Movable limiter insertion and first pump limiter experiments in a reversed-field pinch

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Various kinds of movable limiters are inserted into the plasma and effects on plasma performance are studied in the REPUTE-1 reversed-field pinch (RFP) device [Plasma Phys. Controlled Fusion **28**, 805 (1986)]. The increases in one-turn loop voltage V_l and magnetic fluctuations with nearly constant value of ion temperature are found with an advance of movable limiters, and drastic increases in V_l are observed when the limiter is beyond a certain position. This V_l increase is discussed comparing with theories. The first pump limiter experiments in RFP are tried. Favorable effects such as reductions of V_l and impurity intensities are observed when the limiter head is inserted by ~ 2 cm from the plasma edge.

I. INTRODUCTION

Plasma–wall interaction[1] is very important for physical systems, e.g., central plasma conditions such as impurities, plasma parameters, and confinement can be governed by edge conditions. In RFP[2] (reversed-field pinch) devices that have a larger current density and a larger wall power loading compared with tokamaks, not many studies on this interaction and control of edge conditions[1,3] have been done, in spite of the apparent importance of these topics.

In RFP, limiter studies such as a limiter shape and material are key problems and also control of edge plasma by some means are critical issues to be studied. In addition, anomalous one-turn loop voltage and anomalous ion temperature,[4] which are significant and main critical issues to be understood in RFP physics, are considered to be related with the dynamo activities.[2] The plasma properties by removing,[5] and installing or changing[6,7] the limiter, which modified boundary conditions, were investigated. As for the movable limiter insertion experiments,[8–12] an increase in the loop voltage, and in some cases an increase in the ratio of ion to electron temperatures are found, but other plasma parameters have not been measured. Although some theories are presented from helicity conservation[10,13] and kinetic dynamo models,[14] these phenomena observed have not yet been fully interpreted, and also basic experimental data, namely the shape of the movable limiter, material, plasma parameters obtained, etc., are not enough. Therefore, the mechanism of the voltage increase with a movable limiter insertion (along with changes of plasma parameters) is now an open question and this is a worthwhile topic to be studied.

As for control of edge conditions in RFP, only wall conditioning has been done such as carbonization[15,16] and boronization.[17] Active control of the plasma edge, e.g., pump limiter study (performed only in tokamaks[1,18–22]), needs to be investigated and the feasibility of this study must be examined in order to optimize the edge conditions to be applied to the larger machines, RFX (Reversed Field Experiment),[23] MST (Madison Symmetric Torus),[24] and also to the TITAN[25] studied at the University of California, Los Angeles (UCLA).

The contents of this paper are experimental results using movable limiters up to a half-radius insertion (most of them are the first results using various limiters and results are compared with theories, including measurements of many plasma parameters), and the first pump limiter (the first trial to control edge conditions actively) executed in the RFP machine, REPUTE-1[26] (major and minor radii are $R=82$ cm and $a=22$ cm, respectively). These data, which are very valuable, will be helpful for collecting a database for a future larger device, since this device has a larger wall loading compared with other RFP machines.

In Sec. II, we show the experimental results, i.e., changes of plasma parameters as a function of limiter insertion depth, by using various types of movable limiters after describing the limiter configurations. Discussions on the increase in a loop voltage by inserting limiters are also presented. In Sec. III, the setup of the pump limiter is presented and the first preliminary experimental results are shown. Finally, conclusions are described in Sec. IV.

II. EXPERIMENTAL RESULTS BY MOVABLE LIMITERS

In the previous paper,[11] we have shown the slight increase in the one-turn loop voltage as the movable limiter moves into the plasma in the REPUTE-1 RFP device. In addition, the increasing rate of the loop voltage is weakly dependent on the rotation angle of the limiter plate with respect to the magnetic field line.

In order to see the effects on plasma performance more, we have tested various types of movable limiter, i.e., mainly four types as follows: (1) a rectangular solid made of ceramic (macor), 1.18 cm high (poloidal direction) and 2.08 cm wide (toroidal direction) with 20 cm length (ra-

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dial direction) (stainless steel plates, 0.3 cm thick and 1.48 cm wide, are put on the top and bottom sides) (type A); (2) a larger size of type A, namely 1.18 cm high and 2.98 cm wide with 20 cm length (also two stainless steel plates, 0.3 cm thick and 2.38 cm wide, are located on the top and bottom sides of this limiter) (type B); (3) a disk, 2.5 cm in diameter with 0.4 cm thickness made of stainless steel, connected to a circular cylindar (1.4 cm in diameter made of boron nitride with 24 cm length) (type C); and (4) a stainless steel plate, 3.5 cm wide and 10 cm high, with 0.3 cm thickness and a macor plate of similar size on the back of it, connected to a circular cylinder (1.2 cm in diameter made of macor). These movable limiters are inserted into the plasma from the side port in the REPUTE-1 device.

By rotating movable limiters (type A and B) to change the angle between the limiter head and magnetic field line, the effects on plasma parameters by these limiters are changed only slightly, which is the same with the previous results[11] but different from HBTX1 results.[8] The data shown here are obtained by the type A limiter unless mentioned. Typical plasma parameters analyzed here are, plasma current $I_p=200$ kA, mean (line-averaged) plasma density $\bar{n}_e$ is $(3\text{–}4)\times10^{19}$ m^{-3}, F and Θ are around $-(0.4\text{–}0.5)$ and 2–2.2, respectively. Here, F and Θ are the toroidal and poloidal fields at the plasma edge normalized by the mean toroidal field, respectively.

Figure 1(a) shows a relation between one-turn loop voltage V_l at the time of the maximum plasma current and the insertion depth D of the movable limiter from the plasma edge (wall). With an advance of this limiter into the plasma, an increase in the loop voltage is found. The drastic increase in this V_l around 8 cm is coincided with the abrupt increase in the ratio of soft x-ray intensity, $I_{sx}(a/4)/I_{sx}(0)$, i.e., measured at the chord radius of $a/4$ (a:plasma radius) and at the plasma center by surface barrier diodes,[27] as shown in Fig. 1(b). Here, this ratio contains the normalized impurity radiation emitted from the intermediate to the outer region of the plasma, and the increase in this ratio comes mainly from the $I_{sx}(a/4)$ rise, which indicates the increased impurity radiation, but not the increased electron temperature and density from measurements. These results of drastic increases in V_l and the ratio, $I_{sx}(a/4)/I_{sx}(0)$, may affect the core (the inside region of the plasma, more than 8 cm from the plasma edge) confinement and the hotter region. The increasing rate of V_l as a function of the insertion depth D($D<5$ cm) is nearly the same order as the previous REPUTE-1 results[11] as well as those of HBTX1[8–10] and ZT-40M.[12]

Although the increase in the loop voltage is observed, the ion temperature T_i derived from Doppler broadening of CV line ($\lambda=2271$ A) does not change so much, as shown in Fig. 2. (For the case of a type C limiter, a slight decrease in ion temperature from CV line is found, i.e., $\lesssim20\%$ for a several cm insertion.) The result of the nearly constant ion temperature as a function of the radius with an insertion up to 12 cm, which is beyond half of the minor radius of 22 cm, is the first experiment in RFP machines. This shows that there still exists anomalous ion heating for the case of limiter insertion: ion temperature is extremely high, as expected from a classical theory, and is, in some cases, above an electron temperature as in REPUTE-1. This comes from the anomalous resistivity (non-Spitzer term), even in the deepest insertion case where the degra-

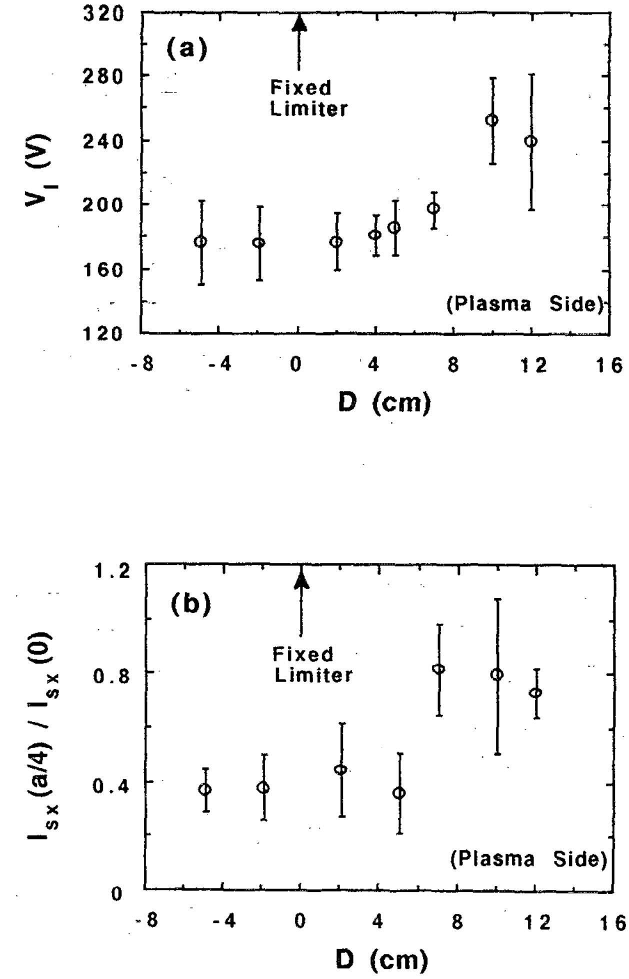

FIG. 1. (a) One-turn loop voltage V_l and (b) ratio of soft x-ray intensity $I_{sx}(a/4)/I_{sx}(0)$ versus insertion depth D from plasma edge.

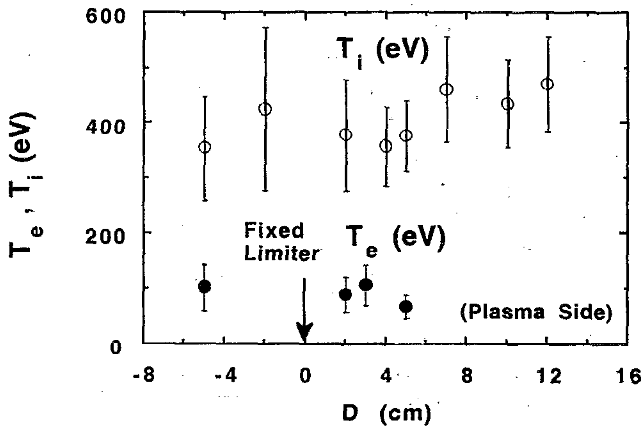

FIG. 2. Ion temperature T_i (open circles) from CV Doppler broadening and central electron temperature T_e (closed circles) by Thomson scattering as a function of insertion depth D.

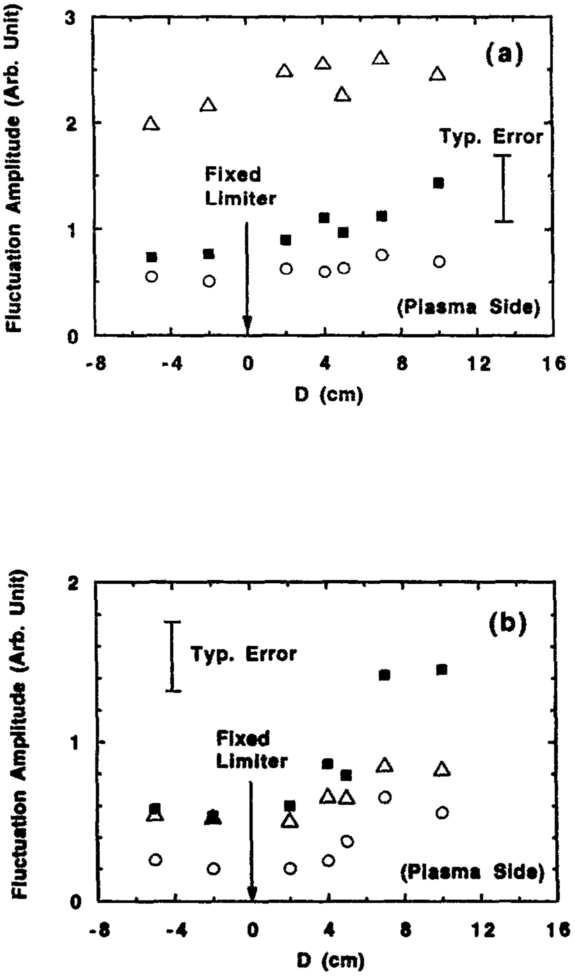

FIG. 3. Fluctuation amplitudes (root mean squares) of toroidal (B_t), poloidal (B_p), and radial (B_r) components of magnetic fields versus insertion depth D for lower (5–50 kHz) (a) and higher (50–200 kHz) (b) frequency ranges.

dation of the plasma parameters such as drastic increases in the loop voltage and impurity intensity. The obtained phenomenon shows a peculiar nature in RFP contrary to a tokamak, in which the ion temperature is well below the electron temperature with an Ohmic heating case and these temperatures decrease abruptly with a limiter insertion.

On the other hand, the central electron temperature T_e by Thomson scattering shows a tendency to decrease slightly with the insertion radius D (Fig. 2). The intensities of H_α, CV, and soft x-ray gradually decreased with D ($D<9$ cm). Note that the data are taken at the same time in this device, and obtained results are nearly the same if we normalize plasma parameters by the mean plasma density.

As for magnetic fluctuations measured by magnetic probes located on the inner wall of the torus,[28] similar changes with V_l are found by inserting movable limiters, as shown in Fig. 3. Here, the amplitude (root mean square) is derived near the time of the maximum plasma current for 0.2 msec time window (sampling time is 2 μsec). Three components of B_t (toroidal), B_p (poloidal), and B_r (radial) fields are measured, and the signals of probes at the inner and outer equator (two positions) for each component are averaged. In addition, two numerical (bandpass) filters of 5–50 kHz [low frequency (LF)] and 50–200 kHz [high frequency (HF)] are used for comparison. The increasing rate of fluctuations of three components are higher for the HF range than that for the LF range. Considering that the observed (CV) ion temperature does not change so much and the confinement is expected to be worse with the limiter insertion, the HF magnetic fluctuations may contribute to the ion heating from the dynamo model;[2] the model shows two energy flows, i.e., Spitzer and non-Spitzer resistivity parts, and the latter channel involves the ion heating and RFP dynamo. Ion heating is dependent on the fluctuation level (ion heating by fluctuations which drives the RFP dynamo through some dissipative process). The experimental results with no limiter insertion,[29] that the increase in HF amplitude leads to the higher ion temperature, are also consistent with the present results.

The results, as shown in Fig. 2, are similar with those in Refs. 9 and 12. Between the three machines HBTX1, REPUTE-1, and ZT-40M, however, somewhat different results are found; the ratio of ion to electron temperatures as a function of insertion depth is nearly constant in ZT-40M, somewhat increasing in REPUTE-1, and clear rising in HBTX1. Note that the ion temperature is determined from the time-of-flight (TOF) system in ZT-40M and from the neutral particle analyzer (NPA) system in HBTX1. This temperature represents the bulk hydrogen one, whereas it represents CV impurity temperature in REPUTE-1. The discrepant results of the ratio may be due to the different error fields near the plasma edge as well as the different geometry and material of the movable limiter. Contrary to the small difference, the ion temperature does not decrease in three machines, which may reflect the anomalous heating mechanism universally existing in RFP's.

The increasing rates of V_l as a function of D($D<4$ cm) obtained in REPUTE-1 are roughly $\sim$3 V/cm, 3–4 V/cm, $\sim$3 V/cm, and 5–6 V/cm for type A, B, C, and D limiters, respectively. Previous results[11] showed $\sim$1 V/cm for the case of a stainless steel plate 0.3 cm thick and 3.5 cm wide. In any case, an abrupt increase in V_l and sudden deleterious effects are not found for a several centimeter insertion using four movable limiters. There is a tendency that rod-type as well as rectangular solid-type limiters raise the increasing rate of V_l higher than a plate-type limiter, and that also an increasing cross section of the limiter brings the higher rate. These are qualitatively similar with ZT-40M results:[12] a small increasing rate was observed by a tile carbon limiter (in contrast to the HBTX1[8–10]) but the plasma was seriously degraded by a graphite rod (25 mm in diameter).

Hereafter, the loop voltage increase is examined and compared with theories. When we take $V_l=180$ V without a limiter insertion and assume the constant and spatially uniform resistivity regardless of the movable limiter position, $\sim$9 V/cm can be expected if a plasma diameter diminishes with the same rate of the insertion depth. This value is large compared with the four cases mentioned above, which indicates the existence of a non-Spitzer resistivity, a smaller limiter effect to reduce the plasma radius and plasma parameters, and a decreased resistivity.

The first two reasons are plausible to explain the data, since the last one does not explain the results due to the facts that the central electron temperature does not change very much (at least does not increase) and impurity line intensities do not decrease appreciably with an insertion of the movable limiters. According to Ref. 10, the increasing rate of V_l is $\Delta V/d = \Delta\chi w(\Theta/\pi a^2) \sim 0.06$ V/cm (ΔV: increment of loop voltage, d: depth inserted into the plasma) if we use the value $\Delta\chi$ (potential difference between the points of exit and entry of the field lines) = 15 V, w (limiter width) = 1 cm, and $\Theta = 2$ for the limiter insertion case. In order to explain the experimental data, $\Delta\chi$ or a projection area wd must be multiplied by a factor of several tens. In addition, the voltage increase obtained is not proportional to the projection area if the area is determined by the poloidal magnetic field near the plasma edge: it is only qualitatively true and weakly dependent on this area, as are the same results in that paper (Ref. 10). For the plasma shift case, $\Delta V/d = \Delta\chi(4R\Theta/\pi a^2)$ is calculated to be 20 V/cm, which is larger than the data.

In Ref. 13 it is claimed that V_l is determined by the edge region V_e as defined by the limiters, field errors, and a plasma shift: $\Delta V = (E_\parallel/a^2\pi)V_e$ ($E_\parallel$ is parallel electric field). If we take $\Theta = 2$ and a width of edge error region of 1 cm, $\Delta V/d$ is roughly more than 150 V/cm, which is also larger than the experimental values by more than one order of magnitude. Here, the height of a liner of the bellows section and a pedestal (2 cm in diameter) for mounting fixed limiters are 1.2 and 1 cm, respectively. Even if the plasma column shifts by several centimeters, which leads to the increase in V_e, $\Delta V/d$ is still larger than the obtained results by nearly a factor of 10.

Several years ago, we removed the fixed limiters to increase the plasma radius from 20 to 22 cm and a reduction of the loop voltage was found, which is nearly inverse proportional to the cross section of the plasma [fixed limiters, made of Inconel 625 and total numbers of 126, are 2 cm poloidally and 7.8 cm toroidally in length with 0.6 cm thickness (radial direction)]. This means $\Delta V/d \leqslant 10$ V/cm for the $I_p = 200$ kA case. (There are no fixed limiters installed for the present experiments.)

From the discussions above, it is difficult for the concept of the helicity balance[13] and also the surface term,[10] i.e., potential difference, of the helicity balance equation to explain the results quantitatively in REPUTE-1. Although an electron momentum diffusion to the plasma edge[14] may account for the anomalous loop voltage partly, the verification of this theory is out of scope owing to the difficulty of evaluating the theoretical value as mentioned in that paper. The one-turn loop voltage is considered to be divided into two parts:[2] the Spitzer resistivity part and nonclassical part. From the modified Bessel function model for analyzing the RFP equilibrium,[30] the nonclassical part is estimated to be $\sim 30\%$ of the observed voltage in REPUTE-1. If we consider that the voltage increase with the limiter insertion comes from the change of the Spitzer resistivity part due to a reduction of current-carrying cross section, ~ 6 V/cm can be expected, which can explain the experimental results very well. The smaller size of the movable limiter can be interpreted to have a smaller limiter effect on the plasma radius reduction.

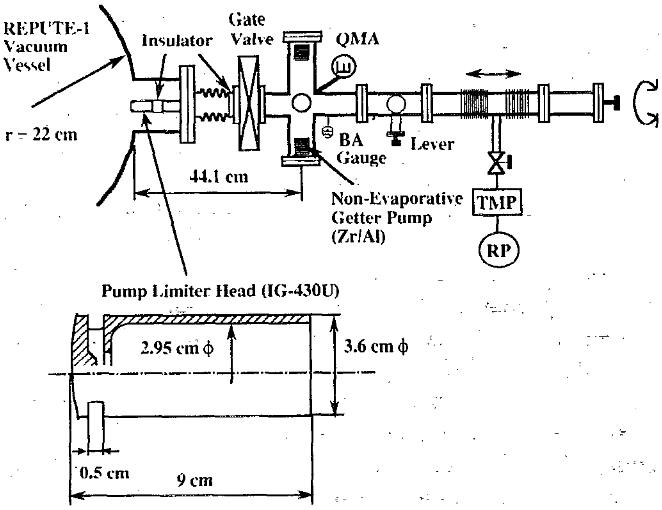

FIG. 4. Schematic view of pump limiter system.

Of course, it cannot be excluded partly that V_l increases with an insertion of the limiter due to a worse production of the plasma in the presence of an obstruction (the movable limiter) and due to an increase in the impurity contents. We do not, however, observe a large increase in impurity intensity with $D < 4$ cm. In any case, we must bear in mind, further, that the experimental results should be examined considering the importance of the geometry and material of the movable limiter, and an error field (an absolute value as well) region.

III. FIRST PUMP LIMITER EXPERIMENTS

The configuration of the pump limiter is as follows (see Fig. 4): the limiter head is a circular cylindrical shape (3.6 cm in outer diameter and 9 cm in length) made of carbon (Toyo Tanso Corp., IG 430U) with two slits on the side of the cylinder, 0.5 cm long (radial direction of the torus) and 2.15 cm wide, positioned 180° away from each other. This head can be rotated for the slits to see the plasma with a different angle, e.g., poloidal and toroidal directions, and is connected to a pipe to be moved and pumped. At the back of the head, two Gr/Al getter pumps (ULVAC Japan Ltd., SORB-AC-100D, with pumping speed 580 1/sec for hydrogen gas and 110 1/sec for nitrogen gas), backed by a turbomolecular pump with a pumping speed of 60 1/sec and a rotary pump, are located.

The slow conductance part is a region between a pump limiter head and the pumps (several tens of 1/sec). The pumping speed $S_p = (1/4)v_t S$ at the slits of the head is, however, estimated to be as high as 1200–2900 1/sec if all the incident particles can be collected and passed through into the head. Here, v_i is a proton velocity with a temperature of $T_i=5$–30 eV and S is an area of slits. [Note that the central (CV) ion temperature is ~ 400 eV.] Considering a collection efficiency at the head, the real pumping speed S_p is estimated to be more than several hundreds of l/sec. The lowest value of S_p can be obtained if we take $v_i \sim 0.3C_s$ as is usually used in the scrape-off layer. Here, $C_s=(kT_e/m_i)$ is ion (acoustic) sound velocity where m_i is the ion mass. In this case a reduction of S_p by a factor of 3–4 is expected. In our experiments, of course, the pump limiter head is inserted through the scrape-off layer into the outer region of the plasma.

During a discharge, charged particles are collected through the head and accumulate to be $\leqslant 10$ mTorr in the connecting pipe, considering the conductance, pumping speed, and particle flux. This value is a few times higher than a filling pressure (a few mTorr) in the vacuum chamber to initiate the plasma discharge. The estimated number of trapped particles by this head during one shot of the discharge ($\leqslant 3$ msec) is an order of $\leqslant 1\%$ of the total numbers of particles in the whole plasma. Although this value is small (of course, no pumping effect on charged particles can be expected during a discharge without a pump limiter), this head acts as a limiter (which works more than the wall) because of the insertion of the head into the plasma, and can partly affect the plasma behavior, especially near the plasma edge.

The plasma parameters operated are nearly the same as those performed by movable limiters in Sec. II. The mean plasma density $\bar{n}_e$ does not change so much with this pump limiter, partly due to a short time ($\leqslant 3$ msec) of the discharge duration. Contrary to the results obtained by movable limiters (see Fig. 1), the minima of loop voltage V_l and H_α intensity are observed by the use of the pump limiter inserted around 2–3 cm from the plasma edge, as shown in Figs. 5(a) and (b), in addition to the same trend of CV line intensity. (In spite of the use of the carbon head, impurity intensities are not enhanced.) Furthermore, the ratio of soft x-ray intensity, $I_{sx}(a/4)/I_{sx}(0)$, is decreased on this position by about 25%, as shown in Fig. 3(c), which indicates a reduction of impurity radiation on the outside of the plasma core. Needless to say, a further insertion of this head ($D>3$ cm) leads to unfavorable effects such as an increase in the loop voltage, which is the same trend of the limiter insertion case in Sec. II due to the effect of introducing a limiter itself rather than the effect of the pumping. These favorable results for the $D\sim 2$ cm case indicate reductions of numbers of neutral as well as impurity particles near the plasma edge by the use of this pump limiter.

In order to check the material difference that the results are obtained by the use of the carbon (pump limiter head) whereas movable limiters are made of the stainless steel and ceramic, we used two movable limiter with a carbon head (3.5 cm in diameter with 0.5 cm thickness and 3.2 cm with 0.4 cm) to affect the plasma parameters. From two cases, we observe the same trend with other movable limiters and do not find the phenomena such as minima of H_α line intensity and loop voltage obtained by the pump limiter. This result excludes the possibility of the material difference.

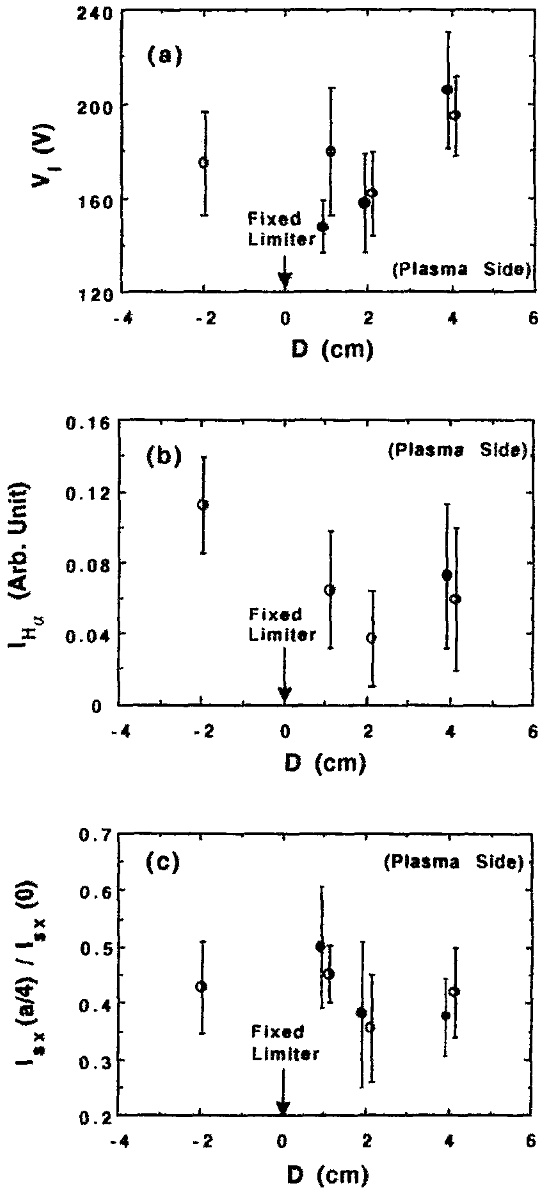

FIG. 5. (a) One-turn loop voltage V_l, (b) H_α intensity, and (c) ratio of soft x-ray intensity $I_{sx}(a/4)/I_{sx}(0)$ versus insertion depth D (closed and open circles show that the normal directions of open slits are parallel and perpendicular to the poloidal field, respectively).

Although favorable effects are found, no appreciable changes of plasma parameters between different angles of slits (limiter head), i.e., normal directions of the slits are toroidal or poloidal ones, are found. This may be due to (1) the tilting angle of the total magnetic field (sum of the poloidal and toroidal magnetic fields), (2) the disorder of the magnetic field near the plasma edge from error fields and magnetic fluctuations[31–34] (the relative level is more than a few percent), and (3) effects of neutral particles to be collected. Here, the angle between the total magnetic field at the plasma surface and a central line of the torus estimated from the measured fields (poloidal field is dominant) is ~14°. This means that an intensity ratio between two cases, i.e., the normal directions of slits are parallel and perpendicular to the poloidal direction, is tan (14°) =0.25 if the particles run along the field line. Although these factors mask the angle dependence, we can see that the voltage decrease is larger for the parallel direction case (Fig. 5), and results of the hydrogen pressure also support the pump limiter functioning given below.

From the residual gas analysis by a quadrupole mass analyzer (QMA) with a sampling time of 0.2 sec, the maximum hydrogen pressure after the plasma discharge is weakly decreased with the mean plasma density. Although the sampling time is slow compared with a discharge duration, QMA data contain the information partly from the effect of the discharge itself: this portion is roughly a few tens of the percentage of signals.

From the absolute intensity of the H_α measurement,[35] a particle confinement time is proportional to the mean plasma density $\bar{n}_e$, which shows the independence of the particle flux to the wall on $\bar{n}_e$. Therefore, from the experimental results it can be understood that the trapping efficiency is nearly constant with $\bar{n}_e$. For the deep insertion case of $D=4$ cm, the hydrogen pressure when the normal direction of the slits views the poloidal field is higher than that when the slits view the toroidal field, which indicates the functioning of this pump limiter. Although a trapping coefficient cannot be estimated owing to a lack of data, e.g., radial profiles of density and temperature, the first obtained results seem to be encouraging under the high heat load in RFP (wall power loading $\geqslant 5$ MW/m^2 on average). For future work, a test of an improved limiter head with a high pumping speed (and conductance) and a larger area are needed to become a valuable database to be applied to the larger machines.

IV. CONCLUSIONS

Using four kinds of movable limiters, changes of plasma parameters are studied in the REPUTE-1 RFP device. With an advance of the limiter into the plasma, monotonic increases in loop voltage V_l and magnetic fluctuations (especially the HF part) are found with an increasing rate dependent on the shape of limiters. On the other hand, gradual decreases in H_α, soft x-ray and CV intensities as well as the central electron temperature T_e are observed, with nearly constant ion temperature T_i derived from the CV line regardless of movable limiter position D. Drastic increases in the loop voltage and impurity intensities are found as the limiter is beyond a certain position of $D\sim 8$ cm. The V_l increase is examined and discussed comparing with theories based on the helicity conservation and kinetic dynamo models. This increase mainly comes from the reduction of a current-carrying cross section.

The first pump limiter experiments using carbon heads with two slits have been done in a RFP device, and favorable effects on plasma performance are observed; contrary to movable limiter experiments, a slight decrease in loop voltage V_l as well as minima H_α and CV, and $I_{sx}(a/4)/I_{sx}(0)$ intensities are obtained with an insertion depth D around 2–3 cm.

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