(Tues 7/9 1:30pm)

ERROR FIELDS AND ROTATION - ITER

by

R.J. La Haye

General Atomics

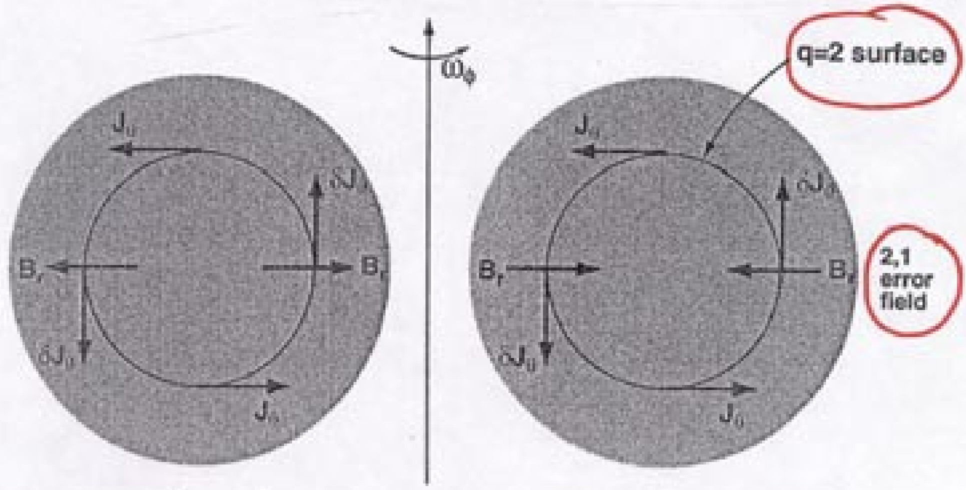
Presented at SNOWMASS
for the MHD Working Group
Snowmass, Colorado

JULY 7–19, 2002

LOCKED MODES IN TEARING STABLE PLASMAS ARE CAUSED BY TORQUES FROM HELICAL CURRENTS AT RESONANT FLUX SURFACES

- A locked mode is the result of a change of state from "slipping" to locked. A slipping plasma opposes reconnection (or "penetration") of the resonant error field
- A rotating q=m/n rational surface acts as a thin conducting layer. A helical current induced by static B_{rmn} to oppose magnetic reconnection produces a $\delta J_\theta \times B_r$ drag (torque), reducing plasma rotation.

$$\Rightarrow T_{\phi mn} = -R \times \left(\frac{B_{rmn}^2}{\mu_o}\right)\left(\frac{r_{mn}}{qR}\right)(2\pi R\, 2\pi r)\left(\frac{1}{\omega\tau_{rec}}\right)$$



- Torque balance leads to an expression for frequency

$$\frac{\omega}{\omega_o} \approx \frac{1}{2} + \frac{1}{2}\sqrt{1 - \frac{C\,B_{r21}^2\,\tau_v}{\omega_o^2\,\tau_A^2\,B_T^2\,\tau_{rec}}}$$

- Error field "penetration", or mode-locking, occurs when $\omega/\omega_o = 1/2$. The penetration field is then

$$\boxed{\frac{B_{r21}}{B_T} \approx \frac{\omega_o\,\tau_A}{2}\left(\frac{\tau_{rec}}{\tau_v}\right)^{1/2}}$$

ADVANCED TOKAMAK

- n=1 error field torque greatly increased ("error field amplification", Boozer 2001)
  - Due to proximity to stable n=1 ideal limit
- Required rotation to avoid locking, $\omega/\omega_0 \geq 1/2$ at q=2
  - $$\omega_0\tau_A = 200\left(\frac{B_{r21}}{B_{\phi 0}}\right)\left(\frac{\tau_V}{\tau'_{rec}}\right)^{1/2}$$ (DIII-D benchmark)
- Required rotation to stabilize n=1 RWM, $\omega_0\tau_A \gtrsim \omega_c\tau_A$ at q=2
  - $$\omega_0\tau_A = \frac{\left[100\left(\frac{B_{r21}}{B_{\phi 0}}\right)\left(\frac{\tau_V}{\tau'_{rec}}\right)^{1/2}\right]^2}{\omega_c\tau_A} + \omega_c\tau_A \rightarrow \omega_c\tau_A \text{ at } B_{r21}/B_{\phi 0} \equiv 0$$ (DIII-D benchmark)
    - ★ Generally more restrictive than $\omega/\omega_0 = 1/2$
- Example is DIII–D 103158.01600, $\beta_N/\beta_{N,\mathrm{nowall}} \approx 1.6$
  - 9.5 MW of 80 kV co-beams, $B_{r21}/B_{\phi 0} \approx 3\times 10^{-5}$
    - ★ Actual rotation at q=2 is $\omega_\phi/2\pi$=7.5 kHz, $\omega_\phi\tau_A$=0.019
    - ★ Calculated electron diamagnetic drift $\omega_{*e}/2\pi$=–5.6 kHz
    - ★ n=1 ideal kink RWM onset of instability
- Rotation assumptions are key for prediction
  - $\omega_0=\omega_{*e}$ works well experimentally in ohmic discharges
  - Assume $\omega_0=\omega_{*e}$ in rf heated AT with no beams?
  - Investigate tangential beams for AT rotation

203-02/df

TABLE I: CONVENTIONAL TOKAMAK

Relative critical m/n = 2/1 resonant error field for locking in ohmic target discharges in I_p flattop at $G = \bar{n}_{20}\, \pi a^2 / I_p = 0.2$ with neo-Alcator confinement. All quantities evaluated at q = 2 Note $A'_0 r_{21} \equiv -2\ m = -4$, parabolic, parabolic squared T_e and D_2 assumed.

	DIII—D*	JET	IGNITOR	FIRE"	ITER'
$\omega_0 \equiv \omega_{*e}$ (10^4 rad/s)	0.83	0.26	0.96	0.72	0.082
τ_A (μs)	0.34	0.32	0.11	0.16	0.35
τ_R (s)	0.54	2.4	6.2	4.0	58
τ_E (s)	0.030	0.091	0.22	0.21	0.96
$\tau_v \equiv 4\ \tau_E$ (s)	0.12	0.36	0.86	0.84	3.8
τ_{rec} (s)	0.0063	0.018	0.024	0.019	0.17
$\tan^{-1}(\omega_0 \tau_{rec})^{-1}$(deg)	1.1	1.2	0.2	0.4	0.4
$B_{r21}/B_{\phi 0}$ (10^{-4})	3.0	0.9	0.9	0.9	0.3

*$B_{\phi 0} = 1.3$ T, $I_p = 1.0$ MA, $R_0 = 1.7$ m, a = 0.6 m, LSND, $q_{95} = 3.5$, $\bar{n}_{20} = 0.18$.

$B_{\phi 0} = 2$ T, $I_p = 2$ MA, $R_0 = 3.0$ m, a = 1.0 m, LSND, $q_{95} = 3.5$, $\bar{n}_{20} = 0.13$.

$B_{\phi 0} = 13$ T, $I_p = 11$ MA, $R_0 = 1.32$ m, a = 0.47 m, LSND, $q_{95} = 3.6$, $\bar{n}_{20} = 3.2$.

"$B_{\phi 0} = 8.5$ T, $I_p = 5.7$ MA, $R_0 = 2.0$ m, a = 0.53 m, DND, $q_{95} = 3.5$, $\bar{n}_{20} = 1.3$.

'$B_{\phi 0} = 5.3$ T, $I_p = 15$ MA, $R_0 = 6.2$ m, a = 2.0 m, LSND, $q_{95} = 3.8$, $\bar{n}_{20} = 0.24$.

- $\omega_0 \equiv \omega_{*e}$, $\omega_0/2\pi \approx 130$ Hz very low
- $\Rightarrow B_{r21}/B_{\phi 0} \leq 3\times10^{-5}$ which is doable
  - ★ But a large extrapolation
  - ★ And comparable to best correction in DIII–D

ITER has an excellent error field correction coil and has done extensive error field studies for machine design.

TABLE II: ADVANCED TOKAMAK

Relative critical m/n = 2/1 resonant error field for locking or RWM in $1.5 < q_{min} < 2$ discharges with $\beta_{N,\,no\ wall} < \beta_N < \beta_{N,\,ideal\ wall}$. High dissipation regime assumed with $\omega_c\,\tau_A$ at q=2 ≡ 0.019 from DIII—D experiments.

	DIII—D*	JET	IGNITOR	FIRE′	ITER-FEAT′
ω_0 (10^4 rad/s)	5.0	—	—	3.2	0.5
τ_A (μs)	0.4	—	—	0.34	0.70
$\omega_0\,\tau_A$	$0.020 \geq 0.019$	—	—	$0.011 < 0.019$	$0.0035 < 0.019$
τ_R (s)	18	—	—	14	2000
τ_E (s)	0.12	—	—	0.30	3.0
τ_v (s)	0.24	—	—	0.60	6.0
τ'_{rec} (s)	0.11	—	—	0.072	3.8
$\tan^{-1}\left[\left\lvert\frac{\Delta'_0\,21^r}{4}\right\rvert(\omega_0\,\tau'_{rec})\right]^{-1}$ (deg)	61	—	—	77	28
$B_{r21}/B_{\phi0}$ $(10^{-4})\rvert_{RWM}$	0.3	—	—	No RWM stab.	No RWM stab.
$B_{r21}/B_{\phi0}$ $(10^{-4})\rvert_{locking}$	0.6	—	—	0.2	0.1

*$B_{\phi o}$ = 2.1 T, I_p = 1.6 MA, R_0 = 1.7 m, a = 0.6 m, LSND, q_{95} = 3.6, 9.5 MW tan beams, $\bar{n} = 0.4\ \bar{n}_{GR} = 0.53\times10^{20}\ m^{-3}$.

Experiments planned for 2003 campaign.

No AT operation planned.

″$B_{\phi o}$ = 8.5 T, I_p = 5.4 MA, R_0 =2.0 m, a = 0.53 m, DND, 34 MW rf, $\bar{n} = 0.65\ \bar{n}_{GR} = 4.0\times10^{20}\ m^{-3}$, q_{95} = 3.7, q_{min} = 1.4.

′$B_{\phi o}$ = 5.3 T, I_p = 10 MA, R_0 = 6.2 m, a = 1.86 m, 35 MW rf, q_{95} = 4.6, q_{min} = 1.6, $\beta_N/4\,l_i$ = 1.5, $\bar{n} = 1.0\ \bar{n}_{GR} = 0.9\times10^{20}\ m^{-3}$.

- $\omega_0 \equiv \omega_{*e}$, for rf only, $\omega_0/2\pi \approx 0.8$ kHz, $B_{r21}/B_{\phi0} \approx 1\times10^{-5}$ for locking which is difficult to achieve
  - ★ With 30 MW/0.5 MV tan beams ≈ 2 kHz
    - . . . $B_{r21}/B_\phi \Rightarrow 3\times10^{-5}$ which is doable
      - — Stable to n=1 [redacted] locking only
      - ∴ no RWM rot. stab.

≡

★ will need RWM feedback stabilization