

## **Investigation of the existence of an improved confinement regime in simple magnetized toroidal plasmas**

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### **Introduction**

During low confinement mode (L-mode) in tokamak discharges [1], a large fraction of anomalous particle and heat transport at the plasma edge is attributed to the presence of isolated structures, dubbed *blobs*, in which density and temperature are increased with respect to the surrounding plasma. Blobs extend along the field lines and propagate radially away from the confined plasma resulting in heat and particle transport. Blob transport is convective and may extend to the far Scrape-Off Layer (SOL), typically yielding flat density profiles and a significant particle flux near the wall of the device, affecting divertor heat loads and wall recycling. Recent results [2] from fast framing cameras on the NSTX and Alcator C-Mod tokamaks show that both turbulence and blobs are substantially reduced during high confinement mode (H-mode) with respect to the Ohmic or L-mode regimes.

In the toroidal device TORPEX [3], an experimental configuration has been identified, in which blobs with properties similar to those observed in tokamaks are found to originate from coherent interchange waves [4, 5]. The flexibility of the TORPEX device is used to explore the accessibility to an improved confinement regime, recently predicted by theory [6], by varying various experimental parameters.

### **Theory background**

In TORPEX, a vertical magnetic field  $B_z$ , superposed on a toroidal field  $B_t$ , creates helicoidal field lines with both ends terminating on the torus vessel. Instabilities and turbulence driven by magnetic curvature and plasma gradients result in radial particle and heat transport. At the same time the plasma is progressively lost due to flows along the field lines. Similarly to the tokamak SOL, this magnetic configuration, which we will refer to as simple magnetized torus (SMT), features open field lines,  $\nabla B$ , and magnetic field curvature.

In TORPEX plasmas, drift modes dominate the electrostatic fluctuation spectrum for low values of  $B_z$ , while a gradual transition to interchange instabilities is observed when the magnitude of the magnetic vertical field is increased [7].

Recent three-field fluid simulations have been performed to study the interchange dominated regime of the TORPEX device [6]. Two turbulent regimes, akin to L- and H- confinement regimes in tokamaks, are clearly revealed by the simulations. The ratio  $\gamma/v'_{E \times B}$  (see below for the definition) controls the L-H transition, which is observed for  $\gamma/v'_{E \times B} \approx 1$ .

Figure 1 illustrates some features of the two confinement regimes. In the L-mode, smooth density and temperature profiles with negligible shear flow are observed. The plasma propagates in the radial direction in the form of blobs, as shown in Fig. 1(c). By increasing the plasma source strength, reducing the vertical magnetic field, or increasing the ion mass, a transition to an H-mode occurs. In the H-mode, a strong shear of the  $\mathbf{E} \times \mathbf{B}$  velocity, Fig. 1(d), reduces the perpendicular transport with respect to the L-scaling. The plasma profiles steepen, as shown by the electron temperature and density scale lengths in Fig. 1(a,b).

## Experimental results

The experiments are performed in the toroidal device TORPEX (major radius  $R = 1$  m, minor radius  $a = 0.2$  m) in which hydrogen, helium and neon plasmas are produced by means of microwaves in the Electron Cyclotron (EC) range of frequencies. A low level of EC power  $P_{EC} \approx 400$  W is used for these experiments. A vertical magnetic field  $B_z$  ranging from 2 to 4 mT is superposed to a toroidal magnetic field of  $B_t = 76$  mT on axis. The plasma source is localized on the high-field side, which insures negligible plasma production on the low field side and results in a vertically elongated plasma configuration. For the three gases, Fig. 2 shows 2D profiles of the time-averaged electron pressure,  $p_e = n_e T_e$ , the inverse equilibrium radial pressure gradient scale length, defined as  $L_{pe}^{-1} = \nabla_r p_e / p_e$ , and  $\mathbf{E} \times \mathbf{B}$  velocity shear, obtained from Langmuir probe measurements.

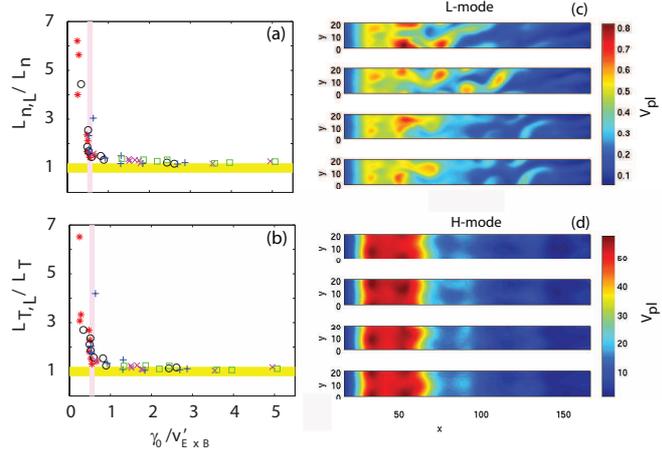


Figure 1: *L- and H- mode features from numerical simulations. (a,b) Dependence of electron temperature and density scale lengths with respect to L-mode values upon the ratio  $\gamma/v'_{E \times B}$ . Snapshots of the 2D plasma potential at different times showing the formation of blobs in the L-mode (c) and an interchange wave propagating without ejection of blobs in the H-mode (d).*

The plasma potential is computed from  $V_{pl} = V_{fl} + \mu T_e/e$ , where  $V_{fl}$  is the floating potential, and the coefficient  $\mu = \log(m_i/2\pi m_e)$ . The  $\mathbf{E} \times \mathbf{B}$  velocity is evaluated from  $\mathbf{v}_{E \times B} = (-\nabla V_{pl} \times \mathbf{B})/B^2$ , with  $B = \sqrt{B_z^2 + B_t^2}$ .

These plasmas are characterized by the presence of an interchange mode which is localized at the position of minimum  $L_{pe}^{-1}$  and propagates upwards with a velocity consistent with the time-averaged  $\mathbf{E} \times \mathbf{B}$  velocity profile. The interchange mode has parallel wave number  $k_{||} \approx 0$  and vertical wave number

$k_z = 2\pi\Delta_z$ , where  $\Delta_z = 2\pi RB_z/B_t$  is the field line vertical return distance in the poloidal plane. Sheath effects are not expected to affect strongly the linear properties of the interchange mode [6], since  $k_\Delta^2 \rho_s^2 \gg \sigma \sqrt{L_{pe}/(2R)}$ , where  $\sigma = \Delta_z/(2\pi L_v)$  with  $L_v = 0.4$  m being the SMT height. Thus, the longest wavelength mode allowed in the system corresponds to the fastest growing instability, with a growth rate comparable to the interchange growth rate  $\gamma \sim \sqrt{2c_s}/\sqrt{RL_{pe}}$ , where  $c_s$  is the ion sound speed. Figure 3 shows the dependence of the maximum  $\gamma$  and  $\mathbf{E} \times \mathbf{B}$  velocity shear upon the mass number for the three gases of the scan. The maximum  $\gamma$  decreases with increasing gas mass from  $\gamma \approx 3.5 \times 10^{-5}$  s for hydrogen to  $\gamma \approx 1.5 \times 10^{-5}$  s for neon.

Conversely, the maximum  $\mathbf{E} \times \mathbf{B}$  velocity shear increases with the gas mass from  $v'_{E \times B} \approx 0.5 \times 10^4$  s<sup>-1</sup> for hydrogen to  $v'_{E \times B} \approx 6 \times 10^5$  s<sup>-1</sup> for neon.

Using these values, we can compute the ratio  $\gamma/v'_{E \times B}$  that controls the transition to the H-mode according to the theory. For hydrogen, we find  $\gamma/v'_{E \times B} \cong 6 - 7$ . This suggests that hydrogen plasmas are in the L-mode regime, consistently with the observation of blob ejection previously reported [4, 5]. For neon, we find  $\gamma/v'_{E \times B} \cong 0.3 - 0.4$ , which, from theory, should correspond to an H-mode. From Fig. 2, we observe that the maximum

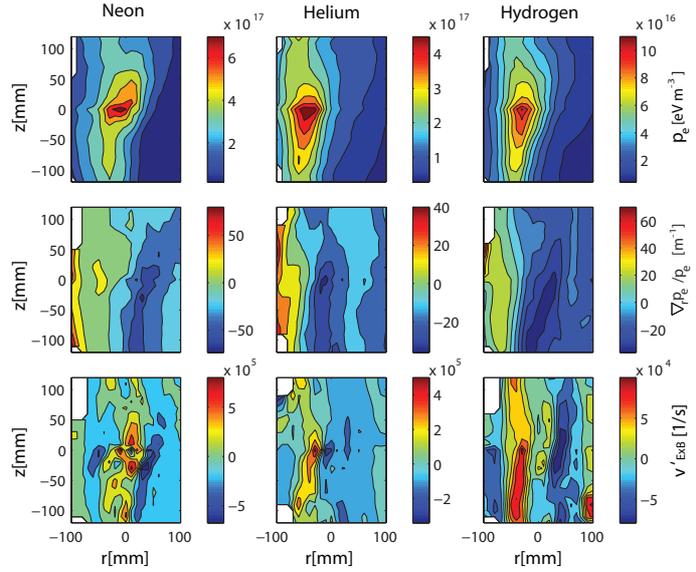


Figure 2: For three different gases, 2D poloidal profiles of the time-averaged plasma pressure, the inverse equilibrium radial pressure gradient scale length  $L_{pe}^{-1}$ , and  $\mathbf{E} \times \mathbf{B}$  velocity shear from Langmuir probe measurements.

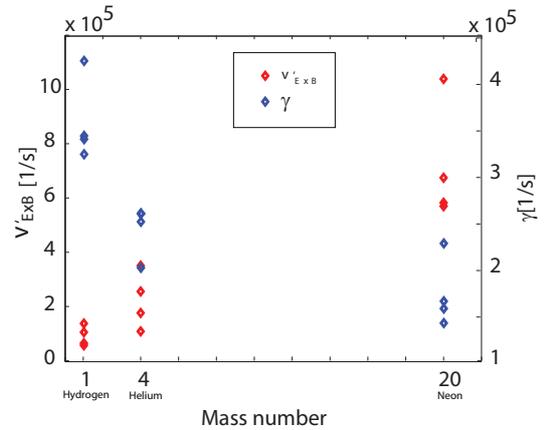


Figure 3: Dependence of interchange linear growth rate  $\gamma$  (red diamonds) and  $\mathbf{E} \times \mathbf{B}$  velocity shear (blue diamonds) upon the mass number for the three gases of the scan.

values of both  $|L_{pe}^{-1}|$  and  $v'_{E \times B}$  are increased in the neon case with respect to the hydrogen and helium cases. This is also consistent with an improved confinement.

In Fig. 4, we show four different snapshots of two dimensional ion saturation current profiles for hydrogen and neon from an array of 86 Langmuir probes covering the entire poloidal cross section [8]. While, in the case of hydrogen, the ejection of blobs is visible on the low field side of the plasma, blobs are not clearly seen in the neon case. This suggest that the steepening of the profiles in neon may be linked to a reduction of perpendicular transport associated with blobs.

### Summary

Stimulated by theoretical predictions and numerical simulations, we have conducted a search for an improved confinement regime in the simple magnetized plasma of the TORPEX device. Using different gases, we can vary the ratio  $\gamma/v'_{E \times B}$  that, from theory, controls the turbulence regime. In hydrogen and helium plasmas, where  $\gamma/v'_{E \times B} \gtrsim 0.7$ , blobs are observed to be ejected from interchange waves. In neon plasmas, where  $\gamma/v'_{E \times B} \lesssim 0.4$ , the ejection of blobs is substantially reduced, leading to a steepening of the electron pressure profile. This is consistent with numerical simulations of H-mode plasmas in the interchange dominated regime.

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### References

- [1] S. J. Zweben, Phys. Fluids **28**, 974 (1985); J. A. Boedo, *et al.*, Phys. Plasmas **8**, 4826 (2001); S. I. Krasheninnikov, Phys. Lett. A, **283**, 368 (2001).
- [2] S. J. Zweben, Phys. Plasmas **13**, 056114 (2006).
- [3] A. Fasoli, B. Labit, M. McGrath, S. H. Müller, G. Plyushchev, M. Podestà, and F.M. Poli, Bull. Am. Phys. Soc., **13**, 119 (2003).
- [4] S. H. Müller, A. Diallo, A. Fasoli, I. Furno, B. Labit, and M. Podestà, Phys. Plasmas, **14**, 110704 (2007).
- [5] I. Furno, B. Labit, M. Podestà, *et al.*, Phys. Rev. Lett. **100**, 055004 (2008).
- [6] P. Ricci, *et al.*, *High and low confinement modes in simple magnetized toroidal plasmas*, accepted for publication in Phys. Rev. Lett.
- [7] F. M. Poli, P. Ricci, A. Fasoli, and M. Podestà, Phys. Plasmas, **15**, 032104 (2008).
- [8] S. H. Müller, A. Fasoli, B. Labit, M. McGrath, O. Pisaturo, G. Plyushchev, M. Podestà, and F. M. Poli. Phys. Plasmas **12**, 90906 (2005).

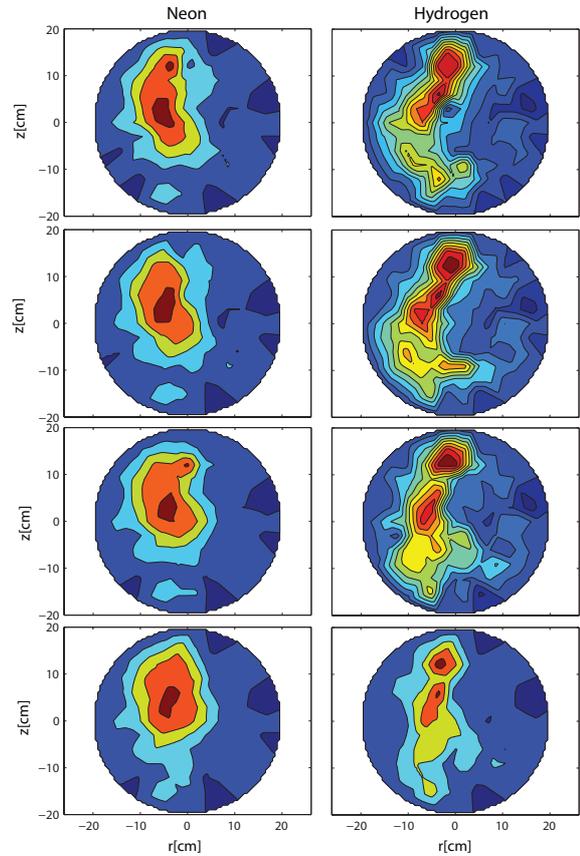


Figure 4: At different times, 2D profiles of the ion saturation current. In hydrogen, the ejection of blobs is clearly visible on the low field side. In neon, this is not observed.