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Gyrokinetic simulations of particle transport in pellet fuelled JET discharges

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* See the author list of "Overview of the JET results in support to ITER" by X. Litaudon et al. to be published in Nuclear Fusion Special issue: overview and summary reports from the 26th Fusion Energy Conference (Kyoto, Japan, 17-22 October 2016)

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Abstract

Pellet injection is a likely fuelling method of reactor grade plasmas. When the pellet ablates, it will transiently perturb the density and temperature profiles of the plasma. This will in turn change dimensionless parameters such as a/L_n , a/L_T and plasma β . The microstability properties of the plasma then changes which influences the transport of heat and particles. In this paper, gyrokinetic simulations of a JET L-mode pellet fuelled discharge are performed. The Ion Temperature Gradient/Trapped Electron (ITG/TE) mode turbulence is compared at the time point when the effect from the pellet is the most pronounced with a hollow density profile and when the profiles have relaxed again. Linear and nonlinear simulations are performed using the gyrokinetic code GENE including electromagnetic effects and collisions in a realistic geometry in local mode. Furthermore, global nonlinear simulations are performed in order to assess any nonlocal effects. It is found that the positive density gradient has a stabilizing effect that is partly counteracted by the increased temperature gradient in the this region. The effective diffusion coefficients are reduced in the positive density region region compared to the intra pellet time point. No major effect on the turbulent transport due to nonlocal effects are observed.

1. Introduction

Pellet injection is the likely fuelling method of reactor grade plasmas. Unlike when using fuelling by gas puffing, injecting a pellet into the plasma temporarily perturbs both the density and temperature profiles, resulting in changes in dimensionless parameters such as a/L_n , a/L_T , collisionality and plasma β . The density profile may become hollow

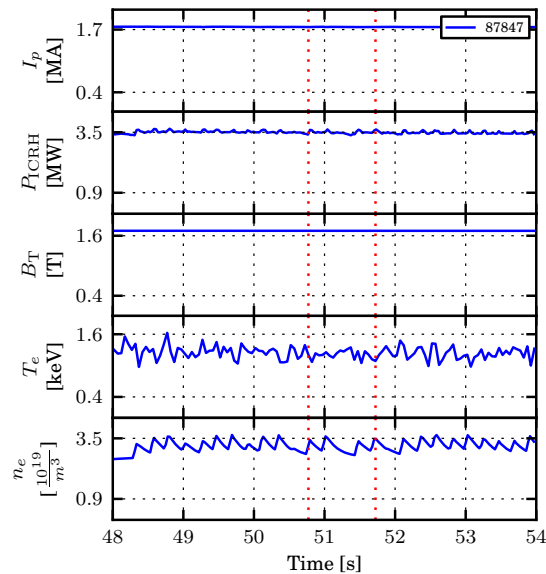


Figure 1: Time evolution of the plasma current, ICRH power, toroidal magnetic field, electron temperature on the magnetic axis, and line averaged core electron density during the flat top. Time points of analysis indicated with dotted lines.

35 with regions of positive density gradients and steeper negative density gradients on the
 36 outside of the pellet ablation peak. This will in turn affect microstability and transport
 37 properties of the discharge. Hydrogen pellet injection experiments were performed
 38 during the JET hydrogen campaign in 2014. The target were L-mode ICRH-heated
 39 hydrogen plasmas. The diagnostic set-up was optimised to measure the post pellet
 40 evolution of the density profile with high spatial resolution and the pellet injection
 41 frequency (14 Hz) was chosen with respect to sampling time of the Thomson scattering
 42 measurements (50 ms) to exploit a 'stroboscopic' effect and virtually enhance the
 43 time resolution of the profile measurement. Accurate equilibrium reconstruction and
 44 Gaussian process regression fits [1] of the kinetic profiles were performed to provide the
 45 basis for gyrokinetic analysis of the pellet cycle and characterise the transport properties
 46 of these pellet fuelled plasmas. The discharge under study here is no. 87847 with a
 47 toroidal magnetic field of 1.7 T, a plasma current of 1.75 MA and 3.45 MW of ICRH
 48 power. The time evolution of the plasma current, ICRH power, and magnetic field,
 49 along with the electron temperature and density are shown in Figure 1. Microstability
 50 analysis of a typical MAST pellet fuelled discharge was previously performed in [2] where
 51 a stabilization of all modes in the negative a/L_n (positive density gradient) region was
 52 found. The quasilinear gyrokinetic code QuaLiKiz [3] has been previously used to study
 53 the microturbulence during the L to H transition which is also associated with hollow
 54 density profiles, it was shown that the TE mode was stabilized and that the particle
 55 flux was highly sensitive to the sign of R/L_n [4].

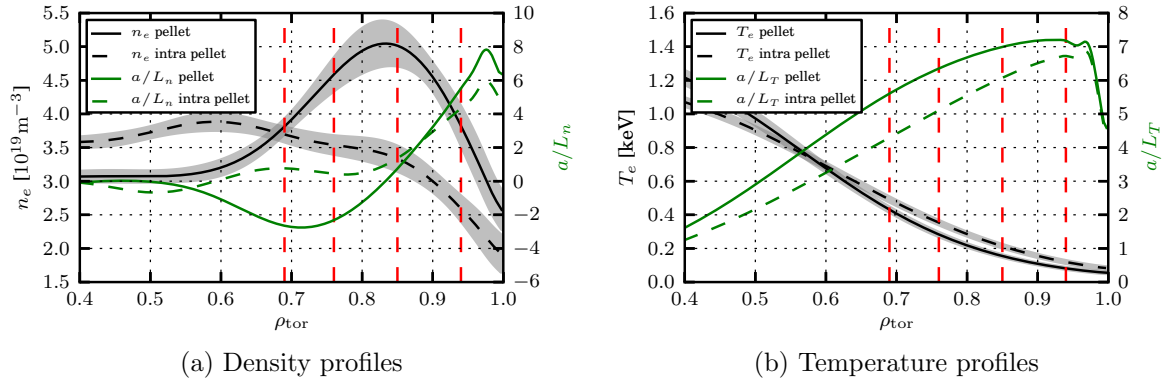


Figure 2: Profiles of density and temperature at the two time points. Dashed lines indicate radial positions of the gyrokinetic analysis.

56 The discharge is analysed at several radial positions around the density peak and
 57 at several time points after the injection of the pellet. The focus is on the time point
 58 when the density peak from the ablation pellet is the largest, $t = 0.0042$ s after the
 59 pellet injection, referred to as 'pellet'. The results are compared and contrasted to
 60 the time point when the peak is relaxed again at 0.034 s, referred to as 'intra pellet'.
 61 The profiles of temperature and density and the resulting normalized gradient scale
 62 lengths are shown in Figure 2 and the discharge parameters are given in Table 1. The
 63 gyrokinetic code GENE [5, 6] is used to study the transport due to Ion Temperature
 64 Gradient/Trapped electron mode (ITG/TE) [7, 8, 9, 10, 11, 12, 13] turbulence. These
 65 modes are the main source of particle transport in the core of tokamak plasmas [14].
 66 Both linear and nonlinear simulations are performed in a flux tube domain, including
 67 finite β effects and collisions in realistic geometry. We note that the collisionality is high
 68 in the present discharge and have included collisionless simulations in order to connect
 69 our results to more reactor relevant conditions. Since the pellet causes the density to vary
 70 significantly over a rather narrow radial region, the possible role of nonlocal phenomena
 71 is also studied in nonlinear global simulations in a reduced physics description including
 72 only electrostatic effects and adiabatic electrons. Because of this, the global simulations
 73 cannot describe particle transport or the TE mode, but a comparison of heat fluxes
 74 to similar local simulations can nevertheless indicate whether there are any nonlocal
 75 effects. Since this is a hydrogen discharge, simulations are also run with deuterium in
 76 order to assess any effects going to reactor relevant isotopes. The paper is organized
 77 as follows. In section 2 the discharge parameters and simulation setup are introduced,
 78 followed by the linear GENE results in section 3. In section 4 the local nonlinear results
 79 are presented and in section 5 follows the study of the isotopic effect. In section 6 global
 80 effects are investigated and finally in section 7 we have the concluding remarks.

ρ_{tor}	t [s after pellet]	n [$10^{19}/\text{m}^3$]	T [keV]	a/L_T	a/L_n	η	ν_{ei} [c_s/a]	β [%]	q	\hat{s}
0.69	0.0042	3.81	0.43	5.60	-2.64	-2.12	1.39	0.20	1.61	1.32
0.69	0.034	3.69	0.49	4.29	0.77	5.57	1.05	0.22	1.60	1.34
0.76	0.0042	4.59	0.28	6.35	-2.32	-2.74	3.73	0.16	1.86	1.64
0.76	0.034	3.54	0.35	5.11	0.42	12.2	1.89	0.15	1.85	1.66
0.85	0.0042	5.01	0.15	7.00	0.74	9.46	13.00	0.10	2.30	2.20
0.85	0.034	3.34	0.21	6.08	1.36	4.47	4.74	0.09	2.30	2.22
0.94	0.0042	3.83	0.08	7.16	5.50	1.30	34.44	0.04	3.01	3.42
0.94	0.034	2.60	0.12	6.71	4.33	1.55	11.36	0.04	3.01	3.43

Table 1: Discharge parameters of the four radial positions and two time points. n is the density, $T = T_e = T_i$ is the temperature, $a/L_T = a/L_{T_e} = a/L_{T_i}$ is the normalized temperature gradient, a/L_n is the normalized density gradient, $\eta = L_n/L_T$, ν_{ei} is the electron-ion collision rate, β is the electron β , q is the safety factor and \hat{s} is the magnetic shear.

81 2. GENE simulation setup

82 GENE solves the nonlinear gyrokinetic Vlasov equation coupled with Maxwell's
83 equations in order to find the distribution functions of the species, $f(\mathbf{R}, v_{\parallel}, \mu, t)$, the
84 electrostatic potential, $\phi(\mathbf{x}, t)$ and the parallel components of the magnetic vector
85 potential and magnetic field, $A_{\parallel}(\mathbf{x}, t)$ and $B_{\parallel}(\mathbf{x}, t)$. It is a Eulerian δf -type code
86 where the coordinate system is aligned to the background magnetic field with x as
87 the radial coordinate, y as the binormal coordinate, and z as the parallel coordinate.
88 Collisions are modelled using a linearised Landau-Boltzmann collision operator [15].
89 Magnetic fluctuations perpendicular and parallel to the magnetic field are included in
90 all simulations. A numeric equilibrium reconstructed using the EFIT++ code [16] is
91 used in either a local, flux-tube domain or global domain. In the simulation, $T_i = T_e$
92 is assumed, and impurities are not included in the simulations. Fast particles and rotation
93 are not expected to play an important role in this low- β , ICRH heated discharge and
94 are not included.

95 3. Linear results

96 For the linear GENE simulation, a resolution typically used is $[n_x, n_z, n_{v_{\parallel}}, n_{\mu}] =$
97 [16, 64, 32, 24]. In cases where subdominant modes are discussed an eigenvalue solver
98 is used, otherwise an initial value solver is used. The linear eigenvalues in SI units at
99 $k_y \rho_s = 0.3$ as a function of ρ_{tor} for the pellet and intra pellet time points are shown
100 in Figure 3. The growth rates at this wave number are reduced in the positive density
101 gradient region $0.62 < \rho_{\text{tor}} < 0.8$ compared to the intra pellet time point, for both
102 collisional and collisionless cases. The eigenvalue spectra at four radial positions around
103 the pellet ablation density peak are shown in Figure 4 at the pellet and intra pellet time
104 points. The four radial points are at $\rho_{\text{tor}} = 0.69$ and $\rho_{\text{tor}} = 0.76$ in the positive gradient
105 region, $\rho_{\text{tor}} = 0.85$ at the peak density and at $\rho_{\text{tor}} = 0.94$ in the negative gradient

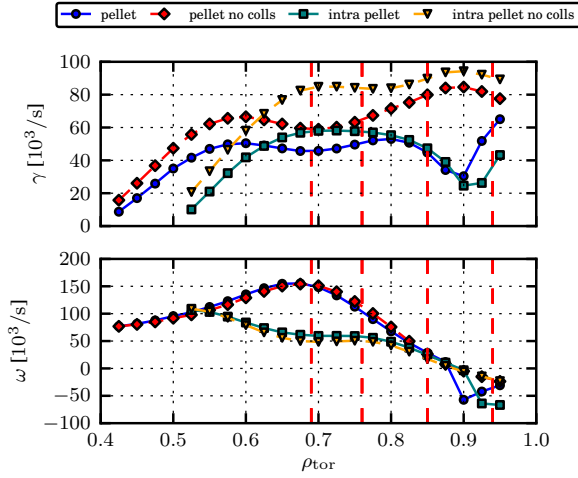


Figure 3: Linear eigenvalues for $k_y \rho_s = 0.3$ as a function of ρ_{tor} at the two different time points, with and without collisions.

106 region. The eigenvalue spectra is dominated by the ITG mode for $k_y \rho_s < 1.2$ in the four
 107 cases as indicated by the positive real frequency. In the positive density gradient region,
 108 $\rho_{\text{tor}} = 0.69$ and $\rho_{\text{tor}} = 0.76$, the pellet growth rates are slightly reduced in normalized
 109 units for $k_y \rho_s < 0.7$ compared to the intra pellet time point in the collisional case. In
 110 the collisionless case the effect is more pronounced. Primarily without collisions, there
 111 is a subdominant TE mode which also has reduced growth rates at the pellet time
 112 point. This stabilization is likely due to more favourable trapped particle drifts.[17] At
 113 $\rho_{\text{tor}} = 0.85$ and $\rho_{\text{tor}} = 0.94$ the ITG mode is instead destabilized at the pellet time
 114 point, with and without collisions. The same is true for the TE mode which is only
 115 destabilized without collisions.

116 In Figure 5 scans in temperature and density gradients are shown at the pellet
 117 and intra pellet time points, for $k_y \rho_s = 0.3$ and $\rho_{\text{tor}} = 0.69$. The results are similar
 118 at $\rho = 0.76$ and at other wave numbers in the ITG wave number range. The pressure
 119 gradient as considered in the curvature and ∇B drifts is calculated self-consistently from
 120 the density and temperature gradients. In the a/L_T scan, the growth rate is reduced in
 121 the pellet case at similar a/L_T , with a greater reduction in the collisionless case. The
 122 ITG threshold is increased from $a/L_T \sim 1$ in the intra pellet case to $a/L_T \sim 3$ in the
 123 pellet case. In the a/L_n scan a reduction in growth rate is seen in the collisional case
 124 both going to large positive and negative density gradients, while in the collisionless
 125 cases a large value of a/L_n is destabilizing. At similar a/L_n the pellet time point
 126 is more unstable because of the higher a/L_T . Taken together, going from the intra
 127 pellet to the pellet time point there is a stabilizing effect due to negative a/L_n but a
 128 destabilizing effect due to an increase in a/L_T that partially undoes the stabilization,
 129 resulting in the growth rate spectra exhibited in Figure 4. A similar situation was seen
 130 at MAST with counteracting density and temperature gradients at the inside of the

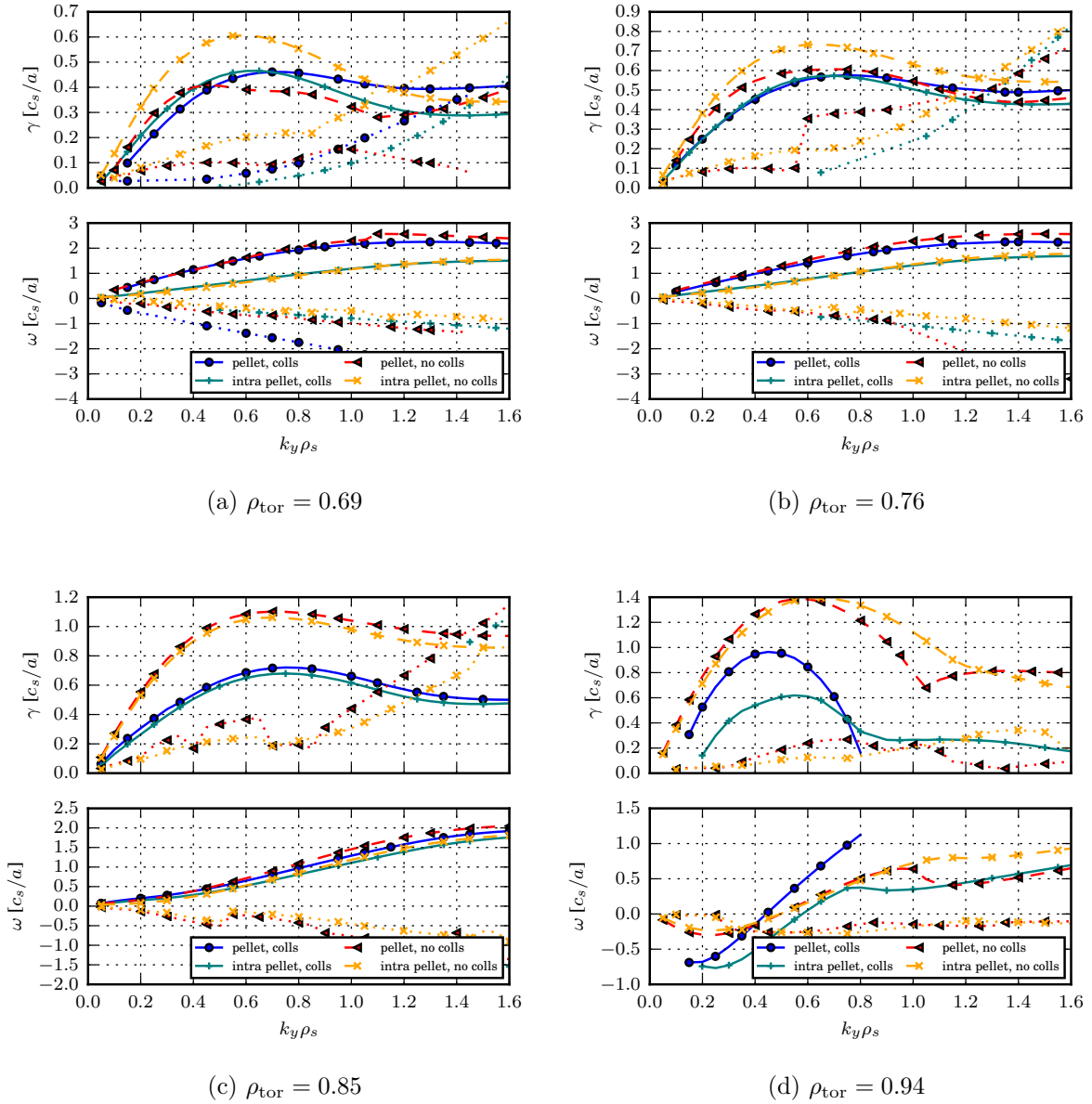


Figure 4: Eigenvalue spectra at the four radial distances at the two different time points, with and without collisions, TE mode dotted.

131 pellet ablation peak [18]. In previous gyrokinetic simulations in the positive gradient
 132 region at MAST, however, a complete stabilization of the ITG and TE modes in this
 133 wave number range was observed [2]. In that experiment, the observed reduction in the
 134 magnitude of $\eta_i = |L_{n_e}/L_{T_i}|$ going from the reference to the pellet profiles was however
 135 much larger in the positive density gradient region. The situation at MAST was also
 136 different close to the pellet density peak where the ITG growth rates were reduced and
 137 the micro tearing mode became dominant. This was due to an increase in β from 2.5
 138 % to 4.5 %, whereas at JET β increases only slightly from 0.09 % to 0.10 %, and the

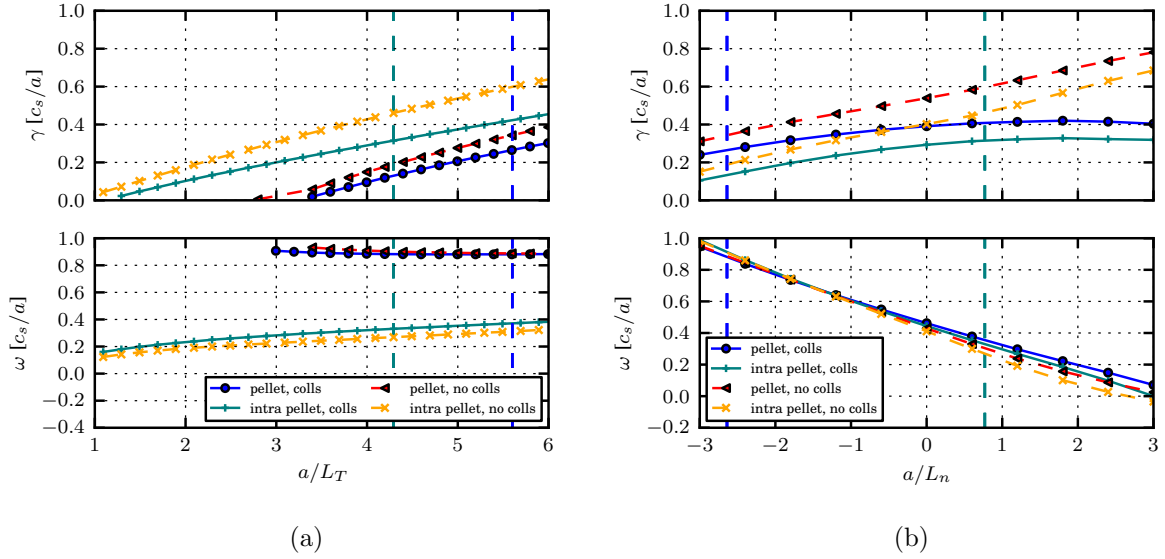


Figure 5: Eigenvalue scans at $k_y \rho_s = 0.3$ in temperature and density gradients at the two different time points at $\rho_{\text{tor}} = 0.69$ with and without collisions. Vertical lines indicate the experimental density and temperature gradients at this radius.

139 effect from the increase of η_i is more important here, destabilizing the ITG mode.

140 4. Nonlinear results

141 4.1. Flux-tube simulations

142 For the nonlinear local GENE simulations, a simulation domain in the perpendicular
 143 plane of 125 to 250 ion larmor radii in the poloidal direction and 110 to 240 in the
 144 radial direction was typically used, with a typical resolution of $[n_x, n_{k_y}, n_z, n_{v_{\parallel}}, n_{\mu}] =$
 145 $[144, 48, 32, 64, 16]$. The typical covered poloidal wave number range is $0.05 \leq k_y \rho_s \leq$
 146 2.4 . The four radial positions chosen for the nonlinear simulations are $\rho_{\text{tor}} = 0.69$ and
 147 $\rho_{\text{tor}} = 0.76$ in the negative a/L_n region, $\rho_{\text{tor}} = 0.85$ close to the peak of the pellet
 148 ablation profile and $\rho_{\text{tor}} = 0.94$ in the positive a/L_n region. In order to make a more
 149 straightforward comparison between the fluxes at different radial positions, the fluxes
 150 and resulting effective diffusion coefficients are shown in SI units.

151 In Figure 6a the particle fluxes and diffusion coefficients at these radial positions
 152 are shown for the collisional case. The particle flux is inwards on the inside of the
 153 pellet ablation peak and changes sign on the outside. The particle fluxes are of similar
 154 magnitude but with different sign on each side of the pellet ablation peak. There is
 155 a slight asymmetry with the larger fluxes being on the outside. In the negative a/L_n
 156 region the diffusion coefficients are lower just after the pellet than at the intra-pellet
 157 time. In the collisionless case, shown in Figure 6b, the inward particle pinch is stronger
 158 at both time points in the positive gradient region. A similar trend for negative a/L_n ,

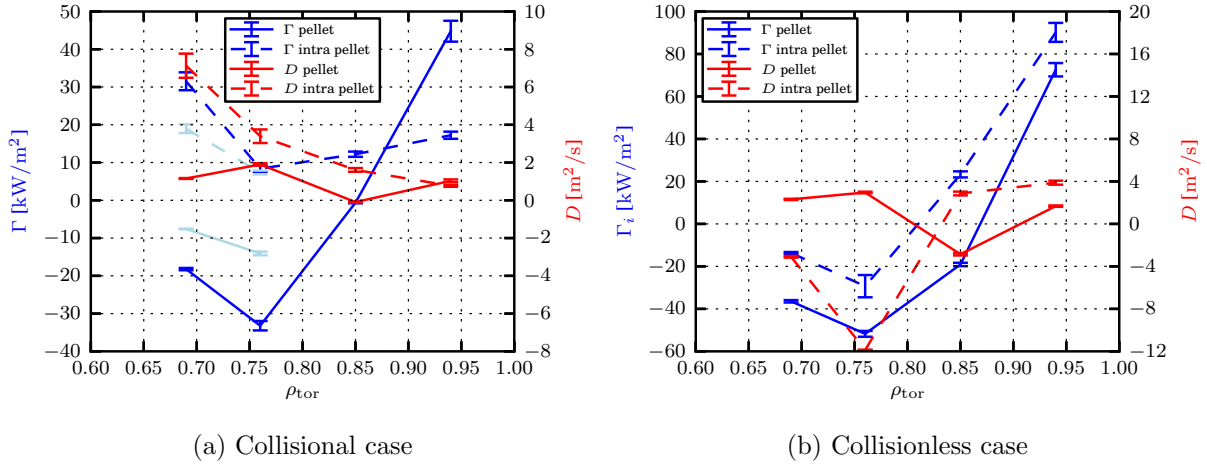


Figure 6: Nonlinear particle fluxes and effective diffusion coefficients. Light blue lines indicate the sensitivity to a 20% reduction in a/L_T .

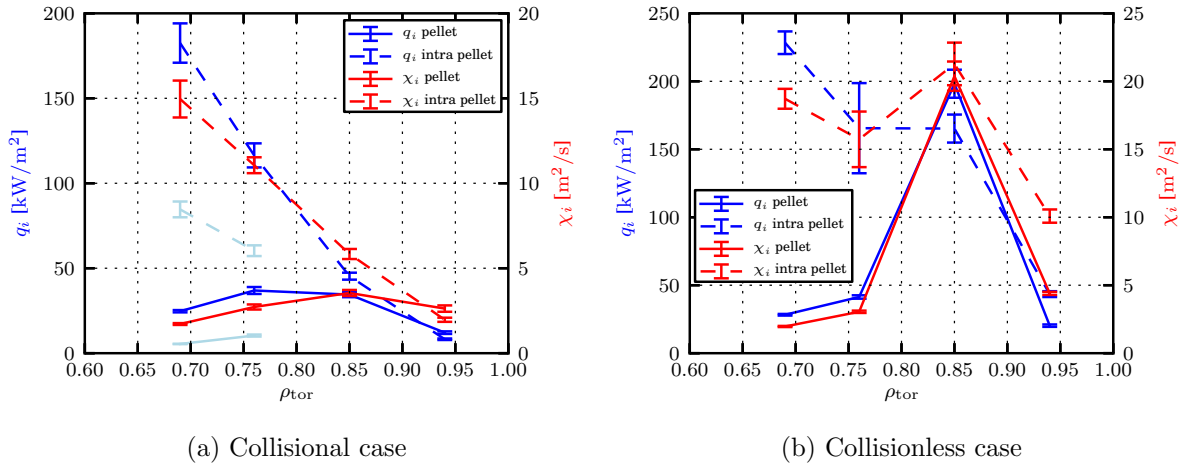


Figure 7: Nonlinear ion heat fluxes and effective heat diffusivities. Light blue lines indicate the sensitivity to a 20% reduction in a/L_T .

159 with a less inward particle flux as the collisionality increases, was found in [4]. At
 160 the intra pellet time point the flux has changed direction to inwards, compared to the
 161 outward flux at this time point in the collisional case. The magnitude of the effective
 162 particle diffusion coefficients are still smaller at the pellet time point compared to the
 163 intra pellet time point in the positive gradient region.

164 The nonlinear ion heat fluxes are shown in Figure 7. The outward heat fluxes are
 165 greatly reduced in the negative a/L_n radial range compared to the intra pellet case in
 166 both the collisional and collisionless cases, while they are more similar at the $\rho_{\text{tor}} = 0.85$
 167 and $\rho_{\text{tor}} = 0.94$ positions. This, and the similar reduction in diffusion coefficients, is
 168 connected to the reduction in nonnormalized growth rates, as shown in Figure 3, in the

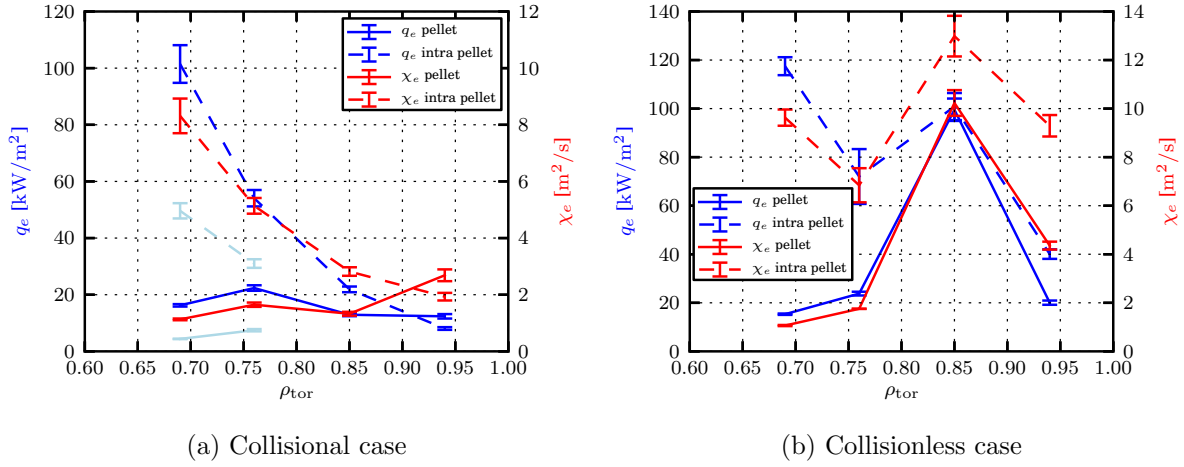
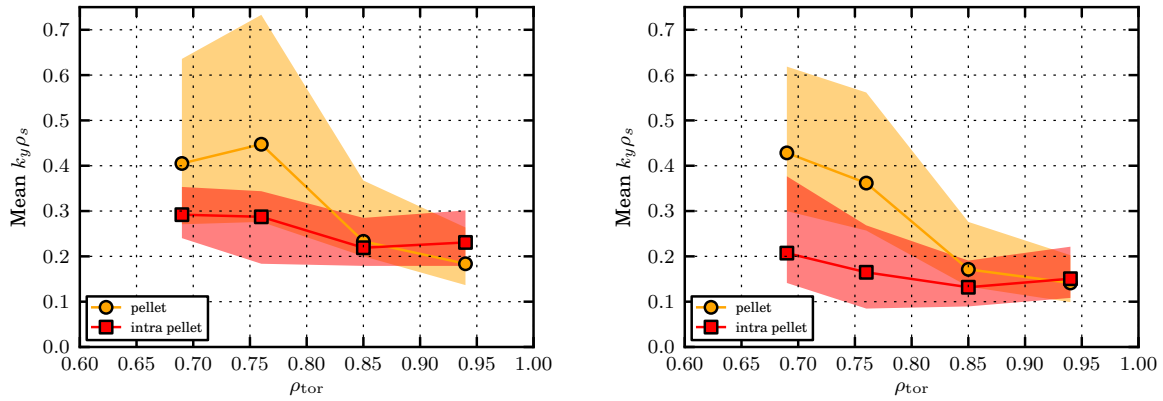


Figure 8: Nonlinear electron heat fluxes and effective heat diffusivities.

(a) Mean $k_y \rho_s$ of the ion particle flux, with collisions (b) Mean $k_y \rho_s$ of the ion particle flux, without collisionsFigure 9: Mean $k_y \rho_s$ for the ion particle flux along with a measure of the width of the spectra.

169 positive gradient region. The electron heat fluxes, shown in Figure 8, follow the same
 170 trend as the ion heat fluxes.

171 In Figure 9 the ion particle flux weighted mean $k_y \rho_s$ is shown along with a measure
 172 of the width of the flux spectra. The width is taken as the range of wave numbers
 173 responsible for 25% of the flux over and under the indicated mean. In both the collisional
 174 and collisionless cases the mean wave number of the turbulence is lower in the intra pellet
 175 case in the negative R/L_n region, which is consistent with the larger heat fluxes at the
 176 intra pellet time point.

177 **5. Comparison of H and D main ions**

178 In JET, the confinement in the core region of ELMy H-mode plasmas has been observed
 179 to decrease with isotope mass, with $\chi_i \propto m^{0.73 \pm 0.4}$ [19]. However, in more recent L-
 180 mode JET discharges and in H-mode discharges in JT-60U and ASDEX Upgrade an
 181 improvement in confinement going from lower to higher hydrogen isotope masses have
 182 been observed [20, 21, 22]. This is in contrast to the gyro-Bohm scaling on turbulent
 183 transport which predicts $q_i \propto m_j^{1/2}$. This inconsistency has been called the isotope
 184 effect. Several explanations have been proposed, such as stronger zonal flows with
 185 heavier isotopes which reduces the turbulent transport [23]. In gyrokinetic modelling
 186 the effect from zonal flows have been shown to reduce the heat fluxes compared to
 187 the gyro-Bohm scaling for CBC parameters [24]. For an ITER scenario the interaction
 188 between ExB shear, zonal flows, magnetic geometry and electromagnetic effects has
 189 been shown to play a role in the explanation of the isotope effect on the particle and
 190 heat fluxes [25]. In global gyrokinetic simulations, it has been shown that GAMs also
 191 can play a role in the explanation of the isotope effect [26].

192 In the present modelling, the main ion isotope is changed from hydrogen to
 193 deuterium with unchanged density and temperature profiles. Finite β effects and
 194 collisions are included, as before. In species units, with $c_j = \sqrt{T_e/m_j} \propto m_j^{-1/2}$ and
 195 $\rho_j = \frac{c_j}{eB/m_j c} \propto \sqrt{m_j}$, the spectra are rather similar with the growth rates only slightly
 196 reduced in the deuterium case, as shown in Figure 10, with the strongest effect at
 197 $\rho_{\text{tor}} = 0.69$. The difference vanishes for $k_y \rho_j < 0.6$ without collisions. This indicates
 198 that the fluxes should follow the gyro-Bohm scaling if no nonlinear effects differ between
 199 the hydrogen and deuterium simulations. This is verified with the nonlinear fluxes shown
 200 in Figure 11. Here, the fluxes are shown in species units, $Q_{gB_j} = c_j n T (\frac{\rho_j}{a})^2 \propto \sqrt{m_j}$ and
 201 $\Gamma_{gB_j} = c_j n (\frac{\rho_j}{a})^2 \propto \sqrt{m_j}$ so that any differences show the deviation from the gyro-
 202 Bohm scaling. For the particle fluxes, shown in Figure 11a, with a deuterium main ion
 203 the outward fluxes at the intra pellet time point are slightly reduced while the inward
 204 particle fluxes at the pellet time point are increased. The D and H heat fluxes, shown
 205 in Figure 11b are within the error bars. Zonal flow activity, as indicated by the average
 206 shearing rate $\left\langle \left\langle \left| \frac{d}{dx} v_{E \times B, y} \right|^2 \right\rangle_x^{1/2} \right\rangle_t$, is similar for hydrogen and deuterium.

207 **6. Global simulations**

208 For the global nonlinear simulations the electrons were treated in the adiabatic
 209 limit. Although particle transport and the TE mode cannot be described in this
 210 simplified physical description, a comparison to similar simulations in the local limit
 211 is nevertheless illuminating. The radial simulation domain covered $\rho_{\text{tor}} = 0.505 - 0.995$
 212 with a dampening buffer zone beyond $\rho_{\text{tor}} = 0.945$, which is greyed out in the
 213 figure. The poloidal direction spanned 350 ion larmor radii. The grid was chosen as
 214 $[n_x, n_{k_y}, n_z, n_{v_{\parallel}}, n_{\mu}] = [768, 48, 64, 48, 32]$. The normalised gyroradius $\rho_* = \rho_i/a$ ranges

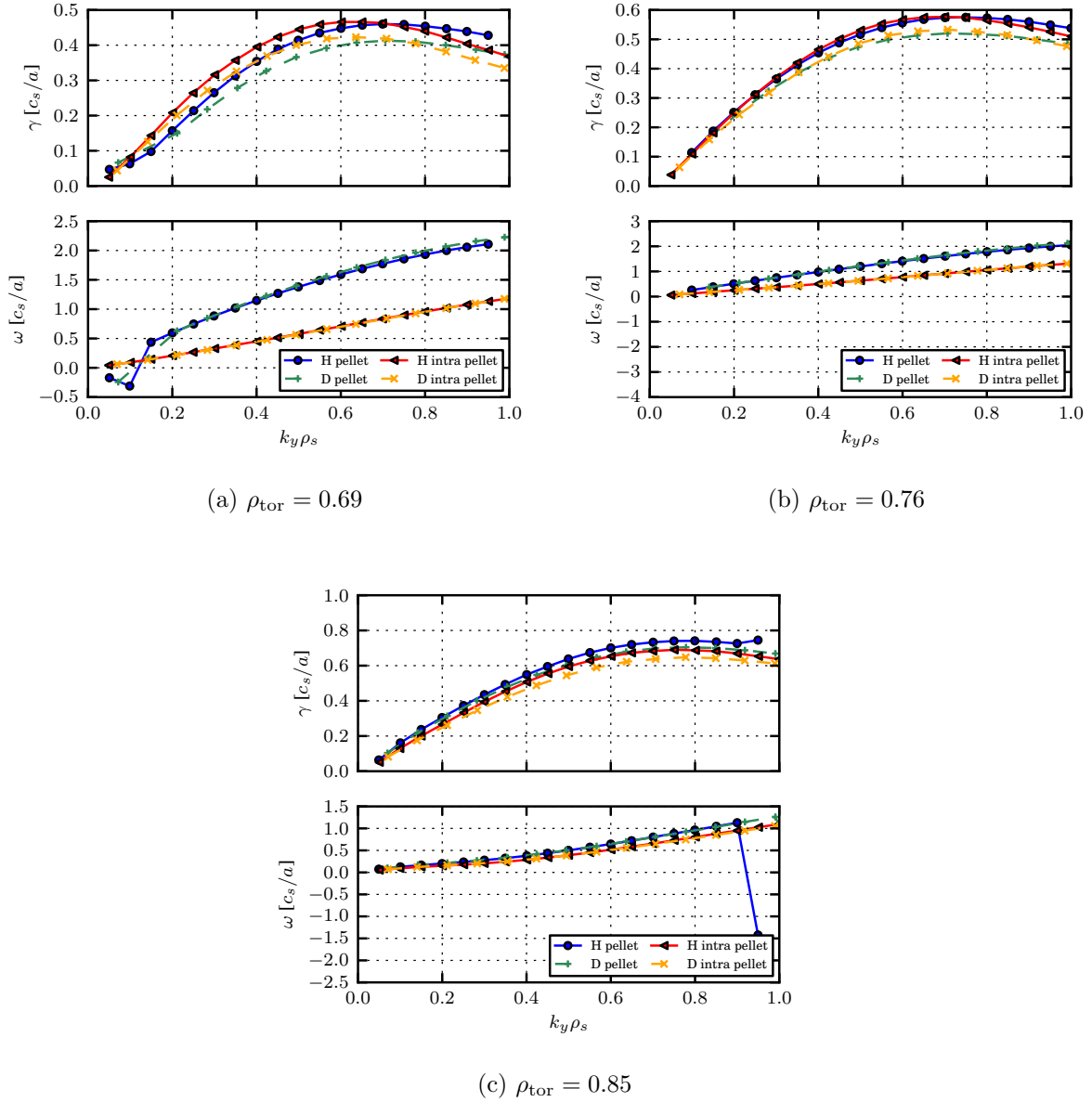


Figure 10: Eigenvalue spectra in species units at three radial distances with hydrogen and deuterium main ions.

215 between $1/600$ and $1/1200$ in the considered plasma region. Thus, we only expect that
 216 nonlocal phenomena can play a role for the pellet time point where the density gradient
 217 profile is peaked with a width of Δ_n and a $\rho_{*,eff} = \rho_i/\Delta_n$ of around $1/300$ [27, 28].

218 We compare the heat flux from the global simulation for the pellet time point with
 219 local simulations with the same physics model at several radial positions in Figure 12.
 220 Qualitatively, i.e. in the shape of the heat flux profile, we find similarities with the local
 221 results with electrodynamic effects in Figure 7a but with an overall smaller level of flux.
 222 For $\rho_{\text{tor}} < 0.7$ agreement between global and local simulations within the error bars is

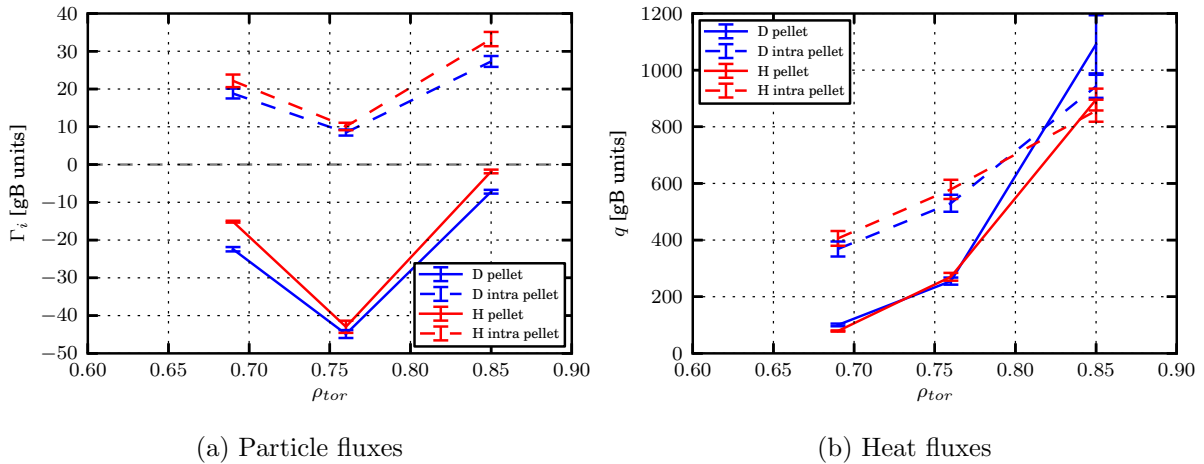


Figure 11: Particle and heat transport in species units at the pellet and intra pellet time points with hydrogen and deuterium main ions.

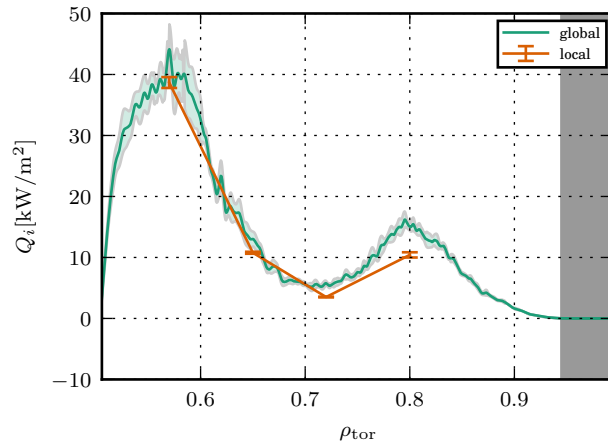


Figure 12: Radial turbulent ion heat flux at the pellet time point in global and local simulations with adiabatic electrons

223 found. At radial positions further out, however, a smaller heat flux is observed in the
 224 local simulations, in particular for $\rho_{tor} = 0.80$.

225 In summary, we find that nonlocal effects do not seem to play a major role for
 226 this particular scenario and the previously presented flux-tube results are a reasonable
 227 approach for modelling turbulence after pellet injection in this JET discharge.

228 7. Conclusions

229 In this paper transport analysis of a pellet fuelled L-mode JET discharge has been
 230 performed using the gyrokinetic code GENE. Linearly it was shown that the dominating
 231 ITG-mode was slightly stabilized in normalized units on the inside of the pellet ablation
 232 peak compared to the intra pellet interval when the density gradients had relaxed. While

233 the negative a/L_n was stabilizing, this was partially counteracted by the increase in a/L_T
 234 on the inside of the pellet ablation peak compared to the intra pellet gradients, resulting
 235 in similar growth rates. Nonlinearly, the particle fluxes on each side of the peak were
 236 slightly asymmetric with the larger fluxes being on the outside of the peak. This is a
 237 similar but smaller effect than was seen at MAST [2]. The effective diffusion coefficients
 238 were reduced compared to the intra pellet time point. In collisionless simulations, the
 239 particle fluxes were larger and more asymmetric around the peak, with stronger outward
 240 fluxes on the outside, but an inward flux at the top of the pellet ablation peak. The
 241 magnitude of the effective diffusion coefficients were still reduced compared to the intra
 242 pellet time point. In a comparison of hydrogen and deuterium plasma with with the
 243 same profiles as before, the particle fluxes only slightly deviated from the gyro-Bohm
 244 scaling. In global simulations no major effect on the turbulent transport due to nonlocal
 245 effects could be observed.

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