Turbulence at High Plasma β

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Gyrokinetics for ITER

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Motivation and Experimental Results

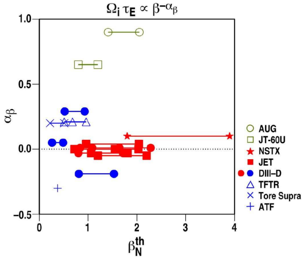
Definition

$$\beta \equiv \beta_e = \frac{8\pi n_{e0} T_{ref}}{B_{ref}^2}$$

Features in

- bootstrap fraction $\propto \beta$
- fusion reaction rate $\propto \beta^2$
- (kinetic) ballooning threshold
- magnetic fluctuations and transport

β scalings of confinement time differ:



- JET ’04: no β dependence
- ASDEX ’07: $\propto \beta^{-1}$
- JET ’08: $\propto \beta^{-1.4}$

But: fixing parameters difficult

GENE and Previous Results

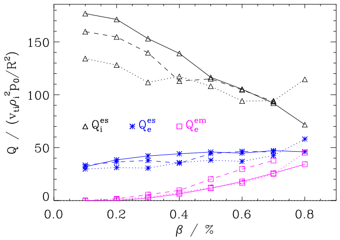
The GENE code
www.ipp.mpg.de/~fsj/gene

- nonlinear gyrokinetic equations
- multiple fully kinetic particle species
- collisions and electromagnetic effects
- linear Eigenvalue solver
- radially local and nonlocal modes
- open source

Previous gyrokinetic simulations:

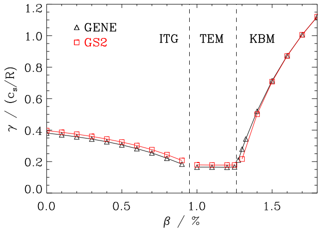
Jenko 2001, Parker 2004, Dannert 2004, Candy 2005, Pueschel 2008

Good agreement:

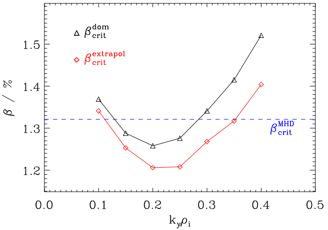


Growth Rates and KBM Onset

Linear analysis
(here: $k_y = 0.2$):
depending on β, one gets dominant **ITG**, **TEM**, or **KBM**

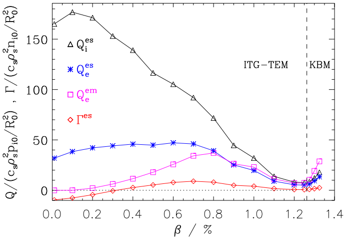


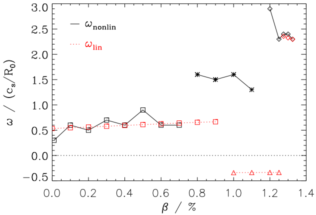
KBM threshold:
destabilization at β_{crit}

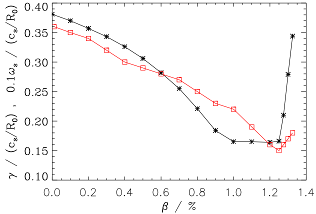


- minimal β_{crit} at nonlinear transport peak
- gradient dependence: only ω_{Ti} significant, β_{crit} increases strongly for low values, exceeds $\beta_{\text{crit}}^{\text{MHD}}$

Nonlinear Transport Levels



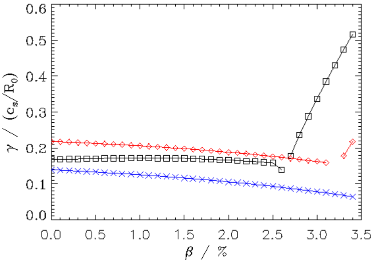


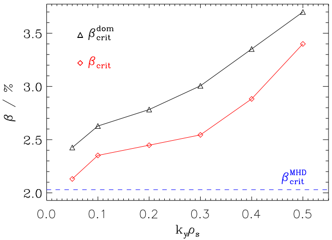


$\Rightarrow$ regimes not same as linear; high-β **transport drop**: mode interaction (Merz 2008) and zonal flows

Growth Rate and KBM Onset

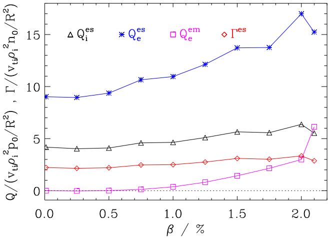
Density gradient driven trapped electron mode:





- KBMs appear first at lowest k_y
- no KBMs appear in the MHD stability regime

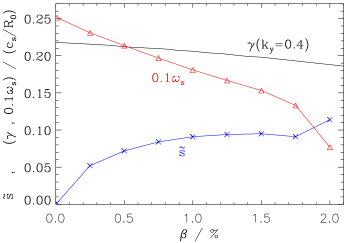
Transport and Zonal Flows



Zonal flows are able to bridge the linear-nonlinear gap

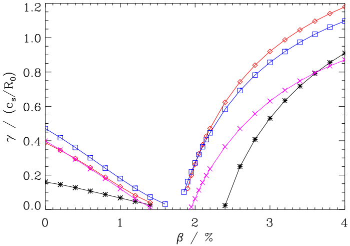
$\Rightarrow$ **different behavior**: slight decrease linearly, increase nonlinearly

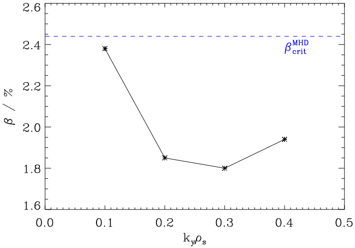
KBM threshold: same as linear threshold



Growth Rate and KBM Onset

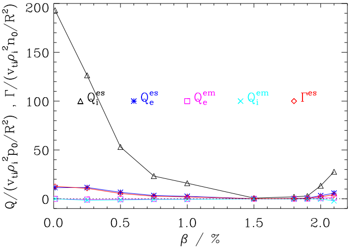
Pure ITG scenario ($\omega_{Te} = 0$),
designed to have gap at intermediate β
between ITG and KBM





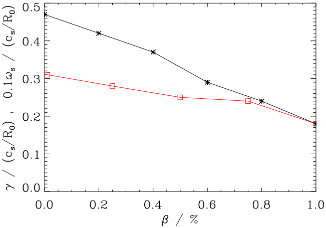
$\Rightarrow$ same as for Cyclone, except for missing TEM regime

Transport and Zonal Flows



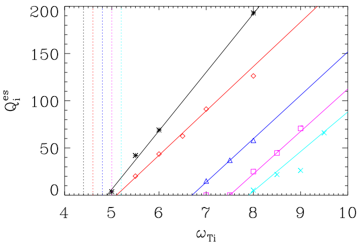
⇒ much **stronger decline nonlinearly** with β,
KBM onset at the same β_{crit}

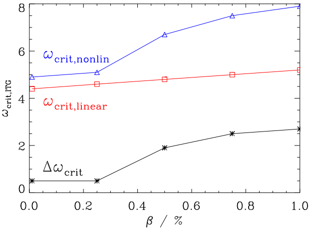
Zonal flow impact on the transport curve:



Sufficient to explain drop?

Dimits Shift Study





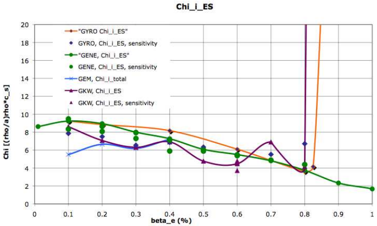
$\Rightarrow$ The **nonlinear upshift** of the critical gradient is **increased** for rising β values

Are zonal flows sufficient to explain this effect?
(work in progress)

Note: one single runoff case was found

Transport Runoff

CBC runoff ($\beta \approx 0.85\%$): no saturation, transport at smallest k_y
Benchmark effort of gyrokinetic codes underway (Bill Nevins):



$\Rightarrow$ **good agreement** on runoff threshold
GENE findings: “stable” region around $\beta \sim 1.2\%$
How to avoid: initial condition; β ramp-up
How not to avoid: larger box, higher resolution

Applications

The radial magnetic field fluctuation B_x influences, e.g.:

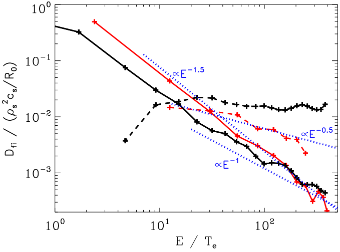
Model for electron heat transport along **perturbed field lines**:

Test particle transport model

$$\chi_e^{em} = q_0 R \left(\frac{T_e}{m_e}\right)^{1/2} \langle B_x^2 / B_{ref}^2 \rangle$$

Redistribution of NBI ions in turbulence (Hauff 2009):

$$D_{em} \propto B_x^2 \, E_{beam}^0$$



Fluctuation Levels

Using β scans to fit straight lines to data:

$$\frac{B_x}{B_0} = \mathcal{C}_x \frac{\beta}{\beta_{\mathrm{crit}}^{\mathrm{KBM}}} \frac{\rho_{\mathrm{i}}}{R_0}$$

$\Rightarrow$ fluctuations strongest for **ITG** turbulence

Radial Fluctuations

$$\begin{aligned} \mathcal{C}_{x,\mathrm{CBC,ITG}} &\sim 0.8 \\ \mathcal{C}_{x,\mathrm{ITG}} &\sim 0.8 \\ \mathcal{C}_{x,\mathrm{CBC,TEM}} &\sim 0.4 \\ \mathcal{C}_{x,\mathrm{TEM}} &\sim 0.2 \\ \mathcal{C}_{x,\mathrm{MT-Doerk}} &\sim 0.2 \end{aligned}$$

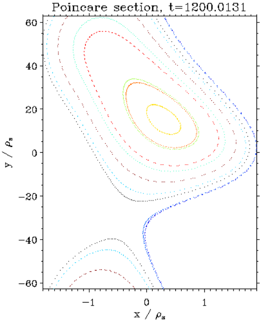
(**caveat**: CBC has no pure nonlinear TEM)

For the corresponding, $\mathcal{C}_y$, slightly higher results are obtained

Field Line Integration

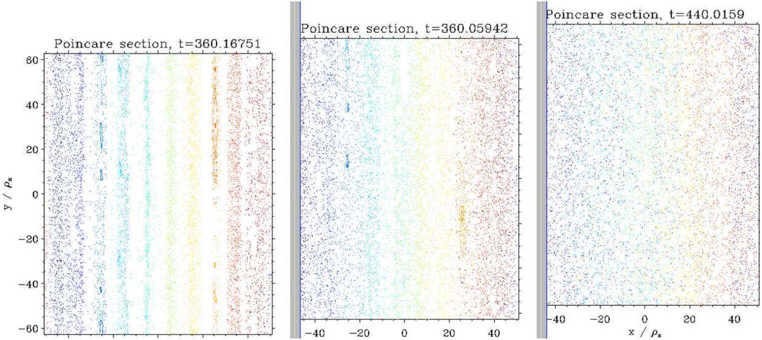
Integration Scheme

- interpolate $B_{x,y}(x, y, z)$
- seed lines at $z = 0$
- obtain $B_{x,y}(\text{lines})$
- calculate new position at $\Delta z/2$, obtain $B_{x,y}$
- use new field at old position



- integrated with the GENE Diagnostics Tool
- optimized
- benchmarked (Bill Nevins)

Flux Surface Destruction



$\Rightarrow$ flux surfaces **disintegrate** at moderate β
nonlinearly, islands are destroyed even at low β
stochastization **independent** of runoff, transport
Application: (micro-)tearing, reconnection

$B_{\|}$: Equations

If $B_{\|}$ is not neglected, have coupled Φ-$B_{\|}$ system ($A_{\|}$ remains decoupled):

$$\begin{aligned}
\Phi &= \bar{C}_3 M_{00} - \bar{C}_2 M_{01} \\
B_{\|} &= \bar{C}_1 M_{01} - \bar{C}_2 M_{00} \\
M_{00} &\sim \sum_j \int J_0 g_j \mathrm{d}^3 v \\
M_{01} &\sim \sum_j \int \mathcal{I}_1 g_j \mathrm{d}^3 v
\end{aligned}$$

Coupling in Vlasov equation via: $\chi = \Phi - v_{Tj} v_{\|} A_{\|} + \mu T_j^{-1} q_j^{-1} B_{\|}$ and via modified FLR corrections to the moments

Independently at high β: equillibrium $j_{0\|}$ effects

$B_{\|}$: Transport and Impact

New $B_{\|}$ component of the (electromagnetic) particle flux:

$$\Gamma_j = -n_{j0}\left((\partial_y\Phi)\mathcal{M}_{00} - v_{Tj}(\partial_y A_{\|})\mathcal{M}_{10} + T_{j0}q_j^{-1}B_0^{-1}(\partial_y B_{\|})\mathcal{M}_{02}\right)$$

Impact: typically, $\Delta\gamma \sim 10-20\%$ is observed near the KBM limit
Stellarators ($\beta \sim 5\%$) and astrophysical applications (e.g., $\beta \gtrsim 1$) can have strong $B_{\|}$ contributions

Computational effort: $\sim 2\%$ more

What is done in GS2?

Points for Discussion

- role of **zonal flows** at large β (Maxwell stress ...)
- **Dimits shift**: what causes the sudden change?
- magnetic **fluctuations**: universality, dependence on parameters
- magnetic **surfaces**: quantitative approaches, effect on turbulence
- **runoff** causes, prevention
- $B_{\|}$: impact, magnetic transport definitions