Changes in core electron temperature fluctuations and transport with isotopic mass in L-mode plasmas at ASDEX-Upgrade

P. Molina Cabrera[1,2], P. Rodriguez-Fernandez[1], T. Görler[2], M. Bergmann[2], R. Bielajew [1],
G. D. Conway[2], K. Höfler[2,3], C. Yoo[1], A. E. White[1],
and the ASDEX Upgrade team*
[1]*Plasma Science and Fusion Center, MIT, Cambridge-MA, United States of America*
[2]*Max Planck Institute for Plasma Physics, Boltzmannstr. 2, 85748 Garching, Germany*
[3] *Physics Department E28, Technical University of Munich, James-Franck-Str. 1, Germany*

Design and operation of future tokamak fusion reactors using a deuterium-tritium 50:50 mix requires a solid understanding of how confinement properties change with ion mass. Turbulent fluctuations have been associated with electrostatic drift-wave modes in tokamaks and are believed to be a major contributor to cross-field transport [1] [2]. This study looks at how low-amplitude temperature fluctuation properties and transport change in L-mode tokamak plasmas when changing ion species between hydrogen (H) and deuterium (D) both through experimental turbulence measurements and modeling. The experimental turbulence data consists of local measurements of ion-scale ($k_\perp < 4\,\mathrm{cm}^{-1}$ $k_\perp \rho_s < 0.42$) electron temperature fluctuations measured in the outer core ($\rho_{Tor} = 0.65 - 0.8$) of ASDEX Upgrade (AUG) using a correlation electron cyclotron emission diagnostic (CECE) [3]. From the modeling side both quasi-linear gyrofluid and non-linear gyrokinetic simulations have been performed using the TGLF and GENE codes, respectively. Heat fluxes as well as temperature fluctuation levels, spectra, and radial correlation lengths have been used as the basis of a validation study. The latest results are presented below.

Turbulence diagnostics are ideally suited to directly measure local turbulence properties and can provide unambiguous evidence of the turbulent transport response to changing ion mass. The scaling of cross-field transport with relative gyroradius $\rho_* = \rho_i/a$ (where ρ_i is the ion Larmour radius and a is the device minor radius) is of great relevance to future devices [4]. Both McKee et al. [5] and Hennequin et al. [6] have studied the response of density fluctuations to changing ion-larmour radius and observed a strong gyroBohm scaling [7] in turbulence radial correlation lengths, fluctuation amplitudes, and decorrelation times over a wide range of scales $k_\perp < 30\mathrm{cm}^{-1}$. There have been relatively little focused efforts to measure *temperature* fluctuation properties with changing ρ^*, even though temperature fluctuations enter directly into

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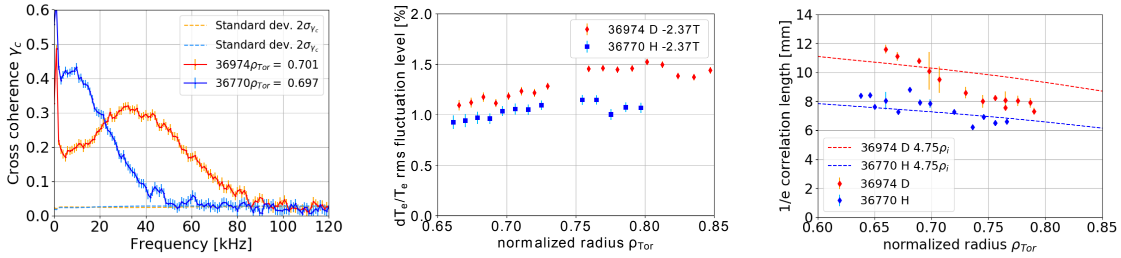
*See author list of H. Meyer et al. 2019 Nucl. Fusion 59 112014 the electrostatic drift-wave turbulence heat flux [2]. Deng et al. [8] is the only study addressing the behaviour of temperature fluctuations with changing ion-mass found in the literature. In contrast to density fluctuations, Deng et al. found higher fluctuation levels in hydrogen over deuterium with a ratio close to the inverse of the ion mass ratio: an inverse gyroBohm behaviour. Understanding this discrepancy has motivated dedicated CECE experiments at AUG.

The plasmas addressed in this study are relatively low density (line average n_e=2.5e19m^{-3}), electron heated L-modes featuring a plasma current of 1MA and an on-axis magnetic field of B_T=-2.37T. An external power of 700kW is applied using second-harmonic electron cyclotron resonance heating (ECRH) at 140GHz. This scenario was first studied in Freethy et al. [9] and has been repeated in both H and D. In order to attempt relatively similar shot conditions between isotopes with a limited number of discharges, the strategy was to keep the plasma current, shape, and external power constant and control the core density via active feedback.

Profiles have been fit with the most up-to-date approaches available at AUG: Markov Chain Monte Carlo (MCMC) integrated data analysis (IDA) [10] for n_e and T_e and Gaussian Process Regression (GPR) [10, 11] for T_i and v_{Tor}. Density profiles are well matched, inside error bars, for both isotopes. Electron temperature is larger in deuterium inside ρ_{Tor}=0.2-0.8. Ion temperature fits show the opposite pattern: a larger ion temperature in hydrogen inside ρ_{Tor}=0-0.8. Note however that in the region where turbulence measurements (defined as ROI for *region of interest* henceforth) are available, ρ_{Tor}= 0.65-0.8, all profiles can be found within 2-sigma of each other. Logarithmic gradient scale lengths inside the ROI are well matched within uncertainty in the electron density, electron temperature, and toroidal rotation. The ion temperature gradient appears larger in H than D, although the difference is just outside of 1-σ error bars.

A CECE diagnostic [3] has been used to measure broadband ($<$1MHz), low amplitude($<$ 1%) temperature fluctuations. It features 28 intermediate-frequency (IF) channels which allow the measurement of radial temperature fluctuation frequency spectra δT_e(f), fluctuation levels ($\delta T_e/T_e$), and radial correlation lengths ($L_r(T_e)$) simultaneously [9]. Figure 1 shows these results for both H and D plasmas. The coherence at ρ_{Tor} =0.7 shows a significantly lower Doppler shift in H over D. Figure 1 also shows both fluctaution levels and radial correlation lengths to be smaller in H vs D. While not shown due to space constraints here, the ratio of fluctuation levels matches within 2-σ errors a $1/\sqrt{2}$ ratio in agreement with a gyroBohm scaling. Furthermore, when dividing correlation lengths by their respective ion-Larmor radius, a constant value between 4 and 5 can be found independant of ion mass, see figure 1 (c). The correlation lengths, thus, also scale well with the Larmor radius and agree with a gyroBohm scaling. These results agree well with scalings in density fluctuations by McKee et al. [5] and Hennequin et al. [6],



(a) (b) (c)

Figure 1: CECE measurements in H (blue) and D (red) (a) Coherence at $\rho_{Tor} = 0.7$. (b) Fluctuation level (integrated inside 5-100kHz) (c) Radial correlation lengths

but they disagree with results in Deng et al. [8].

Power balance simulations have been performed with the TRANSP [12] code. The ion heat flux in H is found larger than in D throughout the entire plasma radius. Inside the ROI, the different is inside error bars, however. In agreement with previous work at AUG by Schneider et al. [13], the electron-ion heat exchange term is found to drive the strong difference in ion heat flux, specially inside $\rho_T < 0.5$. Electrons exchange twice as much heat with H ions than D ions due to their smaller mass. Electron heat flux, as well as electron/ion diffusivities are found to lie inside error bars.

The trapped gyro-landau fluid (TGLF) [14] code has been used both to understand the turbulence physics of these discharges and to validate the code against experiments using different ion masses. TGLF is a quasilinear turbulence solver which uses a fluid approach to solve the linearized electrostatic gyrokinetic equation. The SAT2 zonal-flow mixing saturation rule has been used in this study. The dominant mode growth rates in both H and D plasmas inside CECE's range $k_\perp\rho_s < 0.4$cm are identified as ion-temperature gradient (ITG) modes. Temperature fluctuation levels are extracted from TGLF results using an improved synthetic diagnostic which features the diagnostic antenna pattern Gaussian function in k-space after Bravenec et al. [15]. Using the VITALS framework [16], input uncertainties in input logarithmic gradients and Z_{eff} are varied in an attempt to find the best match to experimental heat fluxes as well as CECE temperature fluctuation levels. The VITALS optimization succeeds in matching all quantities within 1-σ error bars in D. However, ion-heat fluxes are found to be consistently overpredicted in the hydrogen case, particularly strongly in core channels $\rho_{Tor} < 0.65$. These results encourage a revised set of saturation rules for hydrogen plasmas.

Lastly, nonlinear, fluxtube, gyrokinetic simulations have begun with the GENE code. The linear eigenvalue solver shows ITG dominated plasmas in agreement with TGLF. A synthetic diagnostic has been used to quantitatively compare GENE with experimental CECE data. GENE can access the time history of temperature fluctuations and hence frequency spectra and radial correlation lengths can be obtained in addition to fluctuation levels. The synthetic diagnostic revealed the important role that the toroidal rotation has on the temperature fluctuation spectra shape. Using traditional v_{Tor} measurements from charge-exchange recombination spectroscopy (CXRS) as inputs to GENE lead to widly different hydrogen spectra than experiment. The beam blips required to have enough CXRS signal lead to important toroidal momentum input and hence biased v_{Tor} measurements. Using a Doppler backscattering (DBS) diagnostic, the toroidal acceleration due to the beam blips was directly observed in the perpendicular rotation velocity ($v_\perp$). DBS $v_\perp$ estimates in-between beam blips were used to estimate the background pre-blip v_{Tor} using the safety factor from the equilibrium reconstruction. Frequency spectra from GENE using DBS's v_{Tor} estimates lead to a much better agreement in the shape of the spectra. Gradients scans in search for a heat flux match are under progress. This work is supported by the US DoE under grants DE-SC0014264, DE-SC0006419, and DE-SC0017381.

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