Experimental and global gyrokinetic studies of the isotope effect in turbulent plasma dynamics and particle transport at the FT-2 tokamak

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The isotope effect in tokamak anomalous transport of energy and particles has been a long-standing puzzle for already 40 years. This effect is promising for fusion applications, but its reasons are still unclear. In terms of turbulent transport, the typical width of the drift-wave turbulent eddy scales like an ion Larmor radius, and therefore for heavier isotope larger eddies could be expected. Based on these arguments one could expect growing transport with increasing isotope mass, nevertheless, in numerous experiments an opposite direction of effect was observed [1]. It was shown also that the isotope effect is much stronger in tokamaks compared to stellarators. Recently the isotope effect was observed also in tokamak meso-scale turbulence. In several experiments [2-7] the geodesic acoustic mode (GAM), the finite frequency zonal flow, possessing long correlation length in poloidal and toroidal directions, was shown to be much more intensive in deuterium (D) compared to hydrogen (H) discharges. Moreover, GAMs are routinely observed in tokamaks, but only rarely reported in stellarators. GAMs, which are excited in plasma due to nonlinear interaction of drift waves, in their turn, influence the turbulent fluctuations [8] and anomalous transport due to plasma rotation shearing effect associated with them. Therefore, in principle, they could be responsible for the isotope effect in tokamak anomalous transport.

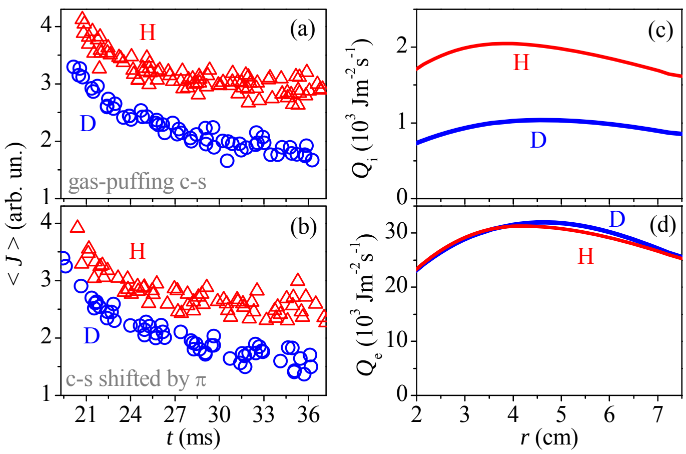

Fig. 1. The H_β and D_β radiation measured in cross-sections with (a) and without (b) gas-puffing (relative toroidal shift equals π). The ion (c) and electron (d) energy fluxes provided by ASTRA.

In the present paper the isotope effect in turbulent transport is studied in similar ohmic FT-2 tokamak H- and D-discharges [6] (with magnetic field: 2.25 T, plasma current: 19.5 kA, central density and temperatures of electrons and ions: 2.5×10^{13} cm^{-3}, 420 eV and 175 eV, respectively) experimentally utilizing standard tokamak and highly localized

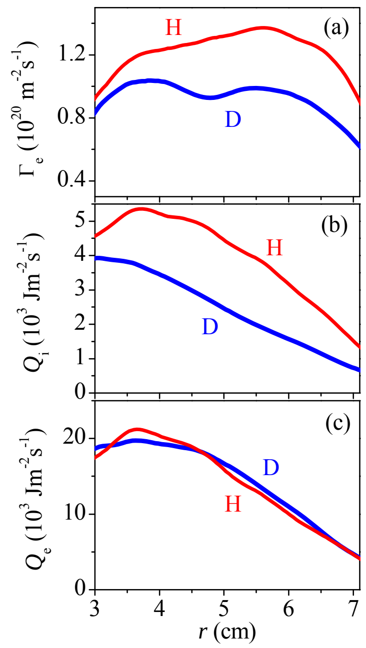

Fig. 2. The electron (a), ion energy (b) and electron energy (c) fluxes provided by GK modeling.

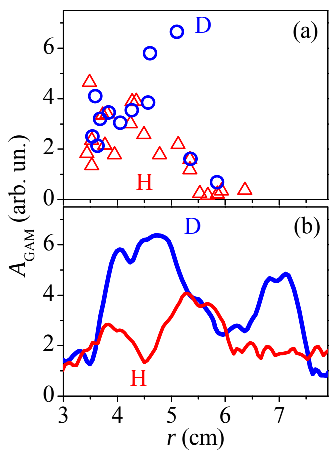

Fig. 3. The spatial distribution of the GAM amplitude in experiment (a) and in GK modeling (b).

turbulence diagnostics, as well as theoretically in the framework of global gyrokinetic (GK) modeling with the global full-f nonlinear code ELMFIRE, which has been benchmarked recently against the FT-2 multi-scale turbulent transport data [9, 10]. As it is shown in fig. 1 and fig. 2, both approaches show a clear isotope effect in particle and ion energy transport, but not in the electron energy confinement. The temporal behavior of H_β and D_β lines radiation integrated over the poloidal tokamak cross-section where the gas-puffing was performed and over another one shifted toroidally by 180° is demonstrated in fig. 1*a*, *b*. As it is seen, the radiation, which is proportional to the ionization source in the discharge [7], is systematically higher in hydrogen, thus indicating better particle confinement in deuterium. This conclusion agrees with the result of GK computation of particle fluxes shown in fig. 2*a* demonstrating a systematic excess in H-discharge. The ion energy flux obtained from experimental profiles using ASTRA modeling is also higher in hydrogen (see fig. 1*c*) in agreement to the GK computation shown in fig. 2*b*. However the electron energy flux appears to be comparable in two gases, as obtained with ASTRA and with the GK modeling (see fig. 1*d* and fig. 2*c*). The meso-scale turbulence isotope effect is well-pronounced in these discharges, both in experiment and in the GK computations, as is seen in fig. 3 demonstrating a much higher level of GAMs in the gradient zone and at the edge in deuterium. This higher GAM level, according to the GK computations, is forced by a higher symmetric Reynolds stress shear component at the GAM frequency. As is seen in fig. 4, it leads to higher energy transfer from the turbulence to the GAM and is accompanied by higher collisional GAM dissipation rate in deuterium (see fig. 5), which is however equal to the power provided by the turbulent drive.

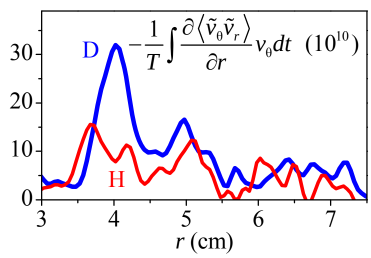

Fig. 4. Power transferred from the turbulence to the GAM.

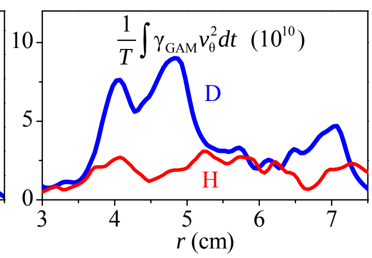

Fig. 5. The GAM dissipation rate.

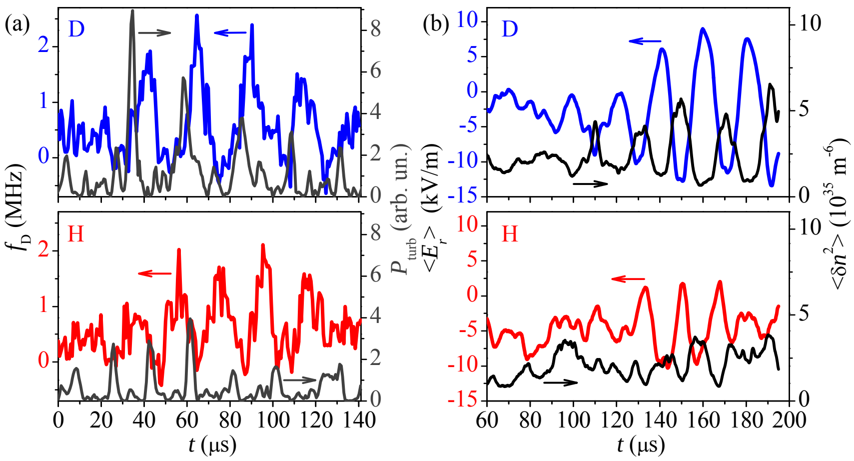

Fig. 6. Temporal variations of the GAM amplitude and the turbulence level in experiment (a) and in GK computations (b) in D (top) and H (bottom).

The intensive GAM activity is leading to modulation of the turbulence level at the GAM frequency, substantially stronger in the D-case, as it is was observed both in experiment (fig. 6*a*) and in the GK computations (fig. 6*b*). However the stronger turbulence modulation by the GAM in D-discharges did not result in the smaller turbulence there. As is seen in fig. 7*a*, the level of turbulent density fluctuations is even higher in the D-case at $r > 4.5$ cm (in spite of the fact component at the GAM frequency is filtered out there), whereas poloidal electric field fluctuations in both gases are comparable (see fig. 7*b*). The frequency and wavenumber spectra of turbulent density fluctuations provided by ELMFIRE are also similar.

At the first sight the results shown in fig. 7*a* and fig. 7*b* contradict to the observations of the isotope effect in the particle transport obtained in the GK modeling and shown in fig. 2*a*, however analysis of the cross-phase and power spectra of density and poloidal electric field fluctuations removes this contradiction. As is seen in fig. 8, the cross-phase of density and poloidal field fluctuations is closer to 90° in deuterium than in hydrogen for typical turbulence frequencies $f < 150$ kHz, whereas the level of poloidal electric field fluctuations is lower there at

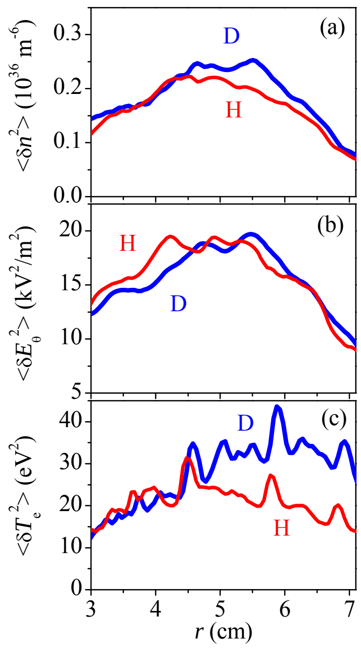

Fig. 7. The radial distribution of density (a), poloidal electric field (b) and electron temperature (c) fluctuations.

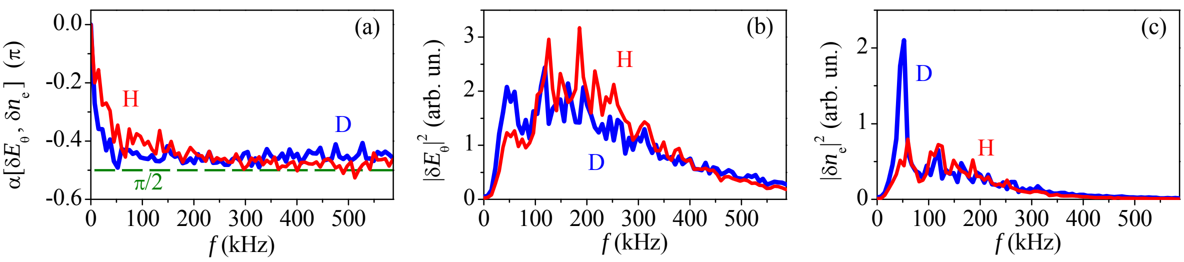

Fig. 8. The cross-phase spectrum (a) of density and poloidal electric field fluctuations at $r = 4.5$ cm. The power spectra of poloidal electric field (b) and density (c) fluctuations.

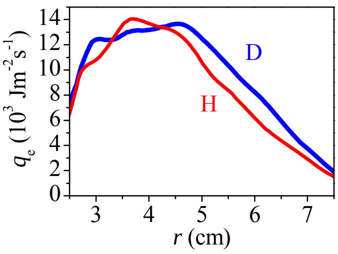

Fig. 9. Radial dependence of the GK electron heat flux.

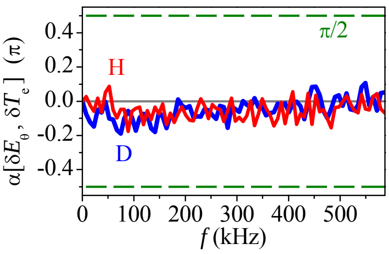

Fig. 10. Cross-phase spectra at r = 6.0 cm.

f > 100 kHz thus making the correspondent turbulent particle flux $\Gamma_e = \langle \delta n_e \delta E_\theta c/B \rangle$ smaller. (The line at frequency f = 40 kHz which is very intensive in D-discharge for density fluctuations and still observable for poloidal electric field fluctuations is related to the GAM oscillations and therefore do not produce any particle transport.) The smaller electron flux in D-discharge should, in principle, result also in smaller convective electron energy flux, however, as is seen in fig. 2*c*, the GK computation in agreement with the experiment (fig. 1*d*) predicts no isotope effect for the total electron energy flux. The latter is only possible, if the turbulent electron heat flux in D-discharge is higher than in hydrogen. The GK modeling confirms this conclusion, as it is seen in fig. 9. The physical reason for the excess of electron heat flux in D-case at r > 4.5 cm is provided by the higher level of electron temperature fluctuations in the D-case in this region (see fig. 7*c*). The cross-phase of electron temperature and poloidal electric field fluctuations is close to zero in both gases (see fig. 10), not decreasing the resulting heat flux.

Summarizing we would like to stress that, as both experiment and the GK computation demonstrate, the isotope effect is present in the turbulent transport phenomena in the FT-2 tokamak at all temporal and spatial scales, however its reasons are still unclear.

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