Turbulence stabilization due to high beta and fast ions in high performance plasmas at ASDEX Upgrade and JET
Acknowledgements

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Outline

- High beta $\beta_s = 8\pi p_{0s}/B_0^2$ is essential for fusion performance (but MHD stability set upper limit)
- Scaling of the energy confinement time $\tau_E$ with $\beta$ is not clear
- $\tau_E$ is limited by plasma turbulence

Theoretical foundation:
- gyrokinetic modeling
- impact of $\beta$ and fast ions ($\beta_{\text{fast}}$)

Analyzing turbulence in experimental scans using gyrokinetic code GENE [Jenko PoP2000]

I) A beta-scaling experiment at ASDEX Upgrade
II) A power scan at ASDEX Upgrade
III) A power scan at JET-ILW (advanced inductive)

Summary and conclusions

www.genencode.org
developed at IPP, Germany
UCLA, LA, USA
UT Austin, USA
EPFL Lausanne Switzerland
CHALMERS, Gothenburg, Sweden
Electromagnetic effects in gyrokinetic turbulence modelling
The gyrokinetic equations solved in GENE

- **Vlasov equation**
  (for each species)

\[
\frac{\partial_t f_{1}}{1} + \left( v_{\parallel} b_0 + \frac{B_0}{B_0^*} (v \nabla \times B + v \nabla B + v_c) \right) 
\cdot \left( \nabla f_{1} + \frac{1}{m v_{\parallel}} (q E_1 - \mu \nabla (B_0 + \bar{B}_1)) \frac{\partial f_{1}}{\partial v_{\parallel}} \right) = \langle C[f] \rangle
\]

- **Gyrokinetic (GK)**
  Maxwell equations
  (incl. FLR terms)

\[
\begin{align*}
\nabla_{\perp}^2 \phi & = -8 \pi^2 \sum_j \frac{q_j B}{m_j} \int dv_{\parallel} d\mu \left( J_0 f_{1j} + \frac{F_{0j}}{T_{0j}} ( (J_0^2 - 1) q_j \phi + \mu J_0 I_1 B_{1||} ) \right) \\
\nabla_{\perp}^2 A_{1||} & = - \frac{8 \pi^2}{c} \sum_j \frac{q_j B}{m_j} \int dv_{\parallel} d\mu v_{\parallel} J_0 f_{1j} \\
B_{1||} & = -8 \pi^2 \sum_j \frac{B}{m_j} \int dv_{\parallel} d\mu \left( \mu I_1 f_{1j} + \frac{F_{0j}}{T_{0j}} ( q_j J_0 I_1 \phi + \mu I_1^2 B_{1||} ) \right)
\end{align*}
\]
The gyrokinetic equations solved in GENE

- **Vlasov equation** (for each species)

- **Gyrokinetic (GK)**
  Maxwell equations

\[
\frac{\partial_t f_1 + \left( v_{\parallel} b_0 + \frac{B_0}{B_{0\parallel}} (v \nabla \times B + v \nabla B + v_c) \right)}{v_{\parallel}} \cdot \left( \nabla f_1 + \frac{1}{mv_{||}} (qE_1 - \mu \nabla (B_0 + \vec{B}_{1\parallel})) \frac{\partial f_1}{\partial v_{||}} \right) = \langle C[f] \rangle
\]

- **Comprehensive physics:**
  Linearized Landau-Boltzmann collisions, ExB + parallel flow shear, experimental geometry, global and local version

- Arbitrary number of kinetic species, incl. impurities + fast ions

- Delta-f method: \( f_{0s} = F_{Ms} + f_{1s} \)
  (for now: \( F_{0,\text{fast}} = F_{M,\text{equiv}} \))

- Typical domain \( L_x \sim 250\rho_s, L_y \sim 120\rho_s, L_{v||} \sim L_{v\perp} \sim 3v_{\text{th}} \)

  192x48x32x48x16x4 \( \sim 10^9 \) grid cells for \( x,y,z,v,\mu \) and species

- Expensive simulations (150k CPUh per nonlinear run)

**Nonlinear solution requires modern supercomputers**
• **Geometric effects**: (Change Grad-Shafranov magnetic equilibrium)

\[
\alpha = -q^2 R \beta \nabla p_0 / p_0
\]

\[
\partial_t f_1 + \left( v_{\parallel} b_0 + \frac{B_0}{B_0^{*\parallel}} (v \nabla \times B + v \nabla B + v_c) \right) \cdot \left( \nabla f_1 + \frac{1}{mv_{\parallel}} (qE_1 - \mu \nabla (B_0 + B_1^{\parallel})) \frac{\partial f_1}{\partial v_{\parallel}} \right) = \langle C[f] \rangle
\]

• **Dynamical effects**, plasma response:

- \( \beta > 0 \) allows for magnetic fluctuations
- modified electric field

\[
\tilde{E}_{1^{\parallel}} = -\nabla_{\parallel} \tilde{\phi}_1 - \frac{1}{c} \frac{\partial \tilde{A}_{1^{\parallel}}}{\partial t}
\]

- modified ExB drift velocity

\[
v \nabla \times B = \frac{c}{B^2} B \times \nabla \left( \tilde{\phi}_1 - \frac{1}{c} v_{\parallel} \tilde{A}_{1^{\parallel}} + \frac{1}{q_j} \mu \tilde{B}_{1^{\parallel}} \right)
\]

• **Fast ions** (NBI, ICRH, Fusion alphas) contribute to **geometry** and **dynamics**

\[
\beta_{\text{tot}} = \beta_{\text{th}} + \beta_{\text{fast}}
\]

**Modification** of electrostatic instabilities: **ITG / ETG, TEM**
[Ion/Electron Temperature Gradient driven instability, Trapped Electron Mode]

**New instabilities**: **KBM, MTM, BAE**
[Kinetic Ballooning Mode, MicroTearing Mode Beta-induced Alfven Eigenmode]
(+){increasing $\beta$ ($\alpha$) can reduce transport:}

- **ITG** transport reduction
  - Linear: adds Alfvénic polarization [Kim PoP' 1993]
  - Nonlinear: increased zonal flow coupling [Pueschel PoP'08]

- **EM fast ion** stabilization: [Romanelli PPCF’10, Holland NF’12, Citrin PRL’13, Citrin PPFC’14, Garcia NF’15]

- **ETG** stabilization in the edge [Jenko PPCF’01]

(-){increasing $\beta$ can enhance transport:}

- Magnetic transport in ITG turbulence [Pueschel PoP’08] due to **nonlinearly excited MTMs** [Hatch PRL’13]

- **MTM** turbulence: $\chi_e$ [Doerk PRL’12, Guttenfelder PRL’12]

- **KBM** turbulence: Initial gyrokinetic results [Pueschel PoP 2008, Maeyama NF 2014]

- **Fast particle** driven turbulence [e.g. Bass PoP’10]

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Which of the effects is relevant for experiments?
Gyrokinetic analysis of an ASDEX Upgrade beta scaling experiment
Main variation: $\beta_B = 1.9\beta_A$

- $\beta$ scan at constant $\rho^*,\nu^*$: $n \sim B^4$, $T \sim B^2$, $\beta \sim B^4$ [expected power scaling $Q_{gb} \sim P \sim B^7 \sim \beta^{7/4}$]
- Weak $\beta$-degradation: $\tau_E \sim \beta^{-0.2}$
- Reference position: $\rho_{tor} = 0.5$
- Imperfect measurements, but relevant turbulence regime can be investigated
Microturbulence regimes in AUG $\beta$ scan: $\rho_{\text{tor}}=0.5$

- **$\beta$ scan** (fixed geometry): transition of unstable ITG - MTM - KBM in both cases
- Ratio $\beta/\beta_{\text{crit}}$ reaches 20% (A) and 40% (B)
  - KBM is stable
- Nonlinear simulations: little MTM transport even in high beta case

Main $\beta$-effect: ITG-stabilization
ITG turbulence simulations at $\rho_{\text{tor}} = 0.5$

Steeper gradients due to $\beta$
Gyrokinetic analysis of ASDEX Upgrade power scan experiments thanks to P. Schneider et al.
Hybrid power scans at AUG and DIII-D [Maggi NF 2010]

Hybrid scenario
- aka: advanced inductive
- Flat q, low shear in the center
- Low density, Low current
- High $\beta_n = \langle \beta \rangle a B_0 / I$
- High fusion gain expected
- Discussed for ITER operation

Previous work (C-wall components) [Maggi NF 2010]
AUG and DIII-D power scans
- $\tau_E$ improves (pedestal and core contributions)
- GK analysis: $\beta$ effects are pronounced

Refinement is scheduled for 2015 AUG campaign
For now: AUG 23227 power scan (W-Wall)

- $n_e$ decreases by 15%, $\beta_N$ increases from $\sim 1.2$ to $\sim 2.4$
- Fast ion pressure increases with power
- $\tau_E \sim 0.08s$ similar (slightly improved at high $\beta_N$)
- Larger $a/L_{Ti}$ at outer radii → reference position $\rho_{tor}=0.7$

Test for $\beta$, ExB, and fast ion effects
Evidence for stabilizing role of fast ions

**Low power**
- $\beta/\beta_{\text{crit}}=23\%$
- little $\beta$-stabilization of ITG
- no impact of fast ions and (N impurities)

**High power**
- $\beta/\beta_{\text{crit}}=0.37 [0.57]$
- $\beta/\beta_{\text{crit}}$ is figure of merit for EM stabilization of ITG
- fast ions lower $\beta_{\text{crit}}$
Evidence for stabilizing role of fast ions

**Low power**
- Excellent **agreement** between power balance and GENE [already w/o fast ions and N]

**High power**
- Two species simulation is **inconsistent** with experiment

Evidence for stabilizing role of fast ions
Evidence for stabilizing role of fast ions

Low power
•Excellent agreement between power balance and GENE [already w/o fast ions and N]

High power
•Including fast ions is essential to reconcile exp. $Q_i$ (and $Q_e$)
•Minor impact of ExB flow shear

Evidence for stabilizing role of fast ions
Gyrokinetic analysis of a power scan in advanced inductive JET plasmas
• $\tau_E \sim P^{-0.30}$ in JET ILW at low triangularity $\delta$ ($\tau_{98y2} \sim P^{-0.69}$)

• Conversion to dimensionless: $\tau_E \sim \beta^{0.5}$ (sensitive: should be taken with care)

• C-wall GK results: EM + fast ion stabilization of turbulence at inner radii

What is the physics behind weaker power degradation?
• $\tau_E \sim P^{-0.30}$ in JET ILW at low triangularity $\delta$ ($\tau_{98y2} \sim P^{-0.69}$)
• Conversion to dimensionless: $\tau_E \sim \beta^{0.5}$ (very sensitive)
• C-wall GK results: EM + fast ion stabilization of turbulence at inner radii

What is the physics behind weaker power degradation?
Fast ions in JET hybrid plasmas (C-Wall)

(1) Increased **fast ion pressure** (inner core)

(2) Reduced **core** transport ($\beta$) + Enhanced **pedestal** stability (Shafranov-shift)

(3) Increased core temperature

(4) Increased $\beta$ ->(2)

-> Better confinement! **Limit:** fast ion transport due to **BAE/KBM turbulence**

**Positive core-edge feedback possible ILW?**
Strong β and fast ion effects in high power case

JET-ILW hybrid P scan (ρ=0.33): microinstabilities
KBM/ITG at low $k$; instabilities at high $k$ TEM/ETG are weak

• $\beta$-stabilization of ITG, very strong in high power case

• Multiple fast ion effects at high power:
  - **dynamic**: stabilization of ITG
  - enhanced KBM/BAE drive
  - **geometric**: stabilization of KBM/BAE

**Strong $\beta$ and fast ion effects in high power case**
JET-ILW hybrid P scan ($\rho=0.33$): thermal transport

Low Power (LP)

- $Q_i$ and $Q_e$ consistent with experiment
- Fast ions not important
- ITG is $\beta$-stabilized
JET-ILW hybrid P scan ($\rho=0.33$): thermal transport

**High Power (HP)**
- **ITG** strongly stabilized due to $\beta$
  (+**dynamic fast ion** effect, not shown)

**Strong $\beta$ stabilization at high power**
JET-ILW hybrid P scan ($\rho=0.33$): thermal transport

**High Power (HP)**

- **ITG strongly stabilized** due to $\beta$
  (+**dynamic fast ion** effect, not shown)
- **Transition** from ITG to KBM/BAE turbulence: $\beta>\beta_{\text{crit}}$

Strong $\beta$ stabilization at high power
Experimentally accessible (in principle):

- **Phase relations:**
  - (transport range $k_y\rho_s<0.7$)
    - ITG: $n\times \Phi \sim 0$
    - KBM $n\times \Phi \sim \pi$
    - note: interchange mode, $\pi/2$ expected
      [Manz PPCF’14, Scott PoP’05]

- **Frequency analysis (FFT)**
  - (in linear drive range $k_y\rho_s<0.4$)
    - KBM $\omega \sim c_s/a$
    - ITG $\omega \sim 0.2c_s/a$

KBM and ITG turbulence can be distinguished
Sensitivity to q-profile

- **HP Alternative equilibrium**
  (q profile within MSE error bars)
  - Lower $q$ (1.2→0.95)
  - Higher magnetic shear $s$ (0.14→0.28)

- **KBM/BAE threshold is sensitive:**
  $\beta_{\text{crit}} \sim s$ [MDH estimate]

- **20% a/L$_{\text{Tcrit}}$ increase**

- **linear GK result** [Jenko PoP01]
  
  \[
  \frac{a}{L_{\text{Tcrit}}} \sim (1+\frac{T_i}{T_e})(1.33+1.91s/q) \sim 1
  \]
  already explains trend

**Accurate equilibrium reconstruction desireable**
JET-ILW hybrid P scan ($\rho=0.33$): thermal transport

Increase of $a/L_{Ti}$ due to $\beta$ and fast ions
Electromagnetic effects are experimentally relevant

- ASDEX Upgrade $\beta$ scan
  - nonlinear $a/L_T$ upshift increases with $\beta$ at $\rho=0.5$
- ASDEX Upgrade power scan
  - ITG turbulence reduced by fast ions at outer radii
- JET hybrid power scan
  - ITG transport reduced by $\beta$ and fast ion dynamics at inner radii
- Thresholds for KBM (and MTM) exist

Conclusions

- Extrapolation to future machines requires understanding of electromagnetic microturbulence
- Beneficial effects may be explored for scenario development
- GK turbulence simulations can be used to calibrate simplified models
- Including $\beta_{\text{fast}}$ (on top of $\beta_{\text{th}}$) is considered for refined $\tau_E$-scaling

Thank You!