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Effect of gas puffing on the mode locking phenomena in a reversed-field pinch device, TPE-RX

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The phase- and wall-locked mode (LM) appears in a reversed-field pinch (RFP) device, Toroidal Pinch Experiment, TPE-RX (R/a = 1.72/0.45 m) [1]. In particular, the LM appears when the plasma current, I_p, exceeds 300 kA. The LM is formed when the core-resonant multiple tearing modes are phase-locked and also wall-locked due to the braking effect of the eddy current in the vacuum vessel, as the mode amplitude grows during the current-rising phase [2]. The heat flux is peaked at the wall-locked position (~100 MW/m^2), and the temperature increment during the discharge is estimated to be as high as 2400 degrees on the plasma-facing side at the locked position when I_p = 350 kA. The vacuum vessel is made from the stainless steel, and the bellows section is 2 mm thick. Thus, it is necessary to mitigate the heat flux caused by LM in order to operate RFP particularly at high I_p.

Recently, we have investigated effects of deuterium gas puffing on the characteristics of LM. We present that the probability for the LM to appear at the gas-puffed location increases as the gas-puffing rate increases, which is consistent with our previous observation that the LM tends to appear as the electron density increases [2]. We have succeeded in reducing the heat flux using deuterium gas puffing with two fast-acting valves. We have also observed that the characteristics of the LM are affected by gas puffing. We present that the maximum temperature increment caused by the LM is halved when the gas-puffing rate is approximately 200 Pa m^3/s. It is discussed that gas puffing increases electron density, n_e, and reduces electron temperature, T_e, thus reducing the field-aligned convective loss at the LM position.

Gas puffing of deuterium gas was conducted in TPE-RX at I_p = 350 kA, using two fast-acting valves (FAVs) placed at $\phi = (3/8)\pi$ (FAV1) and $(11/8)\pi$ (FAV2) radians, where ϕ is the toroidal angle defined so that $\phi = \pi$ at the poloidal gap of the thick shell. The FAVs are triggered simultaneously at t = 20 ms, which is the end of the current-rising phase, with a fixed pulse width of 4.6 ms and voltages for opening and closing the electromagnetic valves. The flux of the gas was varied changing the deuterium pressure at the back of the FAVs, p_{DGP}, in three steps; +100 kPa (GP100), +200 kPa (GP200), and

+300 kPa (GP300) from the atmospheric pressure. As p_{DGP} increases, I_p slightly decreases from 359 to 333 kA and the loop voltage (V_{loop}) slightly increases from 32 to 36 V, while the reversal parameter (F) and the pinch parameter (Θ) do not change at –0.15 and 1.5, respectively. All these values are measured at t = 30 ms when the line-averaged electron density measured at the central chord [$n_{el}(0)$] has a maximum (Fig. 1). Note that $n_{el}(0)$ at t = 30 ms increases from 0.72 X 10^{19} m^{-3} in the case without gas puffing (Std) to 2.2 X 10^{19} m^{-3} in GP300. On the other hand, the central electron temperature (T_{e0}) decreases from 0.60 keV in Std to 0.24 keV in GP300. Characteristics of the confinement properties are reported in Ref. [3].

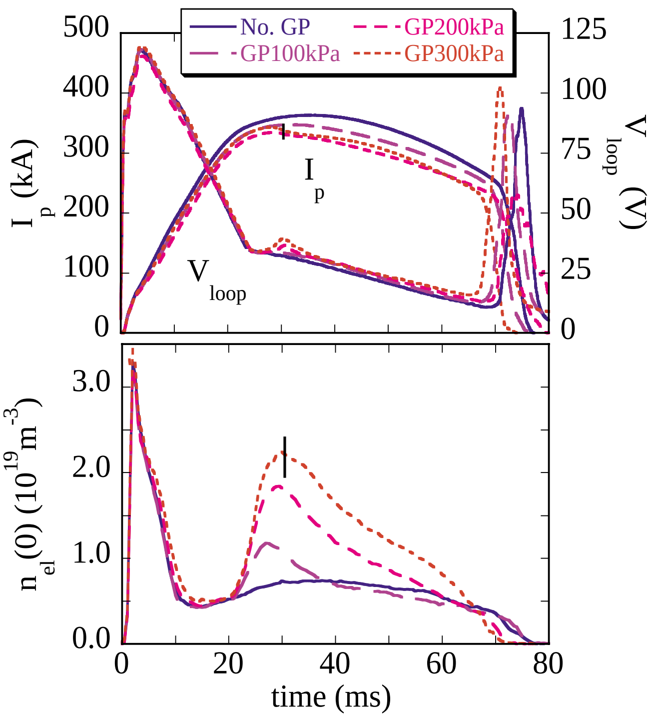

Fig. 1. Waveforms of the plasma current, loop voltage and line averaged density in Std, GP100, Gp200, and GP300

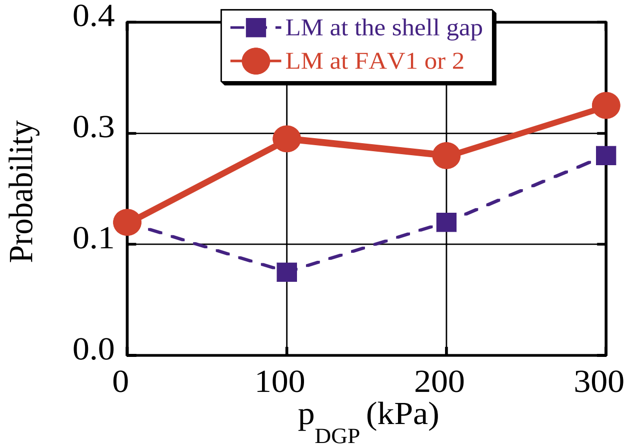

Fig. 2. Probability of the phase- and wall-locked mode to appear at the FAV1 or FAV1 and at the

The horizontal and vertical shifts of the last-closed flux surface (LCFS) are calculated from the signals of the toroidal arrays of the B_r-loop sensors. Then the toroidal location of the LM (ϕ_{LM}) is determined as the angle where the total shift of the LCFS (Δ_{tot}) has a maximum. The toroidal distribution of ϕ_{LM} in Std has a peak of 16% at the shell gap (ϕ=π). With gas puffing, it is found that the probability for the LM to appear both at the shell gap and the location of either FAV1 or FAV2 increases to 24% and 30%, respectively (Fig. 2). The toroidal distribution of the D_α line intensity ($I_{D\alpha}$) is measured. In gas puffing, $I_{D\alpha}$ has peaks at FAV1 and FAV2 with a full width at half maximum of (1/3)π radians. At the locations of the FAVs, $I_{D\alpha}$ rises in 2 ms and decays with an e-folding time of approximately 5 ms. Thus, $I_{D\alpha}$ is localized around the FAVs in gas puffing. In our previous works [1, 2], we showed that the higher filling pressure of deuterium (p_{D2}) give higher probability for the distinct phase-locked structure to appear, and that the higher n_e, hence the lower T_e, in the current-rising phase, lowers the threshold for the phase-locked structure to be formed as well as increases the tearing mode amplitudes. It is speculated here that the higher n_e and lower T_e in the edge region near the FAVs and the shell gap as well caused by gas puffing might enhance the probability for the LM to appear at a particular position because of the same reason for the case of the uniform increase of n_e.

The vessel temperature increment after each discharge (T_w) is measured by thermocouples attached on the equatorial plane of the outside surface of the vacuum vessel. When LM appears, T_w shows a toroidally peaked increment after the discharge (the peak value is denoted as T_{wLM}), indicating an enhanced heat flux caused by severe plasma-wall interaction (PWI) due to the phase-locked structure of LM. The value of T_{wLM} at I_p = 350 kA can be as high as 60 °C, which is estimated to be approximately 2400 °C on the plasma-facing side of the vacuum vessel. The peaking factor, defined as a ratio between the peak temperature increment and the average increment except for the peak, is approximately ten at the LM position. We obtained fifty discharges at Std, GP100, GP200, GP200, and GP300, and performed a statistical analysis. Figure 3 shows histograms of T_{wLM} in the four cases. The result shows that the maximum value of T_{wLM} ($T_{w\text{-}max}$) decreases when p_{DGP} exceeds 100 kPa, and $T_{w\text{-}max}$ in GP300 becomes half of that in Std. Note that the averaged T_{wLM} does not change for all four cases, and that the

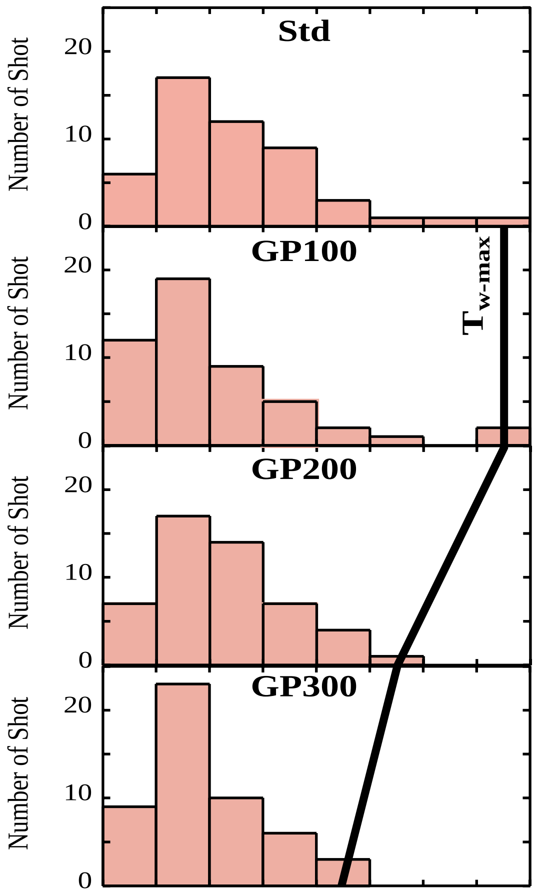

Fig. 3. Histograms of the peak temperature increment measured by thermocouples on the vacuum vessel

histogram has an asymmetric distribution with a peak appearing around 10 °C. This asymmetric profile of the histogram is attributed to a finite shift of the discrete locations of the thermocouples and the magnetically detected LM position, i.e., ϕ_{LM}. In our previous work [1], it was shown that there is a finite toroidal shift between the toroidal angle (ϕ_{TwLM}), where T_{wLM} appears, and ϕ_{LM} It is possible to show that a Gaussian profile of T_w centered with a peak value T_w^* at ϕ_{LM} with a finite shift ($\delta\phi$) from ϕ_{TwLM} can give an asymmetric profile as in Fig. 3 with a maximum abscissa at $T_{wLM} = T_w^*$. Namely, $T_{w\text{-}max}$ in Fig. 3 corresponds to the peak temperature increment at ϕ_{LM}. Thus, it is confirmed that the reduction of $T_{w\text{-}max}$ by gas puffing represents the reduction of the LM-enhanced heat flux. The reduction of the LM-enhanced heat flux is interpreted by the reduction of the field-aligned convective loss, which can be expressed by $n_e v_e T_e \sim n_e T_e^{1.5}$. Although actual values of n_e and T_e in the edge regions are not measured, we confirmed that $n_{el}T_{e0}$ is approximately halved from Std to GP300. Figure 4 shows a positive correlation between $n_{el}T_{e0}^{1.5}$ and $T_{w\text{-}max}$.

The screening effect of the neutral gas, as well as the replacement of direct convective loss with the radiation loss could be alternative candidates to decrease the LM-enhanced heat flux. A real-time sensing of the LM location and gas puffing right at that position might improve the performance in reducing the LM-enhanced heat flux. Gas puffing experiments at higher I_p are also necessary to confirm that this method is applicable for the designed-maximum 1 MA operation in TPE-RX. Those studies are remained for future.

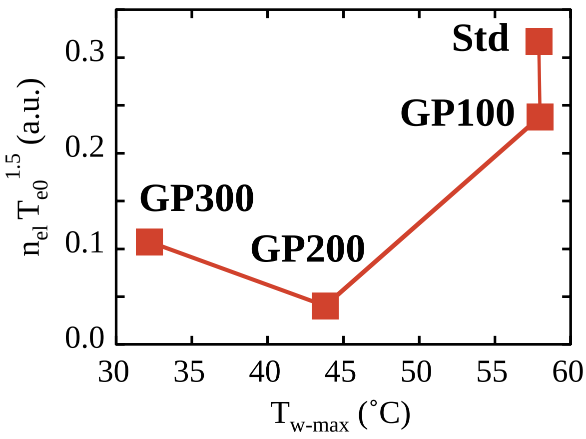

Fig. 4. Correlation between $n_{el}T_{e0}^{1.5}$ and the maximum peak temperature increment, $T_{w\text{-}max}$, for four cases

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