Effects of 3D Magnetic Perturbations on Toroidal Plasmas

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OV/4-3, 2010 IAEA Fusion Energy Conference, 11–16 October 2010, Daejeon, Korea

- **Theses:**[1]

  1) Small 3D magnetic perturbations have interesting & useful effects on toroidal plasmas — directly on toroidal rotation Ω_t; indirectly n_e, T_e, T_i.

  2) Physics elements are beginning to be understood (NTV, ripple effects, FEs, plasma responses); combined & kinetic effects still being developed.

  3) More work is needed to develop a predictive capability for ITER — for low $\Omega_t \sim \Omega_*$, RFA, density pump-out, ripple and TBM modeling, ...

- **Outline:**

  Key physics elements — Ω_t eqn., NTV, ripple, field errors, plasma resp.

  Combined effects — on NTMs and RWMs, with RMPs, plasma transport

  Needs for developing predictive capability for ITER

  Summary

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[1] J.D. Callen, "Effects of 3D Magnetic Perturbations on Toroidal Plasmas," UW-CPTC 10-8R, October 2010, via `http://www.cptc.wisc.edu`.

I. Main 3D Magnetic Field Effects Are On Toroidal Flow V_t

- **Tokamak magnetic field is axisymmetric (2D) plus small 3D magnetic perturbations $\delta\vec{B}$ ($\lesssim 10^{-2} B_0$), which are expanded in a Fourier series.**

- **3D field effects can be classified by toroidal mode number n of $\delta\vec{B}$:**

  Low n ($\sim$ 1–3) non-resonant $\Longrightarrow$ neoclassical toroidal viscous (NTV) damping of V_t

  Medium n (toroidal field ripple) $\Longrightarrow$ edge direct ion losses plus NTV braking of V_t

  Low n (mostly $n = 1$) resonant (with field lines) $\Longrightarrow$ resonant braking, locking, disruption

  High n $\Longrightarrow$ microturbulence-induced Reynolds stress, anomalous V_t transport (OV/5-4)

- **Radial force balance + poloidal flow damping + toroidal plasma torques + ambipolarity constraint $\Longrightarrow$ transport equation for toroidal flow V_t (E_ρ)**

  — see next viewgraph

Plasma Toroidal Rotation Equation Provides Context

- **Magnetic field magnitude will be represented in ψ, θ, ζ coordinates by**[2]

$$|\vec{B}| = \underbrace{|\vec{B}_0(\psi,\theta)|}_{\text{2D, axisymm.}} + \sum_{n,m} \underbrace{\delta B_n(\psi,m)\cos(m\theta - n\zeta - \varphi_{m,n})}_{\text{low } m,n \text{ resonant, non-resonant}} + \underbrace{\delta B_N(\psi,\theta)\cos(N\zeta)}_{\text{medium } n\text{, ripple}} + \underbrace{\cdots}_{\mu\text{turb.}} \, .$$

- **On μs time scale compressional Alfvén waves enforce radial force balance:**

$$\vec{V}_i \cdot \vec{\nabla}\zeta = -\left(\frac{\partial \Phi_0}{\partial \psi} + \frac{1}{n_i q_i}\frac{\partial p_i}{\partial \psi}\right) + q\,\vec{V}_i \cdot \vec{\nabla}\theta \quad \Longrightarrow \quad V_t \simeq \frac{E_\rho}{B_p} - \frac{1}{n_i q_i B_p}\frac{dp_i}{d\rho} + \frac{B_t}{B_p}V_p.$$

- **On the ms time scale poloidal flow is damped to $V_p \simeq (c_p/q_i)(dT_i/d\psi) + \cdots$.**

- **Toroidal plasma torques cause radial particle fluxes: $\vec{\Gamma}_s \cdot \vec{\nabla}\psi = -\,\vec{e}_\zeta \cdot \vec{F}_{\rm orce}/q_s$.**

- **Setting the total radial plasma current induced by sum of the non-ambipolar particle fluxes to zero yields transport equation**[3] **for plasma toroidal angular momentum density $L_t \equiv \sum_{\rm ions} m_i n_i \langle R^2 \vec{V}_i \cdot \vec{\nabla}\zeta\rangle$, $\boxed{\Omega_t(\rho,t) \equiv L_t/m_i n_i \langle R^2\rangle}$:**

$$\boxed{\underbrace{\frac{\partial L_t}{\partial t}}_{\text{inertia}} \simeq -\underbrace{\langle \vec{e}_\zeta \cdot \vec{\nabla} \cdot \overset{\leftrightarrow}{\pi}{}^{3D}_{i\|}\rangle}_{\text{NTV from } \delta B} + \underbrace{\langle \vec{e}_\zeta \cdot \overline{\delta \vec{J} \times \delta \vec{B}}\rangle}_{\text{resonant FEs}} - \underbrace{\langle \vec{e}_\zeta \cdot \vec{\nabla} \cdot \overset{\leftrightarrow}{\pi}_{i\perp}\rangle}_{\text{cl, neo, paleo}} - \underbrace{\frac{1}{V'}\frac{\partial}{\partial \rho}(V'\Pi_{i\rho\zeta})}_{\text{Reynolds stress}^2} + \underbrace{\langle \vec{e}_\zeta \cdot \textstyle\sum_s \vec{\vec{S}}_{sm}\rangle}_{\text{mom. sources}}.}$$

- **Radial electric field for net ambipolar transport is determined by Ω_t:**

$$\boxed{E_\rho \equiv -|\vec{\nabla}\rho|\,\partial\Phi_0/\partial\rho \simeq |\vec{\nabla}\rho|\,[\,\Omega_t\,\psi'_p + (1/n_{i0}q_i)\,dp_i/d\rho - (c_p/q_i)\,dT_i/d\rho],} \quad \omega_E \simeq -E_\rho/RB_p.$$

[2] For microturbulence (μturb) effects see: P.H. Diamond et al., Nuclear Fus. **49**, 045002 (2009); A.G. Peeters et al., OV/5-4, Daejeon IAEA FEC.
[3] a) J.D. Callen A.J. Cole and C.C. Hegna, Nucl. Fusion **49**, 085021 (2009); b) Phys. Plasmas **16**, 082504 (2009); c) Phys. Pl. **17**, 056113 (2010).

II: NTV Is Caused By 3D-induced Radial Drifts Of Ions

- **In axisymmetric (2D) theory, centers of banana drift orbits do not move radially $\Longrightarrow$ ambipolar radial flux $\Longrightarrow$ no 2D NTV torque**

- **Small 3D δB_n cause radial "banana drifts" at speed $v_d^{3D} \sim n\,(\delta B_n/B_0)\,v_{d0}^{2D}$.**

- **Radial excursions of trapped ions are limited by various physical processes:**

  collisions ($1/\nu$ regime) $\Longrightarrow \Delta\rho \sim v_d^{3D}/(\nu_i/\epsilon)$

  collisional boundary layer ($\sqrt{\nu}$ regime) $\Longrightarrow \Delta\rho \sim v_d^{3D}/(|n|\,\omega_E), \qquad \omega_E \equiv d\Phi/d\psi$

  superbanana plateau (sbp, $\omega_E \to 0$, v_{d0}^{2D} limited) $\Longrightarrow \delta\rho \sim v_d^{3D}/[(|n|v_{d0}^{2D}/R_0)^{2/3}(\nu_i/\epsilon)^{1/3}]$

  ⋮

  — see next viewgraph

- **Radial ion drifts $\Longrightarrow$ non-ambipolar radial ion flux $\Longrightarrow$ NTV plasma torque**

- **Experimental tests have confirmed key NTV predictions at $\delta B_n/B_0 \sim 10^{-3}$**

  — see viewgraph #s 6, 7

- **Neoclassical toroidal viscous (NTV) torque[4] induced by a single δB_n is**

$$-\langle \vec{e}_\zeta \cdot \vec{\nabla} \cdot \overset{\leftrightarrow}{\pi}^{3D}_{i\|} \rangle \simeq -m_i n_i \mu_\| \left(\frac{\delta B_n}{B_0}\right)^2 \langle R^2 \rangle (\Omega_t - \Omega_*), \qquad \Omega_* \simeq \frac{c_p + c_t}{q_i} \frac{dT_i}{d\psi_p} \sim \frac{1}{q_i R B_p} \frac{dT_i}{d\rho} < 0.$$

- **NTV damps Ω_t to $\Omega_* < 0$ at rate $\mu_\| (\delta B_n / B_0)^2 \sim (D_i/\varrho_i^2)\,(B_p/B_0)^2$.**

[4] For derivations and summary of radial particle fluxes see K.C. Shaing et al., Nuc. Fus. **50**, 025022 (2010) and THS/P5-13 Daejeon IAEA FEC.

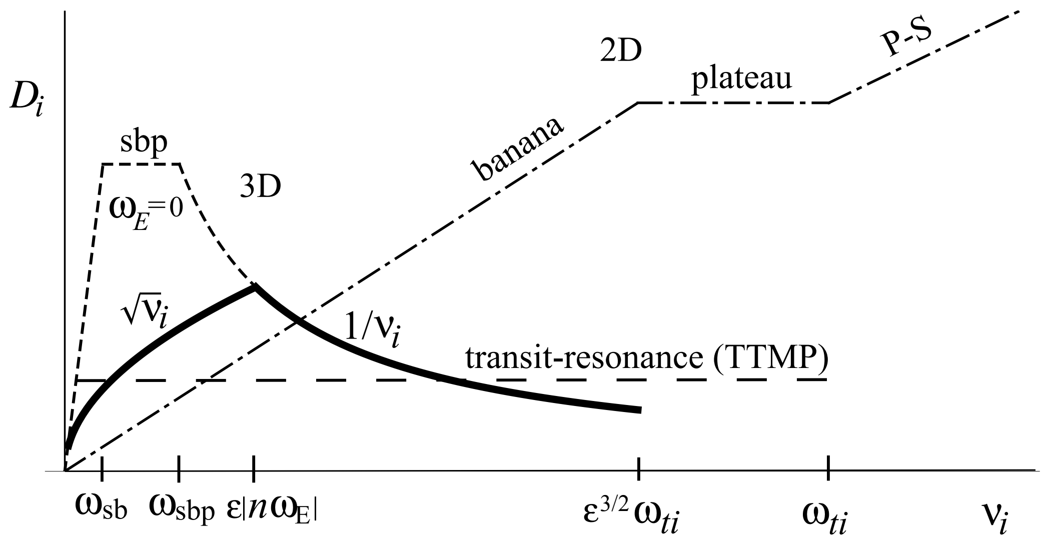

Figure 1: Ion collisionality regimes for particle diffusivity $D_i \propto$ NTV damping frequency $\mu_\|$. Transitions occur at key frequencies: ion transit $\omega_{ti} \equiv v_{Ti}/R_0 q$, $\vec{E}\times\vec{B}$-induced $\epsilon\,|n\,\omega_E|$, superbanana-plateau (sbp) radial drift $\omega_{sbp} \equiv \epsilon\,|n|\,\omega_{d0}$ and superbanana $\omega_{sb} \equiv \epsilon^{-1/2}(\delta B_n/B_0)^{3/2}(|n|\,\omega_{d0})$. The D_i and $\mu_\|$ become large when the radial electric field vanishes: $\omega_E \to 0$ (short dashes curve).

NTV Exp. I: ***NSTX Results Agreed With Early NTV Theory***

- **There have been many indications of NTV torque effects ($\delta B_n/B_0 \sim 10^{-3}$):**

  for 1/3 fields (DIII-D, 2002), in quasi-symmetric stellarator (HSX, 2005), together with resonant n (DIII-D & NSTX, 2006–2010), from rotating MHD modes (MAST, 2010).

- **Figures 2, 3 show first detailed comparisons of NTV theory (in $1/\nu$ regime, neglecting Lagrangian effects[11a]) with toroidal torque data from NSTX.[5]**

[5] W. Zhu, S.A. Sabbagh et al., Phys. Rev. Lett. **96**, 225002 (2006).

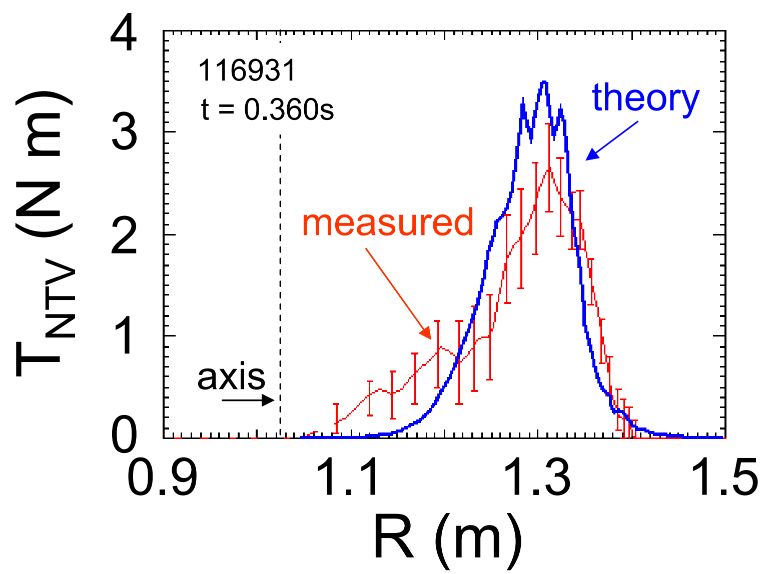

Figure 2: NSTX experimental test**[5]** of the spatial profile and magnitude of NTV-induced torque $\mathbf{T_{NTV}}$ for $\boldsymbol{n=3}$ non-resonant 3D field.

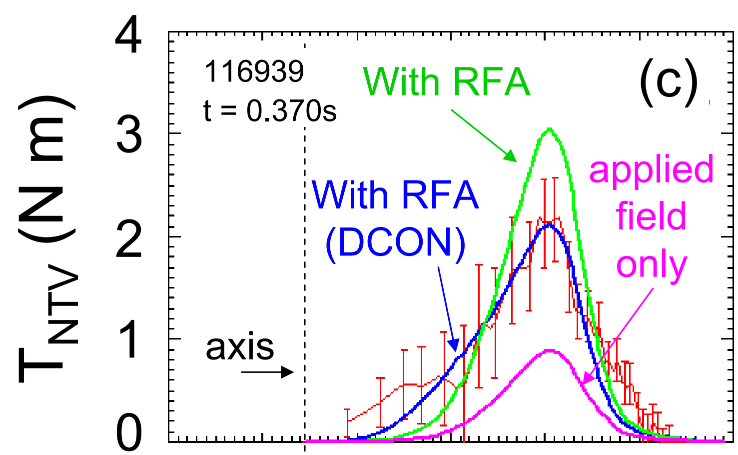

Figure 3: NSTX experimental test**[5]** of the NTV torque shows resonant field amplification (RFA) effects are needed for $\boldsymbol{n=1}$ 3D field.

NTV Exp. II: ***Offset Ω_* And $\omega_E \to 0$ Peak Validated In DIII-D***

- **When I-coils are turned on in $n = 3$ configuration[6] in DIII-D, Ω_t is damped to the diamagnetic-level rotation frequency $\Omega_* < 0$ — see Fig. 4 below.**
- **As Ω_t is varied[7] (via balancing co/ctr NBI beams in DIII-D), peak torque is where $\omega_E \to 0$, in agreement with NTV predictions — see Fig. 5 below.**

[6] A.M. Garofalo et al., Phys. Rev. Lett. **101**, 195005 (2008); Phys. Plasmas **16**, 056119 (2009).
[7] A.J. Cole et al., UW-CPTC 10-1, July 21, 2010 (to be published).

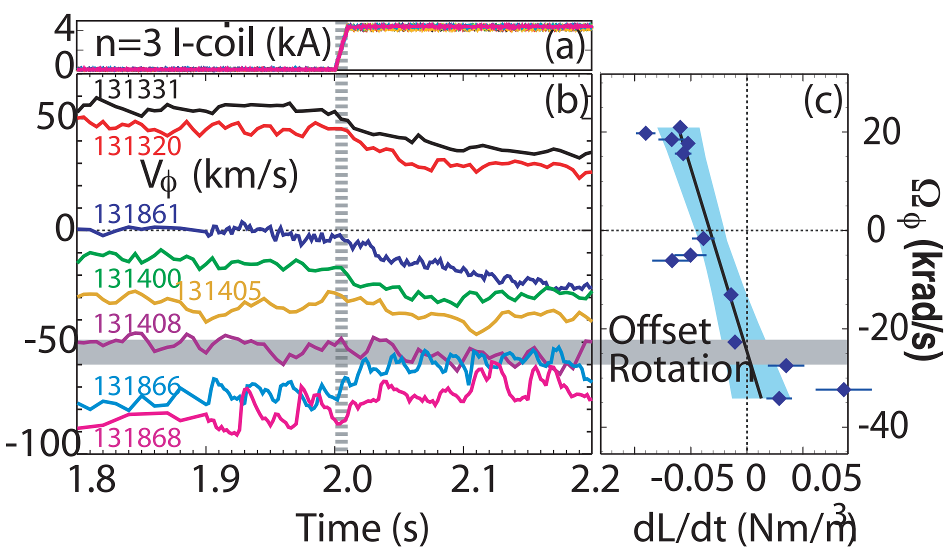

Figure 4: DIII-D experiments validated[6] the NTV-induced damping/braking to offset rotation frequency $\boldsymbol{\Omega_* < 0}$, as predicted by the NTV torque formula.

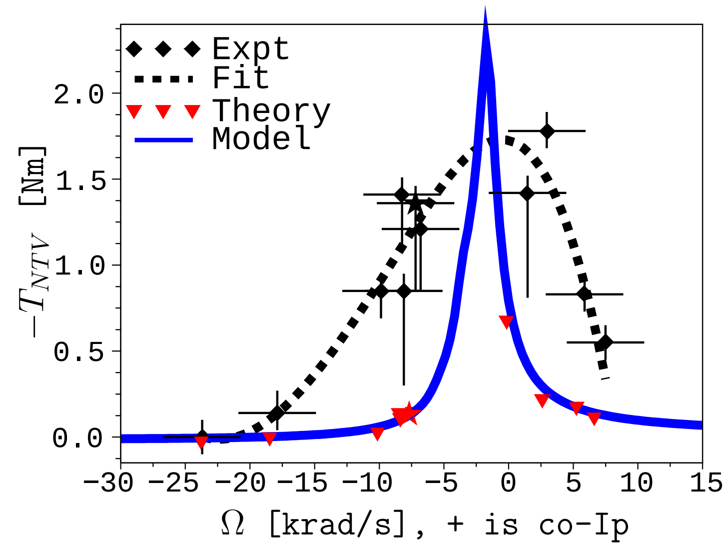

Figure 5: DIII-D experiments validated[7] NTV peak caused by $\boldsymbol{\mu_\parallel(\nu_i, \omega_E)}$ occurs where $\boldsymbol{\omega_E \simeq 0}$ at which $\boldsymbol{\Omega_t \simeq -2}$ krad/s.

III. Toroidal Field Ripple Causes Many Toroidal Torques

- **Toroidal magnetic field ripple ($\delta \equiv \delta B_N/B_0 \lesssim 1\%$) is caused by the finite number N (typically 18–32) of toroidal field coils.**

- **Non-ambipolar particle fluxes and toroidal torques are induced by:**

  Ripple-induced direct ion losses at edge $\Longrightarrow$ radial current $\Longrightarrow$ return current in plasma $\Longrightarrow$ $\vec{J}\times\vec{B}_p$ toroidal torque in counter-current direction $\Longrightarrow$ reduction in Ω_t

  NTV damping effects (TTMP, $\sqrt{\nu_i}$ regime) $\Longrightarrow$ braking of Ω_t toward $\Omega_* < 0$

  Radially drifting ripple-trapped particles $\Longrightarrow$ NTV torque that scales as $(\delta B_N/B_0)^{3/2}$

- **Experimental tests confirm reduction in Ω_t as ripple is increased, with smaller effects on n_e, T_e and T_i transport (but slight density "pump-out")**

  — see next 2 viewgraphs

- **More modeling needed for NTV effects in core, with self-consistent E_ρ (Ω_t)**

Ripple Th.: ***Toroidal Field Ripple Causes NTV & Other Effects***

- **Magnetic field ripple ($\delta B_N/B_0 \lesssim 1\%$) caused by finite number N of toroidal field coils induces various types of 3D NTV effects, which are additive:**

  1) Transit-resonance plateau-type (TTMP) NTV effects are often dominant,

  2) Banana-drift NTV effects are likely in $\sqrt{\nu_i}$ regime because usually $\nu_i < \epsilon\,|N\omega_E|$, and

  3) Ions with $\nu_i < (\delta B_N/B_0)^{1/2} N\omega_{ti}$ can be trapped in ripples (if $\epsilon\,|\sin\theta| < Nq\delta$), drift radially and induce an ion particle flux and NTV torque that scales as $(\delta B_n/B_0)^{3/2}$.

- **At the edge superthermal ions and NBI fast ions can be ripple trapped or have asymmetric banana drift orbits and drift out of the plasma, which:**

  1) Causes a radial ion loss current $\langle \vec{J}_{\rm dl} \cdot \vec{\nabla}\psi_p \rangle$ that induces a radially inward "return current" in the plasma to preserve quasineutrality;

  2) Induces a toroidal torque on the edge plasma in the counter-current direction when this radially inward (negative) plasma return current is crossed with $\vec{B}_p$; and

  3) Is represented in the L_t equation by[3b] a momentum sink $\langle \vec{e}_\zeta \cdot \vec{\vec{S}}_m \rangle = -\,\langle \vec{J}_{\rm dl} \cdot \vec{\nabla}\psi_p \rangle$.

- **Thus, ripple-induced direct loss and NTV effects should both decrease the plasma toroidal rotation frequency Ω_t; NTV effects damp it toward $\Omega_* < 0$.**

- **Ripple-induced reductions in Ω_t have been observed in many tokamaks:**

  ISX-B (1985), JT-60U (2006-08), JET (2008-2010), Tore-Supra (EXC/3-4, 2010).

Ripple Exp.: ***Increased Ripple Induces Large Reductions In Ω_t***

- **Addition of ferritic steel tiles (FSTs) in JT-60U reduced ripple and increased V_t;[8] modeled edge direct loss effects agree[8b] — see Fig. 6 below.**
- **Increasing ripple in JET reduced edge Ω_t without changing other plasma parameters[9] (gas puffing prevents density "pump-out") — see Fig. 7 below.**

[8]a) M. Yoshida et al., Plasma Phys. Control. Fusion **48**, 1673 (2006); b) M. Honda et al., Nucl. Fusion **48**, 085003 (2008).

[9]a) G. Saibene et al., Paper EX/2-1 at 2008 Geneva IAEA FEC (to be published); b) H. Urano et al., EXC/P8-17, 2010 Daejeon IAEA FEC.

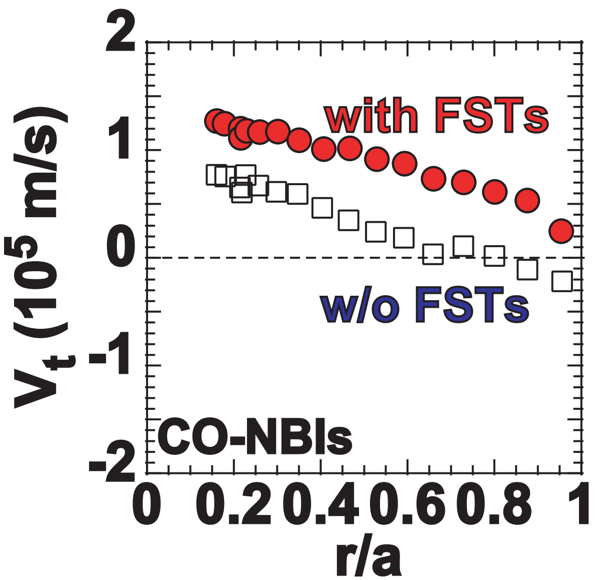

Figure 6: Toroidal plasma flow decreases as field ripple in JT-60U is increased from 1% (with FSTs) to 2% without (w/o) FSTs.[8a]

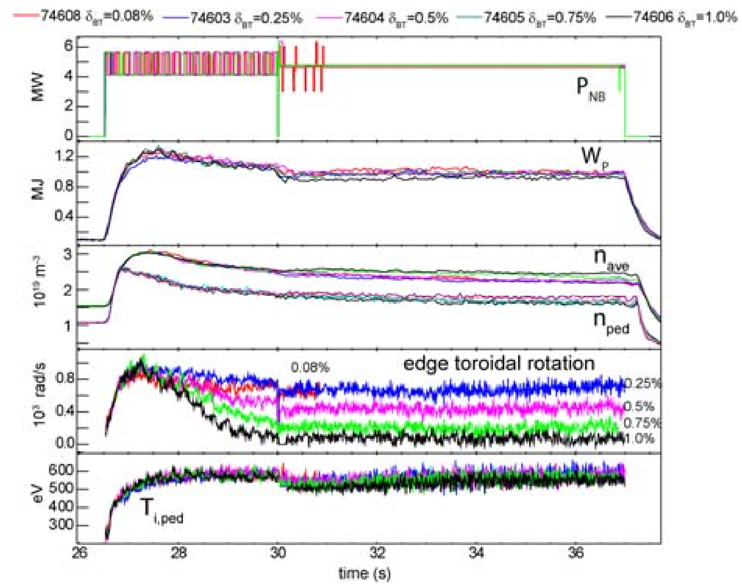

Figure 7: Toroidal plasma rotation decreases monotonically with increasing field ripple (% #s at right of 4th panel) in edge of JET.[9a]

IV. Low n Resonant 3D Fields Cause Locking, Disruptions

- **Field errors (FEs) can introduce resonant 3D fields that produce localized torques at rational surfaces $[\, q(\rho_{m/n}) = m/n \,]$ in the plasma.**

- **Well established (Fitzpatrick) cylindrical model of FE effects predicts:**

  Shielding/screening of FE on and inside of rational surface — if plasma rotates fast

  For slow rotation FE "penetrates" $\Longrightarrow$ toroidal torque $\sim \delta B^2_{\rho\, m/n}$ at $\rho_{m/n}$

  Large FE torque vs $\perp$ viscosity $\chi_{\zeta i}$ $\Longrightarrow$ locked mode $\Longrightarrow$ growing island $\Longrightarrow$ disruption

  — see next viewgraph (# 12)

- **Recent developments in FE-induced $n=1$ locked mode studies:**

  Experiment: FE locking threshold characterized $\Longrightarrow$ $\delta B_{\rho\, 2/1}/B_0 \sim 10^{-4} \propto n_e R_0$

  Theory: two-fluid layer physics plus NTV effects $\Longrightarrow$ closest to $\propto n_e$ scaling but $\chi_{\zeta i}$?

  Compensation: "Correction" of FEs by using additional 3D fields shows that the plasma response to them is critical and the plasma response increases with β

  — see viewgraph # 13

FE Theory: ***Field Errors (FEs) Can Cause Mode Locking***

- **Field errors introduce low n resonant 3D fields which:**

  In the dissipationless ideal MHD model cause no toroidal torque on the plasma, but

  induces dissipative local torques in thin layers around rational surfaces at $q(\rho_{m/n}) = m/n$.

- **The local Maxwell-stress-induced FSA plasma toroidal torque density for a cylindrical model (with a δ-function resistive singular layer at $\rho_{m/n}$) is**[10]

$$\langle \vec{e}_\zeta \cdot \overline{\delta \vec{J}_{\| m/n} \times \delta \vec{B}_{\rho\, m/n}} \rangle \simeq -\, m_i n_i \, (4 n c_A^2) \left(\frac{\delta B^{\rm vac}_{\rho\, m/n}}{B_0} \right)^2 \left[\frac{(-\omega \tau_s)}{(-\Delta')^2 + (-\omega \tau_s)^2} \right] \frac{V \, \delta(\rho - \rho_{m/n})}{V'},$$

  in which $\delta B^{\rm vac}_{\rho\ m/n} \equiv [\delta \vec{B} \cdot \vec{\nabla} \rho]_{\rho_{m/n}}$, $\omega \equiv \vec{k} \cdot \vec{V}_i \Longrightarrow n \, [\omega_E + (1/n_i q_i)(dp_i/d\psi)]$, τ_s is the singular-layer diffusion time, and $\Delta' \sim -2m$ is the tearing mode instability index.

- **This radially localized FE-induced electromagnetic toroidal torque:**

  Competes with the NBI momentum source and radial transport of Ω_t induced by $\chi_{\zeta i}$.

  For $\omega \tau_s \gg 1$ "penetration" of $\delta B_{\rho\, m/n}$ is limited by Ω_t; $\delta B^{\rm vac}_{\rho\, m/n}$ vanishes for $\rho \leq \rho_{m/n}$.

  For large $\delta B^{\rm vac}_{\rho\, m/n}$, the "penetration threshold" is exceeded (e.g., for $\delta B^{\rm vac}_{\rho\, 2/1}/B_0 \gtrsim 10^{-4}$), $\Omega_t(\rho_{m/n})$ is no longer restrained by $\chi_{\zeta i}$ and Ω_t no longer "shields" out resonant torque;

  Then, Ω_t solution bifurcates (in a few ms) to no flow at $\rho_{m/n}$, magnetic reconnection occurs and a growing m/n "locked mode" is induced, which often leads to a disruption.

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[10] R. Fitzptrick, Nucl. Fusion **33**, 1049 (1993). See also `http://farside.ph.utexas.edu/papers/lecture.html`.

FE Status: ***Locking Thresholds, Resonant Field Amplification***

- **Recent FE theory developments:**

  Two-fluid singular layer effects developed.

  NTV shown[a] to increase Ω_t shielding effects.

- **Recent FE experimental developments:**

  Error field locking thresholds characterized.[b]

  Scaling closest to NTV-enhanced scaling.[a]

  Validation tests limited by $\chi_{\zeta i}$ uncertainty.

- **Recent compensations of resonant field errors show that plasma resonant field amplification (RFA) is critical.[c]**

- **Measured RFA agrees with ideal MHD MARS-F calculations,[d] up to near no-wall β limit where non-ideal MHD effects become important — see Fig. 8.**

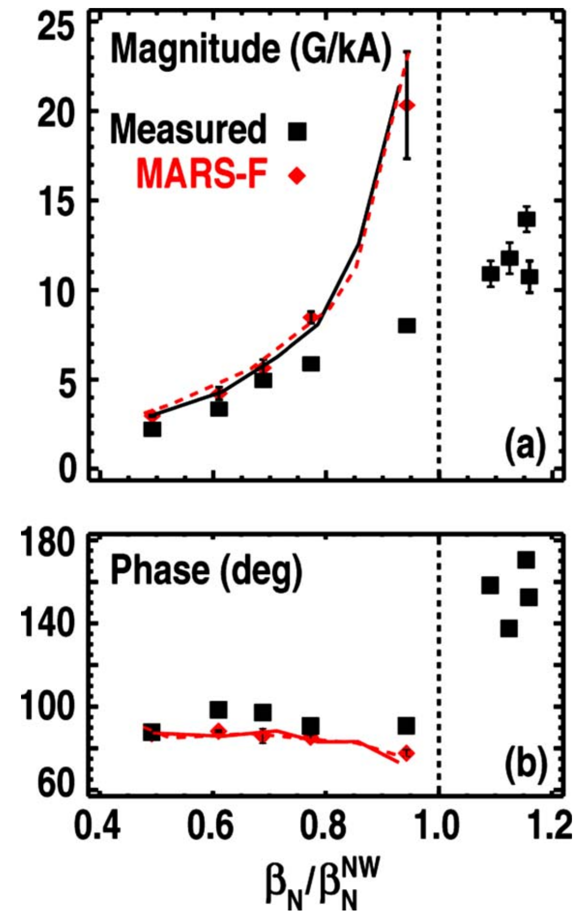

Figure 8: The magnitude of the $n = 1$ resonant 3D field on the DIII-D outer midplane increases about linearly with β.[d]

[a]A.J. Cole et al., Phys. Rev. Lett. **99**, 065001 (2007).
[b]S.M. Wolfe et al., Phys. Plasmas **12**, 056110 (2005).
[c]J.-K. Park et al., Phys. Rev. Lett. **99**, 195003 (2007); EXS/P5-12.
[d]M.J. Lanctot et al., Phys. Plasmas **17**, 030701 (2010).

V. Plasma, Combined Effects Complicated, Being Developed

- **Plasma response to externally applied 3D fields:**

  Amplifies $\delta\vec{B}$ in plasma by coupling to "least stable" $n=1$ kinks, via edge $m > q_{95}$.

  Can be estimated using an ideal MHD model (IPEC, EXS/P5-12), but self-consistent evaluation needs layer physics as in MARS-F (EXS/P5-04, EXS/P5-10) — #s 15, 16

- **Plasma instabilities (NTMs, RWMs) cause additional 3D fields & more FE sensitivity for low Ω_t, increasing β (EXS/5-3, EXS/5-4, EXS/5-5) — # 17**

- **Resonant magnetic perturbations (RMPs) for ELM control (viewgr. # 18):**

  Is based on stochasticity caused by island overlap (Chirikov criterion) — see ITR/P1-30.

  But Ω_t "screening" of RMP fields reduces stochastic region width (THS/P5-04, THS/P5-10) & other effects are considered (EXD/P3-30, THC/P3-06, THC/P4-04, THS/P3-04)

  While RMP effects are not yet fully understood, they are important tools for pedestals.

- **3D fields directly affect Ω_t [global NTV, local FE locking of $\Omega_t(\rho_{m/n}) \to 0$]; n_e, T_e & T_i transport effects are small, except for ripple- and RMP-induced slight density "pump-out" (EXC/P8-17, EXD/8-2, THS/P5-10) — # 19**

FE Plasma Effects I: ***RFA From Coupling To $n = 1$ Global Mode***

- **External 3D fields can amplify resonant components of $\delta\vec{B}$ in plasma by coupling to "least stable" MHD-type eigenmodes[d] — $n = 1$ kink-type.**

- **The largest $\delta B_{\rho\, m/n}$ responses at $m/n = 2/1$, $3/1$ resonant surfaces in the plasma result from[c] (Fig. 10) external $\delta\vec{B}$ which is pitch-aligned with edge $n = 1$ global kink eigenmode components that have $m \gtrsim q \gtrsim q_{95}$ (Fig. 9).**

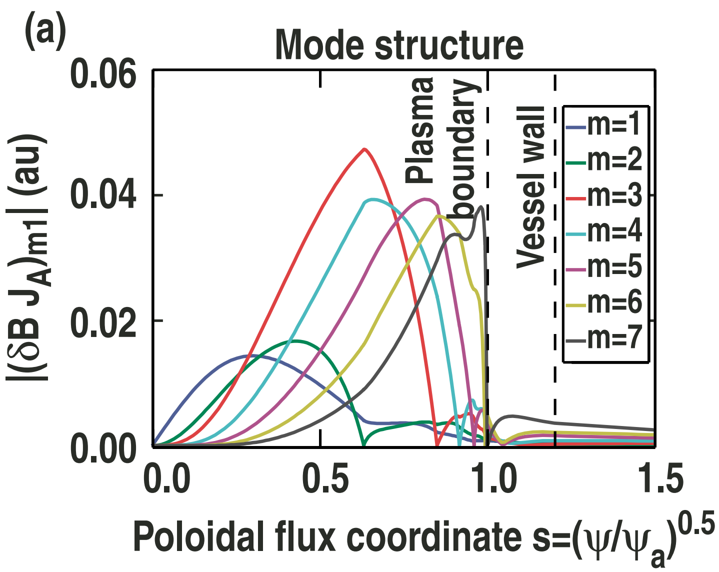

Figure 9: Poloidal mode spectrum of $\boldsymbol{\delta B_{\rho\, m/n=1}(\psi)}$ for an unstable $\boldsymbol{n = 1}$ RWM for $\boldsymbol{q_{95} \simeq 5}$ in DIII-D[d] from MARS-F.

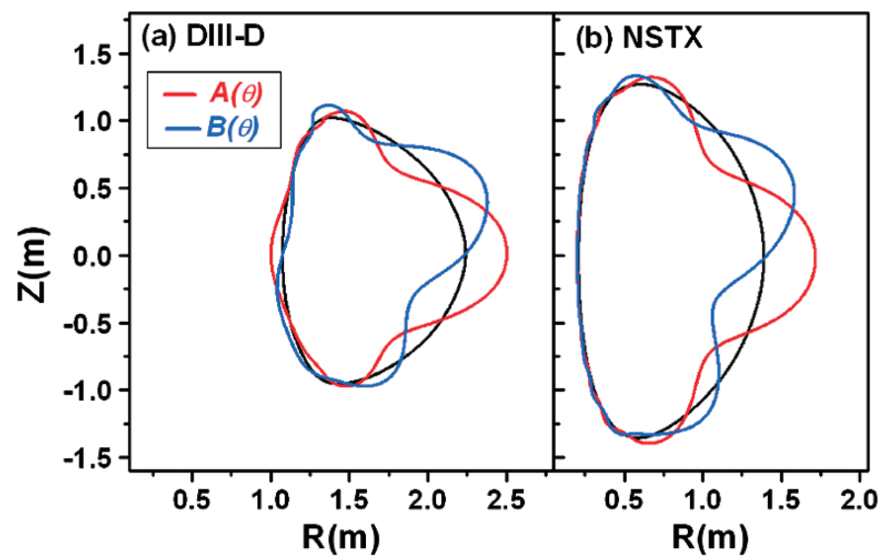

Figure 10: Distributions of external 3D field components from IPEC[11] that maximize[c] the total resonant fields on rational surfaces in: a) DIII-D and b) NSTX.

FE Plasma Effects II: **RFA Modeling Developments Are Needed**

- **RFA and its effects can be estimated using an ideal MHD model:**

  Radial component $\delta B_\rho \equiv \delta\vec{B}\cdot\vec{\nabla}\rho = [\vec{\nabla}\times(\vec{\xi}\times\vec{B}_0)]\cdot\vec{\nabla}\rho = (\vec{B}_0\cdot\vec{\nabla})(\vec{\xi}\cdot\vec{\nabla}\rho)$ must vanish at rational (resonant) surfaces for finite $\vec{\xi}$ in the plasma because $\vec{B}_0\cdot\vec{\nabla} \sim i(m-nq)/R_0 q$.

  In ideal MHD when an external 3D m/n resonant perturbation is applied to a rapidly rotating (i.e., $\omega\tau_s \gg 1$) plasma, a delta-function "shielding current" $\delta J_{\parallel\, m/n}$ is induced.

  An ideal perturbed equilibrium code (IPEC[11]) has been developed to implement this procedure for all rational surfaces using the linear ideal MHD stability DCON code.

  Shielding current $\delta J_{\parallel\, m/n}$ and the dissipatively relaxed $\delta B^{\rm plasma}_{\rho,m/n}$ it could induce are used[c] to estimate resonant toroidal torque using NTV-enhanced two-fluid layer physics.

  This IPEC procedure explained[c] field error compensation trends in DIII-D and NSTX.

  However, subsequent more precise IPEC evaluations have been less conclusive.[11b]

- **Dissipative, non-ideal singular layer effects are critical for determining rotating plasma response and achieving stable plasmas above no-wall limit:**

  $\delta J_{\parallel\, m/n}$, $\delta B^{\rm plasma}_{\rho,m/n}$ & resonant torque T_ζ can be evaluated self-consistently in MARS-F.[12]

  Nonlinear 3D initial value codes (M3D, NIMROD or reduced MHD codes BOUT++, JOREK) can also calculate them and explore dynamics of FE-induced mode locking.

  Resistive MHD or two-fluid layer models are now used; should add neoMHD inertia.

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[11] a) J.-K. Park et al., Phys. Plasmas **14**, 052110 (2007), b) Phys. Plasmas **16**, 056115 (2009), c) EXS/P5-12, 2010 Daejeon IAEA FEC.
[12] a) Y.Q. Liu et al., Phys. Plasmas **7**, 3681 (2000), Y.Q. Liu et al., THS/P5-10, 2010 Daejeon IAEA FEC; b) M.S. Chu et al., THS/P5-04.

MHD Mode Effects: NTMs And RWMs Interact With 3D Fields

- **Direct effects of the 3D fields produced by NTMs and RWMs are:**

  1) RWM-induced $\delta B_n(\psi, m)$ perturbations cause non-resonant low n NTV effects; and

  2) Resonant classical and neoclassical tearing modes bifurcate the magnetic topology and form magnetic islands within the plasma that complicate and modify NTV effects.[4]

- **Ideal MHD-type RWMs are stabilized if Ω_t is large enough for the resistive wall to represent a conducting wall to the rotating plasma:**

  If $\Omega_t \to 0$ magnetic field perturbations penetrate the resistive wall and RWMs can become unstable. RWMs become unstable when toroidal rotation $|\Omega_t|$ is too small.

  Recently, low critical Ω_t explained by[13] stabilizing kinetic effects[14] of fast and thermal ions whose toroidal precessional drifts are resonant with mode rotation frequency ω.

  Even stable RWMs increase RFA of the $n=1$ $\delta\vec{B}$ in the plasma (see Fig. 8).

  This increases NTV damping, sensitivity to low n field errors and excitation of NTMs.

- **Tearing modes can be nonlinearly excited by low m/n (typically 3/2 and 2/1) 3D magnetic perturbations or they can appear "spontaneously."**

  Critical issue is: what is threshold β_N for given combinations of $\delta B_{\rho\, m/n}^{\text{plasma}}$ and Ω_t?

  Recent experiments indicate low Ω_t via NTV affects Δ', β_N limits and 3D sensitivity.[15]

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[13] a) J.W. Berkery et al., Phys. Pl. **17**, 082504 (2010); b) H. Reimerdes et al., EXS/5-4, 2010 Daejeon IAEA FEC; c) S.A. Sabbagh et al., EXS/5-5.
[14] B. Hu, R. Betti, Phys. Rev. Lett. **93**, 1005002 (2004).
[15] R.J. Buttery et al., EXS/P5-03, 2010 Daejeon IAEA FEC.

RMPs: ***Resonant Magnetic Perturbations Have Many Effects***

- **Use of resonant magnetic perturbations (RMPs)[16] to control ELMs is based on edge magnetic stochasticity[17] to reduce pedestal region gradients:**

  Magnetic field stochasticity is caused by island overlap — Chirikov criterion.

  Key RMP effects explained by resonances are: q_{95} sensitivity, divertor flux patterns.

  But some may not be — electron heat transport ∼ same, but density "pump-out."

- **Many possible RMP effects are currently being explored:**

  Most importantly, "screening" of RMP fields by Ω_t reduces stochastic region width.[18]

  n_e pump-out via $\vec{E}\times\vec{B}$ cells,[18a] large $\vec{\xi}\cdot\vec{\nabla}\rho$[18c,d] at X-point, q_{95} resonances[18i] or μturb?[18j]

  Collision lengths may be comparable to magnetic decorrelation length in pedestal.[16c]

  Possible "laminar" helical ribbons of magnetic flux in the pedestal, SOL regions.[19]

  Radial plasma current driven by combination of E_ρ and magnetic stochasticity.[20a]

  Kinetic simulation of RMP effects on pedestal[20b] — screening of RMPs, reduced pedestal E_ρ key for density pump-out, only untrapped particles contribute to RR transport.

- **BOTTOM LINE: RMPs have many effects & are interesting tools for modifying edge plasma transport (n_e, T_e, T_i & Ω_t) and associated edge stability.**

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[16]a) T.E. Evans et al., Nat. Phys. **2**, 419 (2006); b) Nuc. Fus. **48**, 024002; c) M.E. Fenstermacher et al., Phys. Pl. **15**, 056122 (2008), ITR/P1-30.

[17]T.E. Evans et al., J. Nucl. Mat. **145-147**, 812 (1987); A. Grosman, PPCF **41**, A185 (1999); Ph. Ghendrih et al., Nucl. Fus. **42**, 1221 (2002).

[18]a) V.A. Izzo and I. Joseph, Nucl. Fus. **48**, 115004 (2008); b) M.S. Chu et al., THS/P5-04, 2010 Daejeon IEA FEC; c) Y.Q. Liu et al., THS/P5-10; d) A. Kirk et al., EXD/8-2; e) H.R. Strauss et al., NF **49**, 055025 (2009); f) M. Bécoulet et al., 2010 Dublin EPS mtg.; g) L. Sugiyama et al., THS/P3-04; h) Q. Yu and S. Günter, THS/P3-06; i) Y. Liang et al., EXS/P3-04; j) Z. Yan et al., EXC/P3-05.

[19]a) O.Schmitz et al., EXD/P3-30, 2010 Deajeon IAEA FEC; b) Phys. Rev. Lett. **103**, 165005 (2009); c) Nucl. Fusion **48**, 024009 (2008).

[20]a) V. Rozhansky et al., THC/P3-06, 2010 Deajeon IAEA FEC; b) C.S. Chang et al., THC/P4-04, 2010 Daejeon IAEA FEC.

Transport Effects: ***3D Fields Directly Affect*** Ω_t***, Indirectly*** n_e, T

- **3D fields affect** Ω_t **via**

  resonant $\delta B_{\rho\, m/n}/B_0 \gtrsim 10^{-4}$**,**
  NTV for $\delta B_n/B_0 \gtrsim 10^{-3}$**, and**
  TF ripple for $\delta B_N/B_0 \gtrsim 10^{-2}$**.**

- Ω_t **responds to NTV and resonant modes differently:**

  11a: NTV damping is global,
  11b: resonant is local, spreads.

- **Theoretically, 3D-induced** T_e, T_i**, net** n_e **transport are** $\varrho_*^2(B_t^2/B_p)^2$ **smaller.**

- **Experimentally, 3D effects are usually a factor** $\gtrsim 3$ **smaller for** T_e, T_i **transport, when density held constant.**

- **But RMPs, ripple cause density "pump-out" — how?**

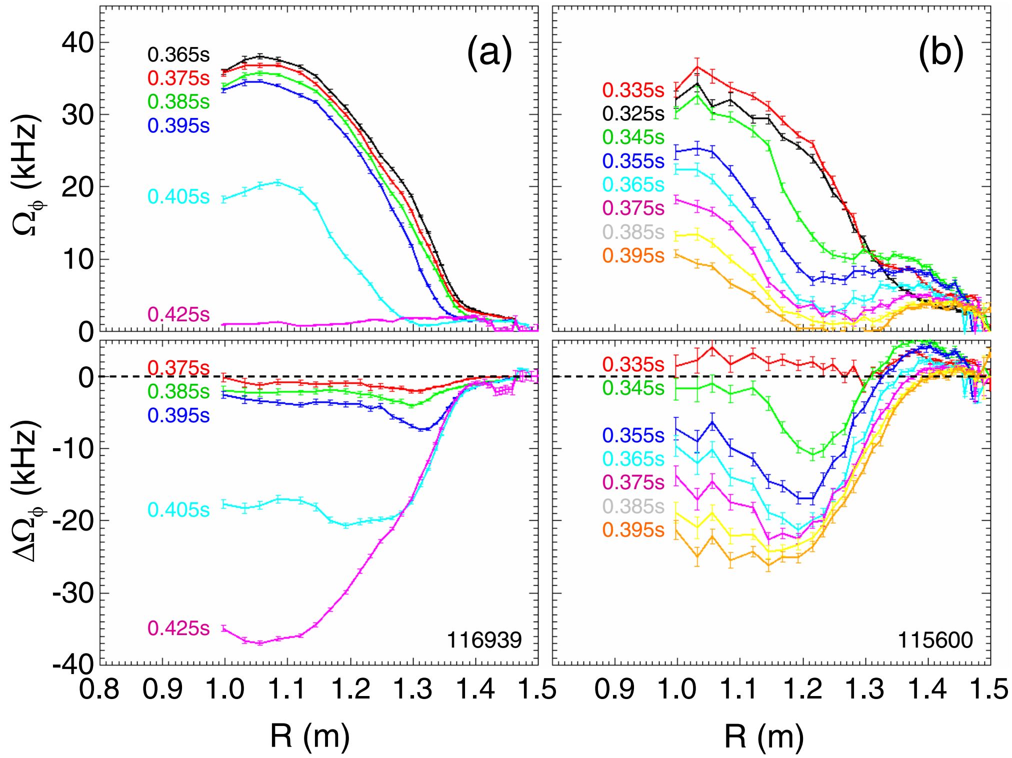

Figure 11: NSTX toroidal plasma rotation profile vs major radius, and difference between initial and subsequent profiles for rotation damping: a) during application of 3D field, and (b) during excitation of rotating tearing instability.[5]

VI. Extrapolation Of 3D Effects To ITER Still Embryonic

- **Test blanket module (TBM) mock-up in DIII-D (ITR/1-3, viewgr. # 21):**

  Results $\sim$ consistent with theory (EXS/P5-12) — reduced Ω_t, slight density pump-out

  Highlights need for NTV, FE & RFA theory for $\delta-$function 3D field (mapping calc.)

- **Major 3D field effects in ITER seem to be (viewgraph # 22):**

  Ripple-induced NTV torque likely causes low $\Omega_t \sim \Omega_* < 0 \Longrightarrow$ greater 3D, β sensitivity

  Density pump-out, RFA effects on $n\!=\!1$ FEs, avoiding locked modes at low Ω_t, high β

- **Needs for improving predictive capability for ITER (viewgraph # 23):**

  Theory: analytic theories of combined 3D effects (RFA, NTMs, RWMs), mapping calc.

  Modeling: Ω_t screening of RMPs, RFA with best layer physics, NTV ripple effects

  Experiments: screening of RMPs with reduced Ω_t in edge, cause of 3D-induced density pump-out, low Ω_t effects on NTMs and RWMs

ITER I: ***What Common 3D Physics Is Involved In TBM Test?***

- **Recent experiments were performed[21] on DIII-D to explore possible effects of field errors introduced by ITER test blanket modules (TBMs, $\delta \sim 1.2\%$):**

  TBM mock-up was toroidally localized ($\Delta\zeta \sim 2\pi/24$) with $\delta \equiv \delta B_N/B_0 \sim$ 1–3%.

  Main effect was braking of Ω_t ($\propto \Omega_t$) with increasing δ, causing $\Delta\Omega_t/\Omega_t$ up to -50%.

  Changes in density (slight pump-out), confinement and β were factor $\gtrsim$ 3 smaller.

  More locking sensitivity to $n=1$ fields, for higher β & lower Ω_t; but easily compensated.

- **Major issue for previous theory is that TBM is toroidally localized, represented by a very large δB_n Fourier spectrum ($\pm\, n$ up to $\gg 2{\times}24$ coils):**

  NTV, FE & RFA theory need to be developed for delta-function-type field ripple.

  Nonetheless, 3D effects of TBM test was estimated by summing over all Fourier δB_n.

- **TBM test results were consistent with[21] 3D effects theory, modeling:**

  Global NTV Ω_t braking semi-quantitatively predicted[21b] by IPEC[11] calculations — very small $n=1$ edge FE from TBM is amplified in core by edge coupling to $n=1$ kink.

  I-coil compensation of TBM-induced $n=1$ FE semi-quantitatively matched[21b] by IPEC.[11]

  TBM mainly affects Ω_t, with lesser effects on n, T transport (slight density pump-out).

[21] a) M.J. Schaffer et al., ITR/1-3, 2010 Dajeon IAEA FEC; b) J.K. Park et al., EXS/P5-12; c) G.J. Kramer et al., EXW/P7-10.

ITER II: ***What Are The Major 3D Fields Issues For ITER?***

- **Plasma torques from edge direct ion losses and ripple-induced NTV (from $N = 18$ coils + FSTs $\Longrightarrow \delta \lesssim 0.4$ % at edge) is likely to cause braking of Ω_t toward $\Omega_* < 0$ — NBI and other torques are likely to be smaller. Lower, diamagnetic-level plasma toroidal rotation Ω_t could have some effects:**

  Greater sensitivity to $n = 1$ external 3D field errors that can induce locked modes?

  Smaller radial electric field shear with less stabilization effects on microturbulence?

  Reduced β_N thresholds for NTMs?

  More reliance on kinetic ion effects to stabilize RWMs above no-wall limit?

  Non-resonant fields in ITER may be able to use NTV effects to control $\Omega_t(\rho, t)$.

- **Some additional important 3D field effects issues are:**

  Precise 3D RMP field characteristics required for stabilization or amelioration of ELMs.

  Density pump-out caused by FEs, RMPs and ripple/TBMs, that is not yet understood.

  RFA effects on $n = 1$ fields in plasmas including singular layer and kinetic effects.

  Determination of how small field errors must be to avoid locked modes as β is increased — and assessment of degree to which dynamic compensation coils might be needed.

What's Needed To Improve Predictive Capability For ITER?

- **Theory of 3D magnetic perturbation effects:**

  Mapping calculation of NTV induced by TBM "delta-function" δB (avoid Fourier exp.).

  Analytic model of $n=1$ "global" resonant plasma response including layer physics.

  Theoretical models of 3D field effects plus toroidal flow and flow shear on tearing modes.

  More development of combined resonant 3D field, NTV and kinetic effects on RWMs.

- **Modeling of 3D magnetic perturbation effects:**

  NTV ripple effects throughout plasma including self-consistent Ω_t (radial electric field).

  More modeling of Ω_t screening effects on penetration of RMPs into edge plasmas.

  More extensive modeling of plasma responses to $n = 1$ global modes including layer physics — with linear eigenmode, reduced MHD and nonlinear initial value codes.

  Complete modeling of Ω_t evolution using comprehensive L_t transport equation.

- **Experimental explorations of effects of 3D magnetic perturbations:**

  More validation of NTV effects in core plasma, particularly for rippled tokamaks.

  Clarify how 3D fields from ripple, field errors and RMPs cause "density pump-out."

  Elucidate effects of 3D fields and rotation on NTMs and RWMs at low Ω_t ($\sim \Omega_*$).

  Studies of screening effects of various toroidal rotation magnitudes on RMPs in edge.

Summary

- **Fundamental physics of the effects of 3D magnetic perturbations on toroidal plasmas has "come of age" over the past 5 years:**

  Transport-time-scale equation for Ω_t evolution including 3D effects is now available.

  NTV theory nearly validated — torque magnitude, offset frequency, peak at $\omega_E \to 0$.

  Toroidal field ripple reduces Ω_t — edge direct ion losses plus (?) global NTV effects.

  Resonant $n = 1$ field error effects, correction — mode locking criteria, need RFA effects.

  Resonant field amplification (RFA) — via "least stable" $n = 1$ kink, edge-resonant FEs.

- **Combination of 3D field effects with other effects are still being developed:**

  NTMs and RWMs interact with low n external $\delta\vec{B}$ — sensitivity increases at low Ω_t.

  Resonant magnetic perturbations (RMPs) — stochasticity limited by Ω_t "screening."

  3D plasma transport effects — directly on Ω_t, but mostly indirectly on n_e, T transport.

- **PREDICTIVE CAPABILITY?: More exploration is needed of the effects of diamagnetic-level flows, RFA and density pump-out caused by 3D fields.**

- **Personal observations about possible "dynamic, interior" coils in ITER:**

  Their requirements and the key physics for RMP control of ELMs are still developing.

  They may be needed to control resonant field error effects as β increases, Ω_t decreases.

  Their non-resonant components could be used to control Ω_t through NTV effects.