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INITIAL RESULTS OF RFP EXPERIMENTS IN REPUTE-1

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Abstract—Experiments of a reversed field pinch device REPUTE-1 constructed in University of Tokyo started in 1984. The conductivity electron temperature and the line-averaged electron density increase approximately linearly with the increase of plasma current in the range up to 240 kA. The study of the effect of the bias toroidal field on the discharge characteristics shows that a higher bias field gives lower resistivity and a higher flat top plasma current. The toroidal flux at the current flat top tends to be a selective value independent of the initial bias field.

1. INTRODUCTION

REPUTE-1 (Reversed Field Pinch, University of Tokyo Experiment) is a reversed field pinch (RFP) device constructed in University of Tokyo to investigate basic plasma physics related to RFP (WATANABE *et al.*, 1984; ISHIGAKI *et al.*, 1984; SAITO *et al.*, 1984). REPUTE-1 became operations in July 1984.

Preliminary results have been reported in the previous paper (YOSHIDA *et al.*, 1985). An RFP Plasma was formed under a thin shell with the current rise times of 0.5 and 1 ms. The major and minor radii are $R = 82$ cm and $a = 20$ cm, respectively. The vacuum chamber is a welded structure using 18 sets of 1 mm thick inconel bellows (inner minor radius 22 cm) and 2.4 mm thick port segments arranged in toroidal geometry. The plasma is isolated 2 cm from the bellows by 127 pieces of inconel limiters (demountable). The vacuum chamber is surrounded by a 5 mm thick stainless steel shell with two electrical breaks in the toroidal direction and one break in the poloidal direction at outer side of the torus. The shell's time constant is 1 ms for vertical field penetration. The 54 toroidal coils of a single turn in series outside the shell can provide a bias toroidal field of 0.25 T and a reversed field of 0.1 T with four reverse times (by $T/2\pi = 1/\omega$) or 0.5, 1, 2 and 4 ms. The plasma current is driven by an iron core transformer of 12 or 24 turns with a flux swing of 1.6 V s^{-1}. Equilibrium vertical field is applied by the vertical field coils wound outside the toroidal field coils. Piezoelectric valves are used for gas puffing. The filling gas pressure is controlled by changing the duration of valve opening, typically 15–50 ms with two valves. An electron gun of 1 kV, 1 A is used for preionization.

2. SCALING OF ELECTRON DENSITY AND CONDUCTIVITY ELECTRON TEMPERATURE

Experiments have been carried out in the range of plasma current $I_p < 240$ kA. Typical time variations of the plasma current I_p, the loop voltage v_L, the line-averaged electron density $\bar{n}_e$ measured by a CO_2 laser interferometer and 0 V line ($\lambda = 2781$ Å) are shown in Fig. 1. The plasma current terminates within 2.2 ms, although there is a margin in the flux of the current transformer. The reason is under investigation.

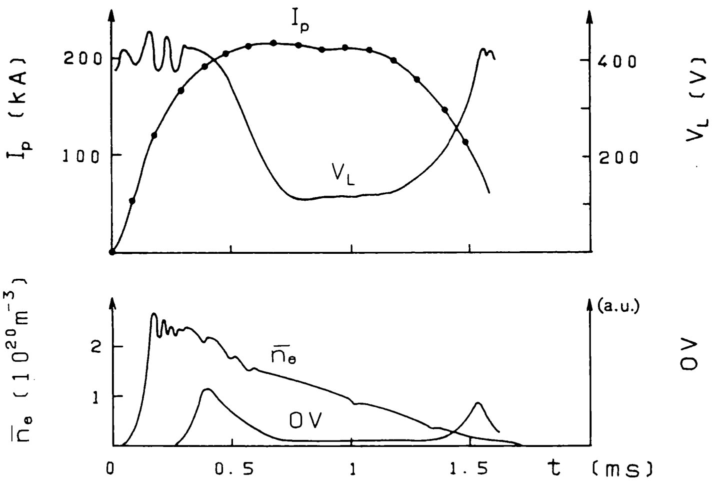

FIG. 1.—The typical time variations of plasma current I_p loop voltage V_L, the line averaged electron density n_e and 0 V line (arbitrary unit). The filling gas is hydrogen.

The toroidal volt-second consumptions $\Phi_F = \int_0^t V_L dt$ from the initiation to the peak of the plasma current normalized by the plasma current I_p in the matched mode are shown in Fig. 2, in which the dependence of Φ_F/I_p on the filling pressure p_0 in the experimental run of August and December 1984 is compared. The reduction in volt-second consumption is clearly observed in the latter experiment due to the likely reduction of impurities.

A systematic scan of operational parameters is carried out in the range of $I_p = 100$–200 kA, $p_0 = 2.0$–4.7 mtorr ($\bar{n}_e = 0.2$–$1.6 \times 10^{20}\ \mathrm{m}^{-3}$ at current peak). To estimate the plasma resistance R_p, the value of loop voltage V_L in the nearly flat top of the plasma current I_p is used, in which the effect of variation of plasma current is taken into account but the effect of variation of plasma induction due to the change of the current profile is neglected. The measurements of the radial profiles of poroidal and toroidal components of magnetic field, $B_p(r)$ and $B_t(r)$, by inserted magnetic probes in the low current operation of $I_p < 150$ kA indicate that the plasma center [at which $B_p(r)$ is zero] shifts about 2 cm outwards. We compare the results of these measurements with the result of Grad–Schafranov toroidal equilibrium code and the center

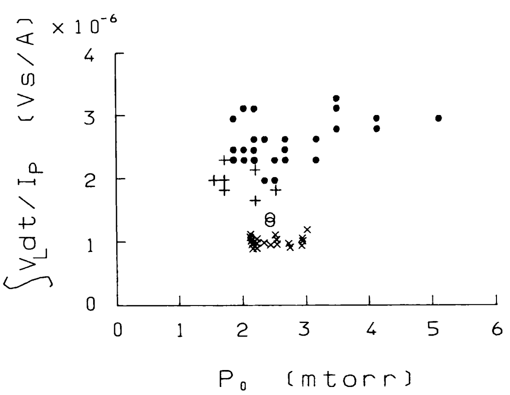

FIG. 2.—Toroidal volt-second consumption Φ_F normalized by I_p during RFP formation phase versus filling hydrogen pressure p_0. Marks + and closed circles are 0.5 and 1 ms rise time operations in August 1984, respectively. Marks X and open circles are 0.5 and 1 ms rise time operations in December 1984.

of plasma boundary shifts about 1.5 cm outwards due to code results, so that we assume that the radius of the plasma cross section is $a_p = 18.5$ cm. From the plasma resistance R_p, one can evaluate the conductivity electron temperature T^{σ}_{e0} on axis under the assumption of the values of Z_{eff} and the geometrical factor g, that is

$$R_p = \frac{2R}{a_p^2}\eta(0)g$$

$$g \equiv \int \eta(j_\phi^2(r) + j_\theta^2(r))2\pi r\,\mathrm{d}r/(\eta(0)\langle j_\phi\rangle^2 \pi a_p^2),$$

where $j_\phi(r)$ and $j_\theta(r)$ are the toroidal and poloidal components of the plasma current density, respectively. $\eta(r)$ is the specific resistivity. The notation $\langle j_\phi\rangle$ is the average value of $j_\phi(r)$ within the plasma cross section. The resistance enhancement factor $\int \eta j^2 2\pi r\mathrm{d}r/(\eta(\mathrm{o})j(0)\langle j_\phi\rangle \pi a_p^2)$ of RFP is typically about two (ORTOLANI, 1985) and the ratio of $j_\phi(0)/\langle j_\phi\rangle$ is about 4 for the modified Bessel function model, so that g value is about 8. The Z_{eff} value is assumed to be 1 for the evaluation of T^{σ}_{e0}. The dependence of T^{σ}_{e0} on I_p is plotted in Fig. 3 for the case of current rise time of 0.5 ms. The observed dependence of T^{σ}_{e0} on I_p is roughly linear in the range of $I_p = 100$–240 kA.

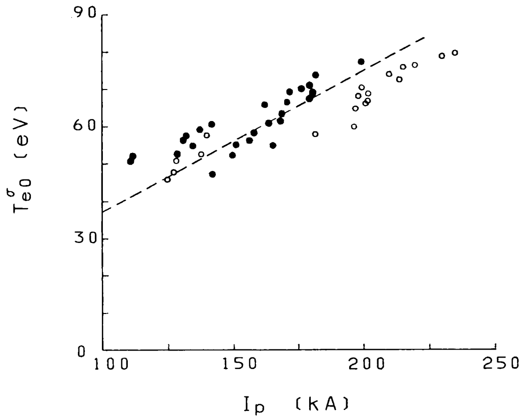

FIG. 3.—The dependence of T^{σ}_{e0} on the plasma current I_p under the assumption of $Z_{\text{eff}} = 1$, $g = 8$. Open circles are the case of hydrogen gas (filling pressure $p_0 = 2.0$–4.0 mtorr) and closed circles are the case of deuterium gas (filling pressure $p_0 = 2.6$–4.7 mtorr). The rise time is 0.5 ms.

Figure 4 shows the line-averaged electron density $\bar{n}_e$ at the current flat top as a function of plasma current for a fixed filling pressure of 3.2–3.3 mtorr. The line-averaged density $\bar{n}_e$ increases approximately linearly with the plasma current I_p. These scalings are consistent with those of ZT–40M (BAKER *et al.*, 1985), OHTE (TAMANO *et al.*, 1985), TPE–1RM (OGAWA *et al.*, 1983), HBTX-1A (CAROLAN *et al.*, 1985), and ETA-BETA II (ANTONI *et al.*, 1985).

3. EFFECT OF BIAS TOROIDAL FIELD AND FILLING PRESSURE ON THE PERFORMANCE OF RFP PLASMA

In a ZT-40M experiment (BAKER *et al.*, 1983), there is a critical pressure, below which the pinch no longer reverses for the case of 1.5 ms rise time. As the initial bias field is increased, the critical filling pressure increases. However, RFP experiments with slow rise times have been carried out mostly in the matched mode and less

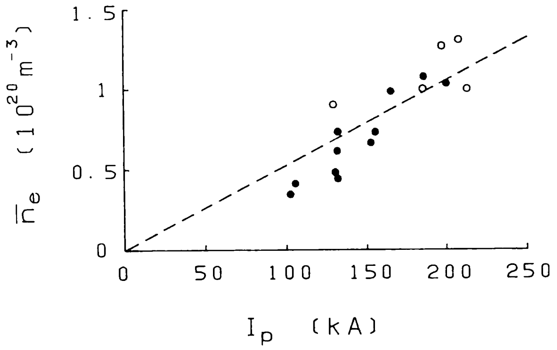

FIG. 4.—The dependence of the line-averaged electron density $\bar{n}_e$ at current flat top (t = 0.8 ms) on the plasma current I_p. Open and closed circles are the cases of hydrogen and deuterium gases, respectively. The rise time is 0.5 ms and the filling pressure is p_0 = 3.2–3.3 mtorr.

attention has been paid to the plasma properties of the unmatched mode, because HBTX1A experiments show that the volts-seconds input to the plasma normalized by the plasma current has a minimum in the matched mode (BODIN *et al.*, 1983). Even though the aided-reversal mode is possible in the REPUTE-1, the following programming of B_ϕ field is found to be experimentally optimum; the circuit of toroidal field coil is programmed to be zero reversal field from the given bias field in the case of no plasma. When the plasma current flows with this operation, a spontaneous reversal of the toroidal field at the wall occurs due to plasma reaction. Therefore, we report here the characteristics of the RFP plasma in the current level of 200 kA, varying the bias toroidal field with this B_ϕ programming and the effect of the bias toroidal field and the filling pressure on the hydrogen plasma performance is studied.

The rise time of the OH primary and the reverse time of the B_ϕ field are 0.5 ms in these experiments. The discharge is initiated 50 μs after the start of OH primary current. The breakdown voltage is 400–500 V. Figure 5 shows the time evolution of the plasma current and the toroidal flux inside the plasma column, the strength of the bias toroidal field $B_{\phi 0}$ being the parameter. The plasma boundary is assumed to be determined by the poloidal limiters. The plasma current is derived from the signal of the Rogowski coil wound outside the vacuum vessel (liner), from which the toroidal liner current is subtracted. The toroidal liner current is computed as the loop voltage divided by the toroidal resistance of the vacuum chamber, 6.5 mΩ: When $B_{\phi 0}$ is high (0.23 T), the initial toroidal flux (2.8×10^{-2} Wb) decreases in time to 1.6×10^{-2} Wb at 0.5 ms; the stage of RFP formation. The plasma current becomes maximum of 216 kA at 0.7 ms. The loop voltage is 135 V; therefore, the plasma resistance is 0.63 mΩ. The toroidal flux is held after the current peak. In the case the intermediate bias field (0.11 T), the initial toroidal flux (1.4×10^{-2} Wb) remains nearly constant; the so called matched mode. The plasma current is smaller compared with the case of a higher bias field, while keeping the voltage of the OH circuit constant. When the bias toroidal field is reduced further (0.07 T), the toroidal flux increases from the initial value of 9×10^{-3} Wb to 1.3×10^{-2} Wb at the RFP formation phase. In this case the plasma current becomes smaller. Plasma properties of three cases are summarized on Table 1. The reason of the dependence of plasma behaviour on the bias field is not clear yet. Since the total discharge duration of plasma is short (~ 1.8 ms), the plasma behaviour in RFP phase is still affected by the history in early

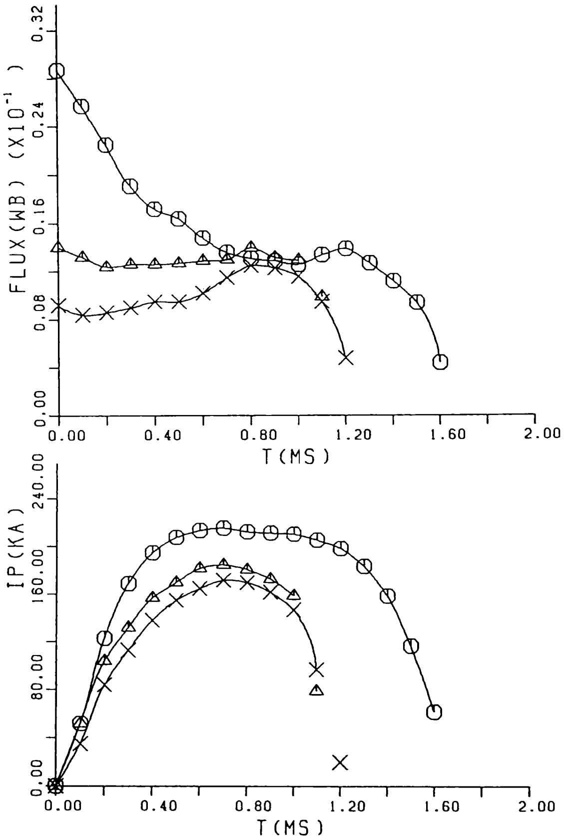

FIG. 5.—Time evolution of toroidal flux (top) and plasma current (bottom), bias toroidal field being the parameter; 0: 0.23 T, Δ: 0.11 T, X: 0.07 T.

phase and the plasma current in RFP phase becomes larger under the same loop voltage and Θ value becomes larger as the results.* We are preparing the bolometric measurement of radiation power for this study.

Figure 6 shows the common F–Θ trajectory with the curve of the Bessel Function Model, where F and Θ are defined as the surface averaged toroidal and poloidal magnetic fields at the plasma boundary, divided by the volume averaged toroidal field inside the plasma column, respectively. The reversal ratio F is obtained from the toroidal flux inside the plasma column Φ, the toroidal coil current I_T, and the poloidal liner current I_L, which is induced by the change in the toroidal flux. The value of Φ is calculated from the signal of the loop wound outside the vacuum chamber,

TABLE 1.—DISCHARGE PARAMETERS OF THREE CASES OF INITIAL BIAS TOROIDAL FIELD

Bias toroidal field $B_{\phi 0}$ (T)	0.23	0.11	0.07
RFP formation time after OH start (ms)	0.5	0.4	0.3
Flat-top Plasma current I_p (kA)	216	185	172
Plasma resistance R_0 (mΩ)	0.63	1.0	1.2
Pinch parameter at the current flat-top	2.0	1.8	1.9

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*The Θ value can be changed by the change of reversed field at the wall, while the initial bias field is kept to be constant. In this operation, the plasma resistance during the current flat top increases for the increase of the Θ value.

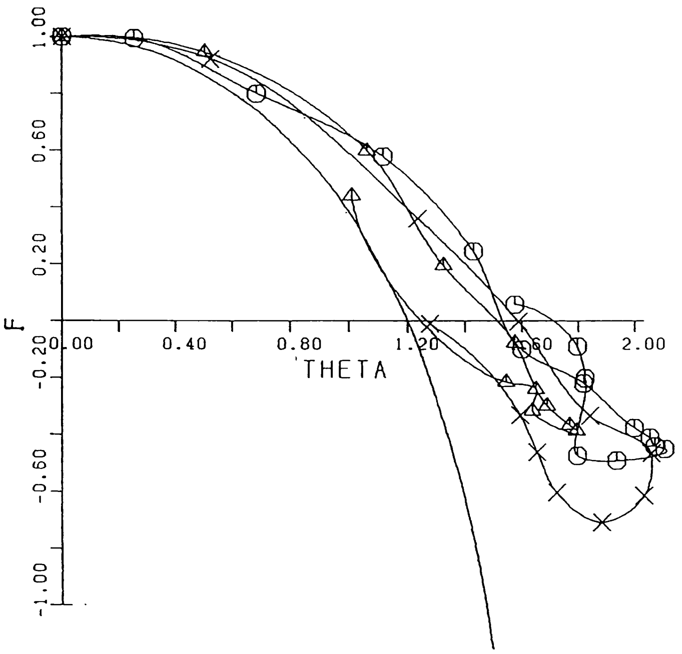

FIG. 6.—Trajectories in F-Θ diagram, bias toroidal field being the parameter; 0: 0.23 T, Δ: 0.11 T, X: 0.07 T. Marks are plotted in every 0.1 ms interval.

from which the flux in the vacuum region calculated from I_T and I_L is subtracted. The pinch parameter Θ is calculated from the toroidal plasma current I_p and Φ. The RFP is set up at 0.5 ms after the start of the OH primary current in the case of the high bias field (0.23 T). The discharge stays at a rather higher Θ value of 2.0 at the flat-top current portion (0.7–1.0 ms). The RFP formation is set up earlier in the case of the lower bias field and the Θ value at the current flat portion is a little lower (around 1.8 in the matched mode), even though each path to the RFP state in F–Θ diagram is almost the same in three cases. The reason for the lower value of Θ in the case of the lower bias field is due to the lower plasma current. As the toroidal flux increases in the low bias case, decreases to 1.6. As the plasma current decreases in the termination phase, Θ decreases furthermore and the reversal state is destroyed. Figure 7 shows the operating window in the filling pressure and the bias toroidal field. When the filling pressure is too low, the toroidal flux decreases monotonically and the RFP is not formed, as for the 1.5 ms rise time case of the ZT–40M (BAKER *et al.*, 1983): the symbol x in the operating window designates this situation. At the high filling pressure, the conductivity electron temperature decreases and the 0 V line is not burnt through. The symbol Δ designates this situation. The initial line-averaged density corresponds nearly to the density when the filling gas is fully ionized, without regard to the bias toroidal field. The density decreases in time gradually; for example, from 2.5×10^{14} cm^{-3} (initial) to 1.5×10^{14} cm^{-3} (at the time of the current peak) in the case of the 4 mtorr filling pressure. The value of I/N is 1.5×10^{-14} A m.

The toroidal flux is reduced to almost the same value in the current flat portion without regard to the initial bias field, which is consistent with the experimental results of other RFPs (for example, OGAWA *et al.*, 1983).

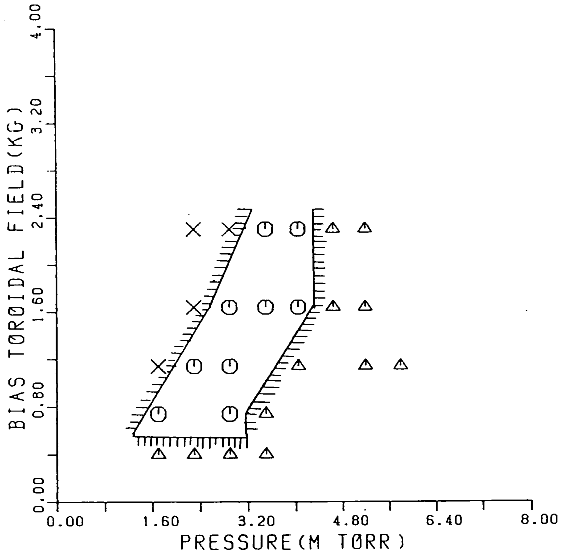

Fig. 7.—Operating window in filling pressure p_0 and bias toroidal field. 0: good RFP, X: no RFP, Δ: bad RFP with heavy radiation loss.

CONCLUSION

The conductivity electron temperature and the average electron density increase approximately linearly with the plasma current in REPUTE-1. The effect of the bias toroidal field on plasma performance is studied. The higher bias field brings lower resistivity and a higher flat top plasma current, even though the Θ value becomes higher as the results. Regardless of the initial bias field, the toroidal flux in the current flat top is almost constant. Our preliminary results of REPUTE-1 experiments in short discharge duration indicate that the operating window for good RFP plasma shifts to the higher filling pressure and the window becomes narrow, as the bias toroidal field is increased.

REFERENCES

Antoni V., Bassan M., Buffa A., Costa S., Giudicotti L. *et al.* (1985) *Plasma Physics and Controlled Nuclear Fusion Research, Conference Proceedings* (*London, 1984*) Vol. 2, p. 487, IAEA Vienna.

Baker D. A., Bausman M. D., Buchenauer C. J., Burkhardt L. C., Chandler G. *et al.* (1983) *Plasma Physics and Controlled Nuclear Fusion Research, Conference Proceedings* (*Baltimore, 1982*) Vol. 1, p. 587, IAEA Vienna.

Baker D. A., Buchenauer C. J., Burkhardt L. C., Caramana E. J., Dimarco J. N. *et al.* (1985) *Plasma Physics and Controlled Nuclear Fusion Research, Conference Proceedings* (*London, 1984*), Vol. 2, p. 439, IAEA Vienna.

Bodin H. A. B., Bunting C. A., Carolan P. G., Giudicotti L., Gowers C. W. *et al.* (1983) *Plasma Physics and Controlled Nuclear Fusion Research, Conference Proceedings* (*Baltimore, 1982*), Vol. 1, p. 641, IAEA Vienna.

Carolan P. G., Alper B., Bevir M. K., Bodin H. A. B., Bunting C. A. *et al.* (1985) *Plasma Physics and Controlled Nuclear Fusion Research, Conference Proceedings* (*London, 1984*), Vol. 2, p. 449, IAEA Vienna.

Ishigaki Y., Saito K., Furuya K., Inoue N., Miyamoto K. *et al.* (1984) *13th Symposium on Fusion Technology*, p. 899, Varese.

Ogawa K., Maejima Y., Shimada T., Hirano Y., Carolan P. G. *et al.* (1983) *Plasma Physics and Controlled Nuclear Fusion Research, Conference Proceedings* (*Baltimore, 1982*), Vol. 1, p. 575, IAEA Vienna.

Ortolani S. (1985) *Twenty Years of Plasma Physics* (edited by B. McNamara), p. 75. World scientific, Philadelphia.

Saito K., Ishigaki Y., Nakazawa T., Toyama H., Morikawa J. *et al.* (1984) *13th Symposium on Fusion Technology*, p. 1153, Varese.

Tamano T., Bard W. D., Carlstrom T. N., Chu C., Curwen B. *et al.* (1985) *Plasma Physics and Controlled Nuclear Fusion Research, Conference Proceedings* (*London, 1984*), Vol. 2, p. 431, IAEA Vienna.

Watanabe T., Kanamori N., Kamiya H., Miyamoto K., Inoue N. *et al.* (1984) *13th Symposium on Fusion Technology*, p. 741, Varese.

Yoshida Z., Inoue N., Nihei H., Uchida T., Sato T. *et al.* (1985) *Plasma Physics and Controlled Nuclear Fusion Research Conference Proceedings* (*London, 1984*), Vol. 2, p. 467, IAEA Vienna.