REVERSED FIELD PINCH EXPERIMENT ON A NEW LARGE MACHINE, TPE-RX

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ABSTRACT

Reversed field pinch (RFP) experiment on a new large machine, TPE-RX has been started from March 1998. Major and minor radii of TPE-RX are 1.7175m and 0.45m, and the maximum designed plasma current (I_p) and discharge duration are 1MA and 100ms, respectively. TPE-RX is being operated in the medium I_p region (I_p < 500kA) with discharge duration about 80ms and RFP discharges with good reproducibility are routinely obtained, where the precise compensation of error field at poloidal gap of thick shell is indispensable. In a series of initial phase of experiment, following results are obtained. Non-inductive part of toroidal loop voltage (R_pI_p) as low as 12 V is obtained at low I_p (~150kA), but it increases with I_p and becomes 22V at I_p ~450kA. However, it is shown that R_pI_p is gradually decreasing as the discharge cleaning has been continued. Further decrease of R_pI_p will be expected under the improved wall condition. In almost of all discharges, especially with large I_p (>250kA) the wall and phase locking of the MHD fluctuations is observed. However, several discharges without this mode locking are found in low Ip and low filling pressure cases. Measurements of electron density ($<n_e>$) by CO_2 laser interferometer, electron temperature (T_e) by soft x-ray pulse height analysis and ion temperature (T_i) by CV Doppler broadening have been started. Measured values are $<n_e>\sim 5\times10^{18}m^{-3}$, T_e ~1000-1200eV and T_i ~ 130±50eV for the discharge with I_p~ 270kA and reversal/pinch parameters ~ -0.1/1.6, although it is possible that this high T_e may correspond to high energy part and low T_i may correspond to the value near the edge since the radiation profile of CV line is very hollow. An interesting dependence of plasma rotation on I_p is found in the Doppler shift measurement of CV line.

1. INTRODUCTION

TPE-RX is a new large reversed field pinch (RFP) machine[1,2] whose major and minor radii are 1.7175m and 0.45m, maximum flux swing of iron core is ±2VS, designed maximum plasma current (I_p) is up to 1 MA and designed discharge duration is 100 ms, respectively. TPE-RX is the successor of former TPE-1RM20 machine and has a comparable size with RFX[3] and MST[4] which are large RFP machines currently operated in the world.

The main purpose of TPE-RX is to demonstrate the possibility that the RFP will become a simple and efficient fusion reactor by showing the improved confinement property through the simultaneous attainment of low toroidal loop voltage (V_{loop} <10V) and large poloidal beta (β_p>0.1) values. Then, the energy confinement time (τ_E) longer than 5ms will be obtained. If the improved confinement in the high pinch parameter region[5] is realized, β_p~ 20% will be obtained and the τ_E exceeding 10 ms can be expected.

The construction of TPE-RX was initiated in the spring of 1997 and the first RFP plasma was obtained at the beginning of March in 1998. Although the discharge cleaning is still under way, the plasma experiment on TPE-RX has been started[6].

In this report, initial experimental results of TPE-RX will be described. The experiment has been conducted in the medium I_p region (< 500kA) mainly because of the capability of power supply, which is almost the same with that used in TPE-1RM20[1].

2. MACHINE CHARACTERISTICS OF TPE-RX

One of the most important characteristics in TPE-RX machine design is its equilibrium system for canceling the poloidal shell gap error field and for controlling the plasma horizontal displacement (Shafranov shift) under the existence of a thick conducting shell[7]. Almost the same technique as used in TPE-1RM20[8] is introduced in TPE-RX with several minor modifications. The equilibrium system of TPE-RX consists of doubly layered thin (0.5mm thickness) copper shells, thick aluminum (50mm thickness) single shell, primary vertical field, control vertical field, saddle coil field, quasi-DC vertical field and pulsed vertical field.

The thick shell provides the main part of the vertical field for plasma equilibrium, stabilizes slowly growing MHD modes and shields external error fields caused by various sources. The thick shell has the proximity of b/a=1.16, where a is the plasma radius and b is the inner radius of the shell. Inside the thick shell, the thin shells are closely attached on a vacuum vessel for stabilizing the fast growing mode with good shell proximity (b/a=1.08). Poloidal shell gaps of two thin shells and thick shell are over lapping each other for compensating the poloidal gap error field caused by the fast variation of plasma.

The primary external vertical field, which is produced by the hybrid poloidal coil (Ohmic coil), provides the first order of compensation of the poloidal shell gap error field. The current flowing in the hybrid poloidal coil, hence the produced vertical field, is almost proportional to the plasma current because of the strong coupling between them by the iron core. The secondary pre-programmed auxiliary vertical field (control vertical field), which is produced with independent vertical field coils, is used for the further accurate compensation of the gap error field which may be dependent on the individual discharge condition. The saddle coils which are wound just outside the poloidal shell gap provides the real time compensation of the gap error field by the feedback control of coil current[9].

In TPE-RX the plasma equilibrium position can be actively controlled by the quasi-DC vertical field, which is produced by the same control vertical field coil and is canceled by the pulsed vertical field during initial breakdown phase. The pulsed vertical field coils are wound on the inner surface of the thick shell (space between the thin shell and thick shell) with return windings on the outer surface of the thick shell. To reduce the necessary strength of quasi-DC vertical field for centering the plasma in the vacuum vessel, the center of the vacuum vessel is shifted by 17.5mm in the outer direction of the torus with respect to the center of the thick shell.

Although preliminary experiments with the quasi-DC vertical field have been made, where the quasi-DC vertical field shows relatively small effect compared with the results in TPE-1RM20, all experimental results reported here were obtained without using the quasi-DC vertical field because the power supply for the quasi-DC vertical field and pulsed vertical field do not have sufficient power.

The vacuum vessel of TPE-RX is composed of equally distributed sixteen bellows sections (2mm thickness) and sixteen thick plate sections (6mm thickness)[10]. They are welded into one piece. All ports are attached on the thick plate sections. The material of them is stainless steel (SUS316L). Two hundred and forty-four molybdenum limiters with mushroom shape (98.5mmϕ) are attached in thick plate sections for protecting the vacuum vessel. Limiter surface protrudes by 5mm with respect to the bellows inner surface. Thirty-four of them are attached at the shell gap section, where the strongest plasma-wall interaction may be anticipated and fourteen limiters are attached in each thick plate section almost equally distributed in the poloidal direction.

3. EXPERIMENTAL RESULTS OF TPE-RX

3-1. Discharge characteristics and loop voltage

From the start of operation, more than six thousands of RFP discharges have been made[11] and the non-inductive part of the toroidal loop voltage, R_pI_p shows gradual decrease as the discharges have been continued (see Fig.1). As shown in Fig.1, this decreasing trend still continues, which indicates that the discharge cleaning has not reached at saturated level and further improvement of wall condition will be expected. In the present stage, the R_pI_p as low as 12V is obtained in low I_p case (~150kA), which is slightly higher than the expected value (~10V).

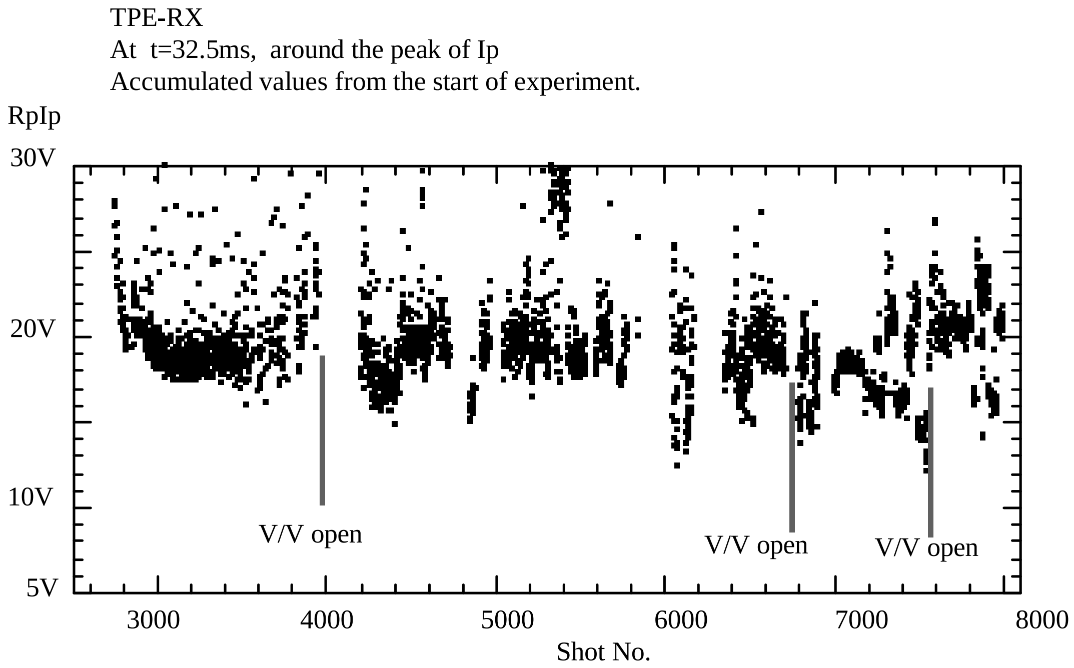

Fig.1 Variation of non-inductive part of toroidal voltage as a function of shot number.

Figure 2 shows wave forms of I_p, toroidal magnetic field, reversal parameter F, pinch parameter Θ, etc. in a typical RFP discharge with I_p~270kA and F/Θ ~-0.1/1.6. F and Θ are defined as $F=B_{tw}/<B_t>$ and $\Theta = B_{pw}/<B_t>$, where B_{tw} and B_{pw} are the toroidal field and poloidal field on the plasma surface, respectively, and $<B_t>$ is the volume averaged toroidal field in the plasma. In this typical discharge the value of R_pI_p = 15-17V is obtained.

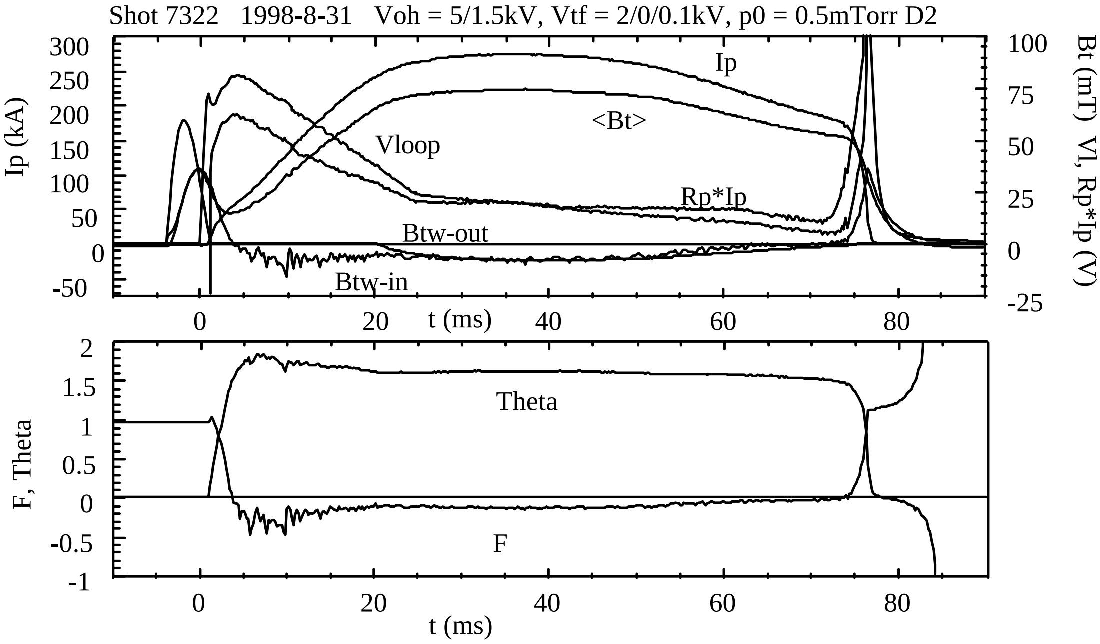

Fig.2 Wave forms of the plasma current, I_p, averaged toroidal field, $<B_t>$, toroidal fields on the plasma, $B_{tw\text{-}in}$, and outside the wall, $B_{tw\text{-}out}$, loop voltage, V_{loop}, non-inductive part of V_{loop}, R_pI_p, F and Θ

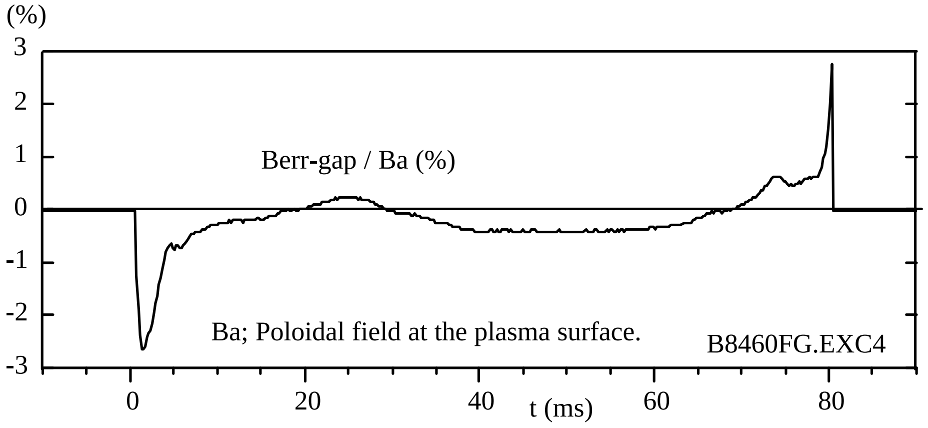

Fig.3 Residual error field at the poloidal thick shell gap after compensation by the saddle coil field.

One problem in the behavior of R_pI_p at the present stage is that the R_pI_p increases with I_p in offset linear manner, $R_pI_p \sim 0.034*I_p+7$, where I_p is in kA. The R_pI_p becomes 22V at $I_p \sim 450$kA. The cause of this trend may be the increasing plasma wall interaction at high I_p, which may be improved by the further wall conditioning and precise plasma equilibrium control with a new power supply which will be installed in near future.

Figure 3 shows an example of the compensation of the shell gap error field by the saddle coil field which is controlled to minimize the vertical flux through the shell gap with feedback control[9]. The averaged error vertical field is reduced within 0.4% of the poloidal magnetic field after the setting up. In the experiment where an additional shell gap error field is applied, it is shown that the plasma performance such as the discharge duration and value of R_pI_p, is affected when the error field becomes 3 - 5% of the poloidal field. It is found that the compensation without the control vertical field is sufficient for the present medium I_p discharges.

Recently the error field with horizontal and/or higher poloidal mode components is found by the detail measurement of magnetic field at the shell gap. Cause of it and its effect on the plasma are now being investigated.

3-2. Phase and wall Locking of magnetic fluctuation

The mode locking of magnetic fluctuation in phase and to the wall of the vacuum vessel is observed almost of all discharges in TPE-RX[11]. The toroidally localized magnetic fluctuation stays at a certain position of the torus, which locally enhances the plasma-wall interaction and may damage the vacuum vessel. This mode locking phenomena is quite similar to that observed in RFX[12]. However, the amplitude of the radial component of wall locked mode is about 2% of the poloidal magnetic field and is smaller than that in RFX.

The positions where the wall locking takes place are scattered almost randomly around the torus with some concentration (20-25%) at the poloidal gap of the thick shell. Local temperature rise of the vacuum vessel in each shot, which is monitored by thermocouples, shows good correlation with the wall locked mode. The peak temperature rise is observed at the almost same place of the wall locking.

In several low I_p cases, discharges without mode locking are obtained in TPE-RX. Although the mechanism why they appear has not been clear, it is found that the operation with low filling gas pressure is a key point[11]. Comparison between the cases with and without mode locking and between the results of TPE-RX and RFX will contribute to understanding and solving the problem of wall locking.

3-3. Measurement of electron density and temperature

The plasma electron density ($<n_e>$) is measured at a central vertical chord by a two-color (CO_2

and HeNe) laser interferometer. The time variation of $<n_e>$ is shown in Fig.4 for the typical discharge with I_p~270kA, where the initial filling pressure of deuterium is 0.5mTorr. The initial peak of $<n_e>$ corresponds to only 40% ionization.

Following the initial peak, the density is pumped out as observed in many RFP experiments, but it is rather slow in TPE-RX (time scale with ~10-15ms) compared with others. After the pump out, the density gradually increases from t~15ms to 25ms, stays at quasi-stationary value, ~ $5\times10^{18}m^{-3}$ from t~25ms to 50ms and then gradually decreases toward the end of discharge for t>50ms. The I_p dependence of $<n_e>$ at this stationary phase is shown in Fig.5. The value of $<n_e>$ increases with I_p and becomes ~ $7.8\times10^{18}m^{-3}$ at I_p~370kA. However, the value of so-called I/N (the ratio of plasma current to line electron density) decreases with I_p, I/N ~ 1.3×10^{-13}A/m at I_p ~ 170kA and I/N ~ 7.5×10^{-14}A/m at I_p ~ 370kA.

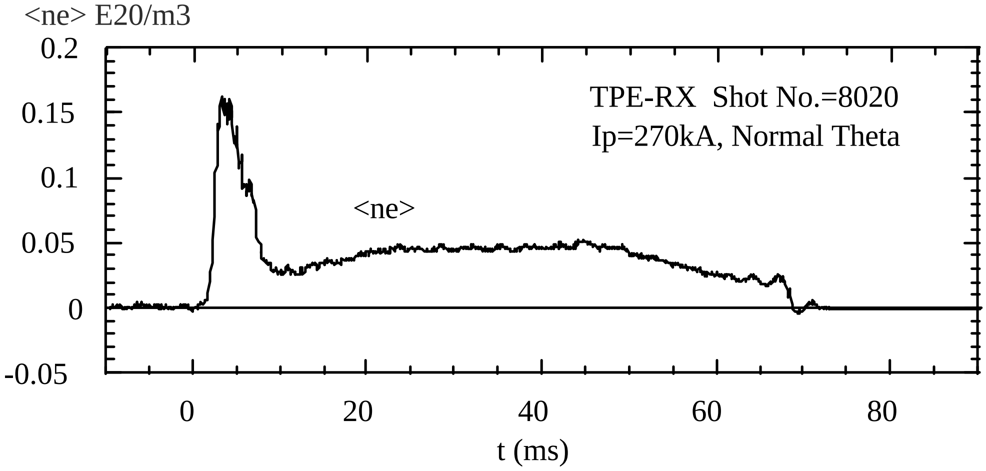

Fig. 4 Time variation of the chord averaged electron density (central vertical chord) in the typical discharge case (I_p ~ 270kA, F/Θ ~ -0.1/1.6, P_0=0.5mTorr). Measured by two-color (CO_2 and HeNe) interferometer.

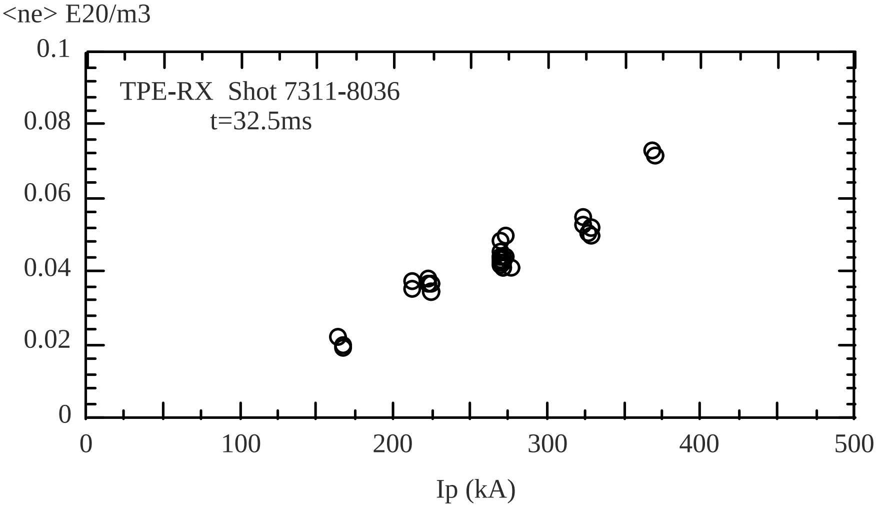

Fig. 5 Dependence of chord averaged electron density (central chord) on plasma current. I_p ~ 170-370kA, F/Θ ~ -0.1/1.6, P_0=0.5-0.7mTorr

In the above experiment the density is not actively controlled and is decided by the recycling at the wall of vacuum chamber. Preliminary experiment of the density control experiment has been made and it is shown that the density can be increased and becomes almost doubled, from ~$5\times10^{18}m^{-3}$ to ~

$1\mathrm{x}10^{19}\mathrm{m}^{-3}$ by a medium gas puffing where the global plasma parameters, such as I_p, V_{loop}, discharge duration, etc., show small variations. However, the density decays within about 10ms after the gas puffing was closed.

It should be noted that the vibration of the interferometer, which is caused by the high speed mechanical contact switch used in the ohmic heating circuit, gives some oscillating variation in $<n_e>$ signal. The effect of this variation is compensated as small as possible but small effect still remains, especially near the end of discharge. It should not be taken as actual plasma variation.

The electron temperature (T_e) is measured by the soft x-ray (sx) pulse height analysis with SiLi detector. The obtained value is about ~ 1000 - 1200 eV for t= 20-40ms in the typical discharge. In the early discharge phase for t=10-20ms the temperature is slightly low, ~870eV. Clear I_p dependence has not been observed. It is well-known that the sx measurement is rather sensitive to the high energy tail of the electron velocity distribution. Moreover, the L-line emission of the molybdenum which is used as the limiter material is strong and masks the sx spectrum at the energy range from 2.3kev to 2.7keV. Therefore, the detail analysis of the sx spectrum becomes difficult and it is not clear at the present stage whether the measured value corresponds to the bulk electron temperature.

3-4. Measurements by spectroscopy

Plasma rotation velocity and ion temperature are measured by the Doppler shift and broadening of the CV line emission (227.1nm)[13]. The measured CV ion temperature is about 130 ± 50eV for the typical discharge with I_p~270kA. The radiation profiles of CV are also measured by another multi-spectrometer system. The measured profile of CV radiation is very hollow and the normalized radius of the maximum radiation is about ~0.9. This means that the CV temperature may not correspond to the core ion temperature. It is also indicated that the electron temperature near the edge is not low, may be in the range around a hundred eV.

The plasma toroidal rotation velocity estimated by the shift of CV line shows peculiar behavior. Its direction and magnitude vary as the I_p increases; opposite direction to I_p at low I_p (~ -5±4km/s at I_p~200kA), around zero at I_p~270kA and the same direction with I_p at high I_p (~ 5±4km/s at I_p~370kA). Possibly this variation is related to the change of the radial electric field. The variation of the radial electric field consistent with this TPE-RX result is reported in the plasma potential measurement on RFX[14]. In the case without the mode locking at low I_p (I_p~ 200kA), the rotation speed increases up to ~ -10±4km/s.

4. DISCUSSION

It is commonly observed in many RFPs that the non-inductive part of toroidal loop voltage is higher than the value estimated form the electron temperature even if a large value of effective ion charge, Z_{eff} is assumed in the calculation of the resistivity. The anomaly part in the loop voltage is comparable or larger than the resistive part in many cases, for example, anomaly part is about 1/2 of the total loop voltage in TPE-1RM20[8].

For the typical discharge in TPE-RX (I_p ~ 270kA, R_pI_p ~ 15V, F/Θ ~ -0.1/1.6), the central value of conductive electron temperature (T_{ec}) is estimated by assuming the polynomial function model (the internal inductance ~1.3 and helical form factor ~7.5) and parabolic temperature profile. If the anomaly part is not taken into account T_{ec} would be ~150eV when Z_{eff}=1 is assumed, ~430eV for Z_{eff}=5 and ~700eV for Z_{eff}=10. These large Z_{eff} values may not be impossible since the molybdenum limiters are used.

However, if the value obtained by sx measurement is assumed to be the bulk central electron temperature, unrealistically large value of Z_{eff} about 20 has to be introduced to explain the present value of R_pI_p. Therefore, the anomaly part should have a large portion in the loop voltage. When the anomaly part is assumed to be one half of the loop voltage, then, the value of T_{ec} would be ~1100eV when Z_{eff}=10 is assumed. This value of T_{ec} is in the same magnitude of the measured value by sx.

In the previous experiments on TPE-1RM20[15] and many other RFPs, β_p~ 0.1 has been obtained in the usual discharge conditions with Θ ~ 1.6. If this β_p value is still held in the present experiment on TPE-RX, the T_{ec} will be ~700eV for the typical discharge if the $T_i = T_e$ and parabolic profiles are assumed. If $T_i = 0.6T_e$ is used, which is the case in TPE-1RM20 experiments, T_{ec} will be ~900eV. These values are not so much different from the value obtained by the sx measurement.

The poloidal beta for the electron pressure is about 7% if the value of T_e obtained by the sx measurement is used as the central electron temperature and the parabolic pressure profile is assumed. Therefore, the total poloidal beta about 10% may not be unrealistic. If we use R_pI_p ~15V and assume β_p~0.1, the energy confinement time of the present experiment on TPE-RX will be ~1.4ms, although the possibility still remains that this high T_e value may not correspond to the bulk electron.

5. SUMMARY

A new large RFP machine, TPE-RX was constructed and is being operated successfully from the March of 1998. The RFP discharges in medium I_p region (<500kA) have been obtained with reasonable duration time (~80ms) routinely. The non-inductive part of toroidal loop voltage, R_pI_p as low as 12V has been obtained for the low I_p case (~150kA) but it increases with I_p and becomes 22V at I_p~450kA. The R_pI_p value has shown the gradually decreasing trend as the discharge cleaning has been continued. It is expected that the further decrease of R_pI_p will be realized when the wall condition of the vacuum vessel is improved.

It is demonstrated that the error field at the poloidal gap of thick shell is correctly compensated, within 0.4% of the poloidal field. This value is well bellow the necessary criteria (~3-5%).

The mode and wall locking of the magnetic fluctuation has been observed in almost of all discharges, which is well correlated with the local temperature rise of the vacuum vessel. However, the several discharges without the mode locking are found in particular conditions with low I_p and low filling gas pressure.

The electron density, $<n_e>$, temperature, T_e and ion temperature, T_i are measured by the CO_2 laser interferometer, soft x-ray pulse height analysis and CV Doppler broadening, respectively. For the typical discharge case with I_p~270kA and F/Θ~ -0.1/1.6, $<n_e>$~ $5\times10^{18}m^{-3}$, T_e~1000-1200eV and T_i ~130±50eV are obtained. However, it is not clear whether these temperature values are corresponding to the core plasma, namely, it is possible that this high electron temperature may correspond to the high energy part and this low ion temperature may correspond to the value near edge since the radiation profile of CV line is very hollow.

By using above values, the poloidal beta for the electron pressure is estimated to be about 7% if the parabolic pressure profile is assumed. Therefore, the total toroidal beta about 10% may not be unrealistic. When we use R_pI_p ~15V and β_p~0.1, the energy confinement time will be ~1.4ms, although several uncertainties and assumptions are included in the estimation.

The plasma toroidal rotation is measured by the Doppler shift of CV line. It is shown that the direction of rotation varies with I_p ; in the same direction with I_p for large I_p (~370kA) and opposite direction for small I_p (~200kA).

It should be noted that the TPE-RX is still under construction since the power supply presently used is the old one which is almost the same with that used former RFP machine TPE-1RM20 whose scale was almost 1/3 of TPE-RX. Therefore, the present operation of TPE-RX is limited in many aspects. It is planned that the power supply will be powered up within following several years.

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