Core microturbulence and edge MHD interplay and stabilization by fast ions in tokamak confined plasmas

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25th Fusion Energy Conference, Saint Petersburg, Russia

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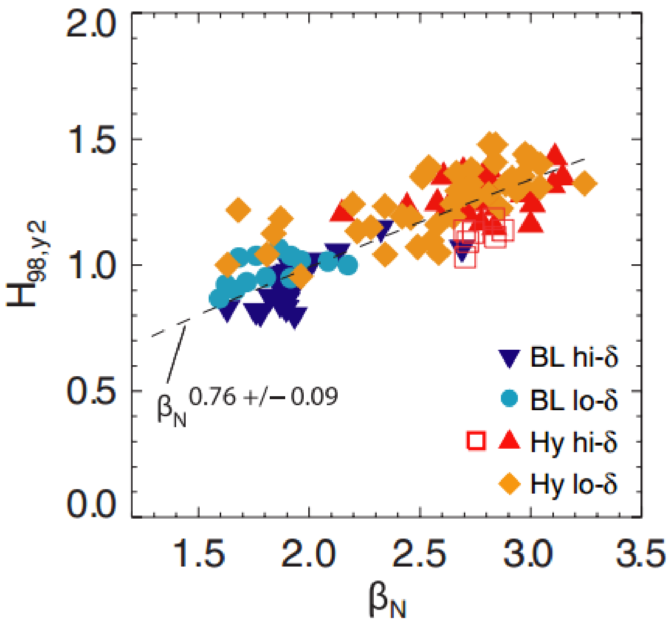
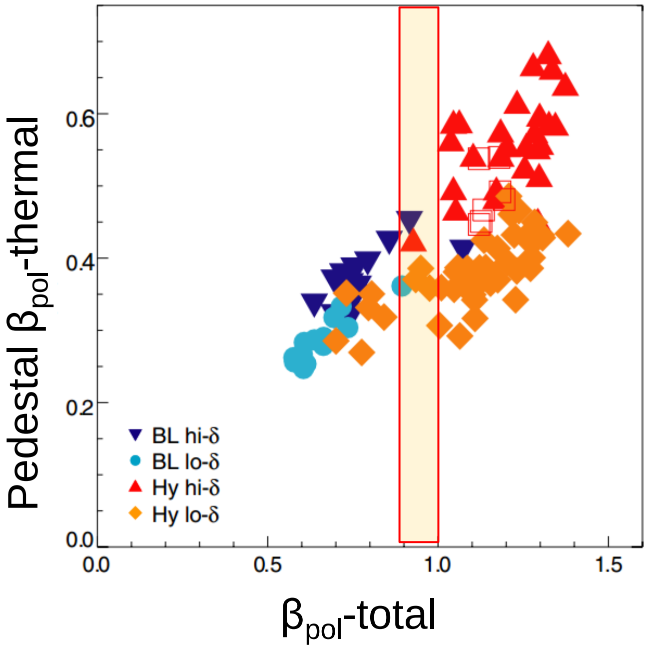
Motivation: High thermal energy confinement in the presence of high β





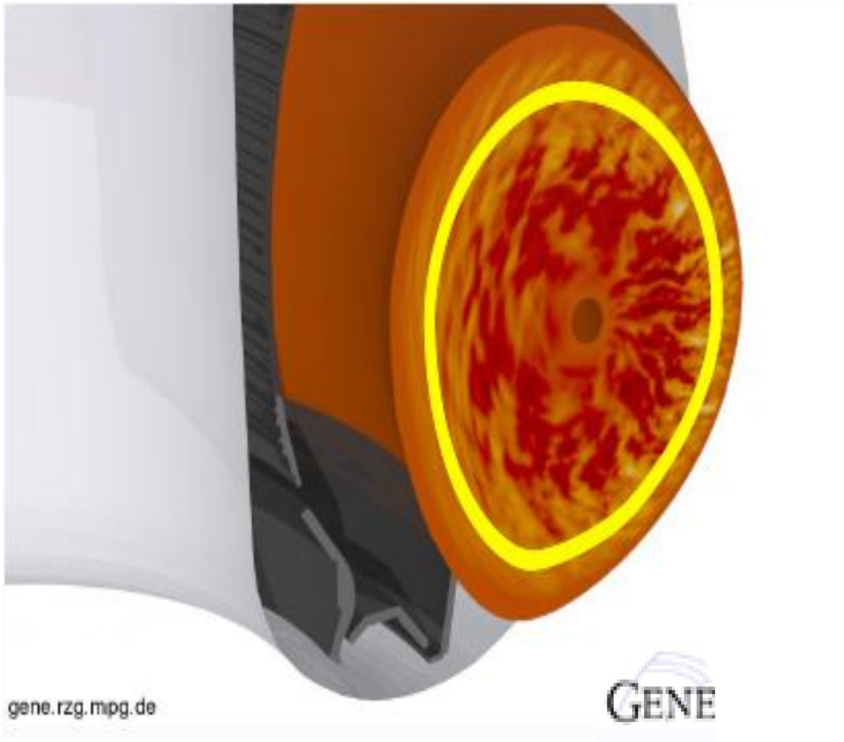
M.N.A. Beurskens et al., NF 2013

- Hybrid scenarios at JET, with improved thermal energy confinement correlated with high β
- Strong linear correlation between β_{pol} (thermal) and $\beta_{pol,edge}$ suggests key role of pedestal
- Picture changes including β_{pol} (fast). Hybrids and baseline split by the $\beta_{pol} \approx 1$ region.
- Diamagnetism already pointed out to be important for hybrid scenarios [J. Garcia and G. Giruzzi PRL 10] [E. Solano and R. Hazeltine NF 2012]
- Significant contribution of fast ions to β in hybrids: What is their impact in the core or edge regions?

Outline

- Tools and discharges used
- Impact of fast ions on microturbulence of JET hybrid regimes: Reduction of ITG turbulence
- Analysis of the physical mechanisms: Electromagnetic effects and pressure gradients important at high β
- Impact of fast ions on the pedestal pressure: Pedestal improvement and core-edge coupling through fast ions
- Extrapolation to ITER
- Conclusions

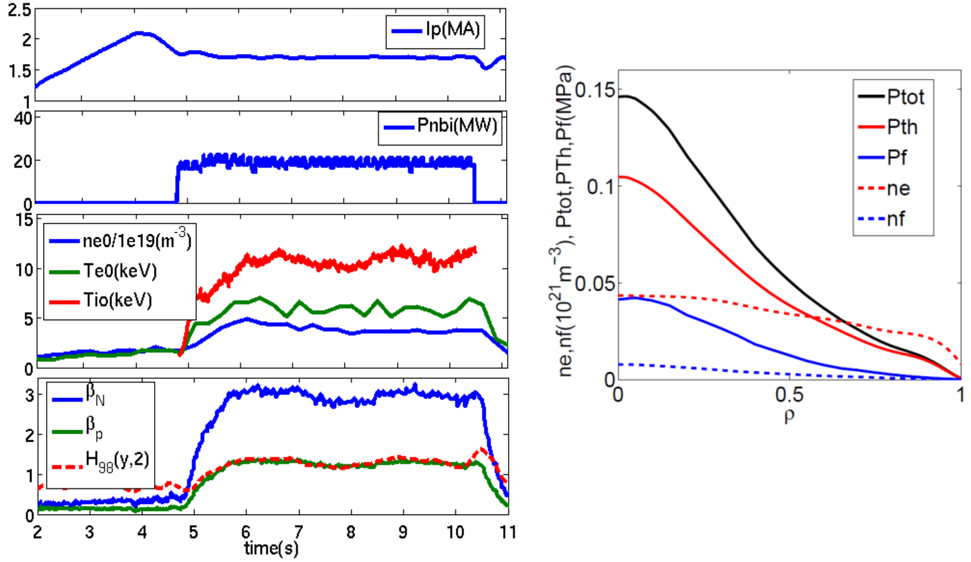
Choice of assumptions



- GENE code [Jenko et al., PoP 2000] is chosen to perform gyrokinetic analysis of core microturbulence
- We include: kinetic electrons, experimental geometry, electromagnetic effects, active C species, active fast ions (D from NBI)
- Local (flux tube) approximation taken (assumed justified for our case: $1/\rho^{*} \sim 500$)
- Both $\delta B_{\perp}$ and $\delta B_{\parallel}$ fluctuations included (∇P included in the curvature-∇B drift)
- ExB and Parallel flow shear included
- Caveat: fast ion distribution approximated by hot Maxwellians

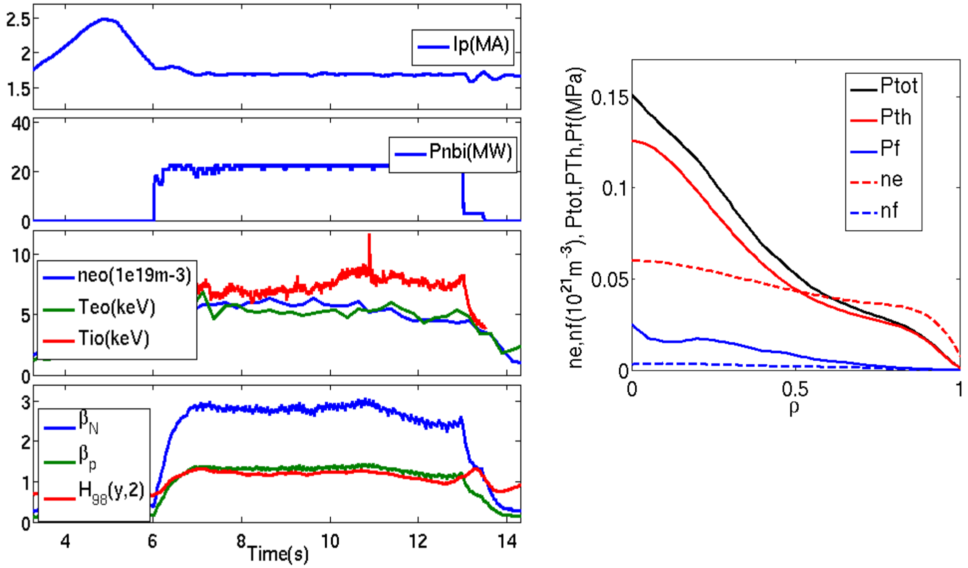
Discharges selected

75225 Low δ



J.Hobirk PPCF 2012

77923 High δ

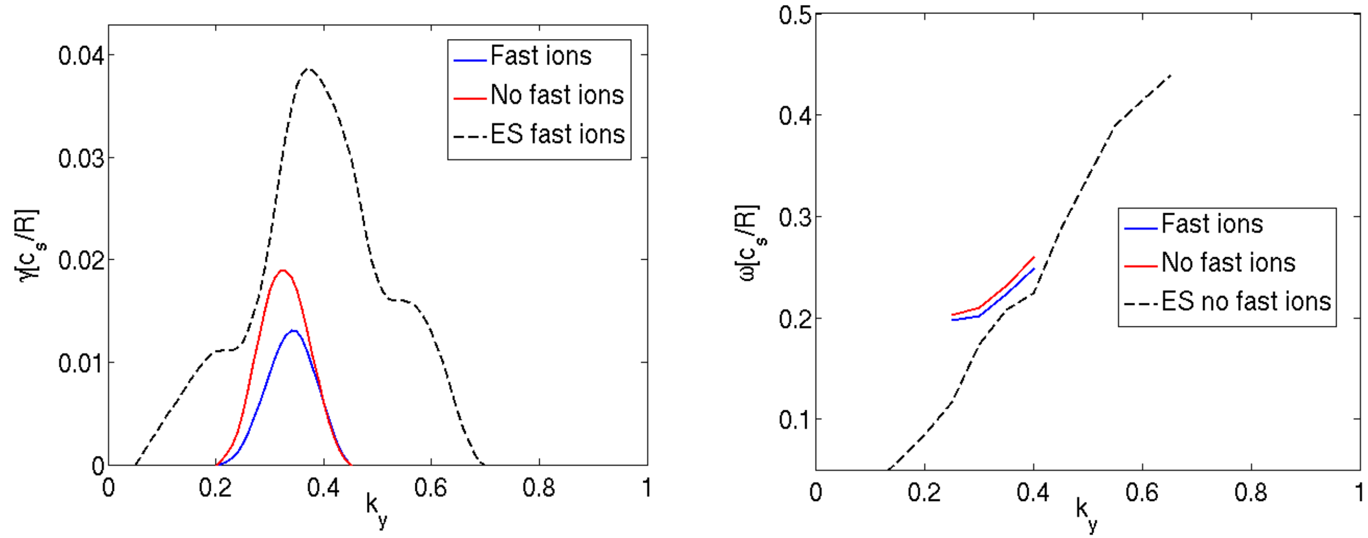


J. Garcia and G. Giruzzi Nucl. Fusion 2013

- Similar improved confinement in both cases, $H_{98}(y,2)=1.3$, and high β_N but different fast ion fraction
- Extensive GENE linear and nonlinear analysis of representative high confinement C-wall low triangularity 75225 and high triangularity 77923 hybrid scenarios both at $\rho = 0.33$

Linear study in inner half-radius: High δ case

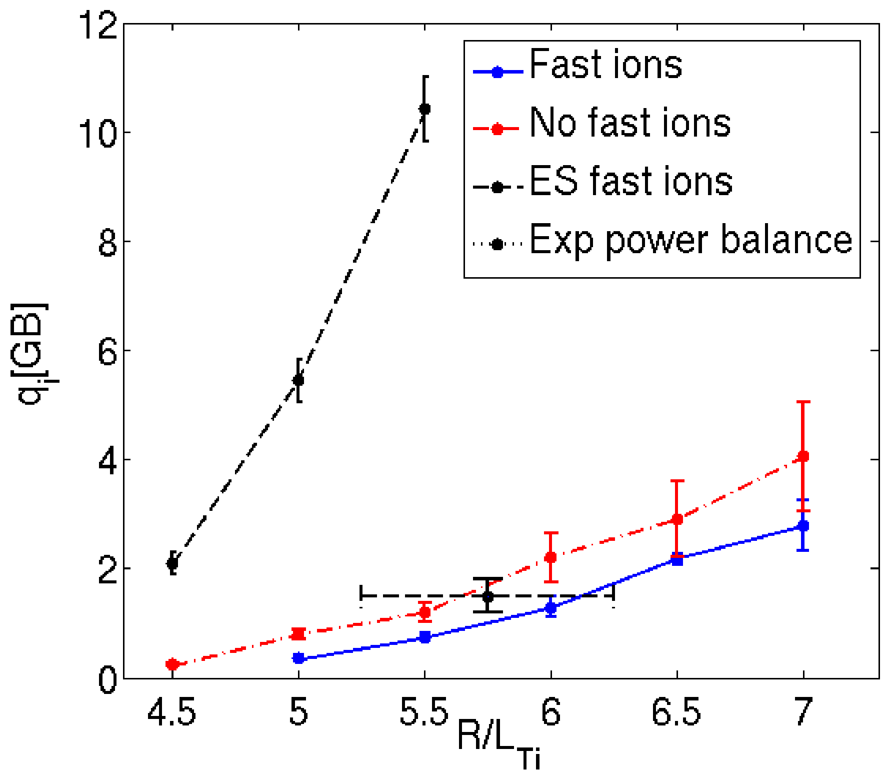
Linear spectra of JET high δ hybrid scenario at $\rho = 0.33$



- ITG modes found in the region $0.2 < k_y = k_y \rho_s < 0.45$
- Significant reduction of maximum growth rate, 35%, by fast ions
- Electromagnetic effects are essential to get this stabilization.

Nonlinear study in inner half-radius: High δ case

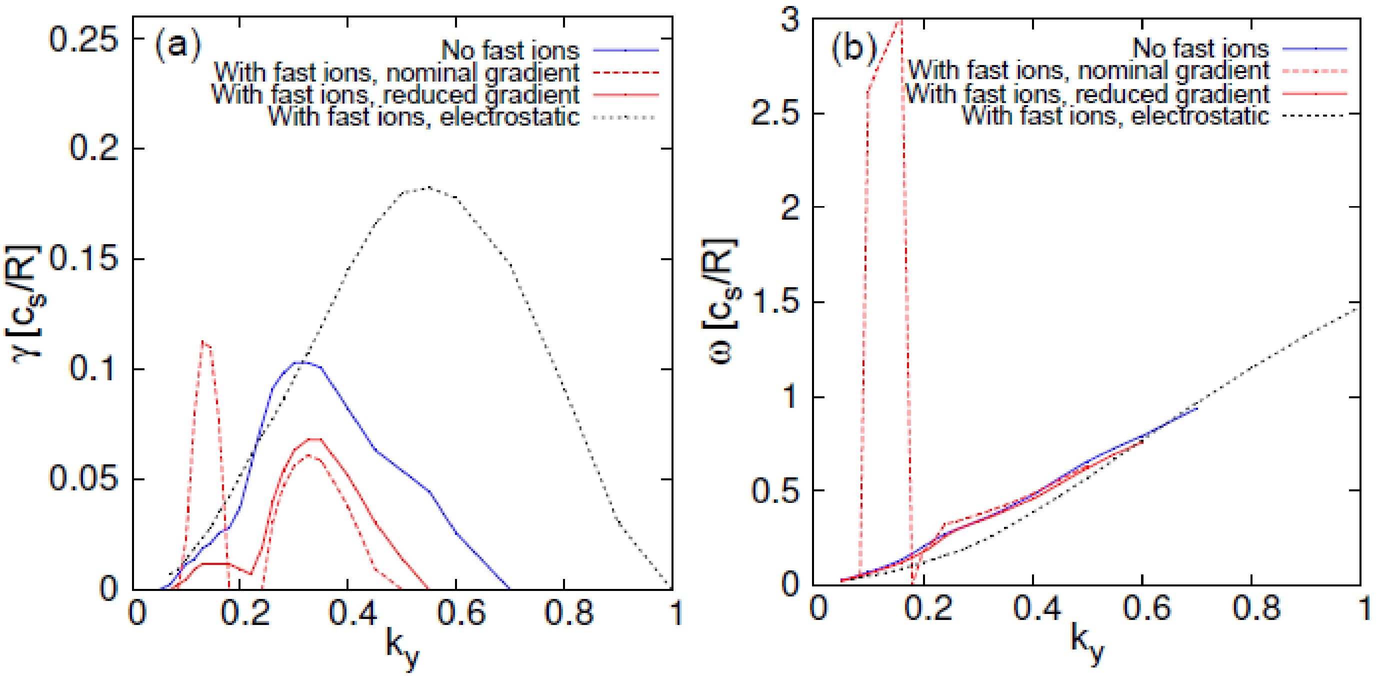
GENE nonlinear simulation of JET high δ @ ρ=0.33. 4 ion species, finite-β, collisions, real geometry, rotation



- Fast ion impact significant, 10% increase of R/L_{Ti} for the same heat flux.
- EM-effects are a key factor in reaching power balance fluxes. Main effect is stiffness reduction.
- Heat flux reduction at constant R/L_{Ti} is stronger than linear reduction
- Extraordinary agreement between experimental and calculated fluxes.

Linear study in inner half-radius: Low δ case

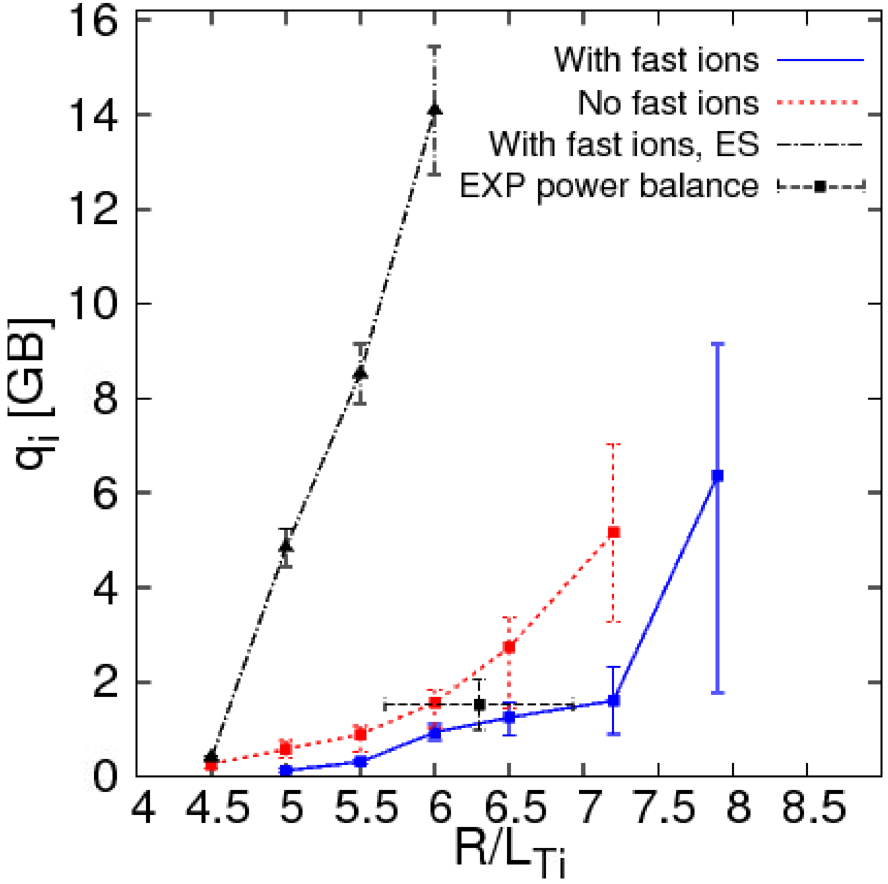
Linear spectra of low δ hybrid scenario at $\rho = 0.33$



- Significant EM-stabilization of ITG modes. Enhanced by fast ions.
- With nominal fast ion pressure (CRONOS/SPOT), fast ion modes at $k_y < 0.2$
- Fast ion mode (consistent with beta induced Alfven Eigenmode – BAE) stabilized by $\approx 30\%$ reduction of fast ion gradient. Likely coupled with KBM branch, thus referred to BAE/KBM.

Nonlinear study in inner half-radius: Low δ case

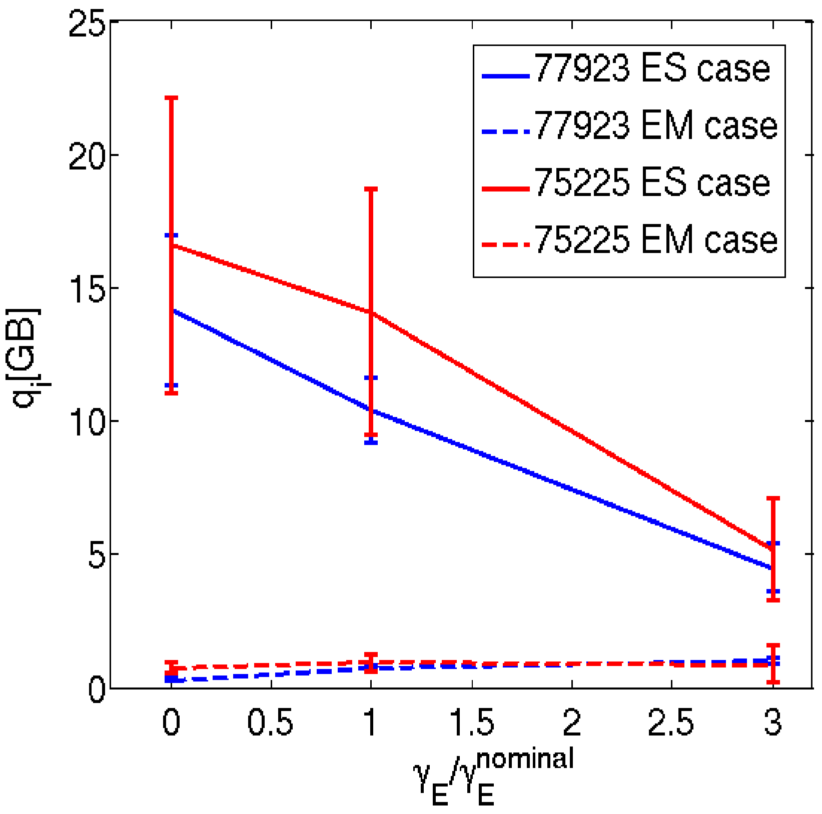
GENE nonlinear simulation of low δ @ ρ=0.33. 4 ion species, finite-β, collisions, real geometry, rotation



- Fast ion effects stronger than previous discharge: 10-20% increase of R/L_{Ti} for the same heat flux
- Only fast ions change the threshold
- EM-effects + fast ions are key factor for obtaining experimental heat fluxes
- Fluxes calculated with reduced fast ion pressure gradient.
- Fast ion transport necessary

Flow shear stabilization ineffective at inner half-radius

Isolation of separate impact of EM-stabilization and $E \times B$ shear stabilization



- For nominal γ_E, weak impact of rotation.
- For 3x higher γ_E, strong impact in electrostatic case. But heat fluxes still well above power balance
- For (realistic) electromagnetic+fast ions case, no $E \times B$ shear stabilization evident at all. Even slight destabilization
- Conclusion: EM-stabilization and fast ions completely dominant over $E \times B$ stabilization at $\rho = 0.33$

Other (non-EM) fast ion stabilization mechanisms of ITG are less important

Fast ions can stabilise ITG turbulence through 3 general mechanisms

- Dilution of main ion species (e.g. Tardini NF 2007)
- Geometric effect: increased Shafranov shift due to suprathermal pressure which alters drift frequencies and stabilises ITG at low magnetic shear (e.g. Bourdelle NF 2005)

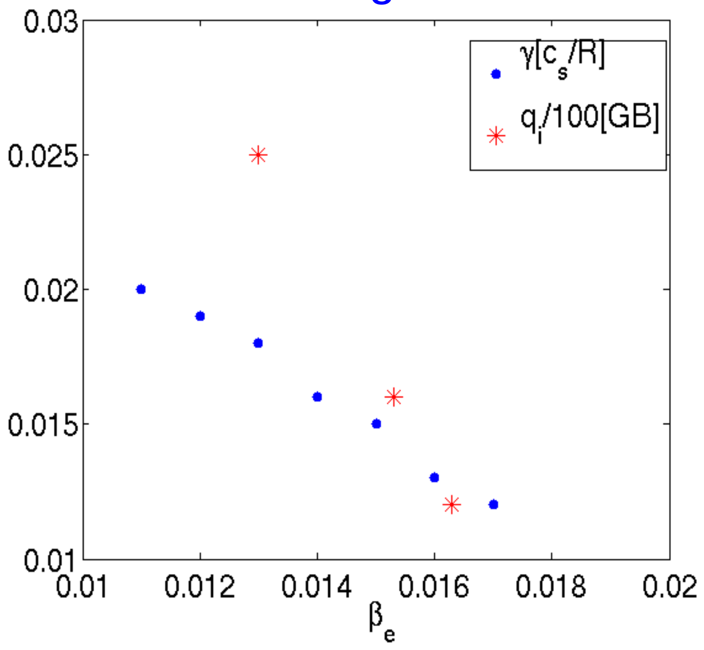
These 2 effects do not dominate in these discharges following dedicated checks

The 3rd stabilizing effect is key in these discharges

- Stabilization by electromagnetic effects.
  - **ANY** pressure gradient stabilizes ITG turbulence in electromagnetic simulations**.**
  - Fast ions provide a net source of pressure gradient as they do not contribute to ITG turbulence
  - Has been analyzed linearly for JET discharges [M.Romanelli PPCF 2011].
  - Nonlinear electromagnetic stabilization is greater than the linear stabilization [J. Citrin PRL 2013]

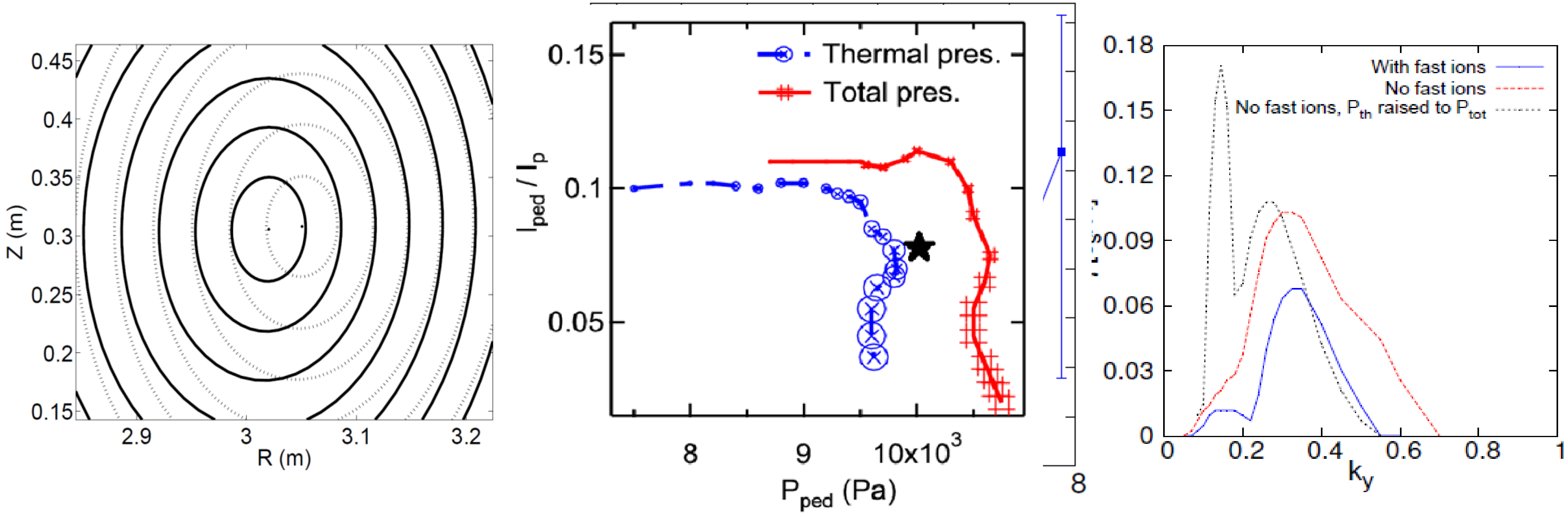
Linear vs non-linear stabilization in hybrid scenarios

High δ



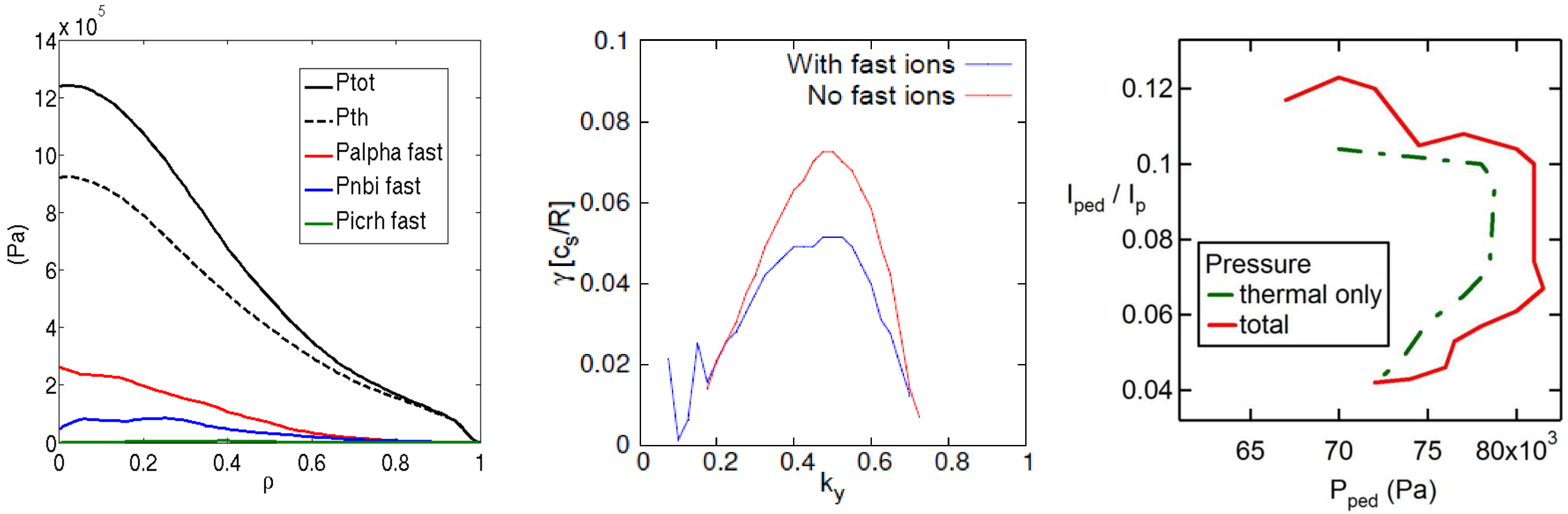
- EM stabilization stronger non linearly: higher ion heat flux reduction with β_e than growth rate reduction
- This has been linked with an increase in zonal flow impact (Pueschel *et al*., PoP 2008, 2010, 2013)
- Further analysis will be performed and inclusion in quasi-linear models required

Edge analysis low δ



- Peeling Ballooning analysis performed with the MISHKA code for low δ
- The extra β_{fast} provided by the fast ions, $\beta_{N,th}$=2.13 β_N=2.9, expands the stable region by 10% through Shafranov-shift
- Alternative linear run: Fast ions pressure is removed and temperature gradients increased to match $P_{thermal}=P_{tot}$: Growth rates highly increased
- Core-edge coupling by fast ions through plasma stiffness
- Other mechanisms for core and edge interplay: C. Challis this conference EX/9-3, R. Cesario et al. PPCF (2013)

Extrapolation to ITER



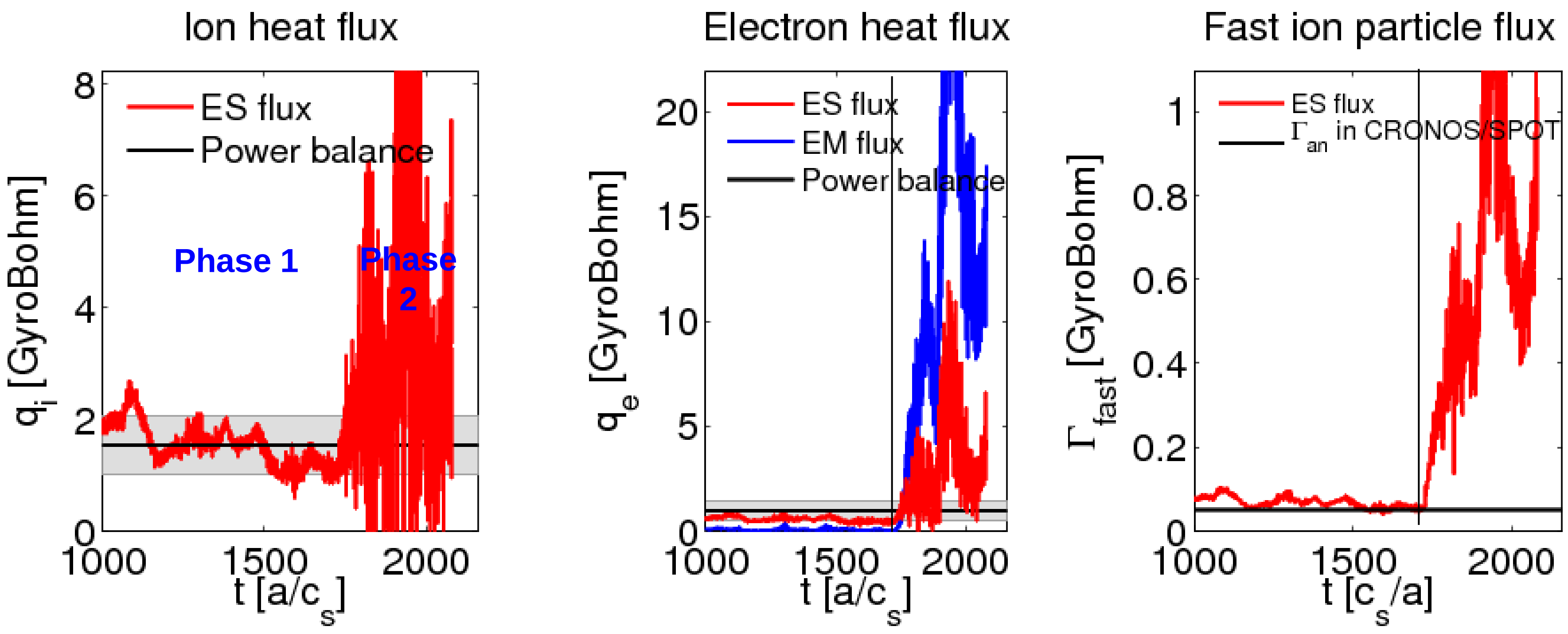
- Same analysis performed to the ITER hybrid scenario [K Besseghir, J Garcia PPFC 2013]
- Fast ions from alphas and beams highly contribute to β and β' due to their high energy
- Maximum ITG linear growth rate reduced by 30%
- The stable pedestal boundary is also expanded by 10%
- Core and edge improvement in ITER expected to be of the same level as JET

Conclusions

- Fast ions and electromagnetic effects are key ingredients for understanding ITG turbulence reduction
- These effects are essential for describing high beta plasmas
- Fast ions increase total β' and β in system, and thus more EM-stabilization in the core and more edge pressure while not adding to the ITG drive.
- Concept of "free β" (as long as below BAE/KBM mode limit)
- Core-edge coupling due to fast ions is a solid mechanism for improved confinement: more efficient at high power!
- Unlike ExB shear, this effect could explain core improved confinement in JET hybrid scenarios
- The impact on ITER hybrid expected to be of the same level as on JET
- Good scaling for Tokamak reactors!

With fast ion mode in NL simulation, fluxes far above power balance levels

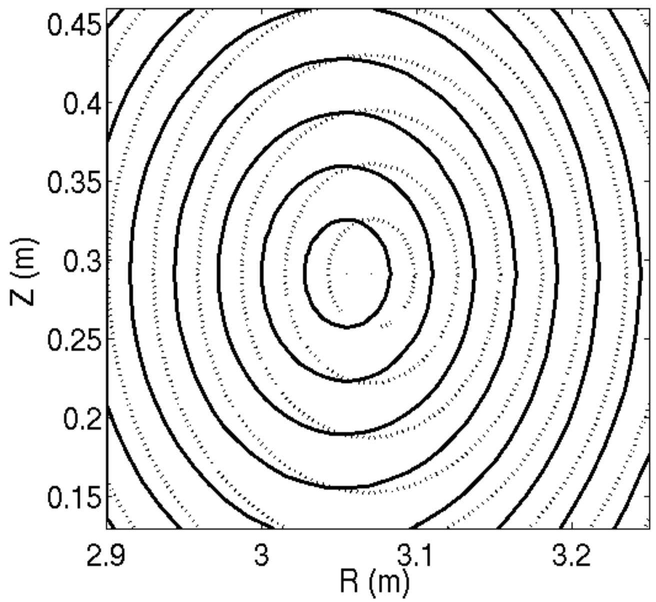
What happens nonlinearly if we allow the BAE/KBM mode to be unstable?

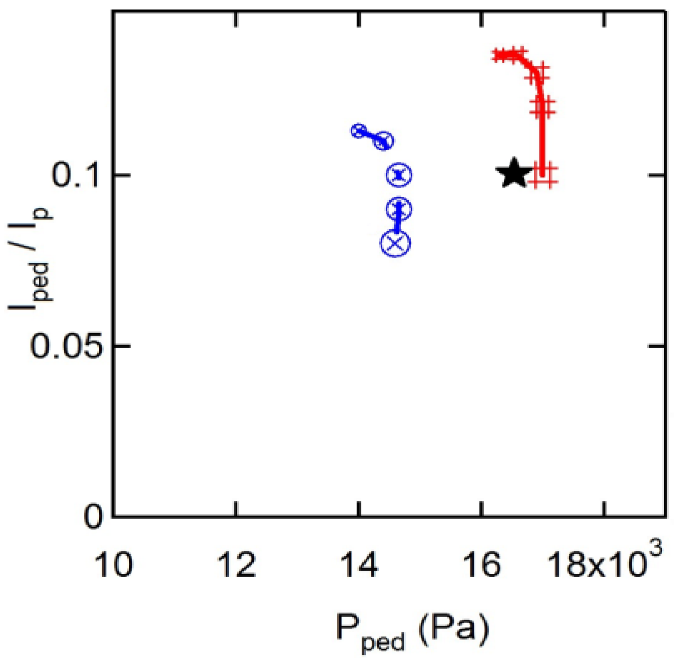


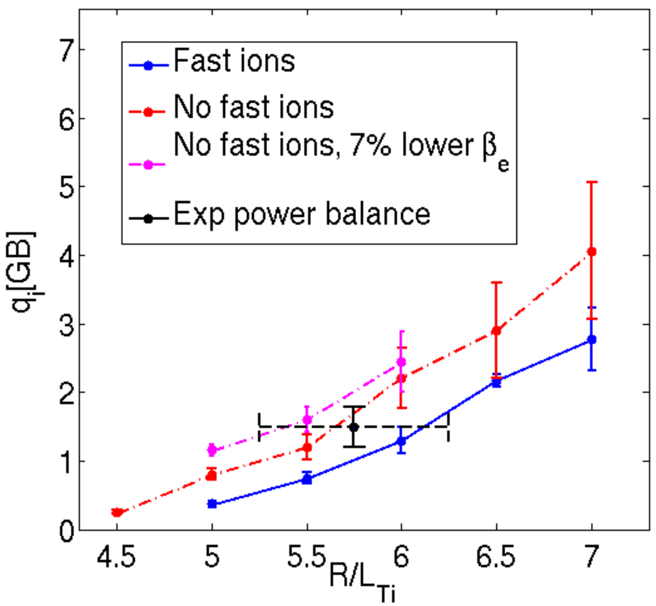
Phase 1: With 30% reduced fast ion pressure (no BAE/KBM mode)
Phase 2: increase to nominal fast ion pressure and restart simulation

- System with fast ion mode has fluxes clearly above power balance values. Limit cycles? Robustly maintained below limit? Needs further study.
- Supports use of a “stiff” fast ion transport model in reduced modelling frameworks

Edge analysis high δ







- Peeling Ballooning analysis performed for high δ discharge
- Lower contribution of fast ions than for low δ, $\beta_{N,th}$=2.46 β_N=2.8.
- However, larger boundary region expansion, by 14%
- Triangularity critically changes the impact of fast ions: from mostly in the core to mostly at the edge.