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Helicity Injection Experiment in the SINP Tokamak

BHATTACHARYYA Krishnendu and RAY Nihar Ranjan*

Plasma Physics Division, Saha Institute Of Nuclear Physics, 1/AF, Bidhannagar, Calcutta-700064 (India)

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Abstract

The current drive or sustainment in magnetized toroidal resistive plasmas can be thought of as a "balance" between helicity injection and dissipation. In the present work, the mechanisms of the "balance" in the fluctuating magnetized resistive plasmas of the SINP tokamak, have been studied experimentally. The result shows that the oscillatory vertical magnetic field and oscillatory plasmas' velocity in a definite phase relationship causes the balancing effect between helicity injection and dissipation and thus sustainment of plasma current for a longer period of time has been observed in the resistive plasmas of the SINP tokamak.

1. Introduction

Recently there has been considerable interest in the idea of driving current in various fusion experiments by means of oscillating current drive helicity injection [1-3]. The method originally proposed for RFP's by Bevir and Gray [1] and called F-θ pumping, involves oscillating the current in the ohmic heating circuit and in the toroidal field circuit in a definite phase relationship. Essential to this proposal is the idea that magnetic helicity (K) in the plasma, which is closely related to the amount of plasma current sustained in a magnetized plasma, decays resistively as the current decays and by transporting helicity flux into the plasma, compensation of helicity loss can be made and the plasma might be indefinitely maintained close to its original state and thus helicity injection provides possible means of current drive in resistive plasmas. Since the magnetic helicity (K) is a linkage between toroidal and poloidal magnetic flux, therefore in a magnetically confined toroidal plasmas, the current drive or current sustainment can be thought of as a balance between helicity injection and helicity dissipation. As a mechanism, for the process of this "balance", the fluctuating magnetized plasma is assumed to have flux conversion mechanisms that convert one component of magnetic field to another, leaving the plasma in a preferred state, and in the process causing rapid penetration of skin currents induced at the plasma edge. There is ample experimental evidence that such a flux conversion mechanism is present in the RFP's and is responsible for maintaining the reversed state [4-5]. This mechanism of flux conversion is not studied very well experimentally in a tokamak plasmas accompanied by fluctuations, although there are attempts to drive current (externally) in a tokamak by oscillating the toroidal and poloidal fields [6] (AC helicity injection) or by injecting magnetized coaxial plasma gun (Spheromak injection), into the Encore tokamak [7]. For transporting helicity flux into the resistive plasmas, it seems that confining magnetic field is to be generated partially by plasma fluctuations within the plasma as an effect of helicity injection [4] and this effect can be effectively treated in a cylindrical plasma using resistive magnetohydrodynamics (MHD), called resistive MHD dynamo. The boundary of the plasma plays a key role on the MHD dynamo in laboratory plasmas and this has been predicted in the helicity dissipation model by Jarobe and Alper [8]. The motivation of the present work is to study the process of helicity "balance" in the low β SINP tokamak accompanied by fluctuating plasma and compare the observed experimental results with the prediction of the model of Jarobe and Alper. In short, the

*Corresponding author's e-mail: nihar@hp2.saha.ernet.in

model is described below: Using the helicity balance assumption, the time rate of change of helicity is given by [8]:

$$dK / dt = -2\int \boldsymbol{E}\cdot\boldsymbol{B}\, d(vol) + 2\int \boldsymbol{E}_v\cdot\boldsymbol{B}_v\, d(vol) \qquad (1)$$

where $\boldsymbol{E}_v$ and $\boldsymbol{B}_v$ are values of electric and magnetic fields that would be produced in a vacuum by the same flux, linking the boundary, that are present in the plasma. The $\boldsymbol{E}$ and $\boldsymbol{B}$ are the fields in the plasmas. The first term on the right is the "dissipation" and the second term is the "injection". For a tokamak having vacuum region between plasma and conducting wall, the injection may be assumed as $2V_\varphi\ \phi$, where ϕ and V_φ are the toroidal flux and loop voltage. In the steady state $dK/dt \equiv 0$, thus,

$$\int \boldsymbol{E}\cdot \boldsymbol{B}\, d(vol) = V_\varphi \phi \qquad (2)$$

From the assumption that helicity dissipation takes place in the cold plasma regions where $E_{\|}$ = constant = $\eta_{spitzer}\ j_{\|}{}^0$, where $j_{\|}{}^0$ equilibrium current density parallel to B_ϕ, and using equation (2) one can write:

$$V_\varphi = (E_{\|}\, V_e\ \theta)/\pi a^2 + IR_k \qquad (3)$$

Where V_e is the volume of the edge region as defined by limiters and field errors; θ is pinch parameter (~ a/R); $IR_k\phi$ represents the dissipation in the bulk of the plasma. Some interesting predictions can be made from the eq. (3): for the given values of $E_{\|}$, V_e , θ and a, the helicity dissipation $IR_k\phi$ can be compensated by increasing the loop voltage *i.e.* increasing the helicity injection rate. We did experiment to explore this phenomenon in the low β SINP tokamak accompanied by fluctuating plasmas.

2. Apparatus and Experiments

The SINP-tokamak is a small iron core tokamak (R = 0.3 m, a_W = 0.085 m, volt-sec = 0.12; stainless steel vacuum chamber wall thickness = 5 mm with two ceramic breaks at two toroidal locations 180° apart; two movable poloidal limiters, mounted at vertically up and down ports at the same toroidal location, adjust the plasma minor radius to a maximum of 0.075 m, one fixed poloidal limiter of minor radius = 0.075 m; the machine has a aluminum shell with minor radius of 0.109 m and thickness of 7 mm surrounding the vacuum vessel, the shell has two poloidal and four toroidal cuts for field penetration). Three independent power supplies deliver unidirectional currents to the toroidal and poloidal field coils and the primary coil of the ohmic transformer. The base pressure is around 1×10^{-7} torr in the vacuum chamber. The plasma current I_φ is measured by Rogowoskii coil, toroidal loop voltage V_φ by an one turn flux loop along the major circumference of the torus surface, whereas there is an one turn flux loop along the minor circumference to measure the toroidal flux and the poloidal loop voltage V_θ. In the present experiment, we operated the SINP tokamak with limiter radius a_L of 0.07 m, gas (hydrogen) filling pressure of 0.2 to 0.3 mTorr, applied V_φ of 27 volts and applied B_{vert} is 15 to 50 Gauss. Typical parameters of the discharges are: peak current I_φ = 5–6 kAmp, $n_e = 3 \times 10^{18}$ m^{-3}, T_e = 10–15 eV, Spitzer resistivity $\eta \approx 5 \times 10^{-5}$ Ω-m and B_φ = 0.15 T.

3. Results and Discussions

The interesting observations come from the effect of variation of the magnitude of vertical magnetic field B_{vert} keeping all other operating parameters fixed. When B_{vert} was above 60 gauss the plasma current rose to a peak value around 12 kAmp and showed its usual behavior (see Fig. 1b), i.e., it rose towards the peak value, stayed nearly constant and decayed slowly thereafter. Total duration of the discharges under this condition were not more than 3 msecs. However, as B_{vert} was gradually lowered we started observing an oscillatory nature in the plasma current I_φ occurring spontaneously. Though the peak current did not rise as high, the discharge duration increased substantially. The number of intrinsic oscillation cycles increased more and more as B_{vert} was lowered further in the range of 20–50 gauss. The observations were highly reproducible and a typical one with B_{vert} = 30 gauss is shown in Fig. 1a. The important features of the experimental measurements on oscillatory plasma current and loop voltages (toroidal & poloidal) shown in Fig. 2 are that the plasma current rose to a peak value of about 6 kAmp at about t = 0.5 msec from the beginning of the current rise (Fig. 2c), after which it started decaying fast in a time scale ~ several hundreds of microsecs. This is then followed by repetitive slow current rise and fast crash for several cycles and the discharge was sustained for more than 5 msecs. Similar oscillatory nature was observed in the signals of V_φ and V_θ respectively (Figs. 2a & 2b). In order to study the helicity balance, as predicted in the model of Jarobe & Alper, plasma's helicity was measured using internal magnetic probes at different minor radius r and using the formula:

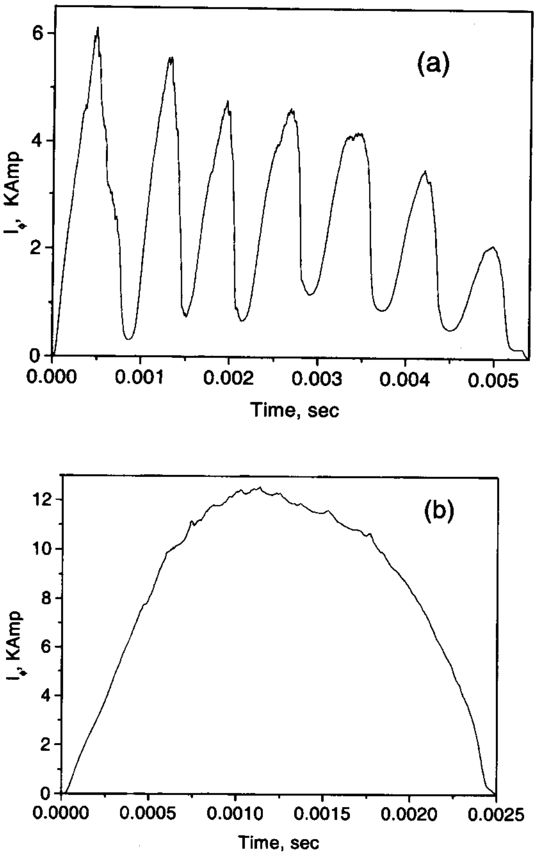

Fig. 1 Plasma current (I_φ) vs. Time

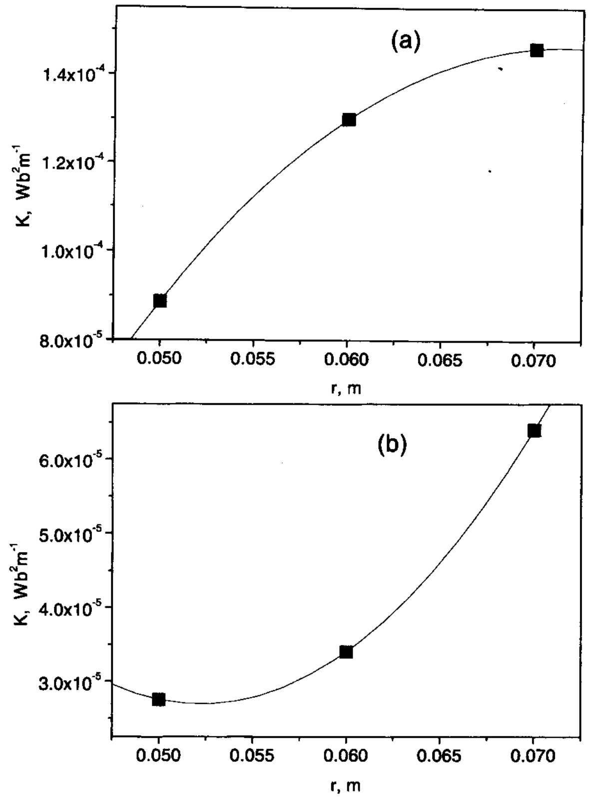

Fig. 3 Helicity (K) per unit length vs. Radius (r): (a) During peak plasma current, (b) After the crash of plasma current.

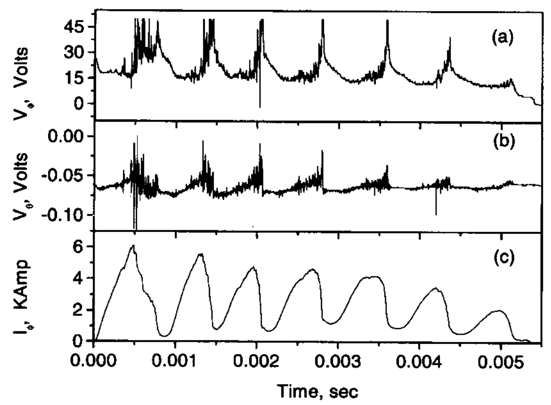

Fig 2. (a)Toroidal loop Voltage (V_φ), (b) Poloidal loop voltage (V_θ) and (c) Plasma current (I_φ) vs. Time.

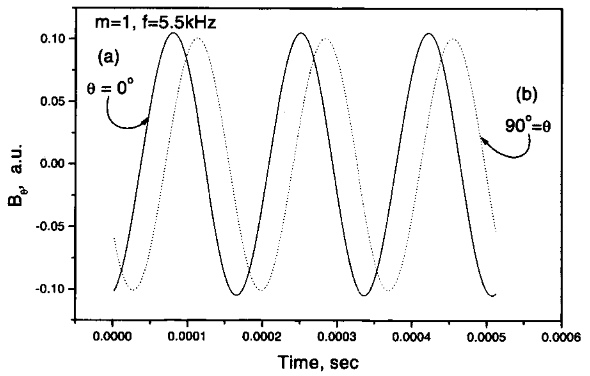

Fig 4. Poloidal magnetic field (B_θ) vs. Time at (*a*) $\theta = 0°$ probe and (b) $\theta = 90°$ probe.

$$K(r) = \left[A_\varphi(r)\,B_\varphi(r) + A_\theta(r)\,B_\theta(r)\right]\pi\, r^2 \quad \mathrm{Wb^2m^{-1}} \qquad (4)$$

Where A's are components of vector potential and B's are components of magnetic fields. The typical estimated values of $K(r)$ at peak I_φ and at minimum I_φ after the crash of current, are shown in Fig. 3. The result (Fig. 3) shows that there is decrease of K by about 70% in the inner region of plasma and about 60% in the outer region of plasma during crash of plasma current. The result (Fig. 2a) shows that the loop voltage V_φ is increased transiently during the fast crash of plasma current (Fig.

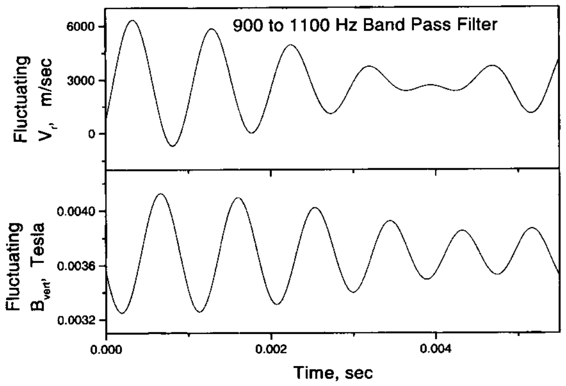

Fig. 5 (a) Fluctuating plasma velocity v_r and (b) Fluctuating vertical magnetic fild B_{vert} vs. Time.

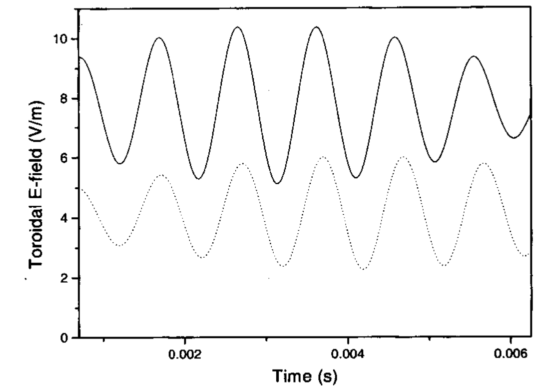

Fig. 6 Toroidal electric field vs. time. Dotted curve estimated from $\boldsymbol{v}_r \times \boldsymbol{B}_{vert}$ and solid curve from V_φ.

2c) *i.e.* helicity injection rate is increased by about 70% to 80%. Here the vacuum region $\approx$ 1%, $\theta \approx 0.23$, $E_{\|} \approx$ 10 V/m and the volt-sec consumption during the transient crash period of current $\approx$ 15% (the stored volt-sec = 0.12). That helicity dissipation during current crash is associated with tearing activity is shown in Fig. 4, as measured by two magnetic probes $\theta = 0°$ and $\theta = 90°$. Therefore the present result shows that under the typical operating condition of the tokamak discharge, the helicity dissipation in the resistive plasma is being compensated by the transiently increased helicity injection rate, as predicted in the model. In order to find out the key role of the vertical magnetic field we have estimated the vertical electric field from the measured value of top-bottom floating potential by Langmuir probes (assuming temperature constant). The result shows that imbalance between $\boldsymbol{E}_{vert} \times \boldsymbol{B}_\phi$ and $\boldsymbol{E}_\phi \times \boldsymbol{B}_{vert}$ forces causes fluctuating plasma velocity $\boldsymbol{v}_r$. Now the fluctuating $\boldsymbol{v}_r$ and fluctuating $\boldsymbol{B}_{vert}$ in the plasma with a definite phase relationship, as shown in Fig. 5, may cause the generation of confining magnetic field in the plasma according to Ohm's law $\boldsymbol{E}_\phi \approx \boldsymbol{v}_r \times \boldsymbol{B}_{vert}$, which we call a flux conversion mechanism due to fluctuating magnetized plasma. Therefore, due to outward particle transport causing up-down asymmetry (observed in tokamaks very often [9]) the flux conversion mechanism can be triggered by oscillating the vertical magnetic field $\boldsymbol{B}_{vert}$ and oscillating the plasmas' velocity $\boldsymbol{v}_r$ and as a result helicity transport from outward to inward may be possible in a tokamak accompanied by fluctuating plasma. The estimated value of toroidal electric field $\boldsymbol{E}_\varphi$ from the measured values of $\boldsymbol{v}_r$ and $\boldsymbol{B}_{vert}$ (Fig. 5) is shown in Fig. 6 (dotted curve) and the estimated value of toroidal electric field $\boldsymbol{E}_\varphi$ from the measured value of V_φ (Fig. 2a) is shown in Fig. 6 (solid curve). The magnitude of $\boldsymbol{E}_\varphi$ (solid curve of Fig. 6) incorporates all other contributions (i.e. $\boldsymbol{j} \times \boldsymbol{B}$, ∇p_e, etc.) besides that from $\boldsymbol{v}_r \times \boldsymbol{B}_{vert}$.

4. Conclusions

In the helicity injection experiment at the low β SINP tokamak accompanied by fluctuating plasma it is observed that the balance between helicity dissipation in the plasma and helicity injection is approximately according to the model of Jarobe and Alper and the vertical magnetic field $\boldsymbol{B}_{vert}$ plays a key role in this balancing process. Also it is observed that due to outward particle transport, inward helicity transport is possible, provided vertical magnetic field and plasma's velocity are oscillated at low frequency with a definite phase relationship. The experiment also shows increase of duration of plasma current i.e. sustainment of plasma due to balancing effect between helicity dissipation and injection. Therefore helicity dissipation due to tearing activity may be balanced by helicity injection in resistive plasmas by means of $\boldsymbol{v}_r \times \boldsymbol{B}_{vert}$ force and current can be driven for a longer period of time in the tokamak, provided there is sufficient amount of stored volt-sec in the tokamak.

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