Isotope dependence of limit-cycle oscillations in ASDEX Upgrade plasmas

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At the edge of fusion plasmas, a regular pulsation of the perpendicular flow velocity $\mathbf{u}_\perp$ and the density fluctuations $\tilde{n}$ can occur at the transition from low to high confinement regimes (L-H transition). These pulsations, sometimes referred to as limit-cycle oscillations (LCOs) [1] or I-phase [2], have frequencies in the low kilohertz range, exhibit a strong magnetic activity and can transition into a type-III ELM phase [3, 4]. These LCOs appear typically close to the L-H transition, raising the question whether the physics involved in the LCOs is related to the trigger of the L-H transition.

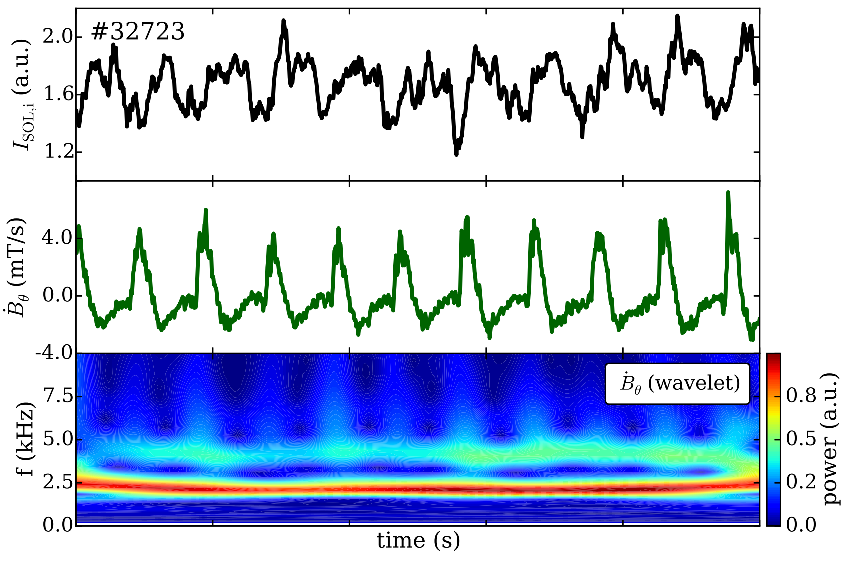

Figure 1: *LCOs at the L-H transition of a helium discharge (B_t = -2.5 T, I_p = 0.8 MA). The oscillations are found in the divertor shunt current (top), the magnetic field fluctuations close to the divertor X-point (middle), and in the wavelet spectrum of the latter (bottom).*

Since the power threshold for the access to the high confinement regime (H-mode) depends on the chosen main ion in tokamaks [5, 6], the dynamics and appearance of the LCOs could be likewise affected. The properties of LCOs in different main ion plasmas are expected to vary due to the variation of the ion mass A and the proton number Z, if these quantities are relevant for the physics of the LCOs. Therefore, isotope studies provide a convenient approach to the experimental validation of LCO models. The data described in the following was acquired in dedicated helium discharges conducted during the ASDEX Upgrade campaign 2015/2016. These experiments complement the data base of LCOs in hydrogen and deuterium from earlier campaigns.

In ASDEX Upgrade, significant differences were found in the L-H power threshold P_{LH} for different isotopes [5]. While helium plasmas exhibit the same power threshold as deuterium plasmas in ASDEX Upgrade after the full tungsten wall was completed, hydrogen plasmas need about 80% more power than deuterium plasmas to access the H-mode.

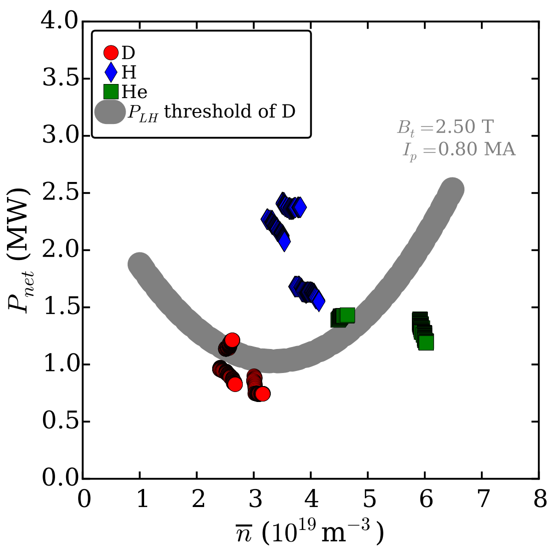

Figure 2: *Range of existence of LCOs for different main ion isotopes. While LCOs in deuterium and helium appear close to the deuterium L-H threshold (grey), the LCOs in hydrogen are found at higher net input power.*

In order to hit the small range of existence of the LCOs, helium plasmas in ASDEX Upgrade were heated with small and increasing power steps of the electron cyclotron resonance heating (ECRH). The use of ECRH does not change the helium concentration in contrast to neutral beam heating, and therefore a helium concentration of about 75% was kept constant over the whole discharge. As it was shown in deuterium discharges [3], the LCOs are not only visible in the fluctuation level $\tilde{n}$ or poloidal flow $\mathbf{u}_{\perp}$ measured with Doppler reflectometry, but also in the divertor shunt current $I_{\mathrm{pol,i}}$ and in a Mirnov coil close to the X-point of the divertor measuring the poloidal magnetic field fluctuations $\dot{B}_{\mathrm{pol}}$. For helium discharges, LCOs are found in the low kilohertz range as shown in Fig. 1. In hydrogen plasmas, the same kind of LCOs can be found, implying that the LCOs exists in plasmas of all kind of main ion isotopes used in fusion experiments.

As shown in Fig. 2, the LCOs measured in deuterium plasmas (red) at a toroidal field of B_t = -2.5 T and a plasma current of I_p = 0.8 MA are found close to the L-H power threshold P_{LH} [5] of deuterium plasmas, which is known from previous studies [2]. However, the LCOs in hydrogen (blue) appear at a significantly higher net input power P_{net} than LCOs in deuterium plasmas. It is well known, that P_{LH} is much higher in hydrogen than in deuterium, and therefore, the range of existence of LCOs obviously depends in the same way on the isotope mass as the L-H power threshold implying that the physics of the LCOs is indeed connected to the L-H transition. In helium plasmas (green), the LCOs appear close to the L-H power threshold as well, but only at much higher line-averaged electron densities $\bar{n}$ compared to deuterium. The fact that the electron densities n_e, for which LCOs were found in helium discharges, are twice as high as for deuterium plasmas, indicates that the ion density n_i could play a role for the appearance of LCOs, since $n_e = Zn_i$ with $Z = 2$ for helium.

It should be emphasized that it was not possible to find LCOs in ECRH heated helium discharges for medium and low line-averaged densities below $\bar{n} = 4 \cdot 10^{19}$ m^{-3}, where the LCOs usually clearly appear at L-H transitions in deuterium and hydrogen plasmas. Instead of LCOs with an almost constant and continuous frequency, a regime of "breathing" oscillations was found (see Fig. 3).

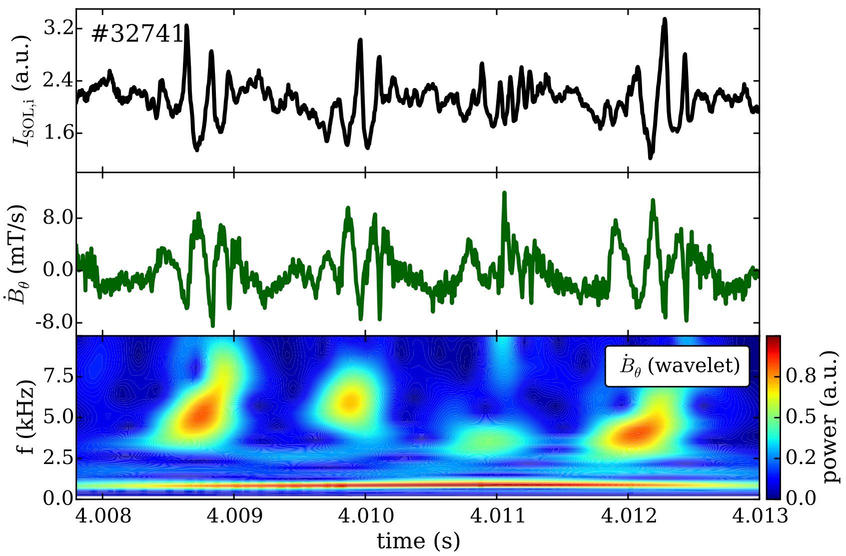

Figure 3: *Low density helium discharges exhibit an amplitude modulated 5 kHz mode of oscillations instead of LCOs. Same representation as in Fig. 1.*

These oscillations exhibit a base frequency of about 5 kHz and an amplitude modulation with a frequency of about 0.8 kHz. This could be related to the “breathing” of geodesic acoustic modes (GAMs) as described in Ref. [7] for deuterium discharges. It was argued that the GAM amplitude is modulated by a low-frequency zonal flow in the range of 200-500 Hz. The modulation shown in Fig. 3, could be interpreted in the same way as a modulation of the amplitude of a GAM at 5 kHz by the low-frequency zonal flow with a frequency of 0.8 kHz. The frequency of the GAM is approximately $f_{\mathrm{GAM}} \approx c_s/(2\pi R)$ with the sound speed $c_s = \sqrt{T_e/m_i}$ and the major radius R. For the helium discharge #32741, the electron temperature slightly inside the separatrix was $T_e \approx 100$ eV, which corresponds to a GAM frequency of $f_{\mathrm{GAM}} \approx 6$ kHz, and is therefore quite close to the measured frequency oscillation of about 5 kHz. However, further measurements with Doppler reflectometry or other turbulence diagnostics suited for fast flow measurements have to be done to confirm this picture.

As shown in Ref. [3], the frequency of LCOs given in units of kHz, f_{LCO}, depends on different plasma parameters which can be summarized as $f_{\mathrm{LCO}} = 0.007/\left(\beta_{\mathrm{t,ped}} q_{95}^{3/2}\right)$ with $\beta_{\mathrm{t,ped}}$ the plasma beta at the pedestal top and q_{95} the safety factor at a normalized radius of 0.95.

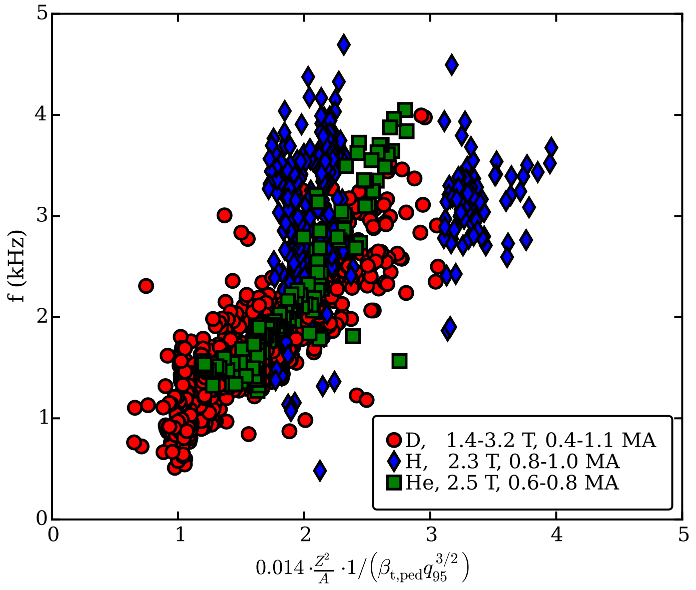

Figure 4: *Frequency scaling of LCOs. The hydrogen and helium discharges fit to the scaling described in Ref. [3], if a correction factor Z^2/A is included.*

The dependence of the LCO frequency on plasma parameters in helium and hydrogen is similar as found in deuterium discharges, however, a correction factor taking into account the isotope mass A and proton number Z has to be introduced in the frequency scaling. The new scaling then reads

$$f_{\mathrm{LCO}} = \frac{0.014 \cdot \frac{Z^2}{A}}{\left(\beta_{\mathrm{t,ped}} q_{95}^{3/2}\right)}.$$

As shown in Fig. 4, the hydrogen discharges (blue) partially extend the range of deuterium discharges (red). The helium discharges (green) fit well into the former scaling based on a regression of deuterium discharges.

In summary, the properties of the LCOs at the L-H transition are very similar for different isotopes. The appearance of the LCOs seems to be strongly related to the L-H power threshold, and for helium LCOs are found only at high densities. If a correction factor is introduced, the frequency scaling of LCOs can be unified for all isotope masses.

References

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