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Proposed Non-neutralized Two-Fluid Plasma Experiment

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Abstract. An experimental test of generating ion flow under a complete charge non-neutral condition is proposed. On the experiment, a quasi-neutral plasma is injected into a pure electron plasma which is confined in a Malmberg type trap. So far, the device named BX-U (Beam Experiment Upgrade) confines only electrons having density of $10^{11 \sim 12}$ m^{-3} for ~ 0.3 s with $B_z \sim 50$ G. After completing a plasma gun, the first series of a two-fluid plasma experiment will be initiated.

I INTRODUCTION

A possibility of extremely high-β equilibrium (β can exceed unity) with a strong sheared flow was theoretically pointed out, which was based on the double-curl Beltrami field [1]. In fact, under some theoretical and simulation works obtain several high-β solutions in both cylindrical and toroidal geometry. The requirement to this high-β equilibrium is to maintain two-fluid effects with the large velocity field whose magnitude is comparable to that of the magnetic field in the plasma. Another significant feature of the high-β equilibrium is that the thermal pressure of plasmas is sustained by the hydrodynamic pressure of the strong shear flow, alleviating the strength of magnetic fields to confine the plasmas which offers attractive benefits including the lowest construction costs among toroidal fusion systems.

To generate such a fast flow in a plasma, a charge non-neutral condition has been proposed [2] which inherently produces a strong self-electric field **E** inside the plasma, causing a fast **E** × **B** sheared flow if we apply an appropriate magnetic field **B**. Then the question is asked on how such a non-neutralized plasma can be produced in laboratory experiments. Although several methods can be considered, we have proposed to add a charge neutral plasma to a pure electron plasma. If the two plasmas are well mixed together, a perpendicular

ion flow would be driven inside the two-fluid plasma due to **E**. Furthermore, if the flow is fast enough in the electrically non-neutralized plasma, the structure of **B** may exhibit a diamagnetic profile, which is required to attain a high-β value, as the theory [1] points out.

In order to explore this way, we have conducted experiments on a toroidal machine Proto-RT [3] and recently, upgraded a small linear device. This machine, named BX-U (Beam Experiment Upgrade), is based on the Malmberg type trap [4] and equipped with a Marshall type plasma gun [5] at the end of the downstream of the device. The goal of BX-U is to demonstrate a fast azimuthal ion rotational flow which is perpendicular to **B** under the charge non-neutral condition and investigate fundamental physics of the non-neutralized two-fluid plasmas especially with the focus on the transport phenomenon related to the flow damping. A description of the BX-U device is explained in Sec. II. The first experimental data of pure electron plasmas and a summary are given in Sec. III and IV, respectively.

II   APPARATUS OF THE BX-U DEVICE

BX-U is a Malmberg type linear trap which is being constructed to investigate the fundamental plasma physics of (1) charge non-neutralization, (2) rotational ion flow induced by **E**, and (3) frictional damping of the ion flow. The primary objective of BX-U is to attain an enough confinement time ($\sim$ 1 s) of pure electron plasmas as a target plasma. Also, the degradation of confinement properties of the electron plasmas caused by an effective frictional force is studied.

Figure 1 shows a photograph of the BX-U device. It has a 15.0 cm inner diameter and 209 cm long vacuum chamber. Most of the vessel is made of 5.0


FIGURE 1. A photograph of the Beam Experiment Upgrade (BX-U). BX-U is one of Malmberg type traps with a plasma gun. This device is being constructed to investigate fundamental physics of electrically nonneutralized plasmas in a linear device on which difficulties encountered on experiments and data analyses in a toroidal geometry are eliminated.

mm thick aluminum (5052B). The device mainly consists of three parts: (1) the electron plasma source, (2) the central confinement region, and (3) the end region. A baking is available to obtain lower pressure, however, the vessel is usually pumped down by only a 250 liter turbo molecular pump and the pressure is about 6×10^{-9} Torr for the present experimental research.

The source region has originally been designed for a new plasma gun which is developed as a modified Marshall gun [5] having an electron source inside the inner electrode. However, only the electron source is so far placed there and the coaxial gun will be installed at the end region to avoid experimental difficulties. Regarding to the electron source, a five turns flat spiral Th-W wire is used. The diameter of the cathode is about 2.5 cm. And, it is directly heated with 12.0 A heater current to emit thermal electrons. About 0.5 cm away from the filament, a metal grid is located as an anode. The acceleration voltage is variable, but usually being set at -40 V. Thus, the space charge limited current from the e-gun is calculated to be about 15 mA enough to supply electrons to the central confinement region.

The central confinement region contains five cylindrical electrodes which produces a potential well to confine electrons. Each of them has 11.2 cm outer and 10.0 cm inner diameters and 9.5 cm long. All of them are made of copper (C1020B-F). Inside the vessel, these electrodes are electrically isolated from the vessel and axially aligned with 0.5 cm gap. Thus, it allows to externally supply independent voltage to each ring to form a negative potential well to trap electrons. The voltage is so far energized from the end region by DC power supplies through bus-bars with ceramic tube covers.
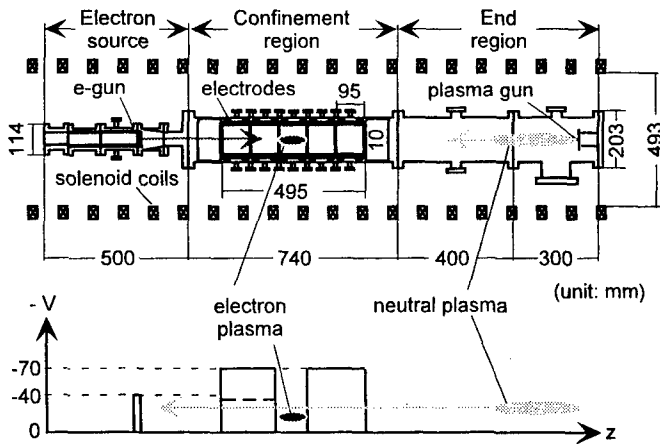
FIGURE 2. Axial profiles of negative potential to trap electron plasmas in the grounded cylindrical tube (the central confinement region) in BX-U. The electrons are injected through the front gate on which the bias voltage is electrically shuttered for 200 times every 2 ms interval.

In the end region, a Marshall type plasma gun will be installed to inject a neutral plasma into a pure electron plasma. However, for the purpose of the first experiments on the confinement properties of pure electron plasmas in BX-U, a metal plate has been so far placed there to detect the electron particle flux which flows out from the central confinement region after opening the potential barrier on the last electrode. By properly programming the gate opening time, the time history of total charge Q of the electron plasmas can be measured, which also provides the confinement time of the electron plasmas.

The Marshall type gun was originally developed for a study of cross-field plasma injection into an axisymmetric mirror machine with an internal ring [6]. The outer and inner diameters of the gun are 3 cm and 1 cm, respectively. Also, the length of the muzzle of it is 10 cm. A tiny magnetically acting valve is used in the middle of the inner electrode. To fire the gun, we will feed a power through an ignitron with 20 kV 9 μF capacitor banks.

On BX-U, the axial solenoidal field is produced by a set of 14 pancake-shaped coils which are energized by a DC power supply. The strength of the field is available up to ~ 0.3 kG. Thus, the value of the Brillouin density limit on BX-U is calculated to be in the range between 5×10^{14} and 8×10^{15} m^{-3}.

III FIRST DATA OF PURE ELECTRON PLASMAS

Since the device was completed in spring of 2000 except the plasma gun, we performed the first experiments to confine pure electrons in a negative potential well. Thermal electrons are extracted from the spiral Th-W cathode and accelerated up to ~ -40 V. The value of both the front and end gates is set precisely at -70 V for this experiment, while the center electrode is grounded to form a negative potential well shown in Fig. 2. When the negative potential of the front gate is down to ~ -40 V for ~ 0.4 ms every 2 ms interval, the thermal electrons enter the grounded cylindrical tube. This scheme is electrically repeated for 200 times to provide enough electrons. During the injection, the end gate is biased strongly negative $(-70$ V) to reflect the electrons.

At the first series of experiments, the time history of Q is measured as a function of axial magnetic field strength B_z. As seen from the data in Fig. 3, the confinement time τ_N of electron plasmas is about 0.3 s for $B_z \sim -50$ G if we define τ_N as $1/e$ folding time of Q.

Since the electron-neutral collision time can be calculated to be 0.3 s for the present background pressure, the observed τ_N seems to be governed by the classical binary collisions, suggesting that the BX-U device works well. However, when the strength of B_z is increased up to 150 G, τ_N decreases to 0.1 s, which is inconsistent with the empirical law observed in past Malmberg trap experiments [7]. The reason is unknown, but it should be attributed to
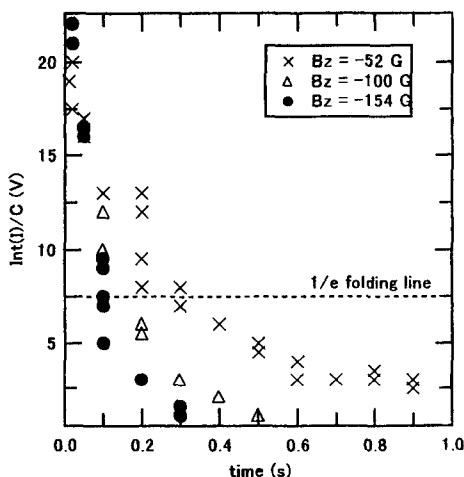
FIGURE 3. Time history of the total charge Q of trapped electrons in the grounded cylindrical tubes for the three different cases of axial magnetic field strength B_z. The value of Q is measured at the metal plate located in the end region. The data show that the confinement time τ_N is about $0.1 - 0.3$ s, however, it becomes shorter with stronger B_z.

some error of experimental setting such as the axial alignment of electrodes of the electron gun. Another possibility of the deterioration may be due to the large ratio of plasma radius to wall radius, which is 0.3 in this experiment. In fact, larger plasmas suffer much effect of the image charge induced on the wall which is one of key parameters to determine the stability property of electron plasmas. Thus, it might cause some macro instability such as the diocotron mode because the cyclotron frequency becomes faster for the stronger B_z cases.

IV   SUMMARY

A linear device, named BX-U (Beam Experiment Upgrade), has been constructed at the University of Tokyo. BX-U is one of the Malmberg type trap which creates a potential well with five cylindrical electrodes. The most significant feature of BX-U is that the device is equipped with a modified Marshall gun in order to inject a neutral plasma into a pure electron plasma. It thus offers an opportunity to explore a new regime of non-neutral plasma physics on which both ion and electron fluids are interacted each other under a charge non-neutral condition. The goal of BX-U is to investigate fundamental physics of ion perpendicular flow and the related phenomena of an electrically non-neutralized two-fluid plasma in a cylindrical geometry.

At the first series of experiments on BX-U, pure electron plasmas are confined in negative potential well. The confinement time is about 0.3 s for weak

B_z cases ($\sim$ 50 G). Since this time is comparable with the electron-neutral collision time ($\sim$ 0.2 s), the confinement properties of BX-U may be governed by the classical diffusion. However, the confinement time becomes shorter with stronger B_z. This seems to be inconsistent with the observations in past experiments on the Malmberg type trap. Further experiments are required to clarify the result.

ACKNOWLEDGMENTS

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