Isotope mass and charge effects in tokamak plasmas

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The effect of primary ion species of differing charge and mass – specifically, deuterium, hydrogen and helium – on instabilities and transport is studied in DIII-D plasmas through gyrokinetic simulations with GYRO [1]. We performed transport analysis of three balanced neutral beam injection DIII-D discharges which have different main ion species (D, H and He).

Overview of target DIII-D L-mode discharges

We chose L-mode phases from three balanced NBI DIII-D discharges which have different main ion species: D (129135, 1275 ms), H (133778, 1250 ms) and He (138767, 2725 ms). The balanced injection yields approximately zero net torque, thereby minimizing the effect of rotation and rotation shear in these plasmas. These were not similarity experiments; that is, the plasma profiles are somewhat different in each of the three discharges. When viewed from above in these lower single-null plasmas, the orientation of the magnetic field ($B \sim 2\,\mathrm{T}$) was clockwise whereas the plasma current ($I_p \sim 1\,\mathrm{MA}$) was counter-clockwise in all cases. ECRH and NBI were the auxiliary heating methods applied. The dominant impurity in these discharges is carbon, and the H and He plasmas contained a considerable amount of deuterium impurity.

The experimental data was pre-processed by the tools ONETWO [2] for the deuterium and hydrogen discharges and by TRANSP [3] for the non-standard helium discharge. The rotation profiles for each species used in the non-linear simulations were calculated from the measured toroidal rotation data for carbon, using a tool based on the neoclassical code NEO [1].

Linear simulations under imposed similarity

In the following two sections the GYRO simulations presented are based on plasma parameter profiles from the deuterium discharge. The only parameters changed in the simulations are the ion charge and mass. In the linear simulations the flows and the impurity content are neglected. The local parameters for $r/a = 0.55$ are the following: $R_0/a = 2.88$, $q = 1.78$, $s = 0.75$, $\kappa = 1.34$, $\delta = 0.107$, $a/L_n = 0.68$, $a/L_{Ti} = 1.89$, $a/L_{Te} = 2.69$, $T_i/T_e = 0.82$, and $\nu_{ei}a/c_s = 0.143$.

Since the linearized collisionless ion gyrokinetic equation depends on mass and charge only through the ion sound speed and Larmor radius the ITG growth rates normalized to species units for adiabatic electron response are the same for hydrogenic ions (see Fig. 1a). However if $Z_i > 1$, as for helium, the appearance of charge in the Poisson equation leads to higher linear

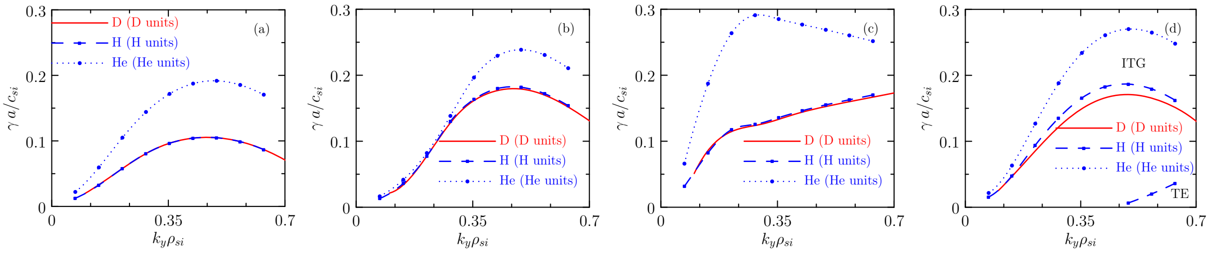

Figure 1: *Growth rates in species units from linear* GYRO *simulations for pure deuterium (solid), hydrogen (dashed) and helium (dotted) plasmas. (a): adiabatic electrons. (b,c): kinetic electrons, no collisions, ITG (b) and TE (c) mode roots. (d): kinetic electrons, with e-i collisions.*

growth rates (the ITG growth rates scale as $\sqrt{Z_i}$). Retaining the kinetic electron response leads to breaking of the perfect similarity of the growth rates between the ions with same charge due to the difference in the parallel motion of the nearly adiabatic circulating electrons (compare the solid and dashed curves in Fig. 1b). On the other hand, new unstable modes can appear such as the TE mode (Fig. 1c), where like for ITG, similarity is found between the growth rates of the hydrogen isotopes, but for ions with different charge a qualitative difference appears in the wave number dependence of the growth rates for higher wave numbers. By including electron-ion collisions in the linear simulations (Fig. 1d), the difference between the ITG growth rates for hydrogenic ions is further increased, and the TE mode is strongly stabilized. For the parameters we studied we found unstable growth rates only for the hydrogen, as the stabilization is the smallest for this species. This effect can contribute to a favorable deviation from gyro-Bohm scaling for hydrogen isotope plasmas.

Nonlinear simulations under imposed similarity

In nonlinear electrostatic simulations under imposed similarity, when realistic effects such as collisions and impurities are taken into account, there can be considerable deviations from perfect gyro-Bohm scaling of the transport which is guaranteed only in the $\rho_* \rightarrow 0$ limit for pure plasmas with adiabatic electron response [see Fig. 2. For pure gyro-Bohm scaling the spectra in species gyro-Bohm units should be identical]. With kinetic electrons and collisions, moving from hydrogen to deuterium a favorable deviation from gyro-Bohm scaling is found, while moving from deuterium to tritium the transport exhibits almost perfect gyro-Bohm scaling due to the saturation of electron-to-ion mass ratio effects and stabilization of sub-dominant modes (see Fig. 2a and b). Including carbon in the simulations leads to a dramatic reduction of the energy fluxes in the hydrogen isotope plasmas (compare Figs. 2c and d), although the linear stabilizing effect of carbon is moderate. Deuterium minority in the hydrogen plasma can also reduce the transport, while naively the opposite trend is expected. Therefore in any comprehensive transport simulation all non-trace impurity species should be taken into account. For helium (compare Figs. 2e and f) the energy transport in species gyro-Bohm units is considerably higher than that for deuterium due to the higher linear growth rates in helium. Carbon has a weaker stabilizing effect in helium than in hydrogen isotope plasmas.

Including all impurities and collisions, the energy transport in a hydrogen or helium plasma can be approximately the same as in a deuterium plasma, which is a strong deviation from gyro-Bohm scaling (predicting $1/\sqrt{2}$ times lower transport in hydrogen and $1/(2\sqrt{2})$ times lower transport in helium plasma). However, this deviation in the hydrogen case is still not sufficient to explain any strong favorable mass scaling of the global energy confinement time.

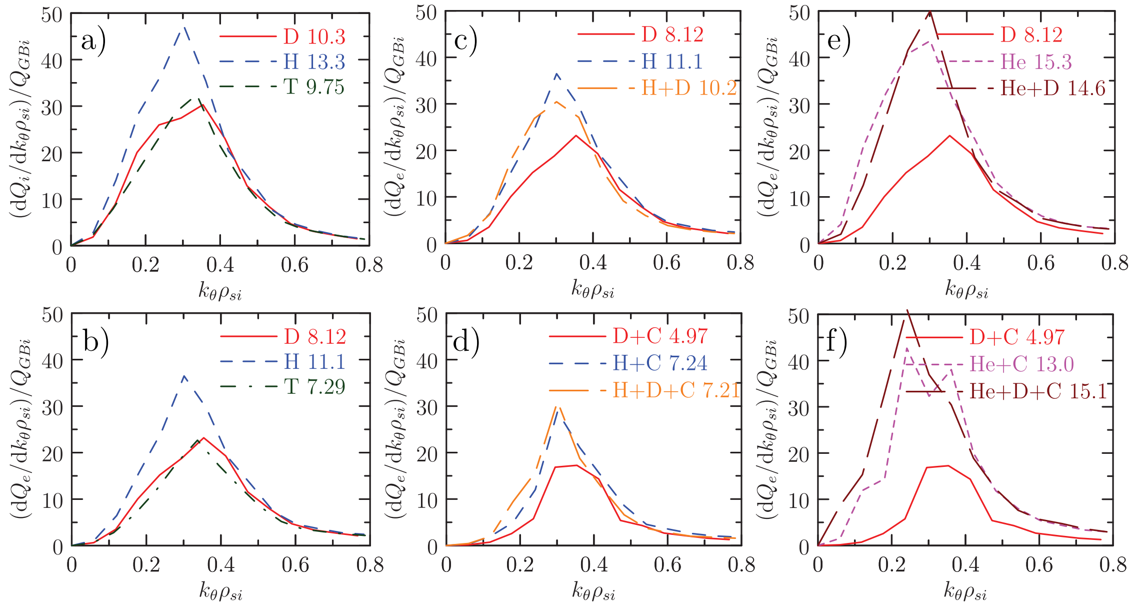

Figure 2: *Ion (a) and electron (b-f) energy flux spectra for different ion compositions based on the profiles from the deuterium discharge. The legends show the ion composition and fluxes in (main-)species gyro-Bohm units (that is, the $k_\theta\rho_{si}$ integral of the spectra curves).*

Transport analysis

Finally the similarity of the discharges was relaxed, and the actual plasma profiles were used, taking neoclassical flows into account. The experimental energy transport in the helium discharge can be reasonably well reproduced, while for the deuterium discharge we find even better agreement (see Fig. 3a-d). The minor differences can be due to uncertainties in the profiles and plasma composition which plays an important role in these discharges. Also, ion and electron temperature profiles calculated by predictive TGYRO transport simulations [1] using TGLF [4] and NEO are quite similar to the experimental profiles for these discharges, as illustrated in Fig. 3e. On the other hand, the exceptionally high gyro-Bohm energy transport in the hydrogen discharge could not been reproduced by GYRO. The discrepancy is likely not due to uncertainties in the profiles as much steeper temperature profiles were necessary in predictive TGYRO-TGLF/NEO simulations to reproduce the experimentally found high level of fluxes (Fig. 3f). Further tests ruled out inaccurate plasma composition, the effect of energetic ions or erroneous energy source profiles as possible sources of the discrepancy. It is not certain if the discrepancy between gyrokinetic/gyrofluid models and experiments in this discharge is related to a previously observed shortfall [5] towards the edge.

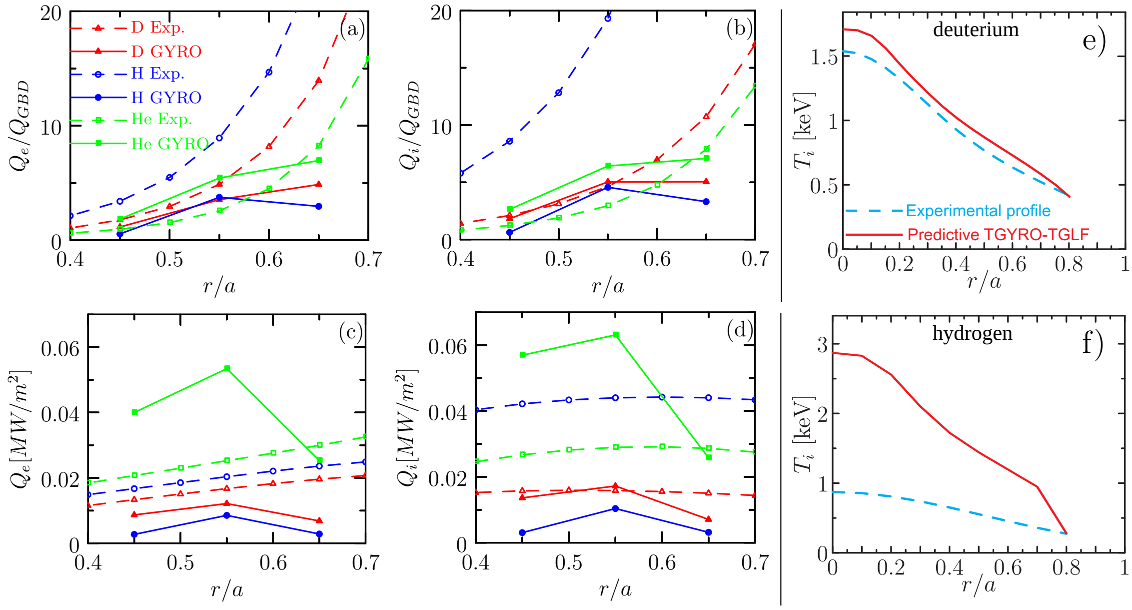

Figure 3: *Electron (a,c) and ion (b,d) energy fluxes in deuterium gyro-Bohm units (a,b) and in* $\mathrm{MW/m^2}$ *(c,d). The experimental (power balance) fluxes are plotted with dashed curves, the full symbols are nonlinear* GYRO *simulations. (e,f): Comparison of ion temperature profiles from predictive* TGYRO-TGLF/NEO *simulations to the experimental profiles, for the D and H shots.*

Conclusions

The growth rates are higher for $Z > 1$ main ions due to the appearance of the charge in the Poisson equation. On ion scales the most significant effect of the different electron-to-ion mass ratio appears through collisions stabilizing trapped electron modes. In nonlinear simulations significant favorable deviations from pure gyro-Bohm scaling are found due to electron-to-ion mass ratio effects and collisions. The presence of any non-trace impurity species cannot be neglected in a comprehensive simulation of the transport; including carbon impurity in the simulations caused a dramatic reduction of energy fluxes. The transport in the analyzed deuterium and helium discharges could be well reproduced in gyrokinetic and gyrofluid simulations while the discrepancy between experiment and predictions for the hydrogen case could not be resolved.

Acknowledgments

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