The Impact of Anisotropy on ITER Scenarios and Edge Localised Modes

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Motivation

- In JET, ICRH can cause anisotropies of $p_\perp / p_\parallel$ =2.5 [W Zwingmann *et al*.PPCF, 43(11):1441, 2001.]
- MAST has reached $p_\parallel / p_\perp \approx 1.7$ [MJ Hole et al. *PPCF*, 53(7):074021, 2011.]

1. Equilibrium with flow, anisotropy

- Inclusion of anisotropy and flow in equilibrium MHD equations e.g. [R. Iacono, et al Phys. Fluids B 2 (8). 1990]

$$\nabla\cdot(\rho\mathbf{v})=0, \qquad \rho\mathbf{v}\cdot\nabla\mathbf{v}=\mathbf{J}\times\mathbf{B}-\nabla\cdot\overline{\mathbf{P}}, \qquad \nabla\cdot\mathbf{B}=0$$

$$\mu_0\mathbf{J}=\nabla\times\mathbf{B}, \qquad \nabla\times(\mathbf{v}\times\mathbf{B})=0,$$

$$\overline{\mathbf{P}}=p_\perp\overline{\mathbf{I}}+\Delta\mathbf{BB}/\mu_0, \qquad \Delta=\frac{\mu_0(p_\parallel-p_\perp)}{B^2}$$

- If **toroidal flow** only: $\mathbf{v}=-R\phi_E'(\psi)\mathbf{e}_\varphi=R\Omega(\psi)\mathbf{e}_\varphi$

$\Rightarrow F(\psi)=RB_\phi(1-\Delta)$

- If two temperature Bi-Maxwellian model chosen

$$p_\parallel(\rho,B,\psi)=\frac{k_B}{m}\rho T_\parallel(\psi), \qquad p_\perp(\rho,B,\psi)=\frac{k_B}{m}\rho T_\perp(B,\psi)$$

- Can write

$$W(\rho,B,\psi)=T_\parallel\ln\frac{T_\parallel\rho}{T_\perp\rho_0}, \quad H=W-\frac{1}{2}[R\phi_E'(\psi)]^2, \quad T_\perp(B,\psi)=\frac{T_\parallel B}{|B-T_\parallel\Theta(\psi)|}\Big|_\parallel,$$

$$\nabla\cdot\left[(1-\Delta)\left(\frac{\nabla\psi}{R^2}\right)\right]=-\frac{\partial p_\parallel}{\partial\psi}-\rho H'(\psi)+\rho\frac{\partial W}{\partial\psi}-\frac{F'(\psi)F'(\psi)}{R^2(1-\Delta)}+R^2\rho\Omega(\psi)\Omega'(\psi)$$

{H(ψ), T||(ψ), F(ψ), Θ(ψ), Ω(ψ)}

- Implemented in EFIT TENSOR for equilibrium reconstruction [Fitzgerald, Appel, Hole, Nucl. Fusion **53** (2013) 113040]
- Implemented in HELENA-ATF for stability studies [Qu, Fitzgerald, Hole, PPCF **56** (2014) 075007]

Constraining HELENA+ATF

Boundary (R,Z)

Profiles

$$\text{VF2}=\frac{F(\psi)^2}{F(0)^2}, \ \text{VTE}=\frac{T_\parallel(\psi)}{T_\parallel(0)}, \text{VOM2}=\frac{\Omega(\psi)^2}{\Omega(0)^2}, \ \text{VH}=\frac{H(\psi)}{H(0)}, \ \text{VTH}=\frac{\Theta(\psi)}{\Theta(0)}$$

$$H(\psi)=\frac{k_B}{m_i}T_\parallel(\psi)\ln\frac{T_\parallel(\psi)\rho}{T_\perp\rho_0}-\frac{1}{2}\Omega^2R^2, \qquad T_\parallel(\psi)=\frac{mp_\parallel}{k_B\rho},$$

$$F(\psi)=RB_\phi(1-\Delta), \qquad \Theta(\psi)=\frac{m_i}{k_B}\frac{B}{T_\parallel}\left(1-\frac{T_\parallel(\psi)}{T_\perp}\right), \qquad \Omega(\psi)=v_\phi/R$$

Constants

$$\text{B}=\mu_0\rho\frac{k_B}{m_i}\frac{a^2}{\varepsilon^2}\frac{T_\parallel(0)}{F(0)^2}=\frac{\beta(0)}{2}, \qquad \text{HOT}=\frac{m_i}{k_B}\frac{H(0)}{T_\parallel(0)}, \qquad \varepsilon=\frac{a}{R_0}, R_0, B_0$$

$$\text{OMGOT}=\frac{m_i}{k_B}\frac{R_0^2\Omega(\psi)^2}{T_\parallel(0)}, \qquad \text{THTOF}=R_0\Theta(\psi)\frac{T_\parallel(0)}{F(0)}$$

Anisotropy Scans Methodology

Addition of physics produces free parameters that are either not fully constrained (or self-consistent), or it is the inferred quantities (e.g. q profile) that are effectively constrained.

⇒ choose appropriate constraints to resolve impact of pressure anisotropy cf q profile.

1 Constrain to Grad-Shafranov solution
2. Select target $\Theta(\psi)$
3 Constrain thermal energy W_{th} such that $p=(2p_\perp+p_\parallel)/3$. Modify β to match W_{th} by iterating HELENA+ATF until $\Delta W_{th}/W_{th} < \varepsilon_W$
4. Modify current profile to match q. Either

(a) Single – pass: Assume $B_\phi \gg B_\theta$ and low $\beta=2\mu_0 p/B^2$

In the isotropic case: $$J_{\phi,i}=R\left(\frac{\partial p_i}{\partial\psi}\right)_B+\frac{1}{2\mu_0R}\left(\frac{\partial(RB_{\phi,i})^2}{\partial\psi}\right)_B$$

In the anisotropic case: $$J_{\phi,a}=R\left(\frac{\partial p_{\perp,a}}{\partial\psi}\right)_B+\frac{1}{2\mu_0R}\left(\frac{\partial(RB_{\phi,a})^2}{\partial\psi}\right)_B$$

Force $J_{\phi,i}=J_{\phi,a}$. Integrate over ψ: $$F_a^2=F_i^2\frac{1-\Delta^2}{1-\frac{2}{3}\Delta}\approx F_i^2\left(1-\frac{4}{3}\Delta\right)$$

Rerun HELENA+ATF

(b) Iteration: In general the toroidal current can be written

$$J_\phi=-\frac{F(\psi)F\prime(\psi)}{(1-\Delta)R\mu_0}-\left[T_\parallel'(\psi)+H'(\psi)-\left(\frac{\partial W}{\partial\psi}\right)_{\rho,B}\right].$$

Next, we assume: $$J_{\phi,a}+\frac{F_a(\psi)F_a\prime(\psi)}{(1-\Delta_a)R\mu_0}\approx J_{\phi,i}+\frac{F_i(\psi)F_i\prime(\psi)}{R\mu_0},$$

Compute

$$\int_1^{\overline{\psi_n}}\langle J_{\phi,a}(1-\Delta_a)R\mu_0-J_{\phi,i}R\mu_0\rangle(\psi_a-\psi_0)d\psi_n\approx[-F_a^2+F_i^2] \quad (1)$$
$$=-\delta F^2(\overline{\psi_n})+\delta F^2$$

... and then update
$$F^2(\overline{\psi_n})\to F^2(\overline{\psi_n})-\delta F^2(\overline{\psi_n}). \quad (2)$$

Rerun in HELENAT+ATF and compute
$$\Delta q=\int_0^1(q_{target}-q)d\psi_n \quad (3)$$

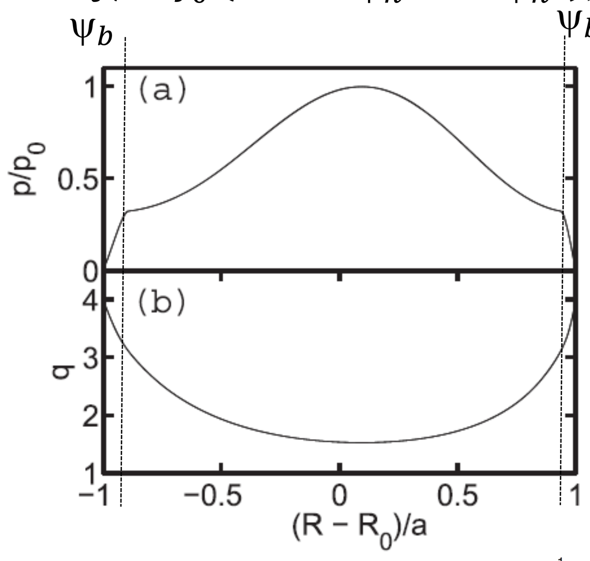
Iterate Eqs. (1) – (3), and the replacement for F until $\Delta q < \varepsilon_q$

2. Ballooning modes in anisotropic plasmas

Aim: explore the impact of anisotropy on n=30 mode for the same q and J_ϕ profile

- As in Huysmans *et al* Phys. Plasmas 8 4292–305, 2001, assume a circular cross-section tokamak, R_0/a=4, β_{pol} =1, and q_a=4.

$$p'(\psi)=p_0(1-\psi_n), \qquad \psi_n<\psi_b$$
$$p'(\psi)=p_0\left(1-\psi_n+p_1\left[\frac{(\psi_n-\psi_b)^2(3-2\psi_n-\psi_b)}{(1-\psi_b)}\right]^{1/4}\right), \qquad \psi_n>\psi_b$$
$$\langle J\rangle=J_0(1-0.8\psi_n-0.2\psi_n^2),$$

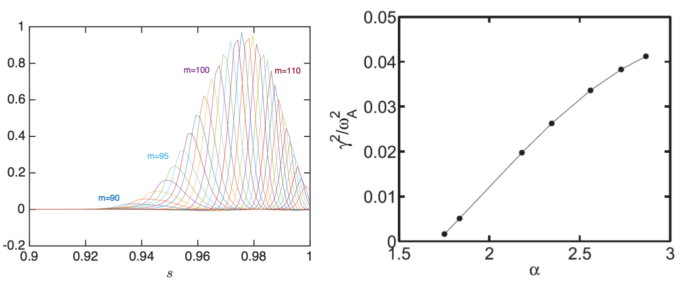


Isotropic radial plasma profiles constructed by HELENA

- investigate the stability of an n=30 ballooning mode using MISHKA [Mikhailovski Plasma Phys. Rep. 23, 844-57, 1997]
- restrict poloidal mode number in range 90<m<120

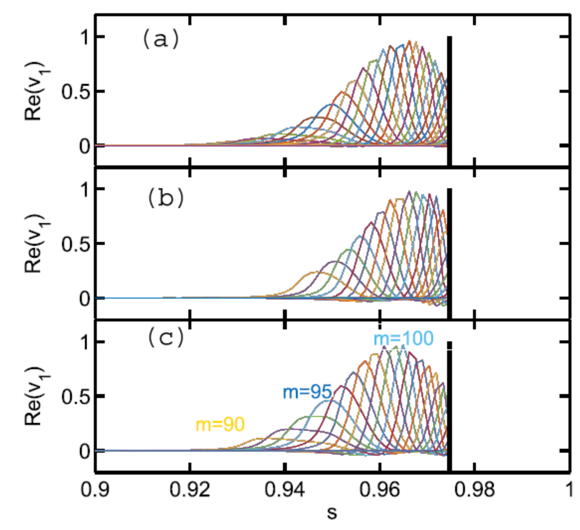
- Eigenmode benchmark
  ✓ Mode structure matches
  ✓ γ^2/ω^2 versus α

$$\alpha=-4\frac{q^2}{\epsilon B_0^2}\frac{V^{1/2}}{dp/dV}$$



Including Anisotropy : Employ Steps (1)-4(a)

- MISHKA-A [Qu et al; Plasma Phys. Control. Fusion 57 095005] extends MISHKA to plasmas with an anisotropy and flow
- MISHKA-A assumes a conformal wall at R_w = 1.
- Adapt HELENA equilibrium to include an "artificial vacuum": set the $p'(\psi_n)$=0 for ψ_n>0.95



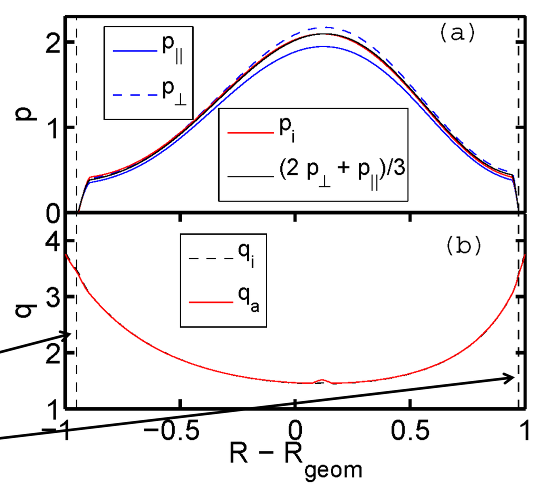
HELENA / MISHKA

HELENA +ATF/ MISHKA-A : Θ=0.0 (isotropic)

HELENA +ATF/ MISHKA-A : $\tilde{\Theta}_0$=0.1 (anisotropic, $p_\parallel/p_\perp$=0.84

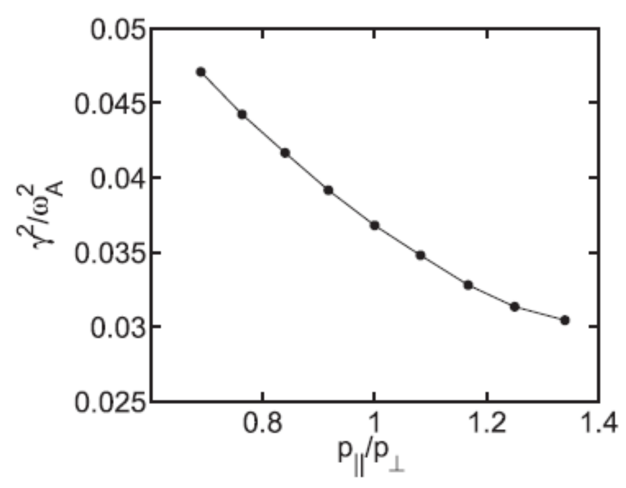
$$\tilde{\Theta}_0=\frac{R_0\Theta_0T_0}{F_0}=\frac{T_0}{T_\parallel}\left(1-\frac{T_\parallel}{T_\perp}\right)$$

e.g. HELENA+ATF equilibrium for isotropic ($\tilde{\Theta}_0$ = 0.0) / anisotropic ($\tilde{\Theta}_0$ = 0.1) plasmas



plasma-vacuum boundary, with vacuum for ψ_n > 0.95

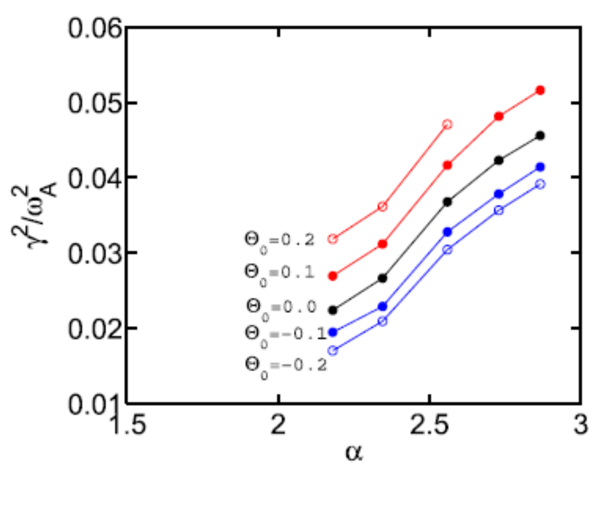
Numerical Scan for n=30 mode:



Growth rate vs $p_\parallel/p_\perp$ (computed at s≈0.96, where eigenfunction peak)
For this calculation is α=2.56

Growth rate changes by 10% over range 0.69 < $p_\parallel/p_\perp$ < 1.34 (ie. $|\tilde{\Theta}_0|$ < 0.2)

__Reason:__ As $T_\perp$ increases over $T_\parallel$, $p_\perp$ surfaces are displaced outboard to bad curvature region *cf* an inward shift of surfaces stabilises the mode.



growth rate vs α for anisotropic plasmas, computed with MISHKA-A with artificial vacuum in the region ψ_n>0.95

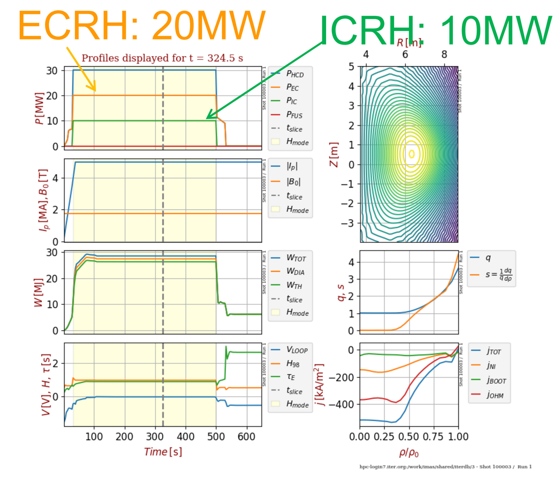
- Over parameter range explored growth rate has same dependence with α
- First step to (s, α) marginal stability boundaries with anisotropy.

- **γ^2/ω^2 increases with increasing $p_\perp/p_\parallel$ (increasing $\tilde{\Theta}_0=T_0/T_\parallel(1-T_\parallel/T_\perp)$.**
- **Suggests *increasing* $p_\parallel/p_\perp$ in the pedestal region might lead to higher ELM-free performance**

3. ITER Pre-fusion power operation

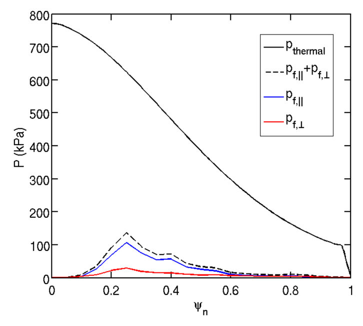
- Pre-fusion power operation H plasma, 5MA, B=1.8T (1/3 field) ICRH scenario: #100003, run 1 at 324s

ECRH: 20MW ICRH: 10MW



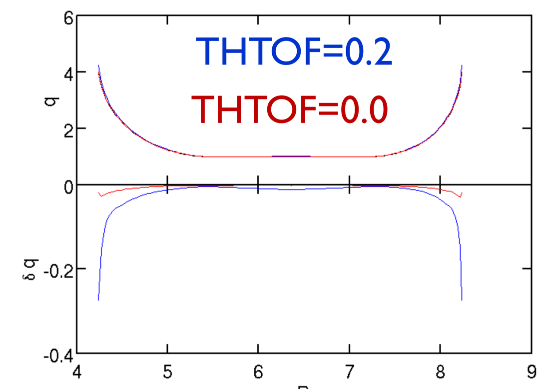
- Fast ion distribution function from SPOT (M. Schneider).

e.g. 15MA, B=5.4T.



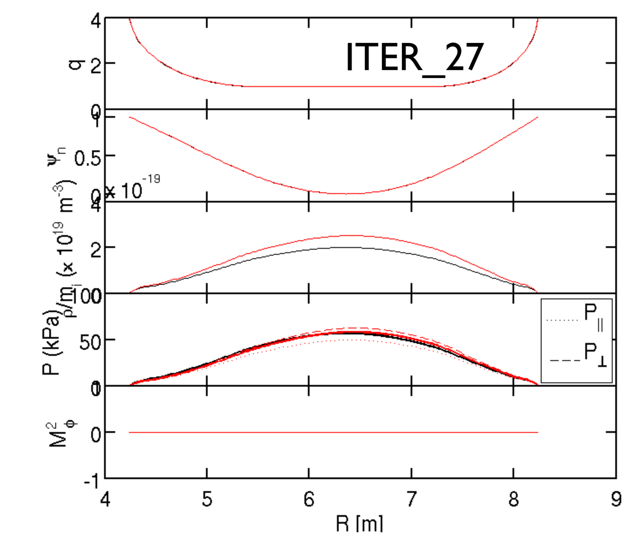
- First Step: Vary central anisotropy $\text{THTOF}=\frac{T_0}{T_\parallel}\left(1-\frac{T_\perp}{T_\parallel}\right)$
- Adjusted -0.2<THTOF< 0.2 to examine impact on equilibrium, continuum, and TAE mode structure.

e.g.

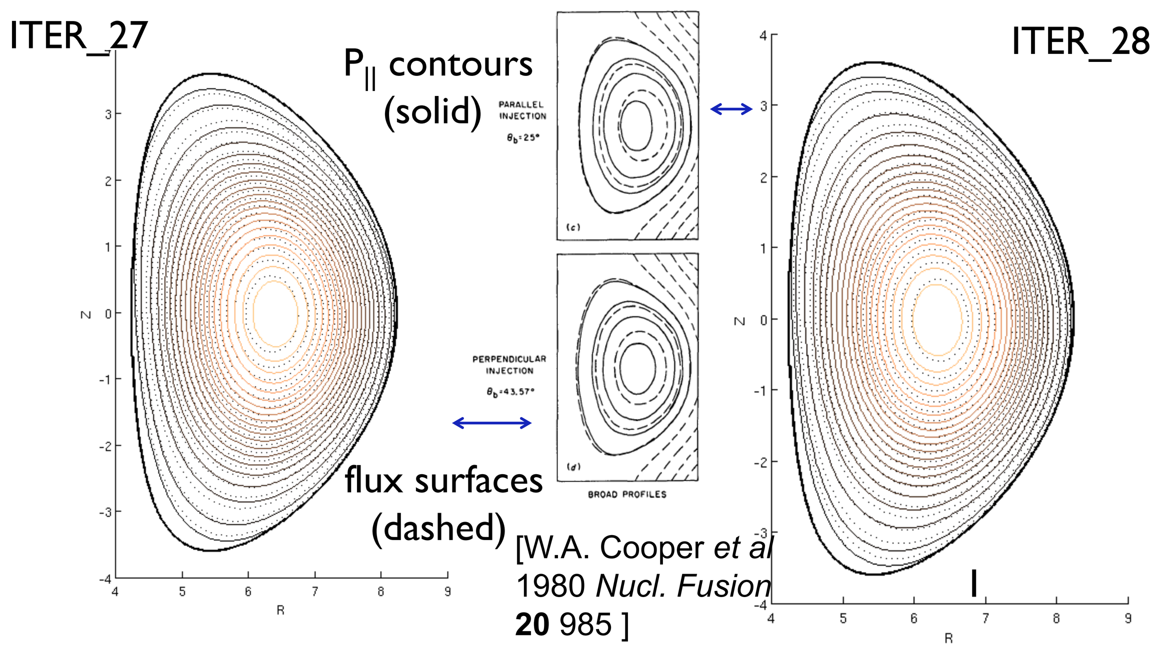


Blue = initial difference
Red = final difference
(~9 iterations)

Cross-section across midplane



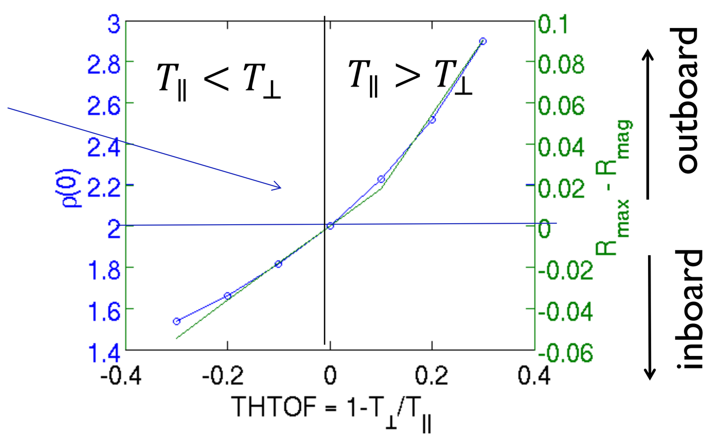
$T_\parallel/T_\perp$ = 0.8 (THTOF=0.2) $T_\parallel/T_\perp$ = 1.2 (THTOF=- 0.2)



[W.A. Cooper *et al* 1980 *Nucl. Fusion* **20** 985]

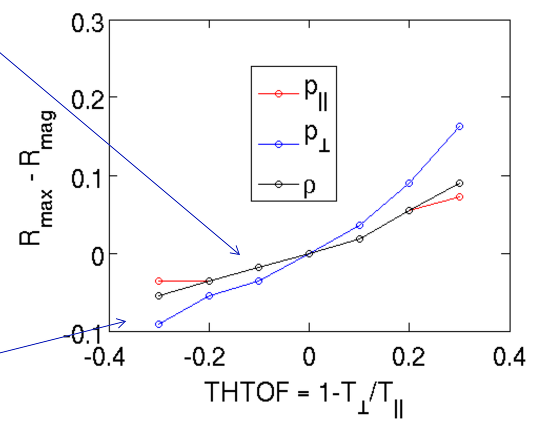
Shift from magnetic axis ∝ anisotropy

$$H(0)=\frac{k_B}{m_i}ln\left(\frac{1}{1-\Theta_0}\cdot\frac{\rho(0)}{\rho_0}\right)$$

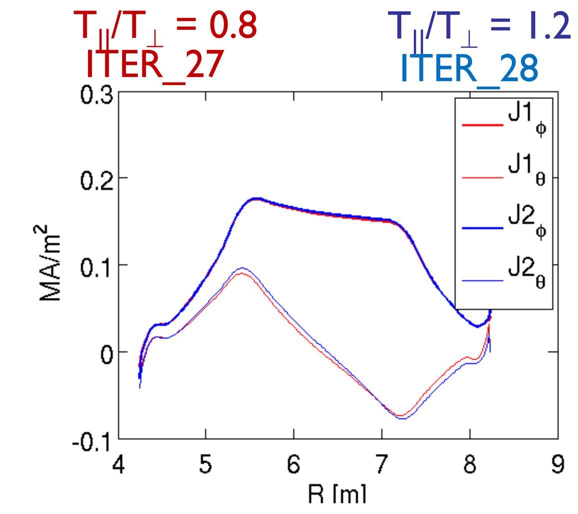


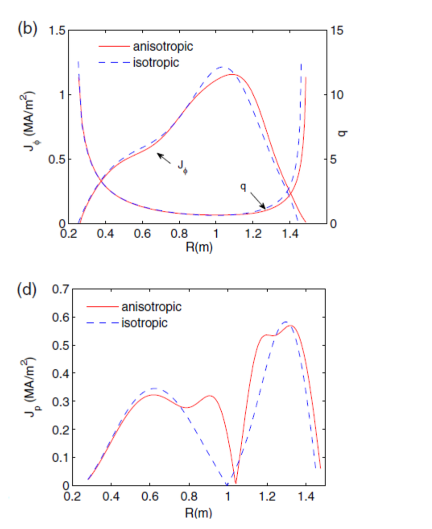
To lowest order :

$$\rho\propto\rho_0(\psi)\frac{B}{|B-\Theta T_\parallel|}$$
$$p_\parallel(R,B,\psi)=\rho T_\parallel(\psi)\propto\rho_0(\psi)\frac{B}{|B-\Theta T_\parallel|}$$
$$p_\perp(R,B,\psi)=\rho T_\perp(B,\psi)=\rho T_\parallel(\psi)\frac{B}{|B-\Theta T_\parallel|}\propto\rho_0(\psi)T_\parallel(\psi)\left(\frac{B}{|B-\Theta T_\parallel|}\right)^2$$



Poloidal current profile differences



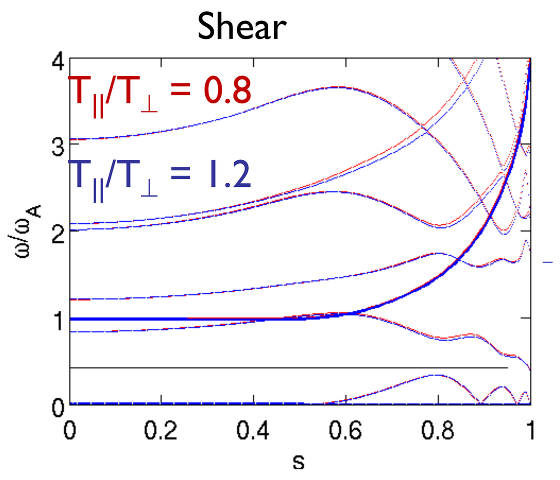


Moderate for ITER, but larger for an ST (EFIT TENSOR with / without anisotropy)

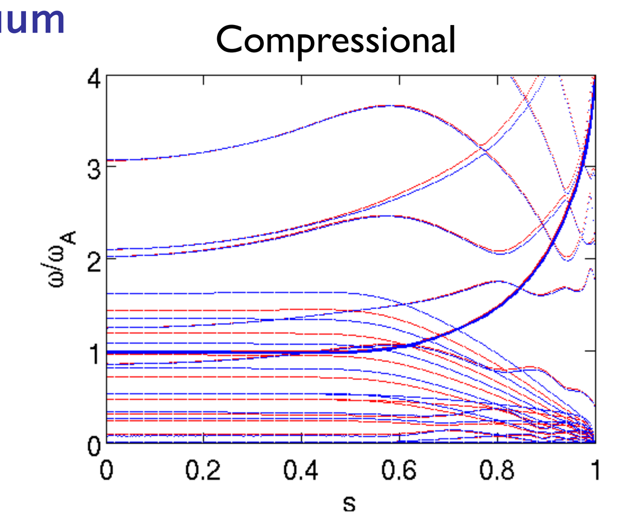
[Qu, Fitzgerald, Hole, PPCF **56** (2014) 075007]

Continuum

Shear



Compressional



- Density / pressure axis shift ∝ anisotropy
- Little difference to shear continuum and gap eigenmodes
- Significant difference to compressional continuum,

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