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STARFIRE POLOIDAL COIL SYSTEMS

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by

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STARFIRE POLOIDAL COIL SYSTEMS*

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Introduction

The poloidal coils for STARFIRE consist of three systems: (1) equilibrium field (EF) coils; (2) ohmic heating (OH) coils; and (3) correction field (CF) coils. The EF coils are superconducting and lie outside the toroidal field (TF) coils. These coils provide the bulk of the equilibrium field necessary to keep the plasma positioned in the vacuum chamber with the desired cross sectional shape and pressure and current distributions. Having these coils outside of the TF coils requires that they have a larger stored energy and larger currents but eases the assembly, maintenance, and reliability of the coils. The STARFIRE OH system is relatively small compared to tokamaks in which the current is entirely ohmically driven. It is designed to provide sufficient flux in the early startup to raise the plasma current to the point (1-2 MA) where the rf current drive can take over.[1] The OH system produces no field in the plasma and so does not affect the plasma equilibrium field. In addition, the OH system is magnetically decoupled from the EF system in order that the charging or discharging of one system does not induce voltage in the other. The OH system is set at maximum current before startup and decreases to zero current during the early part of the startup compared to the EF system which starts from zero current. The CF coils are demountable copper coils located just outside the blanket and shield and inside the TF coils. These coils are designed to help with the plasma initiation, maintain equilibrium in the event of sudden changes in the plasma position, and to prevent and control disruptions. The current in these coils can be changed much faster and more easily than that in the external EF coils. The locations of these coils in STARFIRE are shown in Fig. 1.

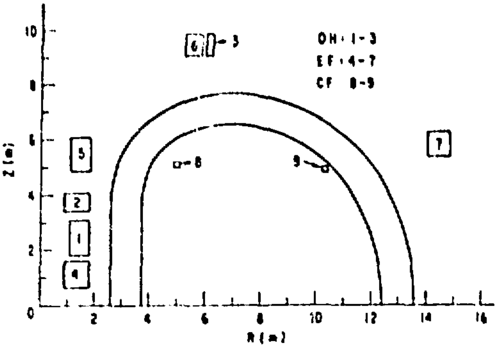

Fig. 1. Poloidal coil locations.

MHD Equilibrium

The reference magnetohydrodynamic (MHD) equilibrium, which the poloidal coils help provide and maintain, has a skin current distribution with a total current of 10 MA. The cross section is moderately D-shaped with an elongation of $\kappa = 1.6$. The toroidal average beta is 0.067 and the poloidal average beta is relatively high at 2.71.[1] The safety factor is 5.1 at the limiter and 1.2 at the magnetic axis. The major radius is $R_o = 7.0$ m, the aspect ratio is $A = 3.6$, and the toroidal field on the center line is $B_{t0} = 5.8$ T.

EF and OH Coil Current Determination

The EF coils must produce the required external field of the reference MHD equilibrium. (This required field is the total field of the equilibrium minus the field of the plasma current itself.) In order to do this a tentative set of EF coil locations is chosen and the currents in the coils are calculated so as to make a least squares fit to the external field calculated from the MHD equilibrium. The energy of the EF system is

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simultaneously minimized to the extent that the error of the least squares fit does not exceed a value of 0.4%. (This value has been found from experience to adequately reproduce the equilibrium and the plasma boundary shape.) The method is described in detail in Ref. 2. The coil locations can then be chosen to be those which have the lowest stored energy for the given accuracy of fit, subject to any engineering restrictions on the coil placement. The method can be further constrained to determine currents such that the EF and the OH systems are decoupled; that is, the mutual inductance, M_{EF-OH}, is negligibly small. The stored energy of the STARFIRE EF system is completely minimized in the sense that if each of the coils were moved a small distance, but not closer to the TF coils, the energy would increase. The distance ($\sim$ 1 m) from the TF coils is necessary to reduce eddy current losses and reduce stray fields which would effectively lower the usable peak field in the TF coils.

The OH system is designed in a similar way except that the least squares fit is made to zero field. In this way the OH field produces no perturbations to the EF field (within the accuracy of the match) all over the plasma region. The OH system energy is also minimized.

The OH system provides 25 V-s to the plasma. If more flux were required, additional similar coils could be added in the center column. The EF system provides 80 V-s to the plasma in addition to that supplied by the OH system, but on a different time scale.

The location and currents of the EF and OH coils are given in Table 1, and their design characteristics are shown in Table 2.

Table 1. Equilibrium-Field and Ohmic-Heating Coil Locations and Currents

Coil #	R_1 (cm)	ΔR (cm)	H_1 (cm)	ΔH (cm)	I (MA-turns)
OH Coils					
1	104	78	180	126	-13.82
2	92	90	341	72	-9.08
3	600	25	914	72	-2.51
EF Coils					
4	92	90	65	90	-11.35
5	104	78	487	126	13.82
6	527	66	914	72	6.69
7	1397	86	535	90	-10.89

Table 2. Ohmic-Heating and Equilibrium-Field Coil Parameters

	OH Coils	EF Coils
Superconductor/Stabilizer	NbTi/Cu	NbTi/Cu
Stability	Cryostable	Cryostable
Cooling	Bath Cooled	Bath Cooled
Operating Temperature	4.2 K	4.2 K
Operating Current	100 kA	100 kA
Average Current Density	1400 A/cm^2	1400 A/cm^2
Total Amp-turns	51 MA-turns	86 MA-turns
Total Amp-meters	600 MA-m	2900 MA-m
Peak Field	8.0 T	4.5 T
Maximum dB/dt (Normal Operation)	0.6 T/s	0.2 T/s
Stored Energy (Self)	1.1 GJ	10.0 GJ
Self-Inductance*	55 mH	500 mH
Mutual Inductance with Plasma*	-0.15 mH	-0.49 mH
Mutual Inductance M_{EF-OH}*	-0.024 mH	

* Based on equivalent parallel current of 200 kA.

Forces on EF and OH Coils

The six OH coils and eight EF coils all exert magnetic forces on each other. In addition, the plasma exerts magnetic forces on all the poloidal coils. Because the plasma, OH coil, and EF coil currents all vary differently with time, the time development of these forces is rather complex. The plasma current builds up gradually over 7 min.; the EF coil current builds up over the same time, but not with an identical time profile. The time development of the OH coil current consists of gradually driving the current to $-I_o$ before plasma initiation and then driving it to zero at a constant rate for 14 s. For calculating the forces on the coils, the following simplified time histories were assumed:

$$
\begin{aligned}
I_{OH} &= I_o\,(t/14-1) && 0 \le t < 14\\
&= 0 && t \ge 14\\
I_p &= I_o\,0.015\,t && 0 \le t < 20\\
&= I_o\,(0.00175\,t + 0.265) && 20 \le t < 420\\
&= I_o && t \ge 420 \quad (4)\\
I_{EF} &= I_o\,0.00975\,t && 0 \le t < 20\\
&= I_o\,(0.00073\,t + 0.1804) && 20 \le t < 220\\
&= I_o\,(0.003295\,t - 0.3839) && 220 \le t < 420\\
&= I_o && t \ge 420
\end{aligned}
$$

where time t is in seconds, and I_0 = 200 kA for the OH and EF coils and 10.1 MA for the plasma. The resulting forces are shown in Figs. 2-4. Because the current in the OH coils is greatest when those in the EF coils and plasma are zero, and vice versa, the forces on the OH coils are predominantly the forces they exert on each other. Similarly, almost all of the forces on the EF coils reach their maximum when the plasma and EF coil currents attain their full values.

Although the forces are large, they are not unmanageable. For example, when the OH coils are carrying full current, coil #1 experiences an axial force of 90.0 MN directed toward coil #2, and coil #2 experiences a force of 107.5 MN directed toward coil #1. The larger force divided by the smaller area (7.75 m^2) corresponds to a compressive stress of only 13.9 MN/m^2 (2010 psi). A potentially more troublesome force is that on coil #7, the 28.8 m diameter EF coil. The axial force of 79.1 MN must be supported at the twelve TF coils it encircles.

Conductor for EF and OH Coils

The conductor design chosen for the EF and OH coils is a flat cable consisting of 26 basic

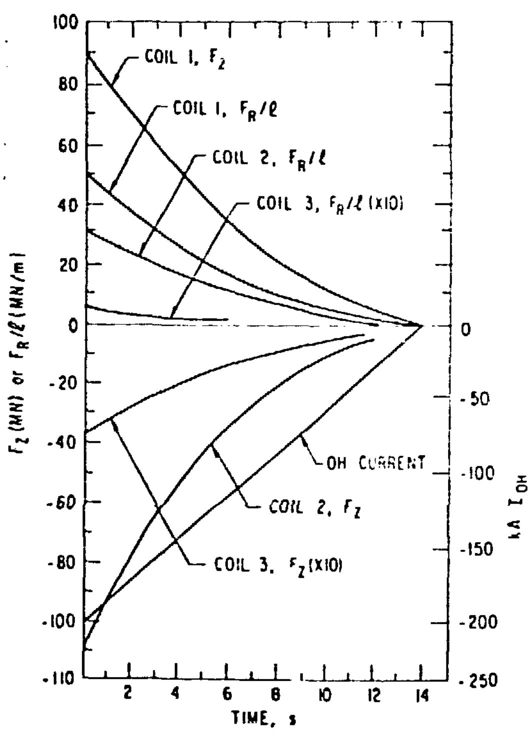

Fig. 2. OH Coils: Forces and Current.

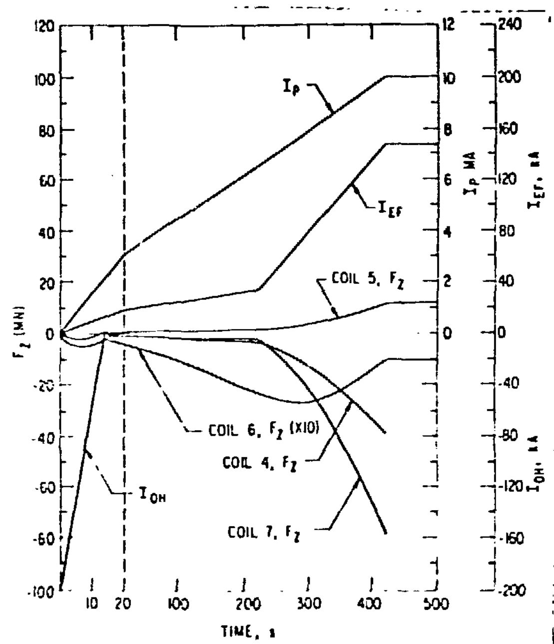

Fig. 3. EF coils, axial forces and currents.

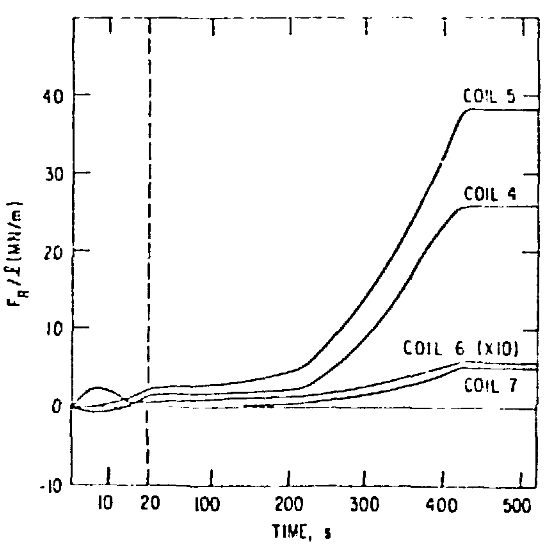

Fig. 4. Radial force per unit length on EF coils.

cables cabled around a central pultruded fiberglass strip, 11.9 cm by 0.2 cm, as shown in Fig. 5. The strip serves to ensure mechanical and dimensional stability during the conductor cabling and coil winding. The conductor carries 100 kA; equivalent 200 kA operation is achieved by operating coils located symmetrically above and below the midplane in parallel.

Each basic cable consists of six copper and superconductor subcables cabled around a central 0.38 cm diameter stainless steel multistrand cable. The stainless steel is introduced to increase the tensile strength of the basic cable. The subcables are electrically insulated from each other to reduce eddy current losses in the cable during charging and discharging.

Each subcable consists of six 0.08 cm diameter superconducting wires cabled around a copper wire of the same size and with twelve more copper wires cabled around the superconducting wires. (See Fig. 5.) In this cable, the superconducting wires are all fully transposed.

Good electrical contact, attained through soldering, between the superconductor wires and copper wires in each subcable provides cryostability for the cable, while the electrical insulation between subcables reduces eddy current losses. In this way, the conductor provides the compromise between cryostability and low ac losses which is required for a pulsed cryostable magnet. The heat flux on the surface of the cable when the superconducting wires are in the normal state will be 0.2 W/cm^2; the heat flux due to the ac losses is estimated to be 0.01 W/cm^2.

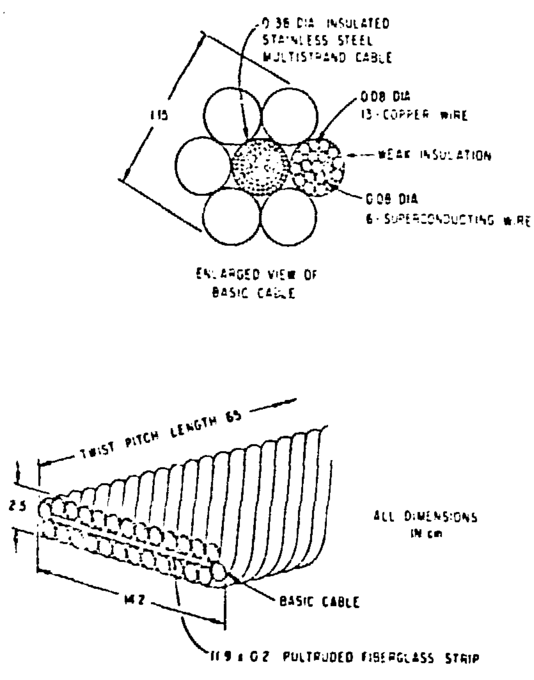

Fig. 5. Cabled conductor for OH and EF coils.

EF and OH Coil Layout

The coils are pancake wound. Each cable is enclosed top, bottom, and on one side by a fiberglass laminate spacer (G-10), which transmits axial and radial stresses. The top and bottom of the spacer have only fifty percent coverage, to permit helium flow past the conductor. On the other side of the conductor is a pultruded fiberglass band, with a longitudinal central groove and fully cut-out "mouse holes". The central groove and mouse holes permit free flow of helium coolant horizontally and vertically. (See Fig. 6.)

Two stainless steel bands 0.476 cm thick are wound with the conductor to support against the hoop tension resulting from the magnetic forces.

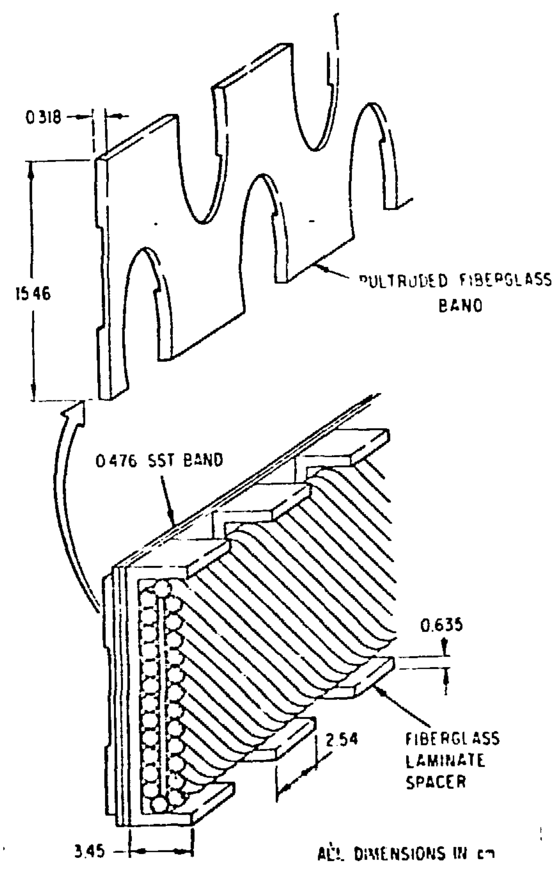

Fig. 6. Support for OH and EF coil conductor.

The coil structure, with layer-to-layer helium channels, banding, and helium vessel is shown in Fig. 7. Plates of G-10, 25-cm thick, are placed between pancakes. Both sides of the G-10 plate will have cooling channels (0.64 cm × 0.47 cm) in the radial direction. The two plates at the top and bottom will be 5-cm thick to have additional cooling channels.

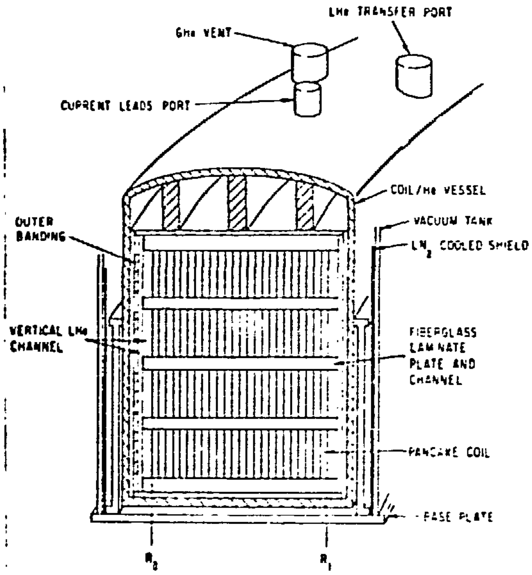

Fig. 7. Structure of outer OH and EF coils.

Correction Field Coils

The CF coils of STARFIRE are used to control the vertical and horizontal position of the plasma. These coils are not energized until the plasma is off center; then the power supplies are turned on to restore the plasma to its correct position. The four CF coils typically operate at about 10% duty factor. They are placed outside the blanket and shield so that they experience a relatively low neutron dosage. The design parameters for these coils are shown in Table 3.

The coil design chosen for the STARFIRE CF coils is very similar to the one adopted for the top and bottom field shaping coils of the General Atomic PGFR design.[3] The current ratings are similar, and the radiation dosage and radial and vertical forces are less for the STARFIRE CF coils than for the PGFR F-coils.

The most critical part of the CF coil design lies in the demountable joints. Fig. 8 is a joint concept applicable to STARFIRE. As shown, each joint consists of two pressure plates and a number of clamping bolts which apply the necessary pressure to all ten individual joints. Sufficient fractional force can be generat[illegible] between the joints to overcome the hoop force. Alumina insulation slabs are placed between turns and between the clamping bolts and also the pressure plates to achieve the necessary insulation. Each coil segment has its own coolant circuits whose connections must be made independently of the clamping assembly.

Table 3. STARFIRE CF Coil Design Parameters

Coil Number	Coil 8	Coil 9
R (m)	4.807	10.159
Z (m)	5.044	4.864
Amp-turns	-0.5×10^6	-0.9×10^6
V_{max} (v)	200	10
B_r (T)	−0.02	−0.02
B_z (T)	−0.02	−0.11
f_r (N/m)	1.0×10^4	9.9×10^4
f_z (N/m)	1.0×10^4	1.8×10^4
ΔR (m)	0.3	0.3
ΔZ (m)	0.2	0.3
σ_t (N/m^2)	1.0×10^6	1.4×10^7
F_z (N)	3.0×10^5	1.1×10^6

Peak I^2R power (total) = 2.3 MW.

Peak inductive power (total) = 210 MW.

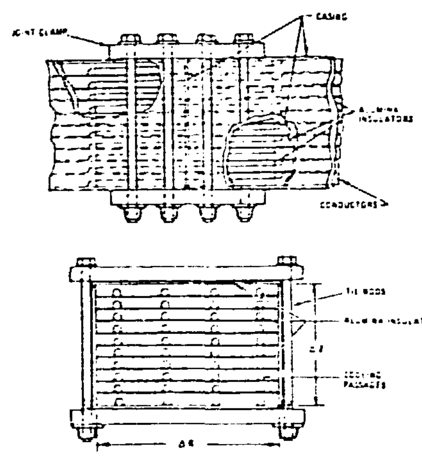

Fig. 8. STARFIRE correction field coil joint concept design.

CR Coil Horizontal Motion Correction

The equation of radial motion of a toroidal plasma column of circular cross section is[4]

$$M\ddot{R} = \frac{1}{2}\mu_o I_p^2 \left(\ln\frac{8R}{a} + \beta_p + \frac{\ell_i - 3}{2}\right) - 2\pi R I_p B_v \quad (2)$$

where M is the total plasma mass, R is the plasma major radius, I_p is the plasma toroidal current, and a is the plasma minor radius. Eq. (2) is not strictly valid for a high beta plasma such as in STARFIRE, but it should be sufficiently accurate to indicate the features of the control system. The quantity, β_p, is given by $\beta_p = 2\mu_o\bar{p}/B_p^2$, where $\bar{p}$ is the average plasma pressure, B_p is the poloidal magnetic field, and ℓ_i is the plasma internal inductance. The vertical field, B_v, includes an EF coil contribution, B_{vo}, which is assumed constant in time during a plasma excursion, as well as the contribution, B_u, due to induced currents in a conducting shell surrounding the plasma and the contribution, B_c, due to control coils.

For a shift, X, in plasma radial position, Eq. (2) can be expanded about the equilibrium major radius, R_o, using $R = R_o + X$, and the minor radius, a_o, using $a = a_o\,(1 + X/2R_o)$. The resulting expression describes conservation of toroidal magnetic flux, and the expression for B_v becomes

$$B_v = (B_{vo} + B_c)\,(1 - nX/R_o) + B_u\ , \quad (3)$$

where n is the index of curvature of the externally applied vertical field, which is determined by the locations and currents of the exterior EF coils.

From Eq. (2) the radial expansion force is a function of the plasma current, I_p, the internal inductance, ℓ_i, and the poloidal beta, β_p. Motion of the plasma column may be triggered by changes in these parameters on a time scale shorter than which the vertical field, B_{vo}, is able to respond. Changes in ℓ_i or β_p may be brought on by MHD activity which rapidly changes the profiles of current density or pressure. Overall changes in I_p may occur due to minor disruptions. In order to prevent rapid subsequent loss of plasma equilibrium, a change in the magnetic fields, B_c and B_u, must occur.

As typical perturbations to Eq. (2), the following parameter disturbances are considered:

$$I_p = I_{po}\,(1 - \mu X/R_o)\,(1 + \delta I_p/I_{po})$$
$$\ell_i = \ell_{io}\,(1 + \delta\ell_i/\ell_{io}) \quad (4)$$
$$\beta_p = \beta_{po}\,(1 + \delta\beta_p/\beta_{po}),$$

where the quantities subscripted with a zero are the equilibrium quantities, and μ is a constant chosen to conserve the poloidal magnetic flux.

For the case of small displacements, $X/R_o \ll 1$, Eq. (2) may be linearized to yield

$$\Gamma\frac{X}{R_o} = \frac{B_c + B_u}{B_{vo}} - \delta S\ , \quad (5)$$

where

$$\Gamma = \frac{1}{2\Lambda_o} + n - \mu - 1$$

$$\Lambda_o = \ln\frac{8R_o}{a_o} + \beta_{po} + \frac{\ell_{io} - 3}{2} \quad (6)$$

$$B_{vo} = \frac{\mu_o I_o \Lambda_o}{4\pi R_o}$$

$$\delta S = \frac{\delta I_p}{I_{po}} + \frac{2\delta\beta_p + \delta\ell_i}{2\Lambda_o}\ .$$

The left-hand term of Eq. (2) is neglected, since it describes motion on the time scale of the poloidal Alfvén time, and only the long time-scale motion is sought in Eq. (5). If there is no conducting wall, the displacement grows at the poloidal Aflvén speed when $\Gamma > 0$ or oscillates at the Alfvén frequency when $\Gamma < 0$. When a conducting shell is present, the growth rate becomes the resistive time constant of the wall. Thus, it is important to have a conducting wall and to design the reactor to have $\Gamma < 0$ for stability. In the STARFIRE design, these conditions are maintained by making the vacuum chamber wall and the neutron multiplier behind the first wall into toroidally continuous conductors of low electrical resistance and by the fact that the EF coil field naturally satisfies $\Gamma < 0$.

CF Coil Vertical Motion Correction

The horizontal motion of a plasma column is stable if $\Gamma < 0$ is satisfied. However, the vertical motion is unstable when the curvature index of the vertical field is negative, as it unavoidably is for an elongated plasma. The growth rate for this instability is also of the order of the poloidal Alfvén time, if no conducting shell exists to slow the motion.

The equation of motion of the plasma column for a vertical displacement in the Z direction is given by

$$M\ddot{z} = 2\pi R_o I_p B_{vr} \quad (7)$$

where B_{vr} is the radial component of the magnetic field due to the EF coils. This field consists of

$$B_{vr} \cong -nzB_{vo}/R_o \quad (8)$$

plus the radial field due to image currents flowing in an inductive first wall of minor radius r_u

$$B_{ur} = -\tau_u \dot{z} \mu_o I_o / 2\pi r_u^2 \ , \qquad (9)$$

where $\tau_u = 1/2\ \mu_o \sigma \Delta r_u$ is the L/R time constant of the wall, and Δ is the thickness of the wall, assumed small in comparison to the plasma minor radius. For the long time-scale mode Eq. (7) reduces to

$$\dot{z} + z \frac{\gamma}{\tau_u} + \xi \frac{b_o}{\tau_u} \ , \qquad (10)$$

where

$$\gamma = -\frac{1}{2} \left(\frac{r_u}{R_o} \right)^2 n \Lambda_o \ ,$$

$$\xi = \frac{r_u^2}{2R_o b_o} \Lambda_o \frac{B_d}{B_{vo}} \ , \qquad (11)$$

B_d is the radial component of a magnetic field disturbance, and b_o is the dimension of the plasma in the z-direction.

The solution to Eq. (10) is

$$\frac{z}{b_o} = \frac{\xi}{\gamma} \left(1 - e^{-\gamma t/\tau_u}\right) \qquad (12)$$

for a step-function disturbance. The growth rate of the motion is

$$\tau = \frac{-2}{n\Lambda_o} \left(\frac{R_o}{r_u} \right)^2 \tau_u \ , \qquad (13)$$

which, for STARFIRE parameters ($n \cong -0.5$, $\Lambda_o \cong 5$) is about four times the first wall time constant of 300 ms. Because the vertical displacement is unstable even if the initial disturbance is small, feedback control of a disturbance must be made on a time scale of about τ_u or shorter in order to limit the displacement to a small fraction of the plasma minor radius. A further discussion of the first wall and blanket/shield effects is given in Ref. 5.

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