Nonlinear electromagnetic stabilization of ITG microturbulence by ICRF-driven fast ions in ASDEX Upgrade

F.N. de Oliveira[1], H. Doerk[2], M.J. Mantsinen[1, 3], C. Angioni[2], R. Bilato[2], V. Bobkov[2], M. Dunne[2], D. Gallart[1], A. Gutiérrez-Milla[1], P. Mantica[4], T. Odstrčil[2], G.Tardini[2], X. Sáez[1], the ASDEX Upgrade Team and the EUROfusion MST1 Team*

[1]Barcelona Supercomputing Center (BSC), Barcelona, Spain

[2]Max-Planck-Institut für Plasmaphysik, Garching, Germany

[3]ICREA, Barcelona, Spain

[4]Istituto di Fisica del Plasma "P. Caldirola", CNR, Milano, Italy

**see the author list of H. Meyer et al., Overview of progress in European Medium Sized Tokamaks towards an integrated plasma-edge/wall solution, accepted for publication in Nuclear Fusion.*

Introduction Electromagnetic waves in the range of Ion Cyclotron Resonance Frequencies (ICRF) have many applications in fusion devices. While their use for external heating of magnetically confined fusion plasmas is well established, their effects on the enhancement of the plasma confinement by microturbulence stabilization have only been recently discovered [1,2]. For this effect a key parameter of merit is $\alpha = -q^2 \beta R \nabla P / P$ where R is the tokamak major radius, β is the plasma beta, q is the safety factor and P is the plasma pressure. By increasing a local plasma pressure gradient and/or beta by ICRF-accelerated resonant ions, we can decrease turbulent transport driven by microinstabilities. We investigate the impact of ICRF-accelerated fast ions in the stabilization of microturbulence in two ASDEX Upgrade H-mode discharges [3]. In these discharges, in addition to 4.5 MW of deuterium NBI, 3.5 MW of ICRF power was applied at a frequency of 30 MHz tuned to a centrally located ^3He minority resonance. The location of the ^3He minority resonance was varied by about 10 cm by changing the toroidal magnetic field from 2.8 T in discharge 31562 to 3 T in discharge 31563. The plasma current was 0.6 MA and the main ion species was deuterium. An increase of up to 80% in the central ion temperature was measured, from 3 keV to 5.5 keV, as compared to the reference discharge 31555 with NBI heating only (c.f. Fig. 1). The normalized logarithmic ion temperature gradient, R/LT_i, reached a high value of about 20, corresponding to a radial gradient of the T_i profile of about 50 keV/m. The ^3He ion density is below 5% of the electron density in all discharges. Thus, the possible effect of main ion dilution [4] on microturbulence stabilization is not expected to be significant.

Methodology We use PION [5] and the Finite Ion Drift Orbit code FIDO [6] to compute the electromagnetic wave parameters and the fast ^3He minority ion parameters. Figure 2 shows the fast ^{3}He minority ion pressure profiles as calculated by FIDO. Discharge 31563 has a steeper fast ^{3}He ion pressure profile due to a more central ^{3}He minority resonance. With the fast ^{3}He ion density, temperature, and pressure profiles as given by FIDO, we evaluate the logarithm of the gradient of the fast ^{3}He ion density and temperature which are used as input parameters in the plasma turbulence code GENE [7]. In this work, a static Maxwellian distribution is assumed for thermal and fast ^{3}He ions in GENE. While this can be generalised in future work, we expect that the observed trends carry over to a more realistic distribution.

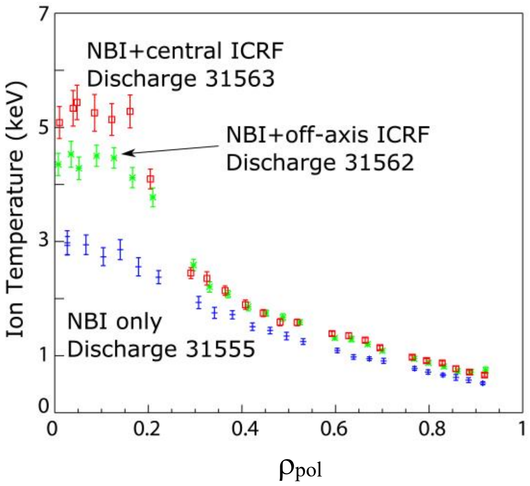

Figure 1: Ion temperature T_i profiles for AUG discharges 31562, 31563 and 31555 [3].

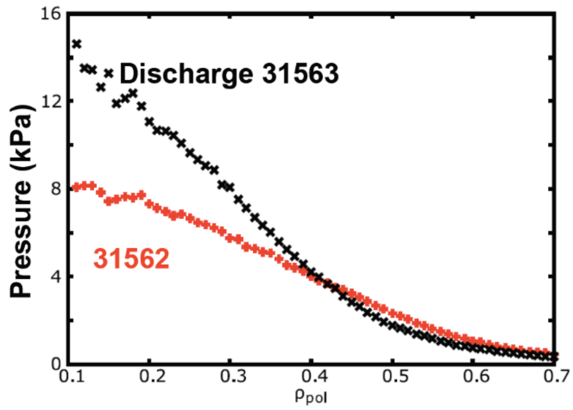

Figure 2: Pressure profiles of ^{3}He ions for discharges 31562 and 31563 as calculated by FIDO.

Linear results Our linear analyses performed with GENE show that electromagnetic activity and the safety factor q have a strong impact on the growth rate of the Ion Temperature Gradient (ITG) instability. This is illustrated by Fig. 3a which shows the spectral analysis with and without electromagnetic effects, and by Fig. 3b which shows the impact of the safety factor q on the instability growth rate. Sensitivity analyses with respect to q and fast ^{3}He ion parameters such as T_f, n_f, R/L_{nf} and R/L_{Tf} were carried out to identify the parameter range that does not include strong Kinetic Ballooning Mode (KBM) activity. In the electromagnetic ITG case, the instability growth rates decrease with increasing q, which is opposite to the electrostatic trend [8]. We find that the instability growth rate decreases with increasing electromagnetic activity. Furthermore, electromagnetic activity can increase due to the presence of fast ions, which can lead to a reduction in the instability growth rate.

Nonlinear results We have carried out non-linear gyrokinetic GENE simulations with and without fast ^{3}He minority ion population. Figure 4 shows electric potential fluctuations with fast ions for discharge 31563. They exhibit coherent structures known as zonal flows. The time-averaged zonal shearing increases by 25-30% when fast ions are included, suggesting an increase in the zonal flow capability to shear the microturbulent mode, and therefore stabilize it, in the case where fast ions are included. Simulations for longer times are on-going in order to confirm this result.

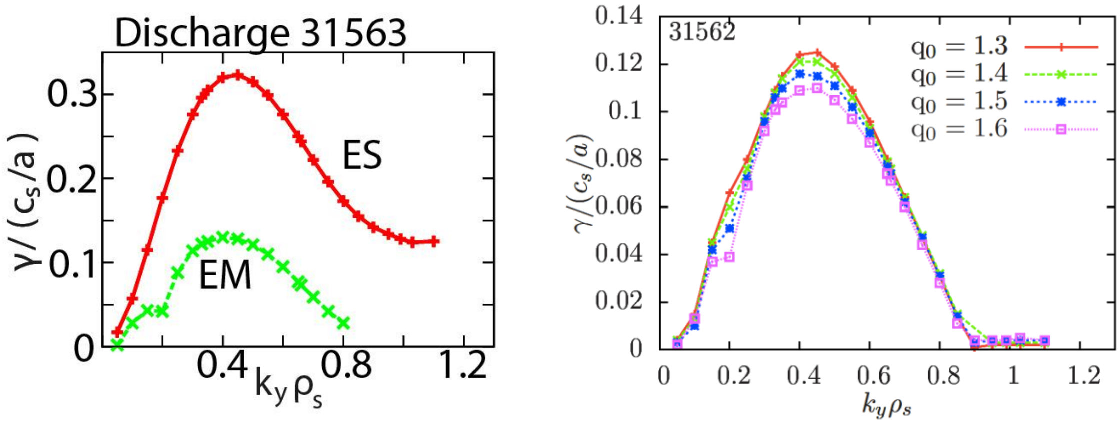

Figure3: (a) Instability growth rate γ with (green) and without (red) electromagnetic (EM) activity as given by linear GENE simulations for discharge 31563. (b) The dependence of the instability growth rate γ on the safety factor as given by linear GENE simulations for discharge 31562.

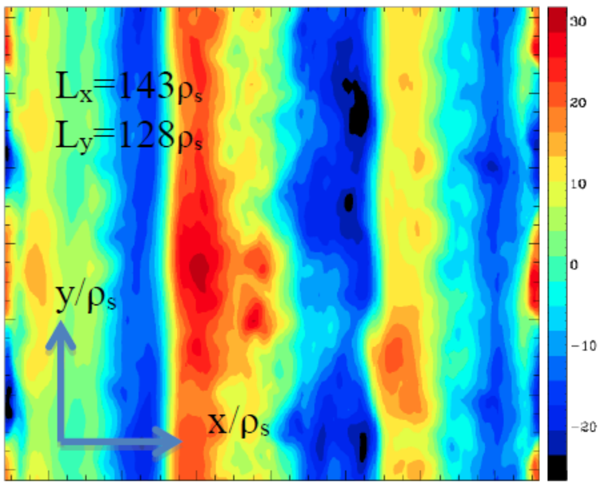

Figure 4: Electric potential fluctuations as given by a non-linear GENE simulation with fast ions for discharge 31563, showing coherent structures known as zonal flows. We use a perpendicular domain size of $143\rho_s$ x $128\rho_s$ in x, y for nonlinear GENE simulations, with a grid of (256x128x24x32x12) in (x, y, z, $v_{//}$, μ) phase space.

Nonlinear GENE simulations allow us to compare the simulated heat fluxes with those obtained by power balance analysis of the experiment. In this paper we focus on ion heat transport and leave the full transport analysis including electrons for a further study. In discharge 31563, the experimental integrated ion heat flux is 1.6 MW at the radial position $\rho_{tor} = 0.25$, deduced from the modelling of the NBI and ICRF heating with the PION, FIDO and TRANSP codes.

The ion heat fluxes as given by non-linear GENE simulations are shown in Fig. 5 for discharge 31563 with fast ions and without fast ions. The statistical time-averaged ion heat flux is 1.3 and 4.5 MW with and without fast ions, respectively. The former is much closer to the experimental value of 1.6 MW than the latter. Our nonlinear simulations thus confirm the transport reduction in the presence of fast ions.

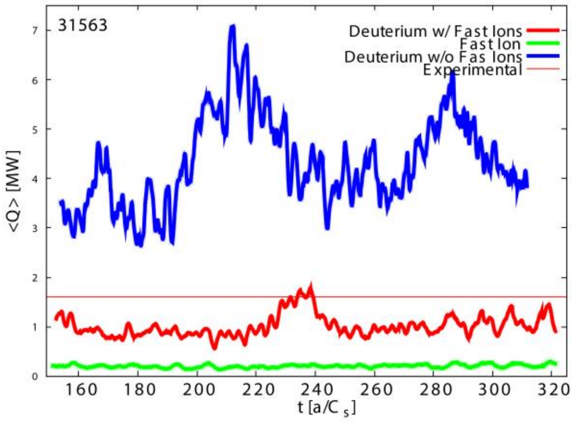

Figure 5: Ion heat fluxes as given by non-linear GENE simulations for discharge 31563 with fast ions and without fast ions. The red horizontal line shows the experimental ion heat flux of 1.6 MW. The time is expressed in terms of GENE normalized units, which is approximately one microsecond. No qualitative change is expected for longer simulation times that are ongoing.

While it is clear from Fig. 5 that adding fast ions destabilises electromagnetic modes, the exact mechanism by which ITG turbulence is reduced by fast ions is still under investigation. For the nonlinear part, our results point towards a relative increase of zonal flow strength, which needs to be confirmed by longer simulation times. For discharge 31562, similar results were obtained as for discharge 31563 in the linear analysis. The non-linear simulation of this discharge is on-going. It is expected to exhibit similar features as that for discharge 31563.

Conclusions We have identified that the presence of ICRF-heated ^3He minority ions can reduce ITG growth rates in ASDEX Upgrade H-mode plasmas with combined NBI and ICRF heating. In nonlinear gyrokinetic simulations with the GENE code, the ion heat flux reduces with fast ions by a factor of about four, reaching a value close to the experimental one. This work can be further improved by including a more realistic fast ion distribution function such as a Bi-Maxwellian, which is a recent new feature in GENE [9].

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under the grant agreement No 633053. The views and opinion expressed herein do not necessarily reflect those of the European Commission. We would also like to thank Red Española de Supercomputación (RES) for the resources granted, as well as the CINECA resources granted through the MARCONI-Fusion project.

References

[1] J. Citrin et al., Phys. Rev. Letters, 111 (2013) 155001.
[2] J. Garcia et al., Nucl. Fusion 55 (2015) 053007.
[3] M.J. Mantsinen et al., AIP Conference Proceedings, vol. 1689. pp. 030005:1-8, 2015.
[4] G. Tardini et al., Nucl. Fusion 47 (2007) 280.
[5] L.-G. Eriksson and T. Hellsten and U. Willén, Nucl. Fusion 33 (1993) 1037.
[6] J. Carlsson, T. Hellsten and L.-G. Eriksson, Proc. Joint Varenna Lausanne Workshop 'Theory of Fusion Plasmas' 1994, p. 351.
[7] F. Jenko, W. Dorland, M. Kotschenreuther and B. N. Rogers, Physics of Plasmas 7 (2000) 1904.
[8] F. Jenko, W. Dorland and G. W. Hammett, Physics of Plasmas 8, 4096 (2001).
[9] A. Di Siena et al., 2016 J. Phys.: Conf. Ser. 775 012003.