CONFINEMENT CHARACTERISTICS OF THE TPE REVERSED FIELD PINCH PLASMAS AND EFFECTS OF THE BOUNDARY CONFIGURATION

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Abstract

Confinement characteristics of the TPE series reversed field pinch (RFP) machines, TPE-1RM15, TPE-1RM20 and TPE-1RM20mod, at Electrotechnical Laboratory (ETL) are summarized. Especially data are synthesized in respect to the effects of the different boundary structures of the machines, where shell proximity and overlapped poloidal shell gaps by the multi-layered shell structure are featured. Comparison of the experimental results is shown in terms of the characteristics of magnetic fluctuations, global confinement properties in general, operation capability of the improved confinement in high pinch parameter (Θ) discharges and locked mode events. Linear growth rate of the unstable modes as a function of the shell distance is numerically simulated. Understandings of RFP plasma physics have also made progress by the most recent intensive experiments on correlation studies between fast electrons and dynamo activities and measurement of the plasma and mode rotation. TPE-1RM20mod was shutdown in December 1996 and new RFP experiment has started in TPE-RX from March 1998. The new machine also succeeds the concept of the shell configuration of the TPE-1RM20.

1. INTRODUCTION

Conductive shell for RFP plasma is generally known to be indispensable to maintain MHD plasma stability as predicted by theories. There have been many experiments in RFPs to study on this issue by replacing conductive shells with resistive or thin shells which have the penetration time for the external vertical field comparable to or shorter than the plasma pulse duration time. The results showed distinctive deterioration of the global confinement properties with typical resistive shell modes seen in magnetic field fluctuations. These results made clear that we need further investigations to have a practical solution for the configuration of the conductive shell together with the studies of a scaling tendency of the MHD instabilities to be suppressed by the shell when the machine is to be graded up for a future reactor relevant plasma. This paper addresses this issue by comparing three RFP machines of different shell configurations. They are all conductive shell machines but the shell proximity and the number of layers of the shell are different. The paper also summarizes other physics experiments conducted in TPE-1RM20 and TPE-1RM20mod.

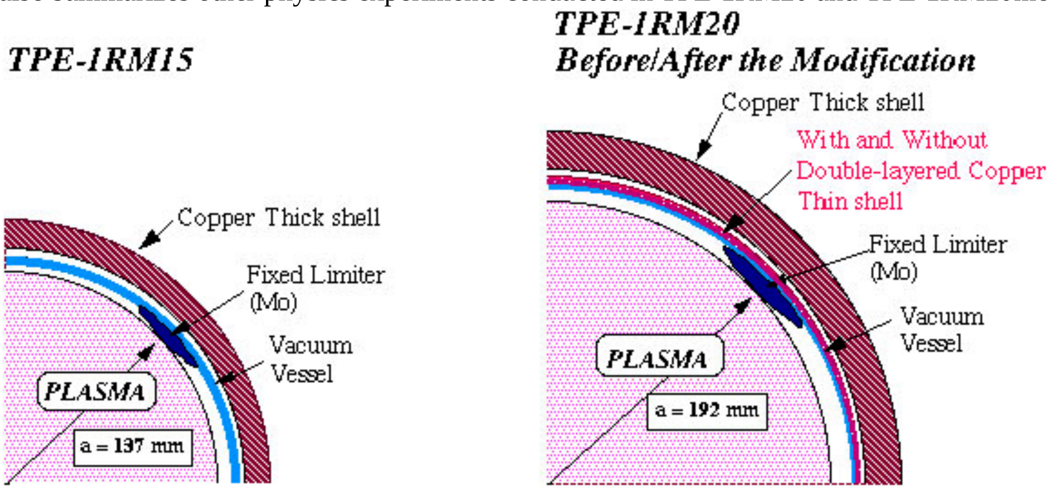

FIG. 1. Cross sectional views of the shell system and vacuum vessel of TPE-1RM15 and TPE-1RM20. TPE-1RM20mod is the one without the inner thin shell from TPE-1RM20.

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We had been studying RFP confinement characteristics at ETL with medium sized machines from 1984 to 1996; TPE-1RM15 (R/a = 0.70 / 0.137 m, b/a = 1.18), TPE-1RM20 (R/a = 0.75 / 0.192 m, b/a = 1.08) [1] and TPE-1RM20mod (R/a = 0.75 / 0.192 m, b/a = 1.12), where R, a and b are major and minor radii of the plasma and the minor radius of the inner most conducting shell, respectively. Note that the shell proximity is usually expressed by b/a. Figure 1 shows the cross sections of TPE-1RM15 and TPE-1RM20. The double-layered thin shell was removed from TPE-1RM20 especially to study the effect of the shell proximity [2], This modified configuration is called TPE-1RM20mod in this paper.

2. MAGNETIC FLUCTUATION AMPLITUDES

Root mean square (r.m.s.) of the magnetic fluctuation amplitude is compared for I_p = 130 kA and Θ = 1.5 for three devices. Magnetic fluctuation was measured by the same insertable magnetic probe with three orthogonal components. It was placed at 20 mm away from the plasma surface through a vertical port hole of each machine. Figure 2 shows the r.m.s. of both tangential (= square-root of (B_t^2 + B_p^2)) and normal (radial) components normalized by the poloidal magnetic field at $r = a$. It shows that relative tangential magnetic field fluctuation amplitude increases with b/a from 1.9 ± 0.2% at b/a = 1.08 to 3.5 ± 0.6% at b/a = 1.18.

This result is qualitatively understood by the numerical simulation of the linear growth rate, γ, by a custom made MHD code with finite plasma pressure. Figure 3 shows the simulated growth rate normalized by the inverse of the resistive time for four different toroidal modes, plotted for Θ = 1.7 as a function of b/a. It shows that the near-axis resonant modes (n = 7-9) increases with b/a where n = 7 dominates others when $b/a \geq 1.12$. A resistive shell mode, internally non-resonant ideal mode in this case, starts to grow at $b/a \geq 1.15$. Qualitative tendency of the square root of the sum of γ^2 as a function of b/a agrees fairly well with relative r.m.s. of the magnetic field fluctuation amplitude (Fig. 2).

3. GLOBAL CONFINEMENT PROPERTIES

Global confinement properties are compared for three shell configurations. Since a direct comparison of the absolute values is not straightforward because of the dependencies on size and constraints for the selection of the plasma parameters other than that on the shell configuration, we show here a relative change of the energy confinement time, τ_E, in respect to the standard operating conditions for each device. Among the experimental scans, Θ-scan is of particular interest to compare because of the recently found improved confinement in high Θ discharges of TPE-1RM20 [3].

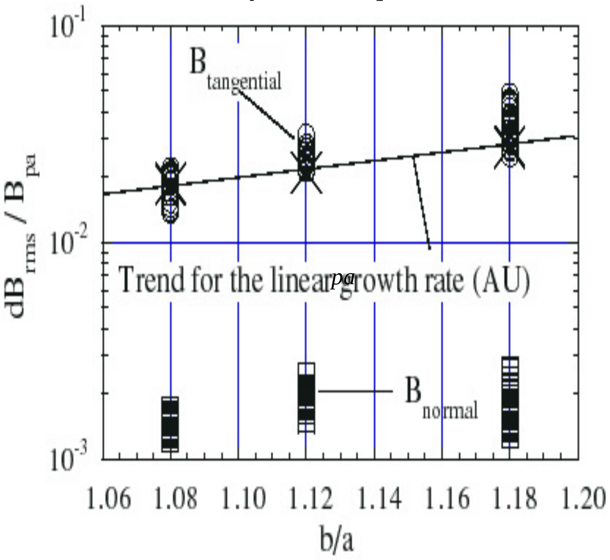

FIG. 2. R.m.s. of the magnetic field fluctuation amplitude normalized by B_{pa}.

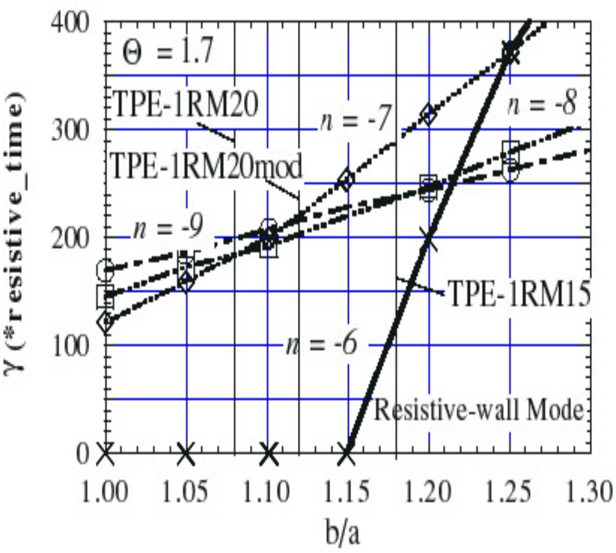

FIG. 3. Numerically simulated linear growth rate as a function of b/a.

Figure 4 shows shot-averaged τ_E versus Θ at I_p = 130 kA, where τ_E is normalized by the average τ_E in the normal Θ value (~1.5). Note that it was difficult to sustain the discharge in $\Theta > 1.8$ in TPE-1RM15 due to the increase of loop voltage. When $\Theta < 1.8$, normalized τ_E stays around unity and does not differ very much among the devices. Difference appears at $\Theta \sim 2$ in between TPE-1RM20 and TPE-1RM20mod, where the former shows a factor of two improvement while the latter doesn't. Poloidal beta, β_p, on the other hand, similarly increases with Θ in these two devices. Thus the difference in the global confinement appears in the input power term rather than the stored energy. The absolute values of τ_E at $\Theta \sim 1.5$ for the three cases are; 0.1 ± 0.03 ms, 0.2 ± 0.1 ms and 0.4 ± 0.2 ms for the data set used in this comparison. The difference in TPE-1RM20 and TPE-1RM20mod is small within the standard deviation, while the difference between TPE-1RM15 and other two is likely to be affected by the size dependence of τ_E. Note that τ_E scales with a^2 when the thermal diffusion coefficient is the same. Relative change of τ_E in Fig. 4 seems to indicate that the shell proximity of the relatively narrow range in concern here improves stability especially for high Θ plasma, although other alternative interpretations, such as a difference in an effective plasma-shell distance due to somewhat different wall conditions, for example, might also be possible.

4. EFFECT OF THE ERROR FIELDS

Another important aspect of the shell configuration in RFP is its shielding effect for the external error magnetic field B_{err}. We compared plasma response against the externally applied vertical error field at the poloidal shell gap of the outermost shell in TPE-1RM20 and TPE-1RM20mod [4]. Figure 5 shows a typical example of the temporal evolution of the non-inductive loop voltage, R_pI_p, with and without an external error field at the poloidal shell gap of the thick shell. When B_{err} larger than 10 % of the poloidal magnetic field at $r = a$ is applied, the R_pI_p, starts to increase at t ~ 5 ms and pulse duration time is shortened to 8.0 or 8.5 ms while it is 12 ms without B_{err}. It is seen that R_pI_p increases more rapidly without thin shell in TPE-1RM20mod than with thin shell in TPE-1RM20, showing a shielding effect of the inner thin shell as expected.

5. OTHER PHYSICS RESULTS IN TPE-1RM20 and TPE-1RM20mod

In TPE-1RM20, particle confinement time of injected Boron, τ_B, was measured by the laser ablation technique and results were compared with numerical simulations [5]. It was shown that τ_B increased with Θ supporting the increase of τ_E in the improved confinement regime. For Θ and I_p scans, τ_B increased with τ_E as $\tau_B = (3.0 \pm 0.4)\ \tau_E$. Temporal evolution and spatial profiles of the BIV line agreed reasonably well with the numerical simulation.

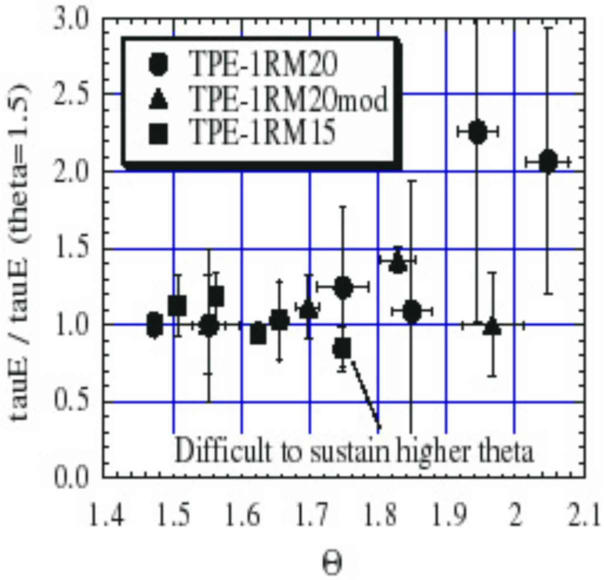

FIG. 4. Comparison of the normalized τ with Θ three shell configurations.

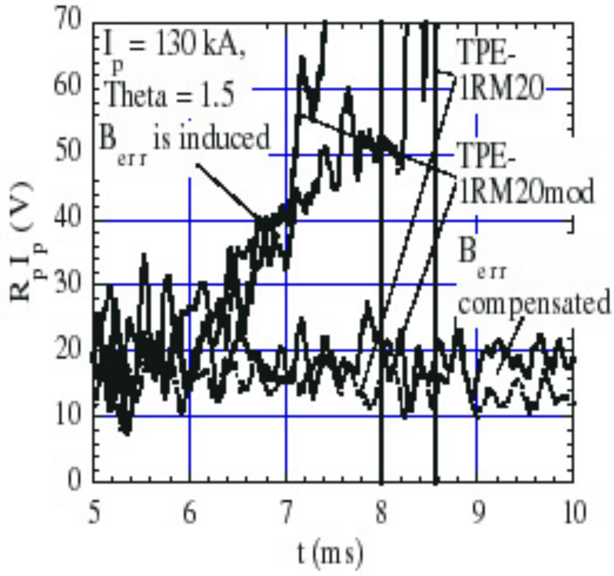

FIG. 5. Behaviour of the non-inductive loop for voltage for induced error field.

Correlation studies between fast electron current, j_F, and other physics quantities were conducted in the edge plasma of TPE-1RM20mod. It was found that j_F had a statistically significant correlation with ***v***x***b*** dynamo electric field [6]. It was also analyzed that fluctuations in the fast electron current had a relatively large correlation with magnetic mode rotation, which might be reducing the apparent coherence between j_F and ***v***x***b*** dynamo.

Measurement of the poloidal plasma rotation was conducted in TPE-1RM20mod [7] from the Doppler shift of the BIV line at r/a = 0.6. The result showed the poloidal rotation of about 5 km/s in the electron diamagnetic drift direction. Though the toroidal rotation was not measured, E_r was estimated to be about +2 kV/m if the toroidal mode rotation speed of 10 km/s was used for the rotation speed of ions in concern.

6. DISCUSSION AND SUMMARY

We featured differences in shell configuration of RFP devices to understand magnetic field amplitudes, relative tendency of τ_E with Θ and effects of the externally induced error field from the data set of three previous TPE devices at ETL. The differences in the shell system are characterized in terms of shell proximity (b/a = 1.08, 1.12 or 1.18) and multi-layered structure (triple or single). We showed that the effect of the shell proximity in this relatively narrow range becomes conspicuous in high Θ discharges ($\Theta \sim 2$) with the improved τ_E, while the difference of τ_E in normal Θ operations is unclear within the shot to shot deviation of the measurements. Shot averaged magnetic field fluctuation amplitude shows an increase with b/a in the normal Θ operations which qualitatively agrees with a numerically simulated linear growth rate with b/a. A multi-layered, inner shell is shown to be effective to passively reduce the error field at the shell gaps. It should be noted that the closer the shell becomes to the plasma, the closer the source of the error field reaches to the plasma at the shell gaps. The multi-layered shell configuration is a solution for this issue without having an elaborate active compensation at the shell gaps. In short, the multi-layered, close-fitting shell structure adopted in the original design of TPE-1RM20 is shown to improve robustness against the intrinsic instability of the plasma and external error field sources.

The concept of this shell configuration is succeeded to a next step, large RFP, TPE-RX (R/a = 1.72/0.45 m) after the shutdown of TPE-1RM20mod in Dec. 1996. TPE-RX has started RFP experiments since March 1998. The issue of the shell configuration especially on the improvement in high Θ region shall be studied very soon.

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