the equilibrium has been recalculated, based on the results from the *ASEQ*. The field indices of the three cases are plotted in Figures 4-4, 4-5, and 4-6. Both vertical and horizontal stabilities are significantly improved compared to the vacuum calculation results.

4.3 Heating and Stress on the Coils

Although copper is an excellent conductor, at 10 kA of current, the coils can heat up pretty fast. The OH and EF coils will heat up at the rate of $4.73°/sec$, for 10 kA of current. Considering the lenght of each operation (shot), the temperature of the coil system will be in the safe range.

There are three major types of stress that coils will experience during the operation: hoop force, attraction between turns, and overturning force of each turn (especially on the solenoid), all of which are from the $\mathbf{I} \times \mathbf{B}$ forces. At 10 kA of

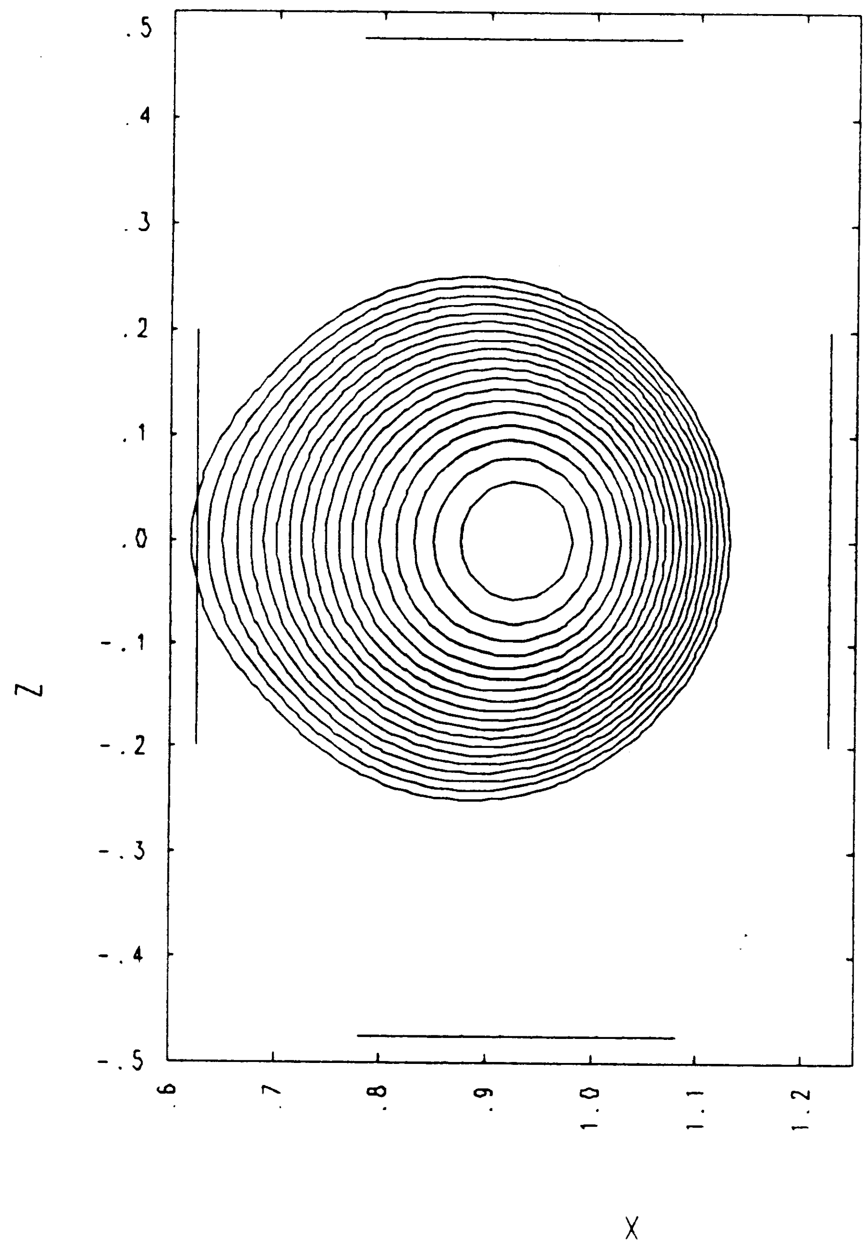


Figure 4-1: Flux Surfaces at $I_{OH} = +8$ kA

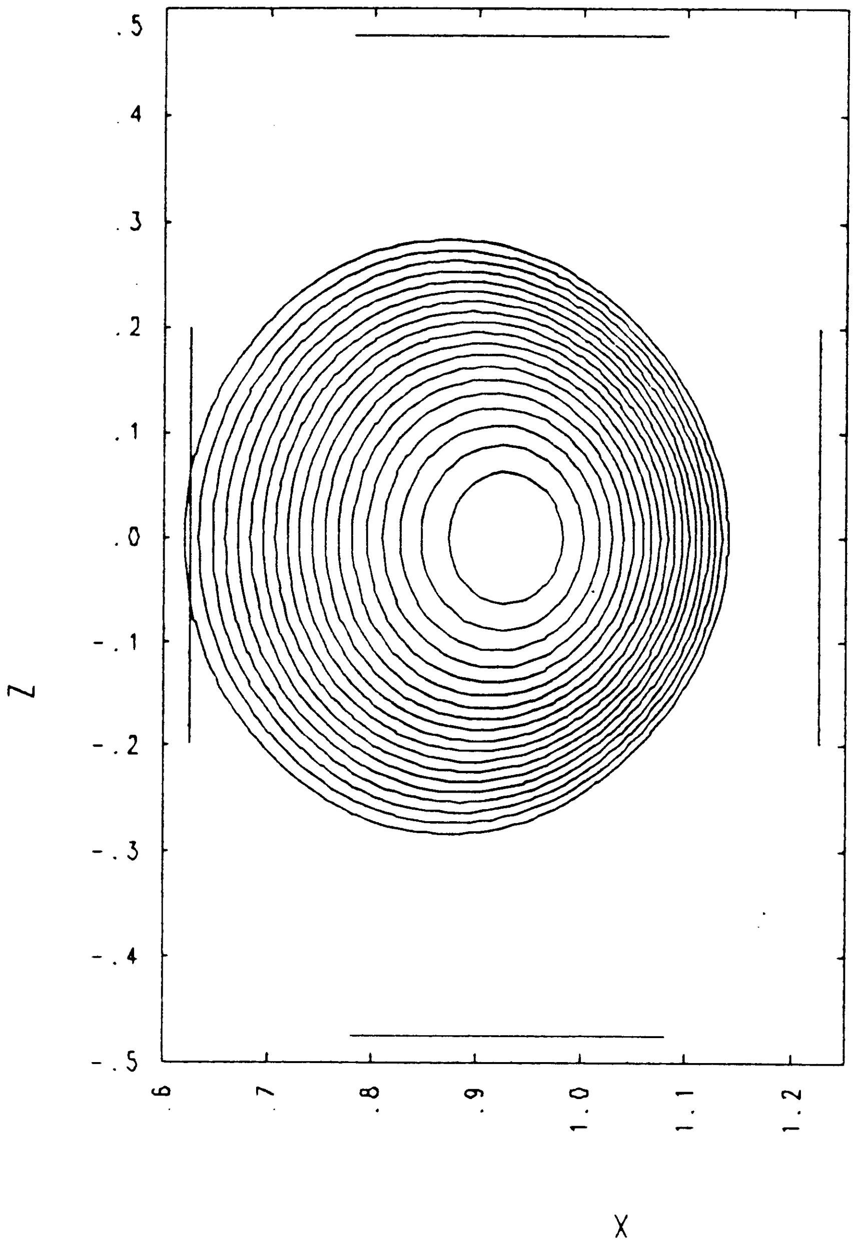


Figure 4-2: Flux Surfaces at $I_{OH} = 0$ kA

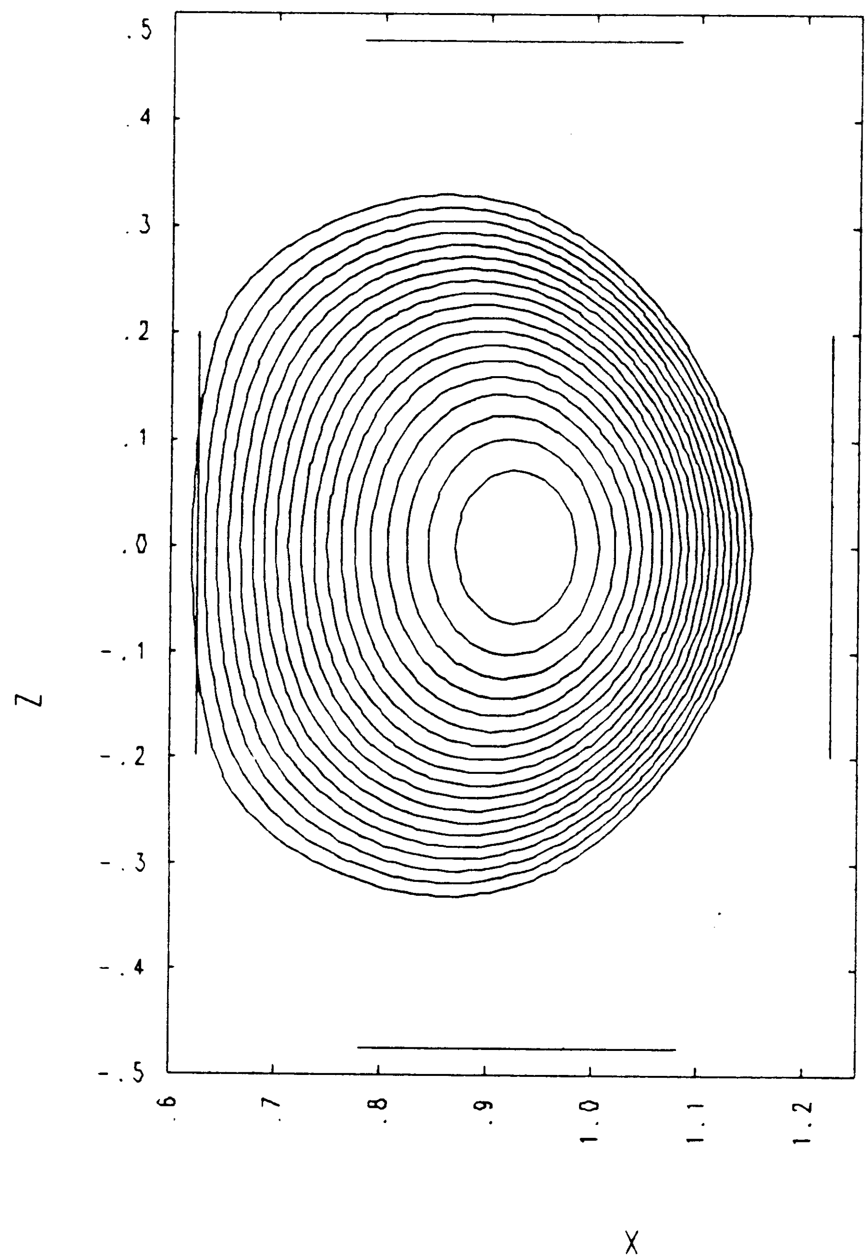


Figure 4-3: Flux Surfaces at $I_{OH} = -8$ kA

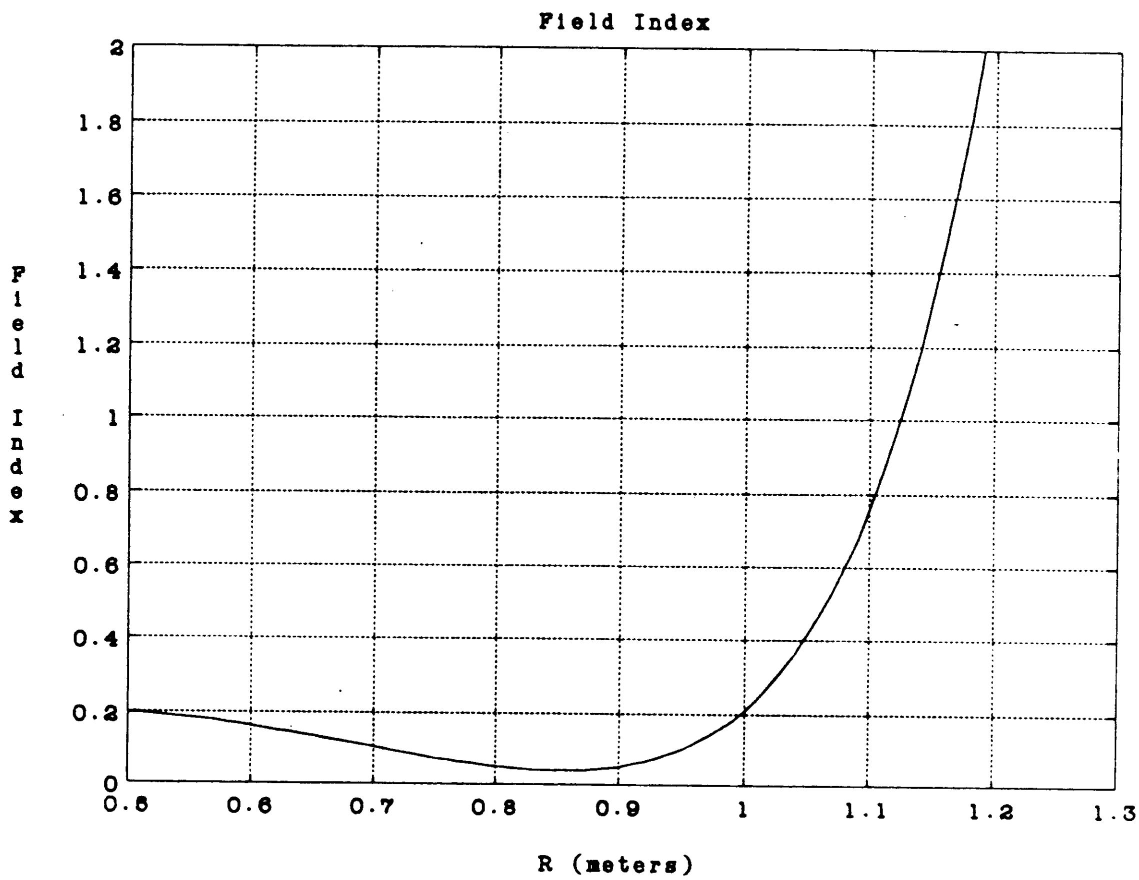


Figure 4-4: Field Index of EF Coils at $I_{OH} = +8$ kA

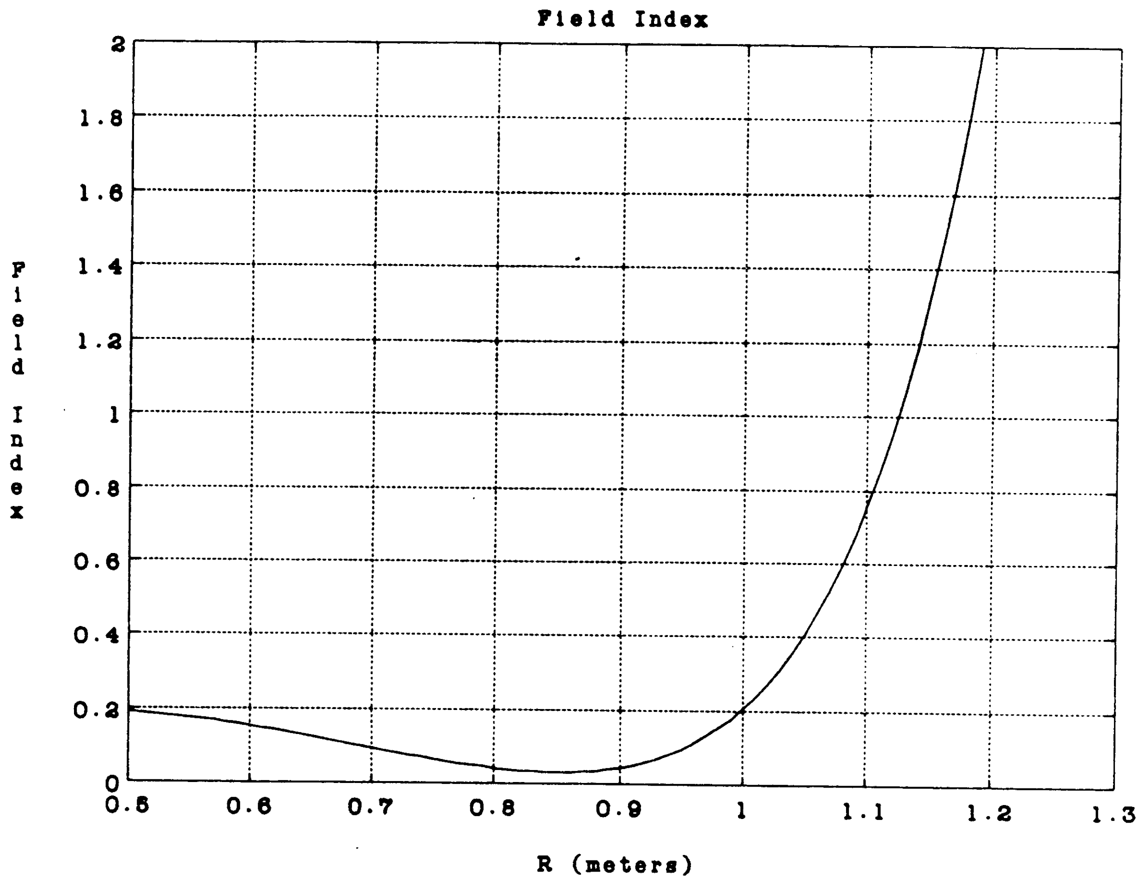


Figure 4-5: Field Index of EF Coils at $I_{OH} = 0$ kA

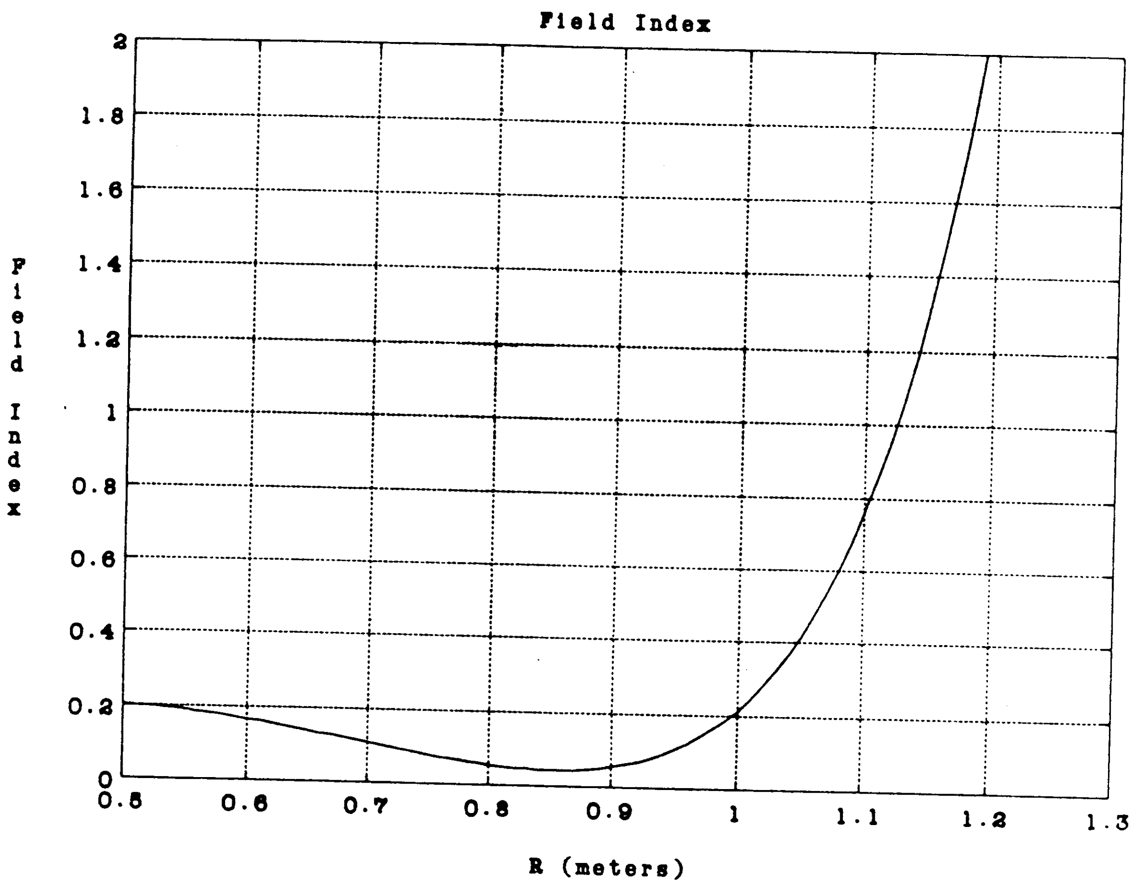


Figure 4-6: Field Index of EF Coils at $I_{OH} = -8$ kA

current, the total stress on the coils will be 2.2 MPa, and this is safely lower than the yield stress of copper.

Chapter 5

Conclusion

The VTF will be able to run two kinds of plasmas, when all of the coil systems are completed. (All of the coils for the vertical field for ECRH plasma, ohmic heating, and equilibrium field have been fabricated and installed, except for the decoupling coils.)

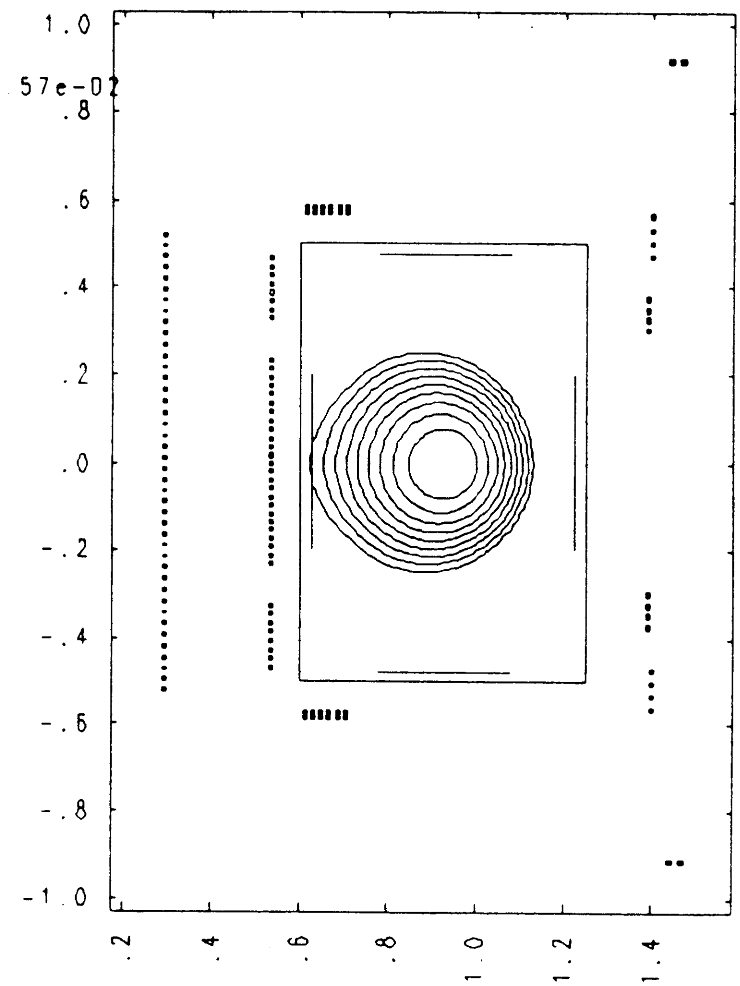
In the ionospheric plasma simulation, the plasma will be formed primarily by ECRH, and the vertical field, in the order of 5 Gauss, will be applied with the use of coils wound according to my calculation. The confinement time of the plasma is expected to be in the order of 1 millisecond.

When completed, th OH and EF coil systems will provide equilibrium and stability necessary for fusion plasma research. The decoupling of the two systems is not perfect, but acceptable, and it can improve if more EF coils can be placed near the solenoid.

Appendix A

Outputs from ASEQ

The following pages contain the outputs from the ASEQ code in Cray Supercomputer at Lawrence Livermore National Laboratory. They are named *f3eqaa0x* and can be printed out on the NERUS printers by the use of *netplot* command with *tekvec* option. The first set is for the OH coil current at +8 kA, the second at 0 kA, and the third at +8 kA.


1.0
57e-02
.8
.6
.4
.2
.0
-.2
-.4
-.6
-.8
-1.0
.2
.4
.6
.8
1.0
1.2
1.4

Geometry

```
R (m)         =   8.75e-01
a (m)         =   2.55e-01
R/a           =   3.44e+00
Kappa         =   9.82e-01
Delta (u,l)=     -3.57e-02 -3

xma   =   0.930  zma   =   0.000
```

COIL CURRENTS

COIL	I(AMPS)
OHCEN	2.000e+05
OHTOPBOT	1.280e+05
NULL	1.920e+05
TRIM	6.400e+04
FAR	-1.134e+05
FAROUT	-4.000e+04
ANTIX	2.448e+05
PLASMA	2.000e+05

```
1 -----------------------------------------------------------------
 SUROU OUTPUT
 -----------------------------------------------------------------

 FROM 2 DIMENSIONAL SUMMATION OVER PLASMA:
 VOLUME   =  1.071635E+00
 VOLMSPH =  1.078225E+00  METERS**3
 AREA     =  1.939209E-01
 AREASPH =  2.128277E-01  METERS**2
 VOLUME INTEGRAL OF P =  1.285459E+04  JOULES
 VOLUME INTEGRAL OF BPOL**2/(2*AMU0) =  8.585292E+03  JOULES
 VOLUME INTEGRAL OF BTOR**2/(2*AMU0) =  2.073825E+06  JOULES
 VOLUME INTEGRAL OF BTOREXT**2/(2*AMU0) =  2.075283E+06  JOULES
 AREA INTEGRAL OF P =  2.260381E+03  NEWTONS
 AREA INTEGRAL OF BPOL**2/(2*AMU0) =  1.540099E+03  NEWTONS
 AREA INTEGRAL OF BTOR**2/(2*AMU0) =  3.916631E+05  NEWTONS
 AREA INTEGRAL OF BTOREXT**2/(2*AMU0) =  3.919216E+05  NEWTONS
 SHAFRANOV MEAN MAJOR RADIUS =  8.978266E-01  METERS
 SHAFRANOV BETA POLOIDAL =  1.099930E+00
 BETA POLOIDAL SPH       =  1.172871E+00
 BETA POLOIDAL AREA      =  1.163071E+00
 LITTLE L SUB I =  7.346188E-01
 MU SUB I =  1.247541E-01
 THERMAL ENERGY =  1.928188E+04
 BETA TOTAL =  6.172938E-03
 BETA POLOIDAL =  1.497280E+00
 BETA TOROIDAL =  6.198492E-03
 S4 =  0.
 DELTA PHI ZERO =  1.175252E-03 WEBERS
 DELTA PHI TOROIDAL = -1.519399E-04
 PLASMA CURRENT =  2.000000E+05  AMPERES
```

```
1
 AV BETA =    6.15808E-03
 AV BFESP =    1.00087E-02
 BETAPOL =   1.16627E+00
 OLD CURRENT (AMPS) =    2.00000E+05
 NEW CURRENT (AMPS) =    2.00252E+05

 BASED ON RO:
     BETA AV =  6.13256E-03
     BETABO AV =  7.49070E-03
     RADIUS =  2.52451E-01
     ASPECT RATIO =  3.83738E+00

 XMA (M) =  9.30000E-01
 ZMA (M) =  0.
 UPSILN =  2.36099E-01

 AV MINOR RADIUS (M) =  2 60279E-01
 AV MAJOR RADIUS (M) =  8 06309E-01
 ASPECT RATIO =  3 09786E+00
 INT. TOROIDAL FLUX (WB) =  4.35026E-01
 INT. POLOIDAL FLUX (WB) =  1.46606E-01
 EXT. FLUX AT AXIS (WB)  =  2.26571E-01

GEOMETRY:
     MAJOR RADIUS (M) =  8.74980E-01
     MINOR RADIUS (M) =  2.54667E-01
     ASPECT RATIO =   3.43578E+00
     ELONGATION =   9.81912E-01
     TRIANGULARITY (U,L) = -3.57451E-02 -3.57451E-02
```

Z COIL (M)	X COIL (M)	I COIL (AMPS)
-2.3257E-01	5.3340E-01	8.0000E+03
-2.1319E-01	5.3340E-01	8.0000E+03
-1.9381E-01	5.3340E-01	8.0000E+03
-1.7443E-01	5.3340E-01	8.0000E+03
-1.5505E-01	5.3340E-01	8.0000E+03
-1.3567E-01	5.3340E-01	8.0000E+03
-1.1628E-01	5.3340E-01	8.0000E+03
-9.6904E-02	5.3340E-01	8.0000E+03
-7.7523E-02	5.3340E-01	8.0000E+03
-5.8142E-02	5.3340E-01	8.0000E+03
-3.8761E-02	5.3340E-01	8.0000E+03
-1.9381E-02	5.3340E-01	8.0000E+03
0.	5.3340E-01	8.0000E+03
1.9381E-02	5.3340E-01	8.0000E+03
3.8761E-02	5.3340E-01	8.0000E+03
5.8142E-02	5.3340E-01	8.0000E+03
7.7523E-02	5.3340E-01	8.0000E+03
9.6904E-02	5.3340E-01	8.0000E+03
1.1628E-01	5.3340E-01	8.0000E+03
1.3567E-01	5.3340E-01	8.0000E+03
1.5505E-01	5.3340E-01	8.0000E+03
1.7443E-01	5.3340E-01	8.0000E+03
1.9381E-01	5.3340E-01	8.0000E+03
2.1319E-01	5.3340E-01	8.0000E+03
2.3257E-01	5.3340E-01	8.0000E+03
4.6595E-01	5.3340E-01	8.0000E+03
4.4604E-01	5.3340E-01	8.0000E+03
4.2613E-01	5.3340E-01	8.0000E+03
4.0622E-01	5.3340E-01	8.0000E+03
3.8631E-01	5.3340E-01	8.0000E+03
3.6640E-01	5.3340E-01	8.0000E+03
3.4649E-01	5.3340E-01	8.0000E+03
3.2658E-01	5.3340E-01	8.0000E+03
-4.6595E-01	5.3340E-01	8.0000E+03
-4.4604E-01	5.3340E-01	8.0000E+03
-4.2613E-01	5.3340E-01	8.0000E+03
-4.0622E-01	5.3340E-01	8.0000E+03
-3.8631E-01	5.3340E-01	8.0000E+03

-3.6640E-01	5.3340E-01	8.0000E+03
-3.4649E-01	5.3340E-01	8.0000E+03
-3.2658E-01	5.3340E-01	8.0000E+03
5.7150E-01	6.1225E-01	8.0000E+03
5.7150E-01	6.3024E-01	8.0000E+03
5.7150E-01	6.4823E-01	8.0000E+03
5.7150E-01	6.6622E-01	8.0000E+03
5.7150E-01	6.8421E-01	8.0000E+03
5.7150E-01	7.0220E-01	8.0000E+03
5.8420E-01	6.1225E-01	8.0000E+03
5.8420E-01	6.3024E-01	8.0000E+03
5.8420E-01	6.4823E-01	8.0000E+03
5.8420E-01	6.6622E-01	8.0000E+03
5.8420E-01	6.8421E-01	8.0000E+03
5.8420E-01	7.0220E-01	8.0000E+03
-5.7150E-01	6.1225E-01	8.0000E+03
-5.7150E-01	6.3024E-01	8.0000E+03
-5.7150E-01	6.4823E-01	8.0000E+03
-5.7150E-01	6.6622E-01	8.0000E+03
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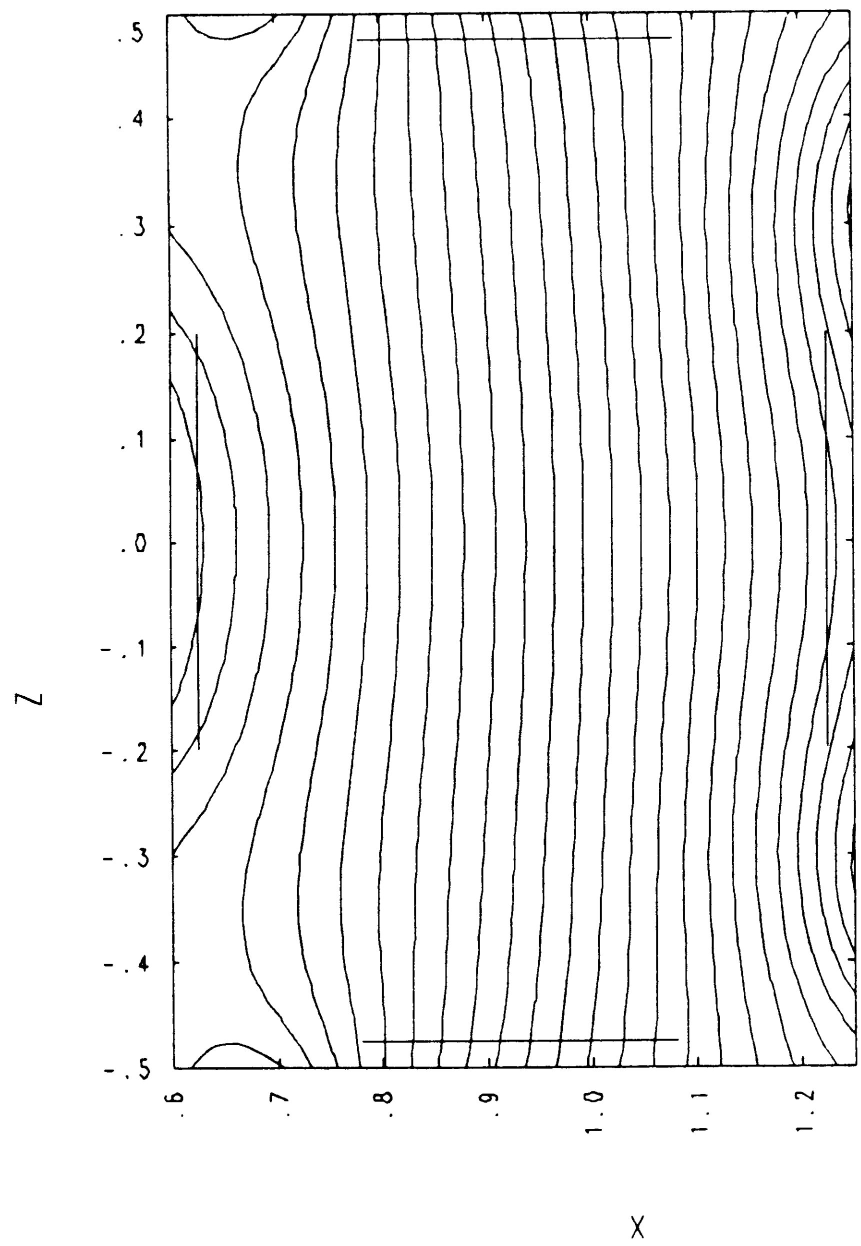
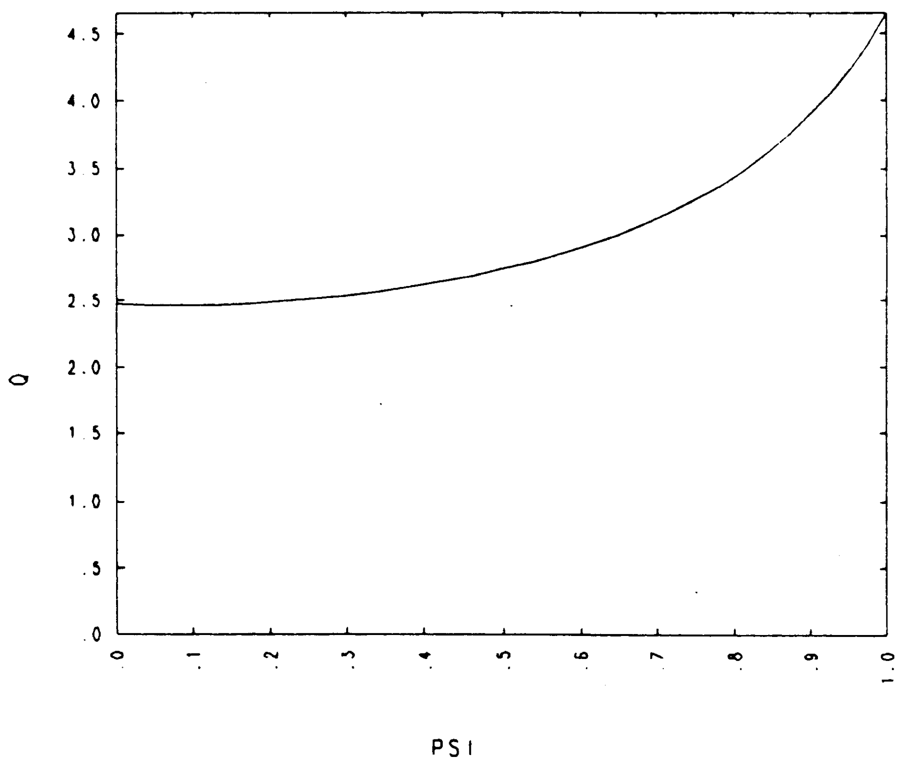
-5.8420E-01	6.4823E-01	8.0000E+03
-5.8420E-01	6.6622E-01	8.0000E+03
-5.8420E-01	6.8421E-01	8.0000E+03
-5.8420E-01	7.0220E-01	8.0000E+03
4.6990E-01	1.4002E+00	8.0000E+03
5.0165E-01	1.4002E+00	8.0000E+03
5.3340E-01	1.4002E+00	8.0000E+03
5.6515E-01	1.4002E+00	8.0000E+03
-4.6990E-01	1.4002E+00	8.0000E+03
-5.0165E-01	1.4002E+00	8.0000E+03
-5.3340E-01	1.4002E+00	8.0000E+03
-5.6515E-01	1.4002E+00	8.0000E+03
3.0083E-01	1.3890E+00	-1.4172E+04
3.2464E-01	1.3890E+00	-1.4172E+04
3.4846E-01	1.3890E+00	-1.4172E+04
3.7227E-01	1.3890E+00	-1.4172E+04
-3.0083E-01	1.3890E+00	-1.4172E+04
-3.2464E-01	1.3890E+00	-1.4172E+04
-3.4846E-01	1.3890E+00	-1.4172E+04

-3.7227E-01	1.3890E+00	-1.4172E+04
9.1440E-01	1.4398E+00	-1.0000E+04
9.1440E-01	1.4652E+00	-1.0000E+04
-9.1440E-01	1.4398E+00	-1.0000E+04
-9.1440E-01	1.4652E+00	-1.0000E+04
1.2700E-02	2.9210E-01	5.8279E+03
3.8100E-02	2.9210E-01	5.8279E+03
6.3500E-02	2.9210E-01	5.8279E+03
8.8900E-02	2.9210E-01	5.8279E+03
1.1430E-01	2.9210E-01	5.8279E+03
1.3970E-01	2.9210E-01	5.8279E+03
1.6510E-01	2.9210E-01	5.8279E+03
1.9050E-01	2.9210E-01	5.8279E+03
2.1590E-01	2.9210E-01	5.8279E+03
2.4130E-01	2.9210E-01	5.8279E+03
2.6670E-01	2.9210E-01	5.8279E+03
2.9210E-01	2.9210E-01	5.8279E+03
3.1750E-01	2.9210E-01	5.8279E+03
3.4290E-01	2.9210E-01	5.8279E+03
3.6830E-01	2.9210E-01	5.8279E+03
3.9370E-01	2.9210E-01	5.8279E+03
4.1910E-01	2.9210E-01	5.8279E+03
4.4450E-01	2.9210E-01	5.8279E+03
4.6990E-01	2.9210E-01	5.8279E+03
4.9530E-01	2.9210E-01	5.8279E+03
5.2070E-01	2.9210E-01	5.8279E+03
-1.2700E-02	2.9210E-01	5.8279E+03
-3.8100E-02	2.9210E-01	5.8279E+03
-6.3500E-02	2.9210E-01	5.8279E+03
-8.8900E-02	2.9210E-01	5.8279E+03
-1.1430E-01	2.9210E-01	5.8279E+03
-1.3970E-01	2.9210E-01	5.8279E+03
-1.6510E-01	2.9210E-01	5.8279E+03
-1.9050E-01	2.9210E-01	5.8279E+03
-2.1590E-01	2.9210E-01	5.8279E+03
-2.4130E-01	2.9210E-01	5.8279E+03
-2.6670E-01	2.9210E-01	5.8279E+03
-2.9210E-01	2.9210E-01	5.8279E+03
-3.1750E-01	2.9210E-01	5.8279E+03
-3.4290E-01	2.9210E-01	5.8279E+03
-3.6830E-01	2.9210E-01	5.8279E+03
-3.9370E-01	2.9210E-01	5.8279E+03

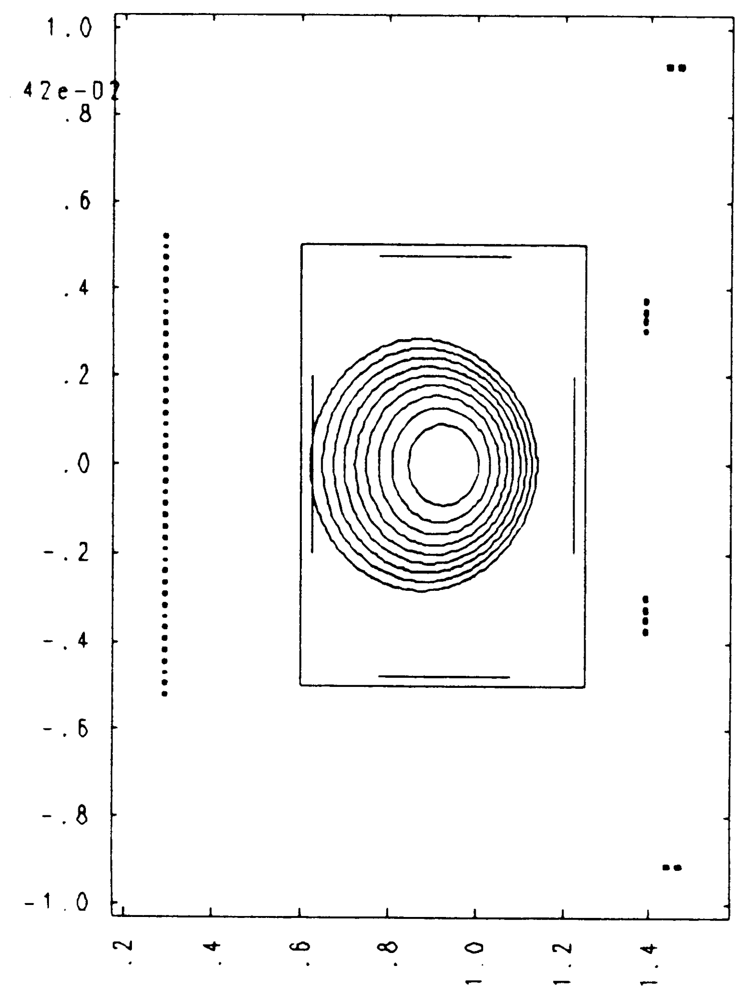
-4.1910E-01	2.9210E-01	5.8279E+03
-4.4450E-01	2.9210E-01	5.8279E+03
-4.6990E-01	2.9210E-01	5.8279E+03
-4.9530E-01	2.9210E-01	5.8279E+03
-5.2070E-01	2.9210E-01	5.8279E+03



EXTERNAL COIL FLUX CONTOURS



Q -VS- PSI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42e-02
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.4
.2
.0
-.2
-.4
-.6
-.8
-1.0
.2
.4
.6
.8
1.0
1.2
1.4

```
              Geometry
R (m)            =    8 80e-01
a (m)            =    2 59e-01
R/a              =    3 39e+00
Kappa            =    1 09e+00
Delta (u,l)=          2 42e-02   2

xma  =   0.930  zma  =    0.000


         COIL CURRENTS
  COIL            I(AMPS)
  ----            -------
OHCEN          0.
OHTOPBOT       0.
NULL           0
TRIM           0
FAR           -1  145e+05
FAROUT        -4  000e+04
ANTIX          2.387e+05
PLASMA         2.000e+05
```

```
1 ------------------------------------------------------------------------
 SUROU OUTPUT
 ------------------------------------------------------------------------

 FROM 2 DIMENSIONAL SUMMATION OVER PLASMA:
 VOLUME   =  1.257606E+00
 VOLMSPH =  1.258547E+00  METERS**3
 AREA    =  2.280396E-01
 AREASPH =  2.486356E-01  METERS**2
 VOLUME INTEGRAL OF P =  1.277995E+04  JOULES
 VOLUME INTEGRAL OF BPOL**2/(2*AMU0) =  8.596949E+03  JOULES
 VOLUME INTEGRAL OF BTOR**2/(2*AMU0) =  2.446828E+06  JOULES
 VOLUME INTEGRAL OF BTOREXT**2/(2*AMU0) =  2.448283E+06  JOULES
 AREA INTEGRAL OF P =  2.251237E+03  NEWTONS
 AREA INTEGRAL OF BPOL**2/(2*AMU0) =  1.548680E+03  NEWTONS
 AREA INTEGRAL OF BTOR**2/(2*AMU0) =  4.640964E+05  NEWTONS
 AREA INTEGRAL OF BTOREXT**2/(2*AMU0) =  4.643549E+05  NEWTONS
 SHAFRANOV MEAN MAJOR RADIUS =  8.953316E-01  METERS
 SHAFRANOV BETA POLOIDAL =  1.093539E+00
 BETA POLOIDAL SPH       =  1.164108E+00
 BETA POLOIDAL AREA      =  1.158683E+00
 LITTLE L SUB I =  7.356133E-01
 MU SUB I =  1.244368E-01
 THERMAL ENERGY =  1.916992E+04
 BETA TOTAL =  5.204779E-03
 BETA POLOIDAL =  1.486568E+00
 BETA TOROIDAL =  5.223066E-03
 S4 =  0.
 DELTA PHI ZERO =  1.171986E-03 WEBERS
 DELTA PHI TOROIDAL = -1.515439E-04
 PLASMA CURRENT =  2.000000E+05  AMPERES
```

```
1
 AV BETA =    5.21148E-03
 AV BFESP =    8.52366E-03
 BETAPOL =    1.16381E+00
 OLD CURRENT (AMPS) =    2.00000E+05
 NEW CURRENT (AMPS) =    2.00205E+05

 BASED ON RO:
      BETA AV =   5.19322E-03
      BETABO AV =   6.38021E-03
      RADIUS =   2.72745F-01
      ASPECT RATIO =   3.55187E+00

 XMA (M) =   9.30004E-01
 ZMA (M) =   1.36424E-14
 UPSILN =   2.77335E-01

 AV MINOR RADIUS (M) =   2.81324E-01
 AV MAJOR RADIUS (M) =   8.05613E-01
 ASPECT RATIO =   2.86365E+00
 INT. TOROIDAL FLUX (WB) =   5.11034E-01
 INT. POLOIDAL FLUX (WB) =   1.45633E-01
 EXT. FLUX AT AXIS (WB)  = -1.32678E-01

GEOMETRY:
      MAJOR RADIUS (M) =   8.79613E-01
      MINOR RADIUS (M) =   2.59301E-01
      ASPECT RATIO =    3.39225E+00
      ELONGATION =    1.09051E+00
      TRIANGULARITY (U,L) =   2.42032E-02   2.42032E-02
```

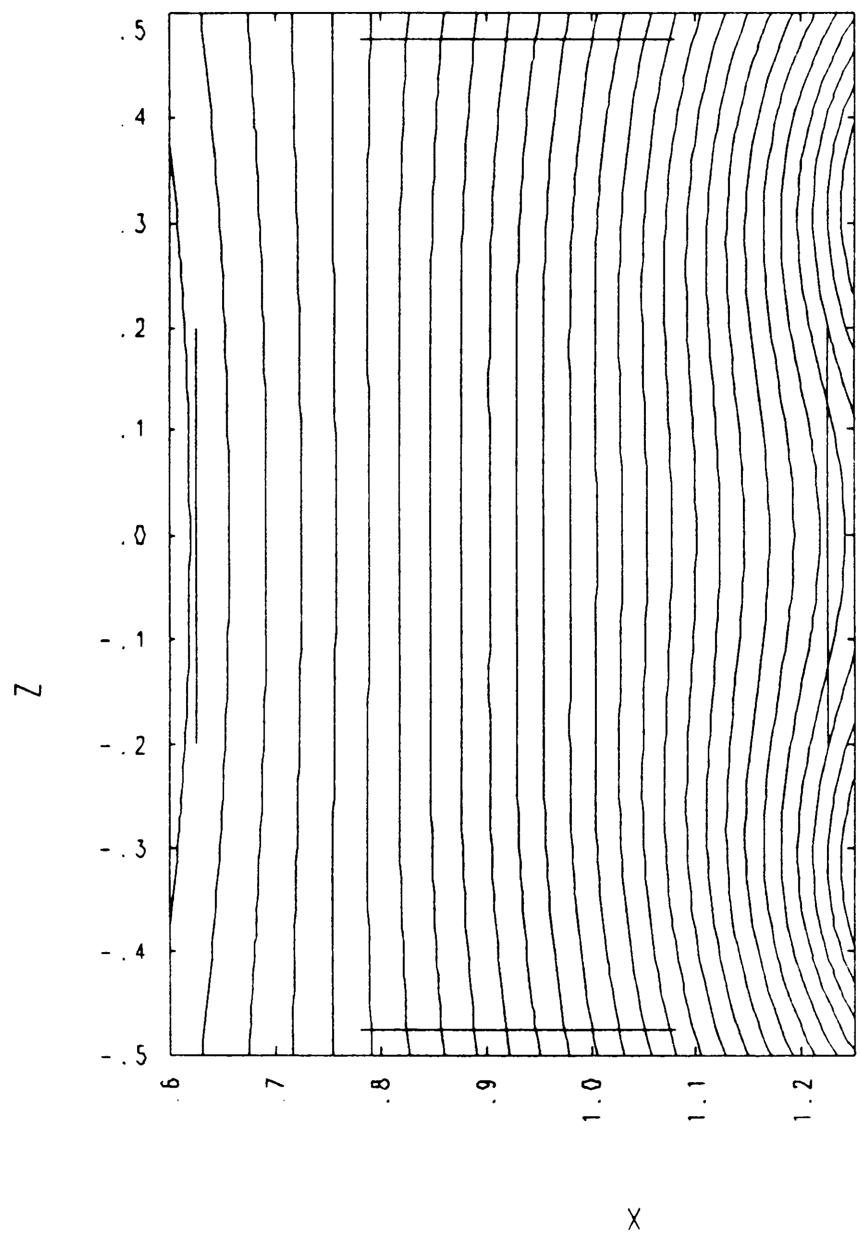
1

Z COIL (M)	X COIL (M)	I COIL (AMPS)
-2.3257E-01	5.3340E-01	0.
-2.1319E-01	5.3340E-01	0.
-1.9381E-01	5.3340E-01	0.
-1.7443E-01	5.3340E-01	0.
-1.5505E-01	5.3340E-01	0.
-1.3567E-01	5.3340E-01	0.
-1.1628E-01	5.3340E-01	0.
-9.6904E-02	5.3340E-01	0.
-7.7523E-02	5.3340E-01	0.
-5.8142E-02	5.3340E-01	0.
-3.8761E-02	5.3340E-01	0.
-1.9381E-02	5.3340E-01	0.
0.	5.3340E-01	0.
1.9381E-02	5.3340E-01	0.
3.8761E-02	5.3340E-01	0.
5.8142E-02	5.3340E-01	0.
7.7523E-02	5.3340E-01	0.
9.6904E-02	5.3340E-01	0.
1.1628E-01	5.3340E-01	0.
1.3567E-01	5.3340E-01	0.
1.5505E-01	5.3340E-01	0.
1.7443E-01	5.3340E-01	0.
1.9381E-01	5.3340E-01	0.
2.1319E-01	5.3340E-01	0.
2.3257E-01	5.3340E-01	0.
4.6595E-01	5.3340E-01	0.
4.4604E-01	5.3340E-01	0.
4.2613E-01	5.3340E-01	0.
4.0622E-01	5.3340E-01	0.
3.8631E-01	5.3340E-01	0.
3.6640E-01	5.3340E-01	0.
3.4649E-01	5.3340E-01	0.
3.2658E-01	5.3340E-01	0.
-4.6595E-01	5.3340E-01	0.
-4.4604E-01	5.3340E-01	0.
-4.2613E-01	5.3340E-01	0.
-4.0622E-01	5.3340E-01	0.
-3.8631E-01	5.3340E-01	0.

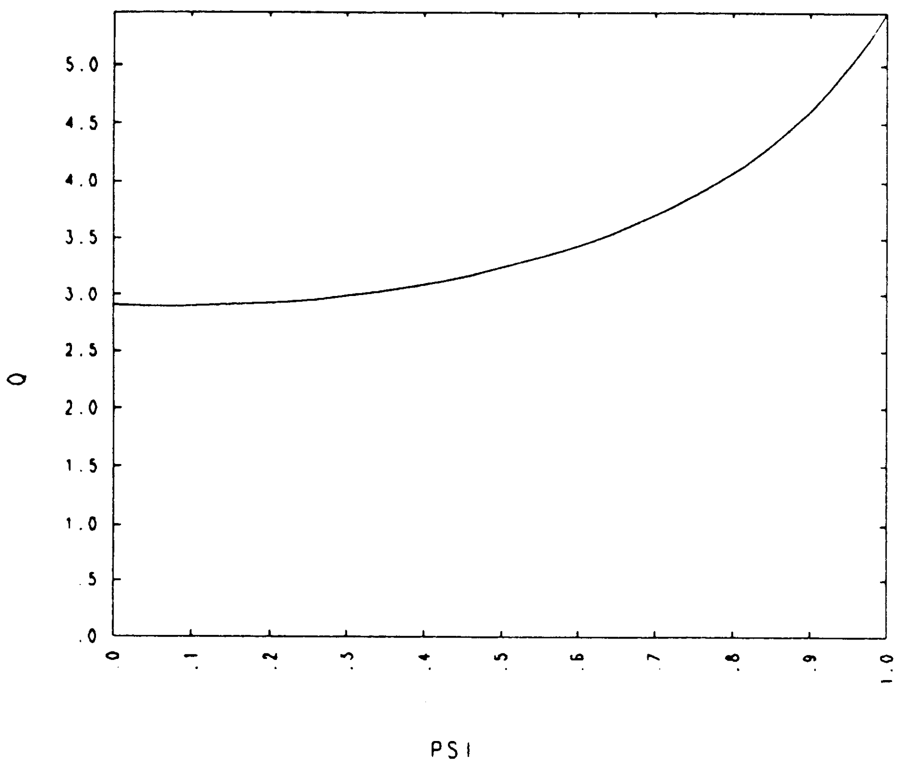
-3.6640E-01	5.3340E-01	0.
-3.4649E-01	5.3340E-01	0.
-3.2658E-01	5.3340E-01	0.
5.7150E-01	6.1225E-01	0.
5.7150E-01	6.3024E-01	0.
5.7150E-01	6.4823E-01	0.
5.7150E-01	6.6622E-01	0.
5.7150E-01	6.8421E-01	0.
5.7150E-01	7.0220E-01	0.
5.8420E-01	6.1225E-01	0.
5.8420E-01	6.3024E-01	0.
5.8420E-01	6.4823E-01	0.
5.8420E-01	6.6622E-01	0.
5.8420E-01	6.8421E-01	0.
5.8420E-01	7.0220E-01	0.
-5.7150E-01	6.1225E-01	0.
-5.7150E-01	6.3024E-01	0.
-5.7150E-01	6.4823E-01	0.
-5.7150E-01	6.6622E-01	0.
-5.7150E-01	6.8421E-01	0.
-5.7150E-01	7.0220E-01	0.
-5.8420E-01	6.1225E-01	0.
-5.8420E-01	6.3024E-01	0.
-5.8420E-01	6.4823E-01	0.
-5.8420E-01	6.6622E-01	0.
-5.8420E-01	6.8421E-01	0.
-5.8420E-01	7.0220E-01	0.
4.6990E-01	1.4002E+00	0.
5.0165E-01	1.4002E+00	0.
5.3340E-01	1.4002E+00	0.
5.6515E-01	1.4002E+00	0.
-4.6990E-01	1.4002E+00	0.
-5.0165E-01	1.4002E+00	0.
-5.3340E-01	1.4002E+00	0.
-5.6515E-01	1.4002E+00	0.
3.0083E-01	1.3890E+00	-1.4316E+04
3.2464E-01	1.3890E+00	-1.4316E+04
3.4846E-01	1.3890E+00	-1.4316E+04
3.7227E-01	1.3890E+00	-1.4316E+04
-3.0083E-01	1.3890E+00	-1.4316E+04
-3.2464E-01	1.3890E+00	-1.4316E+04
-3.4846E-01	1.3890E+00	-1.4316E+04

-3.7227E-01	1.3890E+00	-1.4316E+04
9.1440E-01	1.4398E+00	-1.0000E+04
9.1440E-01	1.4652E+00	-1.0000E+04
-9.1440E-01	1.4398E+00	-1.0000E+04
-9.1440E-01	1.4652E+00	-1.0000E+04
1.2700E-02	2.9210E-01	5.6838E+03
3.8100E-02	2.9210E-01	5.6838E+03
6.3500E-02	2.9210E-01	5.6838E+03
8.8900E-02	2.9210E-01	5.6838E+03
1.1430E-01	2.9210E-01	5.6838E+03
1.3970E-01	2.9210E-01	5.6838E+03
1.6510E-01	2.9210E-01	5.6838E+03
1.9050E-01	2.9210E-01	5.6838E+03
2.1590E-01	2.9210E-01	5.6838E+03
2.4130E-01	2.9210E-01	5.6838E+03
2.6670E-01	2.9210E-01	5.6838E+03
2.9210E-01	2.9210E-01	5.6838E+03
3.1750E-01	2.9210E-01	5.6838E+03
3.4290E-01	2.9210E-01	5.6838E+03
3.6830E-01	2.9210E-01	5.6838E+03
3.9370E-01	2.9210E-01	5.6838E+03
4.1910E-01	2.9210E-01	5.6838E+03
4.4450E-01	2.9210E-01	5.6838E+03
4.6990E-01	2.9210E-01	5.6838E+03
4.9530E-01	2.9210E-01	5.6838E+03
5.2070E-01	2.9210E-01	5.6838E+03
-1.2700E-02	2.9210E-01	5.6838E+03
-3.8100E-02	2.9210E-01	5.6838E+03
-6.3500E-02	2.9210E-01	5.6838E+03
-8.8900E-02	2.9210E-01	5.6838E+03
-1.1430E-01	2.9210E-01	5.6838E+03
-1.3970E-01	2.9210E-01	5.6838E+03
-1.6510E-01	2.9210E-01	5.6838E+03
-1.9050E-01	2.9210E-01	5.6838E+03
-2.1590E-01	2.9210E-01	5.6838E+03
-2.4130E-01	2.9210E-01	5.6838E+03
-2.6670E-01	2.9210E-01	5.6838E+03
-2.9210E-01	2.9210E-01	5.6838E+03
-3.1750E-01	2.9210E-01	5.6838E+03
-3.4290E-01	2.9210E-01	5.6838E+03
-3.6830E-01	2.9210E-01	5.6838E+03
-3.9370E-01	2.9210E-01	5.6838E+03

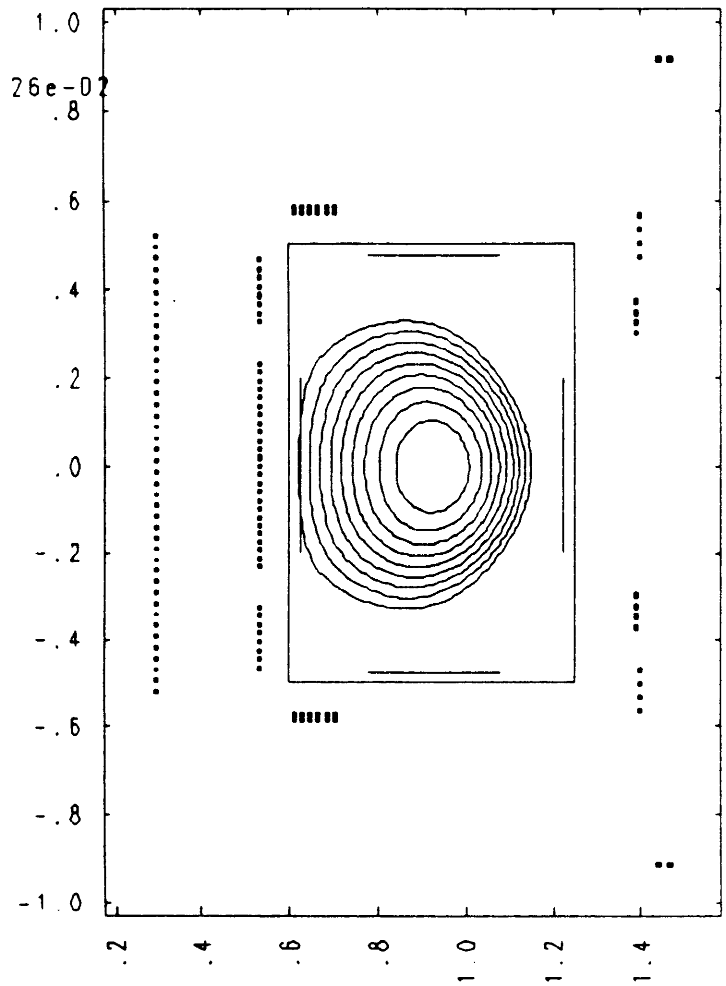
-4.1910E-01	2.9210E-01	5.6838E+03
-4.4450E-01	2.9210E-01	5.6838E+03
-4.6990E-01	2.9210E-01	5.6838E+03
-4.9530E-01	2.9210E-01	5.6838E+03
-5.2070E-01	2.9210E-01	5.6838E+03



EXTERNAL COIL FLUX CONTOURS



Q -VS- PSI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-.2
-.4
-.6
-.8
-1.0
.2
.4
.6
.8
1.0
1.2
1.4

Geometry

R (m)	=	8 85e-01	
a (m)	=	2 65e-01	
R/a	=	3.34e+00	
Kappa	=	1 25e+00	
Delta (u,l)=		8 26e-02	8

xma = 0.930 zma = 0.000

COIL CURRENTS

COIL	I(AMPS)
OHCEN	-2 000e+05
OHTOPBOT	-1.280e+05
NULL	-1 920e+05
TRIM	-6 400e+04
FAR	-1 127e+05
FAROUT	-4 000e+04
ANTIX	2 481e+05
PLASMA	2 000e+05

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SUROU OUTPUT
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FROM 2 DIMENSIONAL SUMMATION OVER PLASMA:
VOLUME   =  1.400313E+00
VOLMSPH =  1.530218E+00  METERS**3
AREA     =  2.551758E-01
AREASPH =  3.074507E-01  METERS**2
VOLUME INTEGRAL OF P =  1.241422E+04  JOULES
VOLUME INTEGRAL OF BPOL**2/(2*AMU0) =  7.650547E+03  JOULES
VOLUME INTEGRAL OF BTOR**2/(2*AMU0) =  2.761396E+06  JOULES
VOLUME INTEGRAL OF BTOREXT**2/(2*AMU0) =  2.762819E+06  JOULES
AREA INTEGRAL OF P =  2.192902E+03  NEWTONS
AREA INTEGRAL OF BPOL**2/(2*AMU0) =  1.386471E+03  NEWTONS
AREA INTEGRAL OF BTOR**2/(2*AMU0) =  5.299618E+05  NEWTONS
AREA INTEGRAL OF BTOREXT**2/(2*AMU0) =  5.302157E+05  NEWTONS
SHAFRANOV MEAN MAJOR RADIUS =  8.921459E-01  METERS
SHAFRANOV BETA POLOIDAL =  1.062244E+00
BETA POLOIDAL SPH       =  1.271303E+00
BETA POLOIDAL AREA      =  1.131107E+00
LITTLE L SUB I =  6.546323E-01
MU SUB I =  1.217387E-01
THERMAL ENERGY =  1.862133E+04
BETA TOTAL =  4.483211E-03
BETA POLOIDAL =  1.622658E+00
BETA TOROIDAL =  4.495632E-03
S4 =  0.
DELTA PHI ZERO =  1.167816E-03 WEBERS
DELTA PHI TOROIDAL = -1.482472E-04
PLASMA CURRENT =  2.000000E+05  AMPERES
```

```
1
 AV BETA =   4.12000E-03
 AV BFESP =   6.86120E-03
 BETAPOL =   1.16953E+00
 OLD CURRENT (AMPS) =   2.00000E+05
 NEW CURRENT (AMPS) =   2.00161E+05

 BASED ON RO:
     BETA AV =  4.10858E-03
     BETABO AV =  5.12167E-03
     RADIUS =  3.00745E-01
     ASPECT RATIO =  3.22119E+00

 XMA (M) =  9.30005E-01
 ZMA (M) = -6.82121E-15
 UPSILN =  3.42356E-01

 AV MINOR RADIUS (M) =  3.12833E-01
 AV MAJOR RADIUS (M) =  7.92132E-01
 ASPECT RATIO =  2.53212E+00
 INT. TOROIDAL FLUX (WB) =  6.30883E-01
 INT. POLOIDAL FLUX (WB) =  1.42351E-01
 EXT. FLUX AT AXIS (WB)  = -4.85747E-01

GEOMETRY:
     MAJOR RADIUS (M) =  8.84943E-01
     MINOR RADIUS (M) =  2.64631E-01
     ASPECT RATIO =   3.34407E+00
     ELONGATION =   1.24636E+00
     TRIANGULARITY (U,L) =  8.26350E-02  8.26350E-02
```

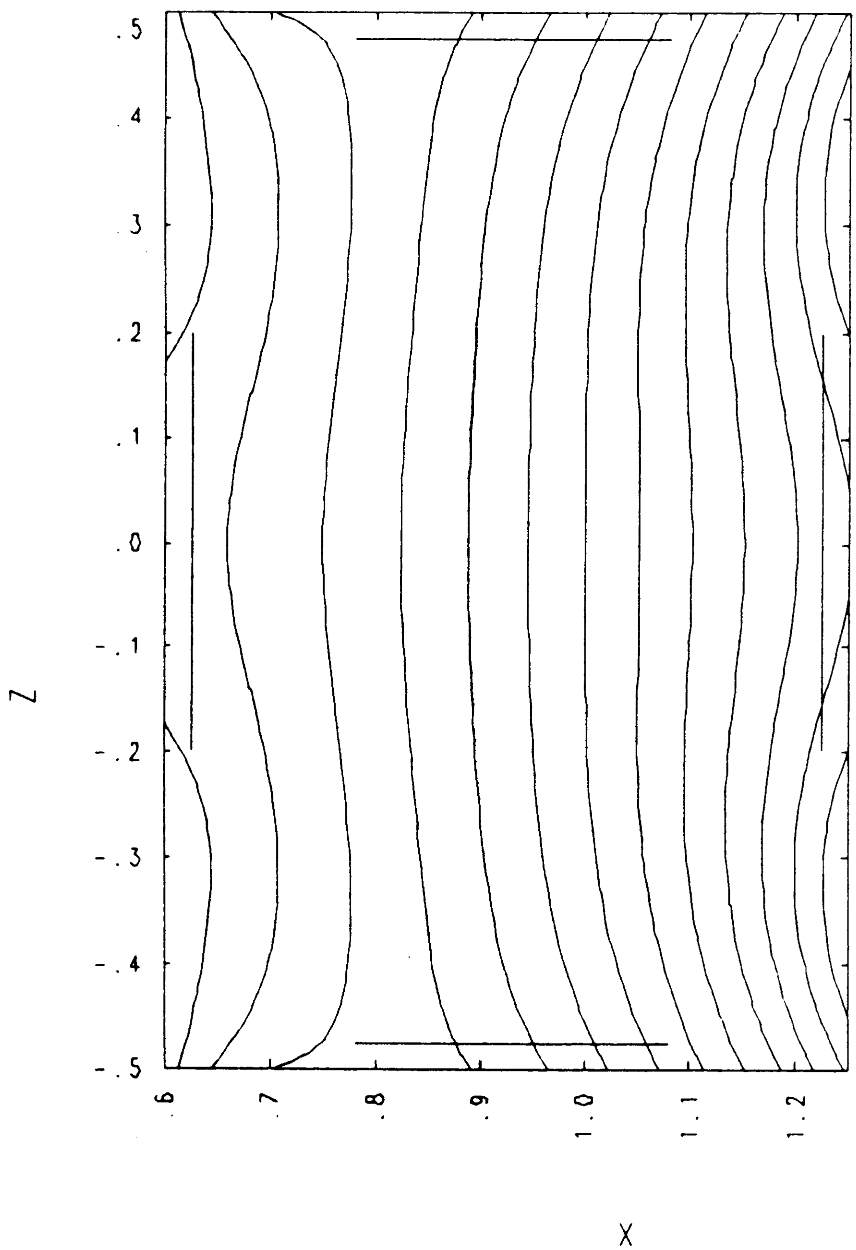
1

Z COIL (M)	X COIL (M)	I COIL (AMPS)
-2.3257E-01	5.3340E-01	-8.0000E+03
-2.1319E-01	5.3340E-01	-8.0000E+03
-1.9381E-01	5.3340E-01	-8.0000E+03
-1.7443E-01	5.3340E-01	-8.0000E+03
-1.5505E-01	5.3340E-01	-8.0000E+03
-1.3567E-01	5.3340E-01	-8.0000E+03
-1.1628E-01	5.3340E-01	-8.0000E+03
-9.6904E-02	5.3340E-01	-8.0000E+03
-7.7523E-02	5.3340E-01	-8.0000E+03
-5.8142E-02	5.3340E-01	-8.0000E+03
-3.8761E-02	5.3340E-01	-8.0000E+03
-1.9381E-02	5.3340E-01	-8.0000E+03
0.	5.3340E-01	-8.0000E+03
1.9381E-02	5.3340E-01	-8.0000E+03
3.8761E-02	5.3340E-01	-8.0000E+03
5.8142E-02	5.3340E-01	-8.0000E+03
7.7523E-02	5.3340E-01	-8.0000E+03
9.6904E-02	5.3340E-01	-8.0000E+03
1.1628E-01	5.3340E-01	-8.0000E+03
1.3567E-01	5.3340E-01	-8.0000E+03
1.5505E-01	5.3340E-01	-8.0000E+03
1.7443E-01	5.3340E-01	-8.0000E+03
1.9381E-01	5.3340E-01	-8.0000E+03
2.1319E-01	5.3340E-01	-8.0000E+03
2.3257E-01	5.3340E-01	-8.0000E+03
4.6595E-01	5.3340E-01	-8.0000E+03
4.4604E-01	5.3340E-01	-8.0000E+03
4.2613E-01	5.3340E-01	-8.0000E+03
4.0622E-01	5.3340E-01	-8.0000E+03
3.8631E-01	5.3340E-01	-8.0000E+03
3.6640E-01	5.3340E-01	-8.0000E+03
3.4649E-01	5.3340E-01	-8.0000E+03
3.2658E-01	5.3340E-01	-8.0000E+03
-4.6595E-01	5.3340E-01	-8.0000E+03
-4.4604E-01	5.3340E-01	-8.0000E+03
-4.2613E-01	5.3340E-01	-8.0000E+03
-4.0622E-01	5.3340E-01	-8.0000E+03
-3.8631E-01	5.3340E-01	-8.0000E+03

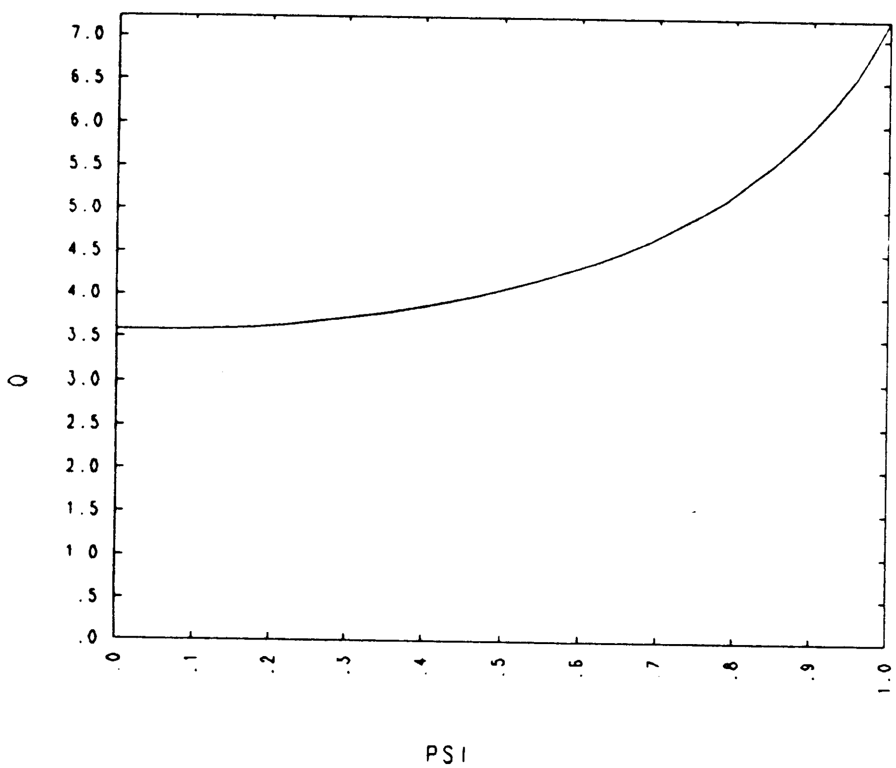
-3.6640E-01	5.3340E-01	-8.0000E+03
-3.4649E-01	5.3340E-01	-8.0000E+03
-3.2658E-01	5.3340E-01	-8.0000E+03
5.7150E-01	6.1225E-01	-8.0000E+03
5.7150E-01	6.3024E-01	-8.0000E+03
5.7150E-01	6.4823E-01	-8.0000E+03
5.7150E-01	6.6622E-01	-8.0000E+03
5.7150E-01	6.8421E-01	-8.0000E+03
5.7150E-01	7.0220E-01	-8.0000E+03
5.8420E-01	6.1225E-01	-8.0000E+03
5.8420E-01	6.3024E-01	-8.0000E+03
5.8420E-01	6.4823E-01	-8.0000E+03
5.8420E-01	6.6622E-01	-8.0000E+03
5.8420E-01	6.8421E-01	-8.0000E+03
5.8420E-01	7.0220E-01	-8.0000E+03
-5.7150E-01	6.1225E-01	-8.0000E+03
-5.7150E-01	6.3024E-01	-8.0000E+03
-5.7150E-01	6.4823E-01	-8.0000E+03
-5.7150E-01	6.6622E-01	-8.0000E+03
-5.7150E-01	6.8421E-01	-8.0000E+03
-5.7150E-01	7.0220E-01	-8.0000E+03
-5.8420E-01	6.1225E-01	-8.0000E+03
-5.8420E-01	6.3024E-01	-8.0000E+03
-5.8420E-01	6.4823E-01	-8.0000E+03
-5.8420E-01	6.6622E-01	-8.0000E+03
-5.8420E-01	6.8421E-01	-8.0000E+03
-5.8420E-01	7.0220E-01	-8.0000E+03
4.6990E-01	1.4002E+00	-8.0000E+03
5.0165E-01	1.4002E+00	-8.0000E+03
5.3340E-01	1.4002E+00	-8.0000E+03
5.6515E-01	1.4002E+00	-8.0000E+03
-4.6990E-01	1.4002E+00	-8.0000E+03
-5.0165E-01	1.4002E+00	-8.0000E+03
-5.3340E-01	1.4002E+00	-8.0000E+03
-5.6515E-01	1.4002E+00	-8.0000E+03
3.0083E-01	1.3890E+00	-1.4093E+04
3.2464E-01	1.3890E+00	-1.4093E+04
3.4846E-01	1.3890E+00	-1.4093E+04
3.7227E-01	1.3890E+00	-1.4093E+04
-3.0083E-01	1.3890E+00	-1.4093E+04
-3.2464E-01	1.3890E+00	-1.4093E+04
-3.4846E-01	1.3890E+00	-1.4093E+04

-3.7227E-01	1.3890E+00	-1.4093E+04
9.1440E-01	1.4398E+00	-1.0000E+04
9.1440E-01	1.4652E+00	-1.0000E+04
-9.1440E-01	1.4398E+00	-1.0000E+04
-9.1440E-01	1.4652E+00	-1.0000E+04
1.2700E-02	2.9210E-01	5.9065E+03
3.8100E-02	2.9210E-01	5.9065E+03
6.3500E-02	2.9210E-01	5.9065E+03
8.8900E-02	2.9210E-01	5.9065E+03
1.1430E-01	2.9210E-01	5.9065E+03
1.3970E-01	2.9210E-01	5.9065E+03
1.6510E-01	2.9210E-01	5.9065E+03
1.9050E-01	2.9210E-01	5.9065E+03
2.1590E-01	2.9210E-01	5.9065E+03
2.4130E-01	2.9210E-01	5.9065E+03
2.6670E-01	2.9210E-01	5.9065E+03
2.9210E-01	2.9210E-01	5.9065E+03
3.1750E-01	2.9210E-01	5.9065E+03
3.4290E-01	2.9210E-01	5.9065E+03
3.6830E-01	2.9210E-01	5.9065E+03
3.9370E-01	2.9210E-01	5.9065E+03
4.1910E-01	2.9210E-01	5.9065E+03
4.4450E-01	2.9210E-01	5.9065E+03
4.6990E-01	2.9210E-01	5.9065E+03
4.9530E-01	2.9210E-01	5.9065E+03
5.2070E-01	2.9210E-01	5.9065E+03
-1.2700E-02	2.9210E-01	5.9065E+03
-3.8100E-02	2.9210E-01	5.9065E+03
-6.3500E-02	2.9210E-01	5.9065E+03
-8.8900E-02	2.9210E-01	5.9065E+03
-1.1430E-01	2.9210E-01	5.9065E+03
-1.3970E-01	2.9210E-01	5.9065E+03
-1.6510E-01	2.9210E-01	5.9065E+03
-1.9050E-01	2.9210E-01	5.9065E+03
-2.1590E-01	2.9210E-01	5.9065E+03
-2.4130E-01	2.9210E-01	5.9065E+03
-2.6670E-01	2.9210E-01	5.9065E+03
-2.9210E-01	2.9210E-01	5.9065E+03
-3.1750E-01	2.9210E-01	5.9065E+03
-3.4290E-01	2.9210E-01	5.9065E+03
-3.6830E-01	2.9210E-01	5.9065E+03
-3.9370E-01	2.9210E-01	5.9065E+03

-4.1910E-01	2.9210E-01	5.9065E+03
-4.4450E-01	2.9210E-01	5.9065E+03
-4.6990E-01	2.9210E-01	5.9065E+03
-4.9530E-01	2.9210E-01	5.9065E+03
-5.2070E-01	2.9210E-01	5.9065E+03



EXTERNAL COIL FLUX CONTOURS



Q -VS- PSI

Appendix B

Sample Codes for ASEQ Input and Vacuum Field Calcualtions

B.1 EQNSIN

The following three sets of codes are input files for ASEQ Code in Cray Supercomputer at the Lawrence Livermore National Laboratory. The coils are entered according to the actual positions. These three codes differ in the OH coil currents: +8, 0, and -8 kA.

```
***Versatile Toroidal Facility ASEQ Input (OH current at +8kA)***
xzero=0.60    alx=0.65    alz=1.    isym=1    ifunc=5
iprnt=-1    irst=5    moment=.f    ionetwo=0    iblip=0
ipnml=0    ipsum= 1    ipccur=1    ipflx1=1    ipflx2=1
ipext=1    ipjcon=0    ipppsi=0    ipgpsi=0    ipqpsi=1
ippx=0    ipjx=0    ipnx=0
idatabs = 0    noplots=.f    irsg=1    ihump=1
$end
tcuro=2e5  b0=2.0    r=0.96    p0=1.0    pdiv=0.02
alfa=-1.5    alfb=+2.88
eguess=0.5    betap=6.0    betag=1.5
$end
epspa=1.e-7  epsba=5.e-5  npa=50    nba=18    nxa=65
nza=65    nocase=0
$end
nvary1=1 ivartype=1


$end
nec=127   vffac=-0.8   vfs=0.  ncset=7
ipec= 25(1) 16(1) 24(1) 8(1) 8(3) 4(2) 42(3)
icset= 25(1) 16(2) 24(3) 8(4) 8(5) 4(6) 42(7)
pec=
-2.3256875e-01  5.3340000e-01  -1.0000000e+04
 -2.1318802e-01  5.3340000e-01  -1.0000000e+04
 -1.9380729e-01  5.3340000e-01  -1.0000000e+04
 -1.7442656e-01  5.3340000e-01  -1.0000000e+04
 -1.5504583e-01  5.3340000e-01  -1.0000000e+04
 -1.3566510e-01  5.3340000e-01  -1.0000000e+04
 -1.1628438e-01  5.3340000e-01  -1.0000000e+04
 -9.6903646e-02  5.3340000e-01  -1.0000000e+04
 -7.7522917e-02  5.3340000e-01  -1.0000000e+04
 -5.8142188e-02  5.3340000e-01  -1.0000000e+04
 -3.8761458e-02  5.3340000e-01  -1.0000000e+04
 -1.9380729e-02  5.3340000e-01  -1.0000000e+04
  0.0000000e+00  5.3340000e-01  -1.0000000e+04
  1.9380729e-02  5.3340000e-01  -1.0000000e+04
  3.8761458e-02  5.3340000e-01  -1.0000000e+04
  5.8142188e-02  5.3340000e-01  -1.0000000e+04
  7.7522917e-02  5.3340000e-01  -1.0000000e+04
  9.6903646e-02  5.3340000e-01  -1.0000000e+04
  1.1628438e-01  5.3340000e-01  -1.0000000e+04
  1.3566510e-01  5.3340000e-01  -1.0000000e+04
  1.5504583e-01  5.3340000e-01  -1.0000000e+04
  1.7442656e-01  5.3340000e-01  -1.0000000e+04
  1.9380729e-01  5.3340000e-01  -1.0000000e+04
  2.1318802e-01  5.3340000e-01  -1.0000000e+04
  2.3256875e-01  5.3340000e-01  -1.0000000e+04
  4.6595000e-01  5.3340000e-01  -1.0000000e+04
  4.4604000e-01  5.3340000e-01  -1.0000000e+04
  4.2613000e-01  5.3340000e-01  -1.0000000e+04
  4.0622000e-01  5.3340000e-01  -1.0000000e+04
  3.8631000e-01  5.3340000e-01  -1.0000000e+04
  3.6640000e-01  5.3340000e-01  -1.0000000e+04
  3.4649000e-01  5.3340000e-01  -1.0000000e+04
  3.2658000e-01  5.3340000e-01  -1.0000000e+04
 -4.6595000e-01  5.3340000e-01  -1.0000000e+04
 -4.4604000e-01  5.3340000e-01  -1.0000000e+04
 -4.2613000e-01  5.3340000e-01  -1.0000000e+04
 -4.0622000e-01  5.3340000e-01  -1.0000000e+04
```

-3.8631000e-01	5.3340000e-01	-1.0000000e+04
-3.6640000e-01	5.3340000e-01	-1.0000000e+04
-3.4649000e-01	5.3340000e-01	-1.0000000e+04
-3.2658000e-01	5.3340000e-01	-1.0000000e+04
5.7150000e-01	6.1224583e-01	-1.0000000e+04
5.7150000e-01	6.3023750e-01	-1.0000000e+04
5.7150000e-01	6.4822917e-01	-1.0000000e+04
5.7150000e-01	6.6622083e-01	-1.0000000e+04
5.7150000e-01	6.8421250e-01	-1.0000000e+04
5.7150000e-01	7.0220417e-01	-1.0000000e+04
5.8420000e-01	6.1224583e-01	-1.0000000e+04
5.8420000e-01	6.3023750e-01	-1.0000000e+04
5.8420000e-01	6.4822917e-01	-1.0000000e+04
5.8420000e-01	6.6622083e-01	-1.0000000e+04
5.8420000e-01	6.8421250e-01	-1.0000000e+04
5.8420000e-01	7.0220417e-01	-1.0000000e+04
-5.7150000e-01	6.1224583e-01	-1.0000000e+04
-5.7150000e-01	6.3023750e-01	-1.0000000e+04
-5.7150000e-01	6.4822917e-01	-1.0000000e+04
-5.7150000e-01	6.6622083e-01	-1.0000000e+04
-5.7150000e-01	6.8421250e-01	-1.0000000e+04
-5.7150000e-01	7.0220417e-01	-1.0000000e+04
-5.8420000e-01	6.1224583e-01	-1.0000000e+04
-5.8420000e-01	6.3023750e-01	-1.0000000e+04
-5.8420000e-01	6.4822917e-01	-1.0000000e+04
-5.8420000e-01	6.6622083e-01	-1.0000000e+04
-5.8420000e-01	6.8421250e-01	-1.0000000e+04
-5.8420000e-01	7.0220417e-01	-1.0000000e+04
4.6990000e-01	1.4001750e+00	-1.0000000e+04
5.0165000e-01	1.4001750e+00	-1.0000000e+04
5.3340000e-01	1.4001750e+00	-1.0000000e+04
5.6515000e-01	1.4001750e+00	-1.0000000e+04
-4.6990000e-01	1.4001750e+00	-1.0000000e+04
-5.0165000e-01	1.4001750e+00	-1.0000000e+04
-5.3340000e-01	1.4001750e+00	-1.0000000e+04
-5.6515000e-01	1.4001750e+00	-1.0000000e+04
3.0083125e-01	1.3890000e+00	-1.0000000e+04
3.2464375e-01	1.3890000e+00	-1.0000000e+04
3.4845625e-01	1.3890000e+00	-1.0000000e+04
3.7226875e-01	1.3890000e+00	-1.0000000e+04
-3.0083125e-01	1.3890000e+00	-1.0000000e+04
-3.2464375e-01	1.3890000e+00	-1.0000000e+04
-3.4845625e-01	1.3890000e+00	-1.0000000e+04
-3.7226875e-01	1.3890000e+00	-1.0000000e+04
9.1440000e-01	1.4398000e+00	-1.0000000e+04
9.1440000e-01	1.4652000e+00	-1.0000000e+04
-9.1440000e-01	1.4398000e+00	-1.0000000e+04
-9.1440000e-01	1.4652000e+00	-1.0000000e+04
1.2700000e-02	2.9210000e-01	1.0000000e+04
3.8100000e-02	2.9210000e-01	1.0000000e+04
6.3500000e-02	2.9210000e-01	1.0000000e+04
8.8900000e-02	2.9210000e-01	1.0000000e+04
1.1430000e-01	2.9210000e-01	1.0000000e+04
1.3970000e-01	2.9210000e-01	1.0000000e+04
1.6510000e-01	2.9210000e-01	1.0000000e+04
1.9050000e-01	2.9210000e-01	1.0000000e+04
2.1590000e-01	2.9210000e-01	1.0000000e+04
2.4130000e-01	2.9210000e-01	1.0000000e+04
2.6670000e-01	2.9210000e-01	1.0000000e+04
2.9210000e-01	2.9210000e-01	1.0000000e+04

```
 3.1750000e-01  2.9210000e-01  1.0000000e+04
 3.4290000e-01  2.9210000e-01  1.0000000e+04
 3.6830000e-01  2.9210000e-01  1.0000000e+04
 3.9370000e-01  2.9210000e-01  1.0000000e+04
 4.1910000e-01  2.9210000e-01  1.0000000e+04
 4.4450000e-01  2.9210000e-01  1.0000000e+04
 4.6990000e-01  2.9210000e-01  1.0000000e+04
 4.9530000e-01  2.9210000e-01  1.0000000e+04
 5.2070000e-01  2.9210000e-01  1.0000000e+04
-1.2700000e-02  2.9210000e-01  1.0000000e+04
-3.8100000e-02  2.9210000e-01  1.0000000e+04
-6.3500000e-02  2.9210000e-01  1.0000000e+04
-8.8900000e-02  2.9210000e-01  1.0000000e+04
-1.1430000e-01  2.9210000e-01  1.0000000e+04
-1.3970000e-01  2.9210000e-01  1.0000000e+04
-1.6510000e-01  2.9210000e-01  1.0000000e+04
-1.9050000e-01  2.9210000e-01  1.0000000e+04
-2.1590000e-01  2.9210000e-01  1.0000000e+04
-2.4130000e-01  2.9210000e-01  1.0000000e+04
-2.6670000e-01  2.9210000e-01  1.0000000e+04
-2.9210000e-01  2.9210000e-01  1.0000000e+04
-3.1750000e-01  2.9210000e-01  1.0000000e+04
-3.4290000e-01  2.9210000e-01  1.0000000e+04
-3.6830000e-01  2.9210000e-01  1.0000000e+04
-3.9370000e-01  2.9210000e-01  1.0000000e+04
-4.1910000e-01  2.9210000e-01  1.0000000e+04
-4.4450000e-01  2.9210000e-01  1.0000000e+04
-4.6990000e-01  2.9210000e-01  1.0000000e+04
-4.9530000e-01  2.9210000e-01  1.0000000e+04
-5.2070000e-01  2.9210000e-01  1.0000000e+04


namec = 'OHCEN', 'OHTOPBOT', 'NULL', 'TRIM', 'FAR', 'FAROUT', 'ANTIX'
$end
nlcds=4  iplim=1
plimxa=0.625 1.225 0.78 0.78    plimza= 0.2  .2   0.475 -0.475
plimxb=0.625 1.225 1.08 1.08    plimzb=-0.2 -.2   0.475 -0.475
$end
ksep=1      psirat=0.95   bungle=0.5
xdiv= 1.00  1.00  1.00  1.00
zdiv= 1.00  1.00  1.00  1.00
$end
lwall=.f    ljet=0     npts=36     numbv=10     ellip=1.6
arad=0.25    deity=0.    rot=0.0    drot=0.   xmar=0.93
nopin=8     minc=10     mth=20      psisur=-0.5   zmar=0.0
zsepr(1)=0.430  zsepr(3)=-0.385
xsepr(1)=0.540  xsepr(3)=0.565
deity2=0.0   ellip2=1.0    npw=5

 xw=.6 .6 1.25 1.25 .6

zw=-.5 .5 .5 -.5 -.5

xg=1.0 0.435   0.640 0.875 0.478  0.610  0.810 0.81
zg=-5.02 -0.465  -0.538 -.02 0.360  0.395  0.14  -0.17
phig=0.0  0.0    0.0   0.0  0.11    0.11   0.0   0.
$end
lmap=.t      lfct=.f      nosurf=29     nquib=1      delp=-.05
nolim=1      kbc=1        iqfunc=1      delflx=0.190966
q0=1.0       qe=3.6       ifunc2=1      betaq=3.     qeppo=100.
```

```
dqfrac=0.5    dqswit=0.005
 $end
 zguess=-0.00 zcont1=0.030   zcont2=0.40
 xguess=.675 xcont1=0.10    xcont2=0.20
 xconx1=+0.010  0.0 -0.005 0.0 xconx2=0.00
 zconx1=-0.20  0.0 +0.016 0.0 zconx2=4(0.00)
 pcon1=-0.00300  +0.0125  +0.0212 +0.0250 +0.00625 +0.00538 +0.0375 0.0375
 pcon2=+0.00  -0.00  +0.00  -0.00  0.0   0.0  0.0375  0.0375
 $end
$end
```

```
***Versatile Toroidal Facility ASEQ Input (OH current at 0kA)***
xzero=0.60    alx=0.65    alz=1.    isym=1    ifunc=5
iprnt=-1    irst=5    moment=.f    ionetwo=0    iblip=0
ipnml=0    ipsum= 1    ipccur=1    ipflx1=1    ipflx2=1
ipext=1    ipjcon=0    ipppsi=0    ipgpsi=0    ipqpsi=1
ippx=0    ipjx=0    ipnx=0
idatabs = 0    noplots=.f    irsg=1    ihump=1
$end
tcuro=2e5  b0=2.0    r=0.96    p0=1.0    pdiv=0.02
alfa=-1.5    alfb=+2.88
eguess=0.5    betap=6.0    betag=1.5
$end
epspa=1.e-7  epsba=5.e-5  npa=50    nba=18    nxa=65
nza=65    nocase=0
$end
nvary1=1 ivartype=1


$end
nec=127   vffac=0.0   vfs=0. ncset=7
ipec= 25(1) 16(1) 24(1) 8(1) 8(3) 4(2) 42(3)
icset= 25(1) 16(2) 24(3) 8(4) 8(5) 4(6) 42(7)
pec=
-2.3256875e-01  5.3340000e-01  -1.0000000e+04
 -2.1318802e-01  5.3340000e-01  -1.0000000e+04
 -1.9380729e-01  5.3340000e-01  -1.0000000e+04
 -1.7442656e-01  5.3340000e-01  -1.0000000e+04
 -1.5504583e-01  5.3340000e-01  -1.0000000e+04
 -1.3566510e-01  5.3340000e-01  -1.0000000e+04
 -1.1628438e-01  5.3340000e-01  -1.0000000e+04
 -9.6903646e-02  5.3340000e-01  -1.0000000e+04
 -7.7522917e-02  5.3340000e-01  -1.0000000e+04
 -5.8142188e-02  5.3340000e-01  -1.0000000e+04
 -3.8761458e-02  5.3340000e-01  -1.0000000e+04
 -1.9380729e-02  5.3340000e-01  -1.0000000e+04
  0.0000000e+00  5.3340000e-01  -1.0000000e+04
  1.9380729e-02  5.3340000e-01  -1.0000000e+04
  3.8761458e-02  5.3340000e-01  -1.0000000e+04
  5.8142188e-02  5.3340000e-01  -1.0000000e+04
  7.7522917e-02  5.3340000e-01  -1.0000000e+04
  9.6903646e-02  5.3340000e-01  -1.0000000e+04
  1.1628438e-01  5.3340000e-01  -1.0000000e+04
  1.3566510e-01  5.3340000e-01  -1.0000000e+04
  1.5504583e-01  5.3340000e-01  -1.0000000e+04
  1.7442656e-01  5.3340000e-01  -1.0000000e+04
  1.9380729e-01  5.3340000e-01  -1.0000000e+04
  2.1318802e-01  5.3340000e-01  -1.0000000e+04
  2.3256875e-01  5.3340000e-01  -1.0000000e+04
  4.6595000e-01  5.3340000e-01  -1.0000000e+04
  4.4604000e-01  5.3340000e-01  -1.0000000e+04
  4.2613000e-01  5.3340000e-01  -1.0000000e+04
  4.0622000e-01  5.3340000e-01  -1.0000000e+04
  3.8631000e-01  5.3340000e-01  -1.0000000e+04
  3.6640000e-01  5.3340000e-01  -1.0000000e+04
  3.4649000e-01  5.3340000e-01  -1.0000000e+04
  3.2658000e-01  5.3340000e-01  -1.0000000e+04
-4.6595000e-01  5.3340000e-01  -1.0000000e+04
-4.4604000e-01  5.3340000e-01  -1.0000000e+04
-4.2613000e-01  5.3340000e-01  -1.0000000e+04
-4.0622000e-01  5.3340000e-01  -1.0000000e+04
```

-3.8631000e-01	5.3340000e-01	-1.0000000e+04
-3.6640000e-01	5.3340000e-01	-1.0000000e+04
-3.4649000e-01	5.3340000e-01	-1.0000000e+04
-3.2658000e-01	5.3340000e-01	-1.0000000e+04
5.7150000e-01	6.1224583e-01	-1.0000000e+04
5.7150000e-01	6.3023750e-01	-1.0000000e+04
5.7150000e-01	6.4822917e-01	-1.0000000e+04
5.7150000e-01	6.6622083e-01	-1.0000000e+04
5.7150000e-01	6.8421250e-01	-1.0000000e+04
5.7150000e-01	7.0220417e-01	-1.0000000e+04
5.8420000e-01	6.1224583e-01	-1.0000000e+04
5.8420000e-01	6.3023750e-01	-1.0000000e+04
5.8420000e-01	6.4822917e-01	-1.0000000e+04
5.8420000e-01	6.6622083e-01	-1.0000000e+04
5.8420000e-01	6.8421250e-01	-1.0000000e+04
5.8420000e-01	7.0220417e-01	-1.0000000e+04
-5.7150000e-01	6.1224583e-01	-1.0000000e+04
-5.7150000e-01	6.3023750e-01	-1.0000000e+04
-5.7150000e-01	6.4822917e-01	-1.0000000e+04
-5.7150000e-01	6.6622083e-01	-1.0000000e+04
-5.7150000e-01	6.8421250e-01	-1.0000000e+04
-5.7150000e-01	7.0220417e-01	-1.0000000e+04
-5.8420000e-01	6.1224583e-01	-1.0000000e+04
-5.8420000e-01	6.3023750e-01	-1.0000000e+04
-5.8420000e-01	6.4822917e-01	-1.0000000e+04
-5.8420000e-01	6.6622083e-01	-1.0000000e+04
-5.8420000e-01	6.8421250e-01	-1.0000000e+04
-5.8420000e-01	7.0220417e-01	-1.0000000e+04
4.6990000e-01	1.4001750e+00	-1.0000000e+04
5.0165000e-01	1.4001750e+00	-1.0000000e+04
5.3340000e-01	1.4001750e+00	-1.0000000e+04
5.6515000e-01	1.4001750e+00	-1.0000000e+04
-4.6990000e-01	1.4001750e+00	-1.0000000e+04
-5.0165000e-01	1.4001750e+00	-1.0000000e+04
-5.3340000e-01	1.4001750e+00	-1.0000000e+04
-5.6515000e-01	1.4001750e+00	-1.0000000e+04
3.0083125e-01	1.3890000e+00	-1.0000000e+04
3.2464375e-01	1.3890000e+00	-1.0000000e+04
3.4845625e-01	1.3890000e+00	-1.0000000e+04
3.7226875e-01	1.3890000e+00	-1.0000000e+04
-3.0083125e-01	1.3890000e+00	-1.0000000e+04
-3.2464375e-01	1.3890000e+00	-1.0000000e+04
-3.4845625e-01	1.3890000e+00	-1.0000000e+04
-3.7226875e-01	1.3890000e+00	-1.0000000e+04
9.1440000e-01	1.4398000e+00	-1.0000000e+04
9.1440000e-01	1.4652000e+00	-1.0000000e+04
-9.1440000e-01	1.4398000e+00	-1.0000000e+04
-9.1440000e-01	1.4652000e+00	-1.0000000e+04
1.2700000e-02	2.9210000e-01	1.0000000e+04
3.8100000e-02	2.9210000e-01	1.0000000e+04
6.3500000e-02	2.9210000e-01	1.0000000e+04
8.8900000e-02	2.9210000e-01	1.0000000e+04
1.1430000e-01	2.9210000e-01	1.0000000e+04
1.3970000e-01	2.9210000e-01	1.0000000e+04
1.6510000e-01	2.9210000e-01	1.0000000e+04
1.9050000e-01	2.9210000e-01	1.0000000e+04
2.1590000e-01	2.9210000e-01	1.0000000e+04
2.4130000e-01	2.9210000e-01	1.0000000e+04
2.6670000e-01	2.9210000e-01	1.0000000e+04
2.9210000e-01	2.9210000e-01	1.0000000e+04

```
 3.1750000e-01  2.9210000e-01  1.0000000e+04
 3.4290000e-01  2.9210000e-01  1.0000000e+04
 3.6830000e-01  2.9210000e-01  1.0000000e+04
 3.9370000e-01  2.9210000e-01  1.0000000e+04
 4.1910000e-01  2.9210000e-01  1.0000000e+04
 4.4450000e-01  2.9210000e-01  1.0000000e+04
 4.6990000e-01  2.9210000e-01  1.0000000e+04
 4.9530000e-01  2.9210000e-01  1.0000000e+04
 5.2070000e-01  2.9210000e-01  1.0000000e+04
-1.2700000e-02  2.9210000e-01  1.0000000e+04
-3.8100000e-02  2.9210000e-01  1.0000000e+04
-6.3500000e-02  2.9210000e-01  1.0000000e+04
-8.8900000e-02  2.9210000e-01  1.0000000e+04
-1.1430000e-01  2.9210000e-01  1.0000000e+04
-1.3970000e-01  2.9210000e-01  1.0000000e+04
-1.6510000e-01  2.9210000e-01  1.0000000e+04
-1.9050000e-01  2.9210000e-01  1.0000000e+04
-2.1590000e-01  2.9210000e-01  1.0000000e+04
-2.4130000e-01  2.9210000e-01  1.0000000e+04
-2.6670000e-01  2.9210000e-01  1.0000000e+04
-2.9210000e-01  2.9210000e-01  1.0000000e+04
-3.1750000e-01  2.9210000e-01  1.0000000e+04
-3.4290000e-01  2.9210000e-01  1.0000000e+04
-3.6830000e-01  2.9210000e-01  1.0000000e+04
-3.9370000e-01  2.9210000e-01  1.0000000e+04
-4.1910000e-01  2.9210000e-01  1.0000000e+04
-4.4450000e-01  2.9210000e-01  1.0000000e+04
-4.6990000e-01  2.9210000e-01  1.0000000e+04
-4.9530000e-01  2.9210000e-01  1.0000000e+04
-5.2070000e-01  2.9210000e-01  1.0000000e+04


namec = 'OHCEN', 'OHTOPBOT', 'NULL', 'TRIM', 'FAR', 'FAROUT', 'ANTIX'
$end
nlcds=4  iplim=1
plimxa=0.625 1.225 0.78 0.78    plimza= 0.2  .2   0.475 -0.475
plimxb=0.625 1.225 1.08 1.08    plimzb=-0.2 -.2   0.475 -0.475
$end
ksep=1      psirat=0.95   bungle=0.5
xdiv= 1.00  1.00  1.00  1.00
zdiv= 1.00  1.00  1.00  1.00
$end
lwall=.f     ljet=0      npts=36      numbv=10      ellip=1.6
arad=0.25     deity=0.     rot=0.0     drot=0.   xmar=0.93
nopin=8      minc=10      mth=20       psisur=-0.5   zmar=0.0
zsepr(1)=0.430  zsepr(3)=-0.385
xsepr(1)=0.540  xsepr(3)=0.565
deity2=0.0    ellip2=1.0    npw=5

 xw=.6 .6 1.25 1.25 .6

zw=-.5 .5 .5 -.5 -.5

xg=1.0 0.435   0.640 0.875 0.478  0.610  0.810 0.81
zg=-5.02 -0.465  -0.538 -.02 0.360  0.395  0.14  -0.17
phig=0.0 0.0    0.0  0.0 0.11    0.11   0.0  0.
$end
lmap=.t      lfct=.f      nosurf=29     nquib=1      delp=-.05
nolim=1      kbc=1        iqfunc=1      delflx=0.190966
q0=1.0       qe=3.6       ifunc2=1      betaq=3.     qeppo=100.
```

```
dqfrac=0.5    dqswit=0.005
$end
zguess=-0.00 zcont1=0.030   zcont2=0.40
xguess=.675 xcont1=0.10    xcont2=0.20
xconx1=+0.010  0.0 -0.005 0.0 xconx2=0.00
zconx1=-0.20  0.0 +0.016 0.0 zconx2=4(0.00)
pcon1=-0.00300  +0.0125  +0.0212 +0.0250 +0.00625 +0.00538 +0.0375 0.0375
pcon2=+0.00  -0.00  +0.00  -0.00  0.0   0.0  0.0375  0.0375
$end
$end
```

```
***Versatile Toroidal Facility ASEQ Input (OH current at -8kA)***
xzero=0.60    alx=0.65    alz=1.    isym=1    ifunc=5
iprnt=-1    irst=5    moment=.f    ionetwo=0    iblip=0
ipnml=0    ipsum= 1    ipccur=1    ipflx1=1    ipflx2=1
ipext=1    ipjcon=0    ipppsi=0    ipgpsi=0    ipqpsi=1
ippx=0    ipjx=0    ipnx=0
idatabs = 0    noplots=.f    irsg=1    ihump=1
$end
tcuro=2e5  b0=2.0    r=0.96    p0=1.0    pdiv=0.02
alfa=-1.5    alfb=+2.88
eguess=0.5    betap=6.0    betag=1.5
$end
epspa=1.e-7  epsba=5.e-5  npa=50    nba=18    nxa=65
nza=65    nocase=0
$end
nvary1=1 ivartype=1


$end
nec=127   vffac=0.8   vfs=0.  ncset=7
ipec= 25(1) 16(1) 24(1) 8(1) 8(3) 4(2) 42(3)
icset= 25(1) 16(2) 24(3) 8(4) 8(5) 4(6) 42(7)
pec=
-2.3256875e-01  5.3340000e-01  -1.0000000e+04
 -2.1318802e-01  5.3340000e-01  -1.0000000e+04
 -1.9380729e-01  5.3340000e-01  -1.0000000e+04
 -1.7442656e-01  5.3340000e-01  -1.0000000e+04
 -1.5504583e-01  5.3340000e-01  -1.0000000e+04
 -1.3566510e-01  5.3340000e-01  -1.0000000e+04
 -1.1628438e-01  5.3340000e-01  -1.0000000e+04
 -9.6903646e-02  5.3340000e-01  -1.0000000e+04
 -7.7522917e-02  5.3340000e-01  -1.0000000e+04
 -5.8142188e-02  5.3340000e-01  -1.0000000e+04
 -3.8761458e-02  5.3340000e-01  -1.0000000e+04
 -1.9380729e-02  5.3340000e-01  -1.0000000e+04
  0.0000000e+00  5.3340000e-01  -1.0000000e+04
  1.9380729e-02  5.3340000e-01  -1.0000000e+04
  3.8761458e-02  5.3340000e-01  -1.0000000e+04
  5.8142188e-02  5.3340000e-01  -1.0000000e+04
  7.7522917e-02  5.3340000e-01  -1.0000000e+04
  9.6903646e-02  5.3340000e-01  -1.0000000e+04
  1.1628438e-01  5.3340000e-01  -1.0000000e+04
  1.3566510e-01  5.3340000e-01  -1.0000000e+04
  1.5504583e-01  5.3340000e-01  -1.0000000e+04
  1.7442656e-01  5.3340000e-01  -1.0000000e+04
  1.9380729e-01  5.3340000e-01  -1.0000000e+04
  2.1318802e-01  5.3340000e-01  -1.0000000e+04
  2.3256875e-01  5.3340000e-01  -1.0000000e+04
  4.6595000e-01  5.3340000e-01  -1.0000000e+04
  4.4604000e-01  5.3340000e-01  -1.0000000e+04
  4.2613000e-01  5.3340000e-01  -1.0000000e+04
  4.0622000e-01  5.3340000e-01  -1.0000000e+04
  3.8631000e-01  5.3340000e-01  -1.0000000e+04
  3.6640000e-01  5.3340000e-01  -1.0000000e+04
  3.4649000e-01  5.3340000e-01  -1.0000000e+04
  3.2658000e-01  5.3340000e-01  -1.0000000e+04
 -4.6595000e-01  5.3340000e-01  -1.0000000e+04
 -4.4604000e-01  5.3340000e-01  -1.0000000e+04
 -4.2613000e-01  5.3340000e-01  -1.0000000e+04
 -4.0622000e-01  5.3340000e-01  -1.0000000e+04
```

-3.8631000e-01	5.3340000e-01	-1.0000000e+04
-3.6640000e-01	5.3340000e-01	-1.0000000e+04
-3.4649000e-01	5.3340000e-01	-1.0000000e+04
-3.2658000e-01	5.3340000e-01	-1.0000000e+04
5.7150000e-01	6.1224583e-01	-1.0000000e+04
5.7150000e-01	6.3023750e-01	-1.0000000e+04
5.7150000e-01	6.4822917e-01	-1.0000000e+04
5.7150000e-01	6.6622083e-01	-1.0000000e+04
5.7150000e-01	6.8421250e-01	-1.0000000e+04
5.7150000e-01	7.0220417e-01	-1.0000000e+04
5.8420000e-01	6.1224583e-01	-1.0000000e+04
5.8420000e-01	6.3023750e-01	-1.0000000e+04
5.8420000e-01	6.4822917e-01	-1.0000000e+04
5.8420000e-01	6.6622083e-01	-1.0000000e+04
5.8420000e-01	6.8421250e-01	-1.0000000e+04
5.8420000e-01	7.0220417e-01	-1.0000000e+04
-5.7150000e-01	6.1224583e-01	-1.0000000e+04
-5.7150000e-01	6.3023750e-01	-1.0000000e+04
-5.7150000e-01	6.4822917e-01	-1.0000000e+04
-5.7150000e-01	6.6622083e-01	-1.0000000e+04
-5.7150000e-01	6.8421250e-01	-1.0000000e+04
-5.7150000e-01	7.0220417e-01	-1.0000000e+04
-5.8420000e-01	6.1224583e-01	-1.0000000e+04
-5.8420000e-01	6.3023750e-01	-1.0000000e+04
-5.8420000e-01	6.4822917e-01	-1.0000000e+04
-5.8420000e-01	6.6622083e-01	-1.0000000e+04
-5.8420000e-01	6.8421250e-01	-1.0000000e+04
-5.8420000e-01	7.0220417e-01	-1.0000000e+04
4.6990000e-01	1.4001750e+00	-1.0000000e+04
5.0165000e-01	1.4001750e+00	-1.0000000e+04
5.3340000e-01	1.4001750e+00	-1.0000000e+04
5.6515000e-01	1.4001750e+00	-1.0000000e+04
-4.6990000e-01	1.4001750e+00	-1.0000000e+04
-5.0165000e-01	1.4001750e+00	-1.0000000e+04
-5.3340000e-01	1.4001750e+00	-1.0000000e+04
-5.6515000e-01	1.4001750e+00	-1.0000000e+04
3.0083125e-01	1.3890000e+00	-1.0000000e+04
3.2464375e-01	1.3890000e+00	-1.0000000e+04
3.4845625e-01	1.3890000e+00	-1.0000000e+04
3.7226875e-01	1.3890000e+00	-1.0000000e+04
-3.0083125e-01	1.3890000e+00	-1.0000000e+04
-3.2464375e-01	1.3890000e+00	-1.0000000e+04
-3.4845625e-01	1.3890000e+00	-1.0000000e+04
-3.7226875e-01	1.3890000e+00	-1.0000000e+04
9.1440000e-01	1.4398000e+00	-1.0000000e+04
9.1440000e-01	1.4652000e+00	-1.0000000e+04
-9.1440000e-01	1.4398000e+00	-1.0000000e+04
-9.1440000e-01	1.4652000e+00	-1.0000000e+04
1.2700000e-02	2.9210000e-01	1.0000000e+04
3.8100000e-02	2.9210000e-01	1.0000000e+04
6.3500000e-02	2.9210000e-01	1.0000000e+04
8.8900000e-02	2.9210000e-01	1.0000000e+04
1.1430000e-01	2.9210000e-01	1.0000000e+04
1.3970000e-01	2.9210000e-01	1.0000000e+04
1.6510000e-01	2.9210000e-01	1.0000000e+04
1.9050000e-01	2.9210000e-01	1.0000000e+04
2.1590000e-01	2.9210000e-01	1.0000000e+04
2.4130000e-01	2.9210000e-01	1.0000000e+04
2.6670000e-01	2.9210000e-01	1.0000000e+04
2.9210000e-01	2.9210000e-01	1.0000000e+04

```
 3.1750000e-01  2.9210000e-01  1.0000000e+04
 3.4290000e-01  2.9210000e-01  1.0000000e+04
 3.6830000e-01  2.9210000e-01  1.0000000e+04
 3.9370000e-01  2.9210000e-01  1.0000000e+04
 4.1910000e-01  2.9210000e-01  1.0000000e+04
 4.4450000e-01  2.9210000e-01  1.0000000e+04
 4.6990000e-01  2.9210000e-01  1.0000000e+04
 4.9530000e-01  2.9210000e-01  1.0000000e+04
 5.2070000e-01  2.9210000e-01  1.0000000e+04
-1.2700000e-02  2.9210000e-01  1.0000000e+04
-3.8100000e-02  2.9210000e-01  1.0000000e+04
-6.3500000e-02  2.9210000e-01  1.0000000e+04
-8.8900000e-02  2.9210000e-01  1.0000000e+04
-1.1430000e-01  2.9210000e-01  1.0000000e+04
-1.3970000e-01  2.9210000e-01  1.0000000e+04
-1.6510000e-01  2.9210000e-01  1.0000000e+04
-1.9050000e-01  2.9210000e-01  1.0000000e+04
-2.1590000e-01  2.9210000e-01  1.0000000e+04
-2.4130000e-01  2.9210000e-01  1.0000000e+04
-2.6670000e-01  2.9210000e-01  1.0000000e+04
-2.9210000e-01  2.9210000e-01  1.0000000e+04
-3.1750000e-01  2.9210000e-01  1.0000000e+04
-3.4290000e-01  2.9210000e-01  1.0000000e+04
-3.6830000e-01  2.9210000e-01  1.0000000e+04
-3.9370000e-01  2.9210000e-01  1.0000000e+04
-4.1910000e-01  2.9210000e-01  1.0000000e+04
-4.4450000e-01  2.9210000e-01  1.0000000e+04
-4.6990000e-01  2.9210000e-01  1.0000000e+04
-4.9530000e-01  2.9210000e-01  1.0000000e+04
-5.2070000e-01  2.9210000e-01  1.0000000e+04


namec = 'OHCEN', 'OHTOPBOT', 'NULL', 'TRIM', 'FAR', 'FAROUT', 'ANTIX'
$end
nlcds=4 iplim=1
plimxa=0.625 1.225 0.78 0.78    plimza= 0.2 .2  0.475 -0.475
plimxb=0.625 1.225 1.08 1.08    plimzb=-0.2 -.2  0.475 -0.475
$end
ksep=1      psirat=0.95   bungle=0.5
xdiv= 1.00  1.00  1.00  1.00
zdiv= 1.00  1.00  1.00  1.00
$end
lwall=.f     ljet=0      npts=36      numbv=10     ellip=1.6
arad=0.25    deity=0.    rot=0.0     drot=0.   xmar=0.93
nopin=8      minc=10      mth=20       psisur=-0.5   zmar=0.0
zsepr(1)=0.430  zsepr(3)=-0.385
xsepr(1)=0.540  xsepr(3)=0.565
deity2=0.0    ellip2=1.0    npw=5

 xw=.6 .6 1.25 1.25 .6

zw=-.5 .5 .5 -.5 -.5

xg=1.0 0.435  0.640 0.875 0.478  0.610  0.810 0.81
zg=-5.02 -0.465  -0.538 -.02 0.360  0.395  0.14  -0.17
phig=0.0 0.0    0.0   0.0  0.11    0.11   0.0   0.
$end
lmap=.t      lfct=.f      nosurf=29     nquib=1      delp=-.05
nolim=1      kbc=1        iqfunc=1      delflx=0.190966
q0=1.0       qe=3.6       ifunc2=1      betaq=3.     qeppo=100.
```

```
dqfrac=0.5    dqswit=0.005
 $end
 zguess=-0.00 zcont1=0.030  zcont2=0.40
 xguess=.675 xcont1=0.10   xcont2=0.20
 xconx1=+0.010  0.0 -0.005 0.0 xconx2=0.00
 zconx1=-0.20  0.0 +0.016 0.0 zconx2=4(0.00)
 pcon1=-0.00300  +0.0125  +0.0212 +0.0250 +0.00625 +0.00538 +0.0375 0.0375
 pcon2=+0.00  -0.00  +0.00  -0.00  0.0   0.0  0.0375  0.0375
 $end
$end
```

B.2 MATLAB Codes Used for Vacuum Field Calculation

The following codes are written so as to calculate the vertical components of the OH and EF coils, magnetic flux due to the OH coils, and field index of the vertical field.

```
%Vertical Component of B-field by Ohmic Heating Coils
%Takes #turns (div, null, trim) and add 25 for center.
%Calculate Bz at z=0 using coils.m
%More accurate positioning of the nulling and trimming coils. 2/2/91
Nsol = Ndiv + Ncen;
N = Nsol + Nnul + Ntri;
cur = 10000*ones(1,N);
Rnul = 23.75*0.0254;
Lnul = 22  *0.0254;
Lcor = 4.25 *0.0254;  %length of the corner for nulling coils.
Rtri = 55.125*0.0254;
Ltri = (18 + 1/2) * 0.0254;
Rnul = [Rnul+Lcor/Nnul*2 : Lcor/Nnul*4 : Rnul-Lcor/Nnul*2+Lcor];
a = [Rsol*ones(1,Nsol) Rnul Rnul Rnul Rnul Rtri*ones(1,Ntri)];
LS1=(18+13/16-.5)*.0254/2;
LD3 = .4723 -.5*.0254/2;
Dels= .01991;
hsol = [-LS1:LS1/12:LS1];
hdiv = [LD3:-Dels:LD3-(Ndiv/2-1)*Dels];
hdiv = [hdiv, -hdiv];
hnul1 = ones(1,Nnul/4)*(Lnul+.5*.0254);
hnul2 = ones(1,Nnul/4)*(Lnul+.0254);
hnul = [hnul1 hnul2 -hnul1 -hnul2];
htri = [Ltri:1.25*.0254:Ltri+3.75*.0254];
htri = [htri, -htri];
if Ncen==25
h = [hsol,hdiv,hnul,htri];
else
h = [hdiv,hnul,htri];
end
r1 = [in:inc:out];
rr =[1 1 1]'*r1;
z1 = [-inc+.005 zoffset+.005 inc+.005];
[m,n]=size(r1)
zz = [ones(n,1)*z1]';
bcoils;
bz1=[0 1 0]*bz;
incN=(roffset-in)/inc;
flr1 = r1(1,1:incN);
flbz1 = bz1(1,1:incN);
totfl = 2*pi*inc*sum(flr1.*flbz1);
plot(r1,bz1);
grid;
```

```
%Vertical Field by Equilibrium Field coils
%single layer decoupling coils.
in=.5;
out=1.3;
inc=.01;
N = Nvi + Nvo + Nvf
cur = 10000 * [-1*ones(1,Nvi) ones(1,Nvo+Nvf)];
Rvi = 11.5*inch;
Rvo = 1.389;
Rvf= Rvo*ones(1,4) + [2 3 2 3]*inch;
Lvo = 13.25* inch;
Lvf = 36  * inch;
asub = Rvi *ones(1,Nvi);
a = [asub         Rvo*ones(1,Nvo) Rvf];
gapthick = ( 1 +gap) * .0254;
if rem(Nvi ,2)==0
 hplus = gapthick * [1/2 : 1 : (Nvi/2 -.5)];
 hminus= -hplus;
 hi= [hplus hminus];
else
 h1 = gapthick * [-(Nvi/2 - .5) : 1 : (Nvi/2 - .5)];
 hi= [h1 h1];
end
houp=(Lvo-1.5*15/16*inch)*ones(1,4) + 15/16*inch*[0:1:3];
hodown=-houp;
hf= [Lvf*ones(1,Nvf/2) -Lvf*ones(1,Nvf/2)];
h = [hi houp hodown hf];
r1 = [in:inc:out];
rr = [1 1 1]'* r1;
[m,n]=size(r1);
zz = zeros(3,n);
bcoils
bz1 = [1 0 0] * bz;
V=[in out .03 .09];
axis(V)
uplot
grid
```

```
%Magnetic Flux due to Ohmic Heating Coils
%Takes #turns (div, null, trim) and add 25 for center.
%Calculate flux using coils.m
%More accurate positioning of the nulling and trimming coils. 2/2/91
Nsol = Ndiv + Ncen;
N = Nsol + Nnul + Ntri;
cur = 10000*ones(1,N);
Rnul = 23.75*0.0254;
Lnul = 22  *0.0254;
Lcor = 4.25 *0.0254; %length of the corner for nulling coils.
Rtri = 55.125*0.0254;
Ltri = (18 + 1/2) * 0.0254;
Rnul = [Rnul+Lcor/Nnul*2 : Lcor/Nnul*4 : Rnul-Lcor/Nnul*2+Lcor];
a = [Rsol*ones(1,Nsol) Rnul Rnul Rnul Rnul Rtri*ones(1,Ntri)];
LS1=(18+13/16-.5)*.0254/2;
LD3 = .4723 -.5*.0254/2;
Dels= .01991;
hsol = [-LS1:LS1/12:LS1];
hdiv = [LD3:-Dels:LD3-(Ndiv/2-1)*Dels];
hdiv = [hdiv, -hdiv];
hnul1 = ones(1,Nnul/4)*(Lnul+.5*.0254);
hnul2 = ones(1,Nnul/4)*(Lnul+.0254);
hnul = [hnul1 hnul2 -hnul1 -hnul2];
htri = [Ltri:1.25*.0254:Ltri+3.75*.0254];
htri = [htri, -htri];
if Ncen==25
h = [hsol,hdiv,hnul,htri];
else
h = [hdiv,hnul,htri];
end
r1 = [in:inc:out];
z1 = [bottom:inc:top];
rr=ones(z1')*r1;
zz = z1'*ones(r1);
coils;
contour(psi,20,r1,z1);
grid;
```

```
%Calculates the field index of the vertical field.
RbyBz=r1(1,1:(n-1))./ bz1(1,1:(n-1));
fndx = -RbyBz .* (diff(bz1)/inc);
V=[in out 0 2];
axis(V);
plot(r1(1,1:(n-1)),fndx)
grid
xlabel('R (meters)')
ylabel('Field Index')
title ('Field Index')
```

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