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LETTER TO THE EDITOR

Preliminary experiments with edge current injection in a reversed field pinch

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Abstract. The first dc helicity injection is tried applying a voltage between two parallel plates, and effects on plasma performance are studied in the reversed field pinch plasma. The injected current is nearly proportional to the applied voltage V_H with a small offset-induced voltage (~ -30 V), and a transient increase in the toroidal flux and a decrease in the poloidal field (plasma takes the more relaxed state) is found near the injection port, regardless of the polarity of V_H. The induced voltage measured as a function of the insertion depth shows the presence of high-energy electrons.

Reversed field pinch (RFP) [1] is a type of toroidal plasma confinement device; it is of interest in plasma physics as a magnetic relaxation process constrained by magnetic helicity connected with anomalous heating and anomalous resistance. In current-carrying toroidal devices, a method of continuously driving the toroidal current is necessary for steady-state operation [2, 3]. The basic idea is to inject 'helicity' into the plasma based on Taylor's principle [4, 5], and a recent trial of dc or ac helicity injection may lead to more efficient methods of doing this [6, 7]. The relaxation process during this injection is also a major concern in RFP, because there exists a nonlinear response such as a dynamo activity. Recently, a simulation study [8] has been done to demonstrate the suppression of the MHD instabilities by dc injection in RFP.

Although a helicity injection scheme may be an important potential tool for current drive and MHD stabilization, as far as we know our report is the first published one concerning attempts to change the plasma properties by dc helicity injection in RFP. Here we present the experimental results on dc helicity injection in the form of the product of the potential difference and the magnetic flux in the RFP machine, REPUTE-1 [9] (major and minor radii are $R = 82$ cm and $a = 22$ cm, respectively). This is the first trial to see the effects on the global plasma performance in connection with the relaxation phenomena, and also to check whether or not this affects impurity production owing to plasma–surface interaction

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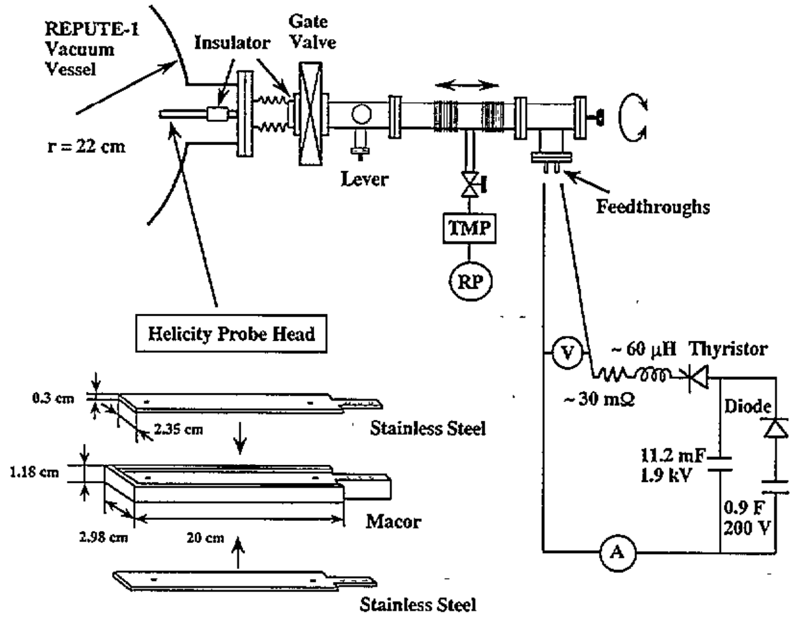

Figure 1. Experimental set-up for helicity injection.

performance in connection with the relaxation phenomena, and also to check whether or not this affects impurity production owing to plasma–surface interaction [10–12], including hot energy electrons near the plasma boundary [13, 14], by inserting an injection probe.

The injection probe is as follows (see figure 1, same as type B in reference [12]): a rectangular solid is made of ceramic (macor), 1.18 cm poloidally, 2.98 cm toroidally and 20 cm radially. Two stainless steel plates (0.3 cm thick and 2.35 cm wide) facing the poloidal direction are put into on both sides of this insulator. Two plates of this probe, which is rotatable (e.g. it is possible to face the toroidal direction) and can be moved radially, are connected to the power capacitor bank (11.2 mF with 1.9 kV maximum charging voltage) through a resistance $R_c \sim 30\,\mathrm{m}\Omega$ and an inductance $L_c \sim 60\,\mu\mathrm{H}$ by a thyristor switch. Typical target plasma parameters analysed here are, plasma current I_p is 130 kA, mean plasma density $\bar{n}_e$ is $(3\text{–}4) \times 10^{19}\,\mathrm{m}^{-3}$, F and Θ are around -0.2–0.4 and 1.8–2, respectively. Here, F and Θ are the toroidal and poloidal fields respectively at the wall normalized by the mean toroidal field. The discharge duration time is ~1.3 ms and the time of the maximum plasma current is ~0.65 ms.

In this experiment, the injected current starts at $t = 0.2$ ms (plasma is initiated at $t = 0$ ms) and the time to reach the maximum current is ~1.2 ms. The obtained data are taken under the condition that the head of the injection probe is inserted to a typical distance $D = 5$ cm from the wall (outer side of the torus). For the case of $D < 5$ cm, the change of plasma parameters by the injection is reduced compared with $D = 5$ cm case. For $D \leqslant 2$ cm case, the probe current I_H is unsettled (I_H differs from shot to shot) and a further insertion of $D > 5$ cm degrades the plasma behaviour [12]. The obtained current I_H is nearly proportional to the applied voltage V_H between two parallel plates for individual time, e.g. $I_H \sim 2$ kA at $t = 0.4$ ms and

$I_H \sim 3$ kA at $t = 0.65$ ms for the $V_H = 300$ V case. Here, the positive V_H is defined such that the electron drift side (along the poloidal field) is positive with respect to the ion drift side. The maximum I_H obtained, which is limited by the damage of the injection probe, is ~9 kA ($t = 1.4$ ms) with a charging voltage of the capacitor of 1.6 kV. Although some thin scratches and erosions on the stainless steel plates are observed, the surface of the macor is relatively clean with no distinct tracks.

From the analysis of the waveform measurements of the circuit current and voltage, the effective resistance and inductance of the load (probe part) are roughly $R_H \sim 30$ mΩ and $L_H \sim$ several μH, respectively. Note that we can calculate that $R_H = 44$ mΩ and $L_H \sim 0.92\ \mu$H if the current path is an annular structure (one turn), 126 cm long (radius of 20 cm) with a cross section of $\Delta r = 5$ cm and $\Delta z = 2.35$ cm, and the electron temperature of $T_e = 7$ eV with $Z_{\rm eff}$ (effective charge) = 1.

Three components (toroidal, poloidal and radial directions) of edge magnetic fields at ϕ (toroidal angle from the injection port) = 19° [15] show that fluctuation levels of low (5–50 kHz) and high (50–200 kHz) frequencies do not change very much with changing V_H. On the contrary, low-frequency parts of I_p (ϕ = 127°) and one-turn loop voltage V_l increase slightly with $|V_H|$.

The mean current density j_ϕ of the plasma current $I_p = 130$ kA (nearly the same as the estimated total poloidal current from the equilibrium) is 85 A cm^{-2}. When we take the surface area as the probe surface (radial direction $\Delta r = 5$ cm and toroidal direction $\Delta z = 2.35$ cm), the mean injected current $j = 225$ A cm^{-2} for $I_H = 3$ kA. In this experiment, the relative helicity injection rate of $V_H B_p S / V_l \Phi$ is 2.5% (B_p is poloidal field, S is surface area of the injection probe facing the plasma poloidally and Φ is toroidal flux), and the relative ohmic injection rate of $V_H I_H / I_p V_l$ is typically 4%. According to Ho [8], we need that the total injected current I_H is an order of I_p and the relative injection rate is several tens of % (and also injected current density j is more than j_ϕ especially at $r \sim 0.8a$) to stabilize the MHD instability (tearing mode). This shows that the experimental values of injection rate and current seem to be too low (near the detecting place of the magnetic probes), in addition to the effects such as the current diffusion, to have this stabilizing effect, although locally this stabilizing criterion may be satisfied.

Here, we report the change of plasma parameters with this dc injection scheme. Figure 2 shows a relative increase in the toroidal flux near and far from the injection port ($\phi = -55°$ and 130° respectively from the injection port) as a function of the V_H at $t = 0.4$ ms. From this figure we can see that the flux increase up to ~10% is independent of the polarity of V_H and that the increase is localized near the injection port. There is a tendency that this flux increase saturates with or nearly independent of $|V_H|$ for $|V_H| > 100$ V. However, the flux increase reduces near the time of the plasma current peak even near the injection port: time evolution of the toroidal flux exhibits a 'hump' near the time of $t = 0.4$ ms. The reason why the voltage is not zero, i.e. ~ -30 V, when the power supply is off (without an injection) will be discussed later. Rotating this injection probe by 90° (two parallel plates face the toroidal direction) leads to the same trend of transient increase in the toroidal flux near the injection port, which means that there is no clear sensitivity on the injection angle. Increasing I_p from 130 kA to 200 kA, this flux change reduces, mainly due to the decrease in the relative injection current I_H/I_p and the enhanced plasma–probe interaction.

In addition to the change of the toroidal flux, the edge poloidal field B_p is also modified by this injection, as shown in figure 3. Here, this field is measured at

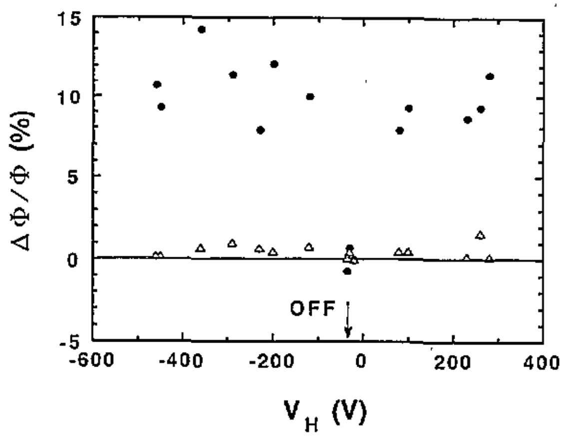

Figure 2. Relative changes of toroidal flux $\Delta\Phi/\Phi$ near ($\phi = -55°$, full circles) and far ($\phi = 130°$, open triangles) from the injection port as a function of applied voltage V_H between two plates at $t = 0.4$ ms.

$\phi = 19°$ [15] ($t = 0.4$ ms), and the average B_p decreases by <10%, also regardless of the polarity of V_H. The edge toroidal fields, also measured at $\phi = 19°$, decrease slightly at $t = 0.4$ ms for $V_H > 0$. From the soft x-ray measurements by the surface barrier diodes ($\phi = 60°$) [16] with an injection, the increase in this intensity is more at the outer chord ($r = 12$ cm) of the plasma than at the central chord. This shows that the injection affects the plasma more at the outer region of the plasma column. However, the impurity intensities such as CV and OV ($\phi = 40°$) do not increase appreciably with V_H (the H_α intensity at $\phi = 180°$ does not change either). Even though a small increase in V_l is observed with an insertion of $D \leqslant 5$ cm [12], the degradation in the plasma properties is not found for the case of the injection.

If we can combine the data of the toroidal flux at $\phi = -55°$ (figure 2) and the average poloidal (figure 3) and toroidal fields at $\phi = 19°$, F and Θ values near the injection port can in principle be derived. This means a breaking of the toroidal symmetry, opposing the generally accepted RFP equilibrium description, but here

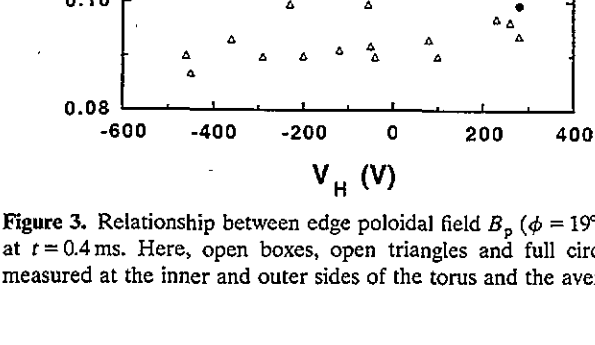

Figure 3. Relationship between edge poloidal field B_p ($\phi = 19°$) and applied voltage V_H at $t = 0.4$ ms. Here, open boxes, open triangles and full circles show poloidal fields measured at the inner and outer sides of the torus and the average field, respectively.

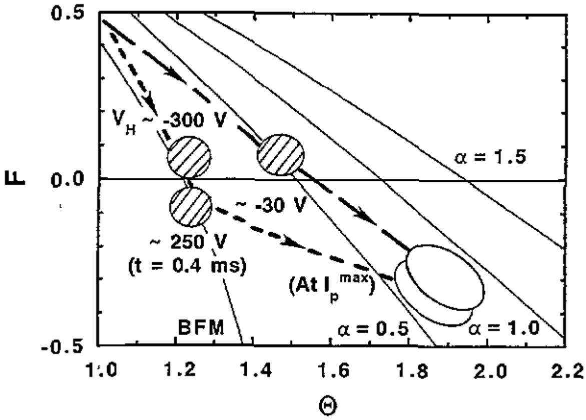

Figure 4. Time evolution of F–Θ trajectories with (near the injection port, short-dashed curves) and without (long-dashed curve) helicity injection. Here the shaded areas are taken at $t = 0.4$ ms (for three cases of $V_H \sim -300$ V, ~ -30 V (without injection) and ~250 V) and open areas near the time of the maximum plasma current I_p^{max}. For comparison, theoretical curves from BFM (Bessel function model) and from the μ profile (index of α is indicated) are also shown.

we define local F and Θ values for convenience from a view point of a localized effect. Figure 4 shows the time evolution of F–Θ trajectories with and without this injection measured near the injection port. Note that the mean F–Θ trajectory with an injection (far from the injection port) is nearly the same as the one without an injection. Here, shaded areas are taken at $t = 0.4$ ms (for three cases of positive and negative applied voltages and no injection) and open areas are at $t \sim 0.65$ ms (at the time of the maximum plasma current I_p^{max}). Curves from the Bessel function model (BFM) and modified Bessel function model [17] are also shown for comparison; the poloidal beta value of β_p is 0.1 with α is a parameter to express the μ profile (ratio of the current density to the magnetic field) as being proportional to $[1-(r/a)^2]^\alpha$. Compared with the injection case, the plasma takes the broader μ profile with an injection regardless of the polarity of V_H, i.e. a more relaxed state (near the BFM curve) at $t = 0.4$ ms, but this effect fades away as time goes on (shifts to the right region of the more peaked μ profile).

It is not certain why the plasma response is nearly the same regardless of the polarity of V_H, but it indicates that the effective current flow takes the same pattern. Of course the direct arc with the shortest path between two plates can be excluded because of the observed (localized but global) effects on the plasma properties described above. The first possibility is that the current path does not obey accurately the mean magnetic field line such as in the model proposed by Rusbridge [18]. However, other RFP experiments might have shown markedly different results if the Rusbridge model were employed. The second possibility is the increased conductivity due to the edge heating by this forced current. At least significant edge heating may not occur because the injected current increases smoothly with time: the effective electrical circuit values can be expressed as time constant ones mentioned before. The third possibility is a trigger to change the equilibrium by this injection, e.g. from one MHD stability region to another. The relaxation phenomena may be expected to allow various angles of helicity (current) injection to cause the same plasma behaviour. According to Kondoh *et al* [19], the plasma can take the relaxed state, considering the attractor of the dissipative structure in the resistive MHD plasma to be due to the injection of the energy not the helicity.

We apply a voltage between two separate conductive electrodes (single-disc type) with an insulation on one surface, located on the $\Delta\phi = 140°$ toroidal away from each other. This set-up is recommended in order to have a higher impedance Z [8], but we do not observe the change of plasma parameters in this configuration. This fact, combined with the aforementioned results, including R_H and L_H values discussed at the end of section 2, indicate that the injected current path is localized near the injection port and then the current is lost by touching the wall near the injection port. Therefore, it is required in future in order to demonstrate this helicity injection scheme more clearly and globally around the torus that the number of injection ports and the local current density are increased as well as designing a more efficient injection probe.

Now we discuss a phenomenon of the non-zero voltage between two plates without an injection. With an advance of the probe head into the plasma, we observe the rise of $|V_H|$ from 0 V (plasma edge) to ~ -30 V (5 cm insertion). The non-zero voltage of V_H can be predominantly explained by the high-energy electrons [13, 14]. In order to have $V_H = \sim -30$ V, we need high-energy electrons of ~30 eV (several times higher than the bulk electron temperature near the plasma edge) with a relative population of several %, whose result agrees with the thermocouple experiments in REPUTE-1 [14]. This result also supports the previous ones on this machine [20] based on the kinetic dynamo theory (KDT) [21].

In conclusion, effects on plasma performance are studied for the purpose of testing the dc helicity injection scheme in the REPUTE-1 RFP device for the first time, applying a voltage between two parallel plates inserted into the plasma edge ($D \sim 5$ cm). The injected current I_H is nearly proportional to the applied voltage V_H, and a transient increase in the toroidal flux by <10% and a decrease in the edge poloidal field by ~10% (plasma takes the more relaxed state) is found near the injection port, regardless of the polarity of V_H.

Although this injection affects the plasma more at the outer region of the plasma column, enhanced impurity production or a degradation of plasma performance are not observed. The induced voltage V_H without an injection measured as a function of D reflects the presence of the high-energy electrons.

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