Alfven Eigenmode stability with beams and alpha-particle profile quasilinear relaxation in ITER

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W60 Burning plasma workshop, July, 2005, Tarragona

PRINCETON PLASMA PHYSICS LABORATORY

Outline

✓ Linear theory on AE stability:

- Use linear NOVA codes:
  NBI contributes to the TAE drive in ITER plasmas (Gorelenkov, NF, EPS'04).

✓ Operational limits for ITER due to TAEs

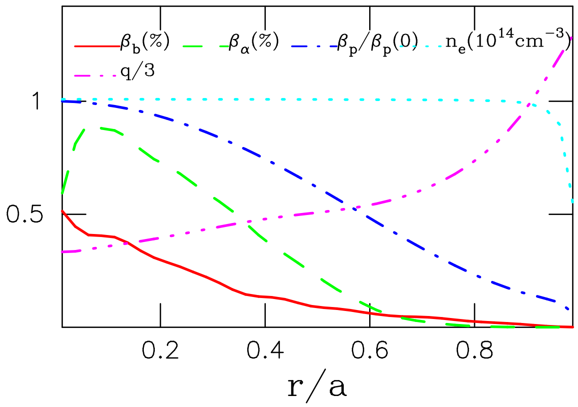
Mail goal:

<u>How can we answer the question today:</u>
<u>what is the expected alpha particle profile will be in ITER?</u>

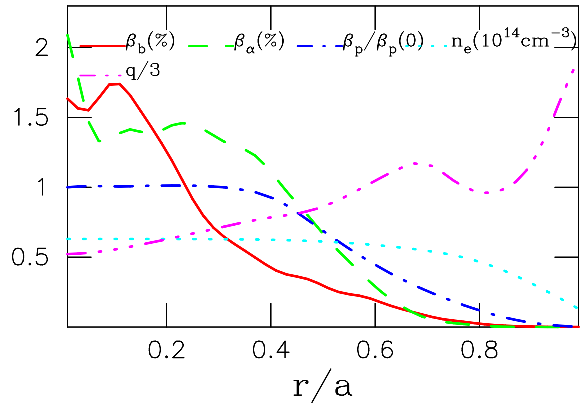
Three ITER plasmas will be studied

PPPL

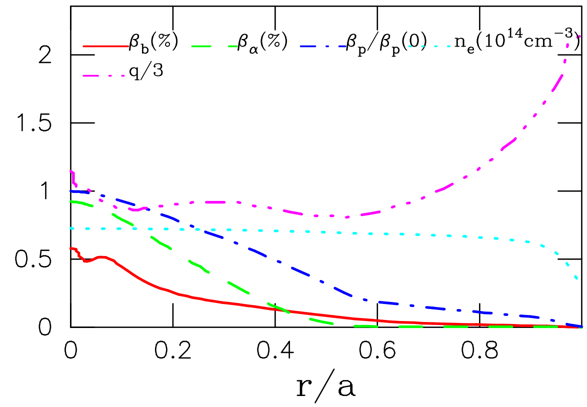
Normal shear



Hybrid



Reversed Shear



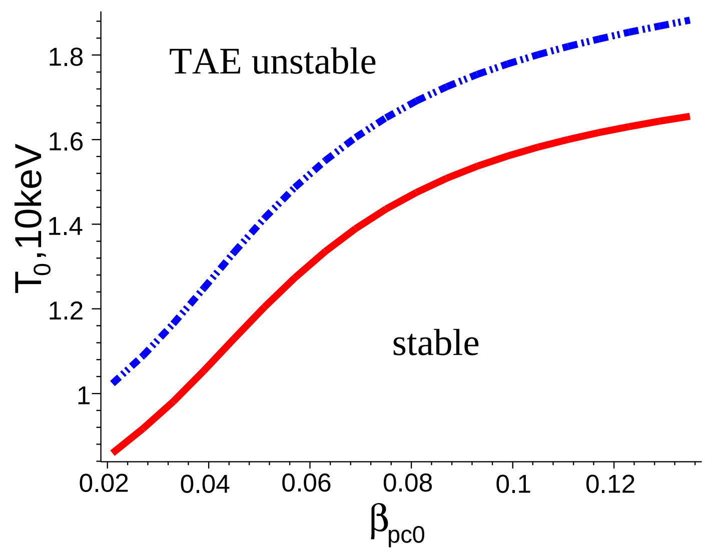
Normal shear plasma with NBI on-axis (TRANSP, R.Budny) $T_{i0} = 19.5keV$, $R_0 = 6.2m$, $a = 2m$, $P_{NBI} = 33MW$ at energy $E_{b0} = 1MeV$, $B_0 = 5.3T$, $\beta_0 = 6.7\%$

Hybrid plasma (TRANSP, R.Budny) $T_{i0} = 33keV$, $\beta_0 = 9.2\%$

Reversed shear plasma (ASTRA, A. Polevoi) $T_{i0} = 25keV$, $\beta_0 = 6.3\%$

Analytical stability domain in $T-\beta$ space for BP

$PPPL$



The stability diagram in the plasma temperature -beta plane for $\eta = 1$ and $\sigma_i = 1$ (solid curve), $\sigma_i = 0.8$ (dash-dotted curve) is similar for BP ($\sigma_i = (n_D + n_T)/n_e$).

Hybrid Ideal MHD/kinetic code NOVA-K is used for linear AE stability calculations

NOVA (Cheng JCP,'87) and NOVA-K (Cheng PhR,'92) codes are used:

✓ NOVA uses analytical input or from TRANSP for plasma parameters

✓ Mode structure is computed within ideal MHD (NOVA)

✓ Perturbative kinetic mode analysis is performed with NOVA-K code

✓ Fast ion drive includes:

- finite orbit width (FOW) and FLR effects (Gorelenkov PoP,'99)
- advanced distribution function model for beam ions

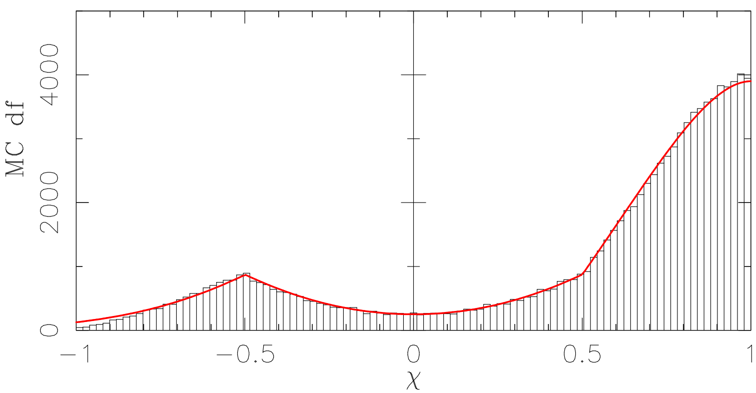
✓ Damping mechanisms included are

- ion/electron Landau
- radiative
- trapped electron collisional
- perturbative continuum damping model

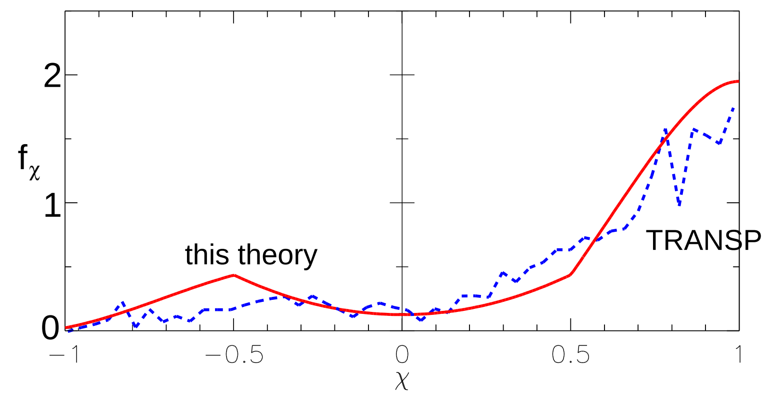
Beam ion distribution function model includes collisional Lorentz scattering

PPPL

Truncated image method vs. Monte-Carlo



TRANSP Lorentz diffusion operator is consistent with image method



Distribution function at $r/R = 1/8$, and $\chi_s = 0.5$, $\chi_0 = 0.8$, $v_*/v_{b0} = 0.48$, $v/v_{b0} = 0.5$ (Gorelenkov NF'04).

Anisotropy drive depends on this model.

Linear results NOVA-K for AEs in ITER

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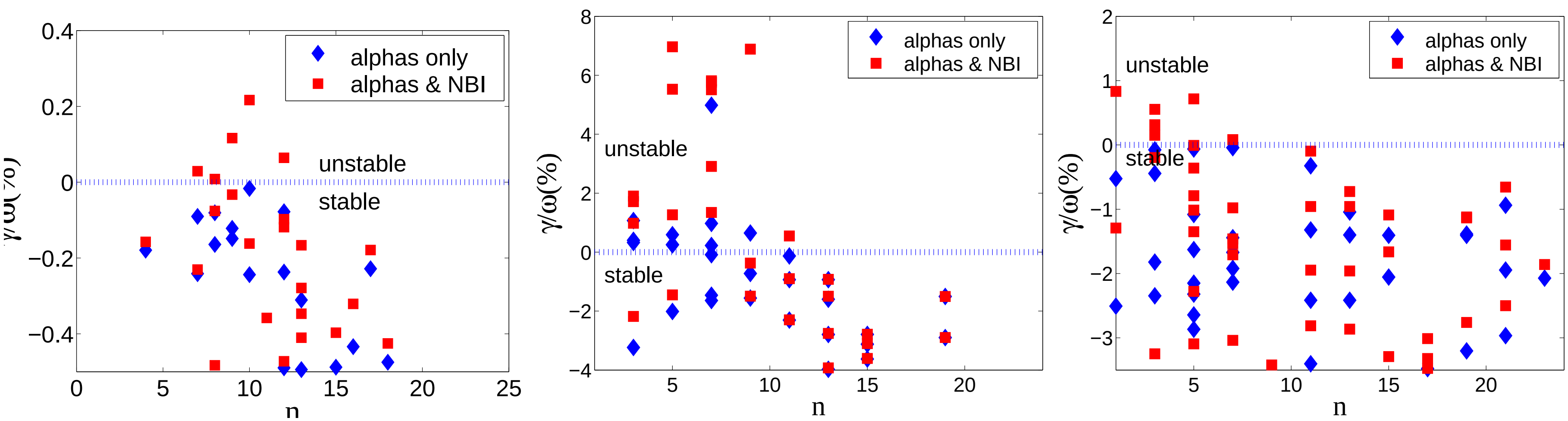
normal shear — $T_{io} = 19.5keV$

hybrid — $T_{i0} = 33keV$

reversed shear — $T_{i0} = 25keV$

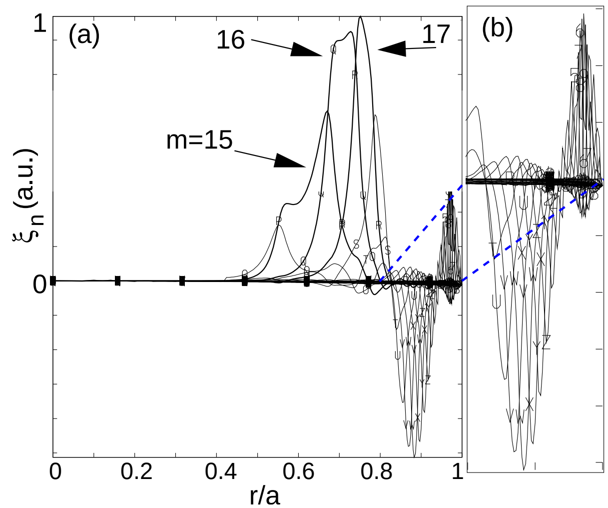


✓ TAEs contribute to the most of the drive.

✓ In ITER $1MeV$ tangentially injected beam ion drive is comparable with the $\alpha-$drive.

- Lowering NBI energy to $0.5MeV$ reduces the beam ion drive.
- $0.5MeV$ energy is enough for good beam penetration.

Example of one unstable $n = 10$ mode in normal shear



Growth rates for nominal $T_{i0} = 20keV$, $0.55m$ off-axis heating.

Ω^2	$\gamma_{ecoll}/\omega(\%)$	$\gamma_{iLand}/\omega(\%)$	$\gamma_{rad}/\omega(\%)$	$\gamma_{\alpha}/\omega(\%)$	$\gamma_{beam}/\omega(\%)$	$\gamma_{\Sigma}/\omega(\%)$
0.96	-0.18	-0.61	-0.43	0.82	0.71	0.31

Injection geometry stabilization of TAE beam ion drive

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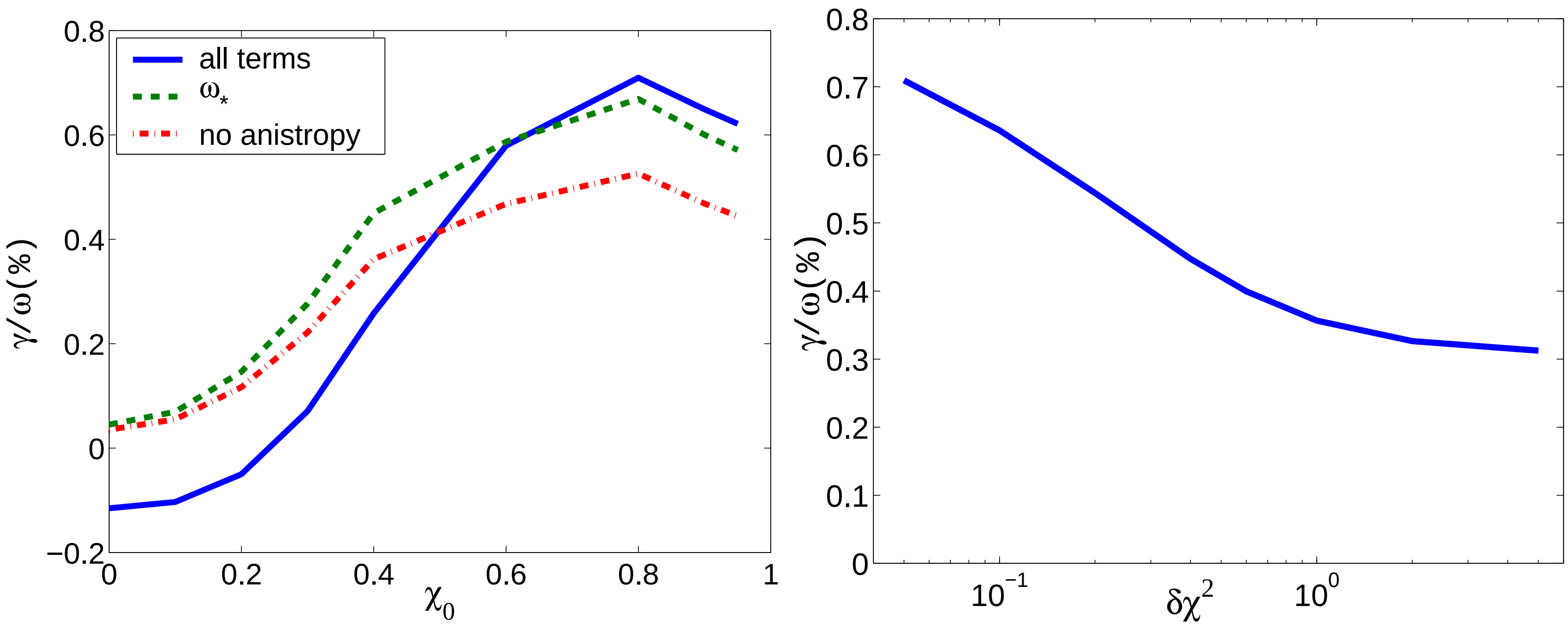
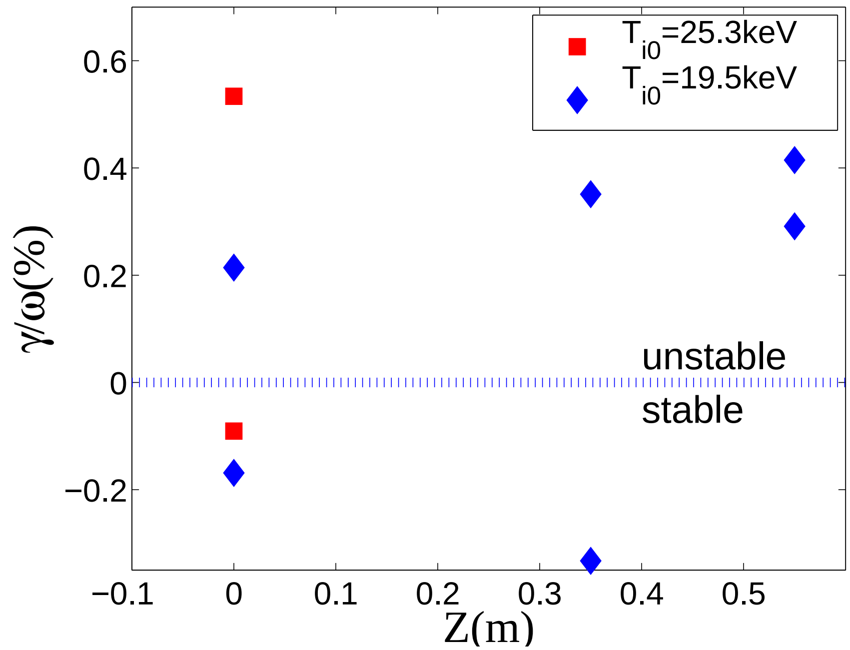
Pitch angle distribution changes trapped to passing ion ratio: $|\chi_0| < \sqrt{2\epsilon}$ is trapped ion domain, and higher $\chi_0 \Rightarrow$ more passing particles

NOVA-K on the drive sensitivity to the pitch angle distribution.

fix $\delta\chi^2 = 0.05$ fix $\chi_0 = 0.9$



Another way to control TAE stability via the vertical scan of NBI and T_{i0}



More TAE unstable plasmas if :

✓ Ion temperature is increased with nominal near threshold at $T_{i0} = 20keV$ (at on-axis NBI)

✓ NBI injection is off-axis $\Rightarrow$ beam beta gradient is larger at $r/a > 0.5$.

✓ Typical drive is $\gamma_\alpha + \gamma_{NBI} \sim 1 - 3\%$.

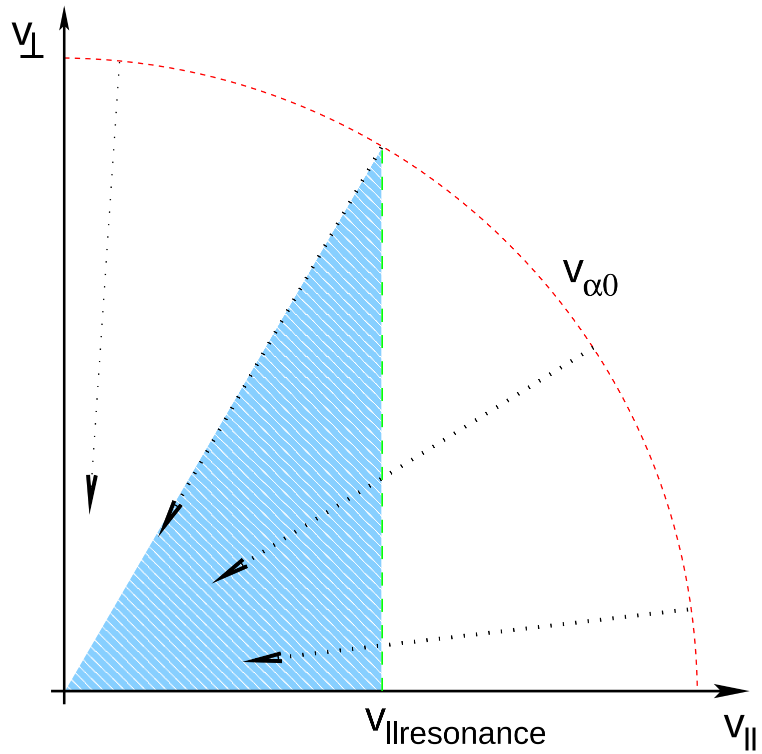
Quaslinear transport model:
How much of alphas population is effected?

Maximum effect from instabilities with $v_{\|}$ resonance

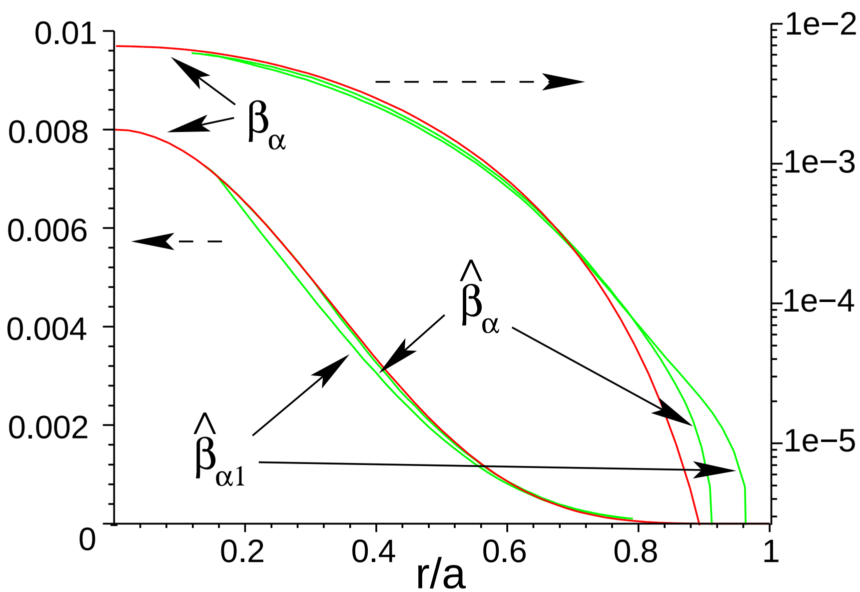
Fraction of effected alpha power (Kolesnichenko '80)

$$P_{\alpha res} = P_\alpha \left(v_{\alpha 0} - v_{\|}\right) v_{\|} / v_{\alpha 0}^2 \leq 25\%$$

Other particles should not interact with such instabilities



Expected effects on alphas profiles (normal shear)



Assume:

- ✓ Quasilinear theory is applicable
- ✓ α's are expected to be redistributed
- ✓ β_α is equilibrium profile
- ✓ $\hat{\beta}_\alpha$ is final profile with near threshold gradient
- ✓ $\hat{\beta}_{\alpha 1}$ is at critical beta at 0.7 of theoretical beta critical

Prescription:

$$\frac{\partial \beta_{\alpha cr}}{\partial r} = -\frac{\gamma_{iL} + \gamma_{ecoll}}{\gamma\prime_\alpha}, \;\; \gamma_\alpha\prime = \gamma_\alpha / \left(\partial \beta_\alpha / \partial r\right)$$

Use the phase space particle conservation law $\int_0^a r \left(\beta_\alpha - \hat{\beta}_\alpha\right) dr = 0$

This model can also predict losses of alphas

at high alphas beta losses are expected:

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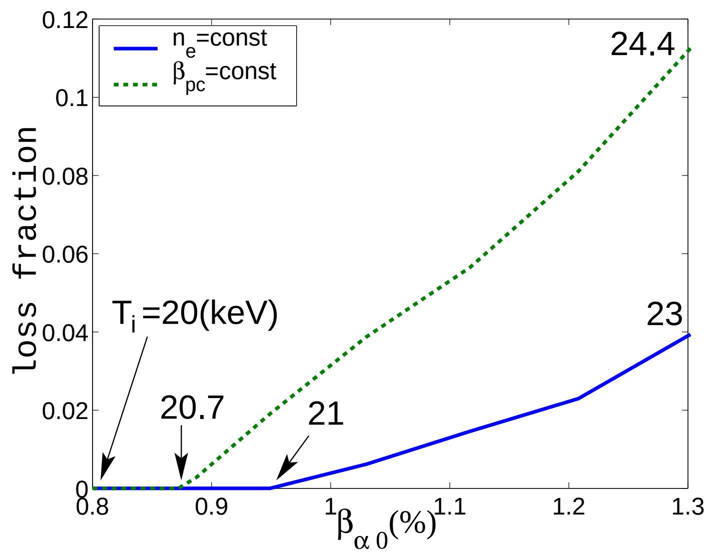
1% alpha's central beta is threshold

5% of all alphas is tolerable for ITER (Putvinskii, NF '99)

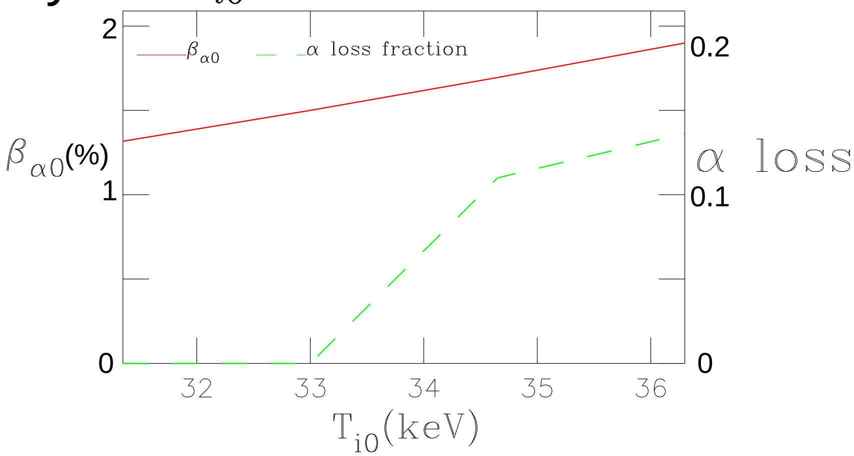


Regular shear plasma in ITER with quasilinear diffusion will be benign to TAE effects

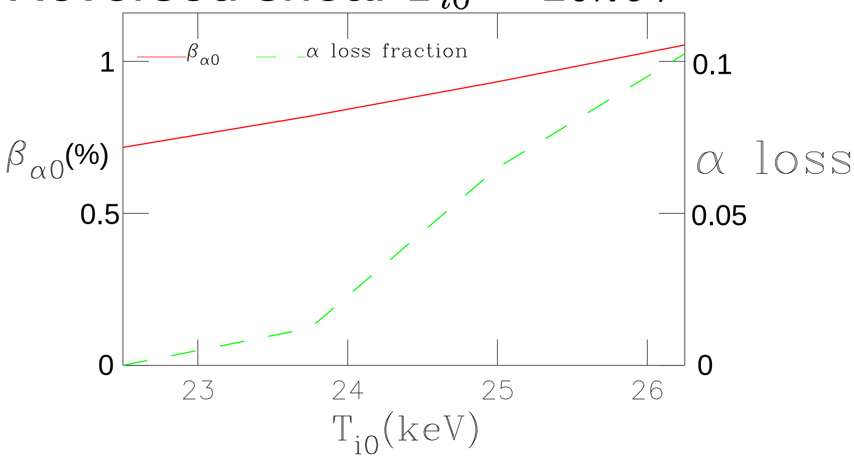
Losses are calculated at fixed beta with ion temperature within $20 < T_{i0}(keV) < 24$ ($\beta_{\alpha 0} \sim T_{i0}^{5/2}$) and density $20 < T_{i0}(keV) < 23$ ($\beta_{\alpha 0} \sim T_{i0}^{7/2}$).

Alpha losses in other ITER scenarios

Hybrid $T_{i0} = 33keV$



Reversed shear $T_{i0} = 25keV$



Use constant plasma beta scan $\beta_\alpha \sim T_i^{5/2}$.

Quasilinear/local TAE theory predicts ITER operating point to be near TAE thershold but rather benign.

SUMMARY

1. Linear NOVA-K simulations predict AEs to be marginally stable in ITER due to fusion alphas.
2. ITER NBI at 1MeV strongly contributes to TAE instability drive comparable to fusion alphas drive.
3. With off-axis injection beam ion beta profile becomes hollow and the space gradient of beam beta increases for $r/a > 0.5$ leading to a stronger drive.
4. Hybrid ITER plasma is the most unstable due to large alpha particle beta $\beta_{\alpha 0} = 1.64\%$ with the growth rate up to 6%. Perturbative theory may not be applicable.
5. A quasi-linear model for alpha particle TAE induced transport predicts the effect of TAEs will be tolerable without imposing large operational restrictions in ITER operating regimes.