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– a new approach to high-β equilibrium –

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Abstract
Departure from the quasi-neutral condition allows us to apply significant two-fluid effects that impart a new freedom to the design of high-performance fusion plasma. The self-electric field in a non-neutralized plasma induces a strong $\boldsymbol{E} \times \boldsymbol{B}$-drift flow. A fast flow produces a large hydrodynamic pressure that can balance with the thermal pressure of the plasma. Basic concepts to produce a toroidal non-neutral plasma have been examined on the internal-conductor toroidal confinement device Proto-RT. A magnetic separatrix determines the boundary of the confinement region. Electrons describe chaotic orbits in the neighborhood of the magnetic null point on the separatrix. The chaos yields collisionless diffusion of electrons from the particle source (electron gun) towards the confinement region. Collisionless heating also occurs in the magnetic null region, which can be applied to produce a plasma.

1 INTRODUCTION

In a non-neutral plasma, the self-electric field induces a strong $\boldsymbol{E} \times \boldsymbol{B}$-drift flow. When the flow velocity is comparable to the Alfvén velocity, significant two-fluid effects incorporate to magnetohydrodynamics (MHD). A fast flow produces a large hydrodynamic pressure that can balance with the thermal pressure of the plasma. We find high-β (> 1) equilibria, which are suitable for the advanced fusion concept (Sec. 2). Such spinning equilibria may also be relevant to high-β plasmas observed in astronomical objects.

We constructed a proto-type experiment device (Proto-RT), and examined the basic mechanisms to produce and confine non-neutral plasmas. Figure 1 shows the geometry of the device. The coil system can produce a variety of magnetic-field configurations by combining a dipole field, vertical field and toroidal field. The dipole magnetic field is generated by an internal ring conductor (5 kA DC). A pair of external coils provides a vertical field to generate a separatrix (Fig. 2). Through the axis of the cylindrical chamber, we can apply a longitudinal current (30 kA DC). The toroidal magnetic field yields a magnetic shear.

This system applies the chaos of electron orbits in the neighborhood of the magnetic null point on the separatrix [1]. High-energy electrons are injected across the separatrix through chaotic orbits (Sec. 3). Radio-frequency (RF) plasma production experiment has demonstrated effective collisionless power absorption due to the chaos of electron motion (Sec. 4).

2 HIGH-β EQUILIBRIUM WITH STRONG FLOW

The relaxed state in an MHD plasma is shown to be a force-free (zero-β) paramagnetic magnetic field (Beltrami field) [2]. However, departure from the quasi-neutral condition enables us to apply significant two-fluid effects (electrostatic potential due to the non-neutrality and the Hall current) that impart a novel structure in the magnetic field. When the magnetic field, whose vorticity is the electric current, and the flow, which is primarily the ion velocity, have comparable magnitudes (in the Alfvén normalized units), the "flow-vorticity alignment condition" (Beltrami condition) must be satisfied simultaneously by the magnetic field and the flow [3]. An equivalent relation can be derived by an generalized relaxed-state argument [4]. The set of new solutions

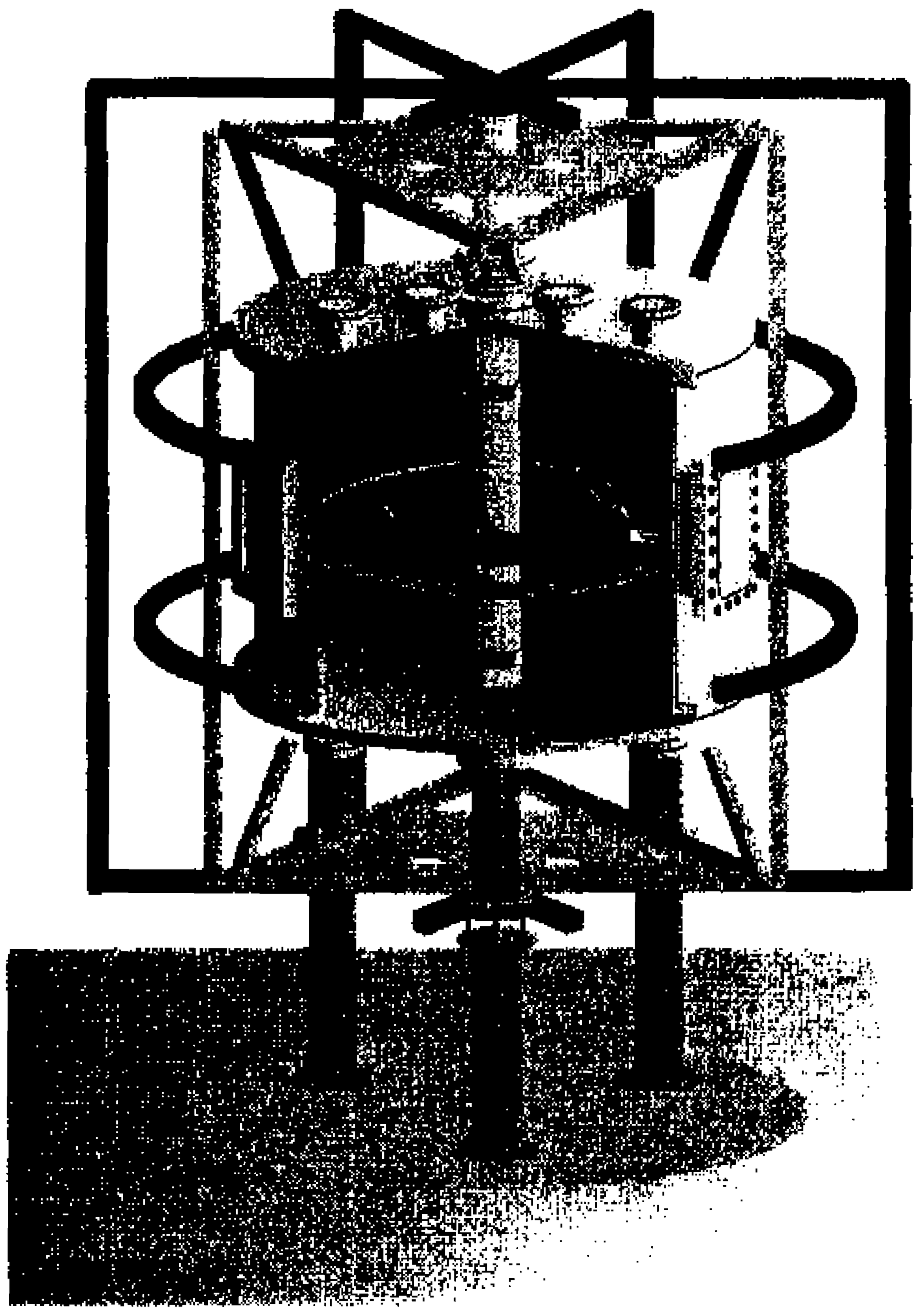

FIG. 1. Schematic view of Proto-RT; a toroidal non-neutral plasma confinement device. Dipole magnetic field is produced by an internal ring conductor. Toroidal magnetic field yields sheared magnetic field.

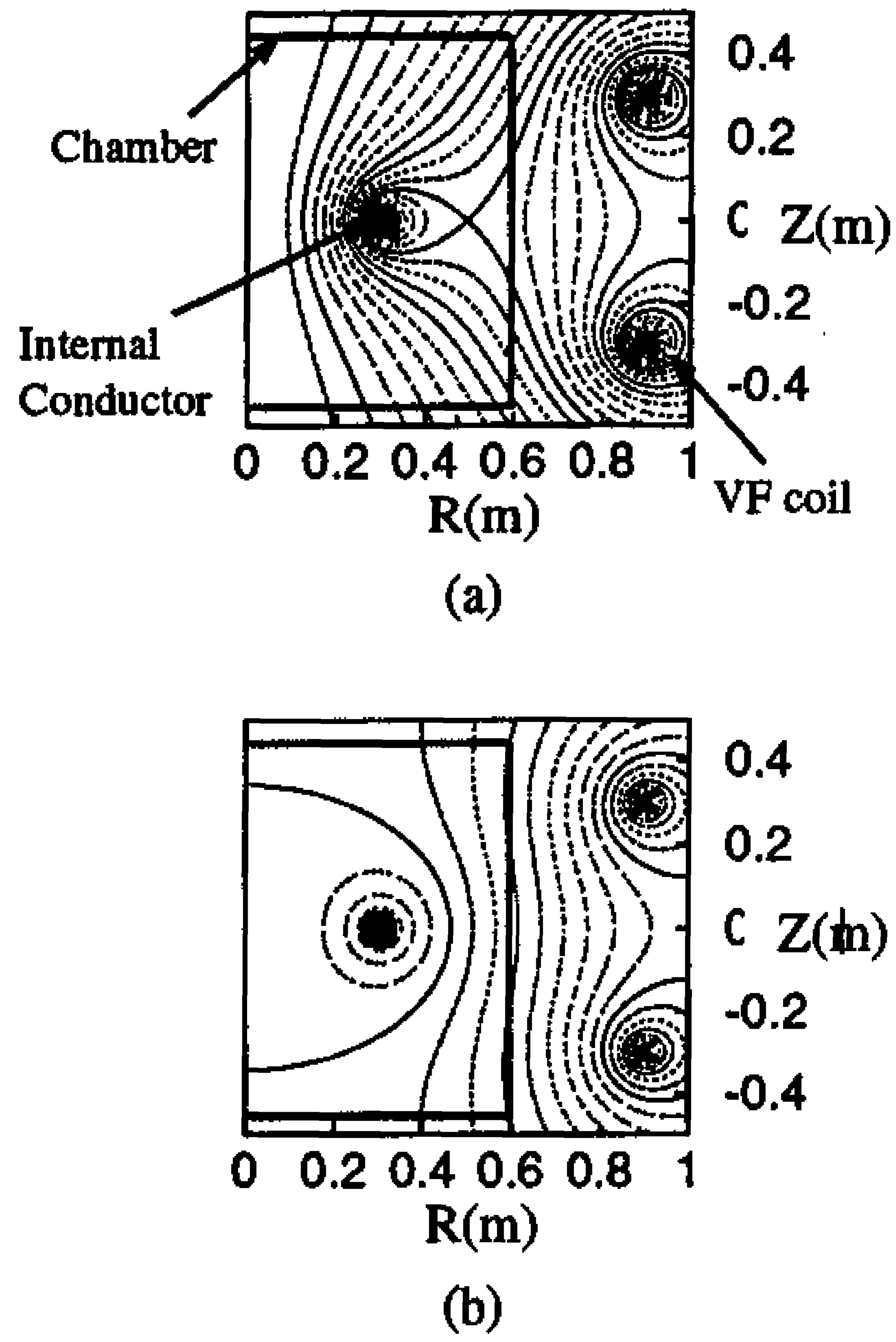

FIG. 2. Two types of magnetic surfaces; (a) The separatrix generates an X-point on the outside of the internal conductor. (b) The magnetic null points are located on the center axis.

contains field configurations which can be qualitatively different from the force-free paramagnetic magnetic fields (which are naturally included in the set). The larger new set may help us to understand a variety of structures generated in plasmas. It also opens up the possibility of experimenting with altogether different configurations, and some of which may lead to a novel regime of high-β plasma confinement.

The theory [3] predicts a generalized Bernoulli condition, which reads

$$\beta_i + \frac{1}{2}V^2 = \text{ constant,} \tag{1}$$

where β_i is the ion beta ratio and V is the ion flow velocity normalized by the Alfvén velocity. We note that the constancy of the left-hand side of (1) holds also in the transverse direction with respect to streamlines. This relation shows that an appropriate sheared velocity field can sustain the ion pressure gradient.

One possible experimental method to generate such a large flow is to introduce an appreciable charge non-neutrality, which drives the $\boldsymbol{E} \times \boldsymbol{B}$ drift spin. In Proto-RT, we started basic experiments to produce non-neutralized toroidal plasma and to study its stability.

3 PRODUCTION OF NON-NEUTRAL TOROIDAL PLASMA

Charged particles can have long orbit lengths in an appropriately designed magnetic field [1]. The key is to create a null point in the magnetic field, which destroys the adiabatic constants of motion. The resultant increase in the degree of freedom brings about chaos of particle motion, and the particle travels a very long distance before it comes back to the particle source. This effect is applied to achieve high efficiency of charged particle trapping.

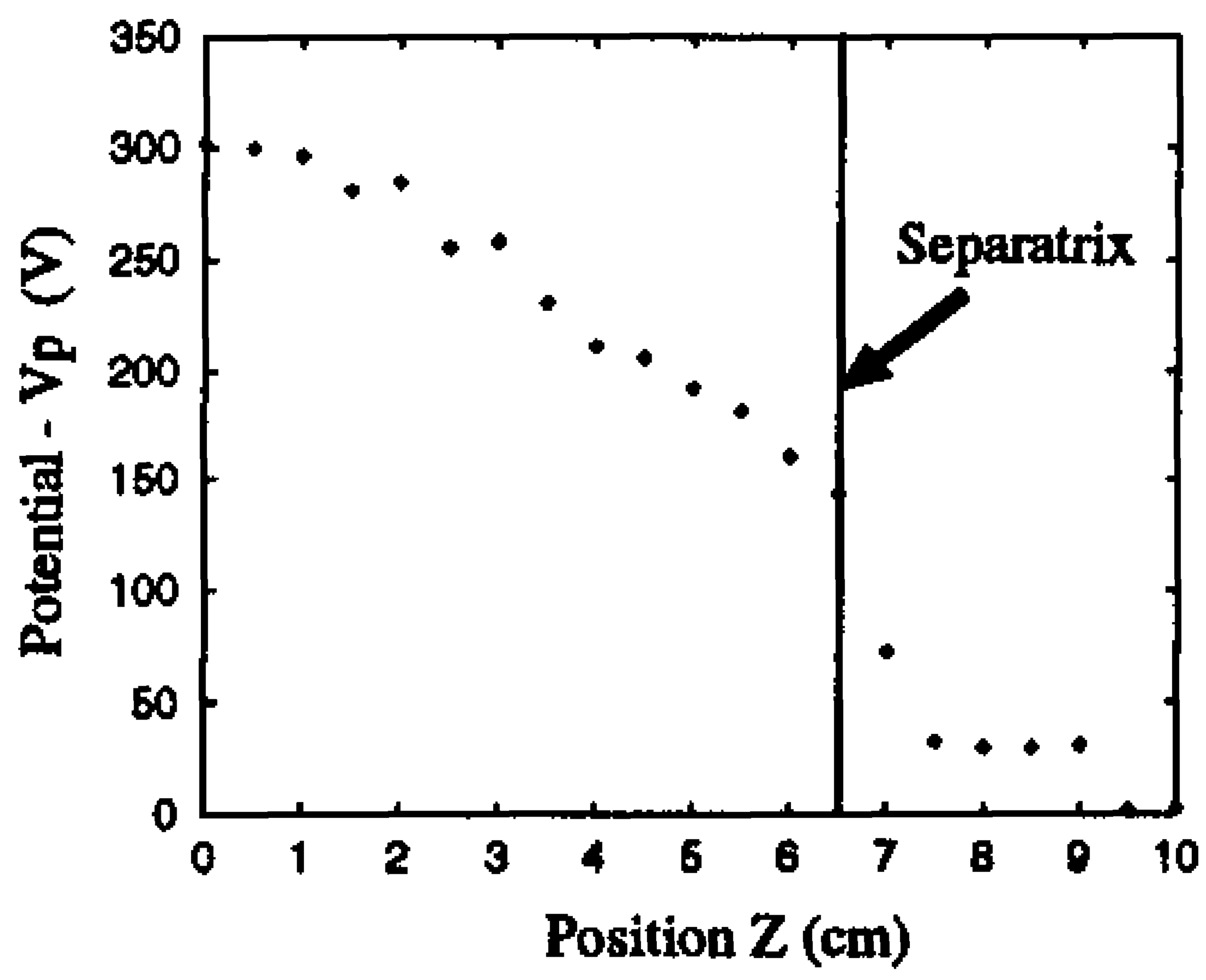

FIG. 3. Radial distribution of the electrostatic potential in a pure electron plasma.

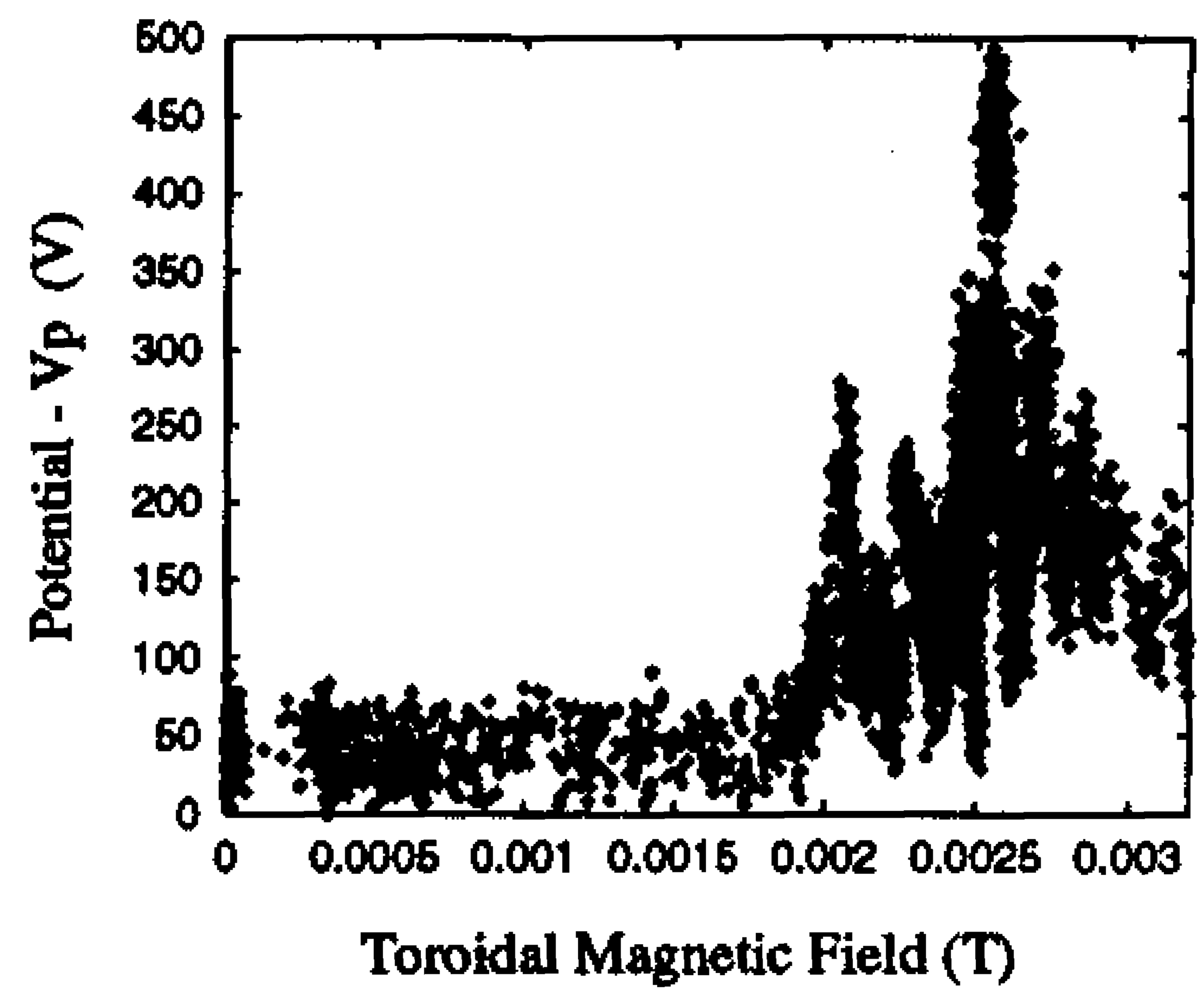

FIG. 4. Dependence of the confined plasma potential to the toroidal magnetic field.

A pure electron plasma is produced by injecting an electron beam. The poloidal magnetic field is of order 10^{-2} T, and the poloidal gyro-radius of an electron at the energy of 1 keV is of order 10 mm, which determines the length scale of the chaos region for the electron motion. The electron gun is placed near the magnetic null point. The calculated average connection length of a chaotic orbit is of order 100 m. Once the electron is decelerated in the confinement region, it will be trapped by the closed magnetic field.

We demonstrated steady state confinement of a pure electron plasma. The maximum electrostatic potential, achieved by injecting electrons with energy of 2 keV, was about 600 V. The corresponding $\boldsymbol{E} \times \boldsymbol{B}$-drift velocity is of order 10^6 m/s. Figure 3 shows the radial distribution of the electrostatic potential. A steep gradient of the potential appears near the separatrix ($z = 65$ mm), implying that the separatrix determines the confinement region. Inside the separatrix, the potential has an almost parabolic distribution. The electron density is of order 10^{12} m^{-3}.

By applying a toroidal magnetic field, we observe significant improvement of the confinement of electrons. The stored charge is a strong function of the toroidal magnetic field (Fig. 4), which implies that the stability of the non-neutral plasma depends on the magnetic shear. We observe electrostatic fluctuations in the frequency range of 10^6-10^7 Hz, which corresponds to the diocotron frequency. The magnitude of the fluctuation is about 10^{-3} of the ambient potential.

4 COLLISIONLESS HEATING AND DIFFUSION INDUCED BY CHAOS

The chaotic motion of electrons in the magnetic null region brings about rapid production of entropy, resulting in efficient collisionless heating of electrons at a low-collisionality regime. This nonlinear process can be applied to plasma production [5].

The combination of the chaos effect due to the inhomogeneous magnetic field and the inelastic collision effect yields an enhanced resistance. Inelastic collisions open a sink of energy (entropy) in the high-energy region of the velocity space. This non-equilibrium system is characterized by the cascade process driven by the mixing effect. The energy dissipation is determined by the speed of the cascade, which is scaled by the Lyapunov exponent, and the energy removal rate in the sink region. The theory predicts that the effective resistance is larger than the classical collisional resistance by factor $10 - 10^2$ [6].

We launch an RF electric field (13.56 MHz) by a toroidal loop antenna. The electric field strength is of order 1 kV/m. These parameters are optimized to maximize the Lyapunov exponent of particle orbits in the magnetic null region [5]. Figure 5 shows a photograph of the plasma light localized in the separatrix region. When we apply the same RF electric field without the magnetic field, the plasma production does not occur.

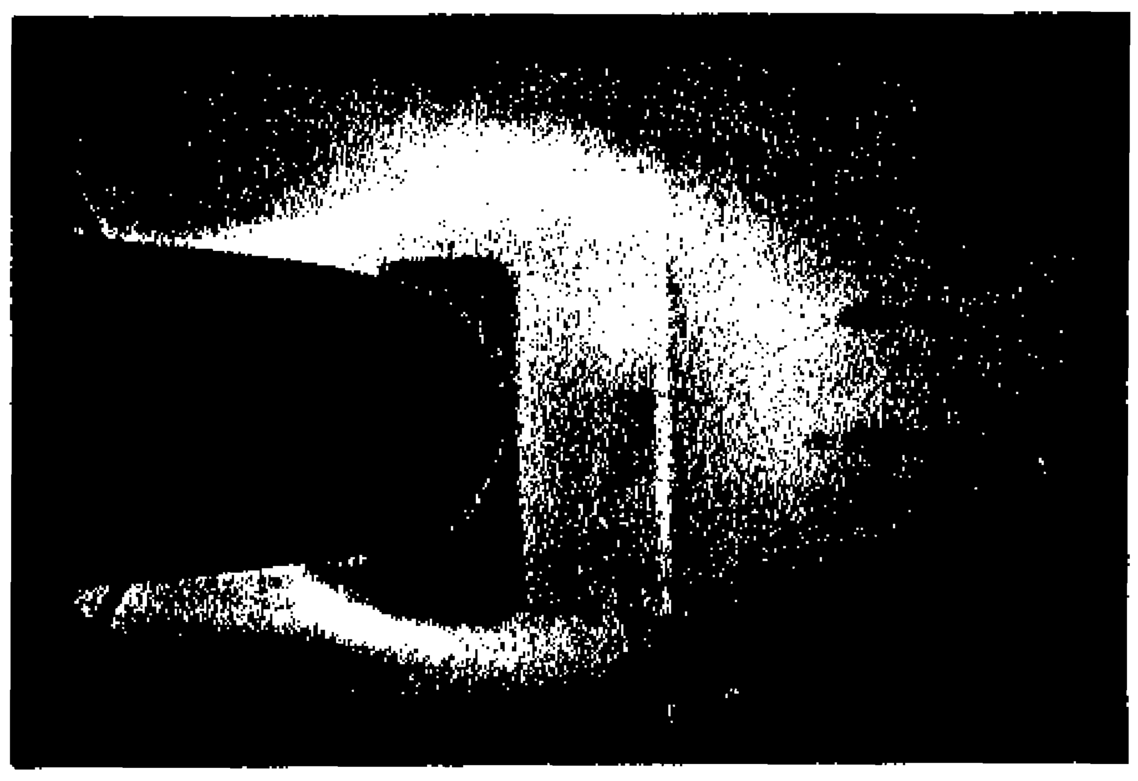

FIG. 5. RF production of a plasma using the chaos-induced collisionless power absorption. The plasma is produced in the magnetic null region and diffuses along the separatrix.

The entropy production due to the chaos is also applied to yield collisionless diffusion of electrons. As a result of the chaotic modulation of the angular momentum, the electrons can move across magnetic surfaces. Numerical simulations show that the spatial inhomogeneity of RF electric field enhances the diffusion of particles.

5 DISCUSSION

We have demonstrated the production of a toroidal non-neutral plasma and its stability in a sheared magnetic field. The experiment has been conducted on a proto-type device that uses insulated rods to support the internal conductor. After exploring characteristics of the non-neutral toroidal plasma, we will upgrade the device employing a levitated internal conductor, and will start the experiment of high-β plasmas. The principle of this confinement method is described by generalized Bernoulli's law. The plasma is primarily confined by the hydrodynamic pressure due to a strong shear flow which is produced by the radial self-electric field. Therefore, this scheme can be regarded as a new type of electric-field confinement.

The present research has many spin-offs. The device can be used as a charged particle trap to confine positrons, anti-protons and so on. The chaos-induced collisionless electron heating can be applied to produce plasmas at low gas pressure ($< 10^{-2}$ Pa) for the use in ultra-fine etching of semiconductors [7]. Moreover, this effect may play an important role in high-temperature plasmas such as solar corona and neutral sheet. At magnetic null points, magnetic field lines can reconnect if there is a finite resistivity (magnetic diffusivity). In many different examples, the classical collisional resistivity is too small to account for the observed reconnection rates. The chaos-induced resistivity is one candidate to explain the anomalous resistivity.

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