Program FLUX

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August 9, 2021

1 Preliminarly Analysis

1.1 Coordinate Systems

- Cartesian coordinates: X, Y, Z.
- Cylindrical coordinates: $R \equiv (X^2 + Y^2)^{1/2}$, $\phi \equiv \tan^{-1}(Y/X)$, Z, so

$$|\nabla\phi| = \frac{1}{R}. \tag{1}$$

- Flux coordinates: $r(R, Z)$, $\theta(R, Z)$, ϕ, where

$$(\nabla r \cdot \nabla\theta \times \nabla\phi)^{-1} = \mathcal{J}, \tag{2}$$

$$\mathcal{J} = \frac{r\,R^2}{R_0}, \tag{3}$$

where R_0 is a convenient scale major radius, flux-surface label r has units of length, and θ is a poloidal angle. $\theta = 0$ on inboard midplane. $\theta > 0$ above midplane.

1.2 Useful Identities

Easily demonstrated that:

$$\mathbf{A} = A^r\,\mathcal{J}\,\nabla\theta\times\nabla\phi + A^\theta\,\mathcal{J}\,\nabla\phi\times\nabla r + A^\phi\,\mathcal{J}\,\nabla r\times\nabla\theta, \tag{4}$$

$$\mathbf{A} = A_r\,\nabla r + A_\theta\,\nabla\theta + A_\phi\,\nabla\phi, \tag{5}$$

$$\mathbf{A}\cdot\mathbf{B} = A_r\,B^r + A_\theta\,B^\theta + A_\phi\,B^\phi = A^r\,B_r + A^\theta\,B_\theta + A^\phi\,B_\phi, \tag{6}$$

$$(\mathbf{A}\times\mathbf{B})_r = \mathcal{J}\,(A^\theta\,B^\phi - A^\phi\,B^\theta), \tag{7}$$

$$(\mathbf{A}\times\mathbf{B})_\theta = \mathcal{J}\,(A^\phi\,B^r - A^r\,B^\phi), \tag{8}$$

$$(\mathbf{A}\times\mathbf{B})_\phi = \mathcal{J}\,(A^r\,B^\theta - A^\theta\,B^r), \tag{9}$$

$$\mathcal{J}\,(\mathbf{A}\times\mathbf{B})^r = A_\theta\,B_\phi - A_\phi\,B_\theta, \tag{10}$$

$$\mathcal{J}\,(\mathbf{A}\times\mathbf{B})^{\,\theta} = A_\phi\,B_r - A_r\,B_\phi, \tag{11}$$

$$\mathcal{J}\,(\mathbf{A}\times\mathbf{B})^{\,\phi} = A_r\,B_\theta - A_\theta\,B_r, \tag{12}$$

$$\mathcal{J}\,\nabla\cdot\mathbf{A} = \frac{\partial\,(\mathcal{J}\,A^{\,r})}{\partial r} + \frac{\partial\,(\mathcal{J}\,A^{\theta})}{\partial\theta} + \frac{\partial\,(\mathcal{J}\,A^{\phi})}{\partial\phi}, \tag{13}$$

$$\mathcal{J}\,(\nabla\times\mathbf{A})^{\,r} = \frac{\partial A_\phi}{\partial\theta} - \frac{\partial A_\theta}{\partial\phi}, \tag{14}$$

$$\mathcal{J}\,(\nabla\times\mathbf{A})^{\,\theta} = \frac{\partial A_r}{\partial\phi} - \frac{\partial A_\phi}{\partial r}, \tag{15}$$

$$\mathcal{J}\,(\nabla\times\mathbf{A})^{\,\phi} = \frac{\partial A_\theta}{\partial r} - \frac{\partial A_r}{\partial\theta}. \tag{16}$$

1.3 Equilibrium Magnetic Field

Equilibrium magnetic field:

$$\mathbf{B} = B_0\,R_0\,[f(r)\,\nabla\phi\times\nabla r + g(r)\,\nabla\phi]\,, \tag{17}$$

$$q(r) = \frac{r\,g}{R_0\,f}, \tag{18}$$

where B_0 is a convenient scale magnetic field strength, and g and f are dimensionless. So,

$$B^{\,r} = 0, \tag{19}$$

$$B^{\,\theta} = B_0\,R_0^2\,\frac{f}{r\,R^2}, \tag{20}$$

$$B^{\,\phi} = B_0\,R_0^2\,\frac{q\,f}{r\,R^2} = B_0\,B_0\,\frac{g}{R^2}, \tag{21}$$

$$B_r = -B_0\,r\,f\,\nabla r\cdot\nabla\theta, \tag{22}$$

$$B_\theta = B_0\,r\,f\,|\nabla r|^{\,2}, \tag{23}$$

$$B_\phi = B_0\,R_0^2\,\frac{q\,f}{r} = B_0\,R_0\,g, \tag{24}$$

and

$$\mathbf{B}\cdot\nabla = B_0\,R_0^2\,\frac{f}{r\,R^2}\left(\frac{\partial}{\partial\theta} + q\,\frac{\partial}{\partial\phi}\right). \tag{25}$$

1.4 Equilibrium Plasma Current

The relation $\mu_0\,\mathbf{J} = \nabla\times\mathbf{B}$ yields

$$\mu_0\,\mathcal{J}\,J^{\,r} = 0, \tag{26}$$

$$\mu_0\,\mathcal{J}\,J^{\,\theta} = -B_0\,R_0\,\frac{dg}{dr}, \tag{27}$$

$$\mu_0\,\mathcal{J}\,J^{\,\phi} = B_0\,\frac{\partial}{\partial r}\big(r\,f\,|\nabla r|^{\,2}\big) + B_0\,\frac{\partial}{\partial\theta}(r\,f\,\nabla r\cdot\nabla\theta)\,. \tag{28}$$

1.5 Grad-Shafranov Equation

The equilibrium force balance relation

$$\mathbf{J}\times\mathbf{B} = \nabla P \tag{29}$$

yields

$$\mathcal{J}\,(J^{\,\theta}\,B^{\,\phi} - J^{\,\phi}\,B^{\,\theta}) = \frac{dP}{dr}, \tag{30}$$

which reduces to the Grad-Shafranov equation,

$$\frac{f}{r}\,\frac{\partial}{\partial r}\big(r\,f\,|\nabla r|^{\,2}\big) + \frac{f}{r}\,\frac{\partial}{\partial\theta}(r\,f\,\nabla r\cdot\nabla\theta) + g\,\frac{dg}{dr} + \frac{\mu_0}{B_0^{\,2}}\left(\frac{R}{R_0}\right)^2\frac{dP}{dr} = 0. \tag{31}$$

1.6 Inhomogeneous Tearing Mode Dispersion Relation

1.7 High-q Limit

Now,

$$\nabla\cdot\delta\mathbf{B} = 0 \tag{32}$$

yields

$$\frac{\partial(\mathcal{J}\,\delta B^{\,r})}{\partial r} + \frac{\partial(\mathcal{J}\,\delta B^{\,\theta})}{\partial\theta} + \frac{\partial(\mathcal{J}\,\delta B^{\,\phi})}{\partial\phi} = 0. \tag{33}$$

Furthermore,

$$\delta\mathbf{B} = \delta B_r\,\nabla r + \delta B_\theta\,\nabla\theta + \delta B_\phi\,\nabla\phi. \tag{34}$$

So,

$$\delta B^{\,r} = \delta\mathbf{B}\cdot\nabla r = |\nabla r|^{\,2}\,\delta B_r + (\nabla r\cdot\nabla\theta)\,\delta B_\theta, \tag{35}$$

$$\delta B^{\,\theta} = \delta\mathbf{B}\cdot\nabla\theta = (\nabla r\cdot\nabla\theta)\,\delta B_r + |\nabla\theta|^{\,2}\,\delta B_\theta, \tag{36}$$

$$\delta B^{\,\phi} = \delta\mathbf{B}\cdot\nabla\phi = \frac{\delta B_\phi}{R^2}. \tag{37}$$

Follows that

$$\delta B_r = \left(\frac{1}{|\nabla r|^{\,2}}\right)\delta B^{\,r} - \left(\frac{\nabla r\cdot\nabla\theta}{|\nabla r|^{\,2}}\right)\delta B_\theta, \tag{38}$$

and

$$\delta B^{\,\theta} = \left(\frac{\nabla r\cdot\nabla\theta}{|\nabla r|^{\,2}}\right)\delta B^{\,r} + \left[|\nabla\theta|^{\,2} - \frac{(\nabla r\cdot\nabla\theta)^{\,2}}{|\nabla r|^{\,2}}\right]\delta B_\theta. \tag{39}$$

But, Eqs. (2) and (3) imply that

$$|\nabla r|^{\,2}\,|\nabla\theta|^{\,2} - (\nabla r\cdot\nabla\theta)^{\,2} = \frac{R_0^{\,2}}{r^{\,2}\,R^{\,2}}. \tag{40}$$

Hence,

$$\delta B^{\,\theta} = \left(\frac{\nabla r\cdot\nabla\theta}{|\nabla r|^{\,2}}\right)\delta B^{\,r} + \left(\frac{R_0^2}{r^{\,2}\,R^{\,2}\,|\nabla r|^{\,2}}\right)\delta B_\theta. \tag{41}$$

Assume that high-q limit is equivalent to $\delta\mathbf{B}$ being curl-free. Follows that

$$\frac{\partial\,\delta B_\phi}{\partial\theta} = \frac{\partial\,\delta B_\theta}{\partial\phi}, \tag{42}$$

$$\frac{\partial\,\delta B_r}{\partial\phi} = \frac{\partial\,\delta B_\phi}{\partial r}, \tag{43}$$

$$\frac{\partial\,\delta B_\theta}{\partial r} = \frac{\partial\,\delta B_r}{\partial\theta}. \tag{44}$$

Previous three equations imply that

$$\delta B_\phi \sim \frac{n}{m}\,\delta B_\theta,\; \frac{n}{m}\,r\,\delta B_r \tag{45}$$

and, hence, that

$$\delta B^{\,\phi} \sim \frac{n}{m}\,\left(\frac{r}{R}\right)^2\delta B^{\,\theta},\; \frac{n}{m}\,\left(\frac{r}{R}\right)^2\frac{\delta B^{\,r}}{r}, \tag{46}$$

Consequently, final term on right-hand side of (33) is of order $(n/m)^2\,(r/R)^2$ smaller than other two terms, and, therefore, negligible. Thus, we get

$$\frac{\partial(\mathcal{J}\,\delta B^{\,r})}{\partial r} + \frac{\partial(\mathcal{J}\,\delta B^{\,\theta})}{\partial\theta} = 0. \tag{47}$$

Follows from (41) and previous equation that

$$r\,\frac{\partial}{\partial r}\left(\frac{r\,R^2\,\delta B^{\,r}}{R_0^2}\right) = -\frac{\partial}{\partial\theta}\left[\left(\frac{r\,\nabla r\cdot\nabla\theta}{|\nabla r|^{\,2}}\right)\left(\frac{r\,R^2\,\delta B^{\,r}}{R_0^2}\right) + \left(\frac{1}{|\nabla r|^{\,2}}\right)\delta B_\theta\right]. \tag{48}$$

Follows from (3), (38) and (44) that

$$r\,\frac{\partial\,\delta B_\theta}{\partial r} = \frac{\partial}{\partial\theta}\left[\left(\frac{R_0^2}{R^2\,|\nabla r|^{\,2}}\right)\left(\frac{r\,R^2\,\delta B^{\,r}}{R_0^2}\right) - \left(\frac{r\,\nabla r\cdot\nabla\theta}{|\nabla r|^{\,2}}\right)\delta B_\theta\right]. \tag{49}$$

Let

$$\frac{r\,R^2\,\delta B^{\,r}(r,\theta,\phi)}{R_0^2} = \sum_j \delta\hat{B}^{\,r}_j(r)\,\mathrm{e}^{\,\mathrm{i}\,(m_j\,\theta-n\phi)}, \tag{50}$$

$$\delta B_\theta(r,\theta,\phi) = \sum_j \delta\hat{B}_{\theta\,j}(r)\,\mathrm{e}^{\,\mathrm{i}\,(m_j\,\theta-n\,\phi)}. \tag{51}$$

Follows that

$$\sum_{j'} r\,\frac{d\,\delta\hat{B}^{\,r}_{j'}}{dr}\,\mathrm{e}^{\,\mathrm{i}\,m_{j'}\,\theta} = -\frac{\partial}{\partial\theta}\sum_{j'}\left[\left(\frac{r\,\nabla r\cdot\nabla\theta}{|\nabla r|^{\,2}}\right)\,\mathrm{e}^{\,\mathrm{i}\,m_{j'}\,\theta}\,\delta\hat{B}^{\,r}_{j'} + \left(\frac{1}{|\nabla r|^{\,2}}\right)\,\mathrm{e}^{\,\mathrm{i}\,m_{j'}\,\theta}\,\delta\hat{B}_{\theta\,j'}\right], \tag{52}$$

$$\sum_{j'} r\,\frac{d\,\delta\hat{B}_{\theta\,j'}}{dr}\,\mathrm{e}^{\,\mathrm{i}\,m_{j'}\,\theta} = \frac{\partial}{\partial\theta}\sum_{j'}\left[\left(\frac{R_0^2}{R^2\,|\nabla r|^2}\right)\mathrm{e}^{\,\mathrm{i}\,m_{j'}\,\theta}\,\delta\hat{B}^r_{j'} - \left(\frac{r\,\nabla r\cdot\nabla\theta}{|\nabla r|^2}\right)\mathrm{e}^{\,\mathrm{i}\,m_{j'}\,\theta}\,\delta\hat{B}_{\theta\,j'}\right]. \tag{53}$$

Operating with $\oint(\cdots)\,\mathrm{e}^{-\mathrm{i}\,m_j\,\theta}\,d\theta/(2\pi)$, we get

$$r\,\frac{d\,\delta\hat{B}^r_j}{dr} = -\mathrm{i}\,m_j\sum_{j'}\left(-\mathrm{i}\,c_{jj'}\,\delta\hat{B}^r_{j'} + a_{jj'}\,\delta\hat{B}_{\theta\,j'}\right), \tag{54}$$

$$r\,\frac{d\,\delta\hat{B}_{\theta\,j}}{dr} = -\mathrm{i}\,m_j\sum_{j'}\left(-\mathrm{i}\,c_{jj'}\,\delta\hat{B}_{\theta\,j'} - b_{jj'}\,\delta\hat{B}^r_{j'}\right), \tag{55}$$

where

$$a_{jj'} = \oint\frac{1}{|\nabla r|^2}\,\mathrm{e}^{-\mathrm{i}\,(m_j-m_{j'})\,\theta}\,\frac{d\theta}{2\pi}, \tag{56}$$

$$b_{jj'} = \oint\frac{R_0^2}{R^2\,|\nabla r|^2}\,\mathrm{e}^{-\mathrm{i}\,(m_j-m_{j'})\,\theta}\,\frac{d\theta}{2\pi}, \tag{57}$$

$$c_{jj'} = \oint\frac{\mathrm{i}\,r\,\nabla r\cdot\nabla\theta}{|\nabla r|^2}\,\mathrm{e}^{-\mathrm{i}\,(m_j-m_{j'})\,\theta}\,\frac{d\theta}{2\pi}. \tag{58}$$

Let

$$\delta\hat{B}^r_j(r) = \mathrm{i}\,\psi_j(r), \tag{59}$$

$$\delta\hat{B}_{\theta\,j}(r) = -\chi_j(r). \tag{60}$$

It follows that

$$r\,\frac{d\psi_j}{dr} = m_j\sum_{j'}\left(-c_{jj'}\,\psi_{j'} + a_{jj'}\,\chi_{j'}\right), \tag{61}$$

$$r\,\frac{d\chi_j}{dr} = m_j\sum_{j'}\left(-c_{jj'}\,\chi_{j'} + b_{jj'}\,\psi_{j'}\right). \tag{62}$$

Hence,

$$\frac{r\,R^2\,\delta B^r(r,\theta,\phi)}{R_0^2} = \mathrm{i}\sum_j\psi_j(r)\,\mathrm{e}^{\,\mathrm{i}\,(m_j\,\theta-n\phi)}, \tag{63}$$

$$\frac{r\,R^2\,\delta B^\theta(r,\theta,\phi)}{R_0^2} = -\sum_j\frac{1}{m_j}\,\frac{d\psi_j}{dr}\,\mathrm{e}^{\,\mathrm{i}\,(m_j\,\theta-n\,\phi)}, \tag{64}$$

$$R^2\,\delta B^\phi(r,\theta,\phi) = n\sum_j\frac{\chi_j(r)}{m_j}\,\mathrm{e}^{\,\mathrm{i}\,(m_j\,\theta-n\,\phi)}. \tag{65}$$

where use has been made of (42). Also have

$$\delta B_r(r,\theta,\phi) = \mathrm{i}\sum_j \frac{1}{m_j}\,\frac{d\chi_j}{dr}\,\mathrm{e}^{\,\mathrm{i}\,(m_j\,\theta-n\,\phi)}, \tag{66}$$

$$\delta B_\theta(r,\theta,\phi) = -\sum_j \chi_j(r)\,\mathrm{e}^{\,\mathrm{i}\,(m_j\,\theta-n\,\phi)}, \tag{67}$$

$$\delta B_\phi(r,\theta,\phi) = n\sum_j \frac{\chi_j(r)}{m_j}\,\mathrm{e}^{\,\mathrm{i}\,(m_j\,\theta-n\,\phi)}, \tag{68}$$

We can write

$$\mathcal{J}\,\mu_0\,\delta J^{\,r} = \frac{\partial\,\delta B_\phi}{\partial\theta} - \frac{\partial\,\delta B_\theta}{\partial\phi}, \tag{69}$$

$$\mathcal{J}\,\mu_0\,\delta J^{\,\theta} = \frac{\partial\,\delta B_r}{\partial\phi} - \frac{\partial\,\delta B_\phi}{\partial r}, \tag{70}$$

$$\mathcal{J}\,\mu_0\,\delta J^{\,\phi} = \frac{\partial\,\delta B_\theta}{\partial r} - \frac{\partial\,\delta B_r}{\partial\theta}. \tag{71}$$

Normally, all three components are zero. However, at kth resonant surface (at which $r=r_k$, where $q(r_k)=m_k/n$) ψ_k, $\psi_{j\neq k}$, and $\chi_{j\neq k}$ are continuous, whereas χ_k is discontinuous. Hence,

$$\mathcal{J}\,\mu_0\,\delta J^{\,r}(r,\theta,\phi) = 0, \tag{72}$$

$$\mathcal{J}\,\mu_0\,\delta J^{\,\theta}(r,\theta,\phi) = -\sum_k \frac{n}{m_k}\,\left[\chi_k\right]_{r_{k-}}^{r_{k+}}\,\delta(r-r_k)\,\mathrm{e}^{\,\mathrm{i}\,(m_k\,\theta-n\,\phi)}, \tag{73}$$

$$\mathcal{J}\,\mu_0\,\delta J^{\,\phi}(r,\theta,\phi) = -\sum_k \left[\chi_k\right]_{r_{k-}}^{r_{k+}}\,\delta(r-r_k)\,\mathrm{e}^{\,\mathrm{i}\,(m_k\,\theta-n\,\phi)}. \tag{74}$$

Now,

$$(\mu_0\,\delta\mathbf{J}\times\delta\mathbf{B})_\theta = \frac{1}{4}\left(\mathcal{J}\,\mu_0\,\delta J^{\,\phi}\,\delta B^{\,r\,*} + \text{c.c.}\right), \tag{75}$$

$$(\mu_0\,\delta\mathbf{J}\times\delta\mathbf{B})_\phi = \frac{1}{4}\left(-\mathcal{J}\,\mu_0\,\delta J^{\,\theta}\,\delta B^{\,r\,*} + \text{c.c.}\right), \tag{76}$$

which implies that

$$\mathcal{J}\,(\mu_0\,\delta\mathbf{J}\times\delta\mathbf{B})_\theta = \frac{R_0}{2}\sum_j\sum_k \mathrm{Re}\left\{\mathrm{i}\,\left[\chi_k\right]_{r_{k-}}^{r_{k+}}\,\psi_j^{\,*}(r_k)\,\mathrm{e}^{\,\mathrm{i}\,(m_k-m_j)\,\theta}\right\}\delta(r-r_k), \tag{77}$$

$$\mathcal{J}\,(\mu_0\,\delta\mathbf{J}\times\delta\mathbf{B})_\phi = -\frac{R_0}{2}\sum_j\sum_k \frac{n}{m_k}\,\mathrm{Re}\left\{\mathrm{i}\,\left[\chi_k\right]_{r_{k-}}^{r_{k+}}\,\psi_j^{\,*}(r_k)\,\mathrm{e}^{\,\mathrm{i}\,(m_k-m_j)\,\theta}\right\}\delta(r-r_k). \tag{78}$$

Let

$$\mathit{\Psi}_k = \frac{\psi_k(r_k)}{m_k}, \tag{79}$$

$$\Delta\Psi_k = [\chi_k]_{r_{k-}}^{r_{k+}}, \tag{80}$$

$$\delta T_{\theta\,k} \equiv \delta\mathbf{T}\cdot\mathbf{e}_\theta = \int_{r_{k-}}^{r_{k+}}\oint\oint(\delta\mathbf{J}\times\delta\mathbf{B})_\theta\,\mathcal{J}\,dr\,d\theta\,d\phi, \tag{81}$$

$$\delta T_{\phi\,k} \equiv \delta\mathbf{T}\cdot\mathbf{e}_\phi = \int_{r_{k-}}^{r_{k+}}\oint\oint(\delta\mathbf{J}\times\delta\mathbf{B})_\phi\,\mathcal{J}\,dr\,d\theta\,d\phi, \tag{82}$$

where $\delta\mathbf{T}(r)\,dr$ is the net electromagnetic torque acting on the plasma between r and $r+dr$. Here, $\mathbf{e}_\theta = (R^2/R_0)\,\nabla\phi\times\nabla r$ and $\mathbf{e}_\phi = R\,\nabla\phi$. Follows that

$$\delta T_{\theta\,k} = -\frac{2\pi^2\,R_0\,m_k}{\mu_0}\,{\rm Im}\,(\Psi_k^\ast\,\Delta\Psi_k)\,, \tag{83}$$

$$\delta T_{\phi\,k} = \frac{2\pi^2\,R_0\,n}{\mu_0}\,{\rm Im}\,(\Psi_k^\ast\,\Delta\Psi_k)\,. \tag{84}$$

1.8 Homogeneous Solution

We can write

$$\delta\mathbf{B} = \nabla\times\delta\mathbf{A}. \tag{85}$$

Suppose that $r\,\delta A_r$, δA_θ are negligible with respect to δA_ϕ. In fact, it is easily demonstrated from $\nabla\cdot\delta\mathbf{A}=0$ that $r\,\delta A_r$, $\delta A_\theta\sim(n/m)\,(r/R)^2\,\delta A_\phi$. It follows that

$$\mathcal{J}\,\delta B^{\,r} \simeq \frac{\partial\,\delta A_\phi}{\partial\theta}, \tag{86}$$

$$\mathcal{J}\,\delta B^{\,\theta} \simeq -\frac{\partial\,\delta A_\phi}{\partial r}, \tag{87}$$

$$\mathcal{J}\,\delta B^{\,\phi} \simeq 0. \tag{88}$$

The neglected terms in the previous three equations are $(n/m)^2\,(r/R)^2$ smaller than the dominant terms. The previous three expressions are consistent with (63), (64), and (65) provided

$$\delta A_\phi(r,\theta,\phi) \simeq R_0\sum_j\frac{\psi_j(r)}{m_j}\,{\rm e}^{\,{\rm i}\,(m_j\,\theta-n\,\phi)}. \tag{89}$$

According to the Biot-Savart law:

$$\delta A_{\,\phi}(\mathbf{x}) = \frac{1}{4\pi}\int\frac{R\,R'\,\mu_0\,\delta\mathbf{J}(\mathbf{x}')\cdot\nabla\phi}{|\mathbf{x}-\mathbf{x}'|}\,d^{\,3}\mathbf{x}'. \tag{90}$$

Assume that

$$\delta A_\phi(R,\phi,Z) = \delta A_\phi(R,0,Z)\,{\rm e}^{-{\rm i}\,n\,\phi}. \tag{91}$$

Hence, can evaluate integral at $\phi=0$ without loss of generality. Follows that

$$\mathbf{x} = (R,\,0,\,Z), \tag{92}$$

$$\mathbf{x}' = (R'\,\cos\phi',\; R'\,\sin\phi',\; Z'), \tag{93}$$

and

$$|\mathbf{x}-\mathbf{x}'| = \left[R^{\,2}+R'^{\,2}+(Z-Z')^{\,2}-2\,R\,R'\,\cos\phi'\right]^{\,1/2}. \tag{94}$$

Now,

$$\delta\mathbf{J}(R',\phi',Z')\cdot\nabla\phi = \delta J^{\,\phi}(R',0,Z')\,\mathrm{e}^{-\mathrm{i}\,n\,\phi'}\,\cos\phi', \tag{95}$$

so

$$\delta A_\phi(R,0,Z) = \frac{1}{4\pi}\int_0^\infty\oint\oint\frac{R\,R'\,\mu_0\,\delta J^{\,\phi}(R',0,Z')\,\mathrm{e}^{-\mathrm{i}\,n\,\phi'}\,\cos\phi'\,\mathcal{J}'\,dr'\,d\theta'\,d\phi'}{[R^{\,2}+R'^{\,2}+(Z-Z')^{\,2}-2\,R\,R'\,\cos\phi']^{\,1/2}}, \tag{96}$$

which can be written

$$\delta A_\phi(R,0,Z) = \frac{1}{4\pi}\int_0^\infty\oint R\,R'\,\mu_0\,\delta J^{\,\phi}(R',0,Z')\,G(R,Z;R',Z')\,\mathcal{J}'\,dr'\,d\theta', \tag{97}$$

where

$$G(R,Z;R',Z') = \oint\frac{\cos\phi'\,\cos(n\,\phi')\,d\phi'}{[R^{\,2}+R'^{\,2}+(Z-Z')^{\,2}-2\,R\,R'\,\cos\phi']^{\,1/2}}, \tag{98}$$

or

$$G(R,Z;R',Z') = \frac{1}{2}\oint\frac{(\cos[(n-1)\,\phi']+\cos[(n+1)\,\phi'])\;d\phi'}{[R^{\,2}+R'^{\,2}+(Z-Z')^{\,2}-2\,R\,R'\,\cos\phi']^{\,1/2}}. \tag{99}$$

Now,

$$\begin{aligned}P^{\,n}_{-1/2}(\cosh\eta) &= \frac{(-1)^{\,n}}{2\pi}\,\frac{\Gamma(1/2)}{\Gamma(1/2-n)}\oint\frac{\cos(n\,\varphi)\,d\varphi}{(\cosh\eta+\sinh\eta\,\cos\varphi)^{\,1/2}}\\ &= \frac{1}{2\pi}\,\frac{\Gamma(1/2)}{\Gamma(1/2-n)}\oint\frac{\cos(n\,\varphi)\,d\varphi}{(\cosh\eta-\sinh\eta\,\cos\varphi)^{\,1/2}}\\ &= \frac{(-1)^{\,n}\,\Gamma(1/2)\,\Gamma(1/2+n)}{2\pi^{\,2}}\oint\frac{\cos(n\,\varphi)\,d\varphi}{(\cosh\eta-\sinh\eta\,\cos\varphi)^{\,1/2}}.\end{aligned} \tag{100}$$

Let

$$\alpha\,\cosh\eta = R^{\,2}+R'^{\,2}+(Z-Z')^{\,2}, \tag{101}$$

$$\alpha\,\sinh\eta = 2\,R\,R'. \tag{102}$$

Hence,

$$\eta = \tanh^{-1}\left[\frac{2\,R\,R'}{R^{\,2}+R'^{\,2}+(Z-Z')^{\,2}}\right], \tag{103}$$

and

$$\alpha = \frac{R^{\,2}+R'^{\,2}+(Z-Z')^{\,2}}{\cosh\eta}. \tag{104}$$

It follows that

$$G(R,Z;R',Z') = \pi\left[\frac{\cosh\eta}{R^{\,2}+R'^{\,2}+(Z-Z')^{\,2}}\right]^{1/2}$$
$$\times\left[\frac{\Gamma(3/2-n)}{\Gamma(1/2)}\,P^{\,n-1}_{-1/2}(\cosh\eta)+\frac{\Gamma(-1/2-n)}{\Gamma(1/2)}\,P^{\,n+1}_{-1/2}(\cosh\eta)\right]. \tag{105}$$

However,

$$\Gamma(3/2-n) = \frac{(-1)^{\,n+1}\,\pi\,(n-1/2)}{\Gamma(n+1/2)}, \tag{106}$$

$$\Gamma(-1/2-n) = \frac{(-1)^{\,n+1}\,\pi}{\Gamma(n+1/2)\,(n+1/2)}, \tag{107}$$

so

$$G(R,Z;R',Z') = \frac{(-1)^{\,n+1}\,\pi^{\,2}}{\Gamma(1/2)\,\Gamma(n+1/2)}\left[\frac{\cosh\eta}{R^{\,2}+R'^{\,2}+(Z-Z')^{\,2}}\right]^{1/2}$$
$$\times\left[(n-1/2)\,P^{\,n-1}_{-1/2}(\cosh\eta)+\frac{P^{\,n+1}_{-1/2}(\cosh\eta)}{n+1/2}\right]. \tag{108}$$

Now, from (74) and (80),

$$\mathcal{J}\,\mu_0\,\delta J^{\,\phi}(r,\theta,0) = -\sum_k \mathit{\Delta\Psi}_k\,\delta(r-r_k)\,{\rm e}^{\,{\rm i}\,m_k\,\theta}. \tag{109}$$

Furthermore, from (79) and (89),

$$\mathit{\Psi}_k = \frac{1}{R_0}\oint\delta A_\phi(r_k,\theta,0)\,{\rm e}^{-{\rm i}\,m_k\,\theta}\,\frac{d\theta}{2\pi}. \tag{110}$$

Hence, we obtain the homogeneous tearing mode dispersion relation,

$$\mathit{\Psi}_k = \sum_{k'} F_{kk'}\,\mathit{\Delta\Psi}_{k'}, \tag{111}$$

where

$$F_{kk'} = \oint\oint\mathcal{G}(R_k,Z_k;R_k',Z_k')\,{\rm e}^{-{\rm i}\,(m_k\,\theta-m_{k'}\,\theta')}\,\frac{d\theta}{2\pi}\,\frac{d\theta'}{2\pi}, \tag{112}$$

and

$$\mathcal{G}(R,Z;R',Z') = \frac{(-1)^{\,n}\,\pi^{\,2}\,R\,R'/R_0}{2\,\Gamma(1/2)\,\Gamma(n+1/2)}\left[\frac{\cosh\eta}{R^{\,2}+R'^{\,2}+(Z-Z')^{\,2}}\right]^{1/2}$$
$$\times\left[(n-1/2)\,P^{\,n-1}_{-1/2}(\cosh\eta)+\frac{P^{\,n+1}_{-1/2}(\cosh\eta)}{n+1/2}\right]. \tag{113}$$

Here, R_k, Z_k are the R. Z coordinates of the kth resonant surface in the plane $\phi = 0$. We can also write

$$F_{kk'} = \oint\oint \tilde{\mathcal{G}}(R_k, Z_k; R_k', Z_k')\, \mathrm{e}^{-\mathrm{i}\,(m_k\,\theta - m_{k'}\,\theta')}\, \frac{d\Theta}{2\pi}\, \frac{d\Theta'}{2\pi}, \tag{114}$$

where

$$\tilde{\mathcal{G}}(R, Z; R', Z') = \frac{g\,g'}{q\,q'\,\gamma\,\gamma'\,B\,B'\,R^2\,R'^{\,2}}\,\frac{(-1)^{\,n}\,\pi^{\,2}\,R\,R'/R_0}{2\,\Gamma(1/2)\,\Gamma(n+1/2)}\left[\frac{\cosh\eta}{R^{\,2} + R'^{\,2} + (Z-Z')^{\,2}}\right]^{1/2}$$
$$\times\left[(n-1/2)\,P^{\,n-1}_{-1/2}(\cosh\eta) + \frac{P^{\,n+1}_{-1/2}(\cosh\eta)}{n+1/2}\right]. \tag{115}$$

Note that

$$\mathcal{G}(R', Z'; R, Z) = \mathcal{G}(R, Z; R', Z'), \tag{116}$$

which implies that

$$F_{k'k} = F^{\,*}_{kk'}. \tag{117}$$

1.9 Inhomogeneous Solution

Suppose that there are currents flowing in a number of external poloidal field coils. Let I_l, R_l, and Z_l be the peak current, and coordinates of the lth field coil. The currents are assumed to modulate like $\mathrm{e}^{-\mathrm{i}\,n\,\phi}$. It follows that

$$\delta J^{\,\phi}_{\rm ext}(R, 0, Z) = \sum_j \frac{I_l}{R_l}\,\delta(R-R_l)\,\delta(Z-Z_l). \tag{118}$$

Hence,

$$\Psi_k = \sum_{k'} F_{kk'}\,\Delta\Psi_k - \sum_l g_{kl}\,\mu_0\,I_l, \tag{119}$$

where

$$g_{kj} = \frac{1}{2\pi}\oint \mathcal{G}(r_k, \theta; R_j, Z_j)\,\mathrm{e}^{-\mathrm{i}\,m_k\,\theta}\,\frac{d\theta}{2\pi}. \tag{120}$$

Thus, we obtain the inhomogeneous tearing mode dispersion relation,

$$\Delta\Psi_k = \sum_{k'} E_{kk'}\,\Psi_{k'} + |E_{kk}|\,\chi_k, \tag{121}$$

where $E_{kk'}$ is the inverse of the $F_{kk'}$ matrix, and

$$\chi_k = \frac{1}{|E_{kk}|}\sum_j h_{kl}\,\mu_0\,I_l, \tag{122}$$

$$h_{kl} = \sum_{k'} E_{kk'}\,g_{k'l}. \tag{123}$$

1.10 Electromagnetic Torques in Presence of External Currents

Suppose that

$$\Psi_k = B_0\,R_0\,\hat{\Psi}_k\,{\rm e}^{-{\rm i}\,\varphi_k}, \tag{124}$$

$$\chi_k = B_0\,R_0\,\hat{\chi}_k\,{\rm e}^{-{\rm i}\,\zeta_k}, \tag{125}$$

$$E_{kk'} = \hat{E}_{kk'}\,{\rm e}^{-{\rm i}\,\xi_{kk'}}, \tag{126}$$

where $\hat{\Psi}_k$, $\hat{\chi}_k$, and $\hat{E}_{kk'}$ are real and positive, whereas φ_k, ζ_k, and $\xi_{kk'}$ are real. (Note that all hatted quantities in this report are dimensionless.) It follows from Eqs. (83), (84), and (121) that

$$\delta T_{\theta\,k} = -\left(\frac{2\pi^{\,2}\,B_0^{\,2}\,R_0^{\,3}}{\mu_0}\right) m_k\,\delta\hat{T}_k, \tag{127}$$

$$\delta T_{\phi\,k} = \left(\frac{2\pi^{\,2}\,B_0^{\,2}\,R_0^{\,3}}{\mu_0}\right) n\,\delta\hat{T}_k, \tag{128}$$

where

$$\delta\hat{T}_k = \sum_{k'=1,K}\hat{E}_{kk'}\,\hat{\Psi}_k\,\hat{\Psi}_{k'}\,\sin(\varphi_k-\varphi_{k'}-\xi_{kk'}) + \hat{E}_{kk}\,\hat{\Psi}_k\,\hat{\chi}_k\,\sin(\varphi_k-\zeta_k). \tag{129}$$

1.11 GPEC Coupling

1.11.1 PRL Derivation

We have

$$\frac{d\psi_p}{dr} = B_0\,R_0\,f(r), \tag{130}$$

$$\mathbf{B}\cdot\nabla\phi = \frac{B_0\,R_0}{R^{\,2}}\,g(r), \tag{131}$$

$$\delta B^{\,r} = \frac{\rm i}{r}\left(\frac{R_0}{R}\right)^2\sum_j \psi_j\,{\rm e}^{\,{\rm i}\,(m_j\,\theta-n\,\phi)}. \tag{132}$$

According to PRL **99**, 195003 (2007),

$$\varDelta_j\,{\rm e}^{\,{\rm i}\,(m_j\,\theta-n\,\phi)} = \left[\frac{\partial}{\partial\psi_p}\,\frac{\delta\mathbf{B}\cdot\nabla\psi_p}{\mathbf{B}\cdot\nabla\phi}\right]_{r_j} = \left[\frac{\partial}{\partial r}\,\frac{\delta\mathbf{B}\cdot\nabla r}{\mathbf{B}\cdot\nabla\phi}\right]_{r_j} = \left[\frac{\partial}{\partial r}\,\frac{\delta B^{\,r}}{\mathbf{B}\cdot\nabla\phi}\right]_{r_j}. \tag{133}$$

It follows that

$$\varDelta_j = \frac{\rm i}{r_j}\left(\frac{R_0}{R}\right)^2\frac{R^{\,2}}{B_0\,R_0\,g_j}\left[\frac{d\psi_j}{dr}\right]_{r_j}, \tag{134}$$

But,

$$\left[r\,\frac{d\psi_j}{dr}\right]_{r_j} = m_j\,a_{jj}\,[\chi_j]_{r_j} = m_j\,a_{jj}\,\varDelta\Psi_j, \tag{135}$$

and

$$\chi_j = \frac{\mathit{\Delta\Psi}_j}{|E_{jj}|}, \tag{136}$$

which implies that

$$\mathit{\Delta}_j = \mathrm{i}\left(\frac{R_0}{r_j}\right)^2 \frac{m_j\, a_{jj}}{g_j}\, \frac{\mathit{\Delta\Psi}_j}{B_0\, R_0}, \tag{137}$$

or

$$\frac{\chi_j}{R_0\, B_0} = -\mathrm{i}\left(\frac{r_j}{R_0}\right)^2 \frac{g_j}{m_j\, a_{jj}}\, \frac{\mathit{\Delta}_j}{|E_{jj}|}. \tag{138}$$

Here, the $\mathit{\Delta}_j$ values can be determined from the GPEC code.

1.11.2 PoP Derivation

Now, $d\psi_p/dr = B_0\, R_0\, f$. It follows that

$$(\nabla\psi_p \times \nabla\theta\cdot\nabla\phi)^{-1} = \frac{R^2\, q}{B_0\, R_0\, g}. \tag{139}$$

Hence,

$$\mathbf{B} = \nabla\phi\times\nabla\psi_p + B_0\, R_0\, g\,\nabla\phi = \nabla\phi\times\nabla\psi_p + q\,\nabla\psi_p\times\nabla\theta. \tag{140}$$

Let $\mathit{\Psi}_p = 2\pi\,\psi_p$ and $d\mathit{\Psi}_p/d\mathit{\Psi}_t = 1/q$. Hence,

$$\frac{d\mathit{\Psi}_p}{dr} = 2\pi\, B_0\, R_0\, f, \tag{141}$$

$$\frac{d\mathit{\Psi}_t}{dr} = 2\pi\, B_0\, r\, g, \tag{142}$$

and [cf. PoP **13**, 102501 (2006), Eq. (41)]

$$2\pi\,\mathbf{B} = q^{-1}\,\nabla\phi\times\nabla\mathit{\Psi}_t + \nabla\mathit{\Psi}_t\times\nabla\theta. \tag{143}$$

We have

$$\delta J^{\,r} = 0, \tag{144}$$

$$\mathcal{J}\,\mu_0\,\delta J^{\,\theta} = -\sum_j \frac{\mathit{\Delta\Psi}_j}{q_j}\,\mathrm{e}^{\,\mathrm{i}\,(m_j\,\theta - n\,\phi)}\,\delta(r - r_j), \tag{145}$$

$$\mathcal{J}\,\mu_0\,\delta J^{\,\phi} = -\sum_j \mathit{\Delta\Psi}_k\,\mathrm{e}^{\,\mathrm{i}\,(m_j\,\theta - n\,\phi)}\,\delta(r - r_j), \tag{146}$$

which implies that

$$\mu_0\,\delta\mathbf{J} = -2\pi\sum_j \mathit{\Delta\Psi}_j, \mathrm{e}^{\,\mathrm{i}\,(m_j\,\theta - n\,\phi)}\,\delta(\psi_t - \psi_{t\,j})\,\mathbf{B}. \tag{147}$$

However, according to PoP **13**, 102501 (2006),

$$\varDelta\Psi_j = -\mathrm{i}\,\frac{\mu_0\,J_c\,\varDelta_j}{2\pi\,m_j}, \tag{148}$$

where

$$\frac{1}{\mu_0\,J_c} = \left(\oint \frac{B^2}{|\nabla\psi_t|^2}\,\frac{d\theta\,d\phi}{2\pi\,\mathbf{B}\cdot\nabla\phi}\right)_{r_j}. \tag{149}$$

It is easily demonstrated that

$$\frac{1}{\mu_0\,J_c} = \left(\frac{R_0}{r_j}\right)^2\,\frac{1}{2\pi\,B_0\,R_0\,g_j}\left[a_{jj}+\left(\frac{r_k}{R_0\,q_j}\right)^2\right]. \tag{150}$$

Hence,

$$\frac{\varDelta\Psi_j}{B_0\,R_0} = -\mathrm{i}\,\varDelta_j\left(\frac{r_j}{R_0}\right)^2\frac{g_j}{m_j\,[a_{jj}+(r_k/R_0\,q_j)^2]}, \tag{151}$$

which implies that

$$\frac{\chi_j}{B_0\,R_0} = -\mathrm{i}\,\frac{\varDelta_j}{|E_{jj}|}\left(\frac{r_j}{R_0}\right)^2\frac{g_j}{m_j\,[a_{jj}+(r_k/R_0\,q_j)^2]}. \tag{152}$$

(Note: This is what is actually implemated in EPEC.) As before, the $\varDelta_j$ values can be determined from the GPEC code.

1.12 Magnetic Island Width

1.12.1 Island Width in r

We have

$$\mathcal{J}\,\delta B^{\,r} \simeq \frac{\partial\,\delta A_\phi}{\partial\theta}, \tag{153}$$

$$\mathcal{J}\,\delta B^{\,\theta} \simeq -\frac{\partial\,\delta A_\phi}{\partial r}, \tag{154}$$

$$\mathcal{J}\,\delta B^{\,\phi} \simeq 0. \tag{155}$$

It follows that

$$\delta\mathbf{B}\cdot\nabla\delta A_\phi = \delta B^{\,r}\,\frac{\partial\,\delta A_\phi}{\partial r}+\delta B^{\,\theta}\,\frac{\partial\,\delta A_\phi}{\partial\theta}+\delta B^{\,\phi}\,\frac{\partial\,\delta A_\phi}{\partial\phi} \simeq 0. \tag{156}$$

We have

$$\delta A_\phi(r,\theta,\phi) \simeq R_0\,\Psi_k\,\mathrm{e}^{\,\mathrm{i}\,(m_k\,\theta-n\,\phi)} \tag{157}$$

in the vicinity of the kth resonant surface. It follows that

$$\mathbf{B}\cdot\nabla\delta A_\phi = {\rm i}\,B_0\,R_0^{\,2}\,\frac{f}{r\,R^2}\,(m_k-n\,q)\,R_0\,\Psi_k\,{\rm e}^{\,{\rm i}\,(m_k\,\theta-n\,\phi)}. \tag{158}$$

Let us search for a function,

$$F(r,\theta,\phi) = F_0(r)+\delta A_\phi, \tag{159}$$

which is such that

$$(\mathbf{B}+\delta\mathbf{B})\cdot\nabla F = 0. \tag{160}$$

It follows that

$$\delta B^{\,r}\,\frac{dF_0}{dr} + {\rm i}\,B_0\,R_0^{\,2}\,\frac{f}{r\,R^2}\,(m_k-n\,q)\,R_0\,\Psi_k\,{\rm e}^{\,{\rm i}\,(m_k\,\theta-n\,\phi)} = 0. \tag{161}$$

However,

$$\delta B^{\,r} = \frac{R_0^{\,2}}{r\,R^2}\,{\rm i}\,m_k\,\Psi_k\,{\rm e}^{\,{\rm i}\,(m_k\,\theta-n\,\phi)}, \tag{162}$$

so

$${\rm i}\,m_k\,\frac{R_0}{r\,R^2}\,R_0\,\Psi_k\,\frac{dF_0}{dr} + {\rm i}\,B_0\,R_0^{\,2}\,\frac{f}{r\,R^2}\,(m_k-n\,q)\,R_0\,\Psi_k = 0, \tag{163}$$

which implies that

$$\frac{dF_0}{dr} = -\frac{B_0\,R_0\,f}{m_k}\,(m_k-n\,q), \tag{164}$$

or

$$F_0(r)\simeq \frac{B_0}{2}\left(\frac{g\,s}{q}\right)_{r_k}(r-r_k)^{\,2}, \tag{165}$$

where $s = r\,q'/q$. Hence,

$$F(r,\theta,\phi) = \frac{B_0}{2}\left(\frac{g\,s}{q}\right)_{r_k}(r-r_k)^{\,2} + R_0\,\Psi_k\,\cos(m_k\,\theta-n\,\phi) \tag{166}$$

is a flux surface function in the island region. Thus,

$$\frac{F}{R_0\,|\Psi_k|} = 2\,X^{\,2}+\cos(m_k\,\theta-n\,\phi), \tag{167}$$

where

$$X = \frac{2\,(r-r_k)}{W_k}, \tag{168}$$

and

$$\frac{W_k}{4\,R_0} = \left[\left(\frac{q}{g\,s}\right)_{r_k}\frac{|\Psi_k|}{B_0\,R_0}\right]^{1/2}. \tag{169}$$

It follows that W_k is the full radial island width in r. Moreover, W_k has no dependence on θ.

1.12.2 Island Width in Ψ_N

We have

$$\frac{d\Psi_N}{dr} = \frac{f}{R_0\,|\psi_c|}, \tag{170}$$

$$\frac{dF_0}{dr} = -\frac{B_0\,R_0}{m_k}\,f\,(m_k - n\,q). \tag{171}$$

Hence,

$$\frac{dF_0}{d\Psi_N} = -B_0\,R_0^2\,|\psi_c|\,(1-q/q_k). \tag{172}$$

Let

$$q = q_k + q_k'\,(\Psi_N-\Psi_{N\,k}) + \frac{1}{2}\,q_k''\,(\Psi_N-\Psi_{N\,k})^2 + \frac{1}{6}\,q_k'''\,(\Psi_N-\Psi_{N\,k})^3, \tag{173}$$

where $' \equiv d/d\Psi_N$. Follows that

$$F_0(\Psi_N) = B_0\,R_0^2\,|\psi_c|\left\{\frac{1}{2}\,\frac{q_k'}{q_k}(\Psi_N-\Psi_{N\,k})^2 + \frac{1}{6}\,\frac{q_k''}{q_k}\,(\Psi_N-\Psi_{N\,k})^3 + \frac{1}{24}\,\frac{q_k'''}{q_k}\,(\Psi_N-\Psi_{N\,k})^4\right\}. \tag{174}$$

Hence, the island extends from $\Psi_{N\,k}+X_{k-}$ to $\Psi_{N\,k}+X_{k+}$, where X_{k-} and X_{k+} are the positive and negative roots, respectively, of

$$X_k^2 + A_k^{(2)}\,X_k^3 = \frac{\overline{W}_k^{\,2}}{4}, \tag{175}$$

where

$$\overline{W}_k = 4\left(A_k^{(1)}\,\frac{|\Psi_k|}{R_0\,B_0}\right)^{1/2}, \tag{176}$$

and

$$A_k^{(1)} = \frac{q_k}{q_k'\,|\psi_c|}, \tag{177}$$

$$A_k^{(2)} = \frac{1}{3}\,\frac{q_k''}{q_k'}. \tag{178}$$

It follows that

$$X_{k\pm} \simeq \pm\frac{\overline{W}_k}{2} - A_k^{(2)}\,\frac{\overline{W}_k^{\,2}}{8}. \tag{179}$$

Alternatively, can say that island extends from $\Psi_{N\,k}+X_{k-}+\Delta\Psi_{N\,k}$ to $\Psi_{N\,k}+X_{k+}+\Delta\Psi_{N\,k}$, where $X_{k\pm} = \pm\Delta_{k\pm}\,x_{k\pm}$, and

$$\Delta_{k+} = \chi_{\rm max}(\Psi_{N\,k+1}-\Psi_{N\,k}), \tag{180}$$

$$\Delta_{k-} = \chi_{\rm max}(\Psi_{N\,k}-\Psi_{N\,k-1}), \tag{181}$$

$$F_{k\pm}(x_{k\pm}) = \frac{2\,A_k^{(1)}}{\Delta_{k\pm}^2}\,\frac{|\Psi_k|}{R_0\,B_0}, \tag{182}$$

$$F_{k\pm}(x) \equiv -x - \ln(1-x). \tag{183}$$

Here, $\chi_{\rm max}$ is the maximum allowable Chirikov parameter. Moreover,

$$\Delta\Psi_{N\,k} = -\frac{A_k^{(2)}}{8}\,(X_{k+} - X_{k-})^2. \tag{184}$$

2 Technical Details

2.1 Flux Coordinate System

Let all lengths be normalized to R_0, and all magnetic field-strengths to B_0. We have

$$\mathbf{B} = \nabla\phi\times\nabla\psi_p + g(\psi_p)\,\nabla\phi, \tag{185}$$

and

$$\nabla\psi_p\times\nabla\theta\cdot\nabla\phi = \frac{g}{q\,R^2}, \tag{186}$$

where $q = q(\psi_p)$.

Let $\Psi = \psi_p/\psi_c = 1-\Psi_N$, where ψ_c is the value of ψ_p on the magnetic axis. (It is assumed that $\psi_p = 0$ on the plasma boundary.) The previous equation implies that

$$\frac{d\theta}{dl} = \frac{g}{q}\,\frac{1}{|\psi_c|\,R\,\sqrt{\Psi_R^2+\Psi_Z^2}}, \tag{187}$$

where dl is an element of poloidal path length on a magnetic flux-surface, and $\Psi_R \equiv \partial\Psi/\partial R$, etc. Furthermore,

$$dR = -\frac{\Psi_Z\,dl}{\sqrt{\Psi_R^2+\Psi_Z^2}}, \tag{188}$$

$$dZ = \frac{\Psi_R\,dl}{\sqrt{\Psi_R^2+\Psi_Z^2}}. \tag{189}$$

It follows that

$$\frac{q(\Psi)}{g(\Psi)} = \frac{1}{2\pi\,|\psi_c|}\oint\frac{dl}{R\,\sqrt{\Psi_R^2+\Psi_Z^2}}. \tag{190}$$

If we define

$$\tan\zeta = \frac{Z - Z_{\rm axis}}{R_{\rm axis} - R} \tag{191}$$

then

$$\frac{dR}{d\zeta} = -\Psi_Z\,F, \tag{192}$$

$$\frac{dZ}{d\zeta} = \Psi_R\,F, \tag{193}$$

$$\frac{q(\Psi)}{g(\Psi)} = \frac{1}{2\pi\,|\psi_c|}\oint\frac{F}{R}\,d\zeta, \tag{194}$$

where

$$F = \frac{(R_{\rm axis}-R)^{\,2}+(Z-Z_{\rm axis})^{\,2}}{-(Z-Z_{\rm axis})\,\Psi_Z+(R_{\rm axis}-R)\,\Psi_R}. \tag{195}$$

It is helpful to define the length-like flux-surface coordinate r, according to

$$\nabla r\times\nabla\theta\cdot\nabla\phi = \frac{1}{r\,R^{\,2}}. \tag{196}$$

It follows that

$$r(\Psi) = \left[2\,|\psi_c|\int_{\Psi}^{1}\frac{q(\Psi')}{g(\Psi')}\,d\Psi'\right]^{1/2}. \tag{197}$$

Let

$$a = r(0). \tag{198}$$

We can calculate $R(r,\theta)$ and $Z(r,\theta)$ from

$$\frac{dR}{d\theta} = -|\psi_c|\,\frac{q}{g}\,R\,\Psi_Z, \tag{199}$$

$$\frac{dZ}{d\theta} = |\psi_c|\,\frac{q}{g}\,R\,\Psi_R. \tag{200}$$

Now,

$$r\,\frac{dr}{d\Psi} = -|\psi_c|\,\frac{q(r)}{g(r)}. \tag{201}$$

So

$$\nabla r = \frac{dr}{d\Psi}\,\nabla\Psi = -|\psi_c|\,\frac{q(r)}{r\,g(r)}\,\nabla\Psi. \tag{202}$$

Hence,

$$a_{jj} = \left(\oint\frac{1}{|\nabla r|^{\,2}}\,\frac{d\theta}{2\pi}\right)_{r_j} = \left(\frac{r\,g}{|\psi_c|\,q}\right)^2_{r_j}\oint\frac{1}{\Psi_R^{\,2}+\Psi_Z^{\,2}}\,\frac{d\theta}{2\pi}. \tag{203}$$

Note that

$$\frac{d\Psi_N}{dr} = \frac{r\,g(r)}{|\psi_c|\,q(r)}. \tag{204}$$

Hence, if $\overline{W}_k$ is the full magnetic island width in Ψ_N at the kth resonant surface then

$$\overline{W}_k = \frac{W_k}{R_0}\,\frac{d\Psi_N(r_k)}{dr}, \tag{205}$$

where W_k is the full island width in r.

2.2 Neoclassical Coordinate System

It is also helpful to define the geometric poloidal angle

$$\mathbf{b}\cdot\nabla\Theta = \gamma(r). \tag{206}$$

It follows that

$$\frac{d\Theta}{dl} = \frac{\gamma\,B\,R}{|\psi_c|\,\sqrt{\Psi_R^{\,2}+\Psi_Z^{\,2}}}, \tag{207}$$

where

$$B\,R = \left[g^{\,2} + |\psi_c|^{\,2}\,(\Psi_R^{\,2}+\Psi_Z^{\,2})\right]^{1/2}. \tag{208}$$

Hence,

$$\frac{1}{\gamma(r)} = \frac{1}{2\pi\,|\psi_c|}\oint\frac{B\,R\,dl}{\sqrt{\Psi_R^{\,2}+\Psi_Z^{\,2}}} = \frac{1}{2\pi\,|\psi_c|}\oint B\,R\,F\,d\zeta. \tag{209}$$

We can calculate $R(r,\Theta)$ and $Z(r,\Theta)$ from

$$\frac{dR}{d\Theta} = -|\psi_c|\,\frac{\Psi_Z}{\gamma\,B\,R}, \tag{210}$$

$$\frac{dZ}{d\Theta} = |\psi_c|\,\frac{\Psi_R}{\gamma\,B\,R}. \tag{211}$$

Note that

$$\frac{d\Theta}{d\theta} = \left(\frac{\gamma\,q}{g}\right)B\,R^{2}. \tag{212}$$

Thus,

$$\frac{1}{\gamma} = \frac{q}{g}\oint B\,R^{2}\,\frac{d\theta}{2\pi}. \tag{213}$$

Also,

$$\frac{\partial B}{\partial\Theta} = -\frac{B}{R}\frac{\partial R}{\partial\Theta} + \frac{|\psi_c|^{\,2}}{B\,R^{2}}\left[(\Psi_R\,\Psi_{RR}+\Psi_Z\,\Psi_{RZ})\,\frac{\partial R}{\partial\Theta} + (\Psi_R\,\Psi_{RZ}+\Psi_Z\,\Psi_{ZZ})\,\frac{\partial Z}{\partial\Theta}\right]. \tag{214}$$

2.3 Neoclassical Parameters

The flux-surface average operator has the following properties:

$$\langle 1\rangle = 1, \tag{215}$$

$$\langle\mathbf{B}\cdot\nabla A\rangle = 0. \tag{216}$$

It follows that

$$\langle A\rangle = \oint R^{2}\,A\,\frac{d\theta}{2\pi}\Big/\oint R^{2}\,\frac{d\theta}{2\pi} = \oint\frac{A}{B}\,\frac{d\Theta}{2\pi}\Big/\oint\frac{1}{B}\,\frac{d\Theta}{2\pi}. \tag{217}$$

Let

$$I_0 = \oint \frac{1}{B\,R^2}\,\frac{d\Theta}{2\pi} = \frac{\gamma\,q}{g}, \tag{218}$$

$$I_1 = \oint \frac{1}{B}\,\frac{d\Theta}{2\pi}, \tag{219}$$

$$I_2 = \oint B\,\frac{d\Theta}{2\pi}, \tag{220}$$

$$I_3 = \oint \left(\frac{\partial B}{\partial\Theta}\right)^2 \frac{1}{B}\,\frac{d\Theta}{2\pi}, \tag{221}$$

$$I_{4,k} = \sqrt{\frac{2}{k}} \oint \frac{\sin(k\,\Theta)}{B^2}\,\frac{\partial B}{\partial\Theta}\,\frac{d\Theta}{2\pi} = \oint \frac{\sqrt{2\,k}\,\cos(k\,\Theta)}{B}\,\frac{d\Theta}{2\pi}, \tag{222}$$

$$I_{5,k} = \sqrt{\frac{2}{k}} \oint \frac{\sin(k\,\Theta)}{B^3}\,\frac{\partial B}{\partial\Theta}\,\frac{d\Theta}{2\pi} = \oint \frac{\sqrt{2\,k}\,\cos(k\,\Theta)}{2\,B^2}\,\frac{d\Theta}{2\pi}, \tag{223}$$

$$I_6(\lambda) = \oint \frac{\sqrt{1-\lambda\,B/B_{\rm max}}}{B}\,\frac{d\Theta}{2\pi}, \tag{224}$$

$$I_7 = \oint \frac{R^2}{B}\,\frac{d\Theta}{2\pi}, \tag{225}$$

$$I_8 = \oint \frac{1}{B^3\,R^2}\,\frac{d\Theta}{2\pi}. \tag{226}$$

It follows that

$$\langle B\rangle = \frac{1}{I_1}, \tag{227}$$

$$C_1 = \left\langle \frac{1}{R^2}\right\rangle = \frac{\gamma\,q}{I_1\,g}, \tag{228}$$

$$\langle R^2\rangle = \frac{I_7}{I_1}, \tag{229}$$

$$\langle B^2\rangle = \frac{I_2}{I_1}, \tag{230}$$

$$C_2 = g^2 \left\langle \frac{1}{B^2\,R^2}\right\rangle = \frac{g^2\,I_8}{I_1}, \tag{231}$$

$$\left\langle \frac{|\nabla r|^2}{R^2}\right\rangle = \frac{\gamma\,q\,a_{jj}}{I_1\,g}, \tag{232}$$

$$\langle(\mathbf{b}\cdot\nabla B)^2\rangle = \gamma^2\,\frac{I_3}{I_1}, \tag{233}$$

$$|\langle \mathbf{B}\cdot\nabla\theta\rangle| = \frac{g}{|q|}\,\frac{I_0}{I_1} = \frac{|\gamma|}{I_1}, \tag{234}$$

$$\left\langle \sqrt{\frac{2}{k}}\,\sin(k\,\Theta)\,(\mathbf{b}\cdot\nabla\ln B)\right\rangle = \gamma\,\frac{I_{4,k}}{I_1}, \tag{235}$$

$$\left\langle \sqrt{\frac{2}{k}}\,\sin(k\,\Theta)\,\frac{(\mathbf{b}\cdot\nabla\ln B)}{B}\right\rangle = \gamma\,\frac{I_{5,k}}{I_1}. \tag{236}$$

Hence,

$$L_c = \frac{1}{|\gamma|}\,\frac{I_2^2}{I_1^2\,I_3}\sum_{k>0} I_{4,k}\,I_{5,k}, \tag{237}$$

$$\omega_{t\,a} \equiv \frac{v_{T\,a}}{L_c} = K_t\,|\gamma|\,v_{T\,a}, \tag{238}$$

$$\nu_{*\,a} \equiv \frac{8}{3\pi}\,\frac{\langle B^{\,2}\rangle}{\langle(\mathbf{b}\cdot\nabla B)^{\,2}\rangle}\,\frac{g_t\,\omega_{t\,a}}{v_{T\,a}^2\,\tau_{aa}} = K_*\,\frac{g_t}{\omega_{t\,a}\,\tau_{aa}}, \tag{239}$$

$$f_c = \frac{3}{4}\frac{I_2}{B_{\rm max}^2}\int_0^1\frac{\lambda\,d\lambda}{I_6(\lambda)}, \tag{240}$$

where

$$K_t = \frac{I_1^{\,2}\,I_3}{I_2^2\,\sum_{k>0} I_{4,k}\,I_{5,k}}, \tag{241}$$

$$K_* = \frac{8}{3\pi}\,\frac{I_2}{I_3}\,K_t^{\,2}. \tag{242}$$

Also,

$$\hat{q}^{\,2} = \frac{q^{\,2}}{2\,r^{\,2}}\left(\left\langle\frac{1}{R^{\,2}}\right\rangle - \frac{1}{\langle R^{\,2}\rangle}\right)\bigg/\left\langle\frac{|\nabla r|^{\,2}}{R^{\,2}}\right\rangle = \frac{q^{\,2}}{2\,r^{\,2}\,a_{jj}}\left(1-\frac{I_1^2}{I_7}\,\frac{g}{\gamma\,q}\right), \tag{243}$$

$$\frac{\langle B_T^2\rangle}{\langle B_p^2\rangle} = \frac{q^{\,2}}{r^{\,2}\,a_{jj}}. \tag{244}$$

2.4 Glasser-Greene-Johnson Parameters

Let

$$J_1 = \frac{1}{2\pi\,|\psi_c|}\oint R\,F\,d\zeta, \tag{245}$$

$$J_2 = \frac{1}{2\pi\,|\psi_c|}\oint R\,B^{\,2}\,F\,d\zeta, \tag{246}$$

$$J_3 = \frac{1}{2\pi\,|\psi_c|}\oint \frac{R\,F}{B^{\,2}}\,d\zeta, \tag{247}$$

$$J_4 = \frac{1}{2\pi\,|\psi_c|^{\,3}}\oint \frac{R\,F}{\Psi_R^2+\Psi_Z^2}\,d\zeta, \tag{248}$$

$$J_5 = \frac{1}{2\pi\,|\psi_c|^{\,3}}\oint\frac{R\,B^{\,2}\,F}{\Psi_R^{\,2}+\Psi_Z^{\,2}}\,d\zeta, \tag{249}$$

$$J_6 = \frac{1}{2\pi\,|\psi_c|^{\,3}}\oint\frac{R\,F}{B^{\,2}\,(\Psi_R^{\,2}+\Psi_Z^{\,2})}\,d\zeta, \tag{250}$$

where

$$B^{\,2} = \frac{g^{\,2}+\psi_c^{\,2}\,(\Psi_R^{\,2}+\Psi_Z^{\,2})}{R^{\,2}}. \tag{251}$$

It follows that

$$E = -\frac{dp/dr}{(dq/dr)^{\,2}}\left(\frac{dJ_0}{dr}-g\,\frac{dq}{dr}\,\frac{J_1}{J_2}\right)J_5, \tag{252}$$

$$F = \frac{(dp/dr)^{\,2}}{(dq/dr)^{\,2}}\left[g^{\,2}\left(J_5\,J_6-J_4^{\,2}\right)+J_3\,J_5\right], \tag{253}$$

$$H = \frac{dp/dr}{dq/dr}\left(J_4-\frac{J_1\,J_5}{J_2}\right)g. \tag{254}$$