Improved Confinement Regimes by Control of Reversal of Toroidal Magnetic Field in TPE-RX Reversed-Field Pinch Plasmas

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Abstract. Improved plasma performances have been achieved in a reversed field pinch (RFP) experiment on toroidal pinch experiment-RX (TPE-RX, major/minor radii = 1.72 m/0.45 m, plasma current < 0.5 MA) by the pulsed poloidal current drive (PPCD) and the quasi-single helicity (QSH) state, which were obtained by controlling the reversal of a toroidal magnetic field. A steady high-density state has been obtained during the PPCD period with a single ice pellet injection, which indicates the marked (up to ten fold) increase in the particle confinement time (τ_p) in PPCD compared with that in the case of ordinary shots. Plasma electron temperature increases during the PPCD period, and poloidal beta increases at least three fold higher than that in the case of an ordinary shot. It has been also found that better plasma performance is observed in the QSH state than in the multi helicity (MH) state, both of which alternatively appear in a single shot under particular operating conditions. Meanwhile, it has been demonstrated for the first time that the QSH state can be obtained with an almost 100 % probability by applying a small positive pulse to the reversed negative toroidal magnetic field. The result of the high-power (~ up to 2 MW) NBI experiment in which the NBI System has been connected to the torus and whose injection experiment has just been started, will be presented. Magnetized plasma flow (MPF) injection has been for the first time demonstrated in RFP plasma. MPF injection shows increases in the electron density and in the toroidal flux, and the reductions in the density pump-out at the start-up phase and in the one-turn toroidal voltage at the flat-top phase are also observed.

1. Introduction

Toroidal pinch experiment-RX (TPE-RX) is one of the largest reversed field pinch (RFP) devices in the world. The major radius R and minor radius a are 1.72 m and 0.45 m, respectively [1]. Improved confinement has been achieved in many RFP devices by pulsed poloidal current drive (PPCD) [2, 3]. The quasi-single helical (QSH) state is also realized for improved confinement operation. Recent progress in these improved confinements in TPE-RX is presented in this paper. Focused high-power-density NBI systems have been developed and installed in TPE-RX [4]. The NBIs have the capability to inject a neutral hydrogen beam with a power of 2 MW and an energy of 25 keV for more than 30 ms. It is necessary for the NBI experiment to increase the plasma electron density and to reduce the beam shine through. The plasma electron density of TPE-RX is low compared with those of other RFP devices. Controlling the plasma electron density is one of the major issues in TPE-RX. Gas puffing had been conducted in TPE-RX, and plasma electron density could be increased [5]. However, magnetic fluctuation also increased probably because of edge cooling caused by the neutral gas. To control the plasma electron density with less edge cooling, an ice pellet injection experiment has been conducted on TPE-RX [6]. The ice pellet is injected into the PPCD plasma, and confinement properties are studied. The NBI experiment will yield information about the beta limit of RFP plasma under ordinary and PPCD conditions with and without ice pellet injection. Magnetized plasma flow (MPF) injection also has been applied on TPE-RX in order to control the plasma electron density and to drive the poloidal current non-inductively [7]. The MPF contains a large amount of magnetic helicity and dense ionized particles. MPF injection has also been demonstrated to assist RFP start-up [8].

Recent developments in PPCD and the confinement properties of TPE-RX are presented in Section 2. A Thomson scattering system using a Nd-YAG laser has been used for measurement and poloidal beta is estimated in Section 2.2. Particle confinement using the D_α line intensity and the total number of particles measured using a laser interferometer is discussed in Section 2.3. The marked density increase during PPCD by ice pellet injection is shown in Section 3.1. The confinement property under ice pellet injection is discussed. The first result for the NBI experiment is reported in Section 3.2. Improved confinement related to spontaneous transition to the QSH state from the multi-helical (MH) state is presented in Section 4.1. Full control of the QSH state has been developed in TPE-RX and is presented in Section 4.2. We describe the results of MPF injection in Section 5, and give a summary in Section 6.

2. Pulsed Poloidal Current Drive

2.1. Pulsed Poloidal Current Drive with Six Stages.

The power supply for the PPCD was power-upped to enable six stages of PPCD operation, by which the PPCD period could be extended and the intensity of the soft X-ray emission measured at central vertical chord (I_{sx}) increases by about a factor of three. Figure 1 shows plasma current (I_p), external applied toroidal magnetic field (B_{t_out}) and I_{sx}. The pulse duration is 65 ms in ordinary discharge, as shown in FIG. 1(a) (see red line). The maximum plasma current is adjusted to be 300 kA for each set of discharge conditions in this paragraph. In PPCD operation, the plasma current is terminated at the end of PPCD operation, and the pulse duration is 35 ms as shown by the green line in Figure 1(a). B_{t_out} is started at t = 20 ms, and B_{t_out} amplitude increases slowly and is kept almost constant during ordinary discharge. In PPCD operation, B_{t_out} is stepped down 6 times as shown by the green line (overlapped with the blue line) in Figure 1(b), which induces a poloidal one-turn voltage and drives poloidal plasma current. PPCD operation is started at t = 18 ms, and the waveform of B_{t_out} is programmed in order to keep the positive value of the parallel electric field ($E_{//}$) at the plasma edge during the PPCD period. After t = 35 ms, $E_{//}$ is not positive, and the discharge terminates. During PPCD, the I_{sx} measured using the surface barrier diode (SBD) increases, as shown in

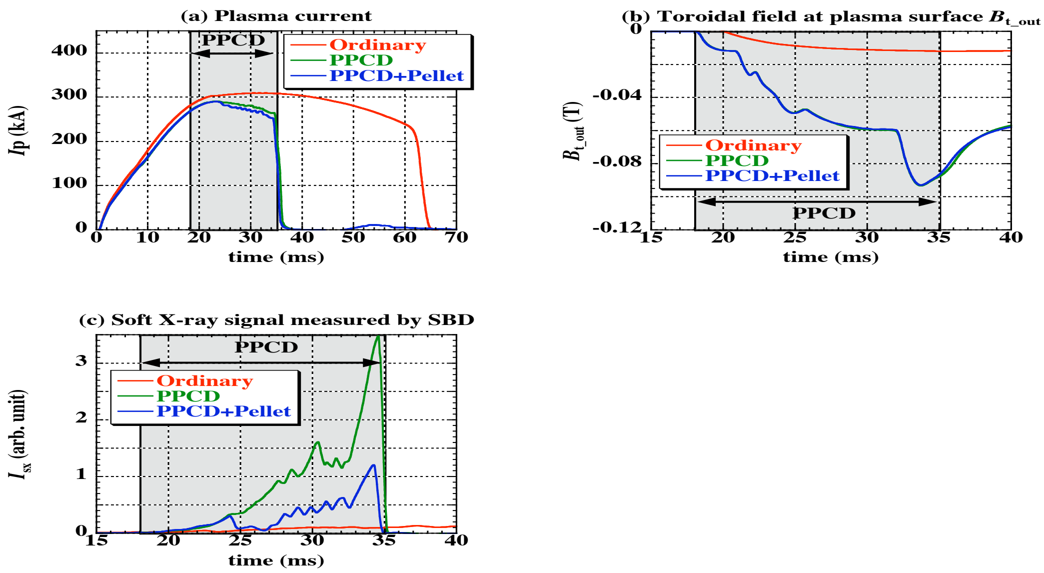

FIG.1. Plasma current (a), toroidal field at plasma surface (b), and soft X-ray signal (c).

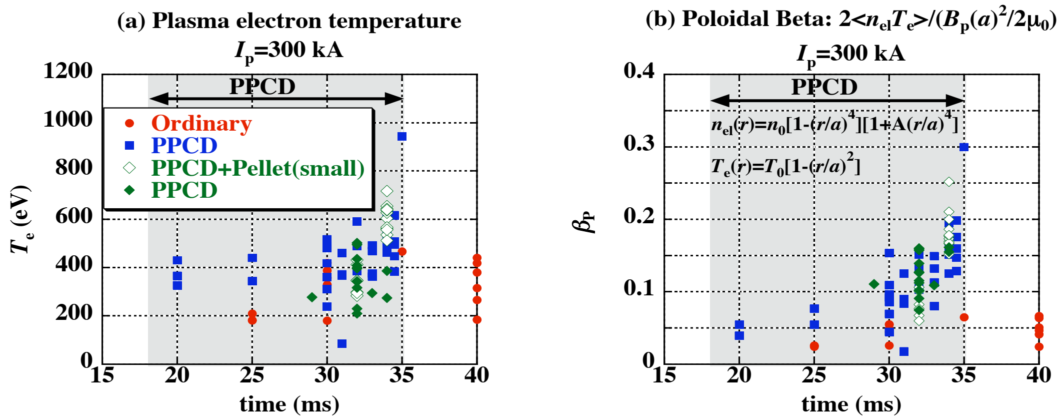

FIG.2. Plasma electron temperature measured using Thomson scattering (a) and poloidal beta (b).

Figure 1(c), which indicates an increase in T_e although I_{sx} depends not only on T_e but also on n_e and also on impurity.

2.2. Thomson Scattering and Poloidal Beta

The Thomson scattering system that uses a Nd-Yag laser and a polychrometer is installed in TPE-RX. This system is a single-laser system, and can measure plasma electron temperature (T_e) (central electron temperature) at one time by one discharge. Red symbols in FIG. 2(a) show T_e for the ordinary discharge, and the ensemble-averaged T_e is about 335 eV at t = 30 ms. Blue symbols show T_e for the PPCD discharge. As suggested, T_e increases with increasing I_{sx} during PPCD, and ensemble-averaged T_e increases to 532 eV at t = 34 ms. The maximum T_e is 934 eV in this experiment. It is shown in FIG. 2(b) that the poloidal beta (β_P) in the ordinary shot is about 4.6 %. Since the electron temperature profile has not been measured in TPE-RX, we assumed the following temperature profile: $T(r) = T_e\,[1-(r/a)^2]$. The electron density profile is measured using a double-chord CO_2/HeNe laser interferometer, whose impact parameters normalized by a are 0.0 and 0.69. We assumed the following electron density profile: $n_{el}(r) = n_0[1-(r/a)^4][1+A(r/a)^4]$. Here, n_0 and A were determined by the two measured chord values. The ion pressure profile used is the same as the electron pressure profile. β_P increases gradually during PPCD, and the ensemble-averaged β_P is 16 % at t = 34 ms. β_P still increases until t = 35 ms, but it is difficult to measure T_e at t = 35 ms because back ground-light emission that screens the scattering light increases just before the plasma crush.

Note that attenuation in the short wavelength range in the Thomson scattering system has been observed during calibration using a standard light source (tungsten lamp). It is possible that the obtained temperature is underestimated, which is slightly lower than the previous results obtained with an other Thomson scattering system. In this experiment, T_e is also slightly lower than the experimental results obtained with the previous Thomson scattering system [9]. The absolute value of T_e should be corrected, but the relative trends under the present experimental conditions are sufficient to discuss the confinement property.

2.3. Particle confinement

As shown in FIG. 3(a), the line-averaged electron density (n_e) measured at the center chord gradually increases during the PPCD period and we observe the improvement of particle confinement in this period [6]. The ratio of the total number of particles (N) estimated from the plasma electron density profile described above to the intensity of D_α emission ($I_{D\alpha}$), which corresponds to the particle confinement time, significantly increases up to ten times longer in PPCD than in the ordinary shot as shown in FIG. 3(b). Optical fibers with a focusing lens are distributed in approximately the toroidal direction. Using this system, D_α line intensities are monitored at 13 of the 16 port sections. The toroidal variation of emission is included into $I_{D\alpha}$. During the PPCD, N increases slowly and $I_{D\alpha}$ decreases. This improved particle confinement and the increase in T_e strongly indicate the substantial improvement in energy confinement.

3 Deuterium Ice Pellet Injection and NBI

3.1. Deuterium Ice Pellet Injection

The ice pellet injector, which had been used in the ETA-BETA II device [10], was installed in the TPE-RX. For each TPE-RX discharge, a single pellet is launched into the plasma. A much higher value of n_e (three times higher than in the ordinary shot) can be obtained by ice pellet injection into the PPCD, which is shown in FIG. 3(a). One pellet is injected 6 ms after the start of the PPCD, the pellet is separated into two pieces, and n_e increases by a factor of two in this case. The high n_e can be constantly maintained till the end of the PPCD period. In contrast, n_e has a strong peak followed by a decay within several ms when an ice pellet is injected into the ordinary discharge. The pellet ablation is separated from the background D_α emission, and the difference in observation geometry between the background emission and the pellet ablation is taken into account in $I_{D\alpha}$. The electron density profile function described above is useful for both center-peaked and edge-peaked profiles. The plasma density profile becomes an edge-peaked profile after pellet injection. $I_{D\alpha}$ increases markedly immediately after ice pellet injection. $N / I_{D\alpha}$ decreases just after the ice pellet injection, but increases again soon. The increase in $N / I_{D\alpha}$ with ice pellet injection is slightly lower than that without ice pellet injection, but is higher than ten times that of the ordinary shot.

I_{sx} also decreases rapidly after ice pellet injection, but is still higher by a factor of more than ten compared with that for the ordinary shot as shown in FIG. 1(c) (see red line). This indicates that T_e is higher than that for the ordinary shot. Thomson scattering is also measured for the ice pellet injection experiment. Green symbols in FIG. 2(a) show the T_e measured for PPCD shots with ice pellet injection. The results for the case with a small pellet are indicated by open symbols in order to separate the effect of the pellet size dependence since the reproducibility of pellet size is poor. In the case that a normal size pellet is injected into the PPCD plasma, T_e is slightly lower than that without ice pellet injection, but β_P remains almost the same because n_e is higher with a pellet. The variation of T_e in the small pellet case is almost the same as the trend of PPCD without pellet injection. The edge cooling does not affect the improvement in improved confinement, although the ice pellet is ablated at the plasma edge. The increase in magnetic fluctuation after ice pellet injection is unclear, and the confinement properties in the PPCD are not markedly degraded by ice pellet injection. This is one advantage of the ice pellet injection compared with other fueling methods in TPE-RX such as gas puffing where the magnetic fluctuation increases simultaneously with density.

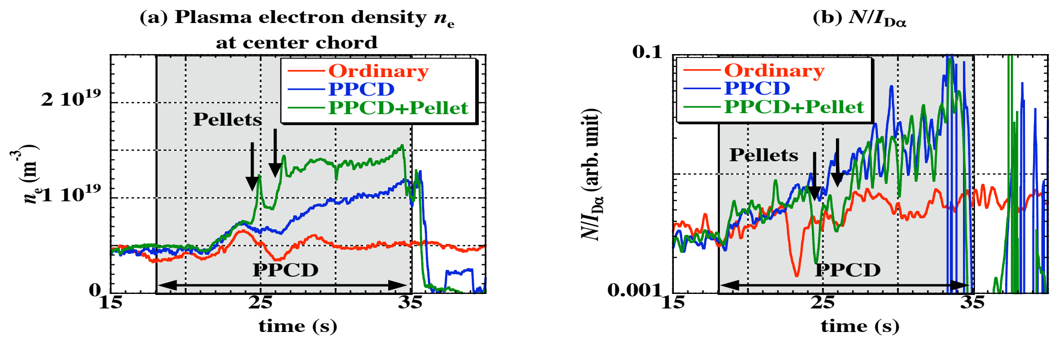

FIG. 3. Plasma electron density (a) and $N/I_{D\alpha}$ (b).

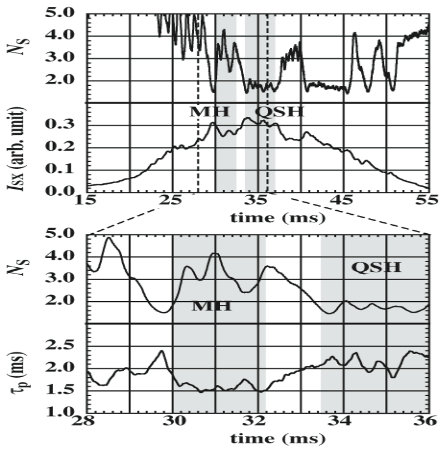

FIG. 4. Spectral index (Ns), soft X-ray intensity (I_{SX}) and particle confinement time (τ_p).

3.2. NBI Experiments with PPCD and Pellet Injection

Two sets of focused high-power-density NBI system toroidally configured 90 degrees apart were installed at the equatorial port of TPE-RX. The specifications of NBI-1 are 25 keV, 25 A, and 15 ms duration, and those of NBI-2 are 25 keV, ~60 A, and 30 ms. To pass the beam through the narrow aperture (~100 mm diameter) of the port, the beam is focused at the focal position and spread into the vacuum vessel. Due to the limitation in accessibility to the machine, the hydrogen neutral beam is injected in the normal direction. In this sense, the main purposes of NBI injection to the RFP are to carry out studies of plasma heating, beta limitation and the behavior of energetic particles (for the purpose of the current drive and momentum injection, the beam must be injected tangentially). Even in the case of PPCD operation, the line-averaged electron density is almost less than ~1.0 x 10^{19} m^{-3}; therefore, it is necessary to inject the beam to higher-density plasma to reduce the beam shine through. To increase plasma density, an ice pellet is injected into the PPCD plasma, then the electron density of more than ~1.0 x 10^{19} m^{-3} is maintained. The I_{sx} emission in the case of the PPCD + ice pellet + NBI combination increases compared with those for PPCD, PPCD + ice pellet or PPCD + NBI operations. This indicates for the first time that the RFP plasma is heated by the NBI. Detail analysis and further studies based on other operation arrangements have been conducted to confirm the effect of NBI on the RFP plasma.

4. Improved Confinement in QSH State

4.1. Improved Confinement in Spontaneously Occuring QSH State

Under appropriate operating conditions, transitions from the MH state to the QSH state and from QSH to MH can spontaneously occur in one discharge and the plasma performances in MH and QSH states can be compared under the same conditions [11]. An example is shown in FIG.4, where the spectral index of toroidal mode number for m = 1 modes (Ns), I_{sx} and τ_p calculated from n_e and I_α are shown in FIG. 4. Ns indicates the purity of the helical state, Ns = 1 corresponds to a pure single-helicity (SH) state and Ns increases as the state differs from it. When all considered modes have the same amplitude, then Ns becomes the number of considered modes. As shown in FIG. 4, an increase in I_{sx} is observed when the plasma is in the QSH state (Ns < 2.5), and it decreases during the MH state. The same trend is observed in the τ_p variation. It is also shown that this improvement corresponds to an increase in the amplitude of the first dominant mode, $b_{(1,6)}$, and a decrease in the amplitude of the second mode, $b_{(1,\mathrm{sec})}$. The dominant mode in this experiment is n = 6. As described below, confinement improvement depends on $b_{(1,\mathrm{sec})}$ as well as on $b_{(1,6)}$. We separated the contributions of $b_{(1,6)}$ and $b_{(1,\mathrm{sec})}$ in order to allow us to obtain insight into the real cause of the

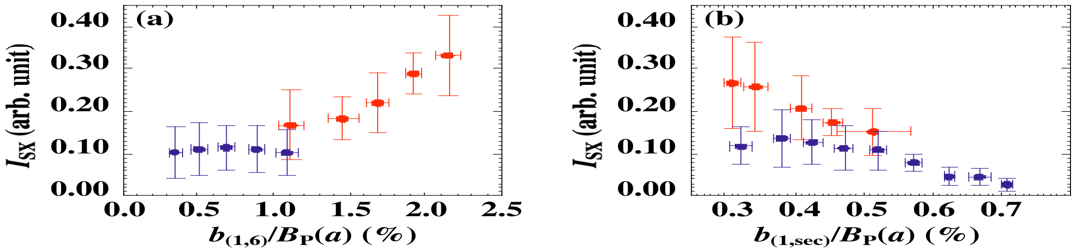

FIG. 5. Contributions of dominant mode (a) and secondary mode (b) to I_{sx}

confinement improvement. Figures 5(a) and 5(b) shows the trend of I_{sx} versus $b_{(1,6)}$ and that of I_{sx} versus $b_{(1,sec)}$, respectively. The red symbol shows I_{sx} in the QSH state and the blue symbol shows I_{sx} in the MH state. The large amplitude of $b_{(1,6)}$ does not degrade confinement improvement, since I_{sx} increases with an increase in $b_{(1,6)}$. The growth of $b_{(1,6)}$ in the QSH state helps extend the regions with well-conserved flux surfaces, which locally increases the particle confinement. Figure 5(b) also shows that the reduction of $b_{(1,sec)}$ in the QSH state is also important for confinement improvement, and $b_{(1,sec)}$ plays a crucial role. This is caused by the reduction of the magnetic stochasticity outside the island. These results indicate that the plasma performance (probably the confinement) can be improved when the state is close to the SH state.

4.2. Control of Quasi-Single Helicity State

Thus far, the transition to QSH has occurred spontaneously and the QSH state could not be sustained for a long period. We found a way to obtain the QSH state in a full control manner and sustain it for a long period almost till the end of discharge [11]. After maintaining the reversal toroidal field at the plasma surface (B_{ta}) in shallow reversal for a certain period, a small positive B_{ta} pulse (2.5 mT and 2 ms width) is applied as shown in FIG. 6(a). Being triggered by this B_{ta} pulse, the transition to the QSH state occurs. The probability of QSH transition is almost 100 %. This QSH is sustained for a long period till near the end of discharge by applying an ordinary reversal of B_{ta} after the QSH transition, which recovers the stable condition again. FIG. 6(b) shows the transition to the QSH state obtained using this method. A single helical mode (m = 1 and n = 6), namely, the innermost core resonant mode, rapidly grows just after applying the positive B_{ta} pulse. Ns suddenly becomes lower than 2 and is maintained at this level. The linear stability calculation of the ideal mode shows that the m/n = 1/6 mode becomes unstable when B_{ta} is positive even if it is very small. A reasonable agreement between the experiment and 3-D simulation is obtained, where the n = 6 mode becomes dominant after the relaxation.

5. Magnetized Plasma Flow Injection

MPF injection has been carried out to control the plasma density, to inject magnetic helicity and to assist the start-up of the discharge [7, 8]. The MPF is generated by a magnetized

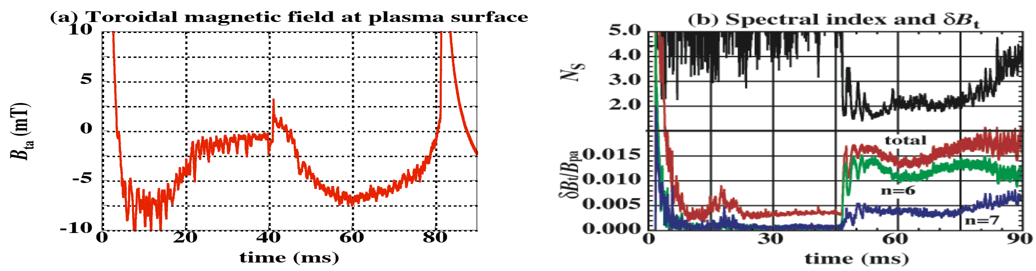

FIG. 6. Toroidal magnetic field at plasma surface (a). Spectral index and m=1 mode amplitudes (b).

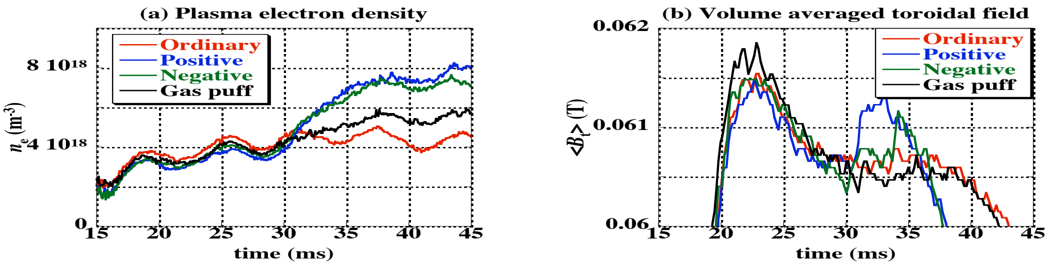

FIG. 7. Line averaged electron density (a) and volume averaged toroidal flux (b).

coaxial plasma gun (MCPG) installed on the mid-plane of TPE-RX. The capacitance of a formation capacitor bank of the MCPG is 367 mF, and the maximum charging voltage is 800 V. The maximum bias flux generated by a set of bias field coils is 9 mWb. The flow velocity of the MPF is 17 km/s, and discharge duration is 3-5 ms. The total helicity content generated by the MCPG is estimated from the gun bias voltage and the bias flux, and the maximum helicity is approximately 2.5 mWb^2 in the present experiment. The polarity of the magnetic helicity can be selected by changing the direction of the bias field.

The MPF is injected into the RFP plasma at t = 30 ms in order to demonstrate the helicity injection and the plasma density control. In this experiment, I_p is 230 kA at the flat-top phase and n_e is 5 x 10^{18} m^{-3} (red line in FIG. 7(a)). n_e increases by a factor of two after the MPF injection (blue and green lines in FIG. 7(a)) and the increase rate is approximately twice as high as that in the case of only the gas puffing operation of the MCPG without MPF (black line in FIG. 7(a)). Note that, the impurity line intensity of MoII and FeI did not change during the injection. This indicates that particle influx is mainly from the D_2 driving gas of the MCPG. We also observed an increase in the volume-averaged toroidal flux ($<B_t>$) as shown in FIG. 7(b). The enhancement of $<B_t>$ after the MPF injection depends on the polarity of the magnetic helicity generated by the MCPG, and is observed only in the case of positive (same sign with the target plasma) magnetic helicity injection, which indicates that the MPF injection directly drives the poloidal current. In the positive helicity case (blue line in FIG. 7(b)), $<B_t>$ increases by approximately 2.4 %. There is no significant change in $<B_t>$ for the negative helicity case (green line) and the case of only gas-puffing operation of the MCPG without MPF (black line) compared with the ordinary shot case (red line). Investigation on the mechanism of the enhancement of the toroidal flux and of the poloidal current drive is still underway.

Start-up operation with prefilling D_2 gas and two preionization filaments are used in the ordinary shot. Instead of these, the MPF is initially injected into a vacuum vessel 2 ms before plasma current is applied. Figure 8 shows n_e both for the ordinary shot (red line) and the MPF start-up assist shot (blue line). In the ordinary shot, the number of particles necessary for the current start-up and for the RFP formation is excessive for the flat-top phase; therefore, the excess particles are pumped out and are absorbed by the vacuum vessel. In the MPF start-up assist shot, the pump-out phenomenon is suppressed, as shown in FIG. 8(a). It is predicted that MPF start-up lowered the neutral particle inflow caused by the recycling process in the start-up phase. The toroidal one-turn loop voltage calculated from I_p and toroidal plasma resistance (R_p) is shown in FIG. 8(b). Toroidal one-turn loop voltage during the flat-top phase is reduced by the MPF start-up assist operation.

6. Summary

Recent progresses in confinement improvement using PPCD and the QSH state in TPE-RX has been presented. The power supply for the PPCD is upgraded to 6-stage pulses of a eversed

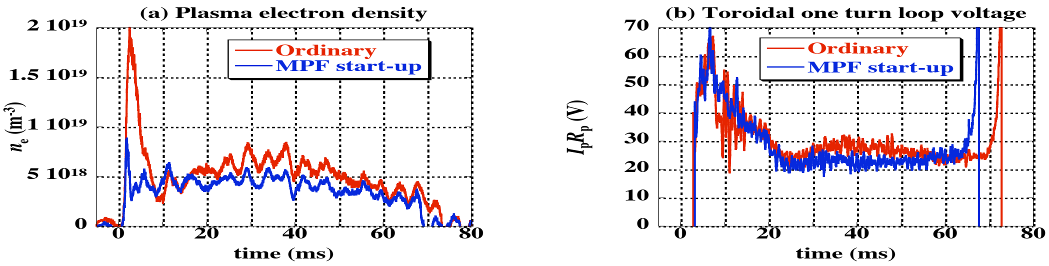

FIG. 8. Line averaged plasma electron density (a) and toroidal one turn loop voltage (b).

toroidal field. The T_e measured by Thomson scattering is 1.5 times higher than that of an ordinary shot. β_p is 15- 20 % and is 3 times higher than that of the ordinary shot. The ratio of the total number of particles to the intensity of D_α emission, which corresponds to the particle confinement time, significantly increases in PPCD, up to ten times longer than in the ordinary shot. Steady high density, which is three times higher than that of the ordinary shot, is achieved by ice pellet injection into the PPCD. Improved confinement properties in PPCD are not degraded by the pellet injection. Improved confinement is also observed during the QSH state that spontaneously occurs. Full control production of the QSH state is achieved. MPF injection can enhance the toroidal flux and fuels the plasma. The pump-out at the start-up phase is reduced. The one-turn voltage at the flat-top phase is also reduced by the MPF start-up assist.

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