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Progress Report for

HIGH BETA AND SECOND REGION STABILITY ANALYSIS
AND
ICRF EDGE MODELING

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PROGRESS REPORT FOR DoE GRANT

HIGH BETA AND SECOND REGION STABILITY ANALYSIS

ICRF EDGE MODELING

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ABSTRACT

This report describes the tasks accomplished under Department of Energy contract #DE-FG02-86ER53236 in modeling the edge plasma-antenna interaction that occurs during Ion Cyclotron Range of Frequency (ICRF) heating. This work has resulted in the development of several codes which determine kinetic and fluid modifications to the edge plasma. When used in combination, these code predict the level of impurity generation observed in experiments on the Princeton Large Torus. In addition, these models suggest improvements to the design of ICRF antennas.

Also described is progress made on high beta and second region analysis. Code development for a comprehensive infernal mode analysis code is nearing completion. A method has been developed for parameterizing the second region of stability and is applied to circular cross section tokamaks. Various studies for high beta experimental devices such as PBX-M and DIII-D have been carried out and are reported on.
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1. **INTRODUCTION**

During the past year, under contract to the Department of Energy (DoE) contract #DE-FG02-86ER53236, a code has been developed which will allow us to routinely analyze equilibria for infernal mode stability. The code solves the MHD equations of Bineau and has been formulated to allow a one step analysis of infernal mode behavior. A procedure to find pressure profiles that give the minimum beta for full second region stability has been completed and is being used to parameterize the second region boundary. Also, several studies of high beta experiments in PBX-M and DIII-D were done. Stable profiles for $q_{edge} < 3.0$ were found in DIII-D. In PBX-M the minimum $q_0$ required for full access was analyzed.

In the area of rf, we have developed a number of computational models which attempt to explain the edge plasma-antenna interaction which occurs during Ion Cyclotron Range of Frequencies (ICRF) heating. It has been well documented that accompanying the desired ion heating, a number of undesired effects are associated with ICRF heating.\textsuperscript{1,2} The most notable of these being an uncontrolled rise in the plasma density and an increased level of impurity contamination. Since ICRF is the preferred candidate for auxiliary heating of the Compact Ignition Tokamak (CIT), an understanding of the interaction of the antenna with the edge plasma is desired.

Fluid and kinetic models of the edge plasma were developed which determine modifications to the edge plasma during ICRF heating. The ponderomotive force has been incorporated into the ion single-fluid equations. The solutions of these equations determines the density and potential perturbations to the edge plasma and the particle flows in the vicinity of the antenna. The fluid model predicts that with 400 kW applied to a Princeton Large Torus (PLT) ICRF antenna, the particle flux to the antenna is doubled over its ohmic value. Kinetic modeling of ions in the vicinity of the antenna finds that the ion quiver energy results in a non-negligible increase in the impurity sputtering yield of ions which impact the shield. Kinetic modeling of electrons finds that the parallel electric field which results as a consequence of Fast wave excitation acts to heat electrons near the shield surface. The resulting increase in electron temperature is expected to raise the sheath potential at the Faraday shield, thereby increasing the sputtering yield by greater than a factor of two.

This report describes the work accomplished over the past year. Included is work which directly pertains to the originally proposed tasks, along with addition work not
originally proposed. In Section 2 of this report a description of high beta and second region stability work is given. The originally proposed work on ICRF edge modeling is given in Sec. 3. In Sec. 4, a description of the additional work in ICRF edge modeling is given. The conclusions of this report are given in Section 5.
2. PROGRESS REPORT ON HIGH BETA AND SECOND REGION STABILITY ANALYSIS

In this section we'll describe progress made on the high beta and second region stability analysis portion of D.O.E. contract #DE-FG02-86ER53236. This research is still on going since the contract is only half over. However, progress has been made on all the proposed tasks. The original tasks proposed were as follows:

Task 1: Development of improved ideal MHD internal mode analysis
techniques and their application to first and second stability region
parameterization.

Task 2: Development of a second stability region boundary optimization
procedure and its application to a wide ranging parameterization of
the second region boundary which attempts to define a criterion
similar to that of Troyon for the first region boundary.

Task 3: Applications to specific high beta devices such as ITER and SRX.

An update on each of the task follows.

2.1 Task 1: Improved Internal Mode Analysis

Most of the time spent under this contract was on improving internal mode analysis. By internal modes we are here referring to so called "infernal" modes and not the n = 1, m =1 instability that occurs when q0 < 1.0. Infernal mode analysis is currently not part of our standard analysis in determining whether an equilibrium is stable or unstable. The difficulty is that infernal modes may occur at non-rational n numbers and have a period which peaks between integral values of n. Many calculations must be done to determine stability. While some people have included an n = 3 calculation, along with the standard ballooning mode and n = 1 analysis, this will only catch the infernal mode occasionally.
The danger of ignoring these modes is that attempts to find configurations that are stable to ballooning and kink modes may result in configurations that are unstable to infernal modes. This is indeed how the importance of infernal modes was initially discovered.

As stated in our proposal as a starting point a code would be written to solve the equations of Hastie and Taylor. This task was completed however, the analysis proved less useful than anticipated. The reason is that in Hastie Taylor's paper and also in a paper by Dewar the approach taken was to revise the traditional high n ballooning formalism to treat cases with low shear. In both analyses, the starting point is high n with 1/n treated as an expansion parameter. The picture resulting from both of these treatments is that the lower n modes can be in resonance with a rational surface and enhance the growth rate. However, in both analyses infinite n modes remaining the most unstable modes. If ballooning modes are stable, there is no beginning point for subsequent expansion. In other words, these treatments can show infernal modification to already unstable ballooning modes but can't treat the case where infinite n ballooning modes are stable and the infernal modes are unstable. This limits the usefulness of these treatments. In the Manickam, Todd and Pumphrey paper they demonstrated that infernal modes can be unstable when ballooning modes are stable. It is just this situation which is the most interesting since it further restricts the stable operating space of a tokamak.

It was decided that starting from a local high n analysis and expanding to lower n would miss what we were most interested in - the situations where infernal modes are present and other modes may be stable, hence, we decided to revise current low n analysis and concentrate on remedying the short comings of PEST to build a tool that would be useful for infernal mode analysis. The original infernal modes were studied with PEST, many runs are needed to trace out the growth rate against n number. This is compounded by the difficulty that the oscillations in the growth rates may have a period which peaks between integral values of n. Although it is often assumed that modes have an integral value of n, non-integral values of n should be considered as well, since only a small change in the q profile is needed to allow the instability to occur at integral values of n. In addition, PEST II is generally only valid for \( \Sigma m_j - n q_e \leq 30 \) and these modes may occur at moderate n numbers and high q_e. Finite n ballooning mode codes are unable to solve for these modes as they only retain the 1/n scaling of the growth rate. Because of this the infernal mode has not been well parameterized.

We felt that many of these short comings could be remedied if we could improve the matrix solution routines. We chose a PEST II type formulation whereby choosing a
different model for kinetic energy two components of the displacement vector \( \xi \) can be eliminated analytically by means of Bineau reduction. This leads the Euler-Lagrange equation

\[
(\rho \omega^2 + F)\xi = 0
\]

where \( F \) is a scalar operator defined by

\[
F\xi = \left( B \cdot \nabla \frac{\nabla \psi}{|\nabla \psi|^2} + \frac{J \times \nabla \psi}{|\nabla \psi|^2} \right) Z + B \cdot \nabla \frac{1}{|\nabla \psi|^2} B \cdot \nabla \xi + 2K\xi
\]

\[

\nabla \cdot \nabla_{||} Z = \nabla_{||} \left( B \cdot \nabla \frac{\nabla \psi}{|\nabla \psi|^2} - \frac{J \times \nabla \psi}{|\nabla \psi|^2} \right) \xi
\]

where \( J \) is the equilibrium current density and \( \nabla_{||} \) is an operator defined by

\[
\nabla_{||} = \nabla - \frac{\nabla \psi \cdot \nabla}{|\nabla \psi|^2}
\]

and

\[
K = \frac{J \times \hat{\mathbf{r}} \cdot (B \cdot \nabla \hat{\mathbf{r}})}{|\nabla \psi|^2}
\]

where \( \hat{\mathbf{r}} = \nabla \psi / |\nabla \psi| \). The above equations are solved by using a Fourier series representation in \( \theta \) and a finite differences in \( \psi \).

The code is currently undergoing a debugging phase. The main difference between it and PEST II is that our code is much faster since the calculation is done entirely in memory while PEST II buffers its matrix elements out to disk. In addition the eigenvalue solver is highly vectorized which further enhances the speed and is more reliable. The chance of obtaining the most unstable mode with one run of the code is extremely high while in PEST II one must first bracket the desired unstable mode and even then it might not converge if the bracket is too large. In a test case, using 20 poloidal harmonics and 100 radial grid points a solution was obtained in about 12 seconds of CRAY time. This is to be compared with approximately 2 minutes of CRAY time for PEST II. Most of the work goes into setting up the matrix to be solved. About 1/3 of the total time is taken up with Fourier analysis alone. The matrix solving portion of the code takes only about 2 seconds.
of the total time. Further improvements in the matrix set up portion of the code are
possible. The code isn't really expected to be a replacement for PEST II. It lacks many
features such as different conducting boundaries. It's main purpose is to analyze an
equilibrium for internal modes in one run that does not use up computer resources and
doesn't require constant interaction with the operator to make sure it converges.

The code will be set up to automatically scan through n so that internal modes will
be detected with one pass through the code. An example of this would be a scan from n =
1 to 5 in increments of \( \Delta n = 0.2 \). It is expected that the total computation time will less
than 5 minutes on the CRAY based on code timings to date. In PEST II this would require
running the code 40 minutes of computer time. Also, because the new code is much faster
than the PEST II code it should be able to tackle larger problems.

2.2 Task 2: Second Stability Region Boundary Optimization

The goal of this task is the development of a second stability region boundary
optimization procedure and its application to a wide ranging parameterization of the second
region boundary. The first part of this task, the development of a second stability region
boundary optimization procedure, has been completed. A code has been written that
predicts the first and second region critical pressure gradient. The code solves the
ballooning equation using local equilibrium assumptions. This allows quantities such as
pressure gradient and shear to be locally varied to see what their effect on stability might
be. In particular, the marginal stability points can be found. The complete procedure is
detailed in an article by M. Phillips et al.\(^6\).

The second part of this task, that of parameterizing the second region, is being done
in conjunction with Steve Sabbagh\(^7,8,9\) at Columbia University. Using the code described
above to find the first and second region critical pressure gradients, equilibrium is analyzed
and a pressure gradient profile is fitted over the second region critical pressure gradient.
The procedure is iterated until the pressure profile converges. The method has been found
to work extremely well in finding the pressure profile that is optimal for determining the
minimum \( \beta \) needed to reach full second region stability. Figure 1 shows the minimum
second region \( \beta \), for circular shaped plasmas, as a function of aspect ratio for \( q_0 = 1.01 \)
Increasing $q_0$ Decreases Second Regime $eta$ and $\varepsilon\beta_p$ Thresholds

- $q_a = 4.1$
- $\alpha_q = 2.5$
- circle
Here the safety factor profile is given by \( q(\psi) = q_0 + (q_a - q_0)\psi^{\alpha_q} \) with \( q_a = 4.1 \) and \( \alpha_q = 2.5 \). In general, the minimum beta needed to attain second region stability decreases as aspect ratio increases. Increasing \( q_0 \) decreases the second regime \( \beta \) and \( \varepsilon_{\text{pol}} \) thresholds. The decrease is more rapid for lower aspect ratio. For a given \( q_0 \) the minimum \( \varepsilon_{\text{pol}} \) is approximately constant function of aspect ratio. Work is in progress to produce a semi-empirical formula to quantify minimum beta requirements for the general case.

2.3 Task 3: Applications to Specific High Beta Tokamaks

The final task is high beta stability studies to specific experiments and proposed devices. A number of stability studies have been done for other experiments including PBX-M and DIII-D. In addition, further studies were done for CIT and ITER but was sponsored by other contracts.

We looked at the question of whether stable profiles for \( q_{\text{edge}} < 3.0 \) could be found in DIII-D geometry. In the past these have been difficult to find, particularly when using a q-profile prescription in the equilibrium code. In most cases the \( n = 1, m = 3 \) kink mode was found to be unstable with a beta limit of zero. This led to the recommendation early on for CIT, that it should be designed to operate with \( q_{\text{edge}} > 3.0 \). Subsequent experiments in DIII-D and JET demonstrated that tokamaks could operate with \( q_{\text{edge}} \) in the range of 2.0-3.0 if you didn’t mind a slight degradation in confinement.

Using \( \langle \text{<B>}/<\text{B} \cdot \nabla \phi> \rangle \) profiles, where the current density goes to zero on the outside edge and further lowering the current density near the edge, profiles that are kink stable up to the ballooning mode beta limit can be found. Figure 2 shows a plot of normalized beta vs \( q_{\text{edge}} \) for \( \delta = 0.1 \) and \( \delta = 0.3 \). These calculations were done for DIII-D geometry with \( B_0 = 1.2 \text{T} \). The beta limit for \( q_{\text{edge}} > 2.0 \) was set by ballooning modes and at that point the profiles were kink stable. Below \( q_{\text{edge}} < 2.0 \) the profiles were unstable to the \( n = 1, m = 2 \) kink, as would be expected, with a beta limit of zero. The profiles are characterized by a fairly flat shear region in the center as can be seen in Fig. 3. Shown also are the profiles that were optimal for \( q_{\text{edge}} > 3.0 \) (\( \alpha_1 = 1.0 \)) and the profile in which the beta limit was set by kinks (\( \alpha_1 > 0.6 \)). As a consequence of the flat central shear the optimum pressure profile is very flat in the center in order to keep the equilibrium stable to Mercier and ballooning modes as shown in Fig 4.
Fig. 2

\[ C_T = \langle \beta \rangle I(\text{MA})/a(m)B(T) \]

\[ C_T^* = \langle \beta^* \rangle I(\text{MA})/a(m)B(T) \]

- Unstable

- \( C_T, \delta = 0.1 \)
- \( C_T, \delta = 0.3 \)
Resulting q profile:

\[ a_1 = 0.6, a_2 = 0.38 \]

\[ a_1 = 1.0, a_2 = 0.52 \]

\[ a_1 = 2.0, a_2 = 1.02 \]

\[ \Delta y \left( \psi - \psi_0 \right) \]

Specified current profile:

\[ a_1 = 2.0, a_2 = 1.02 \]

\[ a_1 = 0.6, a_2 = 0.38 \]

\[ a_1 = 1.0, a_2 = 0.52 \]

\[ \phi A \Delta \cdot B / \langle B \cdot j \rangle \]

\[ \Delta y \left( \psi - \psi_0 \right) / \Delta y \]

\[ \left( \frac{\langle j \cdot B \rangle}{\langle B \cdot \nabla \phi \rangle} \right) \]

\[ \left( \frac{\langle j \cdot B \rangle}{\langle B \cdot \nabla \phi \rangle} \right) \]
The combination of shaping and raising $q_0$ on axis seems the most attractive method of reaching complete second region access. The original stability studies for PBX-M found that a minimum indentation of 0.31 was needed to get complete access to the second region for $q_{\text{edge}} = 4.1$ and $q_0 = 1.02$. A study was done to see what the minimum $q_0$ requirements are at lower indentations in PBX-M geometry. So called "ohmic" current profiles were used. These profiles are the most restrictive as far as complete access to the second stability region. In fact previously it was thought that complete access was impossible for "ohmic" profiles. The following table summarizes the results for an indentation of 0.25.

Table 1: Minimum $q_0$ for Full Second Region Access ($d/2a = 0.25$)

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<th>I</th>
<th>$q_0$</th>
<th>$q_{\text{edge}}$</th>
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<tr>
<td>350kA</td>
<td>1.59</td>
<td>8.03</td>
</tr>
<tr>
<td>450kA</td>
<td>1.37</td>
<td>5.50</td>
</tr>
<tr>
<td>550kA</td>
<td>1.14</td>
<td>4.14</td>
</tr>
<tr>
<td>650kA</td>
<td>1.05</td>
<td>3.21</td>
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This indentation, $d/2a = 0.25$, represents the maximum indentation achieved to date in PBX-M. As can be seen from Table 1 the $q_0$ requirements for complete access to the second region are a strong function of current. The current in PBX-M is typically 550kA indicating if the current profile can be made such that $q_0 = 1.14$ complete access is possible.
3. PROGRESS ON ICRF EDGE MODELING

The proposed work consisted of a number of tasks identified as being of paramount importance in understanding the edge plasma-antenna interaction. These tasks were:

Task 1: Solve the ion single-fluid equations self consistently in two dimensions and investigate the effects of poloidal electric field ripple on particle transport.

Task 2: Investigate the effect of Faraday shields of finite cross section and determine how shield shape affects particle transport.

Task 3: Investigate the effects of finite width antennas and finite plasma pressure, and compare the transport at the center of the antenna to that off-center of the antenna.

As discussed in the proposal, the antenna near-field structure in the vicinity of a PLT Faraday shielded antenna (Fig. 4) results in strong ponderomotive force which acts mainly on the ions. This effect on the ions is shown in Fig. 5. The orbit of an ion which started at $x = 1$ mm, $y = 60$ mm, experiences a drift as a result of the ponderomotive force and enters the shield region at $x = 0$, $y = 51$ mm. In order to solve for the self consistent flows and fields which result as a consequence of the ponderomotive force, task 1 proposed to solve the ion single-fluid equations. Theses equations are:

\[ V_i^{(2)} = \frac{q}{m B_0^2} \left[ E^{(2)} \times B_0 + S_i \times B_0 \right] , \]

\[ S_i = \left( V_i^{(1)} \times B^{(1)} \right) - \frac{M_i}{q} \left( V_i^{(1)} \nabla V_i^{(1)} \right) , \]

\[ V_i^{(1)} = M \cdot E_{rf} , \]
Fig. 4. Antenna near field close to the Faraday shield. The average electric field is 250 V/cm. The shield structure acts to geometrically magnify the electric field in the gap region to three times the average electric field.

\[
\frac{\partial n_i^{(2)}}{\partial t} = -n_0 \nabla \cdot \mathbf{V}_i^{(2)} - \mathbf{V}_i^{(2)} \cdot \nabla n_0 - \mathbf{V}_i^{(2)} \cdot \nabla n_i^{(2)} - \mathbf{V}_z \cdot \nabla n_i^{(2)} + D_i \nabla^2 n_i^{(2)},
\]

\(E_{rf}\) is the rf electric field from the antenna, \(M\) is the ion mobility tensor, and \(n_0\) is the unperturbed density. Using the ANDES\textsuperscript{11} code, \(E_{rf}\) is calculated for a given coupled power. The first term in \(S_i\) is the ponderomotive force (multiplied by \(q/m\)). The ponderomotive force is defined in terms of the electric field as:
Fig. 5. Ion orbit in the vicinity of the Faraday shield. The ion started 1 mm in front of the shield and drifted into the shield region. Also shown is the ponderomotive drift approximation to the Lorentz orbit.
\[ F_{\mu} = \frac{1}{4} \sum_{\mu = R, L, II} \varepsilon_{\mu} \nabla |E_{\mu}|^2 \]

\[ \varepsilon_{\mu} = \frac{-q^2}{M_i \omega (\omega + \sigma_{\mu} \omega_c)} \]

with \( \sigma = 0, \pm 1 \) for \( \mu = \|, R, L \) respectively, where \( \| \) refers to the ordinary wave, \( R \) and \( L \) correspond to the right and left circularly polarized waves. The ponderomotive force is due to a gradient in the magnitude of the electric field, thus the ripple in the near field results in strong ponderomotive force. The flow along field lines is estimated from

\[ V_z = \sqrt{2 \alpha a dz} \equiv C_s \sqrt{\frac{2 n_i^{(2)}}{n_o}}. \]

The perpendicular diffusion coefficient, \( D_\perp \) for the PLT experiments is estimated from an analytic fit to Langmuir probe data. The electric field \( E^{(2)} \), evaluated by assuming that electrons follow Boltzmann's relation is

\[ E^{(2)} = \nabla \left( \frac{kT_e}{q} \ln \left[ 1 + \frac{n_i^{(2)}}{n_o} \right] \right). \]

From the solution of the velocity and continuity equations, the ion flux, \( \Gamma \) to the Faraday shield is evaluated:

\[ \Gamma = -n_o V_{ix}^{(2)} - D_\perp \nabla_x \left( n_i^{(2)} + n_o \right). \]

In order to determine the effect of Faraday shields of finite cross section, task 2 proposed to use the model developed by Smith for finite thickness shields. In task 3, we proposed to include the effects of plasma pressure into the single-fluid equations. Since in Tasks 1 and 2 we proposed to investigate the edge plasma-antenna interaction by assuming toroidal uniformity, in Task 3 it was also proposed to investigate the effect on the edge plasma from antennas of finite toroidal extent. This task proposed to determine the
field structure near the ends of the antenna and determine the transport which results from these fields.

3.1 Task 1: Solution of the Single-Fluid Equations

As the work progressed in solving the single-fluid equations it became evident that the effects of finite pressure (Task 3) should be included in this task since it required little additional effort and added important physics which made the modeling more realistic. This was accomplished by adding the following term to the ion equation of motion

$$\frac{\nabla P_i \times B_0}{M_i n_0 B_0^2}$$

where

$$\nabla P_i = kT_i \nabla (n_0 + n_i^{(2)})$$

The equations were solved on a grid 60 × 150 in the radial and poloidal directions, respectively. The poloidal extent of the grid is equal to a shield spacing since this represents a periodic distance. The radial extent needed to be only ~ 2/3 of the poloidal extent because the ponderomotive force decays sufficiently in this distance. All of the spatial derivatives were solved by finite difference techniques\(^{14}\) and the density gradient along a field line was evaluated as the perturbed density divided by a parallel scale length. The solutions were found not to be very sensitive to the parallel scale length. The equations were solved with a slow turn-on of the rf power (ponderomotive force) to ensure stable convergence.

The resulting fluid code (RFEDGE) was applied to the edge conditions of PLT for the case of 400 kW of power applied to one of the antennas. An edge density of $1 \times 10^{12}$ cm\(^{-3}\) with a perpendicular density scale length of 3 cm was assumed. $T_e$ and $T_i$ were chosen to be 20 eV, and $D_{\perp}$ was chosen to be 1.25 m\(^2\)/s. The diffusion coefficient was
The average rf electric field was determined to be 200 V/cm. In Fig. 6, the perturbation in density that results from the ponderomotive force is shown. The depression in density occurs near the high electric field (gap) region of the Faraday shield. The density depression is only about 3% of the unperturbed density, which translates to a local potential depression of 0.65 V. This is close to the ponderomotive potential, defined as $F_p/q$, which is 0.72 V. The depression in density reaches a steady-state value when the particle flow along field lines is balanced by the flow perpendicular to field lines. The resulting particle flux to the Faraday shield surface is shown in Fig. 7. The flux has an asymmetric component since the ponderomotive force points in opposite poloidal directions at the two edges of the shield. The poloidal ponderomotive force results in a radial particle drift. Near one edge of the shield the radial drift is directed into the shield, while on the opposite edge the drift is directed away from the shield. Figure 8 shows the flow pattern in the vicinity of the shield when the $E \times B$ and diamagnetic drifts are included. The strong poloidal flow is due to the diamagnetic drift. The flow pattern indicates that close to the shield surface, radial transport is significantly enhanced.

The time evolution of the particle flux integrated over the shield surface is shown in Fig. 9. The particle diffusion without rf corresponds to the expected ohmic diffusion. With 400 kW of power applied to the antenna, the particle flux to the shield is doubled. The time evolution of the particle flux indicates that within 5 μsec, steady state is achieved. Since the depression in density is small, fluctuations in the local density could be larger, thus destroying the structure formed by the ponderomotive force. A Fourier analysis of the Langmuir probe ion saturation current shows that above 10 kHz the turbulence in the edge density is greater than 30 db below the steady value. Low frequency turbulence may destroy the density structure in the edge region, but the ponderomotive-induced flows occur on a much quicker time scale, hence the structure will be re-formed. The time scales imply that the fluid analysis, ignoring edge turbulence, is appropriate for determining the particle flows in the edge region.
Fig. 6. Perturbation in density that results from the ponderomotive force. The unperturbed density is $1 \times 10^{12}$ cm$^{-3}$ at the shield surface. The perturbation is largest in front of the gap region of the shield.
Fig. 7. Resulting particle flux to the shield surface as a result of the ponderomotive force. The ohmic diffusion level is shown for comparison.
Fig. 8. Particle flow pattern in the vicinity of the Faraday shield. The strong poloidal flow component is due to the diamagnetic drift.
Fig. 9. Time evolution of the particle flux to the Faraday shield.
The particle flux to the shield, shown in Fig. 10, is found to increase linearly with rf power. This appears to be consistent with $D_\alpha$ measurements made on PLT which also exhibit a linear increase with applied power.\textsuperscript{15} These measurements indicated that for 125 kW of ICRF power the $D_\alpha$ emission at the energized antenna increased by 50%. Emission measurements of CrI and FeI viewing the energized antenna indicated that the production of metallic impurities increased by 305% for the same power. The RFEDGE code predicts a factor of two increase in the particle flux for 400 kW. If the recycling rate of deuterium is unchanged during ICRF heating, the code predictions are about 60% lower than the
experimental observations. Unfortunately, the mechanisms for the release of deuterium in the energy range of the edge ions is not well understood, therefore the model results are not unrealistic for explaining the increased release of deuterium during ICRF heating. However, the fluid model does fail to explain the increase rate of production of metallic impurities which is larger than the corresponding increase in deuterium. Since the production of metallics is likely due to sputtering from edge ions, the energy distribution of ions which impact the Faraday shield must be determined to predict the production rate.

3.2 Task 2: Investigate Faraday Shields of Finite Cross Section

Using the model developed by Smith, the field structure from Faraday shields composed of blades of finite cross section was investigated. We have determined that the field structure for thick rectangular blades is negligible different than for thin blades. The field structure which results when thick blades of nearly round cross section are employed was determined to be of only slight difference to the case of thin blades. It was determined that since the differences in the field structure was small it did not warrant implementation of these fields into the RFEDGE code.

3.3 Task 3: Investigate Finite Antenna Width and Pressure

As mentioned in Sec. 3.1, the effects of finite plasma pressure were incorporated into Task 1. The investigations of Task 2 determined that the field structure in the vicinity of the ends of the antenna was similar to that at the center. The effect of an antenna of finite width was investigated to determine if electrons which transit pass the antenna are heated. This work is presented in Sec. 4.2.