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Compression features of high density electron plasma in a long harmonic trap using a rotating wall technique

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ABSTRACT

We studied radial compression features of electron plasmas in a Penning trap (an assembly of multi-ring electrodes (MRE) housed in a uniform magnetic field) using the rotating wall technique. The magnetic field was 5 T, and the MRE provide a long harmonic potential along the magnetic field axis. The compression features of the plasma were studied by varying the applied rotating electric field frequency, rotating electric field amplitude, compression time, as well as, the magnetic field strength in the Penning trap. The highest density achieved was $\sim 5 \times 10^{10}$ cm^{-3} and the compressed plasma shows slow expansion after the compression, with an expansion rate of 7×10^{-4} s^{-1}.

1. Introduction

Single component plasmas confined in a trap have been studied for many years [1–3]. A rectangular potential [4] or a harmonic potential is used to confine various single component plasmas in a uniform magnetic field [5] as well as in a non-uniform magnetic field [6]. A variety of charged particles such as ions [7], positrons [8], electrons [4], and antiprotons [9,10] are trapped. To confine long plasmas along the magnetic field axis, a Multi-Ring Electrodes trap (MRE) was developed [11].

Cold electron plasmas confined in a trap are used for various applications, including cooling of highly charged ions [12, 13], cooling of antiprotons for low energy antiproton collision experiments, including antihydrogen production [14–16], and for positron accumulation [17]. In these applications, high density and stable electron plasmas are necessary. To control and increase the plasma density, a so-called rotating wall (RW) technique was developed [18,19]. The first experiment successfully demonstrated the compression of 10^9 laser-cooled Mg^+ ions in a Penning–Malmberg trap [18]. The plasma was compressed gradually with increasing the RW frequency and reached a density of $\sim 2 \times 10^8$ cm^{-3} which is as high as ~20% of the Brillouin density limit. Following this experiment, the RW technique was applied to a plasma consisting of 10^9 electrons [19], where the plasma density was increased by a factor of 20 compared to the initial density employing the RW technique, and reached $\sim 1.4 \times 10^9$ cm^{-3}. It was also demonstrated in [19] that the compression rate was dependent on the drive frequency which was in resonance with the so called Trivelpiece–Gould (TG) plasma modes. The experiments reported in [20,21] were the first one that applied the TG modes to compress a positron plasma in a Penning–Malmberg trap.

Further, a compression of 5×10^8 electrons was reported in a cylindrical Penning–Malmberg trap without tuning to the plasma mode frequencies [22]. The plasma density increased with increasing f_{RW} and the density reached 3×10^{10} cm^{-3} at 8 MHz. The density enhancement stopped when the plasma rotation frequency reached the RW frequency. In [23] the rotating wall compression method was applied on a mixed cold antiproton and electron plasma in a 4.46 T Penning–Malmberg trap. Cold and dense non-neutral antiproton plasmas was obtained with particle densities $n \geq 10^{13}$ m^{-3}.

In this report, we present our recent progresses on the electron plasma compression in a harmonic potential with the RW technique. We systematically varied various parameters such as the compression time, RW frequency, RW amplitude, and the magnetic field strength for a plasma of 7×10^8 electrons.

2. Experimental setup

Fig. 1(a) shows a schematic drawing of the setup used in the present experiment, which consists of a superconducting solenoid containing an electron gun, a MRE, a Faraday cup (FC), and a CCD

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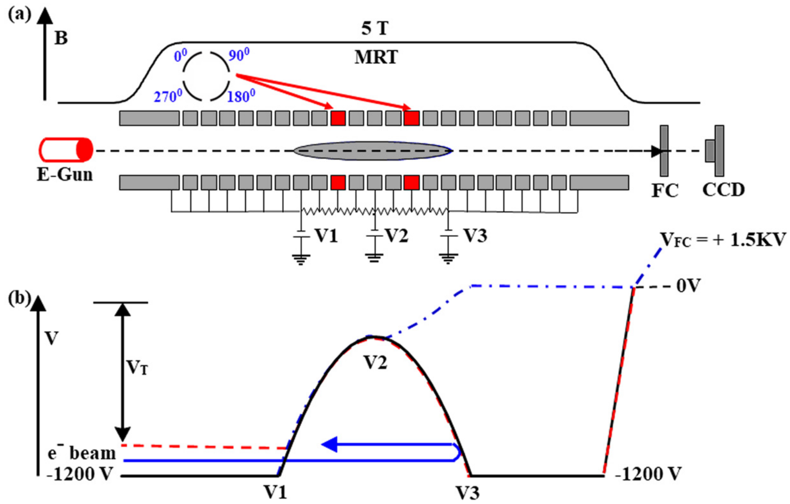

Fig. 1. (a) Schematic diagram of the experimental setup. (b) The potential distributions along the MRE axis during the electron accumulation (the red dashed line), holding (the black solid line), and extraction (the blue dashed–dotted line). (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

camera. The superconducting solenoid provides a magnetic field as high as 5 T. The uniformity of the field along the central trap section is better than 10^{-3}. More details of the experimental setup are given elsewhere [24,25]. The MRE [9] consists of 23 gold-plated copper cylindrical electrodes with the same inner diameter of 3.8 cm. All the electrodes are 2 cm in length and equally separated by 0.3 cm. Two of the electrodes are azimuthally segmented into four to allow application of a rotating field. At both ends of the MRE, two electrodes of 16 cm in length are attached. The MRE electrodes are assembled on a rectangular plate. The electrodes and the rectangular plate are made of gold-plated oxygen free copper. Aluminum nitride (AlN) is adopted as the insulating material, because of its high thermal conductivity, which is essential to cool the MRE effectively by the cold vessel still keeping electrical insulation. Three support rings with multi-contact bands on their outer surfaces allow effective thermal contact between the MRT and the vessel. The bands also absorb mechanical stress induced by heat cycles.

In the present experiment, nine electrodes are used to form the trap which corresponding to the trap length, L_T, of 20.7 cm (see Fig. 1). The MRE is housed in a cryogenic bore tube, which is thermally connected to a cryo-cooler and cooled down to about 10 K to prepare cold plasmas.

The background pressure of vacuum tubes at room temperature upstream and downstream of the cold bore was $< 7 \times 10^{-10}$ torr (the residual gas was mostly H_2 molecules) employing two sets of non-evaporable getter pumps (model GP100 MK5).

A great care was taken to align the MRE axis with the magnetic field axis. The bore tube that housed the MRE is supported by four rods (two rods at each end of the bore tube), which are moved by stepper motors. Each stepper motor can move with a step size of $\sim 10^{-3}$ cm, i.e., the MRE axis can in principle be aligned with the precision better than 10 μradian. The MRE axis and the magnetic field axis were aligned with each other by maximizing the plasma storage time.

Electrons are emitted from the electron gun with a cathode diameter of 0.145 cm. The electron gun is located at about 100 cm upstream from the center of the MRE, and the magnetic field strength at the electron gun is ∼1% of that at the center of the MRE.

The total number of electrons trapped in the MRE is determined by the charge collected during extraction at a fluorescence screen of 2.6 cm diameter, which is used as an FC. The front surface of the FC is made up of an aluminum-coated phosphor material based on an indium-tin-oxide glass plate.

The projected shape of the electron plasma in the MRE as well as the electron number in the plasma are monitored by extracting the plasma on a fluorescence screen with a diameter of 2.6 cm positioned at about 60 cm downstream from the end of the MRE. The magnetic field strength at the screen is ∼0.05 T, i.e., the image on the phosphor screen is magnified by a factor of 10. The image on the fluorescent screen is snapshotted by the CCD camera.

A harmonic well (see Fig. 1b) is prepared by applying proper voltages on the electrodes using a resistor chain which is biased by three DC power supplies V1, V2, and V3. The voltage applied on each electrode is given by $V(z) = V_T z^2/(L_T/2)^2$, where z is the axial central position (distance from the center of the MRE) and V_T is the trap depth which is given by V2–V1. Since the ratio between the electrode length (2 cm) to its diameter (3.8 cm) is as small as 0.53 in the main trap region, potential ripples caused by the arrangement of the electrodes become small, and the difference between the produced potential and a pure parabolic curve was within 0.2% on the trap axis.

The rotating wall field was provided by a function generator (Synthesized Signal Generator MG3641A/MG3642A, Anritsu). This module has one channel output which can be split into two using a 90° phase shifter. Each output was split again into two by using 180° phase shifter. The final four sine-wave voltages with a phase difference of 90° each (0°, 90°, 180° and 270°) were applied to the segmented electrode.

3. Measurements and adjustments

We accumulated and radially compressed the electron plasma in the MRE in the following steps:

(1) Prepare a harmonic potential well with the length of $L_T =$ 20.7 cm and depth of $V_T = 600$ V as shown by the solid line in Fig. 1(b). (V1 = V3 = −1200 V, V2 = −600 V.)
(2) Turn on an electron beam with its energy of 1040 eV. The electron beam is reflected in front of the entrance barrier (V1).
(3) Set V1 = −1034 V for an accumulation time t_a (see the red dashed line in Fig. 1(b)). The electron beam transmits over the entrance barrier into the MRE, and is then reflected at the potential wall at V3 = −1200 V, and again passes through the entrance barrier into free space. A part of incident electrons can be trapped in the MRE if the longitudinal energy is decreased. It was observed by [24] that the combination of the beam–beam interaction and the beam–plasma interaction, are