Nonlinear stabilization of tokamak microturbulence by fast ions

Citation for published version (APA):
Citrin, J., Jenko, F., Mantica, P., Told, D., Bourdelle, C., Garcia, J., Haverkort, J. W., Hogeweij, G. M. D., Johnson, T., & Pueschel, M. J. (2013). Nonlinear stabilization of tokamak microturbulence by fast ions. Physical Review Letters, 111(15), Article 155001. https://doi.org/10.1103/PhysRevLett.111.155001

DOI:
10.1103/PhysRevLett.111.155001

Document status and date:
Published: 01/01/2013

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher’s website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:
www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:
openaccess@tue.nl
providing details and we will investigate your claim.
Nonlinear Stabilization of Tokamak Microturbulence by Fast Ions

J. Citrin,1,4,* F. Jenko,2 P. Mantica,3 D. Told,2 C. Bourdelle,4 J. Garcia,4 J. W. Haverkort,5,1 G. M. D. Hogeweij,1 T. Johnson,6 and M. J. Pueschel7

1FOM Institute DIFFER—Dutch Institute for Fundamental Energy Research, Association EURATOM-FOM, Trilateral Euroregio Cluster, PO Box 1207, 3430 BE Nieuwegein, The Netherlands
2Max Planck Institute for Plasma Physics, EURATOM Association, 85748 Garching, Germany
3Istituto di Fisica del Plasma “P. Caldirola,” Associazione Euratom-ENEA-CNR, Milano, Italy
4CEA, IRFM, F-13108 Saint Paul Lez Durance, France
5Centrum Wiskunde and Informatica (CWI), PO Box 94079, 1090 GB Amsterdam, Netherlands
6Euratom-VR Association, EES, KTH, Stockholm, Sweden
7University of Wisconsin-Madison, Madison, Wisconsin 53706, USA
(Received 21 June 2013; published 7 October 2013)

Nonlinear electromagnetic stabilization by suprathermal pressure gradients found in specific regimes is shown to be a key factor in reducing tokamak microturbulence, augmenting significantly the thermal pressure electromagnetic stabilization. Based on nonlinear gyrokinetic simulations investigating a set of ion heat transport experiments on the JET tokamak, described by Mantica et al. [Phys. Rev. Lett. 107, 135004 (2011)], this result explains the experimentally observed ion heat flux and stiffness reduction. These findings are expected to improve the extrapolation of advanced tokamak scenarios to reactor relevant regimes.

DOI: 10.1103/PhysRevLett.111.155001 PACS numbers: 52.30.Gz, 52.35.Ra, 52.55.Fa, 52.65.Tt

Introduction.—It has been well established that a significant limiting factor of core energy confinement in tokamaks is turbulent transport driven by microinstabilities [1]. The ion-temperature-gradient (ITG) instability [2] has long been identified as an important driver of microturbulence, and is primarily responsible for ion heat losses. ITG modes are driven linearly unstable by logarithmic ion temperature gradients above a critical threshold, i.e., by $R/L_{T_i} > R/L_{T_{i,crit}}$, where the tokamak major radius $R$ is a normalizing factor. These modes saturate in conjunction with nonlinearly excited zonal flows, forming a self-organized turbulent system which sets the transport fluxes [3]. In the following, we term “stiffness” the degree of sensitivity of the ion heat flux to the driving $R/L_{T_i}$. At lower stiffness, higher $R/L_{T_i}$ is attained for the same input heat flux and critical threshold.

Improving core confinement by mechanisms which increase the instability critical thresholds and/or decrease the temperature profile stiffness would increase fusion power in reactors, ultimately reducing the electricity cost. This Letter discusses such a mechanism—nonlinear electromagnetic stabilization of ITG turbulence by thermal and suprathermal pressure gradients—as modeled in simulations and in agreement with experimental observations. This specific effect is most relevant for “hybrid scenarios,” an advanced operating regime developed on present-day tokamaks which may extrapolate favorably to future devices such as ITER [4,5].

The motivation for this study stems from recent experiments where a significant reduction of ion stiffness was reported in conditions of concomitant low magnetic shear $\delta$ and high rotational flow shear. [6,7]. However, until now, nonlinear gyrokinetic simulations have not reproduced the stiffness reduction. $\delta = (r/q)(dq/dr)$, where $q$ is the “safety factor” profile which increases with the ratio between the toroidal and poloidal magnetic fields.

We report on gyrokinetic simulations of discharges reported in Ref. [7], using the GENE code [8]. Nonlinear stabilization of ITG turbulence by thermal and suprathermal pressure gradients significantly reduces the simulated ion heat flux to levels consistent with the measured values, explaining the observed stiffness reduction. This stabilization mechanism is shown to be more effective at low $\delta$, in agreement with observations. The rotational flow shear is seen not to be an important stabilizing factor in this regime. By “stabilization” we mean a reduction, rather than a full suppression, of mode growth rates (in linear simulations) or ion heat flux (in nonlinear simulations), when including the additional physics.

Previously considered linear mechanisms of fast ion stabilization of ITG modes include fast ion dilution of the main ion species [9,10], Shafranov shift stabilization [11], and electromagnetic (i.e., including both electric and magnetic field fluctuations in the model) stabilization by suprathermal pressure gradients [12]. For our discharge parameters, the nonlinear stabilization when including the first two effects scales with the degree of linear stabilization. However, the degree of nonlinear electromagnetic stabilization is significantly greater than the linear case. This nonlinear enhancement is the key factor that explains the experimental results.

Experimental discharges.—A subset of discharges described in Ref. [7] is analyzed at $\rho = 0.33$, where $\rho$ is...
FIG. 1 (color online). Ion heat flux versus $R/L_{Ti}$ from JET data presented in Ref. [7] showing a separation between high and low stiffness regimes at $\rho = 0.33$. The specific discharges studied in this Letter are circled.

The fast ion profiles were calculated by the NEMO/SPOT code [14] for NBI-driven fast ions and by the SELFO code [15] for the ICRH-driven fast ions (3He). SELFO includes finite ion cyclotron orbit width effects, important for an accurate calculation of the ICRH fast ion pressure profile width. Interpretative simulations of the discharges with the CRONOS [16] code yielded safety factor $q$ and $\delta$ values

within $\pm 15\%$ of the motional Stark effect or polarimetry constrained EFIT equilibrium code calculations. The discharge dimensionless parameters fed into the nonlinear gyrokinetic calculations are summarized in Table I. Details of the heating schemes used are in Ref. [6]. The ion heat flux and stiffness sensitivity to the various parameters were extensively studied, and the key parameters which impact the stiffness in this parameter regime are $\beta_e$ and the fast ion profiles.

**Simulation setup.**—The gyrokinetic turbulence code GENE was used in the radially local limit, justified since here $1/\rho^* = 500$ [17,18], $\rho^*$ is the ion Larmor radius normalized to the tokamak minor radius. Typical GENE grid parameters were as follows: perpendicular box sizes $[L_x, L_y] = [170, 125]$ in units of $\rho_i \equiv c_s/\Omega_i$, perpendicular grid discretizations $[n_x, n_y] = [192, 48]$, $n_z = 24$ points in the parallel direction, 32 points in the parallel velocity direction, and 8 magnetic moments. $c_s \equiv (T_e/m_i)^{1/2}$ and $\Omega_i \equiv (eB/m_i)$. $x$ is the GENE radial coordinate, $z$ the coordinate along the field line, and $y$ the binormal coordinate. All simulations included kinetic electrons. Both an analytical circular geometry model [19] as well as an experimental geometry were used. Extensive convergence tests were carried out throughout the parameter space spanned.

The ion heat fluxes correspond to time-averaged values over the saturated state of the simulations, and are in gyroBohm normalized units. The normalizing factor is $q_{GB} = T_i^{2/3} n_i m_i^{0.5} / e^2 B^2 R^2$, where $n_i$ is the ion density and $m_i$ the ion mass. However, for consistency with Refs. [6,7], $n_e$ was used as a proxy for $n_i$ in the normalization in this work. For purely toroidal rotational flow shear, as assumed here, $\gamma_E \equiv (r/q)(d\Omega_i/dr)/(c_s/R)$ is the normalized perpendicular flow shear rate. In the electromagnetic simulations, only the $\delta B_{\perp}$ fluctuations were computed, justified by the relatively low $\beta_e$ values. Including $\delta B_{\parallel}$ in the system had a negligible impact on the heat flux.

**Impact of flow shear.**—The high and low stiffness branches are correlated with low ($\gamma_E \approx 0.1$) and high (0.3)
Impact of electromagnetic effects.—Here we present the significant impact of electromagnetic stabilization. Linear and nonlinear $\beta_e$ scans based on discharge 66404 parameters are shown in Fig. 3. The range of experimental $\beta_e$ values (0%-0.5%) lies significantly below the computed kinetic ballooning mode thresholds. Electromagnetic effects lead to linear ITG mode stabilization with increasing $\beta_e$ [22]. For our parameters, this leads to a growth rate reduction of $\approx 25\%$ at $\beta_e = 0.5\%$, at the upper range of our experimental $\beta_e$ values. The degree of linear ITG mode stabilization, i.e., the relative reduction of $\gamma$ for $\beta_e > 0$ compared with $\beta_e = 0$, is stronger as $R/L_Ti$ is increased. This is consistent with the corresponding increase of the coupling between the electromagnetic shear Alfvén wave and the ITG mode with pressure gradients at any given $\beta_e$ value [22].

A striking observation is that the nonlinear electromagnetic ITG stabilization significantly exceeds the linear stabilization, increasing to $\approx 65\%$ as compared with the linear $\approx 25\%$ at the upper range of the experimental $\beta_e$ values. This is consistent with the GENE results reported in Refs. [23–25], which correlated the enhanced nonlinear stabilization with increased relative zonal flow activity and zonal flow effective growth rates. This increase may be related to the predicted increased coupling to zonal flows in the electromagnetic regime [26]. Future work will investigate these dynamics further. We note that the field structures maintain ballooning parity at the higher $\beta_e$ values and remain consistent with ITG dominated turbulence.

A key point is that the nonlinear electromagnetic stabilization can be significantly augmented by suprathermal pressure gradients. A parameter of merit for the strength of the electromagnetic impact on the linear ITG mode—to which the nonlinear effect is likely linked—is $\alpha = \sum j \beta_j (R/L_{nj} + R/L_{Tj})$, where $j$ sums over all particle species. $\alpha$ is a dimensionless measure of the pressure gradient. We stress that while not an exact parametrization in the general case, $\alpha$ nevertheless captures the qualitative
Importantly, the fast ions increase the modeled ICRH and NBI fast ion contributions simultaneously not contributing to the ITG mode drive. The most significant fast ion contribution to \(q_i\) [gyroBohm units] is obtained at reduced \(R/L_{Ti}\).

The experimentally observed low stiffness is also captured. This is indicated by reduced \(R/L_{Ti}\) runs carried out for discharges 66404 and 73224, displayed in Fig. 5. The low stiffness for 73224 is accompanied by an enhanced threshold up-shift, indicated by marginal stability at \(R/L_{Ti} = 7.9\), significantly above the linear threshold of \(R/L_{Ti,\text{crit}} = 2.5\). This is consistent with Ref. [24], where a threshold shift was accompanied by a stiffness reduction for \(\beta_e > 0\). The seeming lack of threshold modification for discharge 66404 is attributed to residual activity of trapped electron modes, destabilized by the higher \(R/L_a\) and observed at low \(R/L_{Ti}\) in linear analysis of this discharge.

The remaining discrepancies in the flux values between the various simulations and measurements can be reconciled by reasonable variations of the input parameters—such as \(R/L_{Ti}, T_e/T_i, \delta, q,\) and \(Z_{\text{eff}}\)—within the experimental uncertainties. \(Z_{\text{eff}} = \frac{(\sum Z^2 j n_j)}{n_e}\) is the effective ion charge. However, the discrepancies observed when not including the fast ions in an electromagnetic framework are clearly outside this envelope.

We note that discharges in the “high stiffness” branch were also investigated. The significantly lower thermal and suprathermal pressure gradients led to a much reduced impact on the ion heat flux and stiffness reduction compared with the low stiffness branch. This is consistent with the electromagnetic stabilization mechanism being primarily responsible for the splitting of the experimental data into two separate stiffness branches.

Finally, the impact of the electromagnetic stabilization is stronger at low \(\delta\). This is shown in Table II. The simulations—based on discharge 66404—used circular geometry with \(q = 1.7\). This \(\delta\) dependence of the electromagnetic stabilization is in qualitative agreement with the experimentally observed decreased stiffness at low \(\delta\).

**Summary and implications.**—Based on gyrokinetic simulations with the \(\text{GENE}\) code, nonlinear electromagnetic stabilization of ITG modes by both thermal and suprathermal pressure gradients is shown to be the key factor leading to a reduced ion temperature profile stiffness regime at JET. This mechanism provides a clear explanation for the observations. The previously hypothesized

---

**TABLE II.** \(\text{GENE}\) simulations based on discharge 66404 with collisions, circular geometry, two species, and assumed \(T_e/T_i = 1\). The uncertainty values reflect the ion heat flux fluctuations during the saturated state. The electromagnetic stabilization is stronger at low \(\delta\), as reflected by the “stabilization factor,” which is the ratio between the electromagnetic and electrostatic ion heat fluxes.

| \(\beta_e\) [%] | \(\delta\) | \(q_i\) [gyroBohm units] | Stabilization factor |
|-----------------|---------|-----------------|------------------|
| 0.32            | 0.2     | 180 ± 14        | 3.5              |
| 0.32            | 0.2     | 52 ± 11         |                  |
| 0.32            | 0.45    | 230 ± 14        | 2.6              |
| 0.32            | 0.45    | 88 ± 16         |                  |
| 0.32            | 0.7     | 246 ± 26        | 2.7              |
| 0.32            | 0.7     | 90 ± 30         |                  |
mechanism of concomitant low magnetic shear and high rotational flow shear is shown to be insufficient to lead to significant stiffness reduction. The electromagnetic stabilization is also seen to be more effective at low magnetic shear, in line with the experimental trends.

This effect has striking consequences for burning plasma tokamak scenarios, where for larger devices flow shear is expected to be low, but the fast ion component from fusion-α particles will be significant. Evidence of such improved ion energy confinement in JET DT plasmas has been seen [28,29]. The increased strength of the effect at low $\tilde{\delta}$ indicates a more favorable energy confinement extrapolation for burning hybrid scenarios, which contain a significant volume of low $\tilde{\delta}$. Furthermore, hybrid scenarios contain a higher suprathermal pressure fraction than “standard” scenarios, owing to reduced density due to lower current. DT hybrid scenarios at JET may thus achieve improved energy confinement beyond what has been observed in DD discharges. For ITER, this beneficial effect may relax the constraints on pedestal performance and heating and current drive requirements for achieving the scenario, as determined from previous extrapolations [30]. Finally, in the JET stiffness experiments performed until now, flow shear and suprathermal pressure gradients were coredcorrelated. This calls for additional experiments, on various machines, to decouple the impact of these parameters on transport.

This work, supported by the European Communities under the contract of Association between EURATOM/ FOM, was carried out within the framework of the European Fusion Programme with financial support from NWO. This work is supported by NWO-RFBR Centre-of-Excellence on Fusion Physics and Technology (Grant No. 047.018.002). This work is part of the research program “Fellowships for Young Energy Scientists” (YES!) of the Foundation for Fundamental Research on Matter (FOM), which is financially supported by the Netherlands Organisation for Scientific Research (NWO). The authors would like to thank C. Angioni, H. Doerk, R. Dumont, D.R. Hatch, E. Highcock, F. Millitello, F. Ryter, A. Schekochihin, M. Schneider, J. Weiland, and E. Westerhof for stimulating discussions. Resources of HPC-FF in Jülich are gratefully acknowledged. This research used computational resources at the National Research Scientific Computing Center, which is supported by the Office of Science of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. The authors are grateful to D.R. Mikkelsen for assistance. This work was done under the JET-EFDA work programme [31].

*Corresponding author.
J.Citrin@differ.nl

[1] E. J. Doyle et al., Nucl. Fusion 47, S18 (2007).
[2] F. Romanelli, Phys. Fluids B 1, 1018 (1989).
[3] P. Diamond, S.-I. Itoh, K. Itoh, and T.S. Hahm, Plasma Phys. Controlled Fusion 47, R35 (2005).
[4] E. Joffrin et al., Nucl. Fusion 45, 626 (2005).
[5] J. Hobirk et al., Plasma Phys. Controlled Fusion 54, 095001 (2012).
[6] P. Mantica et al., Phys. Rev. Lett. 102, 175002 (2009).
[7] P. Mantica et al., Phys. Rev. Lett. 107, 135004 (2011).
[8] F. Jenko, W. Dorland, M. Kotschenreuther, and B.N. Rogers, Phys. Plasmas 7, 1904 (2000); See http://gene.rzg.mpg.de for code details and access.
[9] G. Tardini et al., Nucl. Fusion 47, 280 (2007).
[10] C. Holland et al., Phys. Plasmas 18, 056113 (2011).
[11] C. Bourdelle, G.T. Hoang, X. Litaudon, C.M. Roach, and T. Tala, Nucl. Fusion 45, 110 (2005).
[12] M. Romanelli, A. Zocco, F. Crisanti, and JET-EFDA Contributors, Plasma Phys. Controlled Fusion 52, 045007 (2010).
[13] F. Ryter et al., Nucl. Fusion 51, 113016 (2011).
[14] M. Schneider, L.-G. Eriksson, I. Jenkins, J.F. Artaud, V. Basiuk, F. Imbeaux, T. Oikawa, JET-EFDA Contributors, and ITM-TF Contributors, Nucl. Fusion 51, 063019 (2011).
[15] J. Hedin, T. Hellsten, L.-G. Eriksson, and T. Johnson, Nucl. Fusion 42, 527 (2002).
[16] J.F. Artaud et al., Nucl. Fusion 50, 043001 (2010).
[17] J. Candy, R.E. Waltz, and W. Dorland, Phys. Plasmas 11, L25 (2004).
[18] B.F. McMillan, X. Lapillonne, S. Brunner, L. Villard, S. Jolliet, A. Bottino, T. Görl, and F. Jenko, Phys. Rev. Lett. 105, 155001 (2010).
[19] X. Lapillonne, S. Brunner, T. Dannert, S. Jolliet, A. Marinoni, L. Villard, T. Görl, F. Jenko, and F. Merz, Phys. Plasmas 16, 032308 (2009).
[20] J.E. Kinsey, R.E. Waltz, and J. Candy, Phys. Plasmas 12, 062302 (2005).
[21] E.G. Highcock, A.A. Schekochihin, S.C. Cowley, M. Barnes, F.I. Parra, C.M. Roach, and W. Dorland, Phys. Rev. Lett. 109, 265001 (2012).
[22] J.Y. Kim, W. Horton, and J.Q. Dong, Phys. Fluids B 5, 4030 (1993).
[23] M.J. Pueschel, M. Kammerer, and F. Jenko, Phys. Plasmas 15, 102310 (2008).
[24] M.J. Pueschel and F. Jenko, Phys. Plasmas 17, 062307 (2010).
[25] M.J. Pueschel, T. Görler, F. Jenko, and D.R. Hatch (to be published).
[26] F. Millitello, M. Romanelli, J.W. Connor, and R.J. Hastie, Nucl. Fusion 51, 033006 (2011).
[27] C. Holland, C.C. Petty, L. Schmitz, K.H. Burrell, G.R. McKee, T.L. Rhodes, and J. Candy, Nucl. Fusion 52, 114007 (2012).
[28] S.E. Sharapov et al., Fusion Sci. Technol. 53, 989 (2008).
[29] D. Testa and M. Albergante, Europhys. Lett. 97, 35003 (2012).
[30] J. Citrin, J.F. Artaud, J. Garcia, G.M.D. Hogeweij, and F. Imbeaux, Nucl. Fusion 50, 115007 (2010).
[31] See the Appendix of F. Romanelli et al., Proceedings of the 24th IAEA Fusion Energy Conference 2012, San Diego, USA [International Atomic Energy Agency (IAEA), Vienna, 2012]. (All the members of the JET-EFDA collaboration appear in the appendix of this paper.)