APPLICATION OF CHAOTIC ELECTRON MOTION FOR PLASMA PRODUCTION AND NON-NEUTRAL PLASMA TRAP

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1. Introduction

Null points in magnetic fields destroy the adiabatic invariants of charged particle motion, resulting in a chaotic motion. The mixing effect of the chaos produces efficient collisionless dissipations (heating and diffusion) in the system of electrons. The entropy production is represented by an effective resistance in a macroscopic description. This "chaos-induced resistance" enables plasma production at a low gas pressure suitable for ultra-fine plasma etching.

The same effect of chaos can be applied to obtain a large trapping efficiency in a non-neutral plasma confinement device. Charged particles can have long orbit lengths in a toroidal magnetic configuration that has a null point. The non-periodic orbit of chaotic motion travels a very long length before it comes back to the particle source, and hence, a slow method of modulating the kinetic energy applies to induce an effective diffusion of the particles toward the trapping region.

Experiments have been done on a proto-type internal-conductor device, which can produce a variety of magnetic-field configurations by combining a dipole field, vertical field and toroidal field. 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. Through the axis of the cylindrical chamber, we can apply a longitudinal current (30 kA DC). The toroidal magnetic field yields a magnetic shear.

2. Chaos-induced collisionless heating

Nonlinearity stems in the equation of motion of a charged particle from the spatial inhomogeneity of electromagnetic fields. The "magnetic null point" yields a strong enough nonlinearity to generate "chaos" of the particle motion [1]. The chaotic motion of electrons brings about rapid production of entropy, resulting in efficient heating of electrons at a low-collisionality regime. This nonlinear process can be applied to plasma production that meets the increasing demand for low-gas-pressure plasma source suitable for the use in ultra-fine etching of semiconductors [2, 3]. Moreover, this effect may play an important role in high-temperature plasmas such as solar corona, neutral sheet and fusion plasmas. At the magnetic null point, magnetic field lines can reconnect if there is a finite resistivity (magnetic diffusivity). In many different examples, the classical collisional resistivity, which is due to the scattering of current-carrying electrons by field particles, is very small and it cannot account for the realistic reconnection rates. Some different mechanisms have been proposed to explore the "anomalous resistivity", including the effect of the chaos.

First, we consider a collision-less electron that obeys Newton's equation of motion;

$$m\frac{d^2}{dt^2}\boldsymbol{X} = -e\left[\boldsymbol{E} + \left(\frac{d}{dt}\boldsymbol{X}\right) \times \boldsymbol{B}\right], \quad (1)$$

where m is the electron mass, e is the elementary charge, $\boldsymbol{E}$ and $\boldsymbol{B}$ are the electric field and magnetic field, respectively. If $\boldsymbol{E}$ and $\boldsymbol{B}$ are spatially homogeneous fields, (1) is a linear equation with respect to $\boldsymbol{X}$. For example, let us assume that $\boldsymbol{B}$ = constant and $\boldsymbol{E} = \Re e^{i\omega_0 t}\boldsymbol{E}_0$ ($\boldsymbol{E}_0$ = constant). If the frequency ω_0 is not resonant with the cyclotron frequency $\omega_c = eB/m$, the particle motion is periodic, and hence "heating" cannot occur. If we can introduce "disorder" to the system, we can heat electrons. Collisions randomize the phase of oscillations of particles, resulting in non-zero average of energy transfer from the electric field to particles. The other possible mechanism is the chaos that is a deterministic dynamics producing complex orbits of particles. Here, we consider a strongly inhomogeneous magnetic field that makes (1) nonlinear with respect to $\boldsymbol{X}$. When the adiabatic invariance of the magnetic moment is destroyed in the magnetic null region, the degree of freedom increases enough to generate chaotic motion of electrons.

In the collision-less chaotic system, an approximate canonical equilibrium is achieved after the rapid mixing phase that produces the entropy. There is an essential difference between the present collision-less chaotic system and the usual collisional system. The former system can absorb energy from the radio-frequency (RF) electric field in the first mixing phase, while the energy saturates and an approximate equilibrium state appears. In the latter case, however, unceasing heating must occur when we continue to apply an RF electric field without assuming an energy loss mechanism.

If we combine the chaos effect due to the inhomogeneous magnetic field and the inelastic collision effect, we obtain 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 (typically of the order of $\omega_0/10$), and the energy removal rate in the sink region. The effective resistivity is enhanced by the mixing effect of the chaos by a factor of $10 - 10^2$ in comparison with the case of $\boldsymbol{B} = 0$. The effective collision induced by the chaos is comparable to the scattering in a neutral gas of 0.1 Pa. These estimates are consistent to experimental observations [2, 3].

Radio-frequency (RF) plasma production experiment has demonstrated effective collision-less power absorption due to the chaos of electron motion, which may also be applied to induce an inward diffusion of electrons toward the confinement region (Sec. 3).

3. Production of non-neutral plasma

Charged particles can have long orbit lengths in an appropriately designed magnetic field [4]. The key is to create a null point (separatrix) in the magnetic field, which destroys the adiabatic constants of motion. The resultant increase in the degree of freedom results in chaotic 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.

A toroidal non-neutral plasma trap has been developed with applying the chaos of electron orbits in a separatrix region. 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. Electrons are injected by an electron gun placed near the separatrix. The calculated average connection length of a chaotic orbit is of order 100 m, which is comparable to the mean free path due to collisions with neutral particles at the pressure of 10^{-4} Pa.

By a movable probe, we measured the radial distribution of the electrostatic potential. A steep gradient of the potential appears near the separatrix ($z = 72$ mm), implying that the separatrix determines the confinement region. Inside the separatrix, the potential has an almost flat distribution, which shows that the electron density has a parabolic distribution. The electron density is estimated to be $3 \times 10^{11}\ \mathrm{m}^{-3}$. By applying a toroidal magnetic field, we observe significant improvement of the confinement of electrons.

4. High-β plasma with strong shear flow

The advantage of the dipole magnetic field to confine high-β plasmas and RF-induced particle injection were discussed by Hasegawa *et al.* [5]. In our experiment, we generate a strong flow by producing a non-neutral plasma. When the flow velocity is comparable to the Alfvén speed (which is smaller than the ion sound speed, if $\beta > 1$), a different high-β equilibrium appears in which the plasma pressure is primarily balanced by the dynamic pressure of the flow. This configuration is described by a generalized Bernoulli's law [6]. The innovative methods described in the preceding sections can be applied to produce a non-neutral high-β plasma.

References

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