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Experimental Studies on Two-Fluid Plasmas by use of Lithium Ion and Electron Plasmas
リチウムイオン流体と電子流体を用いた２流体プラズマの実験的研究

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To answer for questions about two-fluid plasmas, we have started new experimental research by use of the remarkable properties of two non-neutral plasmas. In the experiment, a lithium ion (Li^+) plasma with a low density is used to enlarge the ion skin depth. Because of non-neutral plasmas, both ion and electron temperatures can be held down low, which can alleviate uncertainness due to thermal motions. In this conference, we present the motive, our experimental method, and the current status of this research, along with several simultaneous confinement data of Li^+ and electron plasmas.

1. Why Two-Fluid Plasma Difficult?

With progresses of theoretical and computational studies on plasmas, the "two-fluid plasma" not to be able to express by the simple definition for an ordinary plasma has become one of hot topics in many plasma-related fields. In general, it is considered that the ordinary plasma consists of enormous ions and electrons. And, when it starts to move, both the ion fluid and the electron one move together while they keep electrical neutrality.

In contrast, by the way of thinking called the two-fluid plasma, the ion fluid and the electron one can move independently each. As a result, there is more degree of flexibility of the two-fluid plasma than the one-fluid, that is, the MHD plasma on such properties as plasma motion, confinement, and stability. Using these unique features, many trials to explain phenomena that could never be understood by the knowledge of MHD have thus been performed flourishingly.

The two-fluid plasma model is not a novel way of thinking. About fifty years ago, in the bible of plasma physics, a detailed set of two-fluid plasma equations had been already derived [1]. And, from the obtained result, the famous transport coefficients were calculated. In view of this origin, the two-fluid plasma is classic rather than fantastic. A frontier of modern plasma science particularly the laboratory plasmas have finally, so to speak, arrived at the category of the two-fluid plasma model.

About the current trend of the experimental study on the two-fluid plasma, attentions are paid to “two-fluid effects” not directly to the two-fluid plasma. This is probably due to the fact that those two-fluid effects are thought to appear from the two-fluid plasma. Theoretically, typical driving terms of causing the two-fluid plasma state in the fluid equations are considered to be the diamagnetic current term and the hall one. Then, let us consider the plasma on which these terms act strongly. Perhaps one can list up several possible examples which include high-β plasmas such as FRC, a magnetic reconnection domain, a hall thruster, and space plasmas. Also, even in low-β plasmas showing diamagnetic distribution or a suppressed instability, some two-fluid effects are considered to participate locally.

However, there is little number of experimental reports mentioning about two-fluid effects. Besides, those papers have simply pointed out the possibility that the two-fluid effects participate in the observed results, by indicating, for example, the difference between the ion velocity field and the electron velocity one. This is probably attributed to the fact that the space scale showing the two-fluid effects is considered to the order of the ion skin depth λ_i. In general, λ_i becomes thin, for example, λ_i is ~ 0.1 cm for the ion density n_i of ~ 10^{13} cm^{-3}. Thus, the direct measurement will be difficult. Another difficulty is that the position targeted for the active measurement does not completely stay at the same location all the time but moves in time, because the two-fluid plasma is intrinsically dynamic, having velocity and electric fields [1]. This fact strongly suggests that some passive instruments, which can clearly measure changes in time of spatial distributions, are suitable.

Thereby, the understanding of the two-fluid effects are still poor, let alone the two-fluid plasma. From these reasons, the two-fluid plasma is like a puzzle, an open question for laboratory plasmas. More sophisticated new method is thus needed to understand the two-fluid effects and the two-fluid plasma as well. To answer for these questions, we proposed a new basic experiment of generating a two-fluid plasma state by merging a lithium ion (Li^+) plasma and an electron (e^-) plasma in a linear device.

2. Possibility of Direct Generation of Two-Fluid Plasma State by Use of Non-Neutral Plasmas

Both Li^+ and e^- plasmas are classified as a non-neutral plasma. The reason to be called in this way is because they are comprised only of a single sign of charged particles. Consequently, those plasmas are not neutral electrically, in other words, have strong self-electric fields **E**. So, when a non-neutral plasma is confined in a magnetic field **B**, it must always carry out a *fluid* movement **V** perpendicular to both **E** and **B**, called **E x B** fluid drift or **E x B** flow. Thus, in the case where both Li^+ and e^- plasmas are confined in the same **B**, they exhibit reverse motion each other in the direction perpendicular to **B**. If such two plasmas can be merged well together, then we may generate an initial state of a two-fluid plasma experimentally.

There are other reasons to use the non-neutral plasma. First of all, when we consider a cylindrical geometry, the density of the non-neutral plasma is limited by the Brillouin density [2]. This value is ~ 10^6 cm^{-3} for the Li^+ plasma when B ~ 1 kG, which is relatively low. As a result, λ_i of the Li^+ plasma is enlarged significantly. Here, assuming that the characteristic plasma length L, which is almost equivalent to the machine radius, is 10 cm, the value of L/λ_i becomes sufficiently small to around 0.01 where some two-fluid effects are expected to appear considerably; in theory, L/λ_i < ~ 30 is required. For ordinary MHD plasmas, L/λ_i < ~ 100, because of λ_i ~ 0.1 cm as mentioned.

The second reason is that the non-neutral plasma can be produced by a low energy beam, not the ionization of a neutral gas. For example, the e^- plasma is usually produced with some small filaments that can eject thermoelectrons. The produced e^- plasma is thus as *quiet* as plasmas in Q-machines. Plasma temperatures are also low; a couple of electron volts or less is the typical value without any cooling. These properties will remove uncertainness due to thermal motions of charged particles from fluid experiments, which actually the big advantage for investigating phenomena caused by the fluid motion.

The third reason is that the non-neutral plasma exhibits much of collective phenomena associated with ordinary neutral plasmas. For example, through a self-organization process of four e^- beams emitted from four filaments *apart from* the machine axis, a single e^- plasma can be successfully formed on the machine axis. In fact, this is the method that we employ to the BXU machine. Hence, the result outputted from the experiment using Li^+ and e^- plasmas will also have universality in plasma physics, although both density and temperature are extremely low.

The final reason is that the non-neutral plasma in cylindrical symmetry has superior confinement time. In principle, such a plasma can be confined forever. This property has been explained [2] by introducing the total canonical angular momentum P_θ. For non-neutral plasmas, P_θ is not only a constant of the motion but also a very strong constraint on the allowed radial positions of the charged particles. Due to the long confinement, the non-neutral plasma can be relaxed to thermal equilibrium with keeping P_θ.

Then, one may ask a fundamental question on P_θ. Will each P_θ be still conserved, even when Li^+ and e^- plasmas are merged together in the same **B**? In other words, do they maintain their initial motions so as to follow their fluid equations independently, Or do they form a single neutral MHD plasma quickly? To address the question, we will experiment it on BXU.

3. Current Status of BXU Experiment

Currently, we have successfully confined both Li^+ and e^- plasmas simultaneously. The confinement time of e^- plasmas is so far ~ 10 s longer than the binary Coulomb collision time. Thus, the e^- plasma is ready for the next merging experiment. On the other hand, the Li^+ plasma lasts only ~ 1 ms. To improve it, some methods for confining the Li+ plasma longer have been tested. Also, we have been developing several new diagnostics applied to the next merging experiment.

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