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Differential Ion Cooling in a Q-Device

by

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Abstract

A new method of ion cooling in a Q-device is described. Experiments show that a temperature ratio $T_e/T_i \sim 3$ is attainable, and that a high degree of ionization is maintained in the plasma column except for the small region where a dense neutral cloud is localized to perform the ion cooling through ion - atom collisions.

CONTENTS

I. INTRODUCTION

In recent experiments[1] it has been demonstrated that Landau damping of ion acoustic waves plays an important role in plasmas with $T_e \simeq T_i$, where T_e and T_i are the electron and the ion temperature respectively.

It has also been shown[2] that in a plasma with $T_e/T_i > 1$, Landau damping is partially eliminated. $T_e/T_i > 1$ is obtained by cooling the ions relative to the electrons; the cooling is effected by ion - neutral collisions, the neutrals being a cold inert gas (argon) covering the full plasma region.

In this report we describe experiments on differential ion cooling where $T_e/T_i > 1$ is obtained without lowering the degree of ionization. In the earlier experiments[2], in which a homogeneous neutral background was used for the cooling purpose, the ion - neutral collisions were not only effective in ion cooling, but also changed the dynamical behaviour of the ion fluid. This drawback is eliminated by the cooling technique described, in which the main idea is to localize a neutral Cs cloud in a small part of the plasma column and pass the plasma flow through this region.

II. EXPERIMENTS

The experiments were performed in the Risö Q-machine. As Q-devices[3] are in common use, only a short description is given. Fig. 1 gives an outline of the device with its new feature.

The plasma is produced by ionization of a neutral Cs beam on a hot Ta-plate. It is confined radially by a homogeneous B-field perpendicular to the Ta-plate and is terminated on the cold end plate. The diameter and length of the plasma column are 3 and 120 cm respectively. The ion and electron temperatures are normally assumed equal to the temperature of the hot Ta-plate, 2500 °K.

The new feature consists of a copper tube (4 cm Ø, 15 cm long) and an additional Cs oven (B, fig. 1). The temperature of the copper tube is raised to ~200 °C by radiation from the hot Ta-plate, and a neutral Cs beam is injected into the tube from the Cs-oven. In this way a dense cloud of neutral Cs is maintained in the tube, allowing a low neutral pressure in the main part of the vacuum vessel. This low Cs pressure outside the copper tube is obtained by cooling the walls of the vessel to ~-15 °C, at which temperature the Cs atoms escaping from the copper tube condense on the walls, leaving a Cs pressure $< 10^{-6}$ mm Hg.

Two sets of experiments were performed to examine this ion-cooling technique:

A. Experiments on the ion-cooling efficiency, and

B. Examination of the confinement of the neutral Cs cloud.

A. Ion-Cooling Efficiency

The method from recent experiments[2)] was used to estimate the ion temperature. The underlying idea is to measure δ/λ for small-amplitude ion acoustic waves excited by a plane grid immersed in the plasma. δ is the damping distance and λ the wave-length. From calculations based on Landau's treatment of the Vlasov equation, δ/λ is known to be a sensitive function of T_e/T_i.

Under normal conditions, i.e. without heating of the Cs oven B, the results shown in fig. 2 were obtained. Here the phase velocity v_{ph} and δ/λ are plotted as functions of frequency. It is found that $v_{ph} \simeq 2 \cdot 10^5$ cm/sec and $\delta/\lambda \simeq 0.7$, which is in accordance with theory if $T_e \simeq T_i$ and if the plasma drift velocity is of the order of the ion thermal velocity.

When the neutral Cs cloud is introduced by heating oven B, the results plotted in fig. 3 are obtained. The phase velocity is lowered to $v_{ph} \simeq 1.3 \cdot 10^5$ cm/sec, and δ/λ is increased to ~ 1.2.

Using these results and the computations of ref. 2, one obtains $T_e/T_i \sim 3$. This value is found to be an upper limit to the temperature ratio. If the density of the neutral Cs cloud in the copper tube is increased by further heating of the Cs-oven (B), the plasma density is found to decrease. This effect demonstrates, in itself, the interaction between the neutral cloud and the plasma flow.

It should be mentioned that a low-frequency and low-level noise is observed when the interaction between the plasma and the neutrals takes place.

B. Neutral-Cs Distribution

The distribution of neutral Cs was examined in another series of measurements. In this experiment the plasma was switched off by leaving the generating Ta-plate and the Cs-oven A cold during the measurements.

On a neutral detector, consisting of a positively biased hot tungsten wire and an outer collector (see insert fig. 4) we measured the saturation current (I_s) at different positions along the axis. In fig. 4 this current is plotted versus the distance from the centre of the copper tube to the detector.

It is found that $I_s \propto x^{-3}$ for $x > $ ca. 40 cm. This is the expected dependence under the assumption that all Cs-atoms are emitted from the inner surface of the copper tube and that the mean free path for atom - atom collisions is long compared with the dimensions of the tube.

At $x = 50$ cm a saturation current $I_s \simeq 1$ μA is found. This current, together with a filament area $A_f = 8 \cdot 10^{-6}$ m^2 (4 cm long, 0.2 mm diameter) and a thermal velocity of the Cs-atoms $C \simeq 0.3 \cdot 10^3$ m/s, gives a neutral Cs-density of $\sim 10^{16}$ m^{-3}. This density corresponds to a background pressure of $\sim 10^{-6}$ mm Hg, which is negligibly low in all cases of interest.

Inside the copper tube the Cs-density, n_o, has not been measured directly, but from the measurements of T_i we know that n_o is sufficiently high for ion - neutral collisions to be important. Consequently the mean free path for ion - neutral collisions, $\lambda_{in} = (n_o \sigma_{in})^{-1}$, where σ_{in} is the cross section for ion - neutral interactions, must be of the same order as the length of the copper tube or shorter. If the ion - atom interaction is a charge exchange process, then σ_{in} is known to be larger than σ_{nn}, where σ_{nn} is the atom - atom collision cross section. It is therefore possible to have a high ion - atom interaction rate in the cloud and a low rate of atom - atom collisions. The latter was assumed for the $I_s \propto x^{-3}$ dependence. If atom - atom collisions are important in the cloud, one would expect an $I_s \propto x^{-2}$ dependence; also in that case a sufficient degree of ionization would be possible in the plasma column.

III. CONCLUSION

The experiments demonstrate that it is possible in a simple way to control the temperature ratio T_e/T_i in the range 1-3 for a Cs-plasma in the Q-device. It is also shown that the neutral Cs cloud that performs the cooling is well confined by the copper tube, which allows a high degree of ionization in the main part of the plasma column. The latter condition is important in experiments where a neutral background pressure influences the plasma motion in an unwanted manner.

An example of the utility of the method is given in a recent experiment on collisionless shocks[4)] in a magnetic Laval nozzle[5)]. In ref. 4 the ions are cooled by the localized neutral cloud before they are accelerated through the Laval nozzle. If a homogeneous background pressure were used to produce the temperature ratio $T_e/T_i \sim 3$-4 as demanded by the theory[6)], the neutrals would also destroy the mode of operation of the magnetic Laval nozzle by placing a drag on the plasma flow. Therefore, differential ion cooling is necessary.

The method described may also be of interest in other types of experiments where the interaction between a Q-machine plasma and a neutral gas cloud is considered. Experiments on coupling between plasma oscillations and ordinary sound waves in a neutral gas are a nearby suggestion.

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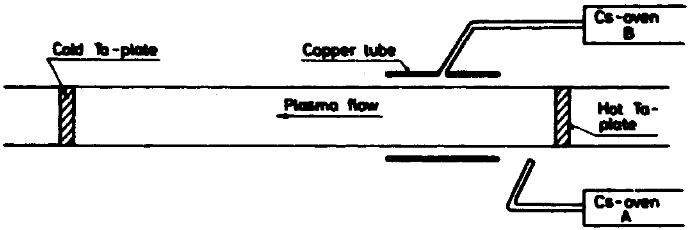

Fig. 1. Schematic of the experimental arrangement.

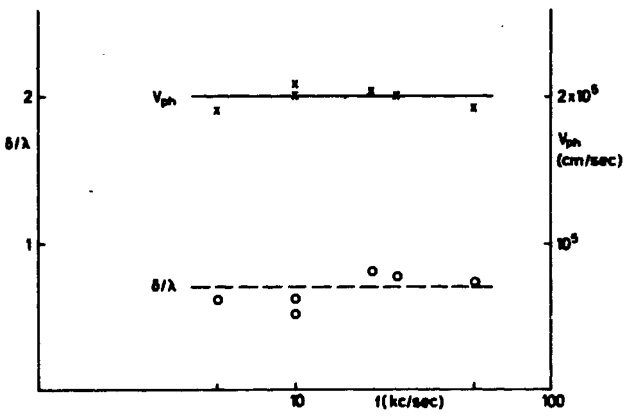

Fig. 2. Phase velocity v_{ph} and damping distance δ over the wave-length λ of an ion acoustic wave with the Cs-oven B cold.

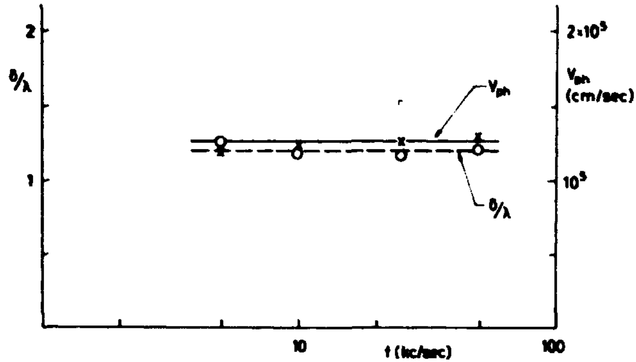

Fig. 3. As fig. 2, but with the Cs-oven B hot.

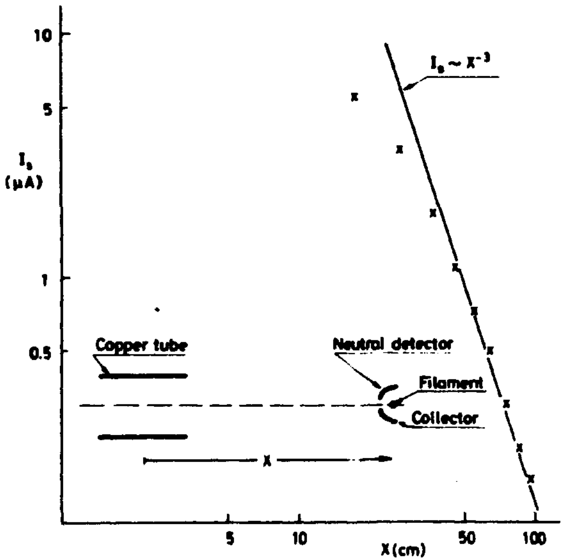

Fig. 4. Current to neutral detector versus the distance x from the centre of the copper tube to the detector.