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

Hauke Doerk

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H. Doerk[1], C.Challis[2], J. Citrin[3,4], M. Dunne[1], J. Garcia[2], T. Görler[1], D. R. Hatch[7], F. Jenko[5], B. Kurzan[1], A. Banon-Navarro[5], R. McDermott[1], M. J. Pueschel[8], P.A. Schneider[1], D. Told[5], E. Wolfrum[1], the ASDEX Upgrade Team[1] and JET contributors*

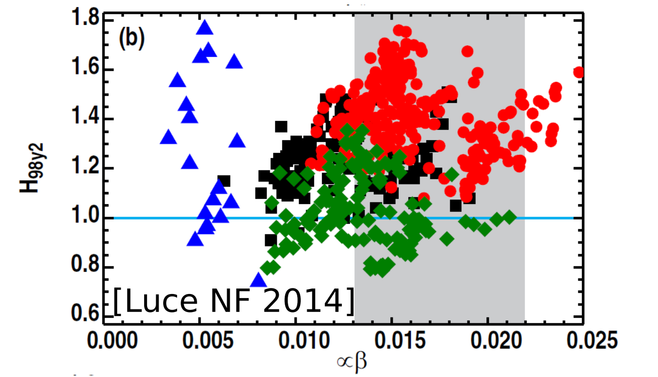
EUROfusion Consortium, JET, Culham Science Centre, Abingdon, OX14 3DB, UK

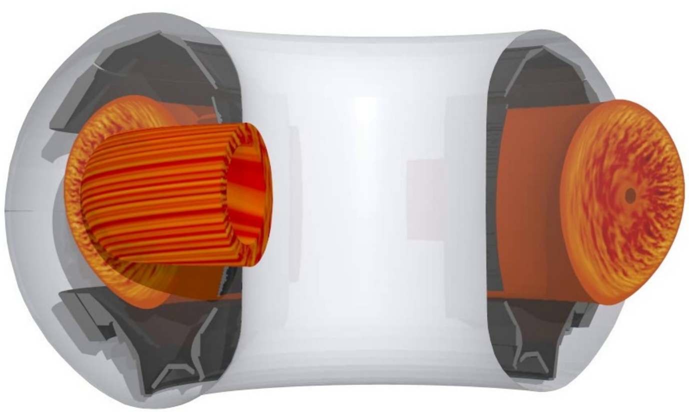
[1]Max-Planck-Institut für Plasmaphysik, Garching, Germany
[2]CCFE, Culham Science Centre, Abingdon, OX14 3DB, UK
[3]CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France
[4]FOM Institute DIFFER, NL-3430 BE Nieuwegein, The Netherlands
[5]University of California, Los Angeles, CA 90095, USA
[7]University of Texas, Austin, TX, USA
[8]University of Madison, Wisconsin, USA
* See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia

Outline

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

τ_E/τ_{98y2} in **advanced scenarios** ($\boldsymbol{\beta_N}\geq 2.4$, $\boldsymbol{H_{98}}\geq 1$)





www.genecode.org
developed at IPP, Germany
UCLA, LA, USA
UT Austin, USA
EPFL Lausanne Swizerland
CHALMERS, Gothenborg, Sweden

- **Theoretical foundation:**
  - gyrokinetic modeling
  - **impact of β** and fast ions ($\boldsymbol{\beta_{fast}}$)

- 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**

Electromagnetic effects in gyrokinetic turbulence modelling

The gyrokinetic equations solved in GENE

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

$$\partial_t f_1 + \left(v_\parallel \mathbf{b}_0 + \frac{B_0}{B^*_{0\parallel}} (\mathbf{v}_{\nabla\chi\times B} + \mathbf{v}_{\nabla B} + \mathbf{v}_c) \right) \cdot \left(\boldsymbol{\nabla} f_1 + \frac{1}{m v_\parallel} \left(q\bar{\mathbf{E}}_1 - \mu \boldsymbol{\nabla}(B_0 + \bar{B}_{1\parallel}) \right) \frac{\partial f_1}{\partial v_\parallel} \right) = \langle C[f] \rangle$$

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

$$\nabla_\perp^2 \phi = -8\pi^2 \sum_j \frac{q_j B}{m_j} \int \mathrm{d}v_\parallel \mathrm{d}\mu \left(J_0 f_{1j} + \frac{F_{0j}}{T_{0j}} \left((J_0^2 - 1) q_j \phi + \mu J_0 I_1 B_{1\parallel} \right) \right)$$

$$\nabla_\perp^2 A_{1\parallel} = -\frac{8\pi^2}{c} \sum_j \frac{q_j B}{m_j} \int \mathrm{d}v_\parallel \mathrm{d}\mu v_\parallel J_0 f_{1j}$$

$$B_{1\parallel} = -8\pi^2 \sum_j \frac{B}{m_j} \int \mathrm{d}v_\parallel \mathrm{d}\mu \left(\mu I_1 f_{1j} + \mu \frac{F_{0j}}{T_{0j}} \left(q_j J_0 I_1 \phi + \mu I_1^2 B_{1\parallel} \right) \right)$$

The gyrokinetic equations solved in GENE

- **Vlasov equation** (for each species)
- **Gyrokinetic (GK) Maxwell equations**

$$\partial_t f_1 + \left(v_{\|} \mathbf{b}_0 + \frac{B_0}{B_{0\|}^*} (\mathbf{v}_{\nabla\chi\times B} + \mathbf{v}_{\nabla B} + \mathbf{v}_c) \right) \cdot \left(\boldsymbol{\nabla} f_1 + \frac{1}{m v_{\|}} \left(q\bar{\mathbf{E}}_1 - \mu \boldsymbol{\nabla} (B_0 + \bar{B}_{1\|}) \right) \frac{\partial f_1}{\partial v_{\|}} \right) = \langle C[f] \rangle$$

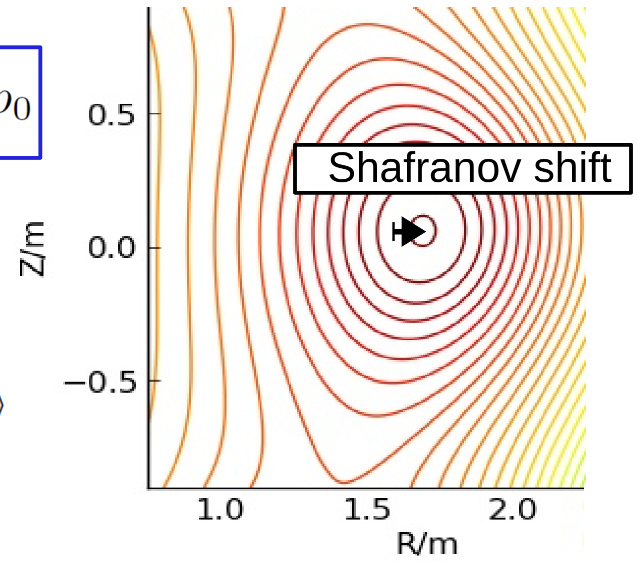
- **Comprehensive physics**: Linearized Landau-Boltzmann **collisions**, **ExB** + **parallel flow shear, experimental geometry,** global and **local** version
- Arbitrary number of kinetic **species**, incl. impurities + **fast ions**
- Delta-f method: $\mathbf{f_{0s} = F_{Ms} + f_{1s}}$ (for now: $F_{0,fast} = F_{M,equiv}$)
- Typical domain $L_x \sim 250\rho_s, L_y \sim 120\rho_s$, $L_{v\|} \sim L_{v\perp} \sim 3v_{vth}$ 192x48x32x48x16x4 ~ **10^9 grid** cells for x,y,z,v,µ and species
- Expensive simulations (150k CPUh per nonlinear run)

Nonlinear solution requires modern supercomputers

Electromagnetic (β-) effects in gyrokinetics

- **Geometric effects: (**Change Grad-Shafranov **magnetic equilibrium)**

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



$$\partial_t f_1 + \left(v_\parallel \mathbf{b}_0 + \frac{B_0}{B^*_{0\parallel}} \left(\mathbf{v}_{\nabla\chi\times B} + \mathbf{v}_{\nabla B} + \mathbf{v}_c \right) \right) \cdot \left(\nabla f_1 + \frac{1}{m v_\parallel} \left(q \bar{\mathbf{E}}_1 - \mu \nabla (B_0 + \bar{B}_{1\parallel}) \right) \frac{\partial f_1}{\partial v_\parallel} \right) = \langle C[f] \rangle$$

- **Dynamical effects**, plasma response:

  -**β>0** allows for **magnetic fluctuations**

  -modified **electric field** $\bar{E}_{1\parallel} = -\nabla_\parallel \bar{\phi}_1 - \frac{1}{c} \frac{\partial \bar{A}_{1\parallel}}{\partial t}$

  -modified ExB **drift velocity**

$$\mathbf{v}_{\nabla\chi\times B} = \frac{c}{B^2} \mathbf{B} \times \nabla \left(\bar{\phi}_1 - \frac{1}{c} v_\parallel \bar{A}_{1\parallel} + \frac{1}{q_j} \mu \bar{B}_{1\parallel} \right)$$

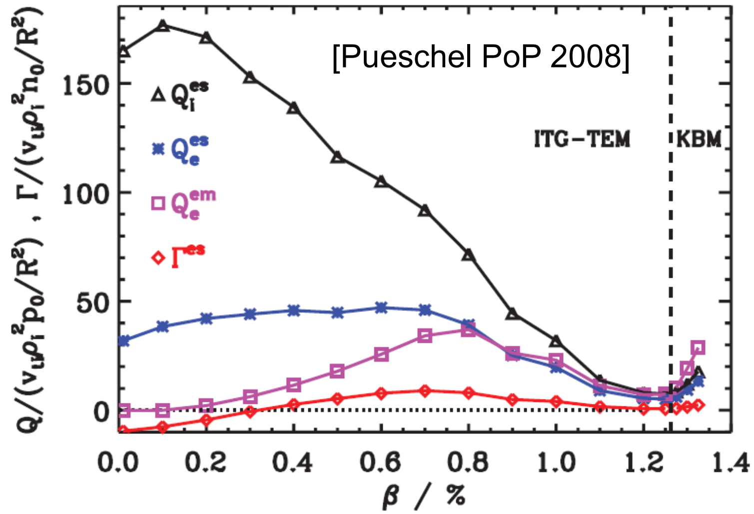
- **Fast ions** (NBI, ICRH, *Fusion alphas*) contribute to **geometry** and **dynamics**
  $\beta_{tot} = \beta_{th} + \beta_{fast}$

- **Modification** of electrostatic instabilities: **ITG / ETG, TEM**
  [**I**on/**E**lectron **T**emperature **G**radient driven instability, **T**rapped **E**lectron **M**ode]
- **New** instabilities: **KBM, MTM, BAE**
  [**K**inetic **B**allooning **M**ode, **M**icro**T**earing **M**ode **B**eta-induced **A**lfven **E**igenmode]

Some previous results on electromagnetic turbulence

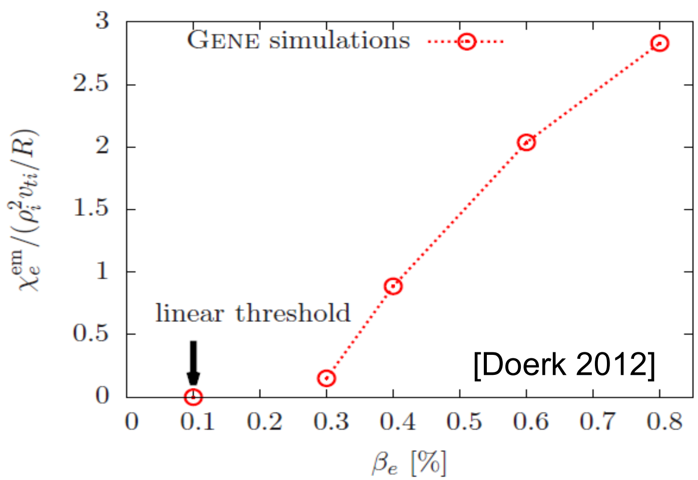
(+)increasing **ß (α) can reduce transport:**

- **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 **ß can enhance transport:**

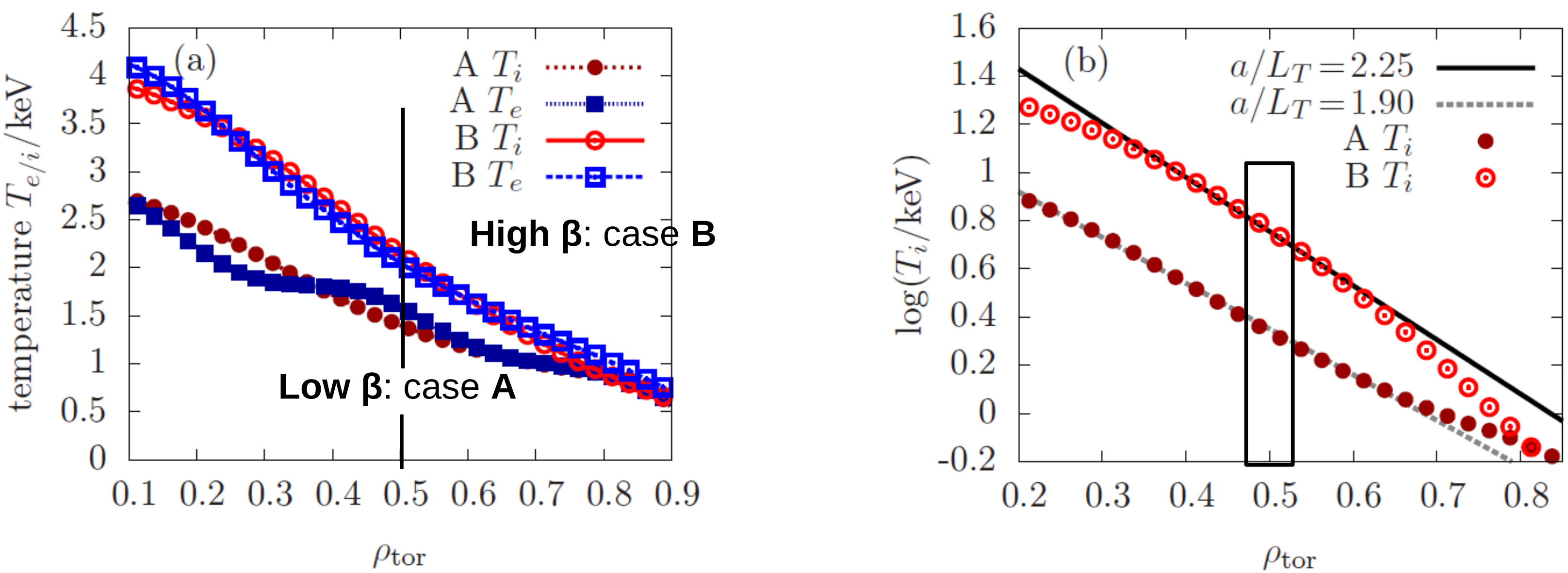
- Magnetic transport in ITG turbulence [Pueschel PoP'08] due to **nonlinearly excited MTMs** [Hatch PRL'13]
- **MTM** turbulence: χ_e [Doerk PRL'12, Guttenfelder PRL'12]
- **KBM** turbulence: Initial **gyrokinetic** results [Pueschel PoP 2008, Maeyama NF 2014]
- **Fast particle** driven turbulence [e.g. Bass PoP'10]



Which of the effects is relevant for experiments?

Gyrokinetic analysis of an ASDEX Upgrade beta scaling experiment

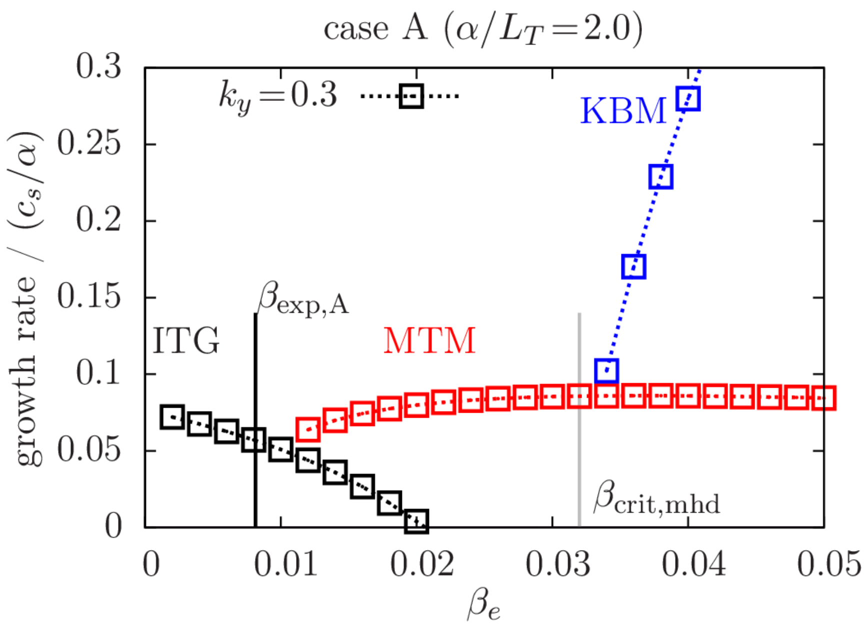
A β scaling experiment at ASDEX Upgrade [Doerk PoP'15]

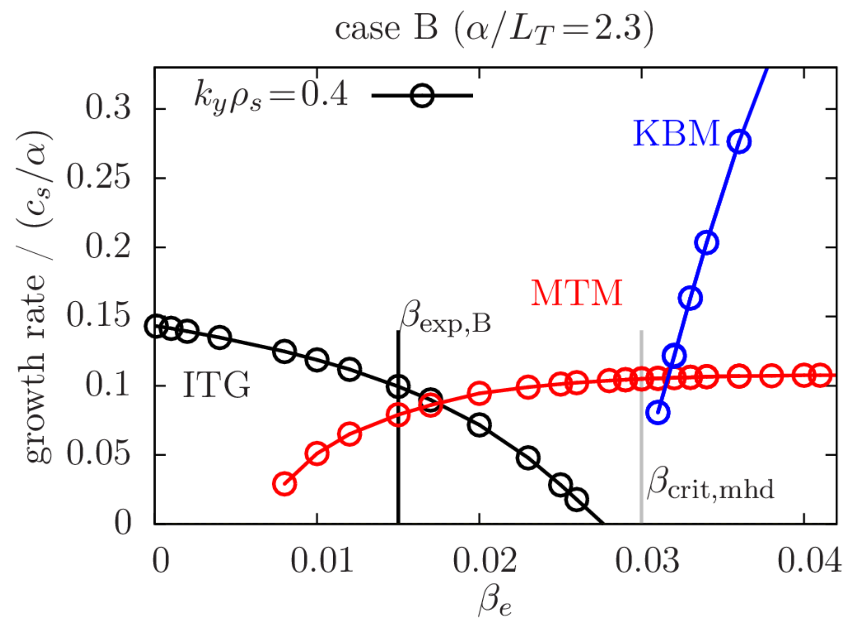


- **β** scan at constant **ρ*,ν*:** n~B^4, T~B^2, β~B^4 [expected power scaling Q_{gB} ~ P ~ B^7 ~ $\beta^{7/4}$]
- Weak **β-**degradation: $\boldsymbol{\tau_E B \sim \beta^{-0.2}}$
- Reference position: $\boldsymbol{\rho_{tor}=0.5}$
- Imperfect measurements,
  but **relevant turbulence regime** can be investigated

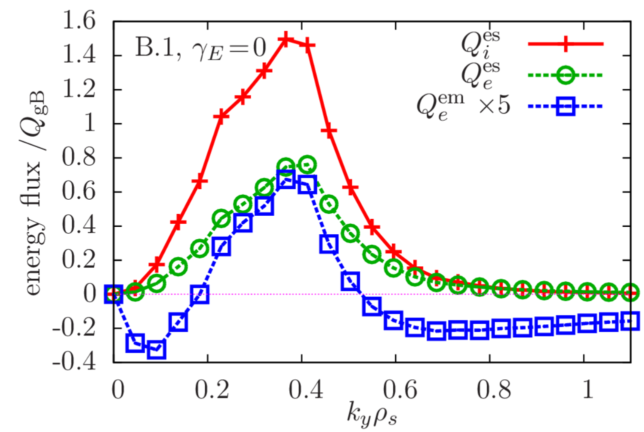
Main variation: $\boldsymbol{\beta_B=1.9\beta_A}$

Microturbulence regimes in AUG β scan: ρ_{tor}=0.5



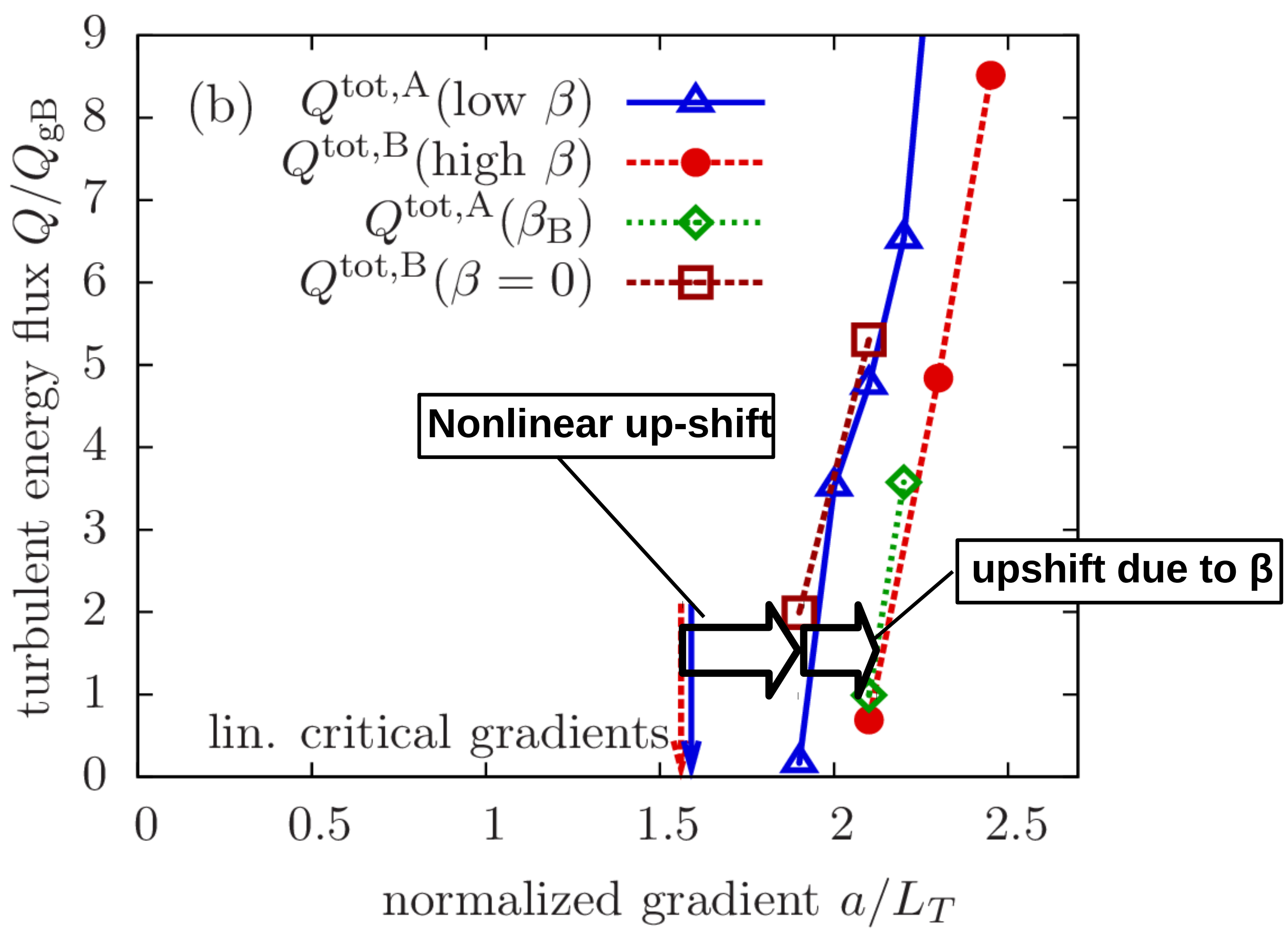


- **β scan** (fixed geometry): **transition** of unstable **ITG** - **MTM** - **KBM** in both cases
- Ratio **β/β_{crit}** reaches **20%** (A) and **40%** (B)
  KBM is stable
- **Nonlinear** simulations: **little MTM transport** even in high beta case



Main β-effect: ITG-stabilization

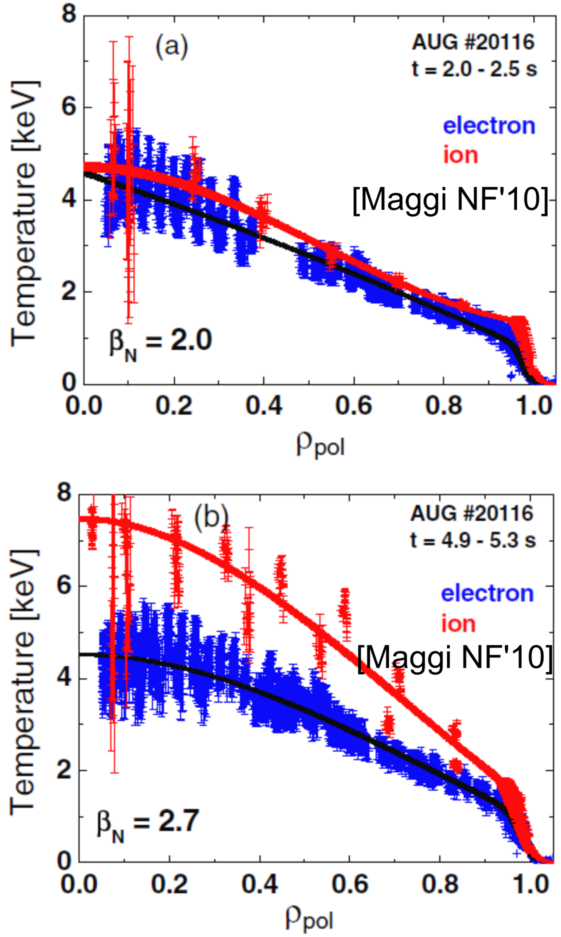
ITG turbulence simulations at ρ_{tor}=0.5

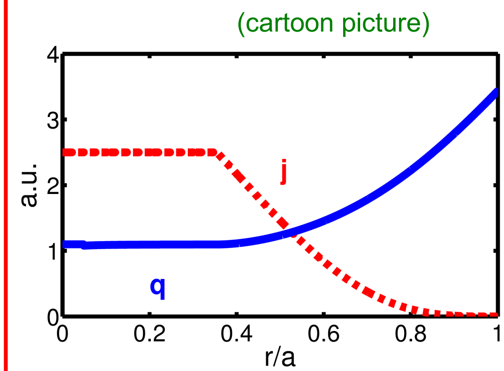


Steeper gradients due to β

Gyrokinetic analysis of ASDEX Upgrade power scan experiments

Hybrid power scans at AUG and DIIID [Maggi NF 2010]





Hybrid scenario

- aka: advanced inductive
- Flat **q**, low shear in the center
- Low density, Low current
- High $\boldsymbol{\beta}_N$ = <**β**>*aB$_0$/I
- High fusion gain expected
- Discussed for ITER operation

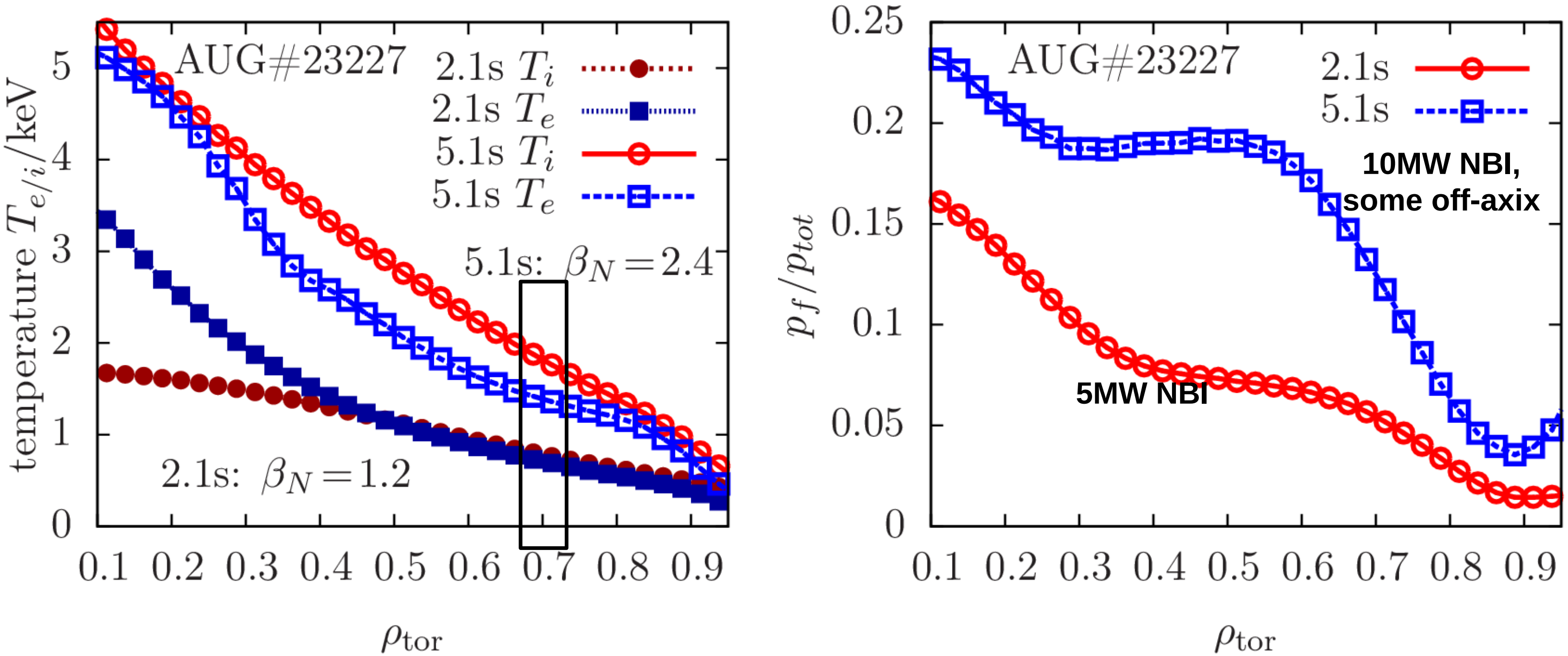
Previous work (C-wall components) [Maggi NF 2010]

AUG and DIIID power scans

- **τ_E improves** (**pedestal** and **core** contributions)
- GK analysis: **β effects** are pronounced

Refinement is scheduled for 2015 AUG campaign

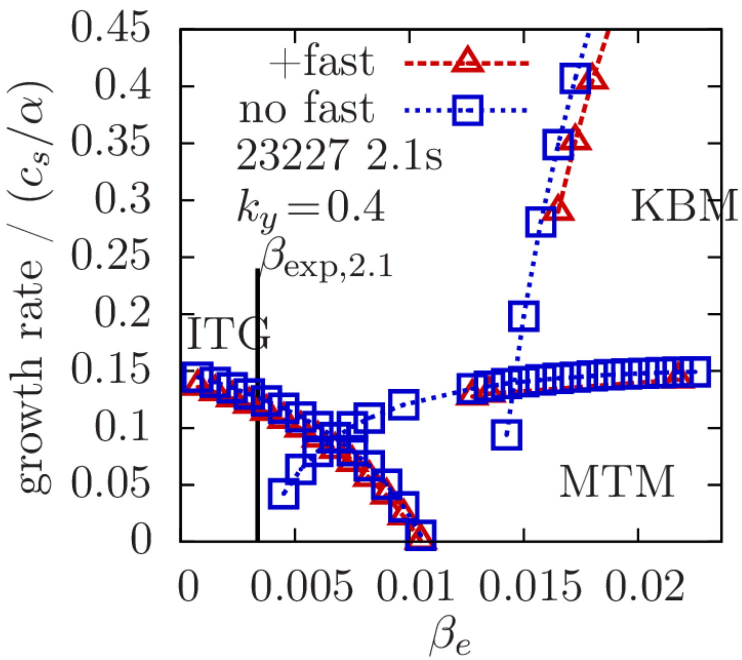
For now: AUG 23227 power scan (W-Wall)

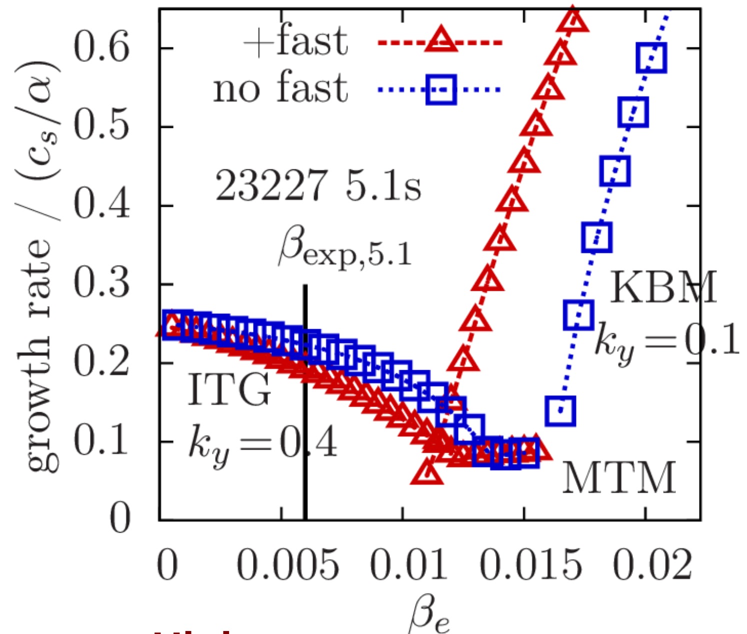


- n_e decreases by 15%, β_N increases from **~1.2 to ~2.4**
- **Fast ion pressure** increases with power
- τ_E**~0.08s** similar (slightly improved at high β_N)
- Larger **a/L_{Ti}** at outer radii → reference position **ρ_{tor}=0.7**

Test for β, ExB, and fast ion effects

AUG power scan (ρ_{tor}=0.7): Microinstabilities





Low power

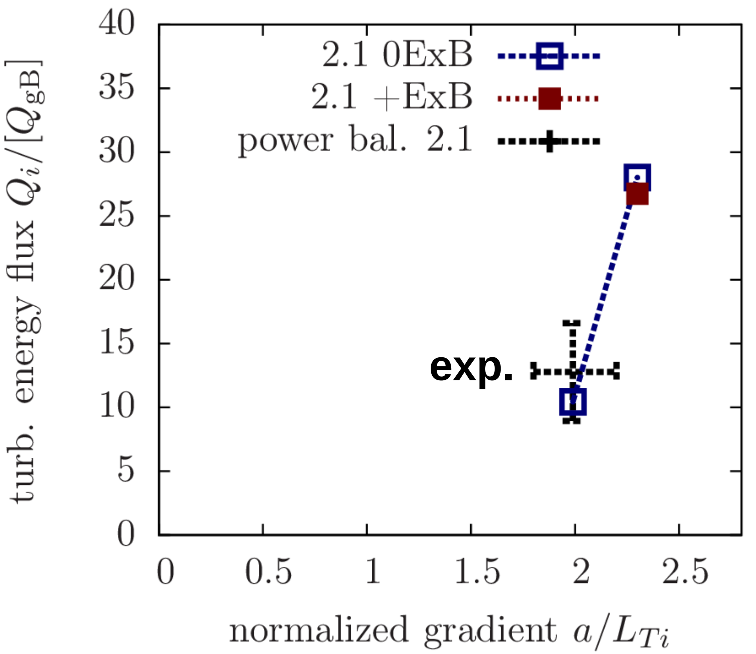
- **β/β_{crit}**=23%
  little **β-**stabilization of ITG
- no impact of
  fast ions and (N impurities)

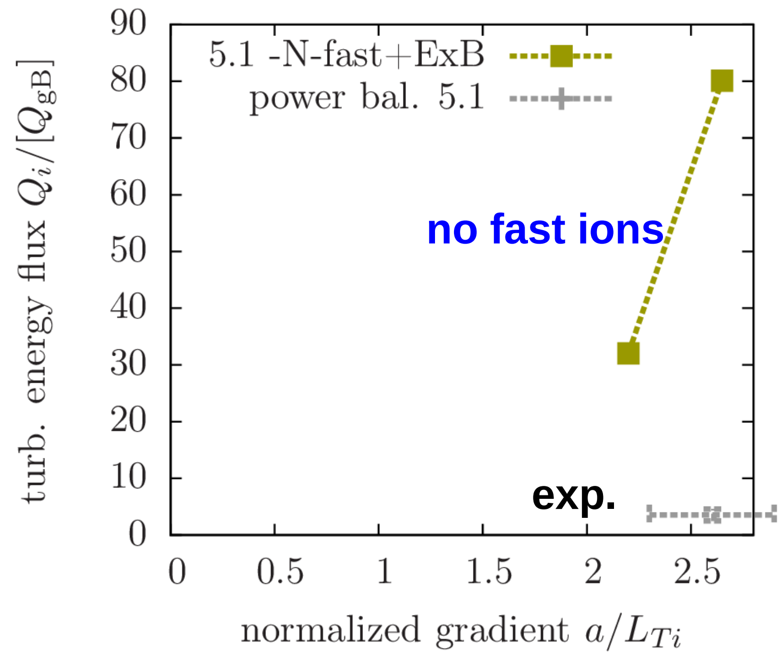
High power

- **β/β_{crit}**=0.37 [0.57]
- **β/β_{crit}** is figure of merit for EM stabilization of ITG
- **fast ions lower β_{crit}**

Evidence for stabilizing role of fast ions

AUG power scan (ρ_{tor}=0.7): low-k turbulence





Low power

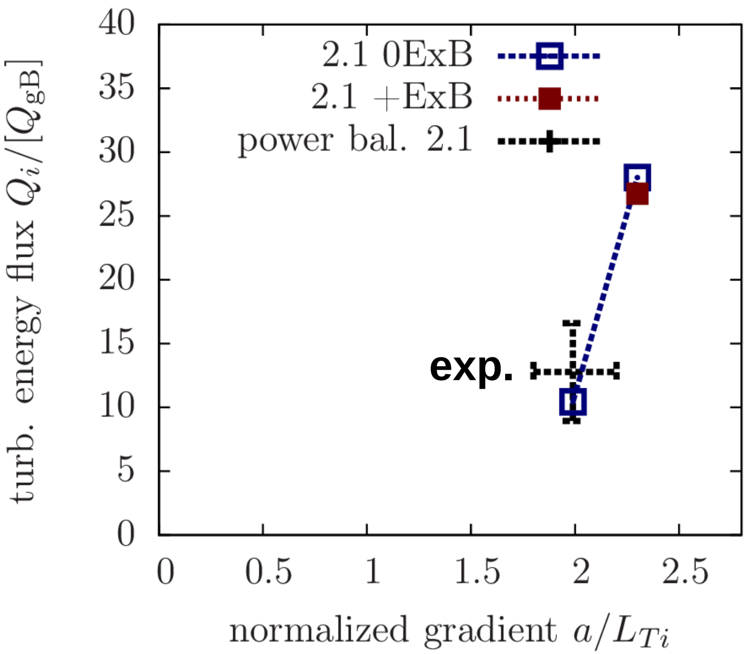
- Excellent **agreement** between **power balance** and **GENE** [already w/o fast ions and N]

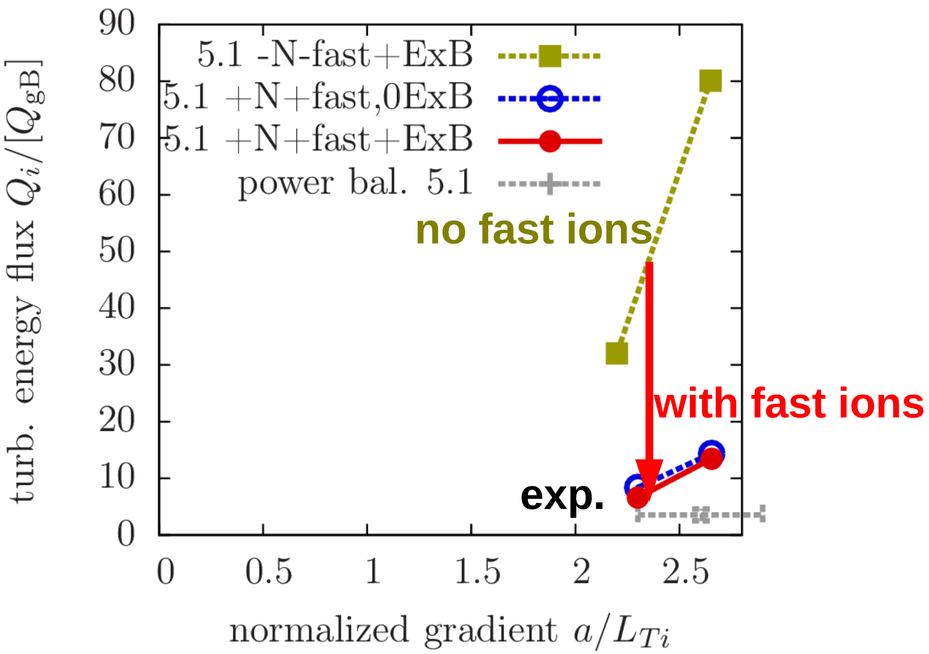
High power

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

Evidence for stabilizing role of fast ions

AUG power scan (ρ_{tor}=0.7): low-k turbulence





Low power

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

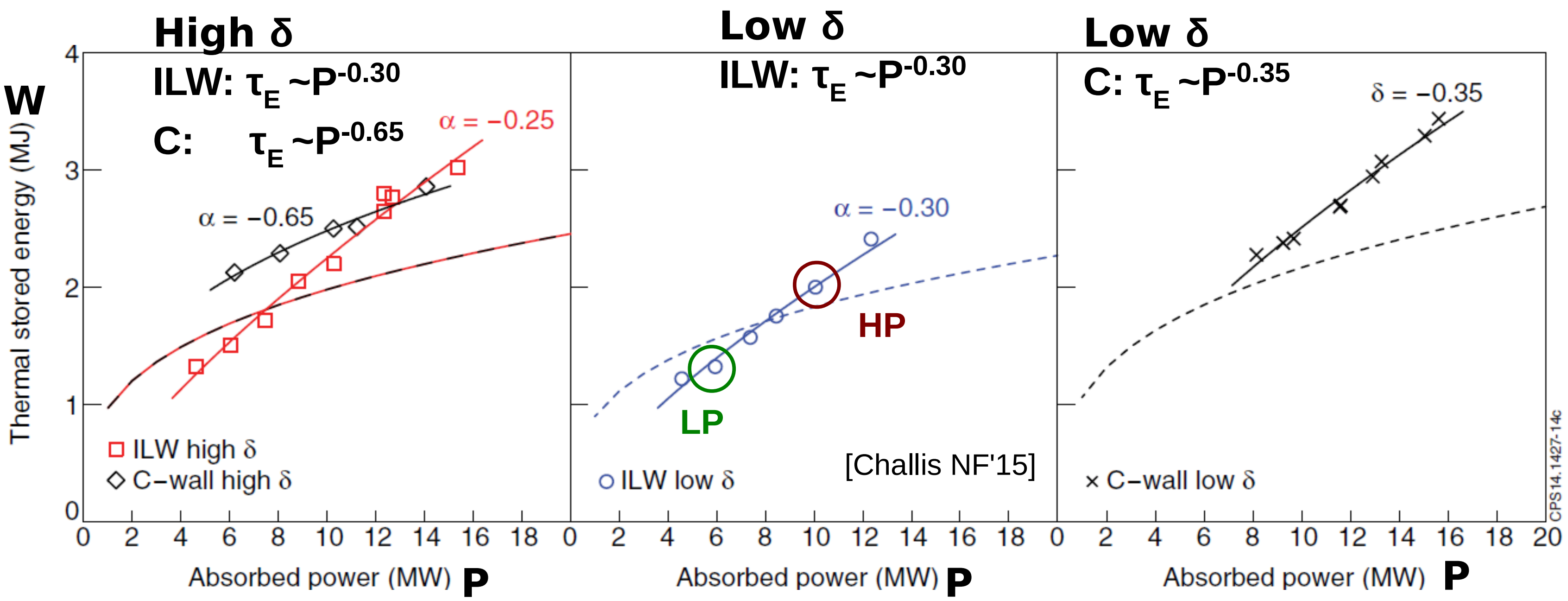
High power

- 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

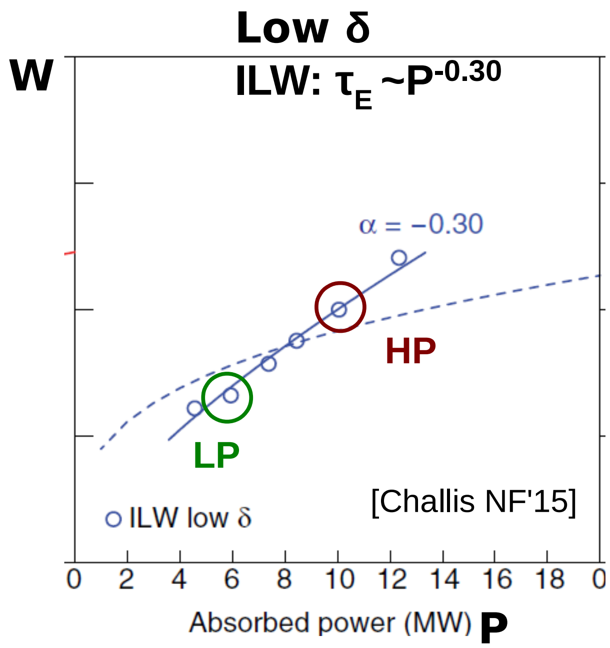
Hybrid power scans at JET [Challis NF 2015]



- $\tau_E \sim P^{-0.30}$ in **JET ILW** at low triangularity **δ** **(**$\tau_{98y2} \sim P^{-0.69}$**)**
- 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?

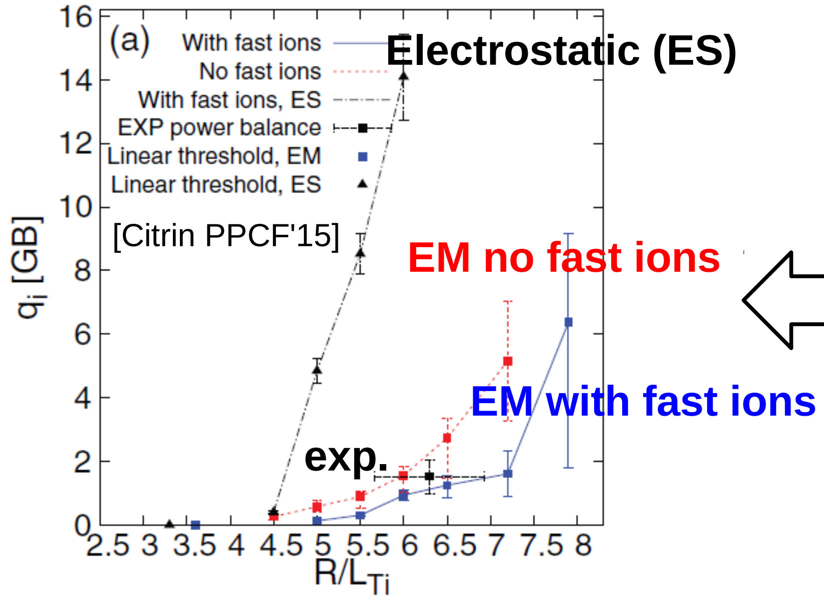
Hybrid power scans at JET [Challis NF 2015]



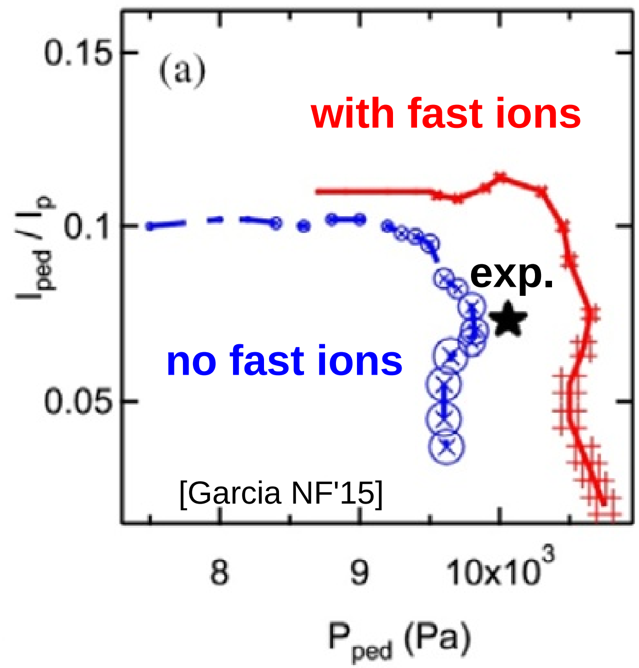
- $\tau_E \sim P^{-0.30}$ in **JET ILW** at low triangularity **δ** **(**$\tau_{98y2} \sim P^{-0.69}$**)**
- Conversion to dimensionless: $\tau_E \sim \beta^{0.5}$ (very sensitive)
- **C-wall** GK results: **EM + fast ion stabilization** of turbulence at inner radii

What is the physics behind weaker power degradation?

inner core ρ=0.33



pedestal



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

(2)Reduced **core** transport **(β) +** Enhanced **pedestal** stability (Shafranov-shift)

(3)Increased core temperature

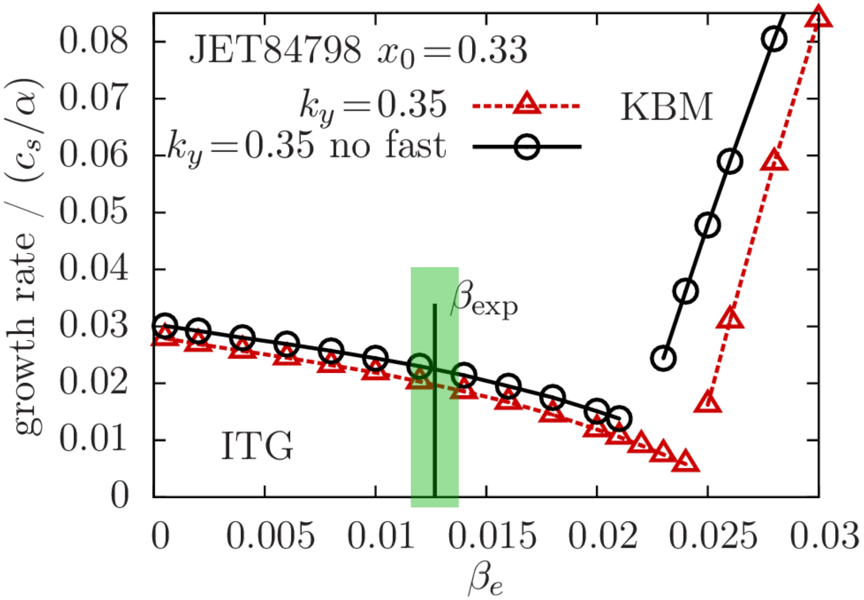
(4)Increased **β** ->(2)

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

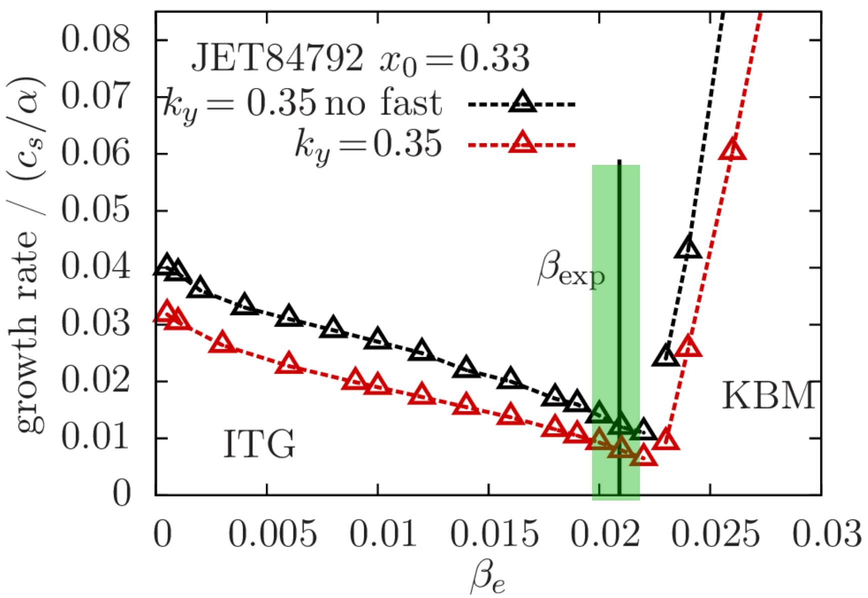
Positive core-edge feedback possible ILW?

JET-ILW hybrid P scan (ρ=0.33): microinstabilities

low power ρ_{tor}=0.33

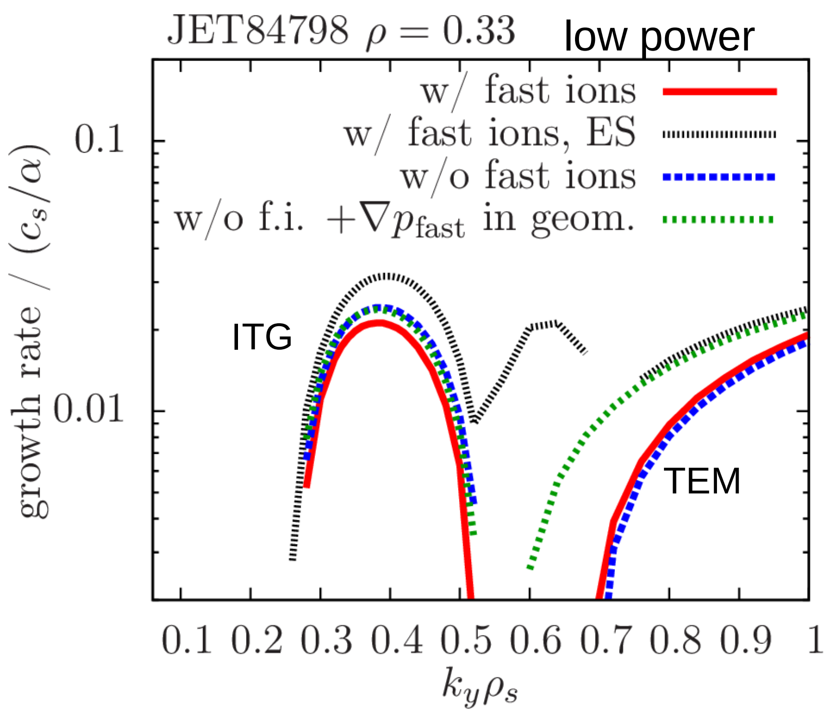


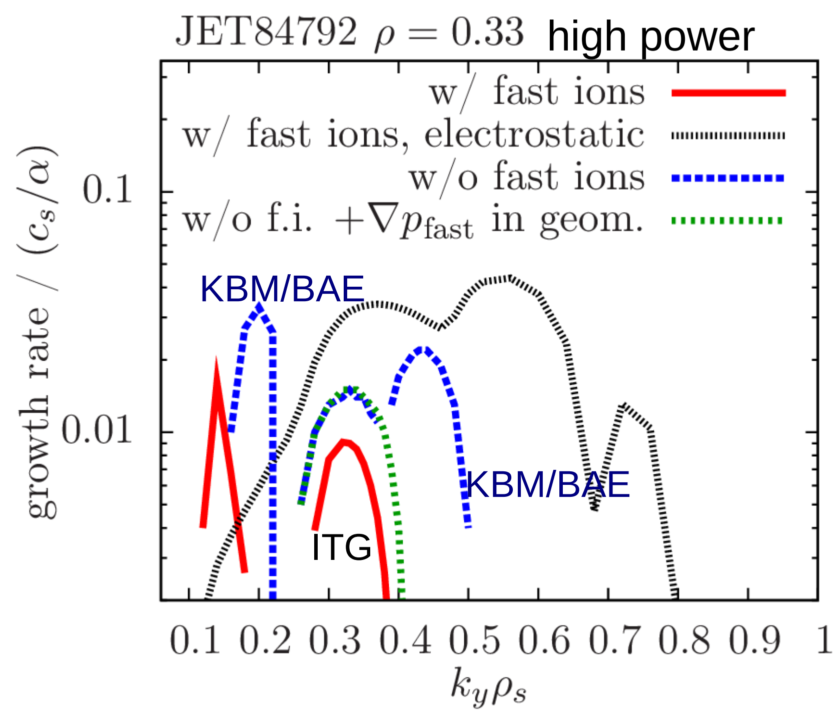
high power ρ_{tor}=0.33



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**
- **β-**stabilization of ITG, very strong in high power case
- Multiple **fast ion effects** at high power:

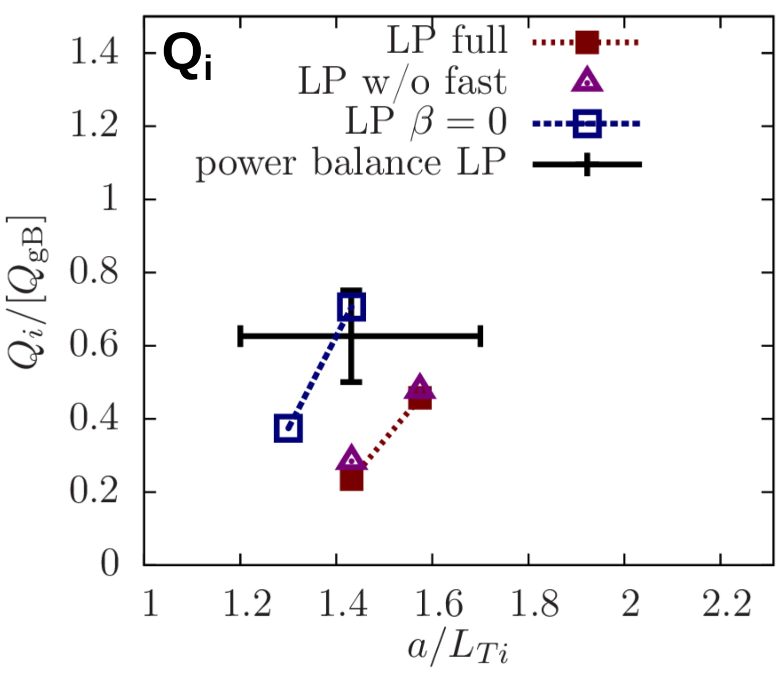
dynamic:
-**stabilization** of **ITG**
-enhanced **KBM/BAE drive**

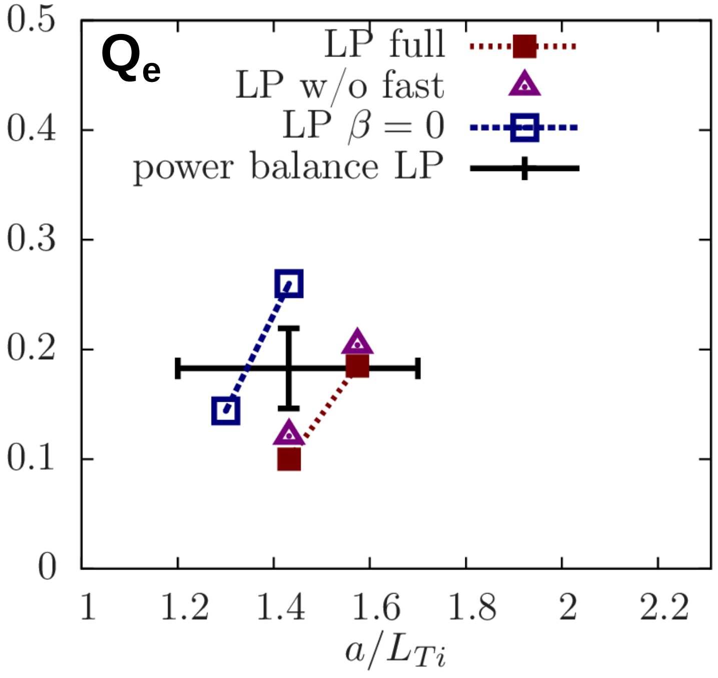
geometric:
-**stabilization** of **KBM/BAE**

KBM/BAE:
- $\omega \sim \omega_{GAM}$
- **∇p** driven (thermal + fast)
- sensitive to **β**

Strong β and fast ion effects in high power case

JET-ILW hybrid P scan (ρ=0.33): thermal transport

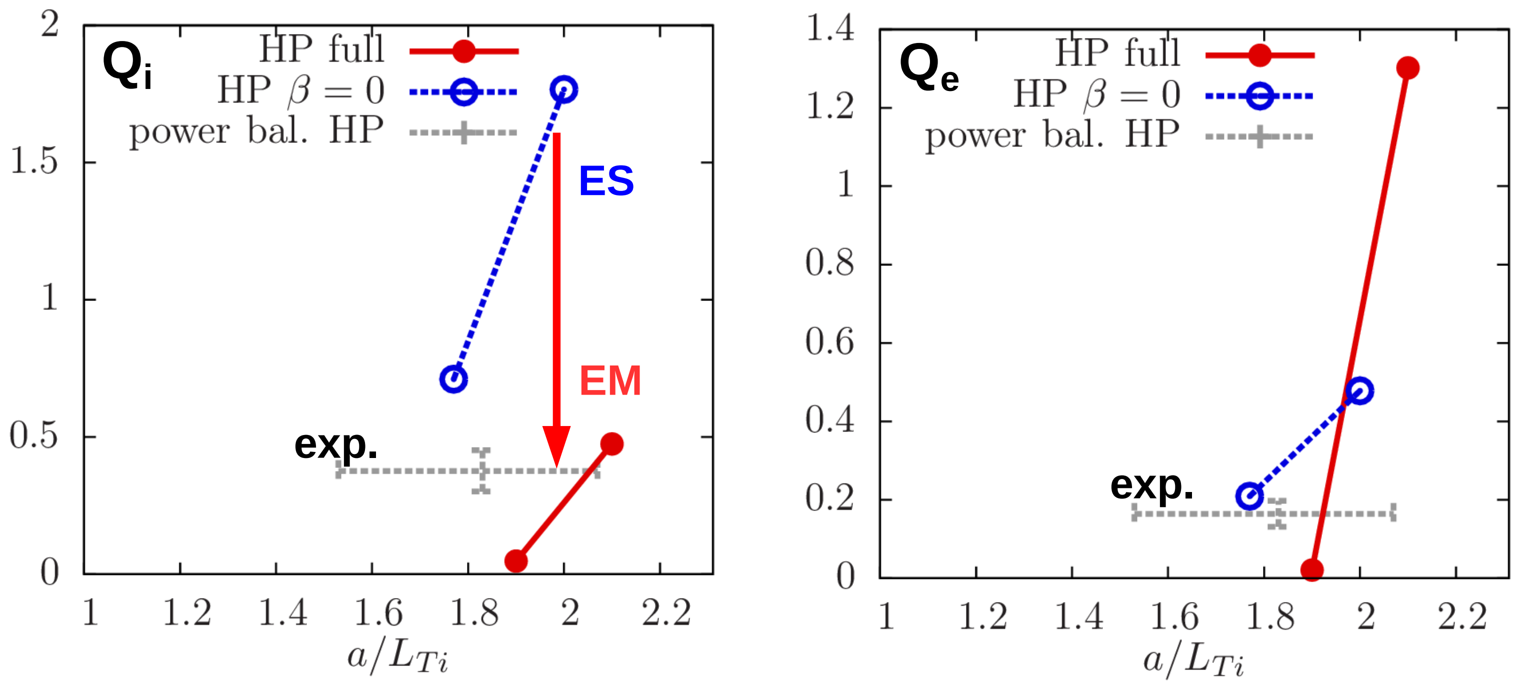




Low Power (LP)

- **Q_i** and **Q_e** consistent with experiment
- Fast ions not important
- **ITG** is **β-stabilized**

JET-ILW hybrid P scan (ρ=0.33): thermal transport

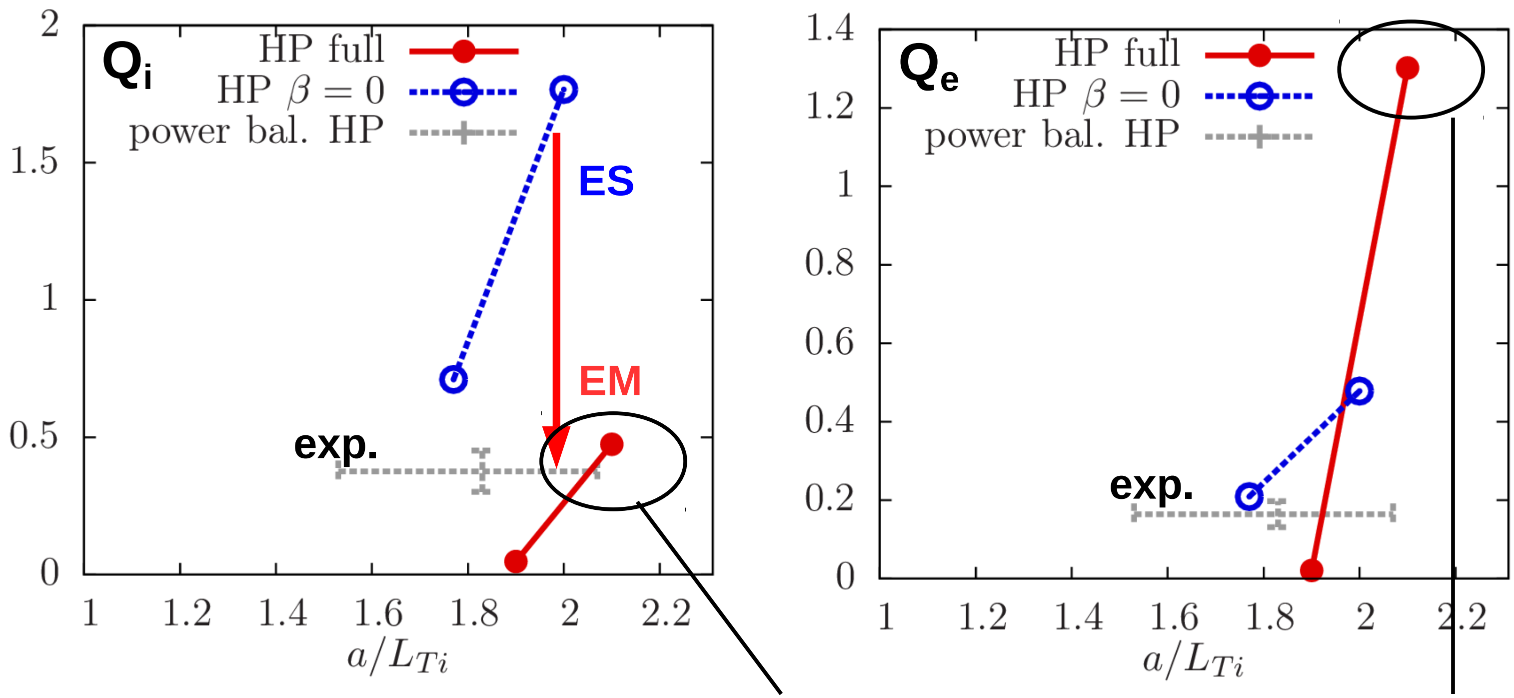


High Power (HP)

- **ITG** strongly **stabilized** due to **β** (+**dynamic fast ion** effect, not shown)

Strong β stabilization at high power

JET-ILW hybrid P scan (ρ=0.33): thermal transport



KBM/BAE turbulence: **high Q_e** (and **Q_{fast}**)

High Power (HP)

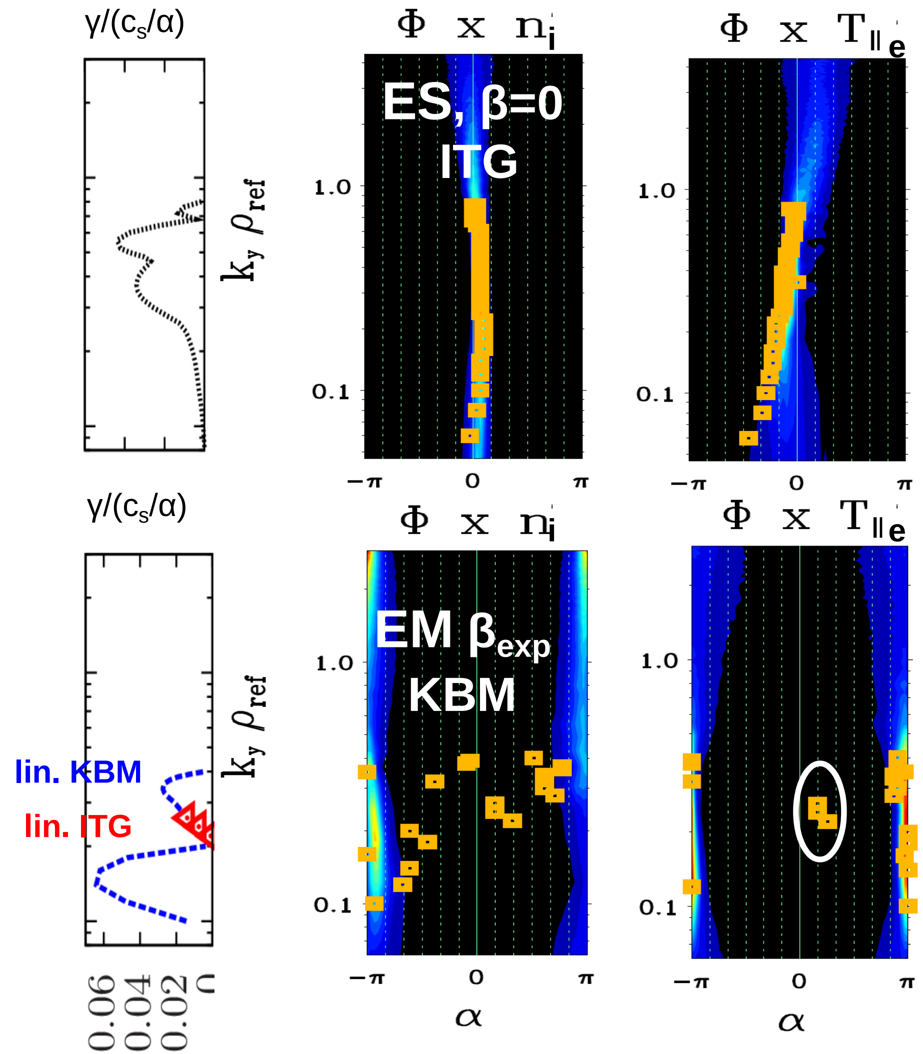
- **ITG** strongly **stabilized** due to **β** (+**dynamic fast ion** effect, not shown)
- **Transition** from **ITG** to **KBM/BAE** turbulence**: β>β_{crit}**

Strong β stabilization at high power

Turbulence characteristics

Experimentally accessible
(in principle):

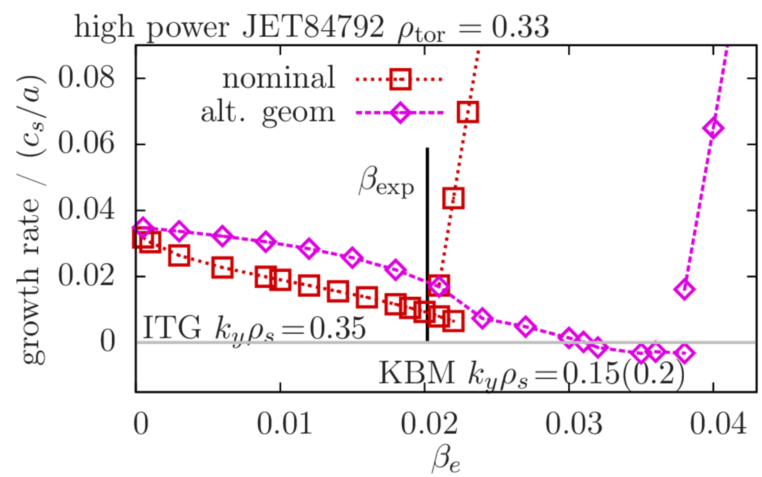
- **Phase relations:**
  (transport range $k_y\rho_s<0.7$)
  -ITG: n x Φ ~ 0
  -KBM n x Φ ~ π
  note: interchange mode, π/2 expected
  [Manz PPCF'14, Scott PoP'05]
- **Frequency** analysis (FFT)
  (in linear drive range $k_y\rho_s<0.4$)
  -KBM $\omega \sim c_s/a$
  -ITG $\omega \sim 0.2c_s/a$

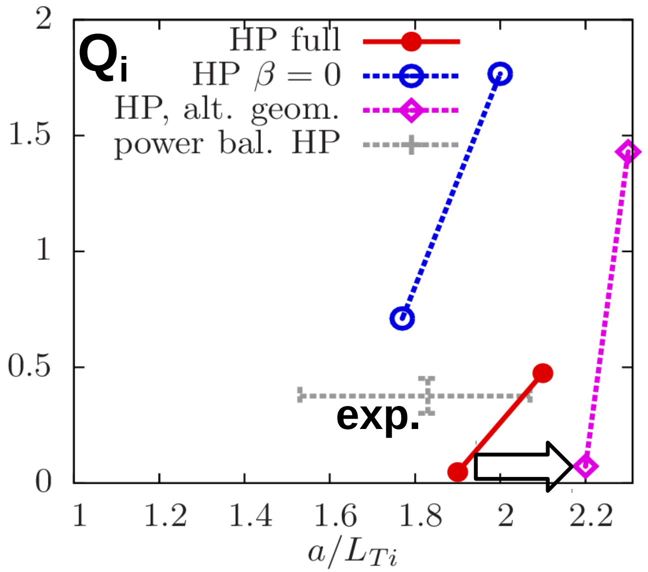


KBM and ITG turbulence can be distinguished

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:** β_{crit}**~s** [MDH estimate]

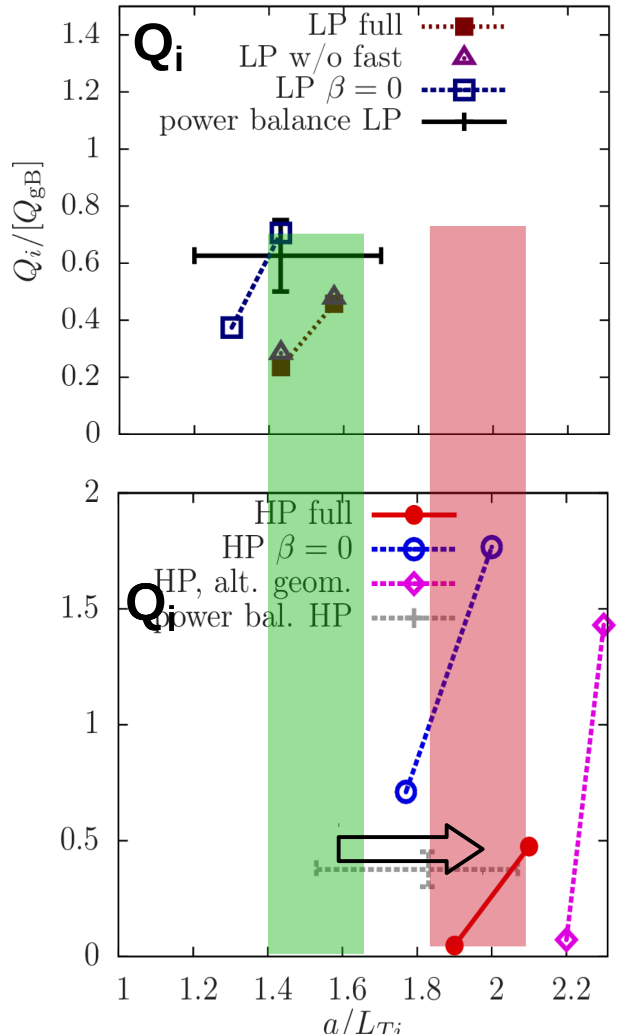




- **20% a/L$_{Tcrit}$** increase
- linear GK result [Jenko PoP01]
  a/L_{Tcrit} ~ $(1+T_i/T_e)(1.33+1.91s/q)$~1
  already explains trend

Accurate equilibrium reconstruction desireable

JET-ILW hybrid P scan (ρ=0.33): thermal transport



Increase of a/L_{Ti} due to β and fast ions

Summary and conclusions

Electromagnetic effects are **experimentally relevant**

- ASDEX Upgrade **β scan**
  -nonlinear **a/L_T upshift** increases with **β** at **ρ=0.5**
- ASDEX Upgrade **power scan**
  -**ITG turbulence reduced** by **fast ions** at outer radii
- JET hybrid **power scan**
  -ITG transport **reduced** by **β** 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 **β_{fast}** (on top of **β_{th}**) is considered for refined **τ_E-scaling**

Thank You!