Trapped Particle Kinetic Effects on Resistive Wall Modes

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Motivations

- Rotational stabilization of RWM may not be effective for ITER.
- Active feedback control may not completely suppress RWM due to wall-shielding.
- Fluid theory may not give accurate predictions.
- Consider mode-particle interaction.
  Trapped particles can be very stabilizing.

Energy principle for RWM

$$\gamma\tau_w = -\frac{\delta W_{tot}^{\infty}}{\delta W_{tot}^{b}}$$

Haney & Freidberg, Phys Fluids (1989)

$$\delta W_{tot}^{b,\infty} = \overbrace{\underbrace{\delta W_F}_{\text{Plasma}} + \underbrace{\delta W_V^{b,\infty}}_{\text{Vacuum}}}^{\delta W_{mhd}^{b,\infty}} + \underbrace{\overbrace{\delta W_K}^{\text{Kinetic}}}_{\text{Re}(\delta W_K)+\text{Im}(\delta W_K)}$$

Stability condition

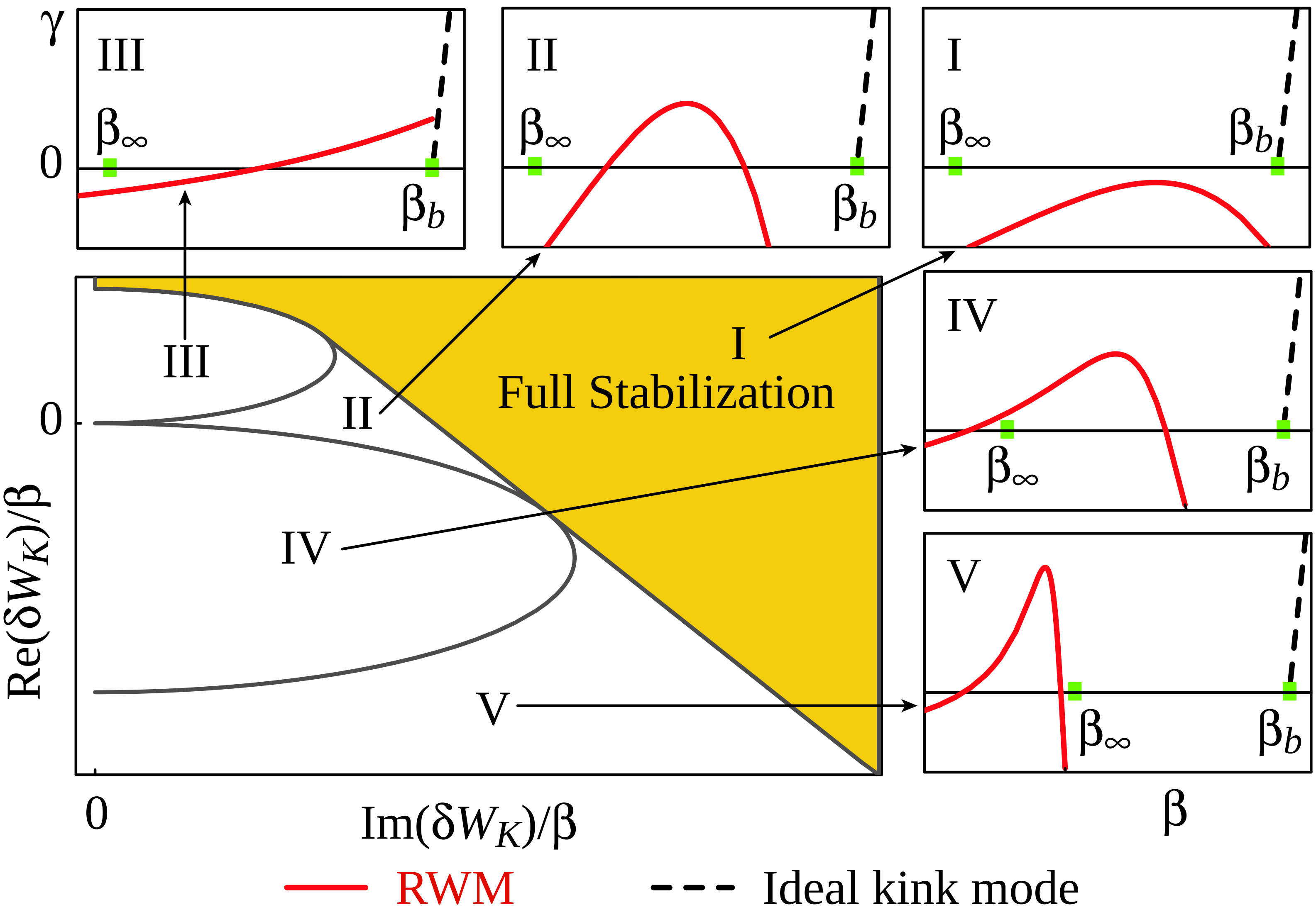
$$|\delta W_K|^2 + \text{Re}(\delta W_K)(\delta W_{mhd}^{b} + \delta W_{mhd}^{\infty}) > -\delta W_{mhd}^{\infty}\delta W_{mhd}^{b}$$

Terms in RWM stability condition

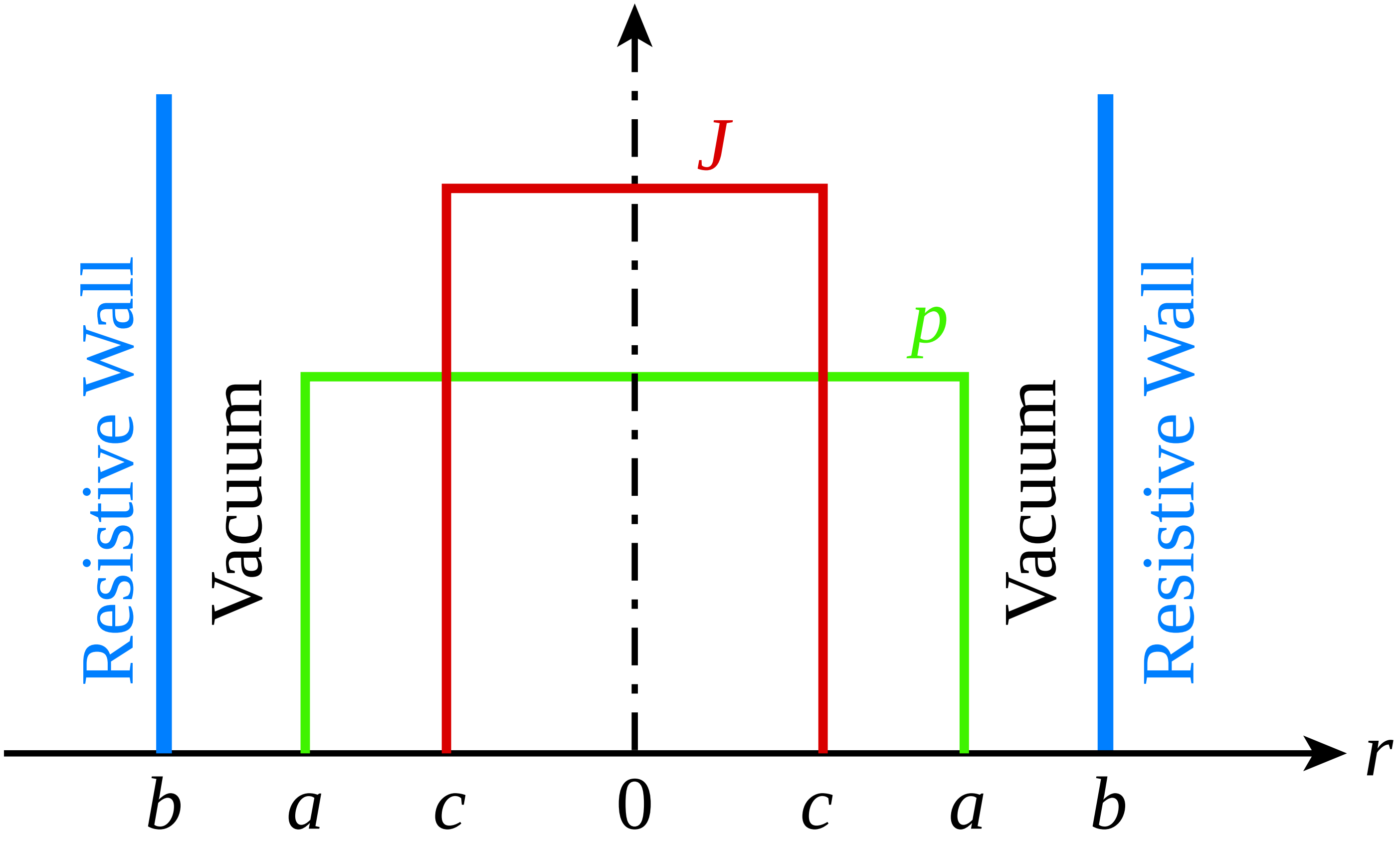
$$|\delta W_K|^2 + \mathrm{Re}(\delta W_K)(\delta W_{mhd}^{b} + \delta W_{mhd}^{\infty}) > -\delta W_{mhd}^{\infty}\delta W_{mhd}^{b}$$

- $\delta W_{mhd}^{\infty} \sim \beta_\infty - \beta$, $\delta W_{mhd}^{b} \sim \beta_b - \beta$, $\delta W_K \sim \beta$
- Instability drive (RHS) is maximized at $\beta \sim (\beta_\infty + \beta_b)/2$, and can be numerically small.
- $\mathrm{Im}(\delta W_K)$ is always stabilizing.
- $\mathrm{Re}(\delta W_K)$ can be stabilizing or destabilizing.

Five RWM stability/instability regions



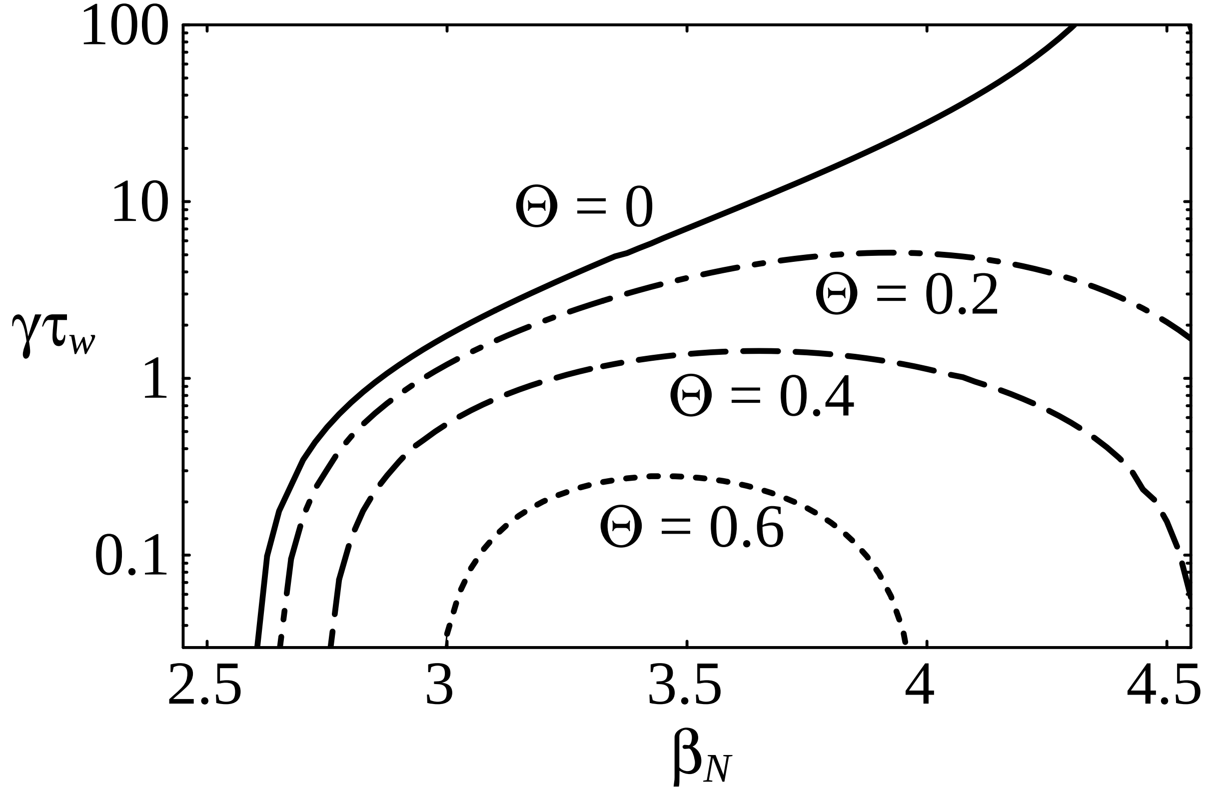
Sharp boundary model for RWM



RWM eigenvalue dispersion relation derived and kinetic effect included self-consistently

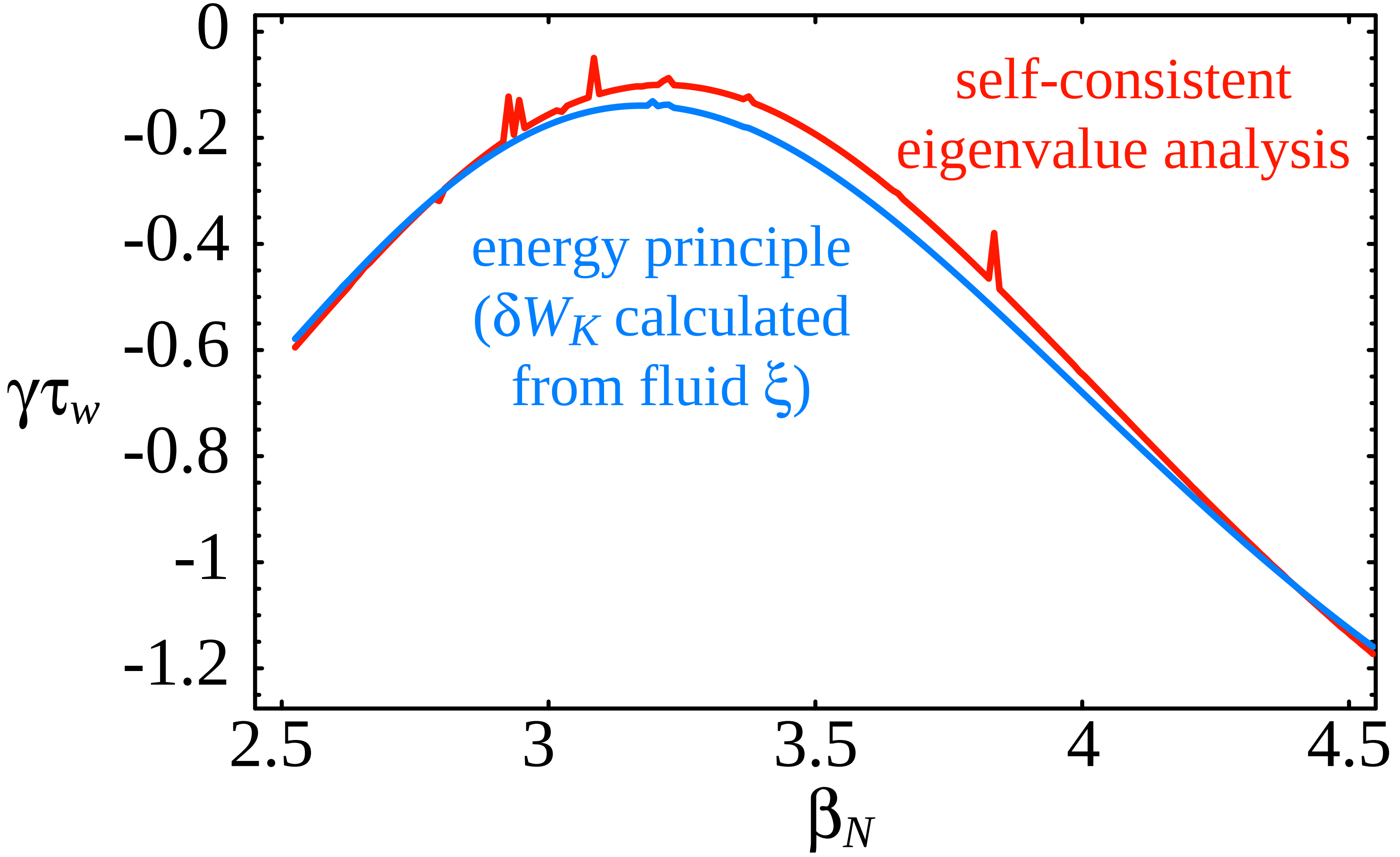
Sharp boundary model shows trapped-ion kinetic effects suppress RWM for ITER-like plasma

Kinetic effect is multiplied by Θ



Hu & Betti, Phys Rev Lett 105002 (2004)

Energy principle compared with eigenvalue analysis for RWM sharp boundary model



Calculate RWM growth rate with ideal MHD code (PEST)

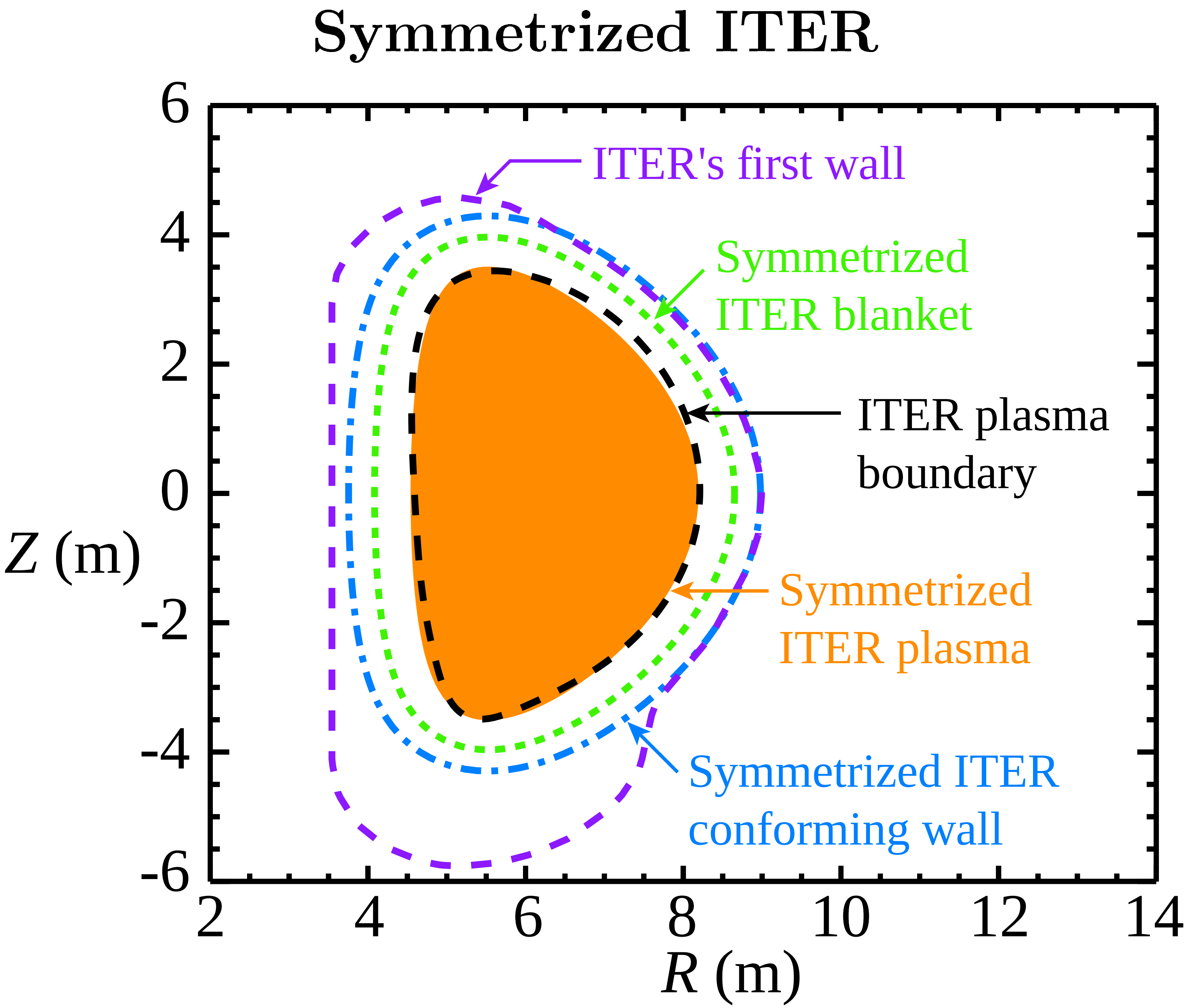
- Wall position and kinetic effect do not significantly change mode eigenfunction inside plasma
- For given equilibrium, obtain eigenfunction at marginal stability by changing wall position using PEST code
- Calculate δW's including δW_K
- Calculate growth rate from energy principle

$$\gamma \tau_w = -\frac{\delta W^{\infty}_{mhd} + \delta W_K}{\delta W^{b}_{mhd} + \delta W_K}$$

Calculate $\boldsymbol{\delta W_K}$

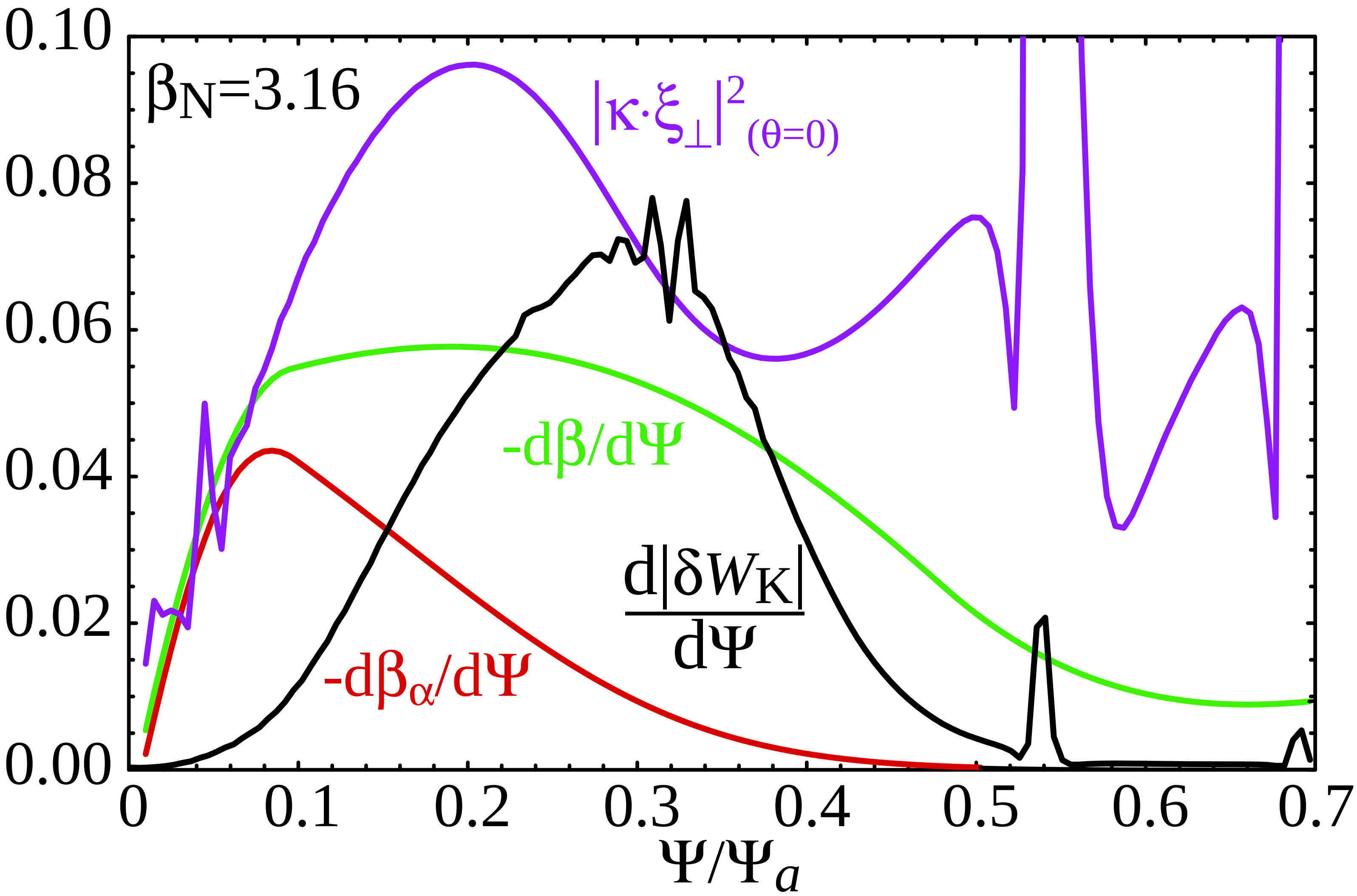
$$\delta W_K = \frac{1}{2}\int d\boldsymbol{r}(\boldsymbol{\kappa}\cdot\boldsymbol{\xi}_\perp)^*\tilde{p}^K$$

- Resonance denominator: $\langle\omega_D\rangle + \omega_E - i\nu_{eff}$
- $\boldsymbol{E}\times\boldsymbol{B}$ drift $\omega_E = \Omega_{rot} - \omega_{*i}$
- Set mode frequency $\omega = 0$
- Consider quasi-stationary regime $\Omega_{rot} < \omega_{*i}$
- Include ions, electrons and α particles

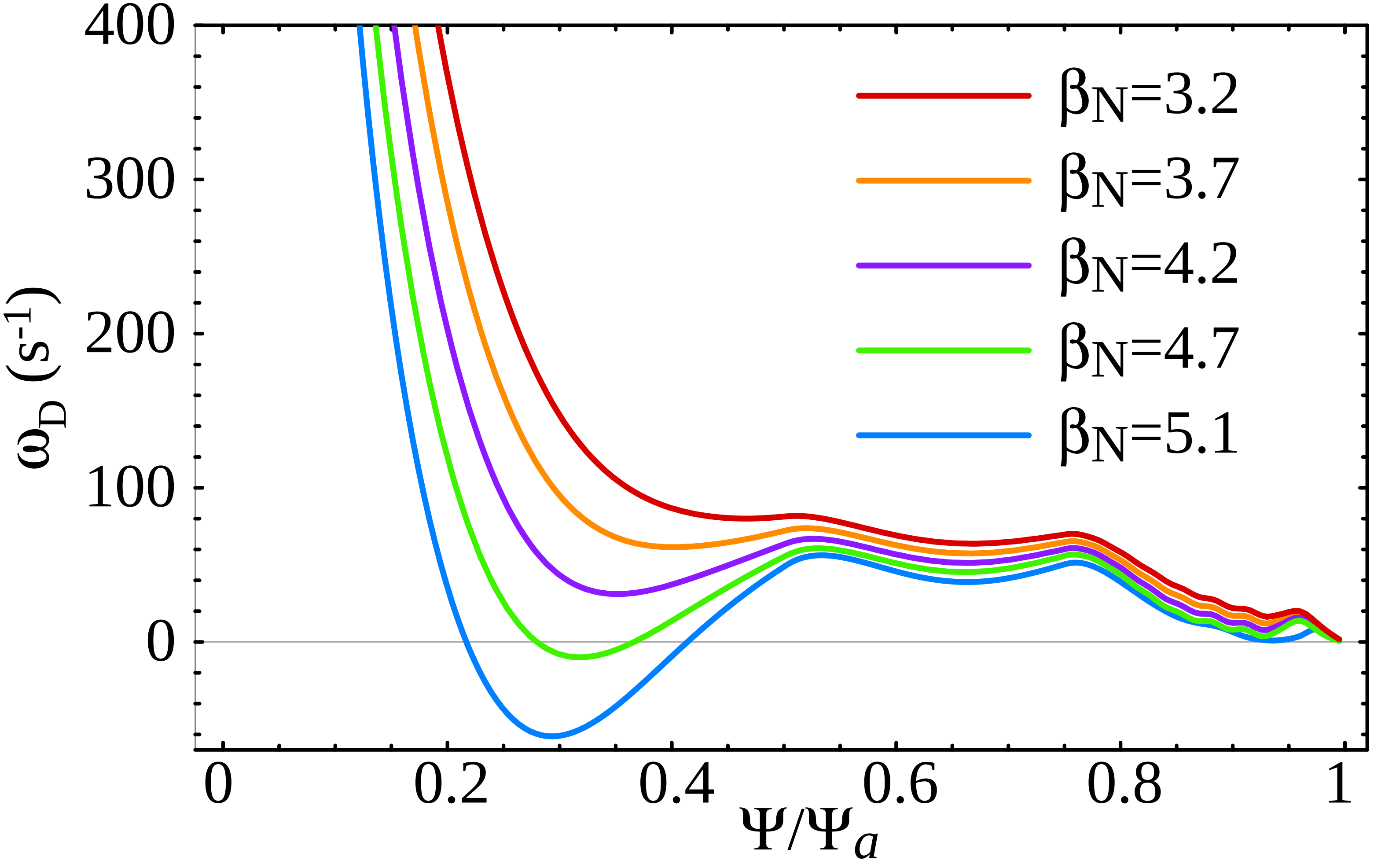


Symmetrized ITER
ITER's first wall
Symmetrized ITER blanket
ITER plasma boundary
Symmetrized ITER plasma
Symmetrized ITER conforming wall
Z (m)
R (m)
6
4
2
0
-2
-4
-6
2
4
6
8
10
12
14

Contribution to δW_K is mainly from inner plasma volume

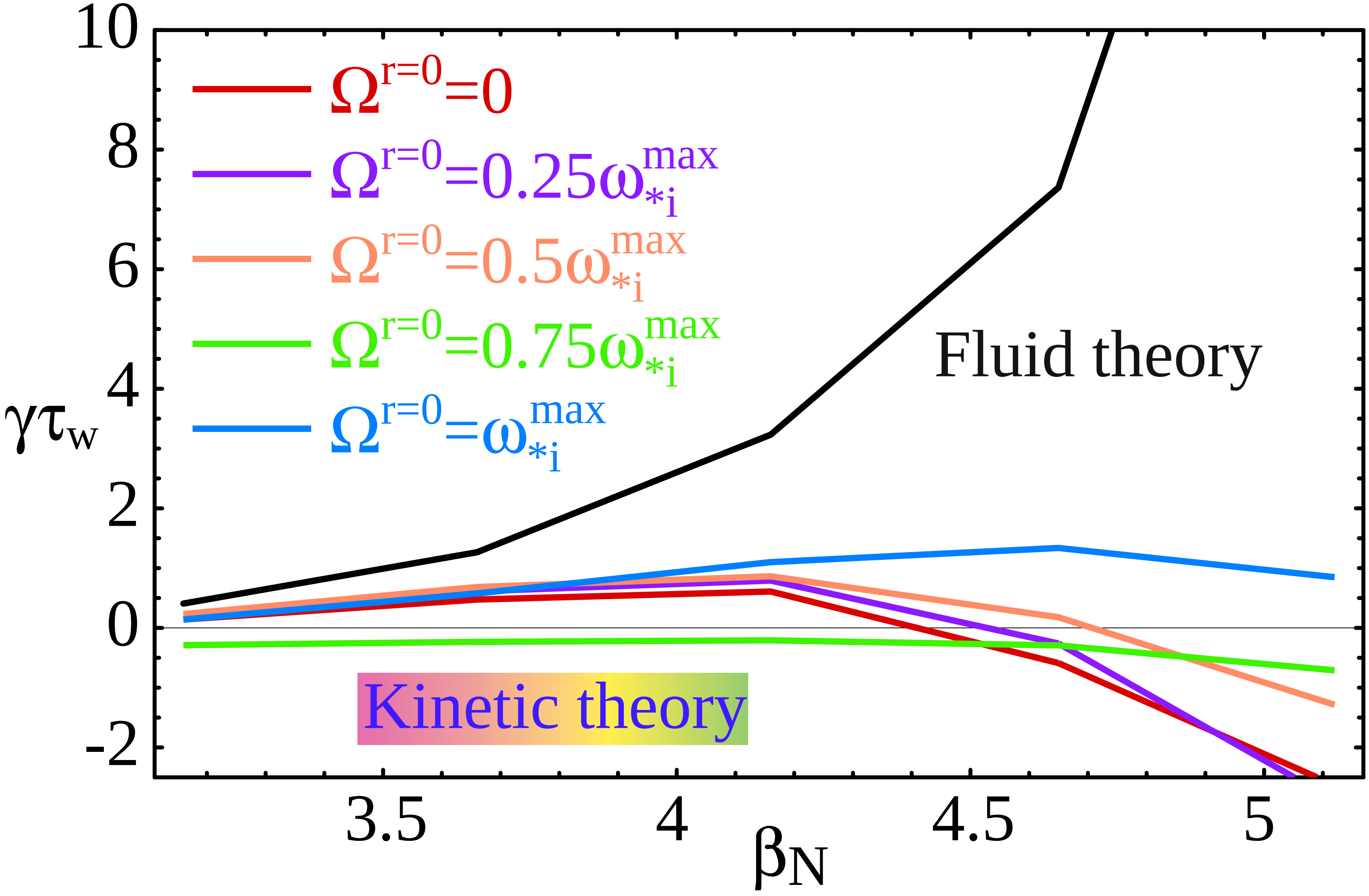


Precession drift frequency ω_D for zero-pitch-angle thermal ions



RWM growth rates of ITER with blanket for different rotations using PEST

Parabolic rotation profile



Remarks

- Trapped particles have significant influence on resistive wall mode
- Pressure gradient significantly reduces ω_D at high β
- Alpha particle contribution can be comparable to those from ions and electrons in fusion reactors.

Acknowledgements

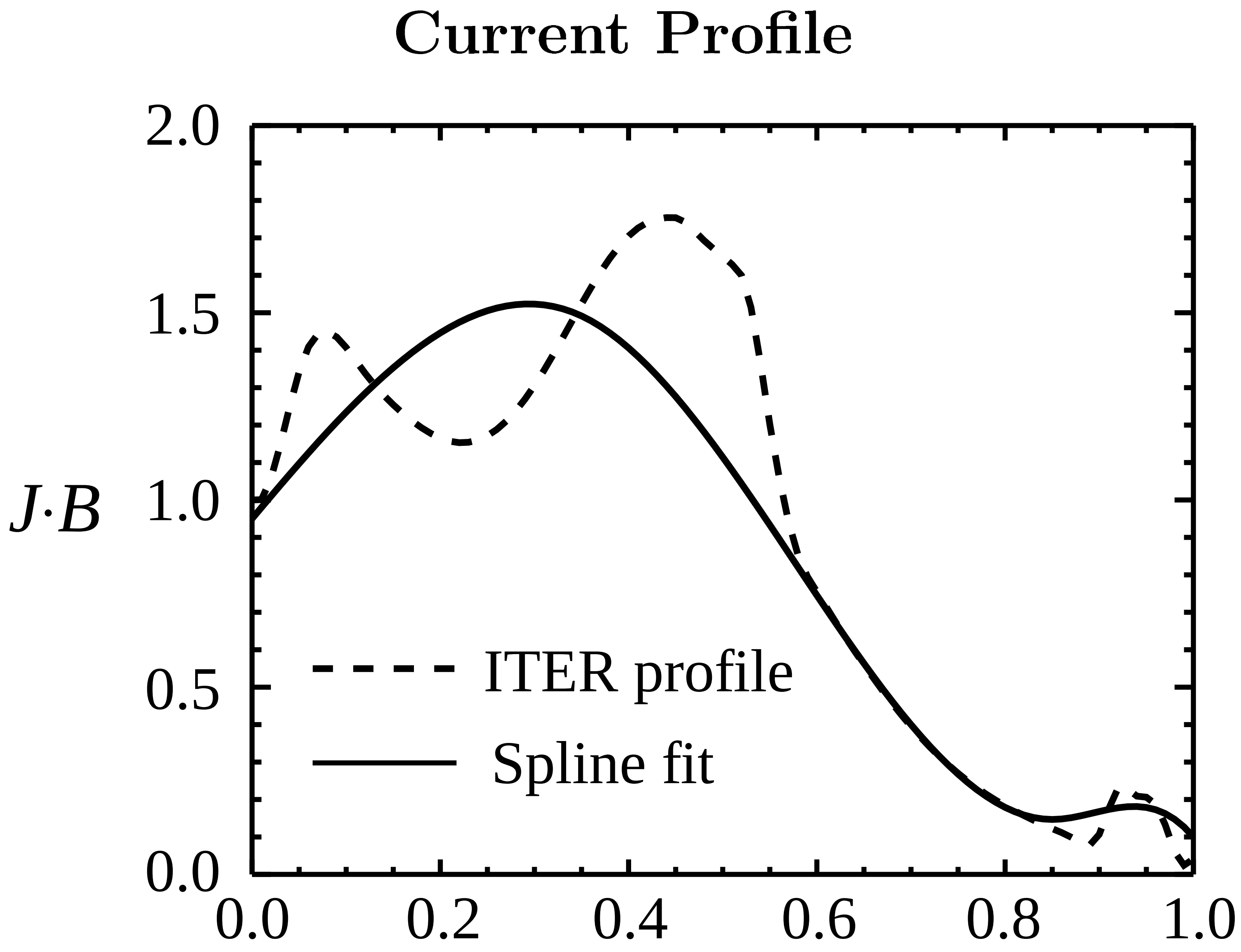
- This work was supported by the US Department of Energy under contract No. DE-FG02-93ER54215 and DE-AC02-76CH03073.
- Thanks to J.P. Freidberg for his suggestion on using MHD code.

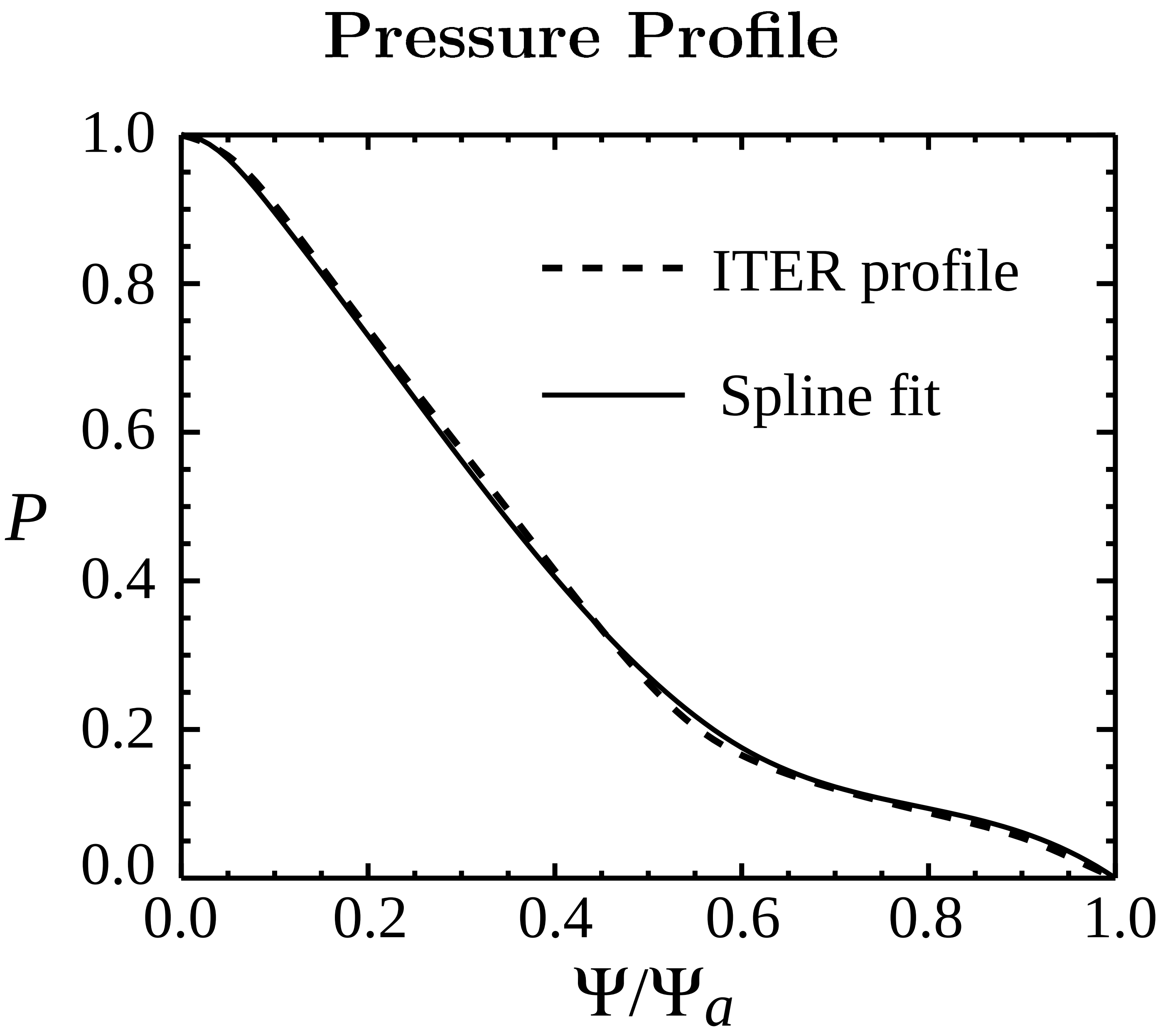
Calculate $\boldsymbol{\delta W_K}$

$$\delta W_K^{i,e} = \sqrt{\frac{\pi}{2}} \int \frac{d\Psi}{B_0} P_{i,e} \int d\Lambda \hat{\tau}_b \int_0^\infty d\hat{\varepsilon} \hat{\varepsilon}^{1/2} e^{-\hat{\varepsilon}} \lambda_{i,e} | \langle \boldsymbol{\kappa} \cdot \boldsymbol{\xi} \rangle |^2$$

$$\lambda_{i,e} = \frac{\omega_{*N}^{i,e} + (\hat{\varepsilon} - 3/2)\omega_{*T}^{i,e} + \omega_E}{\left\langle \omega_D^{i,e} \right\rangle + \omega_E - i\nu_{eff}}$$

$$\begin{aligned} \delta W_K^{\alpha} \ &= \ \frac{3\pi}{2^{5/2}} \int \frac{d\Psi}{B_0} P_\alpha \int d\Lambda \hat{\tau}_b \int_0^1 d\hat{\varepsilon} \frac{\hat{\varepsilon}^{5/2}}{\hat{\varepsilon}^{3/2} + \hat{\varepsilon}_c^{3/2}} \\ &\quad \times \frac{\omega_{*N}^{\alpha}}{\langle \omega_D^{\alpha} \rangle + \omega_E} \left(\frac{\varepsilon_\alpha}{T_\alpha} \right)^2 | \langle \boldsymbol{\kappa} \cdot \boldsymbol{\xi} \rangle |^2 \end{aligned}$$


Current Profile
$J{\cdot}B$
2.0
1.5
1.0
0.5
0.0
0.0
0.2
0.4
0.6
0.8
1.0
Ψ/Ψ_a
ITER profile
Spline fit


Pressure Profile
1.0
0.8
0.6
0.4
0.2
0.0
P
ITER profile
Spline fit
0.0
0.2
0.4
0.6
0.8
1.0
Ψ/Ψ_a