Electrically Nonneutralized Plasmas for Hydrodynamic Confinement

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Abstract. A high-β equilibrium was theoretically predicted by the Beltrami/Bernoulli conditions. In order to obtain such attractive plasmas an innovative method using electrically non-neutralized plasmas has been proposed, and the experiments to demonstrate it have been conducted on Proto-RT and BX-U. Energetic electrons are successfully injected across vacuum magnetic fields and a strong self-electric field, which is sufficient to drive a super-Alfvenic flow in a target plasma, is formed by the electrons. However, in the target plasma frictional forces would damp the flow, resulting in loss of the electrons. An initial experimental result on the loss of electrons is presented.

1. Introduction

When a strong shear flow is driven in plasmas, the set of self-organized states becomes far richer than the conventional prediction. The two-fluid effect brings about an essential coupling among the flow, magnetic field, electric field and the pressure. In order to invoke such effect, which naturally shrinks, one needs to drive a strong shear flow. It is equivalent to giving an internal electric field (non-neutralization) or applying a steep gradient in pressure since these fields are self-consistently coupled. The hydrodynamic pressure of a shear flow can yield a diamagnetic structure [1] that is suitable for high-β plasma confinement (Sec. 2). The H-mode boundary layer in tokamak plasmas is one of the examples of such hydrodynamic structures [2], which is spontaneously generated by the core plasma pressure. Active control of shear flow will extend the applicability of such self-organized state.

In order to produce electrically non-neutralized plasmas, we have explored an innovative method [3] of injecting energetic electrons (2 keV) into a torus through magnetic null (Sec. 3) on Proto-RT (Prototype Ring Trap) device [4] shown in Fig. 1 (a). At the first series of experiments on Proto-RT, electrons had successfully been injected into a vacuum toroidal magnetic field across closed magnetic surfaces. Despite of weak magnetic field strength (~ 0.01 T) of Proto-RT, broad radial profiles of floating potential Φ up to 1 kV have been observed by a high-impedance probe. This result indicates that the high-energy electrons are successfully trapped in closed magnetic fields. The space potential Φ_p formed by the trapped electrons and the expected perpendicular electron flow have also been measured by a pair of emissive and directional probes. Preliminarily measurements show that the value of Φ_p is around hundred volts, which is sufficient to drive a strong flow. In fact, the flow speed can reach super-Alfvenic [4] in a target plasma having n_0 ~ 10^{19} m^{-3} on Proto-RT, because of the weak magnetic field. However, when the electrons are injected to the target plasma, frictional forces (Sec. 4) working on ions would damp the perpendicular flow, resulting in the decrease in the self-electric field caused by loss of the electrons. Currently, damping of flows is one of key physics issues, thus systematic studies on the flow damping will contribute much to plasma physics. Such phenomenon has clearly been observed even in toroidal pure electron plasmas where the collisions against the background neutrals act as the frictional force. In

Fig. 1 (a) Prototype ring trap device: Proto-RT. *(b) Beam experiment upgrade: BX-U.*

order to systematically study on this flow damp and related fundamental physics, we have an experimental plan on our upgraded linear device BX-U shown in Fig. 1 (b) and will operate it soon.

2. High-β plasma equilibrium with strong shear flow

The Beltrami/Bernoulli conditions describe a relaxed state of a general vortex dynamics system. The Beltrami condition demands that the vorticity parallel the flow and the generalized Bernoulli condition implies that the energy density takes a flat distribution [1]. In a two-fluid MHD plasma, these conditions read as simultaneous system of equations both for electrons and ions. By the Beltrami conditions, electrons flow in the direction of magnetic fields **B**, while the ion flow (**v**) parallels **B** + curl **v**; the second term represents the Coriolis force. A linear combination of two force-free fields solves this simultaneous Beltrami conditions [1], which is no longer force free. The pressures are given by the Bernoulli conditions that read as $p_e - en\phi$ = constant and $p_I + en\phi + \rho v^2/2$ = constant, where p_e, p_i, n, ϕ, and ρ are pressures of electrons and ions, number density, electric potential, and mass density, respectively. Adding both equations, we obtain

$$\beta + V^2 = \text{constant} \tag{1}$$

for the velocity V in the Alfven unit [1].

3. Electron injection across magnetic surfaces

As a method of injecting electrons across magnetic fields, we have proposed an innovative method, an application of chaos [3]. In order to demonstrate this idea, experiments are performed on Proto-RT (Prototype Ring Trap).

Proto-RT is one of internal ring devices, which contains an internal ring conductor inside the vacuum vessel to produce poloidal magnetic fields and has externally equipped vertical and toroidal coils. Detailed description about the device is found in Ref. [4]. The fields of Proto-RT are completely static so that experiments can be conducted in well-controlled laboratory settings. Moreover the three coils can independently be energized, which provides a great flexibility to produce various magnetic field configurations such as Dipole-like configuration with/without magnetic shear and closed-field configurations with magnetic null (X point). An electron beam with 2 keV (beam density ~ 5×10^{13} m^{-3}) was launched from a hairpin shaped Tungsten filament of an electron gun.

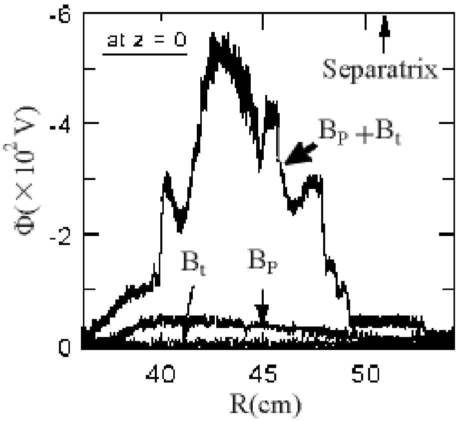

Fig.2.Radial profiles of ϕ measured in three different combinations of B_t and B_P.

The electrons injected from the gun across magnetic fields are successfully confined inside a separatrix. As seen from Fig. 2, the floating potential Φ measured by a high-impedance probe shows spatially broad profile for all of different three magnetic field configurations. The spikes observed in the profile seem to reflect the existence of beam electrons. For an X-point configuration with magnetic shear (the 'B_p and B_t' case), the value of Φ significantly increases up to 500 V, implying that the electrons are well confined inside a separatrix and attain an equilibrium flow.

To verify such equilibrium flow, a pair of emissive and directional probes has been installed in the toroidal electron plasmas. Usually it is very difficult to detect the perpendicular motion of electrons by the probe because the parallel thermal motion of electrons is still faster in strong magnetic field even if the electrons travel across a magnetic field. However, on Proto-RT the strength of **B** is relatively weak (10^{-3} to 10^{-2} T) and moreover, strong **E** (10^3 to 10^4 V/m) would exist in the whole plasma region because of charge nonneutrality. Thus, the perpendicular flow velocity (10^5 to 10^7 m/s) is expected to be comparable to the parallel thermal velocity (~10^6 m/s), which allows the probe to detect the flow.

Figure 3 shows a typical current-voltage characteristics taken from a directional probe at r = 44 cm, which consists of four electrostatic probes (W: ϕ0.7, each being covered by ϕ1.2 ceramic tube), for Dipole-like configuration. Substantial difference of current between the upstream perpendicular- and the downstream perpendicular direction can clearly be recognized. The space potential Φ_p is simultaneously measured by the emissive probe and the value is about 55 eV. As will be shown later, the density of the electron plasmas in Proto-RT is in the range from 10^{12} to 10^{13} m^{-3}. Thus the Debye length λ_D is about 1 - 5 cm for T_e ~ 20 eV which is much longer than the characteristic probe dimension R. On the other hand, the electron mean free path λ against the background neutrals (~10^{16} m^{-3}) for the typical vacuum (3×10^{-7} Torr) is about 10^4 m. These show $\lambda >> \lambda_D >> R$. Therefore, the probe collects orbital motion limit (OML) current. Under this limit, the electron current in the electron-retarding region for cylindrical probe is described by

$$i_{ret} \approx \exp(\phi_p)\left[1+(1/2-\phi_p)S_e^2+({\phi_p}^4/4+\phi_p/4-1/16)S_e^4\right]$$

where ϕ_p is a probe voltage normalized by T_e and S_e $(=v_f/v_e)$ is a ratio of flow speed v_f to electron thermal velocity v_e. From the fitting curves on the measured data, the perpendicular flow and the electron temperature can be estimated to be 6.6×10^6 m/s and ~ 20 eV,

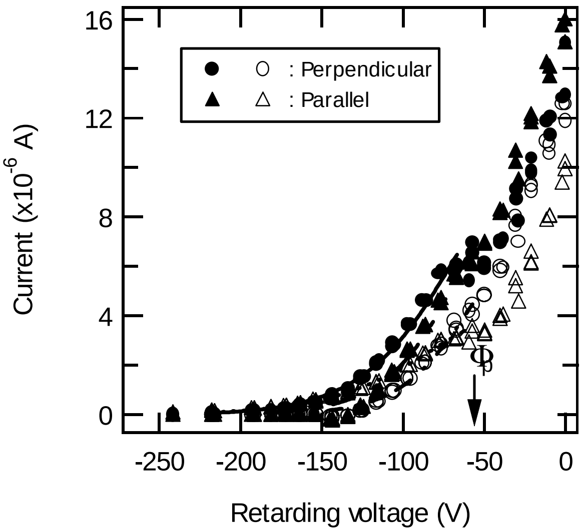

Fig. 3 Current-voltage characteristics of a directional probe installed in electron plasmas.

respectively. This flow direction is corresponding to $-\nabla\Phi_p\times\mathbf{B}$ direction. On the other hand, from the radial profile of Φ_p (Fig. 4, for example) the value of E_r is estimated to be at most 10^3 V/m, indicating 4×10^5 m/s as $\mathbf{E}\times\mathbf{B}$ flow speed. In this experiment for Dipole-like configuration, the electron diamagnetic drift (~ 7×10^3 m/s) is too small to explain the discrepancy. Although the reason is still unknown, it may attribute to the beam components of electrons emitted from the electron gun.

4. Flow damping

As described in Sec. 3, the perpendicular flow velocity of electrons is 10^5 - 10^6 m/s in Proto-RT. This is enough to cause a strong flow if the energetic electrons are still successfully injected and confined even in a background charge neutral plasma with a density of ~ 10^{19} m^{-3}. The expected flow could be super Alfvenic for the plasma in $\mathbf{B}$ ~ 10^{-2} T; indeed for this case v_A (v_A: Alfven speed) ~ 5×10^4 m/s. However, the flow speed would be reduced if the drag force works on ions in a background plasma, resulting in decrease of strength of $\mathbf{E}$ which causes loss of the electrons. In fact, no perpendicular flow was observed in the experiments where the electrons are injected into an RF (13.56 MHz) produced plasma (~10^{12} m^{-3}) with up to 4 kW power at P_0 ~ 5×10^{-5} Torr (~10^{18} m^{-3}). However, in the experiment, ion collision frequency ν_n against neutrals was almost same as the ion gyrofrequency ω_{ci}; ν_n was calculated to be 3.6×10^5 s^{-1}, while ω_{ci} was 3×10^5 s^{-1}. Thus it was hardly to say that the drift motion itself occurred in this experiment.

The damping process of such perpendicular flow can clearly be observed in toroidal electron plasma experiments where collisions against neutrals act as the effective frictional force $\mathbf{F}_{\mathbf{fric}}$. The data plotted in Fig. 4 shows the radial profiles of Φ_p and particle flux nV at Φ_p for the cases of (a) ν_n ~ 5×10^5 s^{-1}, (b) ν_n ~ 5×10^4 s^{-1}, and (c) ν_n ~ 5×10^3 s^{-1} where ν_n is the collision frequency for scattering of electrons moving at v_e ~ 10^6 m/s. Although the data show nV, a tendency of shear flow profile seems to appear. For the case of (b), the difference of nV between the perpendicular upstream- and the downstream direction is almost 0 at r ~ 44 cm where the value of $-\nabla\Phi_p$ is also nearly 0. This difference grows larger outside the region where the negative radial electric field $-E_r$ exists. This flow direction is corresponding to $\mathbf{E}\times\mathbf{B}$ direction. However, no reversed perpendicular flow can so far clearly observed in the inside

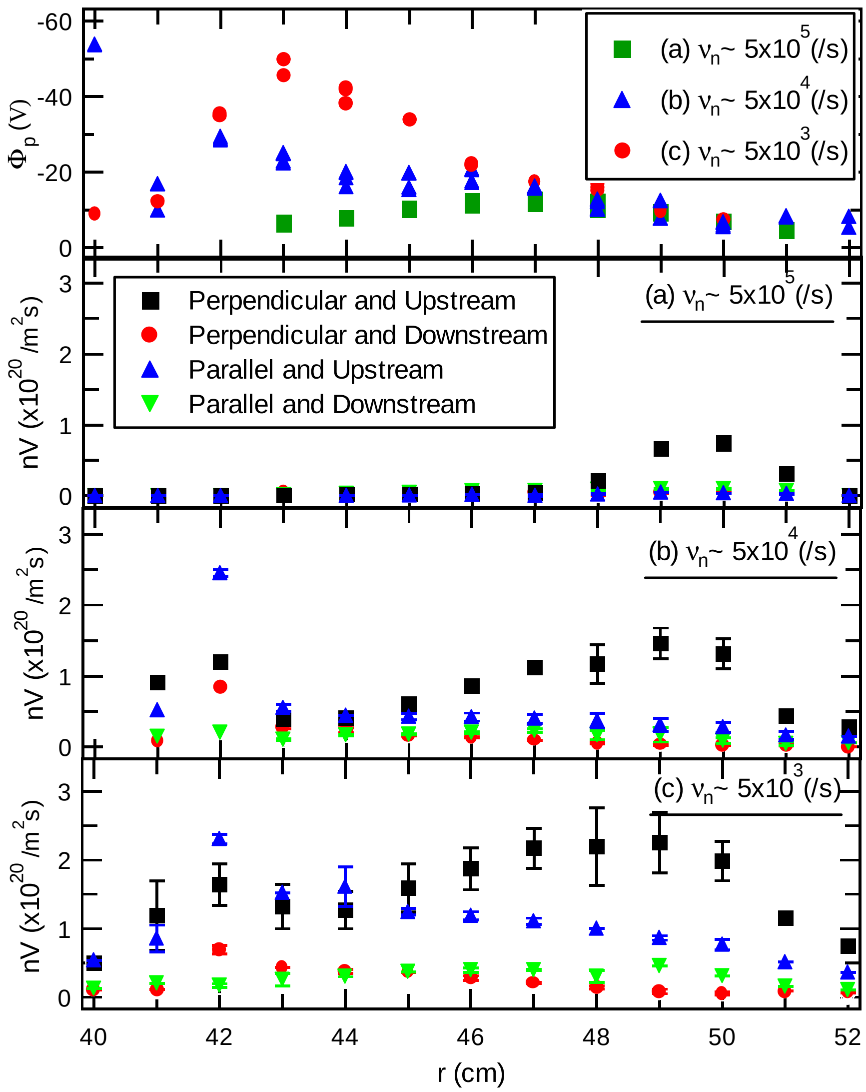

Fig. 4 Radial profiles of the space potential and particle flux measured in Dipole-like configuration for the case of (a) $\nu_n \sim 5\times10^5\ s^{-1}$, (b) $\nu_n \sim 5\times10^4\ s^{-1}$, and (c) $\nu_n \sim 5\times10^3\ s^{-1}$.

of r ~ 44 cm where large scattering of the data are observed, possibly due to strong turbulence around the region. As the flow is damped, the flow profile shifts slightly outside, probably due to the effect of $\mathbf{F}_{\mathbf{fric}}\times\mathbf{B}$ outward drifting. Indeed, the drift is negligible for the case of (c) ($v_d \sim 10^2$ m/s), while for the case of (a) v_d is calculated to be ~ 10^4 m/s. Finally, it should be pointed out that the parallel flow seems to be induced as $\mathbf{F}_{\mathbf{fric}}$ becomes weaker. This experiment is performed on Dipole-like configuration so that we think no parallel flow could be occurred. It actually might attributed to the continuous flowing of electrons from the electron gun. Further studies are required to conclude it confidently.

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